DEVELOPMENT OF THE BAMBOO TEST KIT-IN-A-BACKPACK

by

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This thesis documents the fabrication and use of the 'Bamboo Test-Kit-in-a-Backpack'. 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. The thesis documents proof of concept and validation testing ensuring that results from the test kit are comparable to those of a standard testing machine. A key objective of this work is to endure that tests and sample preparation are practical and simple to conduct on a remote construction site. One critical issue of test specimen tolerance – permitted out-of-squareness of specimen ends is also addressed.

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NOMENCLATURE

A_{culm} net cross section area of culm

D culm outside diameter taken as average of two orthogonal measurements, D_{NS} and D_{EW} at a section.

E_a apparent transverse modulus of elasticity determined from flexure test

E_φ apparent transverse modulus of elasticity determined from edge bearing test

f_{rNS} transverse modulus of rupture determined in N or S quadrants

f_{rEW} transverse modulus of rupture determined in E or W quadrants

h estimate of neutral axis location for curved rectangular beam

I_{culm} moment of inertia of net culm section

L length of culm specimen taken as average of four measurements, L_N, L_S, L_E and L_W

M_{NS} longitudinal moment determined in N or S quadrants

M_{EW} longitudinal moment determined in N or S quadrants

P load applied by the test kit corresponding to specimen failure

R characteristic radius of culm measured to center line of culm wall

t culm wall thickness taken as average of four measurements, t_N, t_S, t_E and t_W at a section

Δ relative vertical deflection between loaded points

Δ_1 displacement of culm 1

Δ_2 displacement of culm 2

σ_c compressive stress

σ_f flexural stress of full culm

τ_L shear strength parallel to fibers

Subscripts N, S, E, and W refer to quadrants of a culm section. These are marked when the culm is selected, prior to cutting, and used to maintain continuity in measured dimensions.

Definitions

Culm	stem of bamboo, typically hollow although solid in some species
Fiber	cellulosic fiber
Internode	region between two nodes in which fiber direction is longitudinal to axis of culm
Matrix	lignin that surrounds the fibers
Node	region of bamboo culm where fibers are no longer only longitudinal and form a thickened section from which leaves and buds emerge
Wall	the radial thickness of the hollow bamboo culm

Abbreviations

ASTM	American Society for Testing and Materials
COV	Coefficient of Variation
INBAR	International Network of Bamboo and Rattan
ISO	International Organization for Standardization
STD DEV	Standard Deviation

1.0 INTRODUCTION AND MOTIVATION

During my trip in 2013 to Brazil with three other Swanson School of Engineering students, we had the opportunity to visit a bamboo plantation, the village of Camburi, and collaborate with Prof. Ghavami and his colleagues at PUC-Rio (see also Richard et al. 2013). We learned a lot about the practical challenges of bamboo construction. Bamboo is a local resource in Brazil; it is thought to be more sustainable to build houses out of bamboo that is grown locally rather than shipping wood from a remote site. The problem is that the strength and mechanical behavior of bamboo isn't well known. Like wood, bamboo is a natural material whose strength varies with treatment, species, harvest, and location along the culm. As a result, it is very hard to predict the strength of the bamboo that is being worked with.

In 2008 and 2010, Dr. Sharma (2010), Derek Mitch (2009 and 2010) and others visited the Darjeeling region in North East India. They too reported considerable variation in bamboo quality and field practices in bamboo construction (Sharma et al. 2008).

A common thread in these observations is that the bamboo materials must be assessed in the field, typically by those completing the construction. Unlike with manufactured (steel) or highly processed (timber) materials quality is not assured *a priori* through standardization. Even site-processed materials, such as concrete, may be assessed *post priori* through standard testing. The potential for local harvest and use of bamboo, while an advantage in many respects, makes assessment of properties and quality control/assessment difficult. The work presented in this thesis represents one proposed means of addressing this challenge.

1.1 GLOBAL HOUSING PROBLEM

One of the biggest challenges to providing adequate housing to the currently 100 million homeless and the 1 billion living in informal settlements worldwide (Erguden 2001) is the ability to use local building materials and technology. With the world's current population growth, it is expected that this crisis will worsen. It is estimated that 95,000 single-family housing units need to be constructed per day to resolve this issue. About two thirds of the need is located in Asia and the Pacific region (Erguden 2001). Even within 'formal' settlements, it is estimated that one third of the world's urban population lacks adequate housing (UN-Habitat 2003). Proper housing allows for a higher quality of life and has numerous economic, social, and cultural impacts (Erguden 2001).

Bamboo can grow in temperate, sub-tropical, or tropical temperatures. 64% of all bamboo species grow naturally in Southeast Asia, 33% in Latin America, and 7% in Africa and the Oceana regions of the world ("Species" 2008). The areas of the world that have the largest need for informal housing have access to naturally grown bamboo. There are on the order of 1200 species worldwide, approximately 100 of these are suitable for load-bearing applications (Liese 1987) and perhaps 20 species are conventionally used for construction worldwide. The choice of species is based on geographic availability. Common species of large diameter bamboo used in construction include *Phyllostachys pubescens* (Moso; primarily in China), *Bambusa* *stenostachya* (Tre Gai; South East Asia), *Guadua angustifolia* (Guadua; South America), and *Dendrocalamus Giganteus* (Dendrocalamus; South East Asia).

Bamboo is often considered a sustainable option because of its quick regeneration. For construction purposes, bamboo can be harvested every three to six years, whereas softwood harvest cycles are about 15 years and hardwoods can be in excess of 50 years ("Uses" 2012). Furthermore, since wood takes so long to mature, it has become a scarcer resource over the years as it is often harvested in a non-sustainable manner.

Although bamboo has many sustainable advantages and is flexible, strong, and lightweight, which all contribute to its suitably as a building material, it is still a natural material whose strength varies depending on the species, age at harvest, geometry, moisture content, and treatment. These variations in strength can't be easily accounted for on the construction site without a suitable method of 'grading' the material. However, bamboo's strength varies between batches and changes with age and height (Wakchaure et al. 2012) making it hard to accurately predict the strength of the material that is being worked with.

Recognizing that bamboo is a locally-available potential solution to providing adequate housing for many developing countries, it is important to create a means of standardization of the material. Standardization allows builders to be more certain of the strength and expected performance of material they are working with. More importantly, standardization provides a "common language" that engineers and builders can use to describe bamboo materials. This is particularly crucial in light of the great variation of species and material properties worldwide. The first steps towards standardization are developing testing methods, and understanding the mechanics of the material in order to establish design criteria. As described in Chapter 2, a great deal of work in this regard has been conducted, although considerably more remains.

The next step toward standardization and therefore wider-spread application of bamboo as a construction material is developing field tests so that the strength can be determined on site. Such an approach may be similar to how the concrete slump test (ASTM C143) can be used to simulate the quality of concrete as it is placed. When we visited the small village of Camburi, the local builders indicated that they often overbuild in order to ensure the structure won't collapse (see Figure 1). Building materials are often the largest construction cost, accounting for 70% of a low-income informal housing unit (Erguden 2001). As a result, if the material costs can be reduced, less-expensive housing can be built.

a) Community center with overbuilt columns and roofing system.

b) Construction of welcome center with overbuilt columns supporting simple roof structure.

Figure 1: Examples of bamboo construction in Camburi, Brazil (photos by Cassandra Thiel).

Currently the world faces a housing crisis that will continue to worsen as populations expand. 330 million urban households around the world live in substandard housing or spend such a large percentage of their income on housing that they cannot afford other basic necessities such as food and health care (Harjani 2014). According to UN-HABITAT (2003), approximately 30% of the world's urban population lives in "slums". Slums are defined as "deplorable conditions where people suffer from one or more of the following basic deficiencies in their housing: lack of access to improved drinking water; lack of access to improved sewage facilities (not even an outhouse); overcrowded conditions; buildings that are structurally unsound; or living in a situation with no security of tenure (without legal rights to be where they are, as renters or owners)." ("Can …" 2015). There isn't only an issue with urban housing. The world's rural population experiences a similar housing problem. The UN similarly estimates that 35% of the world's rural population lives in unacceptable conditions. Overall, this equates to about 2 billion people around the world that need improved housing ("Can…" 2015). Improving housing for families, will improve their overall quality of life: upgrading their health, education, and employment (Harjani 2014).

One step towards ensuring affordable housing is making sure building materials are reasonably priced. For example, in most Latin American cities building codes and planning regulations have increased the cost of building homes. The regulations have "unrealistically high standards for subdivision, project infrastructure, and construction, mak[ing] it impossible to build low-income housing legally" (Gilbert 2000). Setting more realistic standards can help to reduce the cost of construction. Bamboo is a locally-grown and quickly-maturing resource that can be used for housing. If standards can be developed to learn the best ways to build with the material, building costs can be further lowered. Furthermore, standards are a necessity for building in an urban environment in order to ensure a degree of social and community governance. The resulting lower costs can help to alleviate the world's housing problem. Developing countries shouldn't necessarily develop in the same way that developed countries have in the past. Instead, they should utilize their local resources. Arctic peoples utilize ice for housing; in the southwestern U.S. adobe is part of the structural and architectural vernacular. Following this trend, local materials should be used for building materials.

1.2 BAMBOO

Bamboo is a lightweight material that is as strong as steel in tension and stronger than concrete in compression. It has a naturally efficient structural form because it is a functionally graded material both in section and along its length.

The structure of bamboo is composed of culms (stalks) with solid transverse diaphragms or 'nodes' separating hollow inter-nodal regions along its height (Fig. 2a). The circular cross section (Figs 2b) is composed of unidirectional cellulosic fibers oriented parallel to the culm's longitudinal axis embedded in a parenchyma tissue matrix (Janssen 2000). Bamboo is a functionally graded material (FGM) that has evolved to resist its primary loading in nature: its own self-weight and the lateral loading effects of wind. As seen in Fig. 2c, the density of fibers increases from the culm's inner wall to the outer wall. The wall thickness is largest at the base of the culm and decrease with height up the culm. However, the size and quantity of vessels decrease with the height of the culm (used for nutrient transport, their volume may be reduced with increased culm height) and are replaced with bamboo fibers. This addition of fibers compensates for loss in strength and stiffness due to reductions in diameter and wall thickness near the top of the culm, resulting in relatively uniform engineering properties along the entire culm height (Amada et al. 1996). Finally, the thin, dense, silica-containing outer layer of the culm wall serves as protection for the plant but can dull tools when bamboo is used in construction.

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

b) cross section of culm near node diaphragm

c) section through culm wall

Figure 2: Anatomy of bamboo culm (Richard 2014).

Bamboo is also a promising material for earthquake prone regions (Sharma 2010). In January 1999 there was a catastrophic earthquake in central Colombia that exemplified the earthquake resistance of bamboo as a building material. As a result of the earthquake, 70% of the recently built concrete and brick structures failed, while virtually all of the older village buildings made of bamboo remained un-damaged (Goldsmith 2011).

Although bamboo is an extremely practical building material in terms of strength and availability, there are constructability issues associated with bamboo's round shape. Crafting well-made connections that don't expand and contract with seasons (Goldsmith 2011) is difficult and a problem often encountered in the field. Additionally, every species of bamboo has its own structural and mechanical properties. The diameter of a culm can vary up to 200 mm. Proper treatment is also very important to the durability of bamboo. However, some treatment techniques work better than others in preserving bamboo. As a result of the variability in joints, structural properties, size, geometry, and treatments of bamboo, it is important to have some means to evaluate the strength of the culm on site so that bamboo can be used more efficiently and does not have to be overbuilt (Schroder 2010).

2.0 THE NEED FOR FIELD STRENGTH TESTS AND CONSTRAINTS

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.

The objective of developing the portable test-kit-in-a-backpack (the "kit") described in Chapter 3 is to allow the strength of bamboo to be evaluated on site – using appropriate accessible technology - so that resulting structures have a consistent and predictable degree of safety against collapse. Alternatively, such a kit provides a means for builders to rapidly assess the quality of the material they have at hand. This objective directly relates to the fundamental human right of 'safety in the built environmental' (UN-UDHR 1948) and helps to address the global grand challenge of community resilience and sustainability.

2.1 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 22156:2004a] and for determining the mechanical properties of bamboo [ISO 22157-1:2004b and ISO 22157-2:2004c]. 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 on 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 summarized by Harries et al. [2012] and are presently (late 2015) being revised and updated by ISO TC 165. Additional details of the test methods adopted in this work are presented in Chapter 4.

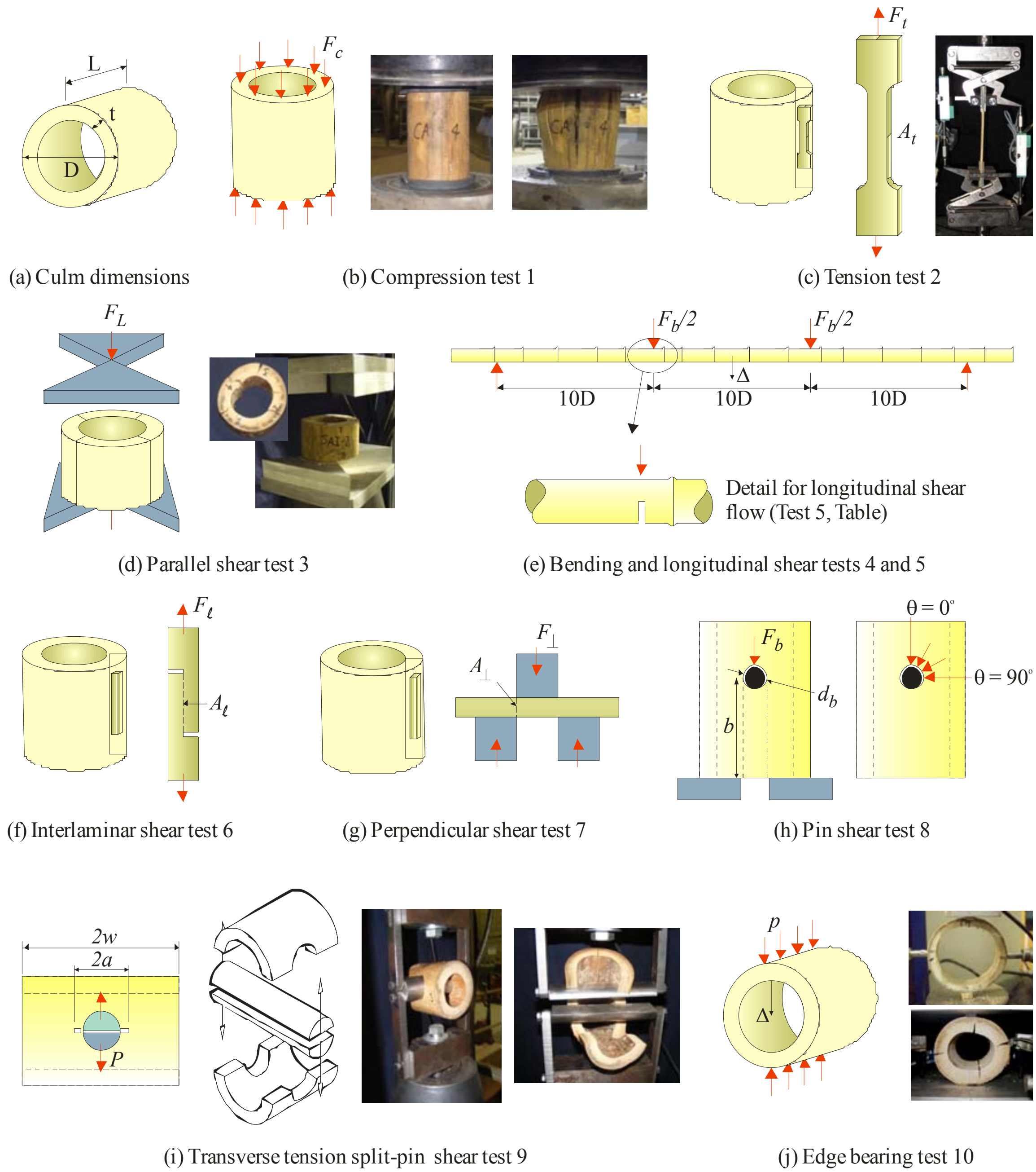


Figure 3: Bamboo Mechanical Property Tests for Bamboo (Harries et al. 2012).

2.1.1 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 other-than ‘scientifically advanced’ nations, 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 (Richard 2013). 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. The extent to which the ends need to be parallel will be investigated in Chapter 6.

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 (ASTM C39). Even the so-called "direct tension test" (ASTM C496) is based on testing a concrete cylinder under a longitudinal compressive load.

2.1.2 INBAR Field Test Methods

The International Network for Bamboo and Rattan (INBAR) is an intergovernmental organization whose purpose is to improve "the livelihoods of the poor producers and users of bamboo and rattan within [the] context of [a] sustainable natural environment." INBAR attempts to accomplish their goal of sustainable development with bamboo and rattan by "consolidating, coordinating, and supporting strategic, adaptive research and development." The efforts to increase the usage of bamboo stems from their desire to improve the safety, durability, and comfort of bamboo structures. Their work revolves around sharing the traditional technologies already developed, developing new technologies and designs, and providing standardization for design and testing. As part of their mission to make bamboo a more widespread material, INBAR (in Nepal) recently developed a series of non-destructive field tests to evaluate bamboo as a construction material. As seen in Figure 4, the design of the "Nepal" test kit included multiple steel frames that could test bamboo culms at full length, full culm compression and flexure as well as the compression of joints. The work reported here aims to create a single apparatus that is smaller, lighter, more versatile and affordable, and user-friendly. In addition, selecting test methods useful to those working in the field was considered.

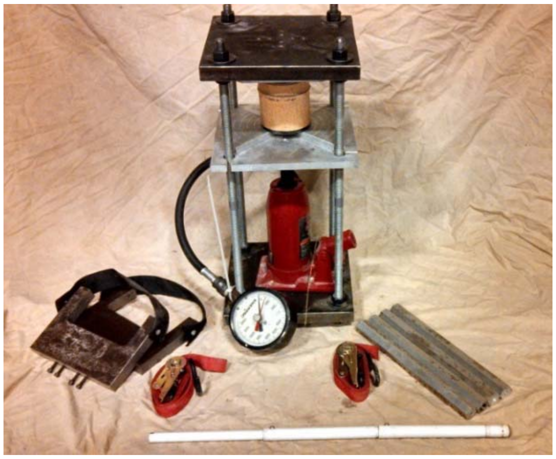
a) connection test b) full-length compression test c) flexural test

Figure 4: “Nepal” test kit (photo: Nripal Adhikary).

3.0 BAMBOO TEST-KIT-IN-A-BACKPACK

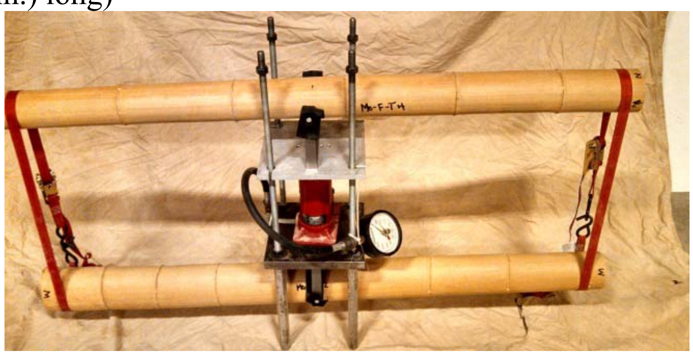
The bamboo test-kit-in-a –backpack ("kit"), shown in Figure 5, is intended for rapid in-the-field assessment of bamboo material properties. It is designed to be an inexpensive, robust, portable test apparatus that may be carried, assembled, operated, and maintained by a single technician. Presently the kit supports full-culm compression, longitudinal shear ('bowtie' test), edge bearing, and culm flexural tests (each is described in Chapter 4). Additionally, it could be further adapted for pin shear tests, connection testing, and a number of small clear specimen tests. This prototype kit 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. The prototype kit shown weighs approximately 40 kg, although this can be easily made lighter by judicious use of aluminum rather than steel (the moving load plate in the prototype shown is aluminum, for instance) and/or by machining unnecessary material from the fixed load plates.

Figures 6 and 7 provide drawings documenting the fabrication of the kit prototype. Following this, guidance for scaling or assembling variations of the kit is provided.



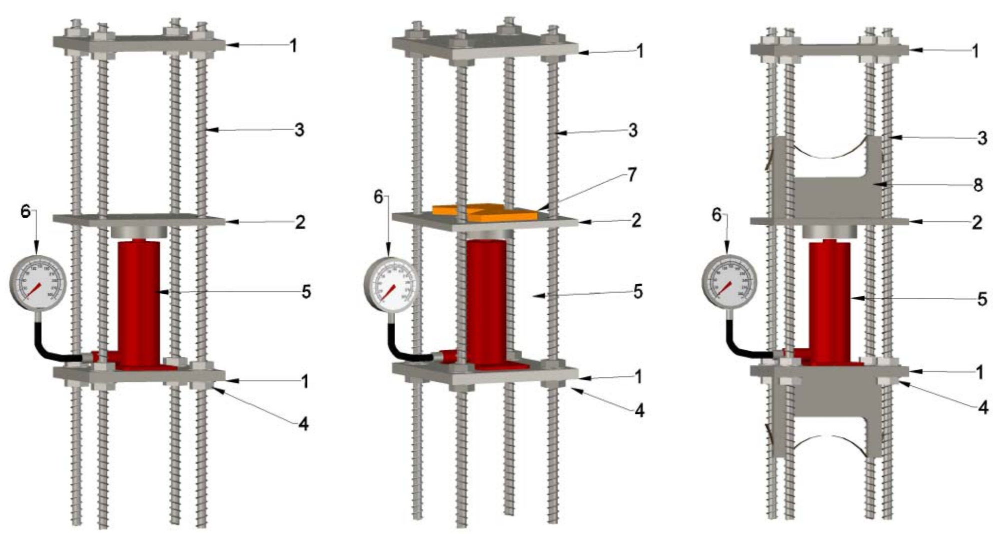
a) test kit (white pump handle is 600 mm (24 in.) long)

b) set-up for longitudinal shear test



c) set-up for short culm flexure test

Figure 5: Prototype test-kit-in-a-backpack.



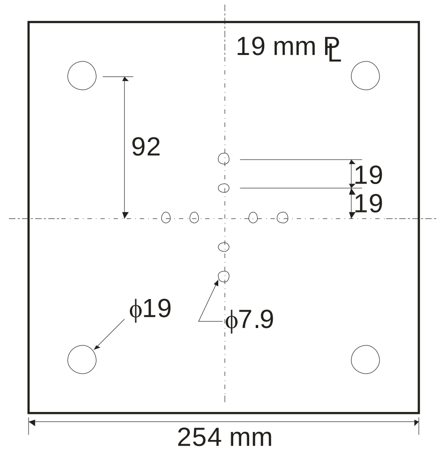
1. 254 x 254 x19 mm fixed reaction plates (2 required; see Fig 7a)
2. 254 x 254 x 12.7 mm moving load plate (see Fig 7b)
3. 16 mm x 1000 mm long threaded rod (4 required)
4. nut and washer assemblies for rods (16 required)
5. 72 kN hydraulic cylinder (bottle jack)
6. high precision pressure gauge
7.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

a) assembly for compression and edge bearing tests

b) assembly for longitudinal shear test

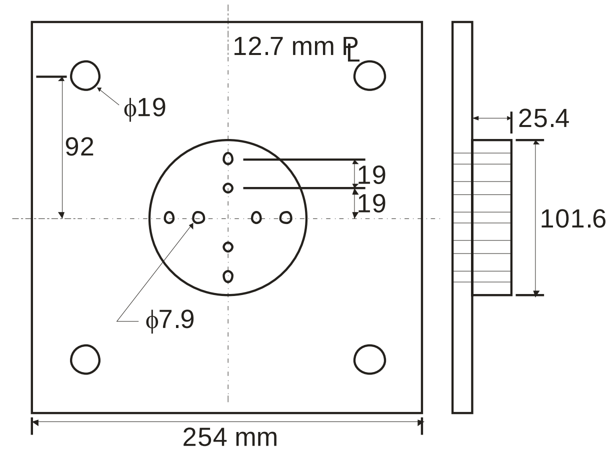
c) assembly for flexure test

Figure 6: Prototype test kit assemblies.

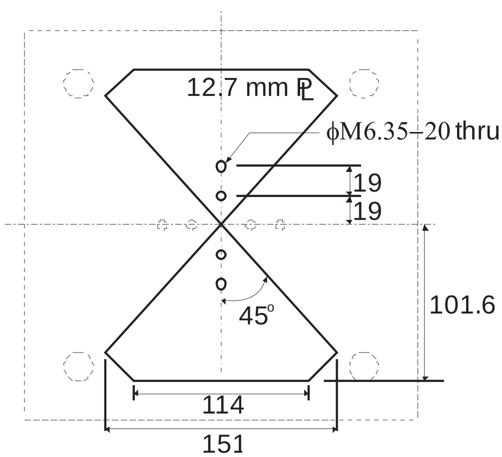


central hole pattern to match hydraulic cylinder base plate

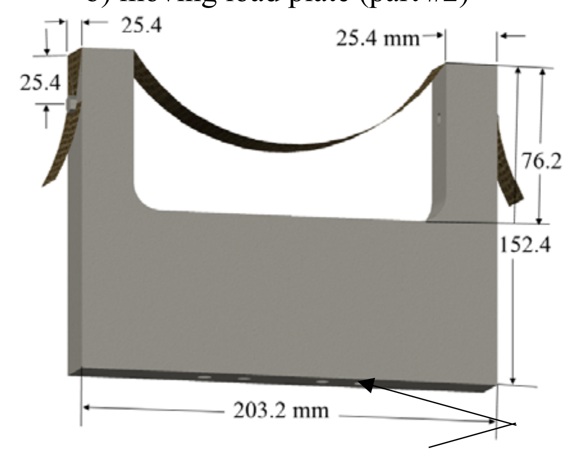
a) fixed reaction plates (2 assemblies; part #1)



b) moving load plate (part #2)



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



hole pattern to match central hole pattern in Fig. 7a

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

Figure 7: Prototype test kit plate details.

3.1.1 Assembly

The reaction plates (part #1 in Fig. 6) 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 '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 center 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. Longer ‘legs’ can be added to the threaded rods to further increase the height of the kit. The extra height is primarily needed for the flexure test in which a full culm is placed beneath the lower reaction plate.

3.1.2 Considerations in Altering or Scaling the Kit

The kit may be scaled up to some extent (scaling down may also be appropriate, although capacity to conduct full-culm compression may be limited). The kit can be scaled up using cables as an alternative to the rods. Cables were originally explored as a more portable option for the test kit. The cables allow the same frame of the kit to be used, providing a larger opening for samples to be tested. The advantage of using longer cables as opposed to longer rods is that the cables can be wound up after use and stored in a backpack achieving a primary goal of the design of the test kit: portability. However after initial testing, the cables proved to be too unstable for ease of use. With the rods, the test kit can be operated and set up by one user; whereas, the cables would require two users for setup. One user would have to hold the upper plate while the second user centered the culm in the apparatus. The possibility of building a stand to hold the top plate was explored and would permit longer specimens to be tested. Although the cables require two operators, there is potential in the cables for larger culm testing and connection testing. In the field, many different methods for connecting bamboo are used. The strength of these connections are often unknown. The kit could help to assess the capacity of connections.

Primary design considerations of the kit include:

Selection of threaded rods – together, these should have a tensile capacity exceeding twice (providing a factor of 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 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. Typically, load spreading is assumed to occur at an inclination of 30° (1:2 slope). Therefore the minimum loading plate thickness (t_p) is a function of the maximum culm diameter (D) to be tested and the hydraulic cylinder diameter (d_c):

$$t_p > \tfrac{1}{4}(D-d_c) \quad (2)$$

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 (P_c), and the yield strength of the plate (F_y):

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

In which the factor 1.8 accounts for a strength reduction factor for the plate equal to 0.90.

It is also suggested that concentric circles be scribed onto the loading and reaction plates to help to center specimens over the hydraulic cylinder.

3.1.3 Test Kit Pressure Gage and Force Conversion

In order to obtain load readings, the hydraulic cylinder must be fitted with a pressure transducer. In the prototype, a precision dial-type pressure gage having a peak needle was used (part #6). The force applied by the cylinder is equal to the product of the 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 a 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:

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

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

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

4.0 TEST METHODS

The following describes the use and limitations of the kit. A simple graphic manual has been produced and will be made available through INBAR. At this time, the manual is available in English, Spanish, Chinese, and Portuguese. Additional versions in Indonesian and Hindi are in preparation.

4.1 BAMBOO SPECIMEN GEOMETRY

The following notation is used for the full-culm bamboo specimens used (see Figure 8):

D = culm outside diameter taken as average of two orthogonal measurements at any section

$$D = (D_{NS} + D_{EW})/2 \quad (5)$$

t = culm wall thickness taken as average of four quadrant measurements at any section

$$t = (t_N + t_S + t_E + t_W)/4 \quad (6)$$

L = length of culm specimen taken as average of four quadrant measurements

$$L = (L_N + L_S + L_E + L_W)/4 \quad (7)$$

The following geometric properties of a culm section are therefore obtained:

$A_{culm} = (\pi/4)(D^2-(D-2t)^2)$ = net cross section area of culm (8)

$I_{culm} = (\pi/64)(D^4-(D-2t)^4)$ = moment of inertia of net culm section (9)

$R = 0.5(D-t)$ = [characteristic] radius of culm measured to center line of culm wall(10)

Additionally,

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

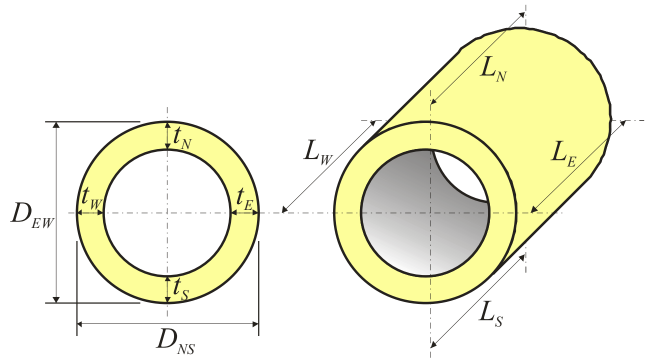


Figure 8: Full-culm specimen dimensions.

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

4.2 CONCENTRIC COMPRESSION TEST

This test method is reported in ISO 22157-1 (2004b). The kit is assembled as shown in Figure 9 and the culm specimen is centered 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 (discussed in greater depth in Chapter 6). Loading is applied through the hydraulic cylinder at a rate that results in failure in approximately two 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.

Figure 9: Concentric compression test.

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: $L \leq 2D$[1]:

$$\sigma_c = P/A_{culm} \quad (11)$$

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:

$$E_c = (\sigma_c@80\% - \sigma_c@20\%)/(\varepsilon_{avg}@80\% - \varepsilon_{avg}@20\%) \quad (12)$$

It should be noted that using strain gauges may not be practical in the field due to the high cost. However, the modulus remains as a practical value for determining the behavior of a material.

[1] Proposed revisions to 22157-1 provide for specimen length equal to the lesser of the outer diameter, D, and 10 times the wall thickness, 10t; however if D is 20 mm or less, the height may be taken as twice the outer diameter, 2D, irrespective of t.

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.

4.2.1 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. Center 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. 11.

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. 11) at each load step and plot the resulting stress-strain curve. The compressive modulus is calculated from Eq. 12.
10. Calculate the ultimate compressive stress from Eq. 11.

4.3 LONGITUDINAL SHEAR (‘BOWTIE’/ ‘BUTTERFLY’) TEST

This test method is reported in ISO 22157-1 (2004b). The kit is assembled as shown in Figure 10 using the ‘bowtie’ insert plates (parts #7; Fig. 7c). The culm specimen is centered 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.

Figure 10: Longitudinal shear test.

The shear strength of the bamboo parallel to the fibers (τ_L) is determined from a specimen whose length is equal to the outer culm diameter (L = D) (see footnote 1). The applied load (P) is distributed over the sum of the shear areas of all four assumed failure planes (i.e.: 4Lt):

$$\tau_L = P/4Lt \quad (13)$$

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. 13 is used and may be interpreted as the lower bound shear strength.

4.3.1 Summary of Test Method:

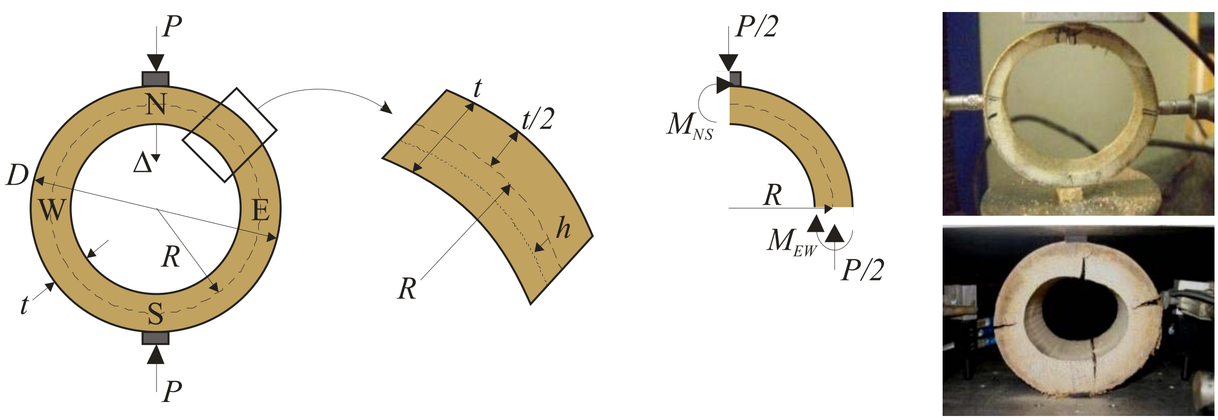
1. Assemble test kit as shown including the bow-tie plates; ensure that the bow-tie plates are oriented in opposite directions on each plate.
2. Cut specimen length such that L = D. Specimen ends should be smooth, parallel and at right angles to culm axis.
3. Obtain dimensions D, t, and L of culm specimen.
4. Center 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.

4.4 EDGE BEARING TEST

The edge bearing test described here and shown in Figure 11 has been developed and formalized by Sharma et al. (2012) although 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 behaviors. The complex failure mechanism of an edge bearing test involves the formation of a pair of multi-pinned arches (seen in Fig. 12d) 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 is a measure of the transverse tension capacity of the culm wall and therefore a quantification of the splitting behavior. 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.

Figure 11: Edge bearing test.



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 12: Edge bearing test specimen geometry and internal reactions.

The edge bearing test is composed of a full culm specimen loaded in compression along the longitudinal axis of the culm (Figs 11, 12a and 12d). The culm specimen is centered 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. 12a). 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 two minutes.

The test is used to determine the transverse (or through-wall) modulus of rupture (f_r) for the culm walls (Eq 14) – 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 and violate plane strain assumptions. Nodes should be excluded from specimens.

	sections along NS axis	sections along EW axis	
transverse (or through-wall) modulus of rupture	$f_{rNS} = M_{NS}\dfrac{12\left(t/2 + h\right)}{Lt^3}$	$f_{rEW} = M_{EW}\dfrac{12\left(t/2 + h\right)}{Lt^3} - \dfrac{P}{2Lt}$	(14)
Where:			
longitudinal moment at quadrant; see Fig 12c	$M_{NS} = \left(\dfrac{PR}{\pi}\right)\left(1 - \dfrac{t^2}{12R^2}\right)$	$M_{EW} = \left(\dfrac{PR}{\pi}\right)\left(1 - \dfrac{t^2}{12R^2}\right) - \dfrac{PR}{2}$	(15)
estimate of neutral axis location for a curved rectangular beam [Young 1989]; see Fig. 12b	$h = R - t\Big/ln\left(\dfrac{2R}{t} + 1\Big/\dfrac{2R}{t} - 1\right)$		(16)
characteristic radius of centerline of culm wall; see Fig. 12a	$R = 0.5(D-t)$		(10)

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 12a 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).

$$E_{\varphi} \approx \frac{3PD^3}{2Lt^3\Delta}\left(\frac{\pi k_1}{4} - \frac{2k_2^2}{\pi}\right) \tag{17}$$

In which: $k_1 \approx 1 + \frac{7.6t^2}{12D^2}$ and $k_2 = 1 - \frac{t^2}{3D^2}$ (18 & 19)

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.

4.4.1 Summary of Test Method:

1. Assemble test kit as shown.
2. Cut specimen length such that L ≈ 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 centered over hydraulic cylinder.
5. Center 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. 14.

If vertical deflection (Δ) was measured, the apparent transverse tangent modulus of elasticity (E_φ) is calculated from Eq. 17.

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, P_i 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. 14.
12. The apparent transverse tangent modulus of elasticity (E_φ) at any step, i, is calculated from Eq. 17 using P_i and Δ_i.

4.5 FULL-CULM FLEXURAL TEST

This test, shown in Figure 13, is modified from the flexure test reported in ISO 22157-1 (2004b) and is based on work completed by Richard (2013). Significant differences from the ISO test include:

- The kit utilizes a midpoint flexural arrangement rather than the third point arrangement promulgated by ISO 22157-1.
- The culm length-to-diameter impacts the mode of failure. Proportionally longer culms are dominated by flexural behavior while shorter culms will be shear critical. However, 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 utilizes '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 the two-culm system. A method for measuring the true displacement of either culm is shown in Figure 14.

Using the flexure saddles (Fig. 7d; 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 13. Alternatively, one culm may be replaced with a steel pipe (or similar) to provide the required reaction, and provide a means of calculating deflection of part of the self-reacting system (Fig. 14b). Using the steel pipe (or similar) will permits the displacement of the test culm to be determined more easily as described in Figure 14.

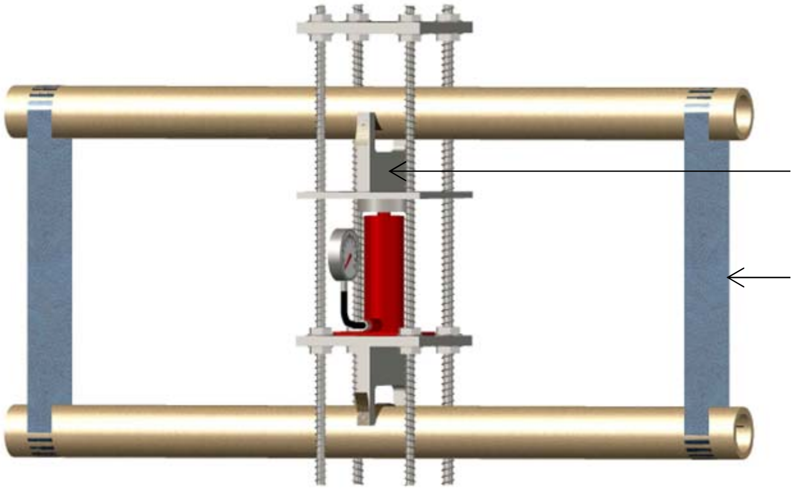


Figure 13: Full-culm flexure test.

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

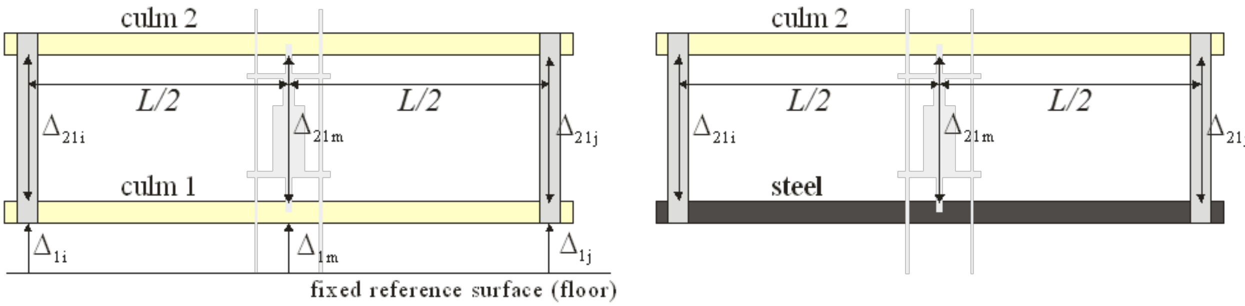
$$\sigma_f = PLD/8I_{culm} \quad (20)$$

It is important to recognize that σ_f 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 fibers. 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.

$$E_a = PL^3/48\Delta I_{culm} \quad (21)$$

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



a) two self-reacting bamboo culms midspan displacement of culm 1:

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

midspan displacement of culm 2:

$\Delta_2 = \Delta_{21m} - 0.5(\Delta_{21i} + \Delta_{21j}) - \Delta_1$

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

midspan displacement of culm 1:

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

midspan displacement of culm 2:

$\Delta_2 = \Delta_{21m} - 0.5(\Delta_{21i} + \Delta_{21j}) - \Delta_1$

Figure 14: Methods for calculating individual culm displacements.

4.5.1 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 using the same L/D ratio.
3. Obtain dimensions D, and t of culm specimen.
4. Center 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).

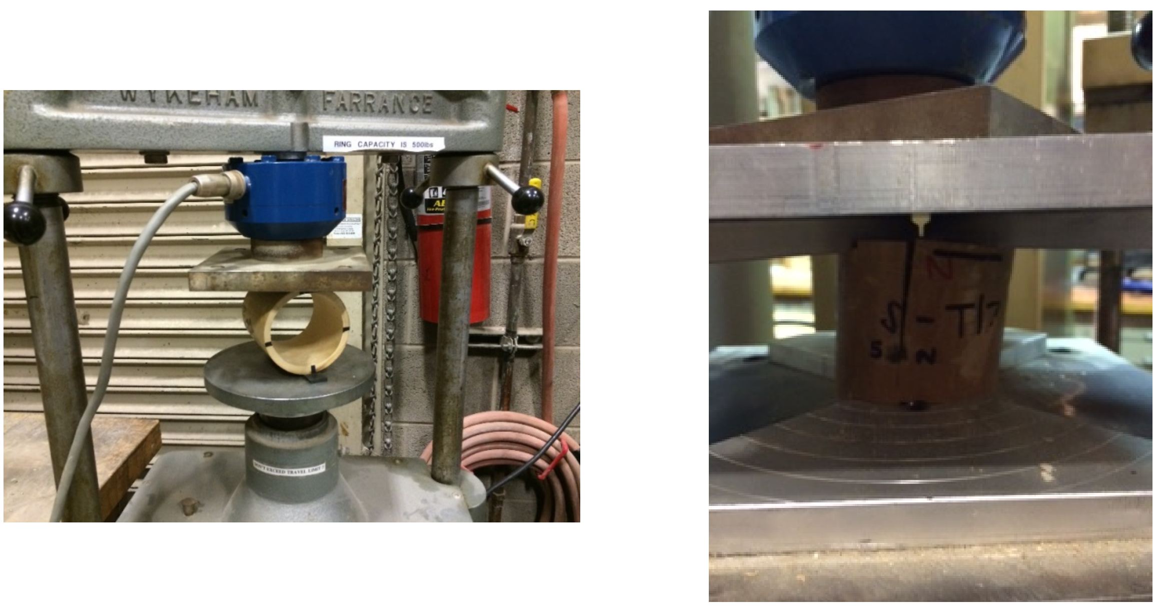
5. Extend the hydraulic piston until the culms are snug against the straps and the culms are parallel; adjust the strap lengths until the culms are parallel keeping the straps equidistant from the saddle.
6. Measure the tested length of the culm, L, as the distance between the centerlines of each strap; 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. 20.
10. If net culm deflection at midspan (Δ) was measured, the apparent transverse tangent modulus of elasticity (E_a) is calculated from Eq. 21.

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. 20.
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. 21.

5.0 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 customized mechanical test frame (MTF). The MTF, shown in Figure 15, is equipped with a calibrated and certified 44 kN (5 ton) 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.



a) edge bearing test b) longitudinal shear test

Figure 15: Mechanical test frame.

Ten sets of four adjacent specimens, all having L = D, were obtained from Moso (*Phyllostachys heterocycla pubescens*) culms and twenty similar sets of two adjacent specimens were obtained from Tre Gai (*Bambusa stenostachya)* 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 material properties and variation of properties. Test results are given in Tables 1 and 2 for Moso and Tre Gai, respectively.

In each case, the statistical p-values (exceeding 0.80 for Moso and 0.7 for Tre Gai) reported in Tables 1 and 2 indicate that the culm diameters (D) and wall thickness (t) dimensions were statistically the same for each test series.

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.

Table 1: Comparison of kit and MTF-generated data (Moso).

	Kit			**MTF**			**p-value**
	n	Mean	COV	n	Mean	COV	
Longitudinal Shear Test							
D	9	83.03 mm	0.12	10	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 N/mm^2	0.12	10	12.69 N/mm^2	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	13.4 N/mm^2	0.35	9	12.5 N/mm^2	0.22	0.37
f_{rNS}	2	20.2 N/mm^2	0.08	1	24.3 N/mm^2	-	-
E_φ	9	1707 N/mm^2	0.23	10	1804 N/mm^2	0.33	0.68

Table 2: Comparison of kit and MTF-generated data (Tre Gai).

	Kit			MTF			p-value
	n	Mean	COV	n	Mean	COV	
Longitudinal Shear Test							
D	11	69.72 mm	0.12	10	66.40 mm	0.13	0.85
t	11	19.87 mm	0.14	10	19.45 mm	0.13	0.73
τ_L	11	7.12 N/mm^2	0.45	10	6.34 N/mm^2	0.35	0.43
Edge Bearing Test							
D	12	82.05 mm	0.03	12	81.86 mm	0.03	0.81
t	12	19.3 mm	0.11	12	19.30 mm	0.14	0.92
f_{rEW}	7	25.71 N/mm^2	0.22	10	25.76 N/mm^2	0.34	0.99
f_{rNS}	8	32.68 N/mm^2	0.36	10	36.39 N/mm^2	0.33	0.50
E_φ	12	139.1 N/mm^2	0.24	12	189.7 N/mm^2	0.28	0.56

The results from the kit and those from the MTF are shown to be statistically similar (p-value in Tables 1 and 2) and to yield similar coefficients of variation (COV in Tables 1 and 2) indicating that the kit has essentially the same performance as the MTF which has high precision displacement control and a calibrated load cell.

6.0 EFFECT OF SPECIMEN END SQUARENESS FOR COMPRESSION TESTS

The issue addressed in this chapter has been raised in discussion of the revisions of ISO 22157[2]. Anecdotally, achieving parallel specimen ends, as is required for compression and shear testing, is especially difficult in the field using the typically available [hand] tools. For this reason, the edge bearing test is particularly attractive. However both the compression test and longitudinal shear test are conducted regularly and are familiar to practitioners since both are addressed in ISO 22157-1 (2004b)

The ISO standards state that compression tests and shear tests must be conducted with specimen ends cut parallel to each other. The problem lies in the word "parallel." In the field, hand saws are typically used to cut culms to length. The tough nature of bamboo and the often 'flimsy' nature of a hand saw blade make achieving parallel ends difficult. For instance, using a typical rip saw, the relative slope (see section 6.1.1) of cut specimen ends varied from 3.5 to 25%. Using a tensioned bow saw (see below), this was significantly improved to a maximum slope of only 5% with one specimen exceeding this at 8%.

Even using an electric cut-off saw has difficulties since the edges of the culm may not be parallel, making use of even a jig or miter box difficult. In the laboratory, what is often done is the culms are first cut to length and then a belt sander is used to achieve parallel ends; a solution

[2] The author attended an ISO TC 165 meeting in Winnipeg in August 2015.

not practical in the field. This chapter investigates the question: *How parallel is 'parallel enough'?*

6.1 TEST PROGRAM

ISO 22157 (2004b) culm compression tests were conducted on specimens having their ends intentionally cut to be non-parallel. The following sections describe the test program conducted.

6.1.1 Measuring degree to which ends are parallel

The slopes of the ends of the saw-cut samples were determined by measuring the heights (cut sample length) at eight sections around the specimen as shown in Figure 16. To determine the maximum slope, the difference in height between the opposite sectors (i.e., 1 and 5; 2 and 6; etc.) was divided by the outer diameter of the sample across these sectors. The sample was classified based on its maximum slope, since this section typically controlled the behavior of failure.

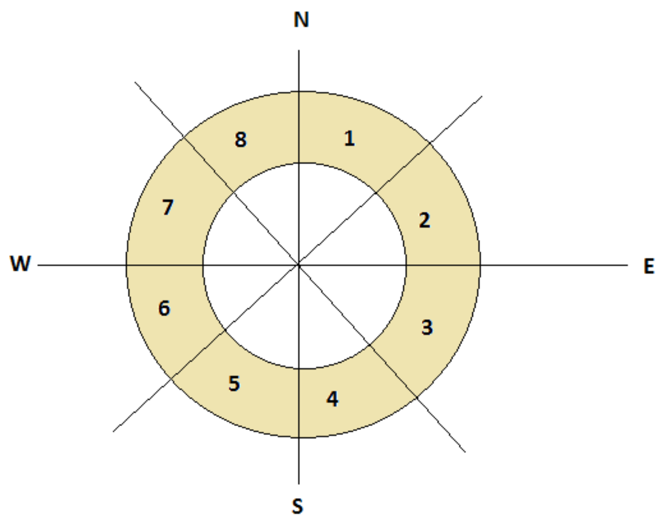


Figure 16: Sections for determining slopes.

6.1.2 Compression Specimens

Compression specimens (Figure 17) were cut from the same culms alternating along the culm length with every second sample being cut by hand and the adjacent sample cut using an electric radial arm saw and refined with a belt sander to make the ends parallel. This allowed for varying degrees of out-of-squareness in samples – ranging from 0.4% to 8%. The location of the sample along the culm was also recorded to ensure that the effect of sample location was taken into account when considering to what degree samples should have parallel ends. The top three internodes of the culm were classified as coming from the "top," the bottom three internodes of the culm were classified as coming from the "bottom," and the remaining internodes were considered part of the middle of the culm. Test results are summarized in Table 1.

Figure 17: Non-parallel-end compression specimens.

The results from the compression testing indicates that even with a slope up to 8%, the results are not significantly impacted (Table 2). Indeed, as shown in Table 2, the compression capacity is actually significantly greater ($p = 0.04$) for specimens with slopes greater than 3% than it is for specimens with slopes less than 1%. This may reflect the fact that the culms having greater slope also tended to come from the top of the culm. As also reported by others (e.g. Correal and Ardelaez 2010), the strength of the bamboo is observed to increase with height along the culm.

Most of the variation in capacity seems to be associated with the location along the culm from which the specimen is cut. The greatest observed capacities are obtained from adjacent internodes near the top of the same culm (specimens 17 – 20). Despite the specimens having slopes varying from 2.4 to 8%, the capacity appears to increase with the increasing out-of-squareness (summarized in Table 3). This would appear to indicate that the slope does not have a negative impact on the stress capacity (as might be expected); but even a slope of 8% does not have a significant impact on the results.

Due to the large impact of sample location, further testing should be conducted with samples from similar locations on the culm with variations in slopes to indicate how much variability is caused by the degree of out-of-planeness rather than the location.

The observed mode of failure may indicate the reason for the observed behavior. The 'high spots' on the culm are first 'crushed down' early in the test, essentially leveling the specimen ends and allowing redistribution of force through the as-yet unloaded portions of the specimen. The behavior, therefore, is analogous to the squash load behavior of a section having residual stresses. The residual stresses affect the stiffness of the section but not the ultimate capacity. The same is true here; the out-of-squareness does not affect the ultimate capacity. This behavior can be seen in Figure 18.

Based on the outcome of this limited pilot, out-of-squareness up to 5% should be acceptable for ISO 22157 compression tests.

Figure 18: Local crushing evident in out-of-plane specimens.

Table 3: Effect of percent slope on compressive capacity.

							compression failure	
sample	**cut by…**	**location**	**slope**	**D_{avg}**	**t_{avg}**	**A**	**load**	**stress**
			%	*mm.*	*mm.*	*mm^2*	*kN*	*N/mm^2*
3	electric saw	B	0.36	183.30	7.37	1805.87	80.44	44.54
12	electric saw	B	0.45	181.48	10.99	3293.95	139.32	42.30
14	electric saw	M	0.85	199.09	10.37	3072.13	137.35	44.71
16	electric saw	M	0.89	200.34	9.64	2781.96	128.03	46.02
6	bow saw	M	1.36	156.60	6.72	1559.57	60.34	38.69
7	electric saw	M	1.55	177.15	6.46	1461.72	69.16	47.32
10	electric saw	T	1.99	146.47	6.34	1346.54	63.28	46.99
2	bow saw	B	2.15	154.69	7.41	1850.48	81.92	44.27
18	electric saw	T	2.39	199.94	8.57	2406.62	116.25	48.30
11	bow saw	B	2.57	164.81	11.29	3419.323	135.87	39.74
15	bow saw	M	2.69	205.10	9.58	2812.09	130.96	46.57
9	bow saw	T	3.48	153.62	6.22	1345.53	61.81	45.94
13	bow saw	B	3.57	193.98	10.46	3120.48	139.30	44.64
17	bow saw	M	4.58	204.37	8.97	2482.86	123.61	49.79
4	bow saw	M	4.91	163.90	7.06	1691.86	77.50	45.81
8	bow saw	T	4.96	139.11	6.37	1403.85	62.79	44.72
20	electric saw	T	4.97	163.42	8.21	2202.72	114.79	52.11
19	bow saw	T	7.57	179.66	8.33	2310.35	118.70	51.38

Table 4: Relationship between sample groups.

	average	COV	t-tests			
	N/mm²		*all*	*B*	*M*	*T*
			all	*< 1*	*1 – 3*	*> 3*
all samples	45.77	0.076	1.00	-	-	-
slope < 1	44.39	0.035	0.25	1.00		
1% < slope < 3%	44.55	0.087	0.48	0.92	1.00	
slope > 3%	47.77	0.067	0.20	0.04	0.12	1.00
all samples	45.77	0.076	1.00	-	-	-
Bottom	43.10	0.049	0.06	1.00	-	-
Middle	45.56	0.075	0.89	0.16	1.00	-
Top	48.24	0.062	0.12	0.01	0.16	1.00

Table 5: Results from four adjacent specimens located near top of culm.

sample	**slope**	**ultimate capacity (N/mm^2)**
18	2.39%	48.30
17	4.58%	49.79
20	4.97%	52.11
19	7.57%	51.38

7.0 CONCLUSIONS AND FUTURE RESEARCH

The test kit's three goals were portability, accessibility, and usability. With these three goals in mind, a kit was designed that was portable, made of easy to obtain materials, and practical to use on a remote construction site. This paper discusses the use of the test kit and supporting equations, the proof of concept and validation testing that was conducted on multiple species of bamboo, and the extent to which specimen ends need to be parallel (keeping in mind practices on remote sites).

Species of Moso and Tre Gai were used for proof of concept testing. Adjacent samples were tested in both shear and edge bearing. The control samples were tested in a standard testing machine, and the test samples in the test kit. The test kit was able to achieve a statistically similar coefficient of variation between both data sets for two different species of bamboo: a thicker walled species of bamboo, Tre Gai, and a thinner walled species of bamboo, Moso. The similar variation between data sets proved that the test kit is a viable way to evaluate the strength of bamboo quickly and easily on a remote construction site, yielding values comparable to those expected in a laboratory environment. Having the ability to determine the strength of the material on site allows for builders to be more certain of the strength of the material they are working with. This reduces the need for overbuilding, as is often the case for bamboo buildings.

Future work will continue improving the acceptance of the test kit and making further improvements to the portability and usability of the device. In the goal of usability, a manual was created that explains how to set up and use the test kit, mostly through the use of pictures. In order to allow it to be understood by a larger audience, the few words in the manual have already been translated from English into Spanish, Chinese, and Portuguese and are currently being translated into French, Hindi and Indonesian as well. This ensures that the kit is usable to people from different parts of the world.

The question of “How parallel is ‘parallel enough’?” arose from the idea of remote field testing. Not only is it important to be able to have a device that can evaluate the mechanical properties of bamboo on site, but it is also important to ensure that the samples can be prepared properly in order to yield accurate results. While compression based testing methods are preferred in the field, most compression based tests require samples to be cut such that their ends are parallel and perpendicular to the culm axis. Cutting samples in this way is not always practical in the field. From testing samples with varying degrees of out-of-squareness in compression and comparing the results to ‘squared’ samples, it was concluded that samples with a relative slope of 5% or less did not significantly affect the results and were practical to cut in the field.

8.0 POSTSCRIPT AND IMPLEMENTATION

The International Network of Bamboo and Rattan (INBAR) is considering adopting the test-kit-in-a-backpack and interest has already been expressed in deploying it in Brazil, and Colombia. To ensure that the kit is portable enough to construct on remote construction sites, it has been designed so that it can be disassembled and fit into a backpack. The test kit is also designed so that it can be built and assembled where it is needed. All parts are easily manufactured in relatively rudimentary machine facilities.

A technical report has been developed reporting the fabrication and use of the kit. There are step-by-step instructions on how to fabricate a kit like the prototype reported here. The kit is comprised of simple materials: steel plates and threaded rods, a bottle jack, and ratchet straps. The second manual is composed of "IKEA-like" pictures that depict the testing process with minimal wording. Additionally, this second document has been translated to Chinese, Spanish, and Brazilian Portuguese with Hindi, Indonesian, and French versions currently in translation.

INBAR will publish the report and manuals. Working with INBAR, an international intergovernmental organization, the manuals are more likely to be available and accepted by a wider audience. The hope is that this 'Bamboo Test-Kit-in-a-Backpack' can be tested in a remote location like Camburi, Brazil. With user feedback, the test kit will be further improved upon.

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