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ORIGINAL

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Analysis of Calcutta bamboo for structural composite materials: physical and mechanical properties

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Abstract The objective of this study was to determine the technical feasibility of producing a structural composite from Calcutta bamboo. The first article on surface characteristics published in this series addressed pH, buffer capacity, wetting, and surface energy (Ahmad and Kamke 2003). In this paper, the physical and mechanical characteristics were considered for their variability with respect to location along the length of the bamboo culm, nodes versus internodes section, and radial versus tangential directions. The physical and mechanical characteristics were also compared to timber species commonly used in the manufacture of structural composites. The characteristics studied were found to have some variability at different locations, sections, and directions. Calcutta bamboo was found to have similar physical and mechanical characteristics to commercial timber species in Malaysia and North America.

Introduction

Dendrocalamus strictus is commonly recognized as Calcutta bamboo (Farrelly 1984), but is also known as male bamboo (Tewari 1992), and solid bamboo (Anon 1992). Calcutta bamboo is the most widely used bamboo in India (Kumar and Dobriyal 1992), especially in the paper industry. It is also used in housing construction, basket making, mats, furniture, agricultural implements, and tools handles. It is the most common species of bamboo sighted in the Indian forest and is available in every state in India (Limaye 1952). This species

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is also found in Burma, Bangladesh, and Thailand, as well as being cultivated in Malaysia, Indonesia, Sri Lanka, and southern parts of the United States (Farrelly 1984; Anon 1972). The suitability of Calcutta bamboo for structural composite products will be dependent upon its physical and mechanical properties. The properties investigated were specific gravity (SG), equilibrium moisture content (EMC), dimensional stability, tensile strength, and bending strength.

SG is the most important single physical characteristic of woody material. SG is the oven-dry weight of any given volume of a substance divided by the weight of an equal volume of water (American Society of Testing Materials (ASTM) 1997). The influence of moisture content and its effects to dimensional stability are studied as a basic concern when using any forest product. Dimensions start to change as the moisture content changes below the fiber saturation point. Properties of wood-based materials are closely related to the amount of water present. Thus, to satisfactorily use bamboo as a raw material for composite products, the physical properties of SG and dimensional stability and their relation with EMC were studied. EMC is defined as the moisture content that is in equilibrium with the temperature and relative humidity of the air (Siau 1995; Forest Products Laboratory (FPL) 1999). EMC is an important in-service factor because wood and other woody materials like bamboo are subjected to long-term and short-term variation in surrounding relative humidity and temperature. Hence, this material is always undergoing changes in moisture content. In most cases, the changes are gradual and affect only the surface of the substrate when briefly exposed to moisture fluctuations. It is not usually desirable to use a material that experiences rapid moisture changes, because moisture affects the physical and mechanical properties of woody materials. Moisture content is the mass of water in the substance expressed as a percentage of the oven-dry mass. Dimensional stability pertains to shrinking and swelling of woody materials in response to changes in the bound water content. Shrinkage is approximately proportional to the amount of water loss from the cell wall.

The strength and durability of wood-based composite products are a function of the mechanical properties of the component materials. A comprehensive knowledge of the mechanical behavior of bamboo enables a safe design for the product's service life. Bamboo is a biological material, like timber, and is thus subjected to variability due to various growing conditions and genetic factors. Bamboo is orthotropic, which means it has particular mechanical properties in three principle directions: longitudinal, radial, and tangential. Studies have been done to investigate the variation of these three directions, as well as variation between the internodes and nodes, and the variation between different locations in the culm (Sattar 1991). The mechanical behavior of the full size culm (round form) (Espiloy et al. 1986; Shukla et al. 1988) and small specimens (Lee et al. 1994; Janssen 1991) has been investigated. Unlike trees, bamboo has no vascular cambium, and therefore, no annual rings that are associated with secondary growth.

In the current study, tension parallel to grain and bending tests were conducted. Anatomical and growth characteristics that were considered in the testing protocol included grain orientation, nodes, and location along the culm.

Experimental

Materials

Calcutta bamboo was acquired from a Southern Asian distributor. This bamboo had an average culm length of 5.5 m (18 ft), a bottom diameter of about 3.3 cm (1.3 in), and a top diameter of about 2.3 cm (0.9 in). The average thickness of the culm wall was 0.97 cm (0.38 in). The average oven-dry density was 643 kg/m^3 (40.1 pcf), while the initial moisture content ranged from 10% to 11%. The culms were cut into 122 cm (4 ft) lengths, and placed in a conditioning chamber (20°C and 65% relative humidity) until an EMC of ~9% was achieved.

Methods

Specimens that were selected from the culms were obtained from four locations relative to the height in the culm, referred to as location 1 at the bottom to location 4 at the top. The specimens from internode and node sections, and at different directions were also taken for the comparison study (Fig. 1). The culm sections were split and skinned, and specimens were randomly selected for the analysis. The specimens were kept in the conditioning chamber until they were used for testing.

Specific gravity

Specimens for SG measurement were taken from the four locations, and node and internode sections. From each location and section, more than 50 specimens were taken for the measurement. The dimension for each location was impossible to standardize due to the changing dimension of the culm. Specimens used were irregular in shape. The standard test method for SG of wood and wood-based materials was used (ASTM 1997). Specimens were cut at least 2.5 cm long with variable thickness and width. Multiple comparisons between the locations, and between the node and internode sections, were carried out using statistical analysis of variance techniques.

Shrinkage and swelling

Specimens for shrinkage and swelling measurement were also taken from the four locations and the two sections. From each location and section, more than 30 specimens were taken for the measurement. The specimens were cut into

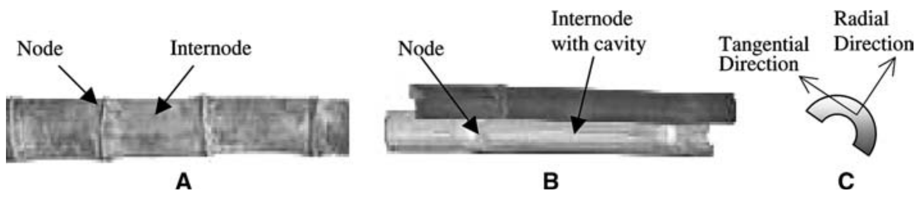

Fig. 1 Macroscopic features of the bamboo culm, showing the longitudinal section (**A**), split section (**B**), and a cross-section view (**C**)

rectangular dimension of at least 2.5 cm long, with variable thickness and width. The shrinkage and swelling of each location, each section (internodes and nodes), and in the longitudinal, radial, tangential directions were measured. Standard method of testing small clear specimens of timber was used to determine the dimensional stability (ASTM 1997). Shrinkage of the specimens was measured from 12% MC ($T = 20°C$ and $RH = 65\%$) to the oven-dry condition. Swelling was measured from the oven-dry condition to the wet condition by soaking the specimens in distilled water. Multiple comparisons between the locations, between the nodes and internodes, and between the three orthogonal directions were conducted using statistical analysis of variance techniques.

Equilibrium Moisture Content

Specimens of equal dimension for EMC measurement were taken from the bottom location of the culm (2.5 cm × 1.3 cm × 0.5 cm). All specimens were cut from adjacent locations to eliminate bias. The apparatus and the procedure of conditioning followed the standard guide for moisture conditioning of wood and wood-based materials (ASTM 1997). The apparatus used and the preparation of the aqueous solutions followed the standard practice for maintaining constant relative humidity by means of aqueous solution (ASTM 1997).

Tension parallel to grain

Due to the small diameter of the culm, it was not possible to prepare large specimens from Calcutta bamboo. Thus, smaller dimensions were used following recommendations in ASTM D143-95 (ASTM 1997). The parallel to grain test utilizes the longitudinal direction. Figure 2 illustrates the tensile test specimen, as well as the three orthotropic directions of bamboo longitudinal, radial, and tangential. The specimen width, thickness, and length were 12 mm (0.472 in), 3 mm (0.118 in), and 120 mm (4.724 in), respectively. The middle section of the specimens was necked-down to 5 mm (0.197 in) to resemble a dog-bone shape. Wooden plates were glued on the sample to prevent splitting, and to enhance failure at the neck during the test. More than 50 specimens were taken from the internodes of locations 1 and 2. About 30 specimens from the nodes were also tested. These specimens were cut so that the node was located in the middle point of the necked-down area. The tension parallel to grain test was conducted on a

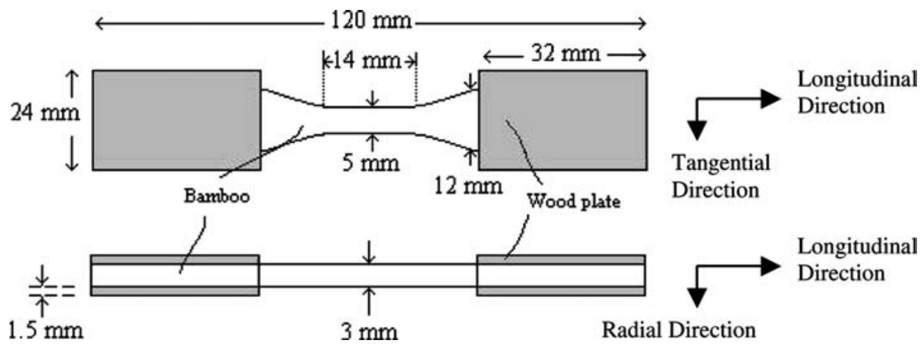

Fig. 2 Tension parallel to grain test specimen showing grain direction

universal testing machine with a crosshead speed of 0.254 cm/min (0.1 in/min). The specimens were conditioned at 20°C and 65% relative humidity for at least 3 weeks. Moisture content was measured on the tested specimens. Ultimate tensile stress (σ_{ult}), tensile stress at proportional limit (σ_{pl}), and stiffness (E) were determined. These values were compared between locations 1 and 2, between the nodes and internodes, and an analysis of covariance was performed.

Bending

Specimens for the bending test were taken along the culm height, between nodes and internodes, as well as between radial and tangential directions. From each location, more than 50 specimens were selected for testing. The specimens used for radial and tangential directions were taken within one culm location. Smaller dimensions were used following recommendations in ASTM 1997. The span, width, and thickness of the bending specimens were 18 mm (0.7 in), 4.5 mm (0.18 in), and 1.3 mm (0.05 in), respectively. The specimens were conditioned at 20°C and 65% relative humidity for at least 3 weeks prior to testing. The bending test was conducted on a miniature testing machine (Rheometrics, MiniMat 2000) at a crosshead speed of 0.254 cm/min (0.1 in/min). Moisture content was measured after the test. Ultimate bending stress (MOR), bending stress at proportional limit (SPL), and stiffness (E) were determined. Multiple comparisons between the location along the height, between the nodes and internodes, and between the radial and tangential directions were conducted.

Results and discussion

Specific gravity

The average SG in the oven-dry condition of Calcutta bamboo used in this study was 0.643 (Table 1). No significant difference in SG between locations was detected (F-value = 0.31). From a manufacturing point of view, the selection of Calcutta bamboo for utilization in composite materials on the basis of its SG would not be affected by the location along the culm. However, it was observed that there were significant differences between nodes and internodes (F-value = 86.78). The SG of Calcutta bamboo is higher compared to all the timber species listed in Table 6 and was higher than the range recommended (below 0.5) for wood composite products. Thus, if composite material from Calcutta bamboo is to be produced, the increase in SG has to be minimized.

Table 1 Mean specific gravity at different locations and sections of *Dendrocalamus strictus* culms

Location	Section	Mean specific gravity (SD)
1	Internode	0.636 (0.056)
2	Internode	0.640 (0.067)
3	Internode	0.651 (0.103)
4	Internode	0.644 (0.107)
1,2,3, and 4	Internode	0.643 (0.086)
1,2,3, and 4	Node	0.785 (0.087)

Shrinkage and swelling

The comparison of the dimensional stability was made along the culm height, between internodes and nodes, and between the three grain directions. The mean dimensional stability of Calcutta bamboo is reported in Table 2. The average radial and tangential shrinkage of internodes for locations 1–4 ranges from 2.5% to 3.7%. The average longitudinal shrinkage ranges from 0.1% to 0.4%. There were some significant differences of shrinkage detected in the radial direction between locations (F-value = 11.98). However, no significant differences were detected in tangential and longitudinal shrinkage of internodes between the four locations (F-value = 2.85 and 0.70, respectively). The average radial and tangential swelling of internodes for locations 1–4 ranges from 13% to 29%, and the average longitudinal swelling for internodes varies from 0.5% to 0.7%. There were some significant differences detected in radial and tangential swelling of internodes between the four locations (F-value = 7.96 and 4.84, respectively), but no significant differences were traced in the longitudinal swelling of the internodes along the culm height (F-value = 1.20). The dimensional stability in the three orthogonal directions was also compared. Internode values of all locations were used in this comparison. The mean radial, tangential, and longitudinal shrinkage of Calcutta bamboo was 3.08%, 3.25%, and 0.18%, respectively, while the mean radial, tangential, and longitudinal swelling was 22.4%, 18.8%, and 0.6%, respectively. There were some significant differences in shrinkage and swelling between the different directions (F-value = 387.96 and 155.89, respectively). Radial and tangential shrinkage are not significantly different from one another, but the longitudinal shrinkage was significantly lower than the other two directions. The same trend was detected in directional swelling.

The dimensional stability in radial and tangential direction is better compared to wood, where shrinkage and swelling are greater in the tangential direction (Table 6). This result is consistent with the dimensional stability of

Table 2 Mean dimensional stability at different locations, sections, and directions of *Dendrocalamus strictus* culms

Location	Section	Direction	Shrinkage% (SD)	Swelling% (SD)
1	Internode	Radial	2.50 (0.75)	13.8 (8.40)
2	Internode	Radial	3.10 (0.64)	24.3 (11.7)
3	Internode	Radial	3.20 (0.68)	24.0 (13.3)
4	Internode	Radial	3.70 (1.25)	28.7 (17.9)
1	Internode	Tangential	2.90 (1.07)	14.6 (9.03)
2	Internode	Tangential	3.70 (1.71)	20.5 (8.59)
3	Internode	Tangential	3.20 (1.05)	16.3 (9.25)
4	Internode	Tangential	3.30 (1.19)	24.7 (17.7)
1	Internode	Longitudinal	0.43 (1.41)	0.64 (0.32)
2	Internode	Longitudinal	0.16 (0.10)	0.51 (0.33)
3	Internode	Longitudinal	0.17 (0.09)	0.60 (0.28)
4	Internode	Longitudinal	0.19 (0.08)	0.59 (0.20)
1,2,3, and 4	Node	Radial	2.85 (2.89)	18.7 (13.7)
1,2,3, and 4	Node	Tangential	0.71 (1.58)	20.6 (11.6)
1,2,3, and 4	Internode	Radial	3.08 (0.96)	22.4 (14.1)
1,2,3, and 4	Internode	Tangential	3.25 (1.15)	18.8 (12.2)
1,2,3, and 4	Internode	Longitudinal	0.18 (0.09)	0.59 (0.29)

other bamboo species. The explanation for this behavior is that bamboo has a different anatomical structure compared to timber. Bamboo lacks radially oriented cells and growth rings like wood. Thus, the dimensional movement is similar in the two directions.

The comparison of the dimensional stability between nodes and internodes were made for all grain directions. There were significant differences detected in shrinkage between nodes and internodes (F-value = 79.97); however, swelling of nodes was not significantly different compared to internodes (F-value = 1.92). Longitudinal shrinkage and swelling at the nodes were not measured since the changes are very small, and were neglected.

From Table 6, the radial and tangential shrinkage (and swelling) from green to oven-dry condition of some timber species lies in the same range to Calcutta bamboo. This is a favorable behavior, and could become a factor that promotes the application of Calcutta bamboo for composite materials.

Equilibrium Moisture Content

The EMC of Calcutta bamboo was determined under five relative humidity conditions. The initial moisture content of the specimens under all conditions was ~12%. Table 3 presents the EMC values for Calcutta bamboo at different environmental conditions. The EMC values for Sitka spruce are also presented in Table 3 for comparison (Siau 1995). In the first condition, the EMC of Calcutta bamboo is 4.2%, while EMC for Sitka spruce is 3.5%. The EMC was achieved in 20 days under the first condition. Condition 2 produced an EMC of 6.4%. In the same condition, EMC for Sitka spruce is 6.5%. The EMC was achieved within 20–25 days. The EMC value in the third and fourth condition were 7.6% and 9.5%, respectively, which was achieved in less than 5 days. The EMC in the fifth condition could not be achieved due to the growth of fungi on the specimens. Eventually, the moisture content increased above 15% for Calcutta bamboo, which is the EMC achievable by Sitka spruce. Bamboo that was conditioned under 20°C and 65% RH was not attacked by fungi. The average moisture content in this condition was 11–12%. Above this condition, bamboo, under prolonged exposure will start to be deteriorated by fungi. Higher temperature (above 55°C) should be used in the future to condition bamboo to higher than 12% moisture content. A chemical treatment could be used to overcome the fungi problem, as long as the chemical did not affect the EMC value. The EMC values for Calcutta bamboo were close to Sitka spruce. The isotherm curves of Sitka spruce are used throughout much of the world for estimating the EMC of timber. In general, this initial study on the EMC of

Table 3 Equilibrium moisture content of *Dendrocalamus strictus* and *Picea sitchensis* (Sitka spruce) under five moisture conditions (ASTM 1997)

Condition	At 20°C with relative humidity (%)	Moisture content (%)	
		Calcutta bamboo	Sitka spruce
1	15.0	4.2	3.5
2	32.5	6.4	6.5
3	40.0	7.6	7.5
4	60.0	9.5	9.5
5	77.0	–	15.0

Calcutta bamboo shows that the patterns are very similar to wood, and the data for Sitka spruce could be used for describing the bamboo–moisture relationship.

This study observed fungal growth when the moisture content was raised to 15%. This is a problem that has been reported by others (Kumar 1992; Aminuddin 1991). Chemical preservative treatments are commonly used for bamboo.

Tension parallel to grain

The average moisture content for the specimens was 11.4%. Table 4 presents the mean tensile strength at different locations and section of Calcutta bamboo. Comparison of the tensile strength and stiffness of the internodes was made between the locations. The mean ultimate tensile strength (σ_{ult}) of location 1 was 156 N/mm^2 while that of location 2 was 185 N/mm^2 . The mean tensile modulus of elasticity (E) of location 1 was 16.8 kN/mm^2, while that of location 2 was 12.7 kN/mm^2 . The mean tensile stress at proportional limit (σ_{pl}) of location 1 was 95.5 N/mm^2 while that of location 2 was 137 N/mm^2 . There were significant differences detected between locations along the culm height for σ_{ult} (F-value = 16.2), σ_{pl} (F-values = 13.2), and E values (F-value = 51.3). The comparison of the internodes and nodes was made only on location 1, with σ_{ult}, σ_{pl}, and E for nodes were 106 N/mm^2, 71.0 N/mm^2, and 17.8 kN/mm, respectively. The analysis of variance indicated that there were some significant differences of σ_{ult} (F-value = 39.9) and σ_{pl} (F-value = 12.7) between the nodes and internodes. There was no significant difference of E (F-value = 0.13) between the nodes and internodes.

Bending

Bending strength and stiffness of locations 1–4, in the radial and tangential directions, and the effects due to internodes and nodes are discussed (Table 5). The average moisture content for the specimens was 9.4%. The analysis of variance indicated that there were no significant differences in MOR (F-value = 1.30), SPL (F-value = 0.02), and E (F-value = 0.03) between the radial and tangential directions. The mean MOR (Table 5) in the radial direction was 137 and 148 N/mm^2 in the tangential direction. Mean MOE in the radial and tangential direction was 9.79 and 9.88 kN/mm^2, respectively. The mean SPL in the radial and tangential direction was 90.9 and 91.9 N/mm^2 .

The differences between internodes and nodes were significant for SPL (F-value = 2.54) and E (F-value = 1.59), except MOR (F-value = 0.28). Table 5

Table 4 Mean tensile strength at different locations and sections of *Dendrocalamus strictus* culms

Location	Section	Mean tensile strength (N/mm^2)		
		Stress at proportional limit (SD)	Ultimate stress (SD)	Young modulus (SD)
1	Internode	95.5 (33.8)	156.1 (37.7)	16,779 (6952.0)
2	Internode	136.7 (26.7)	185.3 (41.8)	12,723 (4496.3)
1	Node	71.0 (22.3)	106.2 (26.8)	17,771 (5354.9)

Table 5 Mean bending strength at different locations, sections and directions of *Dendrocalamus strictus* culms

Location	Section	Direction	Mean bending strength (N/mm²)		
			Stress at proportional limit (SD)	Ultimate stress (SD)	Young modulus (SD)
1[a]	Internode	Radial	91.2 (30.5)	152.3 (39.5)	10,428 (3073.0)
2	Internode	Radial	99.5 (33.1)	149.3 (42.1)	11,305 (3473.5)
3	Internode	Radial	100.0 (26.3)	151.2 (49.1)	11,426 (2919.0)
4	Internode	Radial	113.5 (38.4)	185.5 (52.8)	12,358 (3824.8)
1	Node	Radial	101.0 (30.3)	149.9 (42.4)	9,691 (2774.1)
1[a]	Internode	Radial	90.9 (38.7)	137.1 (52.3)	9,791 (3341.9)
1	Internode	Tangential	91.9 (33.9)	148.4 (45.1)	9,878 (3413.8)

[a] Different sample size

shows that the mean MOR of nodes was 150 N/mm^2 and that of internodes was 152 N/mm^2 . The mean MOE in the node and internode sections was 9.69 and 10.4 kN/mm^2, respectively. The mean SPL for the nodes section was 101 N/mm^2 and internodes section was 91.2 N/mm^2 .

There were some significant differences between the locations along the height of the culm in MOR (F-value = 7.03), E (F-value = 2.32), and SPL (F-value = 3.37), although there are some exceptions. The mean MOR of locations 1–4 was 152.3, 149.3, 151.2, and 185.5 N/mm^2, respectively. Locations 1–3 show no significant difference in MOR; however, location 4 was detected to be significantly different in MOR than other locations. The mean MOE values for locations 1–4 were 10.4, 11.3, 11.4, and 12.4 kN/mm^2, respectively. Locations 1 and 4 were detected to be significantly different to each other. The SPL values followed a different pattern, where locations 1–3 show no significant difference from each other, while locations 1 and 2 were significantly different from location 4. Locations 3 and 4 were not significantly different from one another. The mean SPL values were 91.2, 99.5, 100, and 114 N/mm^2 for locations 1–4, respectively.

Comparing Calcutta bamboo with timber species that are used in structural composites is also necessary. Table 6 presents MOR and MOE of timber species that are used in composite products. Timber species mentioned are yellow-poplar, aspen, pine, Douglas-fir and hemlock (FPL 1999). Mean MOR of yellow-poplar and quaking aspen in the dry condition (12%) are 70.0 and 58.0 N/mm^2, respectively, while the mean MOE values are 10.9 and 8.10 kN/mm^2 . The mean MOR and MOE (dry condition) for one of the pine species, red pine, were 76.0 and 11.2 kN/mm^2, respectively. Douglas-fir and hemlock are important timber species as well. The MOR and MOE for Douglas-fir in dry-condition was 85.00 N/mm^2 and 13.8 kN/mm^2, respectively, while MOR and MOE for hemlock were 61.0 and 8.30 N/mm^2, respectively. The MOR and MOE for light red meranti were 85.2 N/mm^2 and 11.2 kN/mm^2, respectively. The mean MOR of Calcutta bamboo is higher compared to these timber species. The Douglas-fir E value is slightly higher than Calcutta bamboo. However, all of the other timber species mentioned have lower values. From this analysis, Calcutta bamboo is superior or at least at par in its bending strength and stiffness with the timber species commonly used in the wood composite industry.

Table 6 Mean specific gravity, shrinkage, and bending strength of selected timber species (Bodig 1982; Fengel and Wegenar 1984; Freeman 1959)

Species	Specific gravity	Green to oven-dry		Static bending	
		Radial shrinkage (%)	Tangential shrinkage (%)	Ultimate stress (N/mm^2)	Young modulus (N/mm^2)
D. strictus (Calcutta bamboo)	0.64	3.1	3.3	152.3	10,428
Liriodendron tulipifera (yellow poplar)	0.42	4.6	8.2	70.0	10,900
Populus tremuloides (quaking aspen)	0.38	3.5	6.7	58.0	8,100
Pinus resinosa (red pine)	0.46	3.8	7.2	76.0	11,200
Pseudotsuga menziesii (Douglas fir-coast)	0.48	4.8	7.6	85.0	13,400
Tsuga canadensis (eastern hemlock)	0.40	3.0	6.8	61.0	8,300
Shorea spp. (light red meranti)	0.43	4.5	8.5	83.2	11,210

All values given at 12% moisture content, except *D. strictus* (9% mc)

Conclusions

Selected physical properties of Calcutta bamboo have been analyzed. SG of the entire culm was determined to not significantly change along the length, although there are significant differences in SG between nodes and internodes. From a practical point of view, this is a desirable factor because more bamboo woody material can be recovered for products. The dimensional stability of Calcutta bamboo was also measured in different locations along the length of the culm, as well as in different directions, nodes, and internodes. The mean radial shrinkage and swelling in Calcutta bamboo is not statistically different from tangential shrinkage and swelling. Longitudinal shrinkage and swelling are very small and are significantly different when compared to the other directions. In regard to EMC, Calcutta bamboo and wood share common behavior when exposed to different environmental conditions. The SG and the swelling values are much larger than the wood species commonly used in structural wood composites. A laminated product that does not require extensive compression to press the lamina together would be suitable for Calcutta bamboo. Calcutta bamboo is prone to attack by fungi. Thus, Calcutta bamboo, especially for exterior applications, will require application of chemical preservatives for best performance.

Tensile strength and stiffness varied along the length of the culm, with tensile strength lower and tensile modulus higher near the base. Nodes have a lower ultimate tensile stress and stress at proportional limit; however, they do not affect the tensile *E*. The mean radial bending strength and stiffness of Calcutta bamboo are not significantly different from the values in the tangential direction. The bending stress at proportional limit and bending *E* were lower in the nodes. However, there was no significant difference of modulus of rupture between sections. The location along the height of culm also showed an affect on the bending strength and stiffness, although there were mixed results. Generally, the top of the culm had the best mechanical properties.

From a practical point of view, variability in a material is not desirable, such as variation of tensile properties along the length of the culm, or the presence of nodes that reduce the strength. In order to solve this problem, nodes could be removed. However, it would not be economical to discard the nodes. Furthermore, removing the nodes places a limit on the maximum length of the element. In order to use the whole culm in these products, the nodes and locations can be distributed evenly throughout the composite system. Moreover, the better material can be placed on the surface layer, while the lesser could be put in the core, thus, improving material utilization. In addition to the mechanical properties, the raw materials for composite products have to be selected based on their strength to weight ratio. Many timber species, which have a low strength to weight ratio, are not desirable because their density is too high. The selection of Calcutta bamboo for composite products may not be advantageous due to its high density. However, its strength and availability may outweigh this disadvantage.

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