Chapter 4
Mechanical Properties of Calcutta Bamboo

4.1 Introduction

The strength and durability of wood-based composite products are a function of the mechanical properties of the component materials. Analysis of the mechanical properties is the investigation of the material's behavior when subjected to loads. Material reactions under loads are the stress and strain generated within the materials and usually results in deformation [1]. A sufficient knowledge of the mechanical behavior of bamboo enables a safe design for the materials service life. Bamboo reacts in the same fashion as other building materials. However, being a biological material like timber, it is subjected to greater variability and complexity, due to various growing conditions as moisture, soil, and competition. Bamboo is an orthotropic material, which means it has particular mechanical properties in the three directions: longitudinal, radial, and tangential. Studies have been carried out to investigate the variation of these three directions, as well as between the internodes and nodes, and the variation between different locations in the culm [2, 4]. The mechanical behavior of the full size culm (round form) [5, 7-10] and small specimens [3, 8, 11-13] has been investigated. In this study, tension parallel to grain and the static bending tests for small size specimens were conducted.

The tension parallel to grain test was adjusted from the standard methods of testing small clear specimens of timber, ASTM D 143-94 [16]. It is impossible to cut similar specimen dimension suggested by this standard due to the nature of bamboo. Thus, a smaller-scale version was fabricated. The tensile stress at proportional limit (σ_{pl}), ultimate tensile stress (σ_{ult}), and tensile modulus of elasticity (E) were calculated using the Equations 2.5, 2.6 and 2.7 in Chapter 2. [1, 14, 15]:

The bending strength test was also adjusted from the standard methods of testing small clear specimens of timber, ASTM D 143-94 [16]. A miniaturized version was also fabricated for this test. The bending stress at proportional limit (SPL), modulus of rupture (MOR) and bending modulus of elasticity (MOE) were calculated using Equations 2.8, 2.9 and 2.10 in Chapter 2[1, 14, 15]:

4.2 Experimental

4.2.1 Materials

Calcutta bamboo was previously purchased from Bamboo Rattan Works Inc. for the physical property analysis. Specimens from the same bamboo culm were cut for the analysis of mechanical properties. The culm characteristics were presented in Table 3.1 of Chapter 3. The culms were cut into 122 cm (4 ft.) long pieces, and placed in a conditioning chamber for several weeks. Moisture content was monitored until equilibrium was reached (Temperature = 20^{o}C and Relative Humidity = 65%).

4.2.2 Methods

Twenty culms were randomly selected from the thirty culms purchased. The culms were cut into four segments of 4 ft. each. Location 1 is the lower bottom part, location 2 is the upper bottom part, location 3 is the lower top part and location 4 is the upper top part. The segments were split in half, one for pH value and buffer capacity measurement, and the other half was used for mechanical properties, wettability and adhesive penetration. Specimens for mechanical properties were selected randomly. The sampling technique is illustrated in Figure 3.1 in Chapter 3. The term “locations” used in this study was associated with the location along the culm length, while “section” refers to the nodes and internodes. The specimens were placed in a conditioning chamber until they were tested.

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 [16]. The parallel to grain test utilizes the longitudinal direction. Figure 4.1 illustrates tensile test specimen, as well as the three orthotropic directions of bamboo, the longitudinal, radial and tangential. Figure 4.2 illustrates the specimen dimensions. The width, thickness and length of the tension parallel to grain specimen were 12 mm (0.472 in.), 3 mm (0.118 in.) and 120 mm (4.724 in.) respectively.

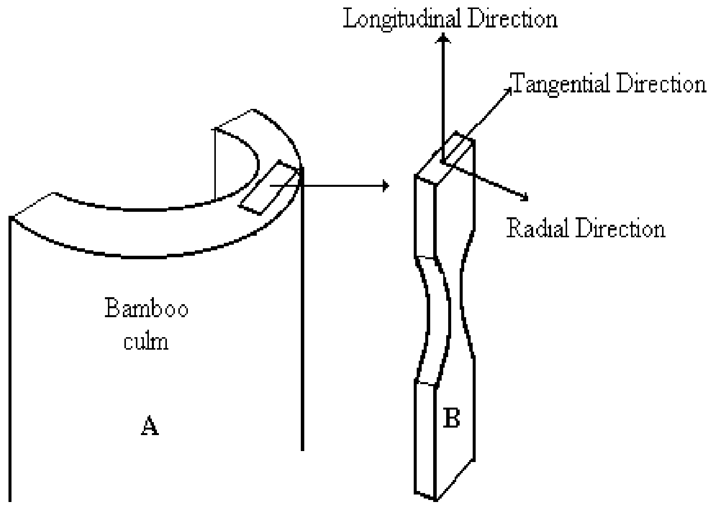

Figure 4.1. Orthotropic axes of bamboo. Half-culm (A), tension test specimen (B).

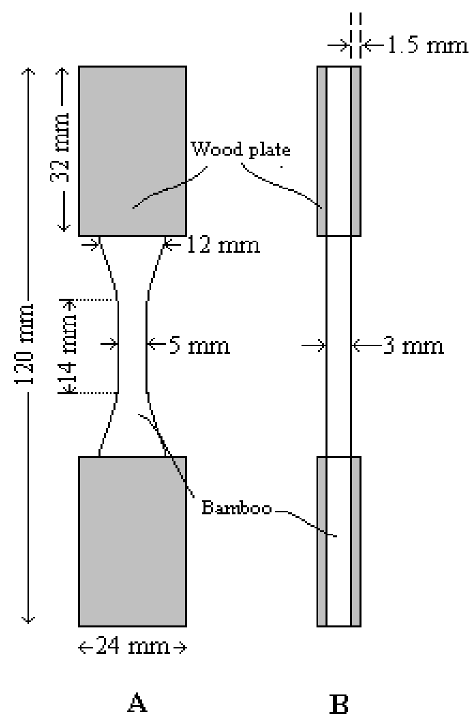

Figure 4.2. Tension parallel to grain test specimen showing front view (A), side view (B).

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 in order 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. Specimens from locations 3 and 4 were not taken due to small culm diameter and wall thickness. 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. Relative density of internodes for each specimen was determined and was used in the analysis of variance. The tension parallel to grain test was conducted on universal testing machine with a cross-head speed of 0.254 cm/min (0.1 in/min). The specimens were conditioned at 20^{o}C and 65% relative humidity for at least three weeks. Moisture content was measured on the tested specimens. Comparison between the location along the height, between the nodes and internodes, and the analysis of covariance were carried out using SAS statistical software package [21].

Bending

Specimens for the bending test were taken from the culm internodes as illustrated in Figure 3.1 in Chapter 3. Specimens from nodes were also taken from the culm to compare the value between internode and node. Comparisons of the bending strength and stiffness were made along the culm height, between nodes and internodes, as well as between radial and tangential directions.

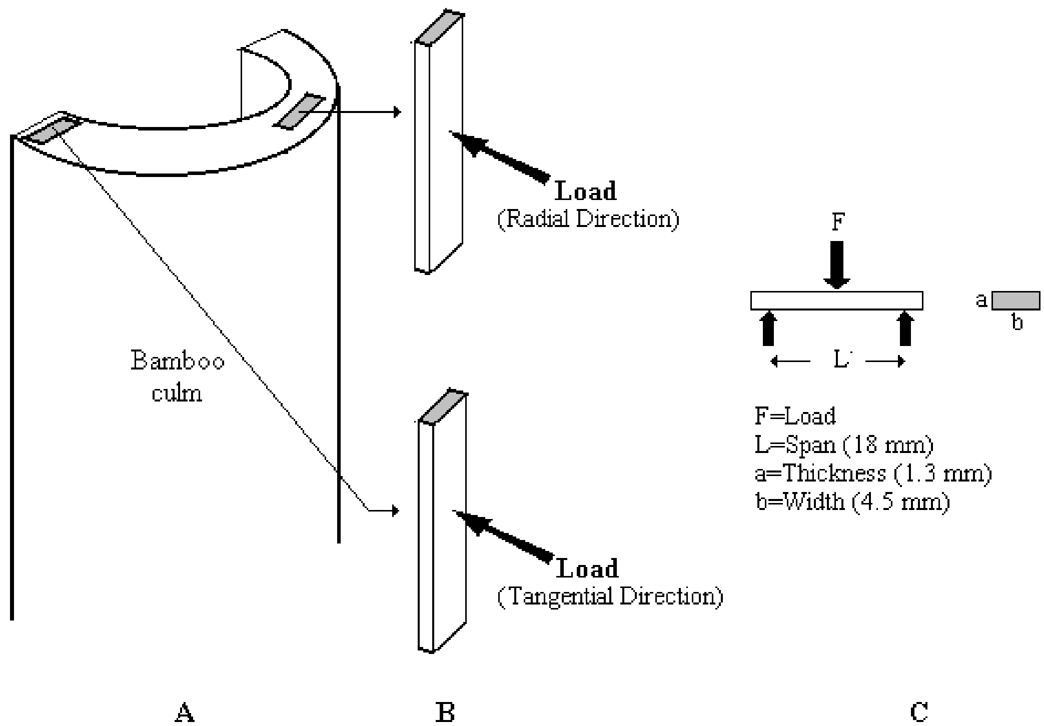

Figure 4.3. Radial and tangential load direction. Half-culm (A), bending specimens (B), dimension of bending specimens (C)

From each location, more than 50 specimens were selected for testing. Figure 4.3 illustrates how the bending specimens were cut from the culm. The specimens used for radial and tangential directions were taken within one culm location. 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^{o}C and 65% relative humidity for at least three weeks prior to testing. The bending test was conducted on a miniature testing machine (Rheometrics, MiniMat 2000) at a cross-head speed of 0.254 cm/min (0.1 in/min). Moisture content was measured after the test. The relative density of internodes for each specimen was determined and was used in the analysis of covariance. Multiple comparisons between the location along the height, between the nodes and internodes, and between the radial and tangential directions were carried out. The analysis of covariance was carried out using the SAS statistical software package.

Statistical Test

Analysis of covariance was performed on the mechanical properties with relative density as the covariate [17,18]. The linear model considered for the study is shown below:

$$y_{ij} = \mu + \alpha_i + \gamma x_{ij} + \varepsilon_{ij} \tag{4.11}$$

where:

y = observation (mechanical property)
μ = mean
α = treatment
x_{ij} = covariate (relative density)
γ = regression coefficient
ε = error

Analysis of variance was performed (using type III: SS(treatment)) on the mechanical properties of different locations. The null hypothesis for the ANOVA is shown below

H_o: $\alpha_1 = \alpha_2 = \ldots.. = \alpha_t = 0$

H_a: At least one of the α differs from 0.

Estimation of mechanical properties was made using the covariate information, and the adjusted mean values were calculated. The treatment levels were compared using the least squares means and Tukey-Kramer test.

4.3 Results and Discussion

4.3.1 Tension Parallel To Grain

The tensile strength and stiffness of locations 1 and 2, as well as internodes and nodes are discussed. The average moisture content for the specimens was 11.4%. Table 4.1 shows the analysis of covariance of this value for the different locations and sections. The analysis shows that there are significant differences between locations along the culm height for the tensile strength and stiffness values. The values between internodes and nodes are also significantly different from each other, except for modulus of elasticity (E). Table 4.2 shows the linear regression equation, mean value, and the adjusted mean value used for the comparison between locations. The mean tensile strength (σ_{ult}) of location 1 was 156.14 N/mm^2 while location 2 was 185.30 N/mm^2. The difference between the locations was 29.16 N/mm^2. The adjusted mean value of the locations 1 and 2 with relative density as the covariant was 156.00 N/mm^2 and 185.44 N/mm^2. The difference is increased to 29.44 N/mm^2. There was a slight increase in σ_{ult} of the adjusted value, however either adjusted or not, the analysis showed that mechanical properties for location 1 were significantly different from those for location 2 (Figure 4.4).

Table 4.1. Analysis of covariance of tension strength and stiffness at Locations 1 and 2, and sections of *Dendrocalamus strictus* culms.

Source of variation	DF	Sum of Squares	F-value
Location:			
σ_{ult}	1	22100.4	16.22 (HS)
E	1	412325296.4	13.21 (HS)
σ_{pl}	1	43635.0	51.26 (HS)
Section			
σ_{ult}	1	49972.1	39.92 (HS)
E	1	5096112.2	0.13 (NS)
σ_{pl}	1	11258.6	12.72 (HS)

(HS) indicates significance at the 1% level of probability
(NS) indicates not significant
Section is nodes and internodes
Strength and stiffness unit in N/mm^2

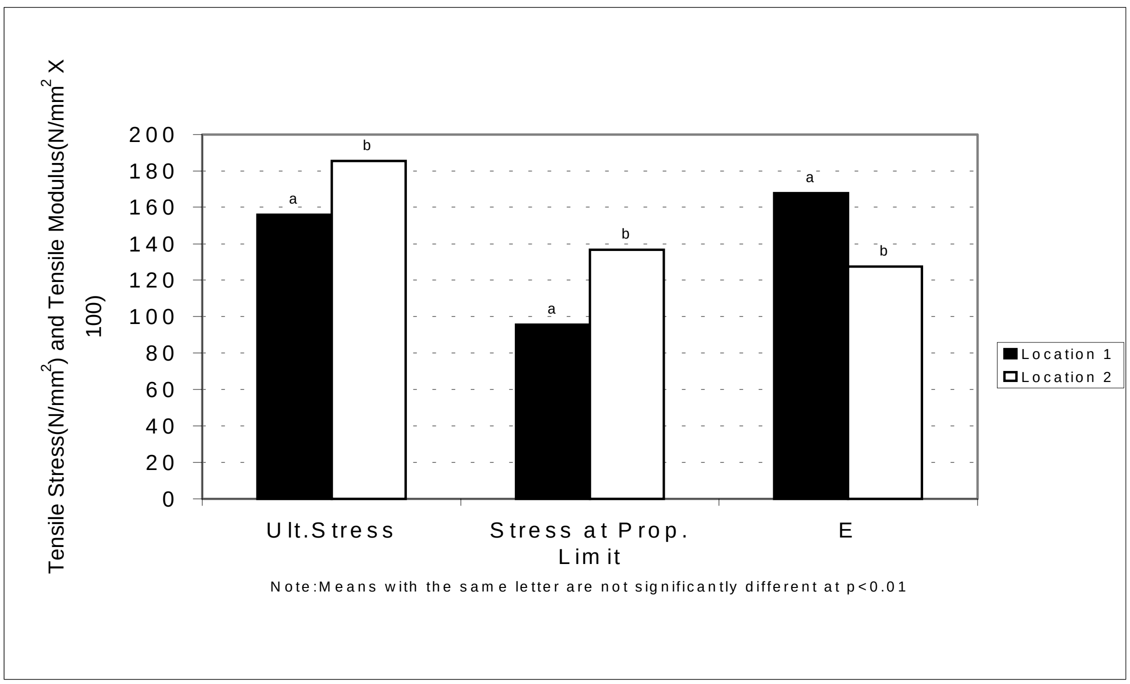

Figure 4.4. Adjusted tensile properties of *Dendrocalamus strictus* at locations 1 and 2 of culm.

The mean tensile modulus of elasticity (E) of location 1 was 16,779 N/mm^2, while location 2 was 12,723 N/mm^2. The adjusted mean values at locations 1 and 2, with relative density as the covariant, were 16,762 N/mm^2 and 12,740 N/mm^2, respectively. There was a slight reduction in E when adjusted for relative density. From the analysis E for location 1 was significantly greater than location 2 (Figure 4.4). The mean tensile stress at proportional limit (σ_{pl}) of location 1 was 95.52 N/mm^2 while for location 2 it was 136.71 N/mm^2. The adjusted mean values at location 1 and 2, with relative density as the covariant, were 95.43 N/mm^2 and 136.80 N/mm^2 respectively. From the analysis σ_{pl} for location 1 was significantly less than location 2 (Figure 4.4).

Table 4.3 shows the linear regression equations, mean values and the adjusted mean values used for the comparison between sections. The comparison was made only on the internodes and nodes of location 1. The mean ultimate tensile stress for internodes was 156.14 N/mm^2, while the corresponding value for the nodes was 106.20 N/mm^2. The adjusted mean values at internodes and nodes, with relative density as the covariant, were 160.24 N/mm^2 and 99.87 N/mm^2, respectively. The ultimate tensile stress of the internodes was significantly greater than the nodes. (Figure 4.5).

Table 4.2. An analysis of covariance for linear regression equation, mean value and adjusted mean value for the comparison of tensile strength and stiffness at different locations.

Relationship	Mean Value Based on Mean Relative Density of Location R_{D1}=0.6920;R_{D2}=0.6908		Adjusted Mean Value of Different Locations (N/mm^2)	
	Mean Value (N/mm^2)	Standard Deviation		
Location (Internodes only)				
$\sigma_{ult.1} = -17.65 + 251.14R_{D1}$	156.1	37.7	156.0	***a***
$\sigma_{ult.2} = 11.80 + 251.14R_{D2}$	185.3	41.8	185.4	***b***
$E_1 = 4002.92 + 30030.70R_{D1}$	16778.7	6952.0	16761.5	***a***
$E_2 = -8024.25 + 30030.70R_{D2}$	12722.8	4496.3	12740.2	***b***
$\sigma_{pl.1} = -8.16 + 149.82R_{D1}$	95.5	33.8	95.4	***a***
$\sigma_{pl.2} = 33.21 + 149.82R_{D2}$	136.7	26.7	136.8	***b***

R_D is Relative Density
Number 1 is denoted for location 1, number 2 is denoted for location 2
Means with the same letter are not significantly different at $p<0.01$by Tukey-Kramer Test and the General Linear Model Procedure.

The mean tensile modulus of the internodes was 16,779 N/mm^2 while the value for nodes was 17,771 N/mm^2. The adjusted mean values of the internodes and nodes with, relative density as the covariate, were 17,422 N/mm^2 and 16,777 N/mm^2, respectively.

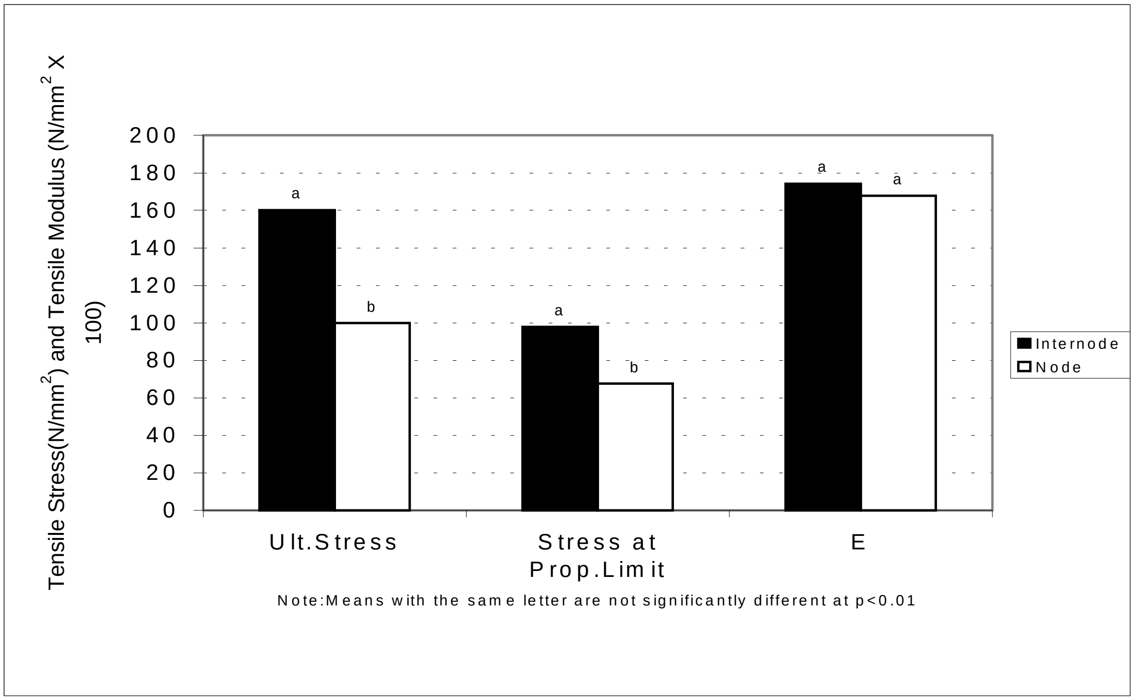

Figure 4.5. Adjusted tensile strength and stiffness. Value of *Dendrocalamus strictus* at different sections of culm

From the comparison analysis, there was no significant difference between the nodes and internodes. The mean tensile stress at the proportional limit for the internodes was 95.52 N/mm^2, while the corresponding value for nodes was 71.01 N/mm^2. The adjusted mean values of the internodes and nodes, with relative density as the covariant were 97.79 N/mm^2 and 67.50 N/mm^2. From the comparison analysis, the σ_{pl} of the internodes was significantly greater than the corresponding value for nodes (Figure 4.5).

There is currently no data available on the tensile strength and stiffness of calcutta bamboo in other studies, thus a direct comparison of calcutta bamboo used in this study cannot be carried out. Comparisons were made with the available data for bamboo species. In Table 3A of Appendix A, the average maximum tensile stress (σ_{ult}) of air-dry (12%) giant timber bamboo (*Phyllostachys bambusiodes*) was 120.06 N/mm^2 (17,413 psi) [3]. The tensile strength of bottom, middle and top locations was 110.83 N/mm^2 (16,074 psi), 118.25 N/mm^2 (17,151 psi) and 131.10 N/mm^2 (19,014 psi), respectively. The study found that the tensile strength significantly increased with culm height. The tensile strength for locations 1 (bottom) and location 2 (middle) in this study also showed a significant increase, where the adjusted mean values were 156.00 N/mm^2 (22,626 psi) for location 1 and 185.44 N/mm^2 (26,896 psi) for location 2. This was consistent with the increasing relative density from bottom to top for both studies. The presence of nodes in the middle of the necked-down area in this study and the study on giant timber bamboo made a significant difference in the tensile strength determined. They claimed that due to its lower tensile strength the nodes created a stress concentration on the narrow neck. The mean tensile strength for nodes and internodes in that study were 102.22 N/mm^2 (14,826 psi) and 137.89 N/mm^2 (20,000 psi) respectively. The adjusted mean tensile strength for nodes and internodes found in this study were 99.87 N/mm^2 (14,485 psi) and 160.24 N/mm^2 (23,241 psi) respectively.

Table 4.3. An analysis of covariance for linear regression equation, mean value and adjusted mean value for comparison of tensile strength and stiffness at different sections.

Relationship	Mean Value Based on Mean Relative Density of Section R_{Di}=0.6920;R_{Dn}=0.7720		Adjusted Mean Value of Different Sections (N/mm^2)	
	Mean Value (N/mm^2)	Standard Deviation		
Section (Internodes vs Nodes)				
$\sigma_{ult.i} = 65.96 + 130.32R_{Di}$	156.1	37.7	160.2	***a***
$\sigma_{ult.n} = 5.59 + 130.32R_{Dn}$	106.2	26.8	99.9	***b***
$E_i = 2614.68 + 20647.89R_{Di}$	16778.7	6952.0	17421.9	***a***
$E_n = 1970.10 + 20647.89R_{Dn}$	17771.3	5354.9	16777.3	***a***
$\sigma_{pl.i} = 45.39 + 72.43R_{Di}$	95.5	33.8	97.8	***a***
$\sigma_{pl.n} = 15.10 + 72.43R_{Dn}$	71.0	22.3	67.5	***b***

R_D is Relative Density
Letter i is denoted for internodes, letter n is denoted for nodes.
Means with the same letter are not significantly different at $p<0.01$by Tukey-Kramer Test and the General Linear Model Procedure.
Internodes and nodes are from location 1 only.

4.3.2 Bending

Bending strength and stiffness of locations 1 to 4, in the radial and tangential directions, and the effects due to internodes and nodes are discussed. The average moisture content for the specimens was 9.4%. Table 4.4 shows the analysis of covariance of these values for the different directions, location along the height of culm and sections. The analysis showed that there was no significant difference in bending strength and stiffness between the radial and tangential directions. The differences between internodes and nodes were significant for all

Table 4.4. Analysis of covariance of bending strength and stiffness at different directions, locations and sections of *Dendrocalamus strictus* culms.

Source of variation	DF	Sum of Squares	F-value
Direction:			
MOR	1	3128.1	1.30(NS)
E	1	250602.2	0.02(NS)
SPL	1	39.9	0.03(NS)
Location:			
MOR	3	33563.8	7.03(HS)
E	3	71711944.5	2.32(HS)
SPL	3	9546.6	3.37(HS)
Section			
MOR	1	462.5	0.28(NS)
E	1	13850064.7	1.59(HS)
SPL	1	2374.4	2.54(HS)

(HS) indicates significance at the 1% level of probability
(NS) indicates not significant

properties, except modulus of rupture. There were significant differences between the locations along the height of the culm, although there are some exceptions. Tables 4.5, 4.6 and 4.7 show the linear regression equations, mean values and the adjusted mean values used for comparisons between directions, sections and locations. Figures 4.6, 4.7 and 4.8 graphically illustrate the comparisons made between the variables. From Table 4.5, the mean MOR in the radial direction was 137.08 N/mm^2 and 148.36 N/mm^2 in the tangential direction. The adjusted mean MOR for the radial and tangential directions were 136.88 N/mm^2 and 148.56 N/mm^2, respectively.

Table 4.5. An analysis of covariance for linear regression equation, mean value and adjusted mean value for the comparison of bending strength and stiffness for different direction.

Relationship	Mean Value Based on Mean Relative Density of Direction R_{Dr}=0.6913;R_{Dt}=0.6851		Adjusted Mean Value of Different Direction (N/mm^2)	
	Mean Value (N/mm^2)	Standard Deviation		
Direction (Internodes Bottom only)				
$MOR_r = 91.77 + 65.54R_{Dr}$	137.1	52.3	136.9	***a***
$MOR_t = 103.46 + 65.54R_{Dt}$	148.4	45.1	148.6	***a***
$MOE_r = 7875.81 + 2771.11R_{Dr}$	9791.6	3341.9	9782.9	***a***
$MOE_t = 7980.42 + 2771.11R_{Dt}$	9878.8	3413.8	9887.5	***a***
$SPL_r = 41.13 + 72.09R_{Dr}$	90.9	38.7	90.7	***a***
$SPL_t = 42.45 + 72.09R_{Dt}$	91.9	33.9	92.1	***a***

R_D is Relative Density
Letter r is denoted for radial direction, letter t is denoted for tangential direction.
Means with the same letter are not significantly different at $p<0.01$by Tukey-Kramer Test and the General Linear Model Procedure.
Radial and Tangential Specimens are from location 1 only.

From the general linear procedure and Tukey-Kramer test (Figure 4.6), the adjusted mean MOR of both directions were not significantly different from each other when relative density was considered. The adjusted mean values for MOE and SPL were also not significantly different in the radial and tangential direction when tested under the same statistical procedures.

Table 4.6. An analysis of covariance for linear regression equation, mean value and adjusted mean value for the comparison of bending strength and stiffness at different sections.

Relationship	Mean Value Based on Mean Relative Density of Section R_{Di}=0.6863; R_{Dn}=0.7080		Adjusted Mean Value of Different Sections (N/mm^2)	
	Mean Value (N/mm^2)	Standard Deviation		
Section (Internodes vs Nodes)				
$MOR_i = 90.50 + 90.03R_{Di}$	152.3	39.5	153.2	***a***
$MOR_n = 86.17 + 90.03R_{Dn}$	149.9	42.4	148.9	***a***
$MOE_i = 10044.06 + 559.53R_{Di}$	10428.1	3073.0	10433.8	***a***
$MOE_n = 9295.14 + 559.53R_{Dn}$	9691.3	2774.1	9684.8	***b***
$SPL_i = 91.77 – 0.78R_{Di}$	91.2	30.5	91.2	***a***
$SPL_n = 101.58 – 0.78R_{Dn}$	101.0	30.3	101.0	***b***

R_D is Relative Density
Letter i is denoted for internodes, letter n is denoted for nodes
Means with the same letter are not significantly different at $p<0.01$by Tukey-Kramer Test and the General Linear Model Procedure.
Internodes and nodes are from location 1 only.

Mean MOE in the radial and tangential direction was 9,791.6 N/mm^2 and 9,878.8 N/mm^2, respectively. The adjusted values were 9,872.9 N/mm^2 and 9,887.5 N/mm^2, respectively. The mean SPL in the radial and tangential direction was 90.9 N/mm^2 and 91.9 N/mm^2. While the adjusted values were 90.7 N/mm^2 and 92.1 N/mm^2. Table 4.6 shows the mean MOR of nodes and internodes was 149.9 N/mm^2 and 152.3 N/mm^2, respectively.

Table 4.7. An analysis of covariance for linear regression equation, mean value and adjusted mean value for the comparison of bending strength and stiffness at different location.

Relationship	Mean Value Based on Mean Relative Density of Locations R_{D1}=0.6863; R_{D2}=0.7218; R_{D3}=0.6778; R_{D4}=0.7225		Adjusted Mean Value of Different Locations (N/mm²)	
	Mean Value (N/mm²)	Standard Devia-tion		
Locations				
$MOR_1 = -16.17 + 245.83R_{D1}$	152.3	39.5	156.1	***a***
$MOR_2 = -28.16 + 245.83R_{D2}$	149.3	42.1	144.4	***a***
$MOR_3 = -16.40 + 245.83R_{D3}$	151.2	49.1	157.1	***a***
$MOR_4 = 7.83 + 245.83R_{D4}$	185.5	52.8	180.3	***b***
$MOE_1 = 3565.96 + 9998.01R_{D1}$	10,428.1	3073.0	10,582.1	***a***
$MOE_2 = 4089.37 + 9998.01R_{D2}$	11,305.6	3473.5	11,105.5	***ab***
$MOE_3 = 4649.84 + 9998.01R_{D3}$	11,426.1	2919.0	11,666.0	***ab***
$MOE_4 = 5134.51 + 9998.01R_{D4}$	12,358.2	3824.8	12,150.6	***b***
$SPL_1 = 16.22 + 109.30R_{D1}$	91.2	30.5	92.9	***a***
$SPL_2 = 20.59 + 109.01R_{D2}$	99.5	33.1	97.3	***a***
$SPL_3 = 25.93 + 109.01R_{D3}$	100.0	26.3	102.6	***ab***
$SPL_4 = 34.55 + 109.01R_{D4}$	113.5	38.4	111.3	***b***

R_D is Relative Density
Number 1 to 4 are denoted for location 1 to location 4
Kramer Test and the General Linear Model Procedure.

The adjusted mean MOR was 148.9 N/mm² and 153.2 N/mm². The difference between the property values was slightly increased when relative density was taken as the covariate. However, the adjusted mean MOR of both sections were not significantly different from each other.

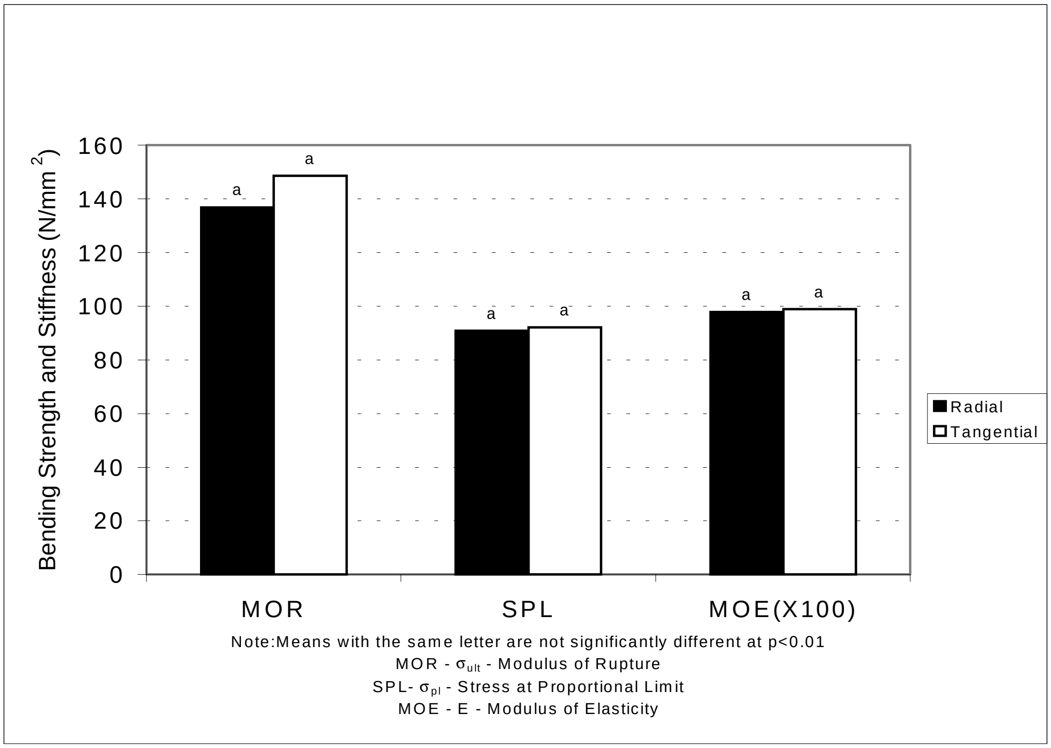

Figure 4.6. Adjusted bending strength and stiffness of *Dendrocalamus strictus* for different directions in the culm.

On the other hand, the adjusted mean values for MOE and SPL at the different sections were significantly different when tested under the same statistical procedures. The mean MOE in the nodes and internodes sections were 9,691 N/mm^2 and 10,428 N/mm^2, respectively. The adjusted values were 9,685 N/mm^2 and 10,434 N/mm^2, respectively. The mean SPL for the nodes and internodes sections were 101.0 N/mm^2 and 91.2 N/mm^2, respectively, while the adjusted values were 101.04 N/mm^2 and 91.2 N/mm^2, respectively.

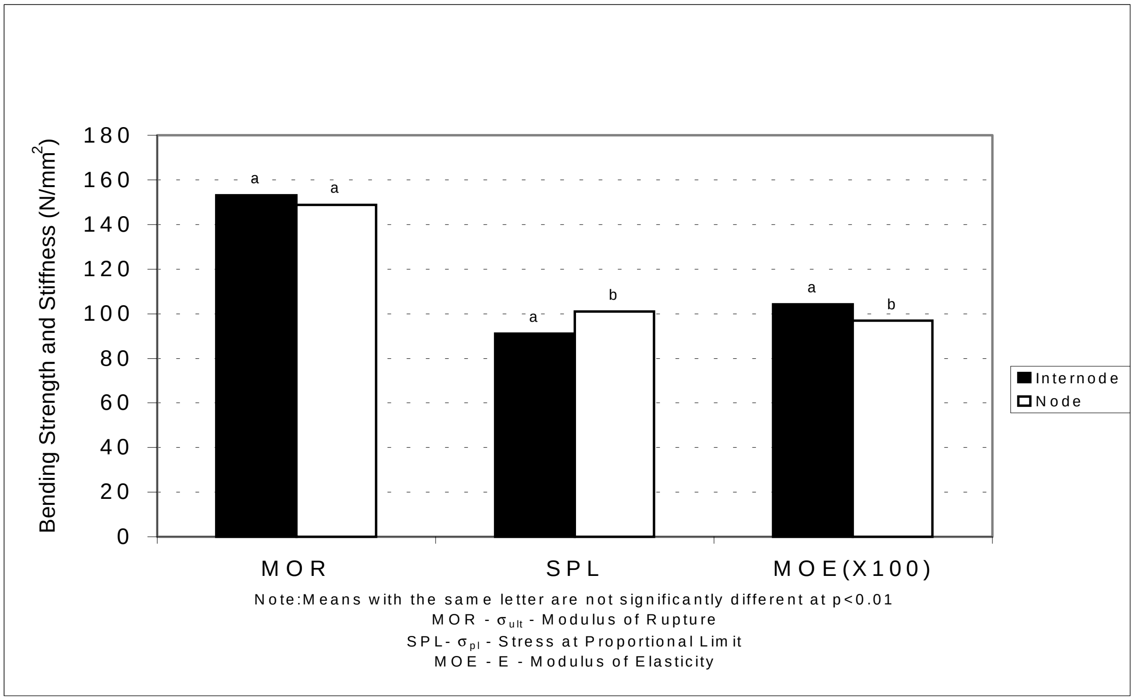

Figure 4.7. Adjusted bending strength and stiffness of *Dendrocalamus strictus* at different section of culm.

From Table 4.7, the mean MOR of location 1 to 4 were 152.3 N/mm^2, 149.3 N/mm^2, 151.2 N/mm^2 and 185.5 N/mm^2, respectively. The adjusted mean MOR of the four locations are 156.1 N/mm^2, 144.4 N/mm^2, 157.1 N/mm^2 and 180.3 N/mm^2. The difference was slightly changed when relative density was taken as the covariate. From the general linear model procedure and Tukey-Kramer test (Figure 4.8), it was found that the adjusted mean MOR of location 1, 2 and 3 were not significantly different from each other. However, the value for location 4 was significantly different from the other locations. The adjusted MOE values for location 1, 2 and 3 are not significantly different from each other, but locations 1 and location 4 differ significantly.

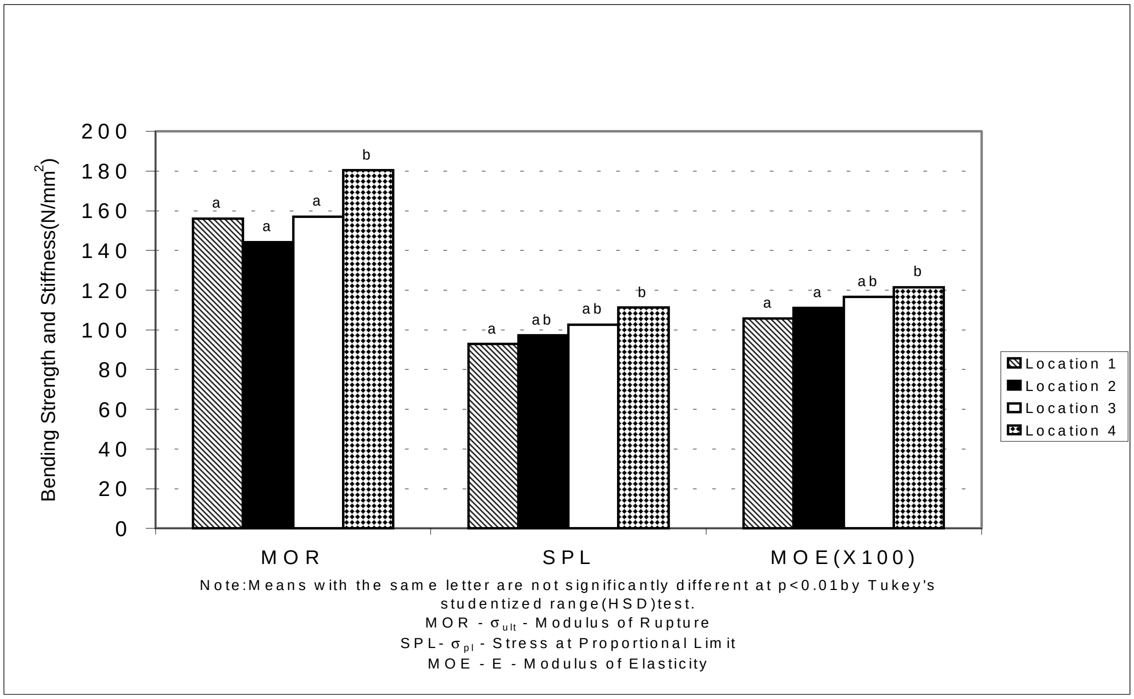

Figure 4.8. Adjusted bending strength and stiffness of *Dendrocalamus strictus* at different location of culm.

On the other hand, locations 2, 3 and 4 show no significant difference. The mean MOE values for locations 1 to 4 were 10,428 N/mm^2, 11,306 N/mm^2, 11,426 N/mm^2 and 12,358 N/mm^2, respectively. The adjusted mean values were 10,582 N/mm^2, 11,106 N/mm^2, 11,666 N/mm^2 and 12,150 N/mm^2, respectively. The SPL values followed a different pattern, where locations 1, 2 and 3 show no significant difference from each other, while locations 1 and 2 were significantly different from locations 4. Locations 3 and 4 were not significantly different from one another. The mean SPL values were 91.2 N/mm^2, 99.5 N/mm^2, 100.0 N/mm^2 and 113.5 N/mm^2 for locations 1 to 4 respectively, while the adjusted mean values were 92.9 N/mm^2, 97.3 N/mm^2, 102.6 N/mm^2 and 111.28 N/mm^2, respectively.

Bending strength and stiffness of calcutta bamboo has been studied by several researchers. Table 4A of Appendix A, presents mechanical properties of calcutta bamboo determined in previous studies. Tewari [13] reported the mean MOR, SPL and MOE in dry condition (10.1%) of calcutta bamboo from Manamur, India as 153.39 N/mm^2 (22,248 psi), 106.54 N/mm^2 (15,452 psi) and 20,063 N/mm^2 (2.91 x 10^6 psi) respectively. The mean relative density in their study was 0.85. Anon [23] reported that the mean MOR, SPL and MOE of calcutta bamboo from Puerto Rico in the dry condition (10.1%), with mean relative density of 0.57, were 83.16 N/mm^2 (12,061 psi), 43.73 N/mm^2 (6,342 psi) and 9,998 N/mm^2 (1.16 x 10^6 psi) respectively.

The regression equation in Table 4.7 was used to adjust for the relative density of the calcutta bamboo from Manamur, India and Puerto Rico. Using the mean relative densities of calcutta bamboo from India and Puerto Rico, which were 0.85 and 0.57, respectively, the MOR, SPL and MOE for locations 1 to 4 is summarized in Table 4.8. The adjusted mean values were calculated using equations in Table 4.7. Comparing the bending strength and stiffness to other bamboo species, calcutta bamboo seems to be in the middle range. Examples of lower and higher values were taken from Table 3A of Appendix A. The test conducted was either in the full size (round form) or small specimen (cut form). One example is given by Sattar [5]. The bamboo species was Mitenga (*Bambusa longispiculata*), which was tested in the round form. The mean MOR, SPL and MOE in dry condition were 49.50 N/mm^2 (7,180 psi), 33.56 N/mm^2 (4,867 psi), 10,066 N/mm^2 (1.46 x 10^6 psi) respectively. The relative density was reported to

Table 4.8. Summary of the adjusted bending strength and stiffness of Calcutta bamboo from India and Puerto Rico.

Relationship	Adjusted Mean Value (N/mm^2)	
	India (R_D=0.85)	Puerto Rico (R_D=0.57)
Locations		
$B\sigma_{ult.1} = -16.17 + 245.83R_{D1}$	192.78	123.95
$B\sigma_{ult.2} = -28.16 + 245.83R_{D2}$	180.80	111.96
$B\sigma_{ult.3} = -16.40 + 245.83R_{D3}$	192.56	123.72
$B\sigma_{ult.4} = 7.83 + 245.83R_{D4}$	216.79	147.95
$BE_1 = 3565.96 + 9998.01R_{D1}$	11,764	9,265
$BE_2 = 4089.37 + 9998.01R_{D2}$	12,288	9,788
$BE_3 = 4649.84 + 9998.01R_{D3}$	12,848	10,349
$BE_4 = 5134.51 + 9998.01R_{D4}$	13,333	10,833
$B\sigma_{pl.1} = 16.22 + 109.30R_{D1}$	109.13	78.52
$B\sigma_{pl.2} = 20.59 + 109.01R_{D2}$	113.50	82.89
$B\sigma_{pl.3} = 25.93 + 109.01R_{D3}$	118.84	88.23
$B\sigma_{pl.4} = 34.55 + 109.01R_{D4}$	127.46	96.85

be 0.91, which was quite high considering that the bending strength and stiffness were low. Another example given in Table 3A of Appendix A is Moso bamboo (*Phyllostachys puberscens*). Small specimens were tested in the green condition and the green relative density was 0.785. Mean σ_{ult}, σ_{pl}, and E were 97.34 N/mm^2 (14,118 psi), 47.94 N/mm^2 (6,953 psi), 7,929 N/mm^2 (1.15×10^6 psi) respectively.

Comparing calcutta bamboo with timber species that are used in structural composites is also necessary. Table 1B of Appendix B presents equations for predicting selected properties of small clear specimens of timber in the green and dry condition (adjusted to 12%) for softwood and hardwood based on the relative density. Table 2B of Appendix B 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 [20]. Mean MOR of yellow-poplar and quaking aspen in the dry condition (12%) are 70.00 N/mm^2 and 58.00 N/mm^2, respectively, while the mean MOE values are 10,900 N/mm^2 and 8,100 N/mm^2. The mean MOR and MOE (dry condition) for one of the pine species, eastern white pine, were 59.00 N/mm^2 and 8,500 N/mm^2. Douglas-fir and hemlock are an important timber species as well. The MOR and MOE for douglas-fir in dry-condition were 85.00 N/mm^2 and 13,800 N/mm^2 respectively, while MOR and MOE for hemlock were 61.00 N/mm^2 and 8,300 N/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 than calcutta bamboo. 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.

4.4 Conclusions

Tensile strength and stiffness of the locations 1 and 2 of the culm were determined to be significantly different from one another. Nodes have a significant influence on the ultimate tensile stress and stress at proportional limit.

however they do not effect the tensile modulus of elasticity value. The bending properties of calcutta bamboo were also measured in different locations, as well as in different directions and sections. The mean radial bending strength and stiffness in calcutta bamboo are not significantly different from the values in the tangential direction. The bending stress at proportional limit and bending modulus of elasticity were significantly different in node and internode sections. 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 strength and stiffness, although there were some mixed results. Generally, location 4 (top of the culm) had the best mechanical properties. While statistically significant, there was a minor difference.

A correlation between strength properties and relative density was also carried out with the analysis of covariance. Although the correlation equations were presented in this study, the relationships are very weak. The mean strength properties were adjusted for the relative density and were found to change the values slightly. Generally, the mean tensile and bending properties are superior, or at least comparable to, other bamboo species, as well as timber species that are commonly utilized in composite products.

From a practical point of view, variability in a material is not a desirable behavior, such as a 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 cut-off for the production of such products as oriented strand board and particleboard. However, it would not be economical to discard the nodes or even technically feasible in the production of parallel strand lumber. In order to use the whole culm in these products, the nodes and locations can to 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 recovery for the production.

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 can be a set-back due to its higher density. However its strength and availability may out weight this disadvantage.

4.5 References

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