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Tensile Strength Analysis of bamboo and Layered Laminate Bamboo composites

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Abstract

Tensile properties of bamboo laminae, prepared from bamboo slivers, selected from different regions of bamboo culms (*Dendrocalamus strictus*), increases from inner to outer region for any cross section and the same is experienced from bottom to top. Application of rule of mixture, on linear regression line drawn from test results, show that fiber strength increases and matrix strength decreases from bottom to top, whereas, fibers modulus decreases and matrix modulus increases from bottom to top of bamboo culms. To increase usability of bamboo like wood, layered laminate bamboo composite (LLBC) is fabricated from laminae using adhesive. The properties of LLBCs obtained were resembled with the properties of the teak wood. Fracture behaviour of laminas and LLBCs under tensile loading conditions were studied using scanning electron microscopy (SEM).

Keywords: Lamina/ply; Laminates; Mode of Failure, Tensile properties, SEM.

Introduction

Bamboo is fast becoming a promising wood substitute and one of the chief reasons for this is that as usable bamboo can be harvested in 3-4 years from the time of plantation as opposed to timber which takes decades[1,2]. Tensile strength of bamboo Culm will depend upon density of bamboo culms along and across the fibers. A section of bamboo clearly shows that fiber density is not uniform; it is higher at outer periphery. While there are several publications on characterization of bamboo. Tensile strength is proportional to volume fraction of fibers and fibers strength is about 600MPa which is 12 times higher than the matrix strength [1]. The volume fraction of fibers is dense in the outer region (60~65%), sparse (15~20%) in the inner region and increases linearly with height by about 20~ 40% [2] .The tensile, compressive and bending strength of raw bamboo culms for different species in the range of 111-219 MPa, 53-100MPa, and 86-229MPa respectively[3]. Some work on variation of tensile properties of bamboo along and across the fiber direction of bamboo has reported but variation of tensile properties of fibers and matrix of bamboo culms along the length of bamboo is hardly reported. Therefore, an attempt has been made to study the variation of tensile properties of bamboo culms along and across the fiber direction as well as variation of tensile properties of bamboo fibers and matrix along the length of bamboo.

While there are several publications on characterization of bamboo composites based on bamboo fibers in polymeric matrix [4-11], very few reports on evaluation of bamboo composites based on laminas exist in the literature [12,13]. Tensile properties of bamboo based laminates need to be investigated thoroughly so that the full potential of bamboo as a fucntionally graded composite could be utilised. This publication reports the tensile properties evaluation of four layered bamboo epoxy laminates.To achieve usability like teak wood timber, we have also compared properties of LLBC with teak wood timber on the basis of strength

Materials and methods

Four year old green bamboo (*Dendrocalamus strictus*) culms were obtained from TERI Gram (Tata Energy and Resource Institute), District Gurgaon (Haryana), India because it grows all over India and it is strong material compare to other species. Moisture content of green bamboo collected were 37% at the time of felling (Digital moisture meter model MD-4G). Moisture content of green bamboo was reduced to 10-12% by sundry. This was done to ensure better adhesion between bamboo laminae and the epoxy resin. A full length bamboo was labeled at nodes and internodes as shown in Fig. 1. Bamboo was cut length-wise into six slats using radial hydraulic splitting machine. Each slat was sliced using sliver cutting machine and crosscut for suitable dimension using hacksaw respectively for outer, middle and inner as shown in Fig.2. Slivers prepared from outer and inner regions were processed on two side planning machine to remove some amount of outer skin which is weak in adhesion. Laminae were prepared from slivers as per ASTM standard D3039. Laminae were in the form of rectangular cross-section which were 200mm overall length, 100mm gage length and 15mm wide with a thickness of 1.5mm as shown in Fig.

3. The shape of laminae was made uniform by using medium fine sandpaper (grade 180) where sanding motion was ±45°.To ensure that the failure should not occur in or near the grip region during testing, the thickness of laminae was increased near the ends by using small tabs which were made from a bamboo itself and attached at the ends of the laminae by using araldite as an adhesive. Tabs (Fig.3.) were 50mm long, 15mm wide and 1.5mm thickness with bevel angle of 30^0-45^0. The tabs were made tapered to reduce stress concentration near the grips. Tabs were needed for the laminae taken from the inter-nodal region only. Tabs were not necessary for laminae having node because failure takes place at the nodes before failure at the grips or other region occurs. To ensure good bonding of tabs, pressure (10 kg/cm^2) is applied between two plates using UTM. After 24 hours of curing, the specimens from inter nodal region were ready for testing. Three samples were prepared from each location for obtaining variation and average of test results. For tensile testing of laminas, 54 samples of without node and 45 samples of with node were prepared from one bamboo culms.

Similarly, more bamboo laminae were prepared from outer regions of other bamboo culms of same species for expecting more strength because in outer regions, volume fraction of fibers is more which are responsible for strength. Further, for fabricating LLBCs, laminae were selected from intermodal because during experiments, it was observed that node is weak in tension. It is noted that width of laminae were generally less due to circular cross section of bamboo culms. Therefore laminae were butt joined using adhesive to make laminates/plies with larger width. The liquid diglycidyle ether of Bisphenol –A type (Araldite LY 556) with curing agent/hardener Triethylene tetramine (TETA, HY 951) was used as adhesive. Tensile strength, young`s modulus, density and curing time at room temperature of adhesive are 30~35MPa, 3-10GPa, 1.3 g/cm^3 and 24 hours respectively. The suggested ratio of araldite and hardener used are 100:23 by weight. The said adhesive will provide a low-viscosity, solvent free room temperature curing laminating system. Due to the very low cure shrinkage, Araldite LY 556 with hardener HY 951 based laminates will be dimensionally stable, free from internal stresses and excellent water resistance [14].

The laminae were butt joined using adhesive to make one laminate of larger width. To make first layer of laminate, laminas were arranged systematically on die cavity of 250mm x100mm x 15m (Fig.4) using adhesive for butt joined. To avoid adhesion between epoxy and die, polyesters sheet were used in between. The first layer of laminate was then coated with adhesive for interfacial bonding. Other laminae were placed over on bottom laminate to make another layer of laminate. In this manner four layers of laminate/ply were stacked together to form one sample of unidirectional LLBCs. This laminate was sandwiched between the plates of die set by applying pressure of 10kg/cm^2 (2.5T) using Universal Testing Machine. This ensured straight slivers during solidification of adhesive and squeezed out of excess adhesive. The sample was left for 24 hrs at room temperature for cross linking of adhesive. Surfaces of specimens were cleaned with acetone. The sample obtained was subjected to sand grinding from all sides so as to obtain smooth surfaces as shown in Fig.5. Ten test specimens were prepared from LLBCs samples using cross cutting and grinding along fiber direction as per ASTM standards D3039 where specimens were in the form of constant rectangular cross section of 200mm overall length, 100 mm gauge length and 16 mm wide with a thickness of 4.57 to 4.69 mm (lamina thickness: 1mm, adhesive thickness: 0.19-0.23mm) as shown in Fig. 6. Thickness of adhesive used in LLBCs have been seen (Fig.10A) from Nikon Microscope. Thicknesses of adhesive were measured with the help of image J software. Tabs were 50 mm long, 16 mm wide and 1.5 mm thickness with bevel angle of 30^0-45^0 (Fig. 6). The sample size needs to be large to draw any conclusion. This report is a very small step in that direction.

3. Tensile testing

The experiments were performed on universal testing machine (Instron) under axial loading. Averages of three measurements were taken of each lamina specimens. The laminae were carefully positioned at the center of the cross-head with its end faces exactly perpendicular to the longitudinal axis to get accurate results. The experiments were conducted at a constant crosshead speed 2mm/min. The load vs displacement plots were obtained for each lamina specimen from the automatic computerized chart recorder with the help of software called testXpert software inbuilt in machine. Typical recorded load –displacement curve for inter nodal and nodal laminae are shown in Figs. 7A and 7B, respectively. Tensile failure strength and its young`s modulus were recorded from machine for all laminae along the length of bamboo selected from outer, middle and inner region of cross section of culms. Using recorded data, graphs were prepared for variation of tensile failure stress and young modulus with intermodal number as shown in Figs. 8A and 8B and with nodal numbers as shown in Figs. 9A and 9B respectively.

Similarly tensile tests were performed on Instron Universal Testing Machine at a cross head speed of 2 mm/min for ten test specimens that were prepared from LLBCs samples. Test specimens were mounted in a properly aligned test frame. Hydraulic grips were used to hold test specimens. The stress-strain curves were generated for each test specimens. A typical recorded stress -strain curve for LLBCs specimens under tensile loading is shown in Fig.10B. Average tensile properties recorded for ten specimens are given in Table 1.

4. Results and discussions

Figs.7A and 7B show that load displacement curves for specimens is almost bi-linear up to ultimate load. As the maximum load is reached, after matrix failure, the fiber failure occurs. It is found that tensile failure strength and young modulus both increases with height and also increases from inner region to outer region due to increase in volume fraction of fibers as shown in Figs 8A, 8B, 9A and 9B. Maximum tensile strength and modulus at the top of outer region for inter nodal specimens were observed as 324MPa and 15.6 GPa whereas at the bottom of inner region, the same were 83MPa and 7.8 GPa respectively. Similarly for nodal specimen, these values, at top of outer region were 160MPa and 15GPa and for bottom of inner region were 34MPa and 6.8 GPa respectively. For whole length of bamboo Culm, average tensile failure strength and young modulus for laminae was 193.63MPa and 9 GPa respectively. Similarly, average failure strength and young`s modulus of outer regions laminae of bamboo culms were 260MPa and 16.9 GPa respectively.

The fiber distribution in the cross section of the bamboo's Culm is dense in the outer region (60~65%) and sparse (15~20%) in the inner region. The volume fraction of fibers (V_f) along the entire length of bamboo increases linearly with height by about 20~ 40% [3]. Using results obtained, the linear regression relationship were plotted for both tensile failure strength and young`s modulus with fiber volume fraction of the specimens as shown in Figs. 11A and 11B respectively. In these figures, left tests results indicates for inner regions, intermediate tests results indicates for middle regions and right test results indicates for outer region of the bamboo culms. Bold lines represent the linear regression line between two parameters. Tests results in horizontal direction indicate variation of volume fraction of fibers and vertical direction indicates tensile properties from bottom to top of bamboo culms. Further, we assume that the mixture principle for composites,

$$\sigma = \sigma_f V_f + \sigma_m (1-V_f) \quad (1)$$

$$E=E_f V_f + E_m (1-V_f) \quad (2)$$

Equation (2) can be applied to the bamboo culms which is naturally mixed composite of cellulose fibers and lignin matrix, where σ_f and E_f is fiber tensile strength and modulus respectively. Similarly σ_m and E_m are matrix tensile strength and modulus respectively. Applying rule of mixture on test results given in linear regression line, we obtained corresponding values for the fibers and matrix which are summarized in Table 2. It is found that fiber strength increases and matrix strength decreases from bottom to top, whereas, fibers modulus decreases and matrix modulus increases from bottom to top.

Failure modes of fractured specimens have been identified using standard failure identification codes (three parts) used in ASTM standards (D3039/section 11.9) as shown in Table 3. Using codes, modes of failures observed in fractured different laminae for inter nodal specimens were DGM, GGT, MGM, MGT and XGM, (Fig.12A). Similarly in nodal samples, modes of failure were mainly LGM and AGM due to brittle fracture (Fig.12B). The failure of specimens for the inter-nodal region starts at the edges. This is because inter laminar shear stresses dominated at the edges. During tensile tests, it was observed that the weakest portion of the bamboo is nodes. In other words, at nodes, bamboo is weak in tension. This is because the fibers are entangled in a various directions at the nodes [2**]**. For all specimens, first matrix failure occurs followed by fiber failure. Fracture propagates spontaneously and the specimen breaks. The load displacement curves (Figs.7A and 7B) show very small yield period after the specimens attains its maximum tensile stress. In fact, the failure is almost immediate which indicates that fibers are brittle. The load displacement curve is also bi-linear for the nodal specimens. But it differs from inter nodal region in respect of the mode of failure, the value of failure stress and displacement at maximum load. Both values are much lower in case of nodal region than that of intermodal region. This could be explained at the level of microstructure by the fact that at the node, the thermoplastin matrix increases while the number of cellulose fibers remains the same. Also , there is a bulge, so though, physically it can take more load because of cushioning effect of matrix , but the ultimate stress reduced.

Fig. 13A and 13B show SEM photographs of the fractured surface of laminae tested in tension for intermodal and nodal regions respectively. A typical pull out of fibers from the lignin matrix can be seen in these photographs, whose features suggest that bamboo is a composite material. The cross section shows the porosity of bamboo.

Fig. 10B shows tensile stress-strain behavior of LLBCs. Tensile stress increased bi-linearly with increasing strain until the point of ultimate load followed by brittle fracture. Above this point, the stress strain curve showed sharp, staggered decreases in stress with small increase in strain. Tensile fracture of unidirectional LLBC is mainly longitudinal cracking. In some specimens, partial damage occurred when the tensile load reached 80% of ultimate stress. Tests results for tensile strength, modulus, standard deviation (S.D.) and Coefficient of variance (C.V.) of

LLBCs are presented in Table 1. It is noted that LLBC`s has increased strength and comparable stiffness than average values of laminae selected from different locations of bamboo culms.

Using Table 3 for codes to represent mode of failure, mode of failure observed on different specimens of LLBCs were generally DGM and MGM (Fig.14). Some specimens start to fail at edge, some at grips and some at multimode. For all layer of laminate, first matrix (bamboo as well as adhesive) failure occurs followed by fibers failure with metallic sound, where fracture propagates spontaneously and the first layer breaks. The material of LLBCs is not homogenous but has an orthotropic property due to which fibers are pulled out from the matrix. Further it is observed that among four layers, any one layer first break. The crack then propagates to other layers. The SEM photographs (Fig.15A and 15B) were taken for fractured surface of a specimens tested in tension for four LLBCs. A cross section of the fracture specimens reveals sheaths of epoxy around a bundle of bamboo fibers and was different from fractures sustained in single bamboo laminae. The outer surface of laminate are infiltrated with adhesive because of high pressure (10kg/cm2) received during sample preparation. In Fig. 15A, the adhesive around some bamboo fibers show good bonding. The lateral surface of the fractured laminate shows the source of the cracks and their subsequently propagation and enlargement. The fiber pull out indicate that there were perfect bonding between bamboo and adhesive.

5. Comparison and advantages

Properties of teak wood reported in literature such as tensile strength is 95-155 MPa, young`s modulus is 10-15.6 GPa and density is 0.62g/cm$^3$ [15- 19]. Properties obtained for LLBCs such as tensile strength is 120-251MPa, young`s modulus is 11.6-17.5 GPa and density is 0.9g/cm^3. Result shows that LLBCs made from outer region laminae has reasonably close to teak wood timber. As compare to single lamina also, LLBC is more usable in terms of building and general purpose material because there is possibility to increase the volume of bamboo composites in all direction by increasing number of layers using suitable equipment as shown in Fig.16. There is reduced tensile property (Average tensile strength is 210MPa and modulus is 9.5GPa) in unidirectional LLBCs made from outer region laminae as compare to average tensile properties of outer regions laminae of bamboo Culm (Average tensile strength is 260MPa and modulus is 16.9GPa).This is due to adhesive presents in former materials which has low strength and modulus than bamboo laminae.

6. Conclusions

(a) The experimental investigations show that tensile strength and Young's modulus of bamboo increases from inner to outer region across any cross section and from bottom to top of bamboo culms due to increase in volume fraction of fibers. The culms strength increases with height to compensate for the deterioration of rigidity due to the culms geometry. Further it is noticed that applying rule of mixture, fiber strength increases and matrix strength decreases from bottom to top whereas fibers modulus (stiffness) decreases and matrix modulus increases from bottom to top.
(b) Nodes are the weakest portion of the culm when it comes to tensile loads. Though, it must be very strong in lateral loads because at joints, the craftsmen invariably try to place the node.
(c) Longitudinal cracking is responsible for failure on single laminae. Modes of failure indicate that fibers presents in the laminae are brittle.
(d) First matrix failure occurs followed by fibers failure of any one layer and subsequently other layers in LLBCs.
(g) There is reduced tensile strength and modulus in unidirectional LLBCs compare to average of laminae of bamboo Culm due to adhesive used in former materials but LLBCs made from outer region laminae has reasonably close to teak wood timber. LLBCs could be more usable in terms of building and general purposes material like, furniture, beam and column etc because there is possibility to increase the volume by increasing number of layers.

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Fig.15. (A) Lateral surface of fractured surface LLBCs, (B) Cross section of fractured surface of LLBC.
Fig.16**.** Expected LLBCs with increased volume

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Table 1
Average Tensile Properties of Layered Laminate Bamboo Composites (LLBCs)

S.N.	Displacement at Max. Load(mm)	Load at Max. Load (KN)	Stress at Max. Load(MPa)	Strain at Max. Load(mm/mm)	Modulus(Aut Young)(MPa)	Energy to break point(J)	Tensile Energy Absorption(N/mm)
Mean	8.845	15.34	210.564	0.1742	9501.95	99.86	123.44
S.D	1.211	2.033	28.83	0.0237	1147	32.281	38.70
C.V.	13.70	13.258	13.69	13.648	25.47	32.32	31.35
Min.	7.90	10.361	151.47	0.133	2214.47	49.409	60.83
Max.	10.79	16.969	251.5	0.212	5937.90	169.98	204.69

Dimension of test specimens: 200mm x 16mm x 4mm with 50mm tab length each side

Table2
Tensile properties of fibers and matrix

Properties	Bottom region		Middle region		Top region	
	fiber	matrix	fiber	matrix	fibers	matrix
Tensile strength (σ MPa)	400	100	415	96	442.5	86.5
Young modulus (E GPa)	51	1	38	7.2	20	10

Table3
Code used for mode of failure

First character		Second character		Third character	
Failure type	code	Failure area	code	Failure location	Code
Angle	A	Inside grip/tab	I	Bottom	B
Edge delamination	D	At grip/tab	A	Top	T
Grip/tab	G	<1W from grip/tab	W	Left	L
Lateral	L	Gage	G	Right	R
Multimode	M	Multiple area	M	Middle	M
Long splitting	S	Various	V	Various	V
Explosive	X	unknown	U	unknown	U
Other	O				

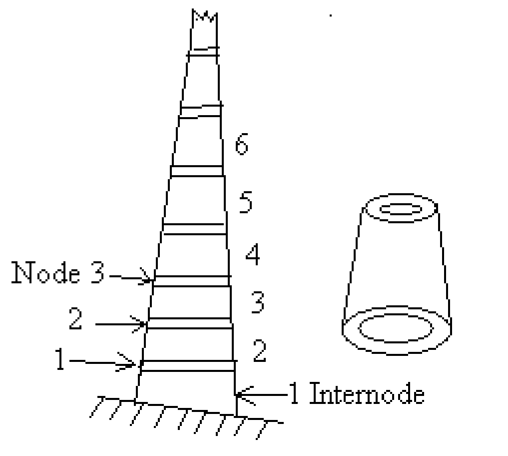


Fig. 1. Bamboo culms and sample.

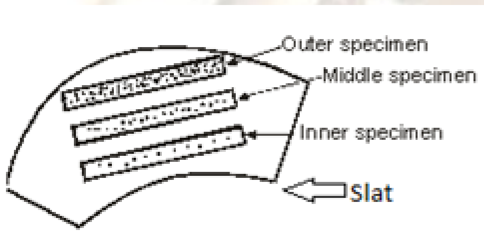


Fig. 2. Location of lamina specimens on slats.

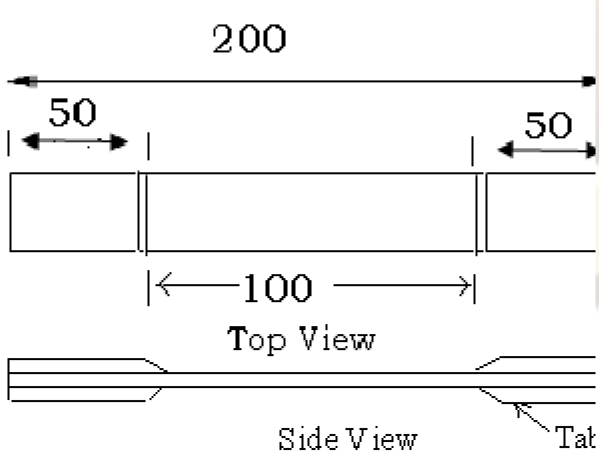


Fig.3. Sketch of lamina Specimens with tab.

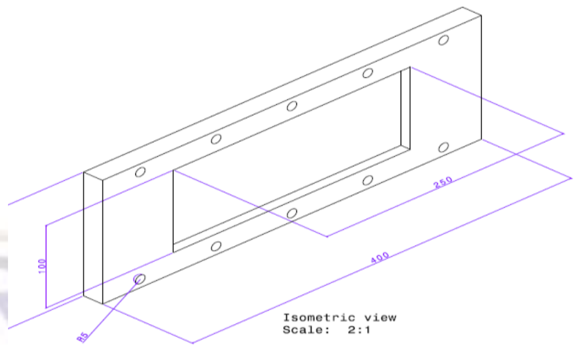


Fig. 4. Die from M.S. Plate.

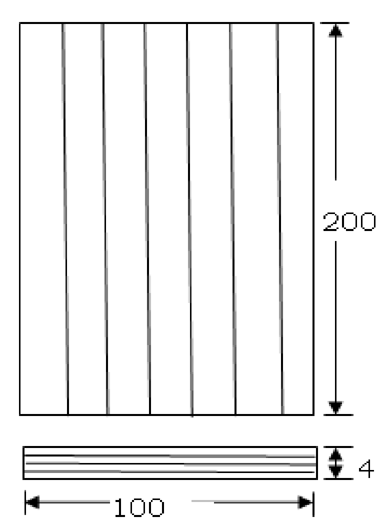


Fig.5. The bamboo epoxy layered laminated bamboo composite.

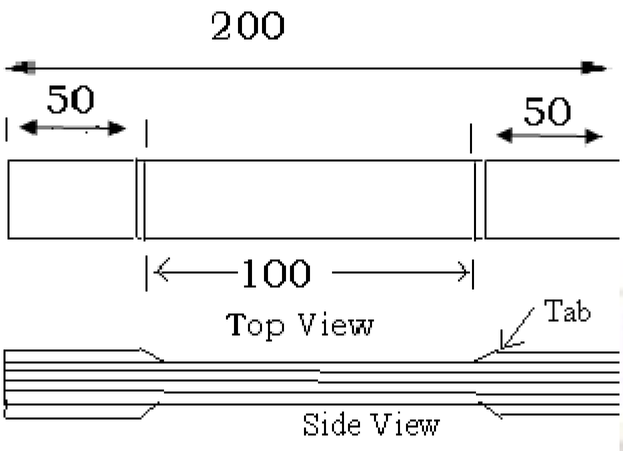
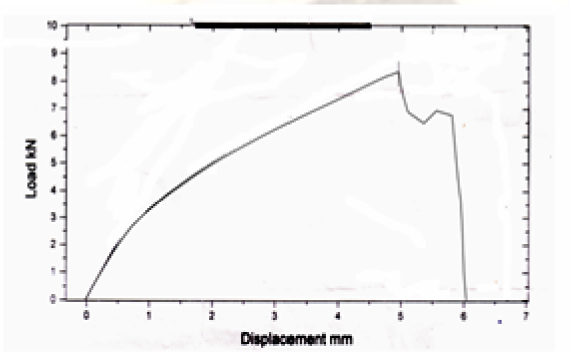
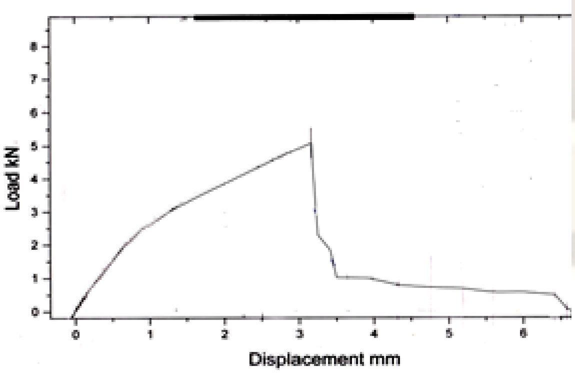


Fig. 6. Sketch of LLBCs Specimens.

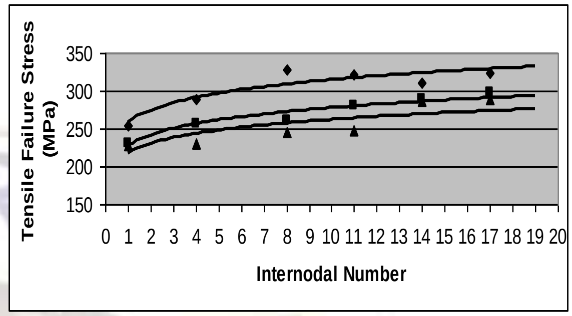


(A)

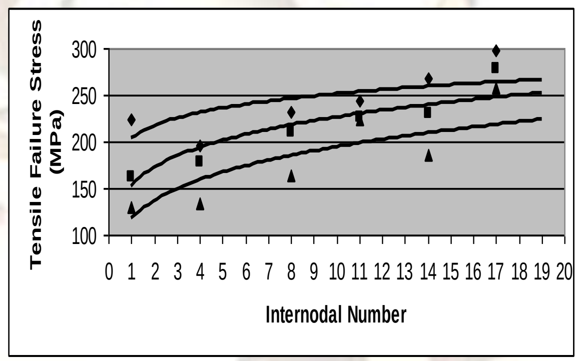


(B)

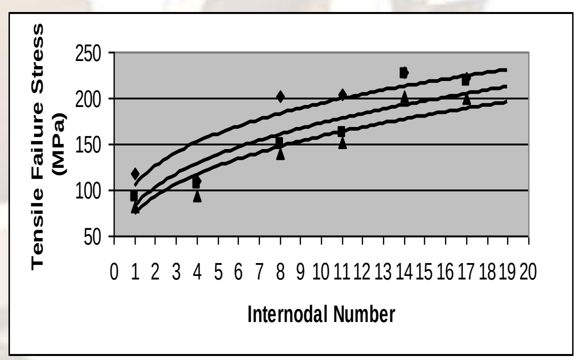
Fig. 7. (A) Load vs. displacement curve for intermodal in tension and (B) load vs. displacement curve with nodal specimens in tension.



(a) Outer Specimen

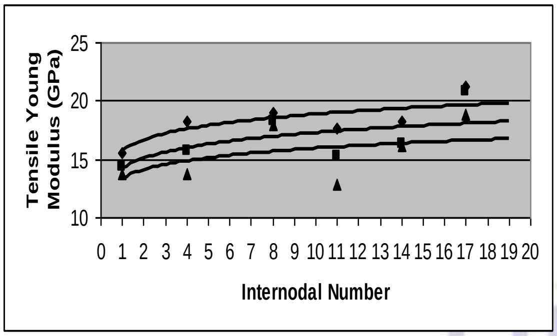


(b) Middle Specimen

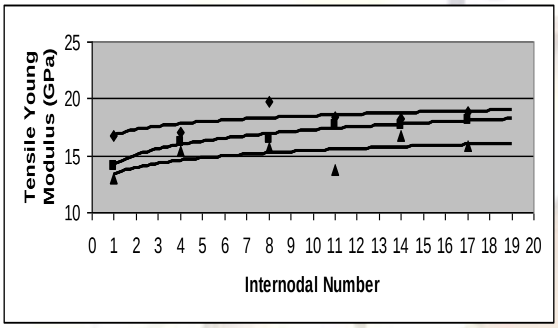


© Inner Specimen

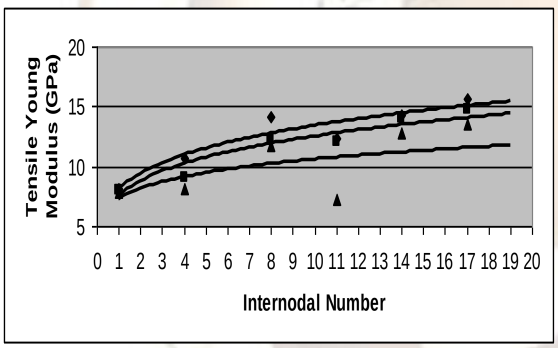
(A)



(a) **Outer Specimen**



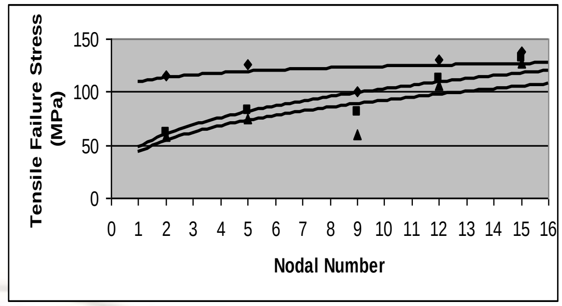
(b) **Middle Specimen**



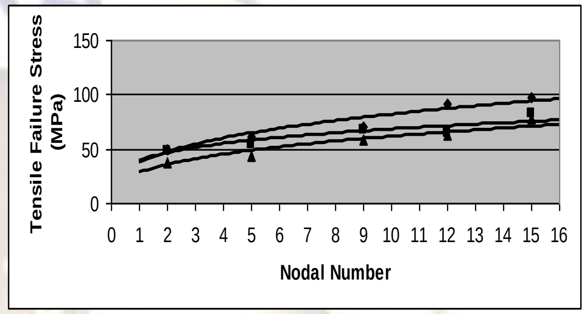
(c) **Inner Specimen**

(B)

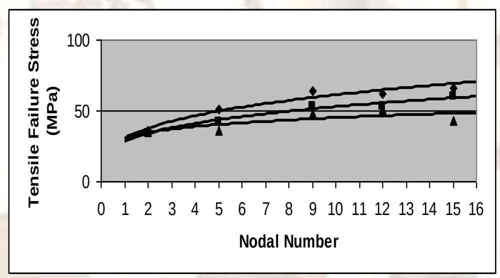
Fig .8. (A) Variation of tensile failure stress with inter nodal number (three specimens at each internodal) and (B) Variation of Young modulus with Inter nodal Number (three specimens at each internodal).



(a) **Outer Specimen**

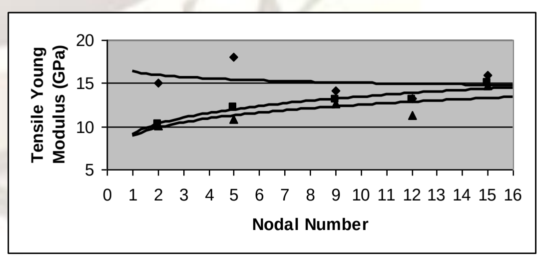


(b) **Middle Specimen**

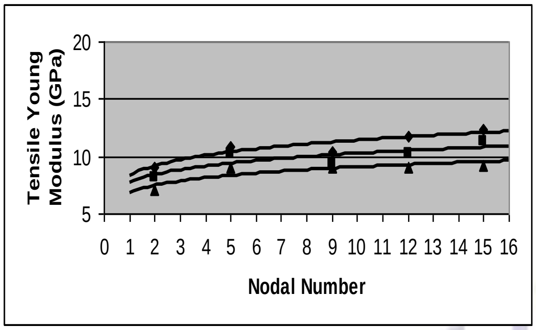


© Inner specimen

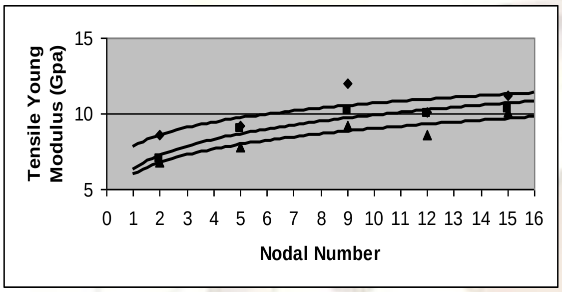
(A)



(a)Outer Specimen



(b)Middle Specimen

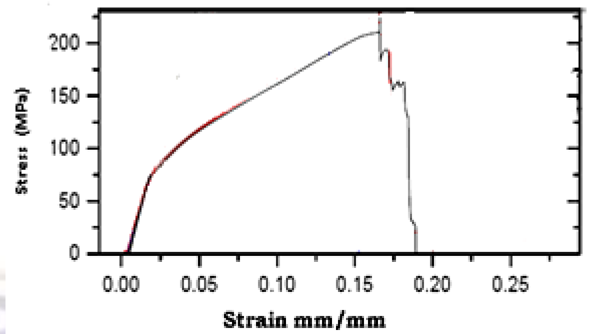


©Inner specimen

(B)

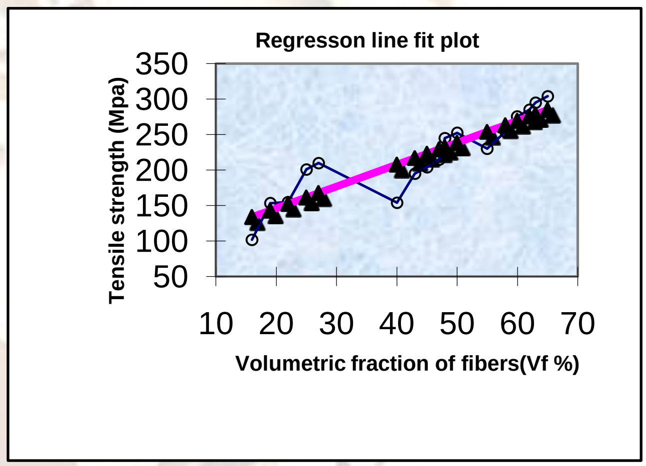
Fig .9A. Variation of Tensile Failure Stress with Nodal Number (three specimens at each nodal) and (B) Variation of Tensile Young Modulus with Nodal Number (three specimens at each nodal).

(A)

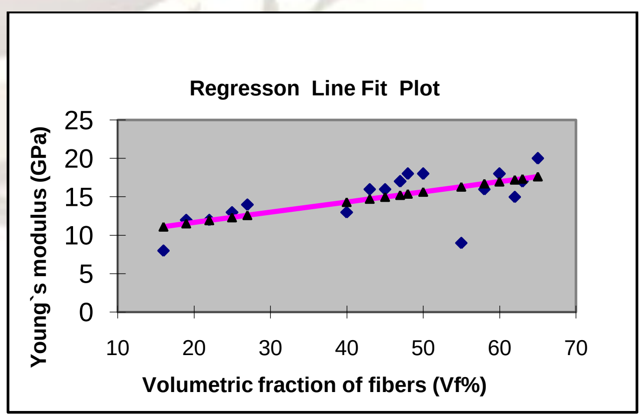


(B)

Fig.10A. Cross sectional image of LLBCs cube and (B) Stress-strain curve for LLBCs specimens under tensile loading.



(A)



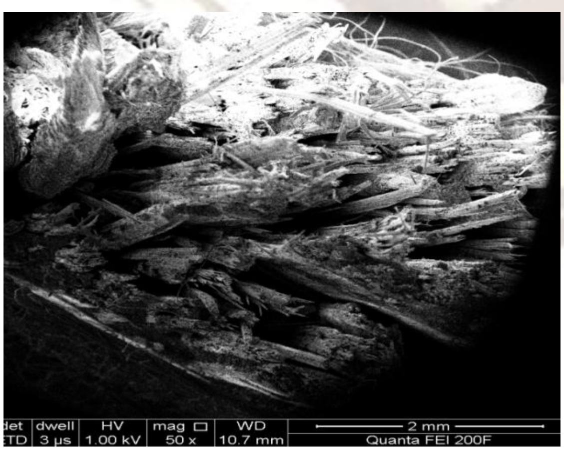
(B)

Fig.11. (A) Linear regression relationship between tensile strength and volumetric fraction of fibers and (B) Linear relationship between Young`s modulus and volumetric fraction of fibers.

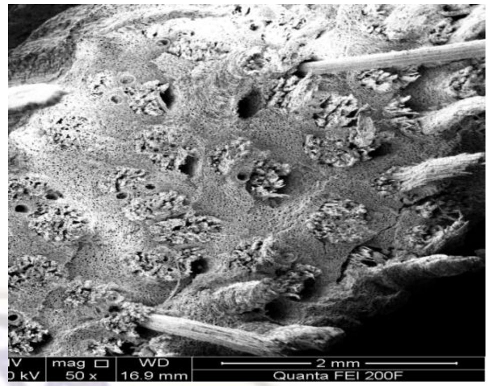
(A)

(B)

Fig.12. (A) Tensile failure mode of single laminas of intermodal and (B) Tensile failure mode of single laminas of nodal.



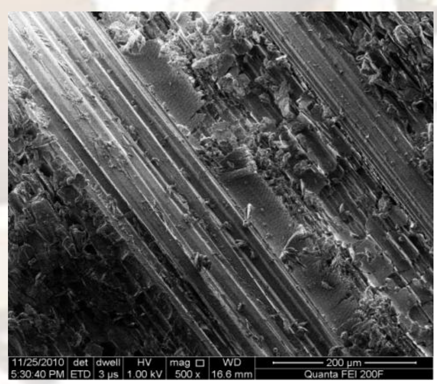
(A)



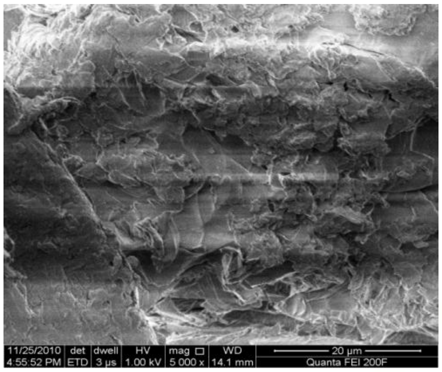
(B)

Fig. 13.(A) Cross section of fractured internodal surface and (B) Cross section of fractured nodal of lamina.

Fig. 14. Mode of failure on Layered Laminate Bamboo Composites.



(A)



(B)

Fig.15. (A) Lateral surface of fractured surface LLBC`s and (B) Cross section of fractured surface of LLBC.

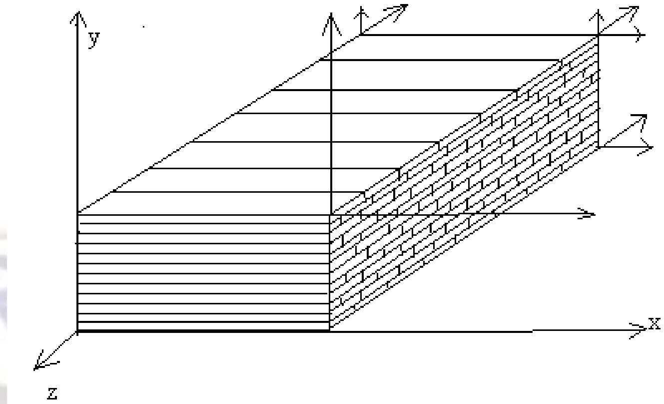


Fig.16. Expected LLBCs with increased volume.