Splitting Capacity Characterization of Bamboo Culms

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Derek R Mitch

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This thesis was presented

by

Derek R Mitch

It was defended on

March 21, 2009

and approved by

Dr. John K. Aidoo, Assistant Professor, Civil Engineering, Rose Hulman IT

Dr. John Brigham, Assistant Professor, Civil and Environmental Engineering

Dr. Piervincenzo Rizzo, Assistant Professor, Civil and Environmental Engineering

Thesis Director: Dr. Kent Harries, Assistant Professor, Civil and Environmental Engineering

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Derek R Mitch, B. Phil

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The history of engineering knowledge with regards to bamboo is surprisingly recent, with the major work on bamboo having been completed by Janssen (1981) and Acre (1993) of the University of Eindhoven, The Netherlands. In their research, both noted that splitting is the dominant limit state in structural applications, which agrees with the author's experience (during our May 2008 visit to India) and that of other researchers. It is because of this dominant limit state that this research focused on the development of an appropriate method of characterizing the splitting strength of bamboo culms. This document focuses on developing and calibrating an appropriate (but simple to conduct) test method for assessing the splitting capacity of full culms.

The proposed split-pin fracture test is founded on a fundamental fracture mechanics approach. This method, while simple to conduct, can account, in a consistent manner, for the high degree of variability present in bamboo geometric and material properties. In order to demonstrate the validity of the proposed test method, a series of tests were performed on a sample of *Bambusa Stenostachya* (Tre Gai) bamboo. In addition to the proposed fracture test, shear and compression tests were performed in accordance with existing ISO standards (ISO 2004b). Of the three test types performed, the compression test had the lowest variability, the shear test had the highest, and the proposed fracture tests had a variability that fell between the two. Thus the fracture test demonstrated that it yields reliable results.

Utilizing the values obtained from both this series of tests as well as those carried out by other institutions, a comparison of common design values was made between Tre Gai and the

select-structural grade of two commonly encountered woods, Douglas Fir and Southern Pine. While the design values for bamboo obtained from different institutions varied considerably, Tre Gai generally exhibited performance superior to that of the two timber species referenced. It can be concluded that Tre Gai, when grown, harvested, and preserved correctly, is a competitive, or in some cases, a superior alternative to wood.

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1.0 PREAMBLE, INTRODUCTION, AND LITERATURE REVIEW

1.1 PREAMBLE

The work presented in this report is part of a larger body of work focusing on the use of sustainable construction practices and materials and their relation to issues associated with hazard mitigation. The following preamble, drafted by all research team members, is offered to provide a degree of context to the reported work.

1.1.1 Motivation, History and Context

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

A critical aspect of sustainable infrastructure is its ability to perform under both service conditions and extreme events. Safety in the built environment is a fundamental right.[1] Recent ‘great’ natural catastrophes have resulted in unacceptably high casualty tolls. The 2001 earthquake in Bhuj, India left over 19,700 dead; the 2003 Bam (Iran) earthquake: over 26,000 dead; the 2004 Aceh earthquake and subsequent tsunami: over 275,000 dead; the 2005 Kashmir earthquake: over 80,000 dead; the 2008 Sichuan earthquake: 70,000 dead. The injured are many times these numbers and the displaced are often an order of magnitude or two greater. In reviewing the litany of statistics, one must acknowledge the clear disparity between developed and less developed regions.

As demonstrated by the October 8, 2005 Kashmir earthquake, the Himalayan region is at particular risk. It is exposed to a high seismic hazard, relatively densely populated by relatively poor people, and is geographically remote. The Himalayan range has experienced approximately 20 devastating earthquakes since 1900. Indian seismological maps indicate high hazard regions as far south as Delhi. Of particular concern is the “Himalayan gap” – a 600 km long region of the central Himalayas extending across Nepal – which has not experienced a recent major event. Seismologists suggest that this region is capable of generating multiple events with moment magnitudes greater than 8.0 (Bilham et al. 2001).

[1] Article 25 of the United Nations Universal Declaration of Human Rights states that “Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services...” Principle #10 of the 1994 Special Rapporteur’s Report to the United Nations Commission on Human Rights states: “All persons have the right to adequate housing, land tenure and living conditions in a secure, healthy and ecologically sound environment.”

1.1.2 Bamboo as a Sustainable Construction Material

In 2004, the International Organization for Standardization (ISO), in partnership with the International Network for Bamboo and Rattan (INBAR), a Beijing-based agency whose aim is to promote bamboo and rattan for poverty alleviation in developing countries, published a standard on structural design using bamboo (ISO 2004a) and a series of methods for determining the mechanical properties of bamboo (ISO 2004b and ISO 2004c). If the use of bamboo is limited to rural areas, the standard 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 all require some degree of standardization (Janssen 2005).

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

1.1.3 Physical Properties and Terminology Associated with Bamboo

Bamboo is not a material well known to civil engineers, thus it is the intent of this work to help characterize its mechanical properties. For an overview of the properties of bamboo as they relate to structural applications, the reader is directed to Janssen (1981) or Arce-Villalobos

(1993). Both Janssen and Arce-Villalobos also provide a review of the extensive nomenclature associated with bamboo and are cited later in this work.

1.1.4 Darjeeling Region of Northeast India

For the sake of appropriate contextualization, this project considers the hill region of the Darjeeling area in northern West Bengal. This area is an economically depressed region of a rapidly emerging country, India. Therefore it epitomizes what Silberglitt et al. (2006) refer to as the widening gap between urban and rural populations. The selection of this region for context is largely independent of the technical goals of this work. Nonetheless, the authors feel that it is important to provide context, if only to better define the scope of the work. The selection of this region is supported by contact with Ms. Gayatri Kharel and a number of other contacts made during a three week visit to Darjeeling, Kalimpong, Mungpoo and Gangtok (Sikkim) in May 2008 (Sharma et al. 2008). Figure 1.1 provides an overview of the northeastern West Bengal area visited in 2008 that forms the contextual basis for this work.

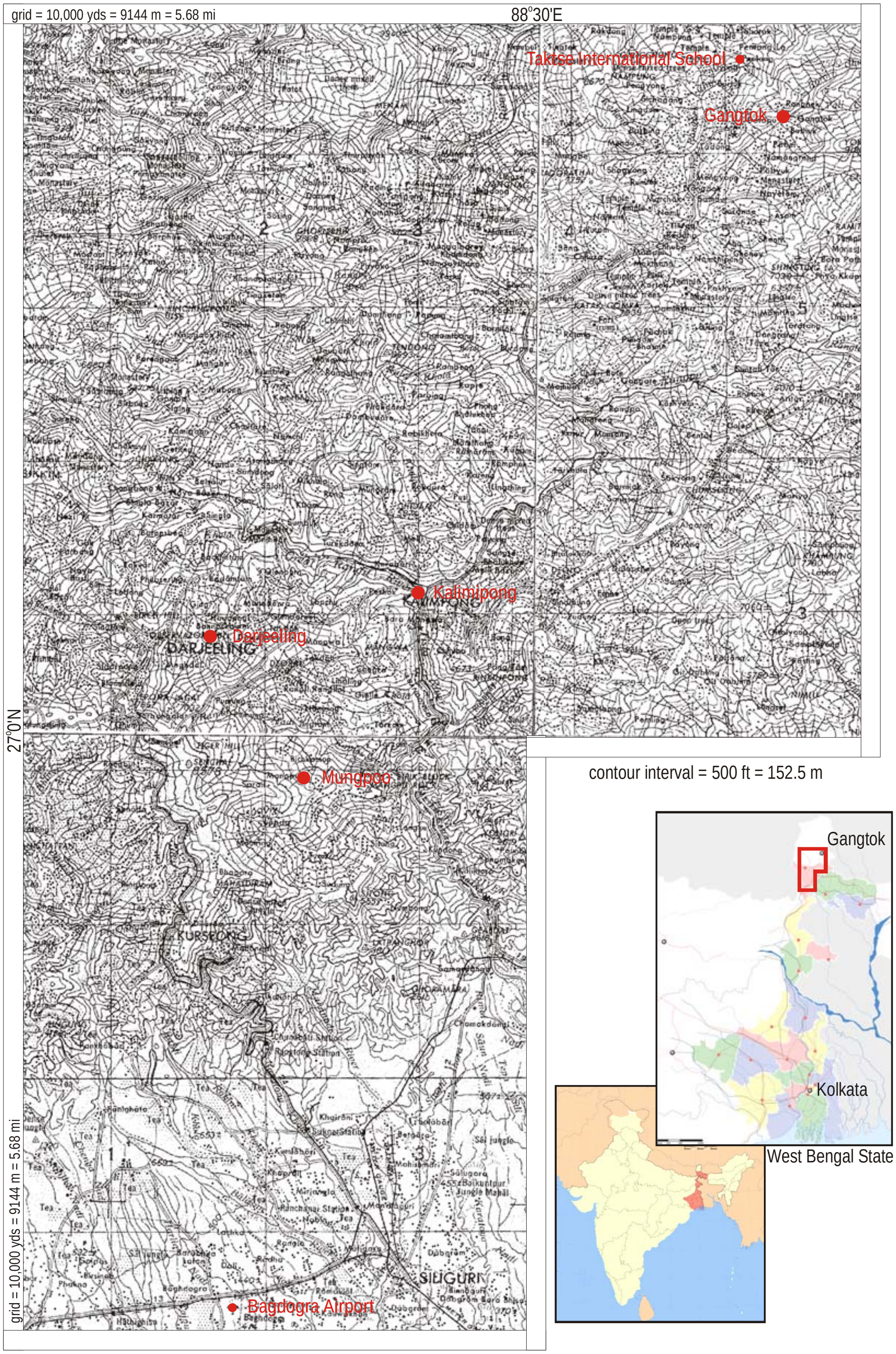


Figure 1.0 Map of Darjeeling Region with sites highlighted.

1.1.5 Objective of Current Work

This research is focused on the development of an appropriate method of characterizing the splitting strength of bamboo culms. Splitting is the dominate limit state (failure mode) for most bamboo in structural applications (Janssen 1981; Arce-Villalobos 1993) and has been documented by the authors (during our May 2008 visit to India) and most other researchers. The research conducted in support of this Honors College thesis is focusing on developing and calibrating an appropriate (but simple to conduct) test methods for assessing splitting capacity of full culms. The proposed test method is founded on a fundamental fracture mechanics approach and therefore can account, in a consistent manner, for the high degree of variability present in bamboo geometric and material properties. While a number of test methods are available in the literature, a) none presently address full culm behavior; b) only one approaches the splitting problem from a fracture mechanics perspective; c) methods reported to provide the same material property result in significantly different values; and d) none have been standardized despite splitting being the dominant limit state for many applications. An additional objective of this work is that the test method developed is a) sufficiently simple; b) requires only basic equipment to perform; and c) is easily scalable to assess a range of bamboo geometries (structural bamboo ranges in diameter from 2 to 10 inches). These criteria are based on the need to use this test method in the field which implies use in under-developed rural areas having no access to engineering test facilities.

1.2 INTRODUCTION

1.2.1 Bamboo and its Physical Properties

Bamboo is being given an increasing amount of attention by developed and developing countries alike, and for good reason. Bamboo grows at a much more rapid rate than the hardwood and soft wood species that are currently utilized for construction purposes. This rapid growth rate translates into an equally rapid harvesting rate – usually a two or three year cycle - thus reducing the amount of land and resources necessary for timber production. This reduced development cost means that it is easier to manage bamboo production at a sustainable rate. Additionally, bamboo species may be grown throughout the temperate, subtropical and tropical world; and as long as the bamboo is grown locally, it will reduce the cost and harmful byproducts of transportation.

Bamboo has been put to extensive use in both the developed and the developing world. In the developed world it tends to be used in value-added applications such as cutting boards, utensils, and flooring. In the developing world it is used in a more utilitarian manner, as either structural members or as strips used for weaving mats (used for walls and flooring). The primary focus of the present work is with the structural applications of bamboo. Before beginning a discussion of the structural uses of bamboo, a brief explanation of bamboo and relevant terms is required.

Bamboo is a member of the grass family, but is unusual in the fact that it is mostly comprised of a rapidly growing woody stem and grows to a very tall height (see Figure 1.1). The stem is the hollow cylinder that most people associate with bamboo, and it is commonly referred to as a “culm”. Bamboo culms also possess a unique physical characteristic known as a “node” (see Figure 1.2a-b). Nodes serve the purpose of allowing a location for leaves to grow, and as a result, the longitudinal fibers of the bamboo are forced to change directions in those areas. This leads to reduced structural properties at the nodes (Arce 1993). In addition to node spacing, culms vary widely in length, diameter, wall thickness, and material properties depending on the species and height along the culm (Janssen 1981). Additionally, bamboo has a higher concentration of fibers towards the outer edge of the culm (Amada 2001). For this reason bamboo may be considered a "functionally graded material" as shown in Figure 1.3.

Despite its many theoretical advantages, the widespread 'engineered' use of bamboo is still hindered by many problems. The three most important ones being: a) the way societies view bamboo; b) its inadequate durability; and c) the lack of sufficient engineering knowledge. Throughout most of the world, bamboo is regarded as "the poor man's timber"; where available, various types of wood are generally preferred. For bamboo to be broadly adopted, this negative mentality will have to change. As this report focused on the mechanical properties of bamboo rather than socio-political issues, the public perception of bamboo will not be explored in further detail.

The second serious problem facing the widespread adoption of bamboo in construction is the fact that even with treatment, bamboo does not last as long as other woods. Untreated bamboo that is in direct contact with the ground tends to last about 2 years, and about 4-7 years when not in direct contact with the ground. Treated bamboos may last for more than 30 years (Kumar 1994). While testing has been done on a broad range of bamboo preservatives and preservation methods, no single method has been exhaustively studied or agreed upon. Treatment choice tends to be regional and based on convenience. This has led to confusion regarding the effectiveness of individual treatments as well as uncertainty about the effects that the treatment methods have on the bamboo's mechanical properties. For bamboo to realize its full potential, an effective method that will enable bamboo to last as long as common woods will have to be developed and broadly accepted.

Figure 1.1 Bamboo stand in Kalimpong, West Bengal (Photo: Mitch 2008)

(a) longitudinal section of culm

(b) node and internode regions

Figure 1.2 Sections of bamboo culm and associated terminology (Janssen 1981)

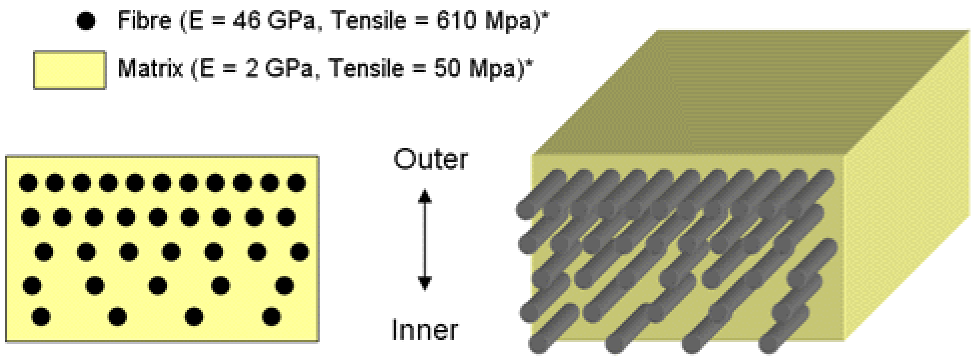


Figure 1.3 Through-thickness grading of bamboo culm wall. Fiber/matrix analogy suggests modeling strategy similar to that used for fiber reinforced polymer (FRP) materials.

The third major problem to the wider use of bamboo is the lack of sufficient engineering knowledge for design purposes. Most modern buildings are constructed out of three primary materials: wood, steel, or concrete. Each of these materials has [inter]nationally recognized design standards that list commonly encountered material properties as well as design aids to simplify and formalize the task of designing a structure. The first significant standard concerning bamboo is ISO Model Code for Bamboo Construction (ISO 2004a), and was formally released in 2004. This code, and other regional research, forms the basis for the most extensive standardization of bamboo construction: Chapter 6, Section 3 of the National Building Code of India (NBCI 2005). This Indian standard is cursory at best; it provides fundamental material properties for about 20 species of bamboo and guidance for design for fundamental actions of compression and flexure. The Indian Code is effectively a performance-based standard as far as bamboo is concerned: if an engineer can demonstrate that a system can adequately resist prescribed loads, then the system is compliant. No other criteria, such as deformation or ductility are considered. The Indian Code is silent on how to qualify or determine material properties of bamboo species other than those listed. A second ISO Model Standard (ISO 2004 b and c) reports standard test methods for bamboo, but again, these are cursory and critical guidance is absent. For engineers to fully embrace bamboo as a building material it will need more thorough documentation and research as well as a history of successful use.

1.2.2 Experiences in India

The Mascaro Center for Sustainable Innovation (MCSI) sent a team to the Darjeeling region of Northeastern India in May 2008, in order to assess the challenges faced in bamboo construction and related sustainable engineering practices in the region. The team discovered that the concept of sustainability was generally accepted by those who had advanced education, while the general populace had a seriously flawed understanding of it. An amusing example of the misunderstanding regarding the “green movement” was a market district in Gangtok, Sikkim. In addition to turning the main market street into a pedestrian mall, the local government also painted the mall buildings green in order to “go green” (Figure 1.4). While the “green mall” is a new local amenity, its development has resulted in increased congestion in the adjacent streets and has done little to promote “sustainability” in the city (although it has been successful from a social perspective). Despite this anecdote concerning the market district, the interest of the local government leads one to believe that sustainability has a future in this region.

Figure 1.4 'Green' market district in Gangtok (Photo: Mitch 2008)

Fortunately, there are many throughout the world willing to try and tackle the previously mentioned difficulties encountered with bamboo construction. One of the most exciting projects currently underway in the hill region near Darjeeling is the construction of St. Joseph's School in Mungpoo (Figure 1.5). St. Joseph's is being developed under the auspices of St. Joseph's College at North Point, Darjeeling and the local NGO Sustainable Hills Environment and Design (SHED). St. Joseph's is committed to maintaining a sustainable development in Mungpoo. A feature of this school is that the structures will all be constructed of locally harvested bamboo. A nearby cinchona plantation will be partially converted to bamboo in an effort to support St. Joseph's and similar construction in addition to providing a source of bamboo from which a home-grown crafts industry may be developed. This development has the additional benefit of keeping the cinchona plantation viable: cinchona is the source of the natural anti-malarial quinine. Quinine production has declined significantly as it is replaced by compounded pharmaceuticals. Thus finding a viable alternative crop for the plantation (that will continue to specialize in plants raised for the pharmaceutical industry) will support the plantation and the local economy.

A further challenge faced in the hill region is the threat of earthquake and earthquake- and rain-induced landslide. SHED and other NGOs are championing the consideration of these hazards in sustainable hill architecture/engineering. The use of bamboo at St Joseph's addresses SHED's primary goals in that it is both a more sustainable product than reinforced concrete, and due to its lighter weight, it is far less prone to cause/experience a fatal collapse in an earthquake.

(a) Administrative building and (uncompleted) canopy over assembly hall.

(b) Classroom building.

(c) Classroom building end elevation.

Figure 1.5 St. Joseph's school in Mungpoo, West Bengal (Photos: Mitch 2008)

The design and construction of St Joseph's School is progressing, albeit slowly due to lack of funding. Main column members are four bamboo culms seated together on a concrete plinth or footing. The plinths are tied together with grade beams to form a raft-like foundation. Additional stability is provided by infilling the raft with stone (Figure 1.6) Steel reinforcing bars project from the plinth and are embedded and subsequently grouted into the bamboo culms. In this manner the culms are kept clear of the ground. The walls are made out of a woven bamboo mat that will eventually by covered with a local mud-plaster. The roof is constructed from corrugated sheets of galvanized steel, which, along with large gutters, form a rainwater collection system. As of May 2008, two buildings are complete, one is under construction, and several more planned for the future expansion of the school.

Figure 1.6 Foundation with plinths and 4-culm columns (Photo: Harries 2008).

While construction quality was generally good (Figure 1.5), many cases of longitudinal splitting of the bamboo culms was observed. This splitting was primarily observed at locations of bolt penetrations (Figure 1.7), however splitting was also observed at some column bases (Figure

1.8). While longitudinal splitting of bamboo is a common failure mode, its prevalence in these lightly loaded structures is cause for concern. Various factors may affect the observed behavior:

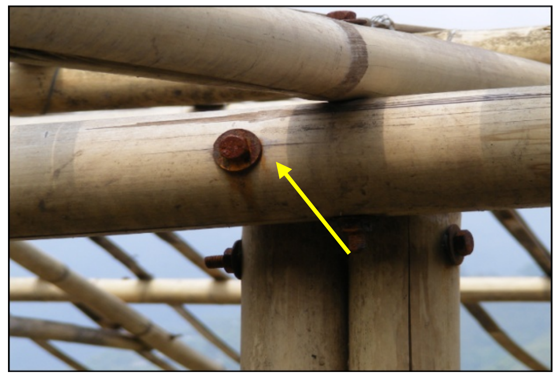
1. The locally available bamboo at Mungpoo is of a different species than that commonly used in construction in Assam (where most of the bamboo technology, building methods and connection schemes were developed).
2. The locally available bamboo at Mungpoo has a thinner wall thickness than that used in Assam. While the theoretical capacity is adequate, the effect of the thinner wall is uncertain.
3. The treatment method used at Mungpoo – intermodal injection of a mix of equal parts creosote and diesel fuel – is only one of a number of accepted methods of treatment. Other methods include dipping, pressure treating and smoking. There is little guidance on the effects of treatment on the properties of the bamboo culm.

(a) column splitting near sawn end

(b) beam splitting near sawn end at dowelled and lashed joint

(c) severe splitting at sawn ends of roof rafters

(d) severe splitting initiated by presence of bolted connection



(e) initiation of splitting at bolted connection

Figure 1.7 Tendency of Bamboo to split at bolts and joints (Photos: Mitch 2008)

Figure 1.8 Bamboo slitting at column base (Photo: Harries 2008)

1.2.3 Objective of Present Work

The susceptibility of, and resistance to longitudinal splitting (cracking) is of fundamental importance in bamboo construction. The objective of this study is to develop a test method that can be used to effectively evaluate the splitting resistance of bamboo. In addition to being able to produce a stable rate of measurable crack growth, the test must be simple enough to be constructed and used in the field as a means of material quality control. The latter requirement is no small task. Presently, the nearest materials testing facility is in Siligiri, a three hour, 85 km drive from Darjeeling and Mungpoo (Figure 1.0).

1.3 LITERATURE REVIEW

1.3.1 General Properties of Bamboo

The history of engineering knowledge with regards to bamboo is surprisingly recent. The first major work was completed by Janssen (1981) of the University of Eindhoven, The Netherlands. In his 1981 thesis, Janssen first explored the composition of a bamboo culm. He developed a mathematical model of the culm by considering it to be a structure composed of a number of substructure ‘cells’. Janssen then explored different mechanical properties of bamboo including bending, shear, tension and compression. Finally, he explored different truss systems and various ways to connect bamboo elements.

From his work on the composition of bamboo, Janssen drew several conclusions:

1. Although bamboo has more than double the number of layers of cell walls as softwood, this does not have an influence on the stresses and displacements of bamboo (Janssen 1981).
2. The angle that the microfibrils of bamboo make with the cell axis has a large impact on the stresses and displacements (Janssen 1981).
3. A numerical of a single substructure cell may be used to predict the Poisson ratio and tensile strength, but cannot be used to predict the compressive strength as pectin prevents the buckling of individual fibers; a more expansive model is required to accurately predict compressive strength (Janssen 1981).

In addition to simple mechanical tests of bamboo, Janssen applied statistics and linear models in an attempt to discover which parameters are related to bamboo's material properties. Some of his conclusions are as follows:

4. An increase in moisture content decreases compressive strength, and the compressive strength increases with height along culm where sample was taken.
5. Shear stress is the cause of failure for smaller spans, and the limiting shear stress is much lower than a typical shear test would indicate (Janssen 1981).
6. In bending, dry bamboo behaves better; strength decreases with the height the sample is taken from the culm (i.e.: strength decreases from bottom to top); and there is a possible relationship between ultimate bending stress and density (Janssen 1981).
7. A new shear test was needed to determine the correct shear strength of bamboo (which he then designed). The new shear test "ISO 22157-1" (ISO 2004) is shown in Figure 1.9 (Janssen 1981).

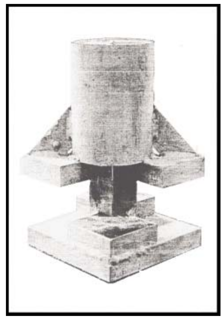


Figure 1.9 Shear test developed by Janssen shown without a bamboo specimen.

8. Shear strength and density are related.
9. A new test method is needed to determine bamboo's tensile strength.

Arce's (1993) work is essentially an extension of Janssen's thesis. He begins with a more in-depth examination of the tensile properties of bamboo. This examination included tensile strength both the parallel (along culm) and perpendicular (transverse) to the primary orientation of the fibers. Arce also attempted to relate different mechanical properties throughout his dissertation. His most important conclusions are as follows:

1. Transverse tension capacity and density are not correlated whereas longitudinal tension capacity and density are.
2. Tension modulus, E, in the transverse direction is about 1/8 that measured in the longitudinal direction.
3. There may be a universal maximum transverse strain that bamboo may experience before failure. Three different species exhibited similar values during testing, approximately 0.0012.
4. Variation in cross-section and modulus of elasticity produce a reduction of no more than 15% in the bending strength and axial stiffness compared to the values a theoretical uniform member would yield.

5. Variation in cross-section and the presence of nodes can reduce bending stiffness by 50%, and axial stiffness by 80%.
6. The slenderness ratios of compression elements should be kept below 50 to avoid global buckling or splitting resulting from flexural behavior.

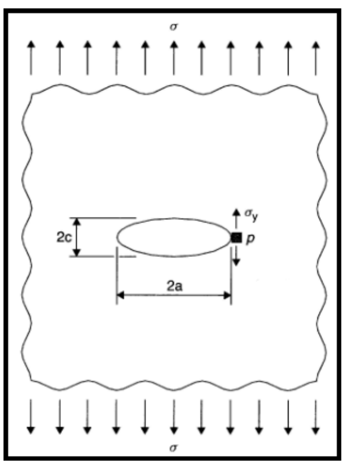
The present understanding of the material properties of bamboo expressed in the ISO Standards (2004a) and the Indian Code (2005) stem largely from the work done in the Netherlands by Janssen and Arce. While these standards are a start, there are many areas that still require further exploration. For example, while Janssen (1981) quotes several researchers in the past who claimed that "the collapse of the bamboo was always sudden and the material was split into pieces parallel to the longitudinal axis", the splitting behavior of bamboo has not been adequately addressed in present standards due to both a misunderstanding of the physical nature of bamboo and inconsistent data.

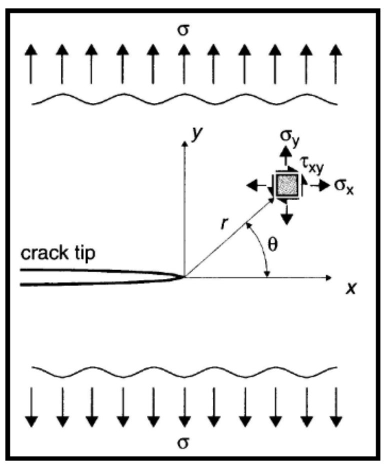
1.3.2 Introduction to Fracture

Wood and bamboo share many similar qualities, thus reviewing the material behavior of sawn timber will help one understand the behavior of bamboo. Additionally, practices and test methods used for timber may be leveraged and modified for use with bamboo. The following review of fracture and timber properties is based on *Fracture and Fatigue in Wood* (Smith 2003). It is important to note that despite the fact that the testing of wood is more formalized than bamboo, there is still not a recognized standard for the testing of wood's fracture toughness. Due to the lack of standardization, standards dealing with the fracture of metals are referenced instead.

Wood is a fibrous material having orthotropic material properties. The majority of timber materials fail through the application of tensile forces; these are often transverse to the grain and are generated by the Poisson effect (i.e. dilation) or flexure-induced longitudinal shear (VQ/It shear). The induced tension failures are described in terms of their fracture properties.

In a classic paper on fracture, Griffith (1921), shows that the flaws in a material are the most important strength-determining parameter. Combined with the stress equation given by Inglis (1913) for an elliptical hole, Griffith was able to analyze and quantify the growth of a crack through an energy balance approach. His solution gives the critical stress at which a crack will propagate until failure, or, conversely, it can give the critical crack length.





(a) geometry of plane (b) region in the vicinity of p

Figure 1.10 Solid plane subject to unidirectional tension having an elliptical hole. (Smith 2003)

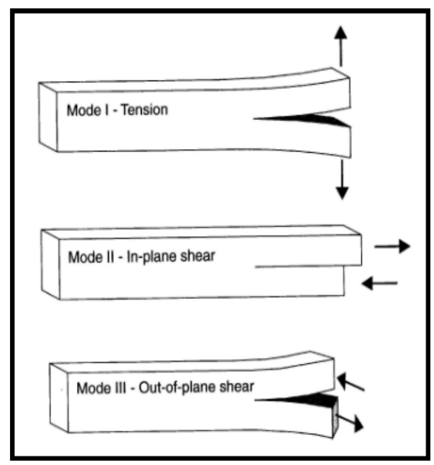


Figure 1.11 Crack deformation modes. (Smith 2003)

Considering the plane solid having an elliptical hole shown in Figure 1.10a, the greatest tensile stress is encountered at point p:

$$\sigma_y = \sigma \left[1 + 2\sqrt{\frac{a}{p}}\right] \quad \text{(Eq 1.1)}$$

Where: *a = half the major axis of the hole*

p = radius at the crack tip

σ = far-field stress

Using the law of conservation of energy:

$$\Pi = U + U_p + W \quad \text{(Eq 1.2)}$$

Where: *Π = total energy of the system*

U = strain energy

U_p = potential energy of load system

W = surface energy from crack formation

After manipulation, Equation 1.1 becomes:

$$\sigma_f = \sqrt{\frac{2E\gamma}{\pi a}} \quad \text{(Eq 1.3)}$$

Where: *σ_f = yield stress*

E = modulus of elasticity

γ = free unit surface energy of the material

After Griffith's paper, two major approaches have been developed to mathematically model crack growth: strain energy release rate and the stress intensity factor. Both methods are based on the assumptions of "Linear Elastic Fracture Mechanics" (LEFM), or the idea that all the applied energy is utilized in the propagation of a crack. The strain energy release rate simply deals with the summation of energy in a system. Unfortunately, the energy analysis becomes more difficult as the size of the system increases. The alternative method, the stress intensity factor, deals with the stresses at the tip of a crack. An advantage of the stress intensity factor is that it can act as a measure of a material's resistance to fracture, or the material's "fracture toughness". Strain Energy Release Rate (G) is a more fundamental property as it is derived from first principles and its units have physical meaning , i.e. the amount of energy needed to create new crack surface, whereas the Stress Intensity Factor (K) has no physical meaning. In addition, both K and G are related to each other.

Strain Energy Release Rate:

$$G = \frac{d}{dA}(F - U) = R \qquad \text{(Eq 1.4)}$$

Where: *dA = incremental increase in crack area*

F = external work of the applied load

R = Crack Resistance

Stress Intensity Factor:

Considering a unit area (Figure 1.10b) some distance from the crack tip (given in polar coordinates, r and θ), the mode 1 local stresses may be determined as:

$$\sigma_x = \frac{K_1}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left(1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right) \qquad \text{(Eq 1.5a)}$$

$$\sigma_y = \frac{K_1}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left(1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right) \qquad \text{(Eq 1.5b)}$$

$$\tau_{xy} = \frac{K_1}{\sqrt{2\pi r}}\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right) \qquad \text{(Eq 1.5c)}$$

Where: $K_1 = \beta\sigma\sqrt{a}$ (Eq 1.6)

β = dimensionless crack-tip geometry parameter

σ = Far field stress

a = crack length

G and K are related through the following equation:

$$G_1 = \frac{{K_1}^2}{E} \quad \text{(Plane Stress)} \qquad \text{(Eq 1.7a)}$$

$$G_1 = (1 - v^2)\frac{{K_1}^2}{E} \quad \text{(Plane Strain)} \qquad \text{(Eq. 1.7b)}$$

Where: *v = Poisson's ratio*

E = modulus of elasticity

Once a crack has been formed, there are three different ways in which it may propagate, Modes I-III, which are shown in Figure 1.11. Mode I (crack opening or "peeling") is propagation through the application of tensile forces perpendicular to the plane of the crack. Mode II ("sliding") is the application of plane shear parallel to the crack direction. Mode III ("tearing") is the application of shear forces perpendicular to the crack direction, but still in the same plane. Each of these modes has a different fracture toughness value, K_I, K_{II} and K_{III}. For most materials, Mode I is dominant; that is $K_I << K_{II}$ or K_{III}. However, with wood (or any other anisotropic material) the other modes may dominate behavior under different conditions. Interaction of modes, particularly involving Modes I and II, and fatigue loading also affect fracture behavior, but such discussions are beyond the scope of this paper.

While the two previously mentioned methods work well for brittle materials, they are often inaccurate for ductile materials. This inaccuracy comes from the fact that both the strain energy release rate and the stress intensity factor are based on the assumption that all the energy is utilized in the propagation of the crack. For a ductile material this assumption is not valid as the plastic deformation of the material will dissipate significant energy. This additional dissipation of energy is referred to as the "toughening mechanisms" of a material. Several examples are shown in Figure 1.12.

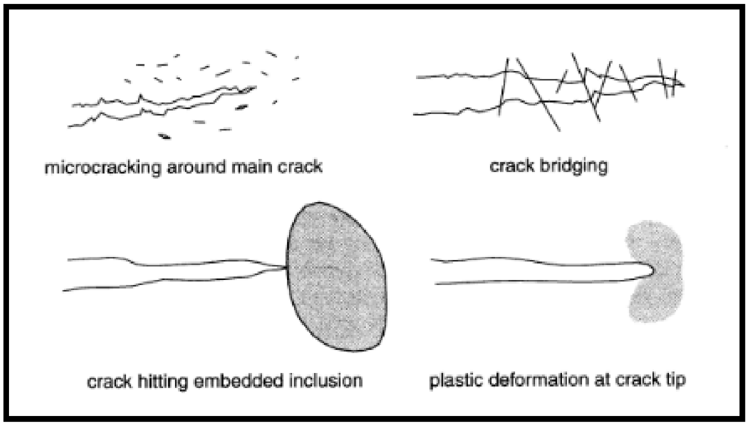


Figure 1.12 Toughening mechanisms (Smith 2003)

A useful tool for quantifying these effects is the R-curve (Figure 1.13). The R-curve is a graph of the resistance to crack growth (R) as the size of a crack (a) grows. This is useful to show that not all toughening mechanisms are employed immediately; some require a certain sized crack to be present. Eventually these mechanisms are overcome and the curve levels off.

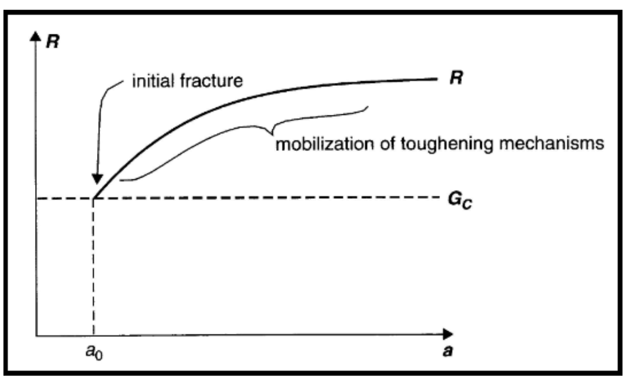


Figure 1.13 R-Curve (Smith 2003)

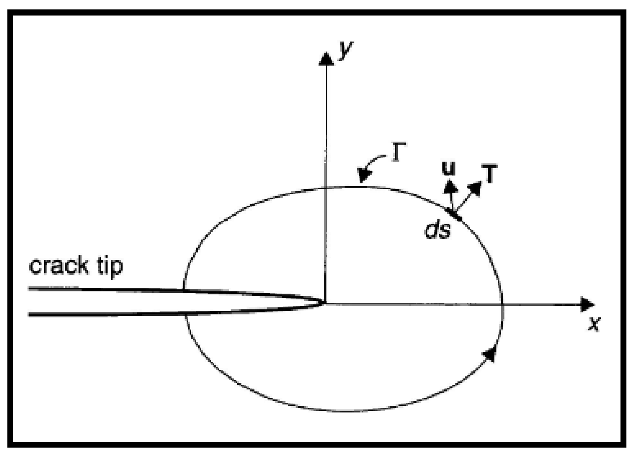


Figure 1.14 J-integral (Smith 2003)

A further tool for analyzing nonlinear fracture materials is the J-integral (Figure 1.14). A J-integral does not attempt to characterize the state of the crack tip, rather it is a path-independent, counter-clockwise contour integral that gives the strain energy release rate for a crack inside its contour. The J-integral is appropriate for elastic materials subject to repeated loading and unloading but it is valid for inelastic materials only for monotonic testing. The contour path may be arbitrarily chosen.

$$J = \oint_{\Gamma} (wdy - T\left(\frac{\partial u}{\partial x}\right)ds \qquad \text{(Eq 1.8)}$$

Where: Γ = *contour of integration*

u = displacement vector

w = strain energy density

*T =σ*n (traction vector across the boundary)*

$\underline{\sigma}$ = *stress tensor*

$\underline{n}$ = *normal vector to the boundary*

With this equation one can calculate fracture toughness, K_1, from:

$$J_1 = K_1^2\left(\frac{1-v^2}{E}\right) \text{ (for plane stress)} \qquad \text{(Eq 1.9a)}$$

$$J_1 = K_1^2\left(\frac{1}{E}\right) \text{ (for plane strain)} \qquad \text{(Eq 1.9b)}$$

Where: J_1 = *work per unit fracture area*

K_1 = *stress intensity factor(fracture toughness)*

v = Poisson's ratio

E = modulus of elasticity

1.3.3 Fracture of Wood

The fracture of wood is a much more complex problem than the fracture of materials like metals, which are typically considered homogenous and isotropic. Wood is anisotropic, heterogenous and nonlinear. For these reasons, it is more difficult to accurately apply current theories and practice to wood than to other materials. Wood also has six different orientations in which cracks may propagate (Figure 1.15). Fortunately, cracks tend to propagate along the grain in wood, thus cracks generally follow the RL and TL orientations. This behavior is generally analogous to that of bamboo splitting.

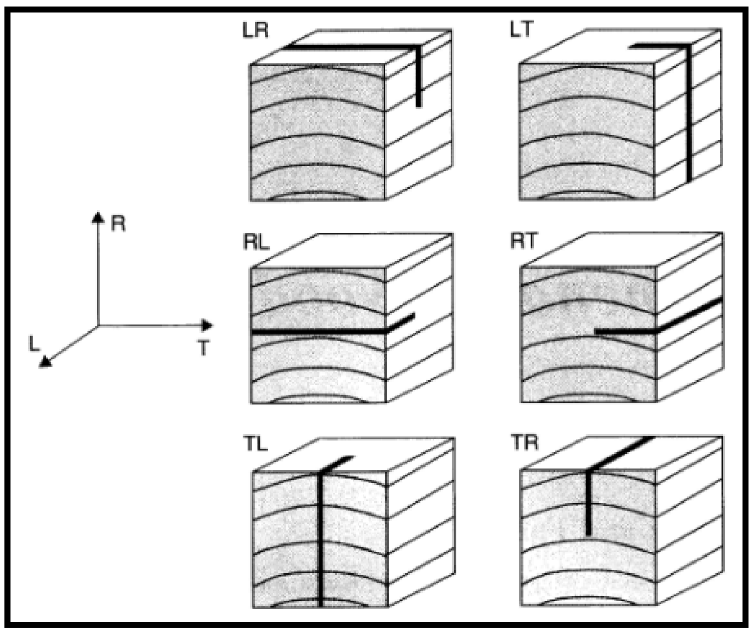


Figure 1.15 Possible directions for crack propagation in wood (Smith 2003)

1.3.3.1 Mode I Perpendicular to the Grain

The variability inherent in wood fracture toughness has resulted in the fact that there is still not a standardized test method. Due to the multiple toughening mechanisms available to wood, different tests that initiate different mechanisms will yield significantly different fracture toughness values. The most commonly encountered test methods are shown in Figure 1.16. Examples of these specimens can be found in ASTM E1823 (2007) and E1820 (2007).

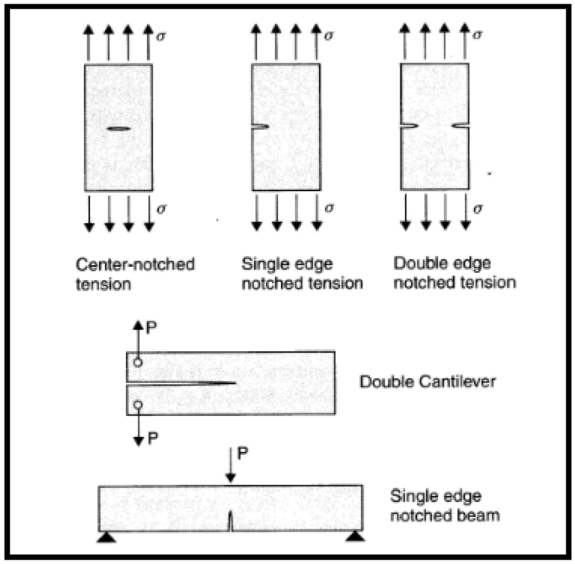


Figure 1.16 Fracture specimens for Mode I failure in wood (Smith 2003)

In general, the double cantilever beam (DCB) gives higher values for K. Thus it can be assumed that the DCB test engages more toughening mechanisms that the other test geometries. In addition, a test in the RL direction will yield a higher K value than a test in the TL direction because of the effect of rays in the wood. The reason being that the rays, the tissue that runs in the radial direction, resist cracking along the grain.

1.3.3.2 Mode I Parallel to the Grain

Tension fracture parallel to the grain is difficult to analyze as many different toughening mechanisms may be engaged. Some of these are crack bridging, microcracking, and Cook-Gordon cracking (Smith 2003). For these reasons mode I fracture parallel to the grain is difficult to achieve, and the specimens generally fail in combination with Mode II. Unfortunately, failures in this direction are generally brittle, thus a better testing method is needed.

1.3.3.3 Mode II

Mode II is especially important for members in flexure and for members with shear-critical connections. Once again, there is no standardized test method for Mode II fracture. The most commonly used types are shown in Figure 1.17. The main reason for the different specimen types is that it is difficult to obtain pure Mode II failure without inducing a component of Mode I. The notched specimens naturally have difficulty arising from the friction that is created at the cracks and the centre-slit beams are difficult to fabricate.

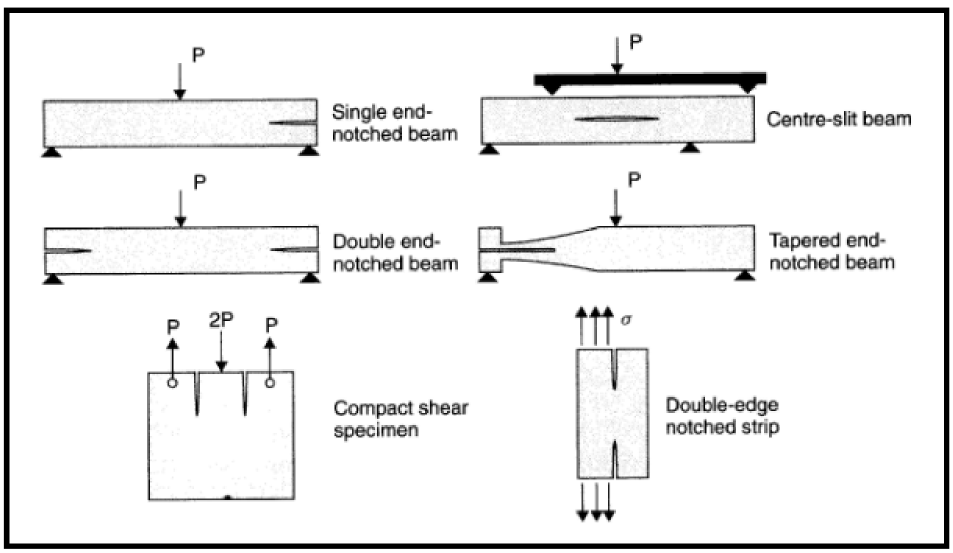


Figure 1.17 Fracture specimens for Mode II failure in wood (Smith 2003)

1.3.3.4 Mode I Arbitrary Angle to the Grain / Mixed Mode

As the grain of wood is often at an angle relative to the sawn timber axes, the fracture strength at an arbitrary angle is an important factor in fracture design (Figure 1.18). This failure type is important because it tends to be the dominate form of failure in real structures. The most significant development in this field is the Hankinson formula (Hankinson 1921) which relates the strength at an arbitrary angle θ with the strength in the longitudinal and perpendicular directions. Unfortunately, the actual strength is dependent not just on the strength in the principal directions, but also on the interaction of the two. Most other equations dealing with mixed mode failure define a "failure envelope" rather than a specific value.

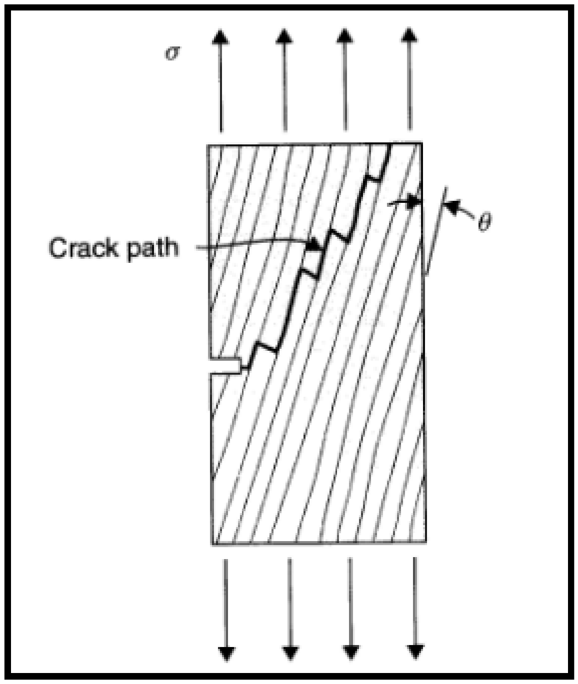


Figure 1.18 Typical crack in wood at an arbitrary angle (Smith 2003)

The Hankinson equation is given as:

$$N = \frac{PQ}{Psin(\theta)^n + Qcos(\theta)^n} \qquad \text{(Eq 1.10)}$$

Where: *N = strength at specified angle*

Q = strength perpendicular to the grain

P =strength parallel to the grain

Θ = specified angle

n = calibration constant (typically n=2)

The mixed failure mode interaction equation is:

$$\left(\frac{K_1}{K_{1c}}\right) + \left(\frac{K_{11}}{K_{11c}}\right)^2 = 1 \qquad \text{(Eq 1.11)}$$

Where: K_I = *mode 1 stress intensity factor*

K_{Ic} = *mode 1 critical stress intensity factor*

K_{II} = *mode 2 stress intensity factor*

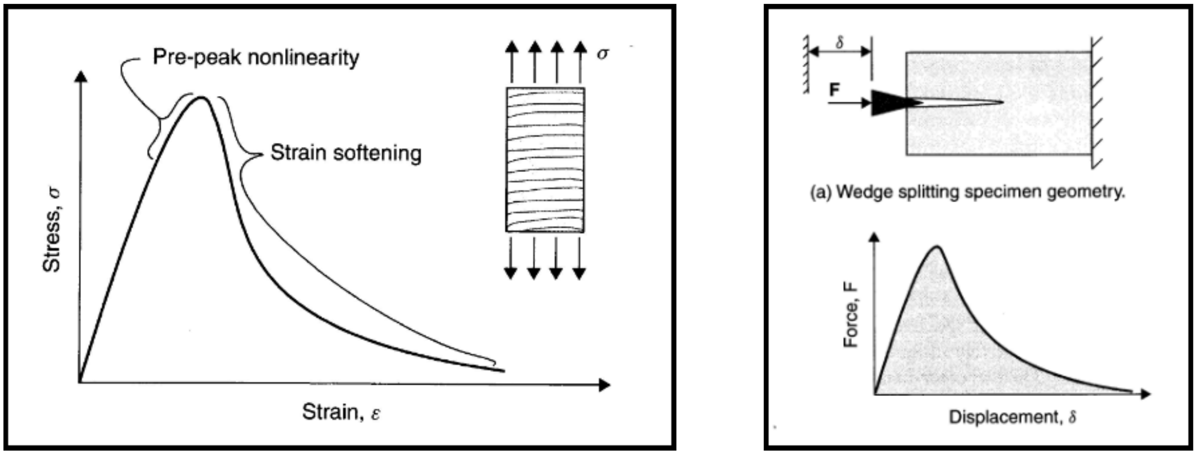
K_{IIc} = *mode 2 critical stress intensity factor*

1.3.3.5 Mode III

Traditionally mode III has been of little interest to engineers as it is not often encountered in wood design.

1.3.3.6 Nonlinear Fracture Characterization

As previously mentioned, LEFM requires all energy to be used in the propagation of a crack. Also mentioned was the fact that wood has a number of toughening mechanisms, which makes the accurate application of LEFM difficult. Nonlinear techniques are required to adequately model wood. The failure of wood can best be described as quasi-brittle, it can fail in a brittle manner, but the failure is less pronounced than with most brittle materials. Figure 1.19a shows a stress-strain curve for wood under tensile stress, which exhibits a linear region followed by a nonlinear region until a maximum stress, which then ends with a nonlinear strain softening. This leads to a different mathematical approach for determining the fracture toughness of wood based upon a combination of the energy required for crack initiation and crack propagation. One of the most popular test methods is a "wedge penetration" test shown schematically in Figure 1.19b. In this test, the work required to split specimen, W, is used to determine the specific fracture energy, G_f, which is interpreted as the fracture energy required to cause crack initiation and propagation to a particular extent of wedge penetration.



(a) Stress-Strain Diagram of wood in tension (b) Wedge fracture test on wood

Figure 1.19 Quasi-Brittle behavior of wood and example of a wedge test (Smith 2003)

Based on the work required to split the specimen, G_f is calculated as:

$$G_f = \frac{\int_0^{\delta max} F(\delta)d\delta}{A} \qquad \text{(Eq 1.12)}$$

Where: *A = newly cracked area*

δ = distance wedge is inserted

F = force required to insert wedge

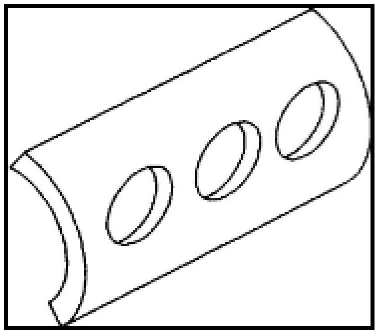
1.3.4 Fracture of Bamboo

1.3.4.1 Work Performed by Arce

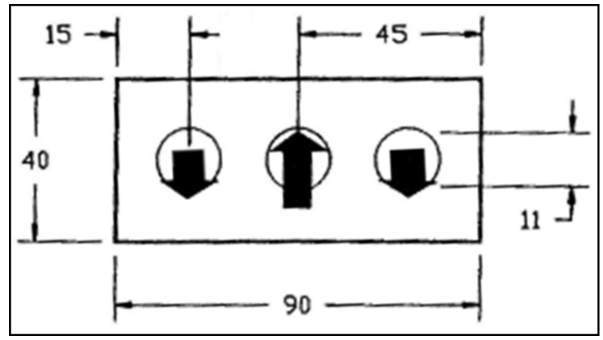
With regards to fracture toughness of bamboo, once again the first work was performed by Arce (1993) at the University of Eindhoven. Arce was primarily concerned with the transverse tension capacity of bamboo, as he hypothesized that the transverse strain capacity was relatively invariable between species, proposing a transverse strain limit of 0.0012. To obtain this value, Arce proposed the use of the specimen shown in Figure 1.20a and 1.20b in conjunction with a finite element model (FE). Computational results showing predicted strain intensity are shown in Figure 1.20c. While Arce obtained similar failure strain values for three different species of bamboo, due to the difficulty of utilizing failure strain rather than failure stress, little subsequent research has focused on this topic.

Unfortunately, there are a number of problems with both Arce's specimen selection and in his FEM modelling. The specimen is a poor choice in that its dimensions cause it to act more like a deep beam than a tensile specimen. Arce acknowledges this and also states that this specimen causes complex stress distributions, which makes the subsequent analysis more complex. Out of plane effects resulting from the wall curvature of the bamboo (Figure 1.20a) are not explicitly accounted for and result in even further complex stress distributions.

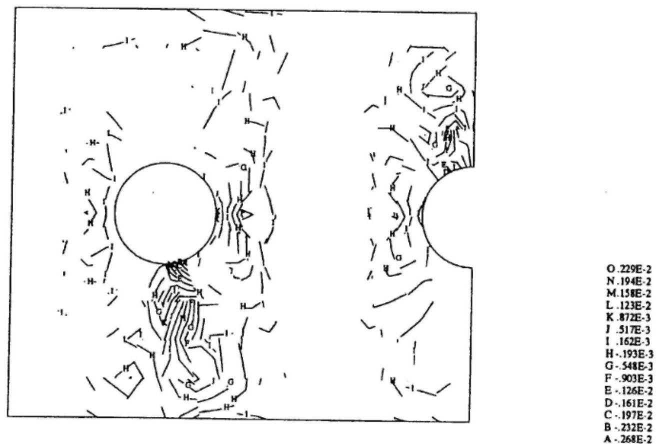
The FEM employed by Arce greatly oversimplifies the complex analysis that needs to be done. While he uses quadratic elements and then partly accounts for the anisotropic nature of bamboo with the use of 2 different moduli of elasticity in different directions, he neglects out-of-plane curvature and the through-thickness material grading (Figure 1.3). The FEM assumes a linear elastic modulus as opposed to a more realistic nonlinear modulus. Additionally, the model omits any role the fibers would play as reinforcement.



(a) bamboo specimen as cut from culm wall



(b) specimen geometry and loading



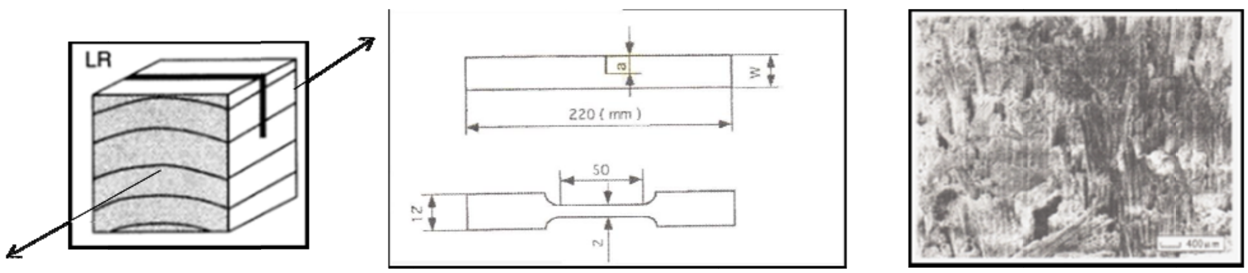
(c) analytical results showing strain intensity

Figure 1.20 Tangential strain specimen and test results reported by Arce (1993).

Despite the omissions of the model and the inherent difficulties of the test method, Arce was able to show that there is no correlation between the density of bamboo and its transverse strength (1993). This is important because the main reason for failure of bamboo is splitting, and the resistance to splitting is based on the transverse strength. Thus, if a certain species of bamboo has a high transverse strength, then it will most likely have a high overall strength. With most wood, there is a strong correlation between the strength and the density. The fact that this relationship is absent from bamboo makes the determination of its strength much less intuitive.

1.3.4.2 Work Performed by Amada

Amada et al. (2001) investigated the fracture properties of bamboo perpendicular to the fibers (LR direction) through the use of a bamboo tensile coupon (Figures 1.21a and b). They discovered that the fracture toughness was closely correlated to the percentage of fibers in the region (volume fraction). They also concluded that the fibers failed before the matrix did, thus the fracture characteristics of bamboo were similar to the first fiber-cracking of FRP (Figure 1.21c). The average value obtained for the fracture toughness was 56.8 MPa·m$^{1/2}$.

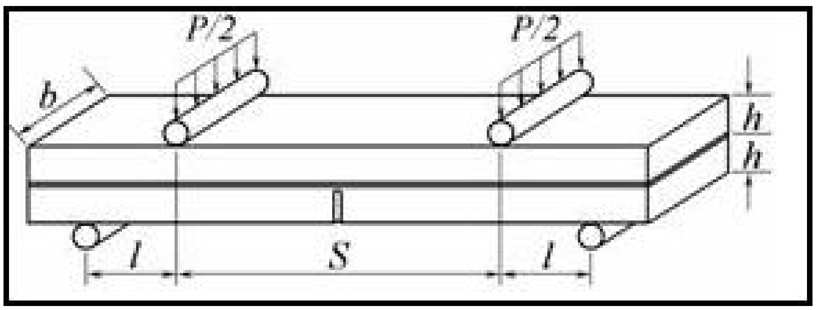


(a) direction of test (b) tensile coupon (c) image of fiber failure

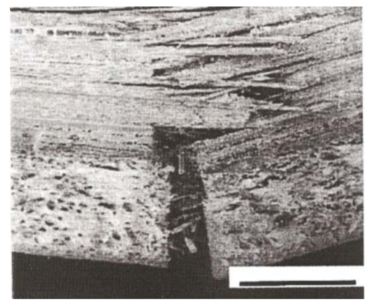
Figure 1.21 Test method and failure type reported by Amada et al. (2001).

1.3.4.3 Work Performed by Low

Low et al. (2006) extended the the work of Amada et al. (2001) through the utilization of synchrotron radiation diffraction, Vickers indentation, Charpy-impact tests, and four point flexural tests (Figure 1.22a). Their objective was to study the effect of age on the mechanical properties and fracture characteristics of bamboo. They determined that younger bamboo has a higher elastic modulus, strength, and fracture toughness than older bamboo. They then determined that crack-deflection and crack-bridging are the major energy dissipative mechanisms for bamboo. Finally, they determined that fiber delamination in the LR direction was the primary mechanism for fracture failure in bamboo (Figure 1.22b). These results were achieved through the use of a four point bending fracture test, which results in tensile stresses on the lower half of the culm and compressive stress in the upper half. The average fracture toughness value for old bamboo was 5.5 MPa·m$^{1/2}$ and the average value for young bamboo was 8.0 MPa·m$^{1/2}$.



(a) 4 Point flexure test



(b) Image of delamination

Figure 1.22 Test method and failure type reported by Low et al (2006).

The results obtained by Amada et al. (2001) are approximately an order of magnitude higher than those obtained by Low et al. (2006). The cause for such a large discrepancy is uncertain, but relevant factors may include the use of different species or difficulties encountered in the different test setups, namely the influence of fiber versus matrix failure and toughening mechanisms. One of the goals of this research program is to investigate the influence of the matrix versus fiber failure.

2.0 CHARACTERIZATION OF MATERIAL BEHAVIOR OF BAMBOO

2.1 SPLITTING BEHAVIOR

This research is focused on the development of an appropriate method of characterizing the splitting strength of bamboo culms. Splitting is the dominant failure mode for most bamboo in structural applications (Janssen 1981; Arce-Villalobos 1993) and has been documented by the author (Figure 1.7) and most other researchers. The objective of this research, therefore is to develop and calibrate an appropriate (but simple to conduct) test method for assessing splitting capacity of full culms. The proposed test method is founded on a fundamental fracture mechanics approach and therefore can account, in a consistent manner, for the high degree of variability present in bamboo geometric and material properties. While a number of test methods are available in the literature, a) none presently address full culm behavior; b) only one approaches the splitting problem from a fracture mechanics perspective; c) methods reported to provide the same material property result in significantly different values; and d) none have been standardized despite splitting being the dominant limit state for many applications. Additional constraints on the development of the test method were the requirements that the test be a) sufficiently simple; b) requires only basic equipment to perform; and c) is easily scalable to assess a range of bamboo geometries. These criteria are based on the need to use this test method in the field which implies use in under-developed rural areas having no access to engineering test facilities.

A new test for determining the fracture toughness of bamboo is required for two reasons. First, the new test would enable engineers to accurately assess the effectiveness of different bamboo species, preservative treatments, and joining methods. Second, the test types used in past literature have yielded inconsistent values, which will hinder future research in bamboo until a more consistent method is developed. In order to satisfy these requirements, the new test must be easy to perform, give stable crack growth rates, and enable the researcher to check the effectiveness of previous methods.

In order to determine an appropriate specimen, this study has taken the approach of considering as many different designs as possible and then analyzing these to decide which specimen designs are worthy of continued consideration. Based on the previously presented information, the following trial specimens have been developed and an initial summary of the benefits, drawbacks, and analytical equation of each is presented in Table 2.1.

Table 2.0 Test Geometries considered

<table>
<tr><td rowspan="4">Specimen A

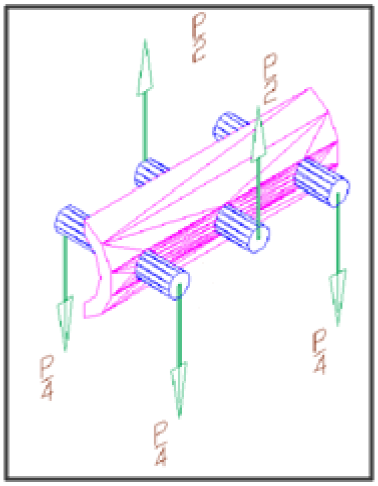



Figure 2.0 Specimen A</td><td>Explanation:</td><td>This is the specimen used by Arce (1993). The central pin is pulled upward while the left and right pins are pulled down. This induces a shear force which will cause fracture along the centerline of the specimen. As a note on the figures in this table, P represents the applied load.</td></tr>
<tr><td>Benefits:</td><td>Relatively simple beam-like specimen</td></tr>
<tr><td>Drawbacks:</td><td>Complex stress concentrations, deep beam behavior, requires analysis through fracture theory.</td></tr>
<tr><td>Equation:</td><td>$$K_1 = \sigma\sqrt{\pi a}\left[\frac{2w}{\pi a} tan\left(\frac{\pi a}{2w}\right)\right]^{1/2}$$</td></tr>
<tr><td rowspan="4">Specimen B

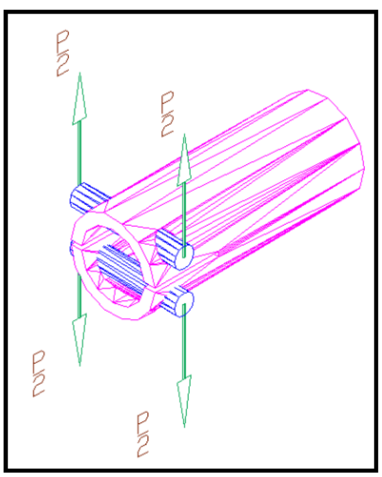



Figure 2.1 Specimen B</td><td>Explanation:</td><td>This is a modification of the classic double cantilever beam (DCB) specimen. Two holes are cut above and below the centerline of the specimen and loading bars are placed through them. Then a small “crack” is cut at the centerline to ensure the fracture begins at a controlled location. The bars are then loaded in opposing directions.</td></tr>
<tr><td>Benefits:</td><td>Relatively stable crack growth, tests matrix strength through shear</td></tr>
<tr><td>Drawbacks:</td><td>Construction time, requires difficult specimen machining, requires construction of crack initiation point, requires analysis through fracture theory. Due to practical pin dimensions, small diameter culms are impractical to test.</td></tr>
<tr><td>Equation:</td><td>$$K_1 = \sigma\sqrt{\pi a}\left[\frac{2w}{\pi a}\tan\left(\frac{\pi a}{2w}\right)\right]^{\frac{1}{2}} \times \left[\frac{0.752 + 2.02\frac{a}{w} + 0.37\left(1 - sin\left(\frac{\pi a}{2w}\right)\right)^3}{\cos\left(\frac{\pi a}{2w}\right)}\right]$$</td></tr>
</table>

<table>
<tr><td rowspan="4">Specimen C

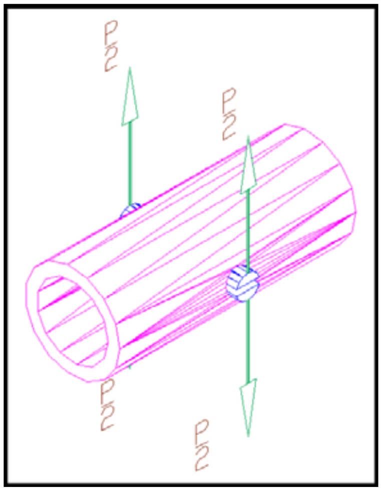



Figure 2.2 Specimen C</td><td>Explanation:</td><td>This newly proposed specimen requires a single hole to be drilled through the center of the specimen. Two halves of a “split-pin” are then inserted and loaded in opposing directions</td></tr>
<tr><td>Benefits:</td><td>Ease of construction, self-centering loading, tests matrix strength through shear</td></tr>
<tr><td>Drawbacks:</td><td>Requires analysis through fracture theory</td></tr>
<tr><td>Equation:</td><td>$$K_1 = \sigma\sqrt{\pi a}\left[\frac{2w}{\pi a} tan\left(\frac{\pi a}{2w}\right)\right]^{1/2}$$</td></tr>
<tr><td rowspan="4">Specimen D

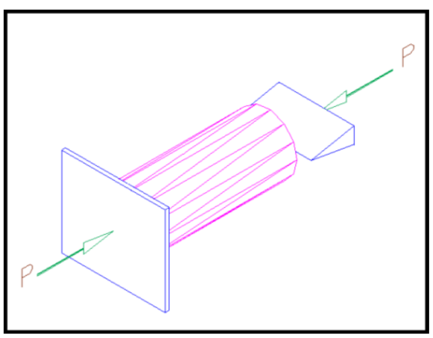



Figure 2.3 Specimen D</td><td>Explanation:</td><td>This is an adaptation of the wedge penetration specimen. A wedge is driven at a constant rate into the center of the specimen.</td></tr>
<tr><td>Benefits:</td><td>Constant rate of crack growth, tests matrix strength through shear</td></tr>
<tr><td>Drawbacks:</td><td>Requires analysis through fracture theory</td></tr>
<tr><td>Equation:</td><td>$$G_f = \frac{\int_0^{\delta max} P(\delta)d\delta}{A}$$</td></tr>
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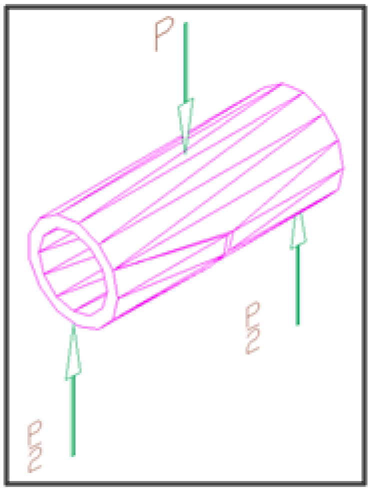
Specimen E



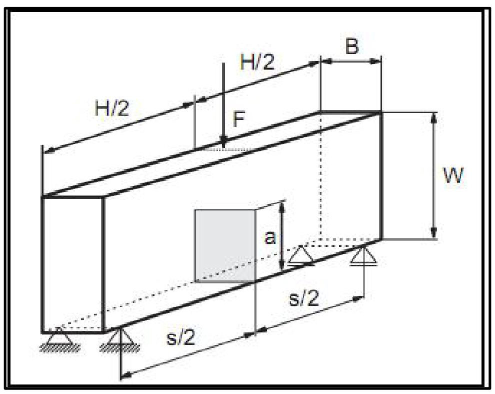


Figure 2.4 Specimen E

</td>
<td>Explanation:</td>
<td>An adaptation of a notched beam (transverse crack uninitiated) test for bamboo where the specimen is placed in a three-point loading test and has a notch cut in the tension zone.</td>
</tr>
<tr>
<td>Benefits:</td>
<td>Relatively simple test setup</td>
</tr>
<tr>
<td>Drawbacks:</td>
<td>Bearing/Crushing of bamboo at loaded areas, shear force changes throughout length, requires analysis through fracture theory, requires crack initiation point</td>
</tr>
<tr>
<td>Equation:</td>
<td>

$$K_1 = \frac{3Fs}{2BW^2}\sqrt{a}\, X$$

$$\left[\frac{1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left[2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right]}{\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}}\right]$$

</td>
</tr>
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Specimen F

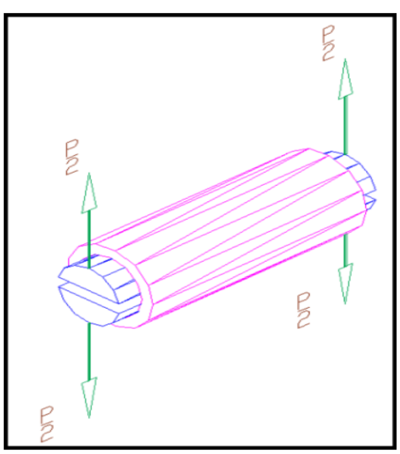
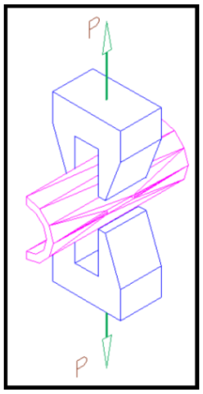
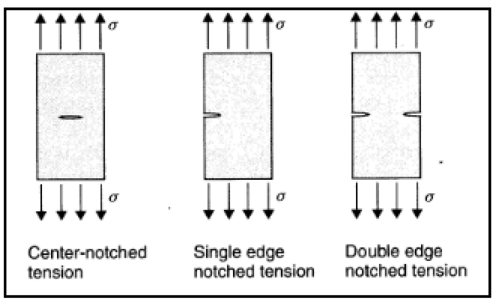


Figure 2.5 Specimen F

</td>
<td>Benefits:</td>
<td>Transverse stress can be calculated from first principles. Tests matrix strength through tension.</td>
</tr>
<tr>
<td>Drawbacks:</td>
<td>Difficult to obtain uniform stress distribution on the inside (bearing failure). Large variation in culm inside diameter makes test setup rather complex.</td>
</tr>
<tr>
<td>Equation:</td>
<td>

$$\sigma = P/A$$

</td>
</tr>
</table>

Specimens G – I   **Figure 2.6** Specimens G-I	Explanation:	Another classic fracture specimen in which one half of a culm is placed within grips which are then loaded in opposite directions. The specimen has: a cut on the left (G), Middle (H), or both sides (I) similar to those shown in Figure 1.16.
	Benefits:	If specimen is cut to grip width, then the tensile stress field is uniform.
	Drawbacks:	Crushing of the bamboo at the grips makes this test nearly impossible to perform.
	Equation 1 (side notch):	$K_1 = \sigma\sqrt{\pi a}\left[\frac{2w}{\pi a}\tan\left(\frac{\pi a}{2w}\right)\right]^{\frac{1}{2}} \times \left[\frac{0.752 + 2.02\frac{a}{w} + 0.37\left(1 - sin\left(\frac{\pi a}{2w}\right)\right)^3}{\cos\left(\frac{\pi a}{2w}\right)}\right]$
	Equation 2 (center notch):	$K_1 = \sigma\sqrt{\pi a}\left[sec\left(\frac{\pi a}{w}\right)\right]^{1/2}$
	Equation 3 (notched both sides):	$K_1 = \sigma\sqrt{\pi a}\left(\frac{2w}{\pi a}\right)^{1/2}\left[tan\left(\frac{\pi a}{2w}\right) + 0.1\sin\left(\frac{\pi a}{w}\right)\right]^{1/2}$

It is felt that a significant feature of a bamboo splitting test is that it utilizes the entire culm section. This will eliminate eccentricities resulting from a semi-circular or arc-shaped specimen. Such eccentricities result in through-thickness bending of the specimen. Additionally, using full culm sections permits the inclusion or exclusion of nodes as desired. The crack arresting or promoting properties of the nodal regions can therefore be investigated. In order to utilize a full culm section as well as produce a stable crack growth rate, this study pursued specimen C geometry.

2.1.1 Development of Specimen C – Fracture Test

The determination of the fracture toughness of specimen C requires the application of fundamental linear elastic fracture mechanics (LEFM). For the test geometry shown in Figure 2.7, the Mode I stress intensity factor, K_1, is given as:

$$K_1 = \sigma\sqrt{\pi a}\left[\frac{2w}{\pi a} tan\left(\frac{\pi a}{2w}\right)\right]^{1/2} \quad \text{(Eq. 2.1)}$$

Where *σ = tensile stress perpendicular to the fibers over the gross area*

2a = initial length of the crack

2w = specimen length

The stress, σ, is determined by dividing the load at failure by the gross area of the specimen at the failure plane:

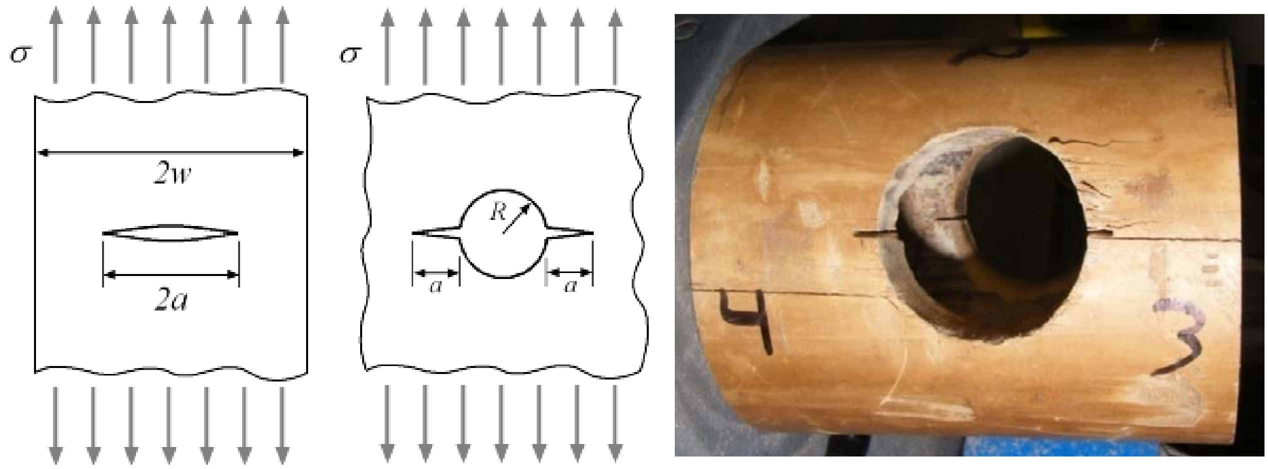
$$\sigma = \frac{P}{2(2w \cdot t)} \quad \text{(Eq. 2.2)}$$

Where *P = total applied load*

t = average culm wall thickness

The scalar ‘2’ in Eq. 2.2 accounts for the fact that the entire culm is tested

And thus two wall thicknesses are engaged



(a) specimen corresponding to Equation 2.1 (efunda.com)

(b) specimen corresponding to Equation 2.3 (efunda.com)

(c) test specimen

Figure 2.7 Fracture test specimen geometry

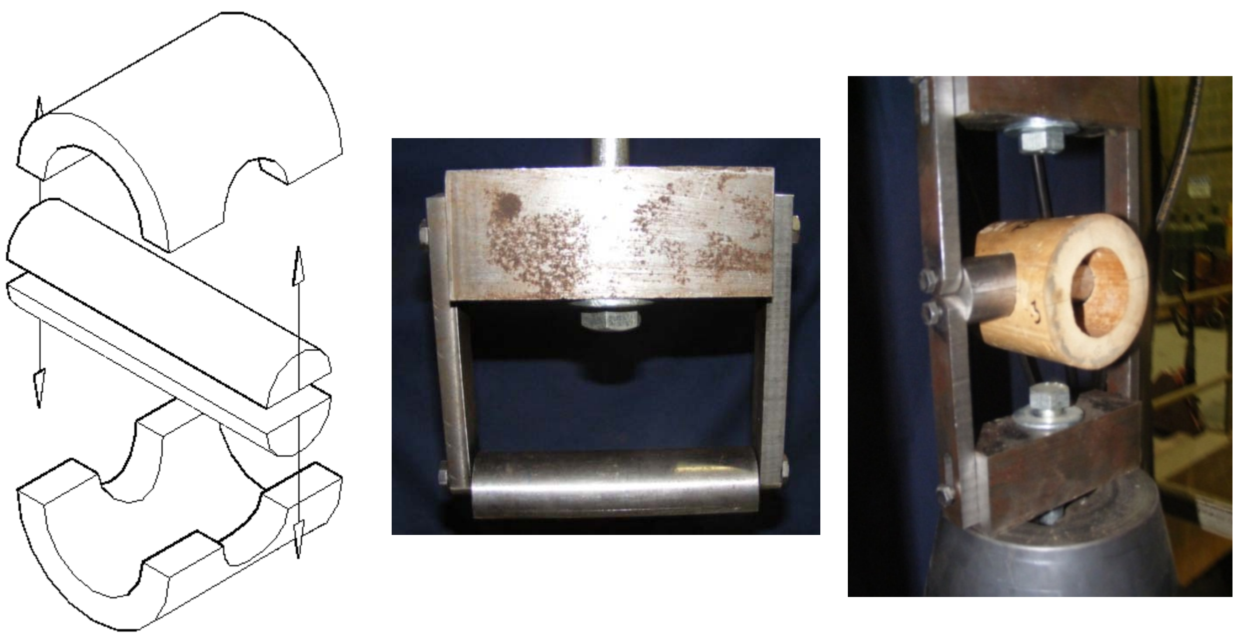
An alternative formulation which empirically accounts for the drilled hole and horizontal crack initiators (as opposed to the horizontal crack 2a only) but not the specimen length (2w) yields K_1 values about 7% greater than those calculated using Equation 2.1.

$$K_1 = \sigma\sqrt{\pi a}\left[1 + 2.365\left[\frac{R}{R+a}\right]^{2.4}\right] \qquad \text{(Eq. 2.3)}$$

Due to the curved nature of the bamboo specimen, it is felt both formulations of K_1 are approximations. Since Equation 2.3 assumes an infinitely wide specimen, the K_1 formulation given in Equation 2.1, which assumes a finite element, will be adopted. The strain energy release rate, G_1, is proportional to the square of K_1, as shown in Eq. 1.7.

The test specimens used in this study utilized a 'loading hole' having a diameter d = 38.1mm (1.5 in.) with crack initiation points, having length a = 3.18 mm (0.125 in.) as shown in Figure 2.7. Thus the value of 2a shown in Figure 2.7a is 44.5 mm (1.75 in.). To create the center hole, a drill press with a 38.1 mm diameter hole saw was used. The hole was created on both sides of the culm in one pass in order to ensure specimen symmetry. The crack initiation points were then marked out with a ruler and cut using a fine-toothed hacksaw blade.

The test setup consists of two clevis test assembles which are pulled in opposite directions. Each assembly is made up of a) the split pin, b) connection bolts, c) connection arms, d) loading bolt and block as shown in Figure 2.8. Since the fracture strength of the bamboo was unknown, the assemblies were designed to carry an applied load of 4000 lbs, which was estimated to be far greater than the expected failure load.



(a) schematic of test specimen and loading

(b) Top half of test set up showing one split pin and yoke

(c) test set up with specimen in place

Figure 2.8 Fracture test set-up.

Once the specimens were installed in the test frame (Fig. 2.9c), they were loaded until failure in displacement control with the cross-head moving at a rate of 0.005mm/sec (0.0002in/sec). This speed is approximately half of the speed prescribed for the shear and compression tests (see subsequent sections), and was chosen due to the fact that the fracture specimens have a much lower failure load. Ten specimens were tested (see Chapter 3) and all failures were brittle in nature. The bamboo generally experienced failure along all four possible surfaces (Fig. 2.10), although some failures of just 2 or 3 surfaces were encountered.

(a) specimen following failure along all four failure planes

(b) close up view of failure plane

Figure 2.9 Fracture test failure modes.

In addition to the new fracture toughness test, tests to assess the bamboo compressive and shear strengths were conducted; these are described in the following sections. Tension parallel to the fibers and flexural strength are also often performed, but were omitted in this program. In the case of the tension tests, the test specimen is a coupon cut from the culm, thus the effects of specimen radius and the variation of through-wall thickness properties of the culm (Fig. 1.3) may cause indeterminate internal stresses affecting the reported tension properties. Additionally, there are some difficulties associated with gripping a fibrous material for tension testing that needs to be overcome before reliable tension tests may be conducted. The flexural test was omitted due to the lack of availability of suitably long culms.

2.2 COMPRESSION TEST

The compression test conducted followed the method prescribed in ISO 22157-1, *Bamboo – Determination of physical and mechanical properties* (ISO 2004b). In this direct compression test (Fig 2.11), the compressive strength of the bamboo is determined by dividing the load at failure, P by the cross-sectional area of the culm:

$$\sigma = \frac{P}{A} \qquad \text{(Eq. 2.4)}$$

The cross-sectional area of the culm is determined by averaging the diameter and wall thickness at four locations at both the top and bottom of the specimen. These measurements yield the inner and outer diameter of the culm, which is in turn used to calculate the area of the cross-section and the subsequent failure stress.

According to the ISO standard, the specimens are to be cut to a length equal to the culm diameter and loaded in the longitudinal direction in displacement control with the crosshead traveling at a rate of 0.01 mm/s (0.0004 in./s). Additionally, the culms require an intermediate layer to reduce friction between the steel loading plates and the bamboo specimen. The ISO standard recommends the use of steel finger shims (ISO 2004b) although it also suggests in the associated *Laboratory Manual* (ISO 2004c) that sulfur-based capping compound (as is used for concrete cylinder compression tests) is also acceptable. The latter was used in the present study. Anecdotal evidence suggests that the use finger shims, while accomplishing the desired behavior is very difficult to implement accurately in practice. This study will permit some discussion of the use of the capping compound alternative. In order to have a specimen having a clear height of one culm diameter following capping, specimens were cut at overall lengths of between 1.25 and

1.5 culm diameters. While this is longer than the capping compound requires, the additional height did not have an adverse effect on the compressive strength.

Testing was carried out in a Baldwin Universal Testing Machine with a fixed lower platen and an upper platen equipped with a ball-joint to account for non-symmetric specimen geometry. A total of twelve tests were performed. All specimens experienced the same type of failure, namely longitudinal splitting followed by buckling of the resulting longitudinal 'strips' (see Fig 2.11c).

(a) schematic of test specimen | (b) test specimen in test machine | (c) typical compressive failure

Figure 2.10 Compression test.

2.3 SHEAR TEST

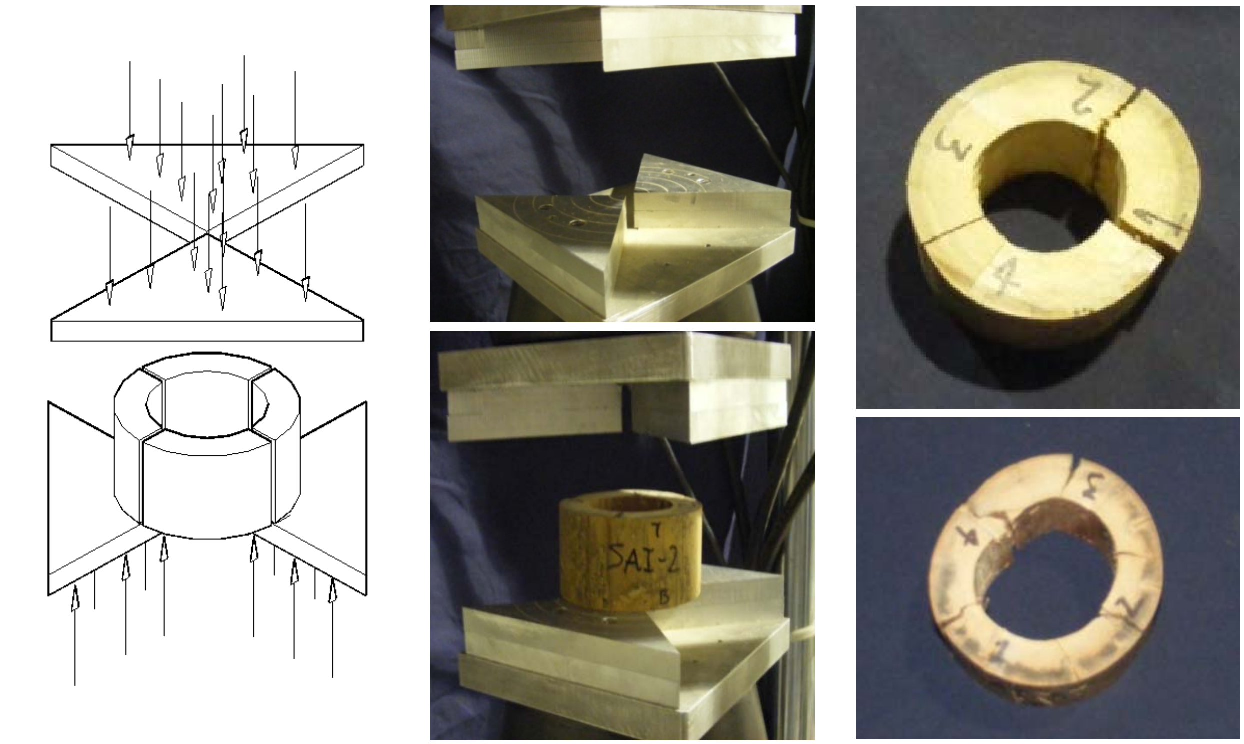
The shear test conducted followed the method prescribed in ISO 22157-1, *Bamboo – Determination of physical and mechanical properties* (ISO 2004b). In this test, developed by Janssen (1981), the cross-section of the specimen is divided into four quadrants. Two of the quadrants are loaded on the top and two are loaded on the bottom, which produces four shear failure planes in the culm. The test set-up is shown in Figure 2.11 and consists of four ‘teeth’ making up the quadrants. The teeth are aligned such that there is a 3 mm (0.125 in.) gap between them creating the ‘shear planes’ in the specimen (Figure 2.11c). The test set-up fabricated for this study was fabricated of aluminum (to keep it light) and was designed to be loaded into an MTS 810 universal test frame having self-centering hydraulic grips. This facilitated reliable and repeatable test alignment. Janssen’s original design (Fig 1.9) included a self-centering core, however this precludes testing specimens that include a node. The test is carried out in displacement control with the crosshead traveling at a rate of 0.01 mm/s (0.0004 in./s). The shear stress is equal to the failure load divided by the sum of the area of the four failure planes located at the intersections of the teeth:

$$\sigma = \frac{P}{\sum_{i=1}^{4} H_i t_i} \qquad \text{(Eq. 2.5)}$$

Where H_i = *height of the specimen at shear plane i*

t_i = *culm wall thickness at shear plane I, taken as the average of the thicknesses at the top and bottom of the specimen.*

An important aspect of the shear specimen is that its ends are parallel resulting in uniform load applied to both ends. To accomplish this, the specimens are ‘faced’ on a wide belt sander following cutting. The belt sander should be wider than the culm diameter so that the facing may be done in ‘one pass’.



(a) schematic of test specimen and setup

(b) test set up (top) and specimen in test machine

(c) typical shear failures with 3 (top) and 4 (bottom) failure planes

Figure 2.11 Shear test.

3.0 EXPERIMENTAL PROGRAM

3.1 SPECIMENS

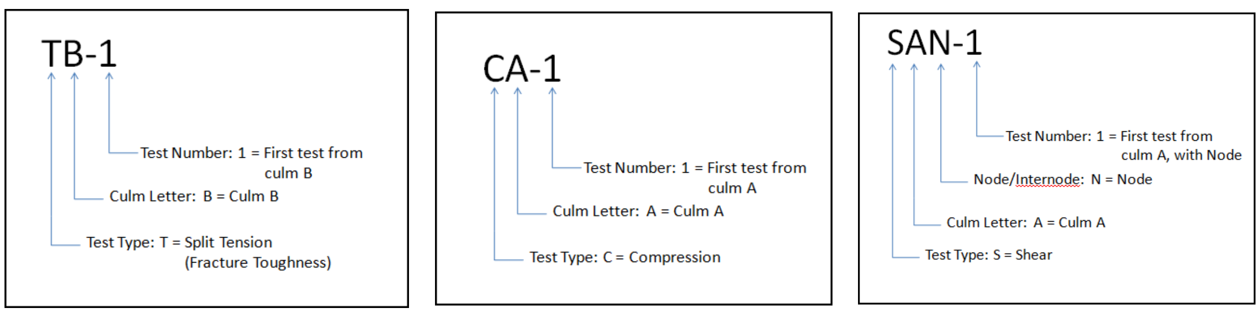
3.1.1 Specimen Description

The bamboo culms used in the experimental program were supplied by Bamboo Craftsman Company of Portland, Oregon. The culms were of the species *bambusa stenostachya* which is more often referred to as Tre Gai. While Bamboo Craftsman sold the bamboo culms in the United States, they were originally imported from a supplier in Vietnam. This supplier applied a vacuum pressure treatment with boric acid to the culms in order to preserve them for transportation and use.

It is important to note that both the geometric and material properties obtained in this series of tests may be considerably different from those obtained in other test regimes due to a variety of factors. While material properties will certainly vary across species, it has also been shown that bamboo's properties vary according to growing climate, height along culm, age, and moisture content. As the culms are provided by a commercial supplier, who does not record this information, there is no readily available way to verify any of these parameters. As the intent of this series of tests was not to address this variability, no effort was made to account for these factors.

3.1.2 Specimen Naming Convention

The specimen naming convention used in this study is shown in Figure 3.0. For ease of testing, a request was made of Bamboo Craftsman Company to sort their inventory and to only provide culms with a diameter of approximately 75 – 100 mm (3 - 4 in.). A total of 13 culms at 1.8 m (6 ft) were received, and of those, 6 were selected for use as test specimens due to their superior physical condition. The culms selected were labeled A through E and L. There was no way in which to determine whether the individual lengths came from the same culm or multiple culms.



(a) fracture specimens (b) compression specimens (c) shear specimens

Figure 3.0 Specimen naming convention.

3.2 GEOMETRY

In addition to the strength properties investigated, the geometry of the bamboo culms must also be documented. Variation in geometry clearly effects member behavior and an understanding and quantification of this variation is necessary to establish reliability and acceptable design values for bamboo materials. In this study, only the bamboo section is of interest (length is not considered). The culm section is defined by its outside diameter and wall thickness.

All test specimens were measured. Their diameter is measured twice, in orthogonal directions, at each end of each specimen. The culm wall thickness is generally measured four times at each specimen end at 90^{o} increments around the specimen.

The measurements were taken using a digital caliper having a resolution of 0.025 mm (0.001 in.). Table 3.1 provides a compilation of measurements taken from different test specimens. The "n" represents the number of measurements from each culm. The results indicate that the outside diameter of each culm is nearly constant over its 1.8m (6') length, whereas the wall thickness of individual culms varies by a considerable amount.

Table 3.0 Measured Culm Dimensions

	Natural Dimensions					
	Outside Diameter (mm)			**Culm Wall Thickness (mm)**		
Culm	**mean**	**stdev (ratio)**	**n**	**mean**	**stdev (ratio)**	**n**
A	90.74	0.023	27	20.71	0.099	64
B	91.07	0.022	11	21.21	0.107	28
C	83.96	0.016	17	16.31	0.144	36
D	89.00	0.016	9	15.25	0.094	24
E	98.03	0.013	4	14.73	0.047	4
L	90.46	0.010	4	13.48	0.053	8
Entire Sample	90.54	0.044	72	18.44	0.177	168

3.3 FRACTURE TESTS

The fracture toughness test requires a number of specimen measurements including specimen length (2w), crack length (2a), and gross section stress (σ) obtained from failure load; these are reported in Table 3.2. The wall thickness of the specimen was taken at the four different expected failure surfaces (emanating from the crack initiation point) and then averaged together. The stress used to calculate K_1 is given by Equation 2.2 and the value of K_1 is given by Equation 2.1.

The ‘failure stress’ is the stress over the actual ***resisting*** area:

$$\sigma_{failure} = \frac{P}{2((2w-2a)\times t)} \qquad \text{(Eq. 3.1)}$$

Finally, the number of failure planes represents the number of surfaces, of the possible four, which split during the test. The number of failure planes is important because a test with fewer than four surfaces should, theoretically, yield a lower-bound fracture toughness than a test which experienced failure in all four planes.

As can be seen from the table below, the fracture test yielded relatively consistent results. The standard deviation was 21% which, while not as consistent as the compression test, is still significantly lower than that of the shear tests. This degree of deviation is consistent with that measured for material properties of both bamboo and other natural materials tested by others (Kretschmann 2008). The consistent standard deviation is confirmed upon inspection of the failure planes. Of the ten tests conducted, six specimens failed along all four planes simultaneously, which indicates that these specimens had an even distribution of stress, and thus an accurate failure capacity.

The average stress intensity factor was determined to be 0.164 MPa·m$^{1/2}$, which is significantly lower than the 5.5 - 8.0 MPa·m$^{1/2}$ range reported by Low et al. (2006) and the 56.8 MPa·m$^{1/2}$ value reported by Amada et al. (2001). While the difference between the values is substantial, it may be explained by the different specimen geometries used. For comparison, the most commonly encountered sawn timber in North America are Douglas Fir and Southern Pine; they have reported stress intensity factors of 0.320 MPa·m$^{1/2}$ and 0.375 MPa·m$^{1/2}$, respectively, in the RL direction (Smith 2003). The higher values for sawn timber reflect the ‘toughening’ effects of the ‘rays’ (radial fibers) in the section geometry.

3.3.1 Fracture Test Specimen Geometry

The different stress intensity factors obtained from different test specimen geometries is due to the stresses associated with failure of each specimen type. In this study, a 'center cracked specimen subject to direct tension' was used (see Figure 2.8a). Low et al. (2006) used a 'single edge notched specimen subject to flexure' (Figure 1.22a). The stress field at the notch in these test methods is similar– direct tension. The failure mode observed by Low et al. is shown in Figure 1.22b and is analogous to that observed in this study (Figure 2.10), although significant toughening effects resulting from the flexural behavior of the specimen are present in Low et al's tests. For example, the 'crushing' of the fibers above the notch that are evident in Figure 1.22b will 'toughen' Low et al.'s specimen.

Amada et al. (2001), on the other hand, tested a 'single edge notched specimen subject to direct tension' as shown in Figure 1.20. The test specimen was oriented so that tension was parallel to the grain rather than perpendicular, as is the case in this study and in Low et al (see section 1.3.4). Thus the stress intensity factor reported by Amada et al. is actually that associated with fiber rupture rather than matrix rupture, which makes the test methods incomparable. Therefore, for anisotropic materials such as bamboo, specimen geometry and orientation are crucial to interpreting fracture test results.

As noted in Chapter 2.1.1, even where specimen geometries are comparable, the assumed local crack geometry affects the calculation of the stress intensity factor. Comparing calculated values of K_1 determined using Eqs 2.1 and 2.3 shows approximately 7% greater values when using Eq 2.3. This observation indicates that such tests are more suitable for making comparisons between specimens rather than assessing absolute values of fracture properties.

Table 3.1 Fracture Test Results

Specimen	Average Culm Wall Thickness, t	Average Crack Length, 2a	Average Specimen Length, 2w	Ultimate Load, P	Failure Stress (EQ 3.1)	K_1 (EQ 2.1)	Failure Planes
	mm	mm	mm	N	MPa	MPa·m$^{1/2}$	-
TB-1	20.6	22.7	101.2	2910.2	1.266	0.205	2
TB-3	19.7	23.0	106.2	2100.3	0.886	0.147	4
TB-4	22.8	23.3	101.7	2380.7	0.948	0.153	4
TD-1	16.0	22.2	104.1	1673.1	0.876	0.144	4
TD-2	15.9	22.8	103.6	1321.6	0.717	0.118	2
TD-3	16.2	22.6	104.9	2118.1	1.095	0.181	4
TE-1	14.8	22.4	104.2	1597.5	0.909	0.149	2
TE-2	14.6	22.5	102.3	2402.9	1.436	0.233	4
TL-1	13.7	22.4	106.2	1802.2	1.071	0.178	4
TL-2	13.2	22.4	104.2	1303.8	0.831	0.137	3
average	-	-	-	1961.0	1.003	0.164	-
stdev	-	-	-	516.1	0.217	0.035	-
stdev ratio	-	-	-	0.263	0.216	0.211	-

3.4 COMPRESSION TESTS

The compression test is the simplest test of the three conducted, and only requires the culm wall thickness, outside diameter, and ultimate load. A total of 12 compression tests were performed; the results are given in Table 3.3. As was mentioned in section 2.2, the compression specimens had their ends ‘capped’ in a sulfur capping compound to minimize the friction between the bamboo and the loading plates. To account for the length occupied by these caps, an additional 0.25 to 0.50 diameters were added to the specimen length. Despite this additional length, the culms reached an average strength of 56.7 MPa. This value is higher than other reported values for compressive strength, as will be seen in chapter 4.

Despite the relatively high level of variability inherent in the material properties of bamboo, the compressive strength of the culms exhibited relatively low variation, having a standard deviation of only 12%. This lower level of deviation leads to the conclusion that the use of sulfur capping compound is an appropriate alternative to using ‘finger shims’ as described by the ISO standard (ISO 2004b).

Table 3.2 Compression Test Results

Specimen	**Average Height**	**Average Culm Wall Thickness, t**	**Average Outside Diameter**	**Ultimate Load, P**	**Ultimate Stress, Eq 2.4**
	mm	mm	mm	kN	MPa
CA-1	129.0	21.1	90.7	290	62.8
CA-2	125.2	20.0	87.6	281	66.3
CA-3	127.2	19.9	91.6	254	56.6
CA-4	126.7	19.7	90.9	225	51.0
CA-5	122.4	21.3	88.4	308	68.6
CB-1	150.3	21.8	90.0	287	61.5
CB-2	148.4	22.9	89.6	259	54.1
CB-3	148.9	23.5	89.0	251	51.9
CC-1	102.1	16.5	84.1	205	58.4
CD-1	154.4	15.9	90.1	172	46.3
CD-2	149.4	12.7	86.1	161	54.9
CD-3	150.3	14.8	87.9	165	48.4
average	-	-	88.8	238	56.7
stdev	-	-	2.2	52	7.0
stdev ratio	-	-	0.02	0.22	0.12

3.5 SHEAR TESTS

The final series of tests performed were the shear tests. This test series consisted of 10 specimens including nodal and internode specimens; the results are presented in Table 3.4.

According to Janssen (1981), the shear strength should be greater at the nodal regions. The reason being that in the internodal regions the fibers run in one direction only, which allows shear forces to propagate in the weaker matrix material. Thus, at a nodal region, where the fibers run in multiple directions, the shear stress must propagate beyond the matrix and overcome a number of stronger fibers, thus increasing the shear strength. The expectation of higher shear strength at the node is confirmed by the results presented in Table 3.4. Specimen SCN-1 has been removed from the calculation of strength as an outlier.

The standard deviation of the test series is 25%, which is more than twice the compression test (12%) and higher than the fracture toughness test (0.22%). The internodal shear tests exhibit a higher variation (30%) than the nodal specimens (22%). One useful metric to understand the variability of the shear test is to compare the number of failure surfaces between the shear and fracture tests. In the shear test, generally only 1-3 surfaces fail at the ultimate load whereas the fracture test generally fractures all 4 surfaces. This indicates a more even distribution of load in the fracture test than the shear test. In the shear test, one would expect the failure plane having the smallest area (smallest culm wall thickness) to fail first. Due to the geometry of test, no redistribution is possible and thus this lower-bound ultimate capacity is captured. A further factor affecting variability of the shear test is that, while the fracture test is unaffected by uneven saw-cuts (as the culm is cut to length), the shear test requires perfectly parallel cuts to yield consistent results. Achieving parallel edges for all four bearing surfaces for the shear test is complicated by slight eccentricities in the culm as well as the fact that bamboo's relatively high hardness makes it difficult to sand down a flat face.

Table 3.3 Shear Test Results

Specimen	Shear Area H x t	Average Specimen Height, H	Average Culm Wall Thickness, t	Ultimate Load, P	Ultimate Stress Eq 2.5	Failure Planes
	mm^2	mm	mm	kN	MPa	
SAN-1	4950	50.70	24.40	54.2	10.95	2
SAN-2	4972	62.98	19.73	32.9	6.62	2
SAN-3	4770	53.38	22.34	43.4	9.10	1
SAN-4	5870	63.90	22.97	51.0	8.69	1
SAN-5	4742	56.69	20.91	53.0	11.17	3
SAN-6	5236	64.89	20.17	45.0	8.60	2
SCN-1	4178	59.23	17.64	19.7	4.70	2
SCN-2	3931	59.81	16.43	47.5	12.08	2
SCN-3	3862	59.41	16.25	47.2	12.21	1
SCN-4	3461	54.74	15.81	24.0	6.94	1
SAI-1	3937	53.99	18.23	33.0	8.38	2
SAI-3	4744	52.24	22.71	23.9	5.03	3
SAI-4	4691	52.43	22.37	50.1	10.68	2
SAI-5	3808	53.07	17.94	27.0	7.09	4
SCI-1	3641	55.45	16.42	49.5	13.58	1
SCI-2	3386	51.88	16.31	22.6	6.68	2
SCI-3	3559	56.53	15.74	32.4	9.09	3
SCI-4	3273	52.24	15.67	31.3	9.56	2
All Specimens			average	39.3	9.2	
			stdev	11.3	2.3	
			stdev ratio	0.29	0.25	
Nodal Specimens			average	44.2	9.6	
			stdev	9.9	2.1	
			stdev ratio	0.22	0.22	
Internodal Specimens			average	33.7	8.8	
			stdev	10.6	2.6	
			stdev ratio	0.32	0.30	

4.0 CHARACTERISITIC PROPERTIES

In the design of modern structures, an understanding of the mechanical properties of different materials is of the utmost important. Generally a large number of tests are performed on a variety of samples to determine the mean and standard deviation of the material properties so that designers may have confidence in the uniform reliability of design values. While materials such as metals and wood are well documented, the lack of engineering interest in bamboo, has led to a deficiency of useful data concerning such basic material properties as compressive, shear, flexural and tensile strengths. While this research program did not investigate either flexure or parallel tension, it did investigate compressive and shear strength as well as the perpendicular tensile strength of bamboo. In this chapter characteristic properties presented by others will be compared to those established in this study.

4.1 DESIGN VALUES

Since experimentally obtained material properties vary significantly, ***design*** values for structures are reduced in proportion to their standard deviation. According to AC 162 *Acceptance Criteria For Structural Bamboo* (ICC 2000), the design values for compressive and shear strength are determined according to equation 4.1 below.

$$S = \frac{B}{C_a} \qquad \text{(Eq. 4.1)}$$

Where *S = Design Stress*

B = Characteristic Value = $(m - K_s) \cdot DOL$

m = Average Ultimate Strength

K = Factor from Table 3, ASTM D2915

s = Standard Deviation

DOL = Duration of load

1.0 for permanent load

1.25 for normal load (x<10 years)

1.5 for wind and seismic

C_a = *Adjustment factor = 2.25*

The value of K is found to correspond to the 95% tolerance limit (5^{th} percentile) with 75% confidence. For a relatively small sample size (as tested here), this value is taken as approximately 2.0. Thus, Eq. 4.1 may be written as:

$$S = \frac{m - 2 \cdot s}{2.25} \qquad \text{(Eq.4.2)}$$

The value of C_a is an essentially arbitrary factor intended to reflect the high degree of variation when testing bamboo. This value may be alternately interpreted as being a material resistance factor φ = 1/2.25 = 0.44.

4.2 COMPARISON TO VALUES OBTAINED BY OTHERS

Listed in Table 4.1 are the values determined during the testing done for this research program at the University of Pittsburgh (PITT) as well as values reported in literature from the University of Washington (UW), the University of Hawaii (UH), and two versions of material testing reports issued by ICC Evaluation Services Inc (ESR-1636-2004 and 2006) for Tre Gai bamboo. Also shown are the average values for bamboo in the group A classification[2] of the National Building Code of India (NBCI 2005). For the results reported here and those reported by the University of Hawaii, design values for the cases in Equation 4.1 were C_a = 2.25 and C_a = 1.0 (i.e. nominal design values) are presented. This was done to give the reader a more complete understanding of the manner in which equation 4.1 reduces the useable design values. Finally, the material properties of Douglas Fir and Southern Pine are listed to give the reader a base by which to compare bamboo. Douglas Fir and Southern Pine are the most common sawn timber species in Western and Eastern North America, respectively. The values are given for 'select structural' grade, which is the highest grade of sawn timber. Other grades have significantly reduced design values.

[2] The bamboo classes prescribed by NBCI are based on experimentally determined material properties. Based on the results of all data reported, Tre Gai falls into Class A.

Table 4.0 Comparision of Design Values

	Tre Gai - Design Values				
	Compression MPa	**Shear** MPa	**Tension Parallel to Fibers** MPa	**Tension Perpendicular to Fibers** MPa	**Flexure** MPa
PITT (C_a = 1.0)	42.8	4.54	-	0.57	-
PITT (C_a = 2.25)	19.0	2.01	-	0.25	-
UW - MEL01-047	15.9	2.85	30.0	-	40.5
ESR-1636-2004 (C_a = 2.25 implied)	7.9	1.41	15.0	-	20.3
ESR-1636-2006 (C_a = 2.25 implied)	4.1	1.28	7.7	-	10.3
NBCI Group A avg	13.0	-	-	-	20.0
University of Hawaii	16.4	3.03	32.7	-	25.5
UH (C_a = 1.0)	11.6	-	-	-	-
UH (C_a = 2.25)	5.1	-	-	-	-
Select Structural - Douglas Fir	11.7	0.66	6.9	-	10.3
Select Structural - Southern Pine	14.5	0.69	11.0	-	19.7

4.2.1 Compression

The compressive strength determined from this research program was substantially higher than values encountered elsewhere. The design compressive strength for Tre Gai from this test series as well as the work performed at the University of Washington and the average from the NBCI group A either meets or exceeds the values for the two timber species shown. The values determined from the two ICC Evaluation Reports as well as one series of tests done by the University of Hawaii, list values that are significantly below those of sawn timber. The reason for this discrepancy is unknown due to a lack of raw data forming the ICC or NBCI data, but may be related to factors such as the age of the culm or its moisture content when tested. While more research will be required to accurately assess the compressive strength of Tre Gai, the presence of such high potential values leads one to believe that if the bamboo is harvested at the correct time and dried, seasoned and preserved in the correct manner, then Tre Gai is a significantly stronger alternative to either Douglass Fir or Southern Pine for compression.

4.2.2 Shear

The shear strength results obtained in this research program are similar to the values reported elsewhere. While one would expect the shear values obtained in this study to be lower than those obtained by different institutions due to the difficulties experienced with the shear test, there is a large discrepancy between the evaluation reports' values and those obtained elsewhere. Unfortunately, an analysis of the potential factors responsible for such disparate values is both beyond the scope of this study as well unlikely to succeed due to a lack of necessary information regarding the testing performed at each institution. Even taking the most conservative value, the higher shear strength of Tre Gai once again indicates that it is a superior alternative to sawn timber.

4.2.3 Perpendicular Tension Strength

The fracture toughness test also yields the tensile capacity of the bamboo in the direction perpendicular to the culm. To the author's knowledge this is the first study in which this value has been reported, and thus there no basis for comparison. It is proposed that with sufficient experimental data, a relationship between perpendicular tension capacity and longitudinal shear could be established since these mechanisms are mostly a function of the bamboo matrix material which is, itself, largely isotropic.

4.2.4 Parallel Tension and Flexural Strength

While this research program did not investigate either the parallel tensile strength or the flexural strength of Tre Gai, a discussion of these values in comparison to their wood counterparts is still useful.

While the use of bamboo as a purely tensile member is rare, the common use of bamboo as a flexural member makes the parallel tension strength of bamboo an important property. The flexural strength should be interpreted as the flexural modulus of bamboo – that is: it is the value of the extreme tensile stress in a flexural specimen at failure. Once again, experimental data reported by UW and UH are significantly greater than those prescribed by the ICC Evaluation Reports. When compared to the design values for Douglas Fir, Tre Gai is clearly superior, although its tensile strength is lower than that of the Southern Pine. The same conclusion can be drawn for parallel tension as for flexural strength, namely that although it might not always be superior, Tre Gai will at least be competitive with other commonly used sawn timber.

5.0 RECOMMENDED TEST METHODS

In this chapter a brief commentary on the test methods adopted is provided. The compression test and shear test performed were based on those presented in the ISO Standard (ISO 2004b and 2004c). The fracture test was developed as part of this work. As such Section 5.3 presents a proposed draft test method in the ISO format for this test.

5.1 COMPRESSION TEST

The compression test for bamboo is straightforward and is very similar to that for wood or other materials. The ISO specification of one diameter for the specimen height is appropriate as it results in a splitting rather than a buckling failure. In the standard, the researcher is given the option of using either steel finger shims or sulfur capping compound to reduce the frictional forces acting on the ends of the bamboo specimen. The use of capping compound is the superior choice for a number of reasons. First, the use of capping compound is familiar to researchers whereas the use of shims is less common and awkward in the lab, resulting in a possible source of error. Second, the creation of perfectly parallel ends on a bamboo specimen is very difficult to achieve, thus the capping compound can be used to make up for a small degree of skew. Finally, capping compound yields very reliable results. Thus, the compression test as specified in the ISO standard is reliable, accurate, and is generally recommended for future testing. It is particularly well suited to the rapid assessment of bamboo culm compressive strength.

5.2 SHEAR TEST

The shear test for bamboo presents some unique challenges. An accurate shear specimen requires parallel end faces, which is very difficult to obtain due to bamboo's high hardness. Further complicating the test is the fact that the shear test requires a high degree of positioning accuracy. Specifically, the 'teeth' of the shear test must be perfectly aligned during the test if one is to obtain accurate values. For this reason the use of self-centering grips is highly recommended as they will reduce both the potential error as well as the time necessary to set up each test. Despite these challenges, the test is adequate to determine the shear strength of bamboo in a moderately consistent and accurate manner and is thus recommended for future research.

5.3 FRACTURE TOUGHNESS

The following proposed test method formalizes the method described in Chapter 2.1 and places this in language similar to that used by the ISO Standard *Bamboo – Determination of physical and mechanical properties* (ISO 2004b).

X Fracture Toughness

X.1 Scope

This clause specifies a method for fracture toughness tests on bamboo culms.

X.2 Principle

This method permits the determination of the:

a. stress intensity factor of bamboo culms, and
b. the tensile strength of culms perpendicular to the longitudinal fiber direction.

X.2.1 Notation

$2a$ = length of equivalent crack; $2a = F + 2g$

D = outside diameter of culm

F = diameter of split pin loading apparatus

g = length of crack initiator

H = length of test specimen

K_1 = Mode 1 crack intensity factor

P = applied load to cause failure

t = culm wall thickness

σ = tensile stress perpendicular to the fibers over the gross area under stress

σ_p = tensile strength perpendicular to the culm length

X.3 Apparatus

X.3.1 testing machine, capable of applying uniaxial tension having a precision equal to at least 1% of the anticipated failure load. The test machine should have some method of 'self-centering' the grips used to hold the *split pin apparatus* described in X.3.2.

X.3.2 split-pin apparatus capable of loading the culm by applying a tensile load through the hole in the middle of the test specimen. The split pin apparatus has a split pin having a diameter F. each side of the pin is supported by a yoke which is then held in the *testing machine*. The yoke must be wide enough to accommodate the culm diameter, D. An example of such an apparatus having a pin with F = 38.1 mm and a yoke width of 152 mm is shown in Figure X.3.

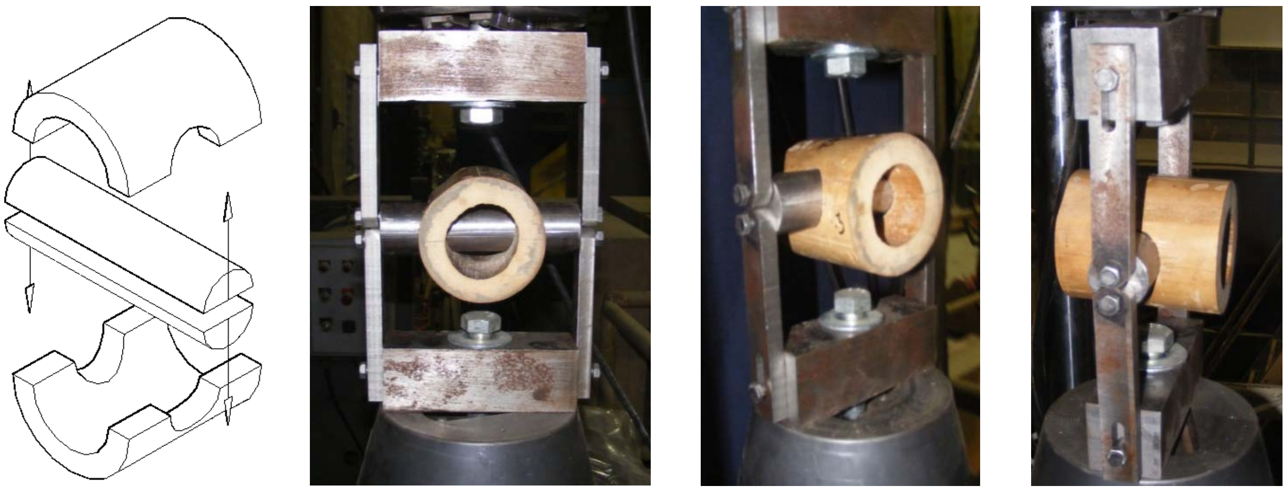


Fig X.3: Example Test Setup having F = 38.1 mm and a specimen having D = 100 mm.

X.3.3 drill press, capable of producing a hole through the culm in one pass.

X.3.4 hole saw, having a diameter F and capable of cutting through both culm walls in one pass (i.e.: the saw length must exceed D).

X.3.5 saw, with a blade kerf of 1.5 mm or less.

X.4 Preparation of test culms

X.4.1 Test culms shall be without visually apparent defects with particular emphasis on the lack of existing splitting along the expected failure plane. The length of the culm, H, shall be at least equal to one culm diameter, D.

X.4.2 The specimen will have a hole in the center through which the split pin will be inserted. The hole shall have a diameter F. The value of F shall fall between 0.10D and 0.50D. The hole should pass through both sides of the culm, having been drilled with a single pass of the *hole saw*. The “single pass” requirement is to ensure the proper alignment of the holes on either side of the culm. An example of the test specimen is shown in fig. X.4.

X.4.3 Crack initiators will be cut on either side of the hole (see Figure X.4). The crack initiators shall have a length g = 3 mm. The initiator is cut with the *saw* having a kerf less than 1.5 mm.

Fig X.4 Specimen Geometry

X.5 Procedure

X.5.1 The culm is placed in the *split-pin apparatus* which is then placed in the *test machine* such that both the specimen and split-pins are horizontal in order to ensure an even distribution of load. The specimen should also be centered within the yoke to ensure even loading.

X.5.2 The loading of the culm shall be carried out uniformly at constant speed. The speed of testing shall be controlled by the rate of movement of the loading head of the *test machine,* which shall be 0.005mm/sec.

X.5.3 The maximum load, that at which the specimen fails, P, and the number of planes that fail, shall be recorded.

X.6 Calculation and expression of results

X.6.1 The stress intensity shall be calculated using the following formula:

$$K_1 = \sigma\sqrt{\pi a}\left[\frac{H}{\pi a} tan\left(\frac{\pi a}{H}\right)\right]^{1/2}$$

Where σ is the tensile stress perpendicular to the fibers over the gross area under stress, determined as:

$$\sigma = \frac{P}{2(H \times t)}$$

and 2a is the initial length of the crack determined as:

$$2a = F + 2g$$

X.6.2 The tensile strength perpendicular to the culm length shall be calculated as:

$$\sigma_p = \frac{P}{2\left((H-2a) \times t\right)}$$

X.7 Test Report

The test report shall include the following information:

a. the name and address of the laboratory, the date of testing, and the name of the test technician;

b. a reference to this part of ISO 22157, and to applicable national standards;

c. details of the test specimens, as described in X.4;

d. temperature and air humidity in the laboratory;

e. equipment used, and any other information which may influence the use of the test results;

f. test results - P and number of failure planes and the actual specimen dimensions (H, D, F and g), and any other information which may influence the use of test results (e.g. position along the culm);

g. calculated (derived) results, K_1 and σ_p;

h. details about the statistical treatment of the test results, including the methods used and the results obtained;

i. data about the adjustment to a 12% moisture content, if applicable.

6.0 CONCLUSIONS AND FUTURE RESEACH

The history of engineering knowledge with regards to bamboo is surprisingly recent, with the major work on bamboo having been completed by Janssen (1981) and Acre (1993) of the University of Eindhoven, The Netherlands. In their research, both noted that splitting is the dominate limit state in structural applications, which agrees with the authors experience (during our May 2008 visit to India) and that of other researchers. It is because of this dominant limit state that this research focused on the development of an appropriate method of characterizing the splitting strength of bamboo culms. This research focused on developing and calibrating an appropriate (but simple to conduct) test method for assessing the splitting capacity of full culms.

The proposed test method is founded on a fundamental fracture mechanics approach and therefore can account, in a consistent manner, for the high degree of variability present in bamboo geometric and material properties. While a number of test methods were available in the literature, a) none addressed full culm behavior; b) only one approached the splitting problem from a fracture mechanics perspective; and c) none have been standardized despite splitting being the dominant limit state for many applications. An additional objective of this work was that the test method developed was a) sufficiently simple; b) required only basic equipment to perform; and c) is easily scaled to assess a range of bamboo geometries (as structural bamboo ranges in diameter from 2 to 10 inches). These criteria were based on the need to use this test method in the field, which implies use in under-developed rural areas having no access to engineering test facilities. This group of requirements has been met with the split-pin fracture test proposed. By utilizing a split-pin loading method, not only is the test relatively simple to construct and test, it also accounts for unusual specimen geometry and yields reliable values.

In order to demonstrate the validity of the proposed test method, a series of tests were performed on a sample of Tre Gai bamboo. In addition to the proposed fracture test, shear and compression tests were performed in accordance with existing ISO standards (ISO 2004b). Of the three test types performed, the compression test had the lowest variability, the shear test had the highest, and the proposed fracture tests had a variability that fell between the two, which demonstrates a reasonably low level of variation in the new test. Thus the fracture test demonstrated that it yields reliable results.

Utilizing the values obtained from both this series of tests as well as those carried out by other institutions, a comparison of common design values was made between Tre Gai and the select-structural grade of two commonly encountered woods, Douglas Fir and Southern Pine. While the design values for bamboo obtained from different institutions varied considerably, Tre Gai generally exhibited performance superior to that of the two timber species referenced. It can be concluded that Tre Gai, when grown, harvested, and preserved correctly, is a competitive, or in some cases, a superior alternative to wood.

6.1 FUTURE RESEARCH

As the engineering interest in bamboo is recent, there are many areas still requiring further investigation. In particular, the following topics arose during this research program.

6.1.1 Fracture Testing Geometry

The proposed fracture test appears to yield both reliable and accurate results, but so far only one geometry has been tested. It has yet to be shown whether a change in the pin diameter, the culm diameter, or the size of the initial crack will have any effect on the stress intensity obtained. It is further proposed that selecting a pin diameter similar to that used for bolted connections may help to develop appropriate values for design.

6.1.2 Variability Inherent in Bamboo

The issue of the variability of bamboo culms was highlighted when comparing the values obtained from this study to those obtained by others. Past studies have shown that different conditions, such as age, preservation technique and length along the culm, will influence material properties (Janssen 1981). While researchers are aware of this issue, growers and distributers of bamboo have made no effort to distinguish between these factors. A reliable method must be devised for suppliers of bamboo to assign different grading levels to their products. This will enable more efficient designs and more accurate testing in the future.

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