International Journal of Metallurgical &
Materials Science and Engineering (IJMMSE)
Vol.2, Issue 2 June 2012 20-37

STUDY OF SOME MECHANICAL PROPERTIES OF BAMBOO LAMINAE

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ABSTRACT

Mechanical properties of bamboo laminae, prepared from bamboo slivers selected from different regions of bamboo culms of dendrocalamus strictus species, increases from inner to outer region for any cross section and the same is experienced from bottom to top. Mode of failure were identified at macroscopic level as suggested in ASTM standard and their mechanism were examined at microscopic level using SEM analysis of fractured surfaces under different type of tests. Mechanical properties of laminas were found good enough to increase usability of bamboo like wood.

KEYWORDS: Laminae; Mechanical properties; SEM.

INTRODUCTION

Aminuddin and Latif (1991) has reported that the bamboo has phenomenal growth rate potential, with some species growing at a rate of 15 to 18 cm daily, with maximum height in just four to six months. Wang et al (1987) stated that there are about 60 to 70 genera and over 1,200 – 1,500 species of bamboo in the world. Dendrocalamus strictus species is commonly recognized as culcutta bamboo, male bamboo and solid bamboo. Colcutta bamboo is most widely used bamboo in India, specially in paper industry(Ferrelly,1984). Lee et al. (1994) determined the physical and mechanical properties of giant timber bamboo (Phyllostachys bambusoides) grown in South Carolina, USA. This study concluded that moisture content, height location in the culm, presence of nodes and orientation of the outer bark affect the mechanical and physical properties. Some of the mechanical properties of bamboo pole is enough for structural purposes where specific tensile strength of bamboo is four times better than that of steel (Lakkad and Patel, 1980). Bamboo is camparable to steel in terms of strength and stiffness efficiency while the production energy required for bamboo (per m^3) is only 0.1% of that required for steel as calculeted(Chung et al., 2002). Naik (2004) has reported that the tensile , compressive and bending strength of natural round hallow bamboo culms for different species were in the range of 111-219 MPa, 53-100MPa, and 86-229MPa respectively.The establishment of the International Network for Bamboo and Rattan (INBAR) contributed to the renewed intrest in research on bamboo for development of new products and to increase of usability of bamboo(Janssen, 2000). Tensile strength are proportional to volume fraction of fibers of bamboo where 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% . Therefore the bamboo belongs to the class of material known as functionally graded material (FGM) (Amada et al., 1997). Above properties and benefits indicate that there are need of more study on bamboo to aid and promote its application in the modern world. Furthermore, the majority of the publication reported the mechanical properties of natural hollow bamboo either as a single specimen while very few reported about some of the mechanical properties of laminae selected from different location on natural round hollow bamboo. Bamboo culm or pole can be convereted into the engineered bamboo timber like wood(3d) by suitable arrangement of slivers/laminae with the help of adhesive. Bamboo timber can be used as wood substitute . Therefore, we report here the variation of some mechanical properties such as tensile, compressive and flexural properties of laminae prepared from slivers along and across the fiber direction from bottom to top of bamboo culms.

MATERIALS AND METHODS

Four year old green bamboo (Dendrocalamus strictus species) culms were obtained from TERI Gram , District Gurgaon (Haryana), India. Moisture content of green bamboo collected were 37% at the time of felling (Digital moisture meter model MD-4G). Moisture content is then reduced to 10-12% by sundring. A full length bamboo was labeled at nodes and internodes as shown in Fig. 1. Dry bamboo was cut length-wise into six slats using radial hydraulic splitting machine. Each slat was sliced using sliver cutting machine for getting slivers from outer, middle and inner regions as shown in Fig.1. Laminae were prepared as shown in Figs. 2, 3 and 4. Processes used to evaluate some of the mechanical properties are given in Table 1. Three specimens were prepared from each location for obtaining average of test results along and across of bamboo culm. The shape of laminae were made uniform by using medium fine sandpaper (grade 180) where sanding motion was ±45°.

Table 1

Process used to evaluate mechanical properties

Mechanical properties	Standards Used	Dimension of specimens (Overall length x gage length x width x thickness)	Machine used and capacity	Cross head speed
Tensile	ASTM standard D3039	200mm x 100mm x 15mmx1.5mm (Fig.2)	Instron UTM(5T)	2 mm/min
Compressive	ASTM standard D3410	120mm x 6 mm x 16mm x 1mm (Fig. 3)	Instron UTM(10T)	2 mm/min
Flexural	ASTM standard D7264	200mm x 16mm x 2 mm (Fig. 4)	Instron UTM(5T)	2 mm/min

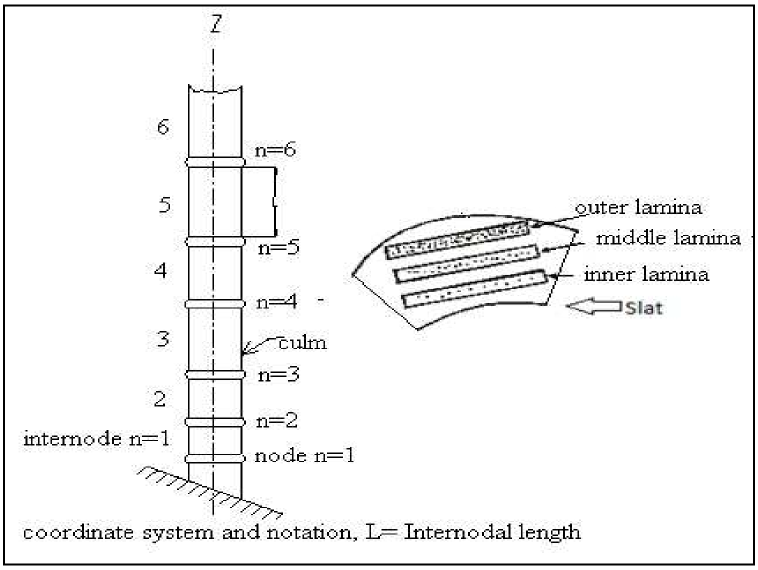

Fig. **1**. Bamboo culms and location of laminas on slats.

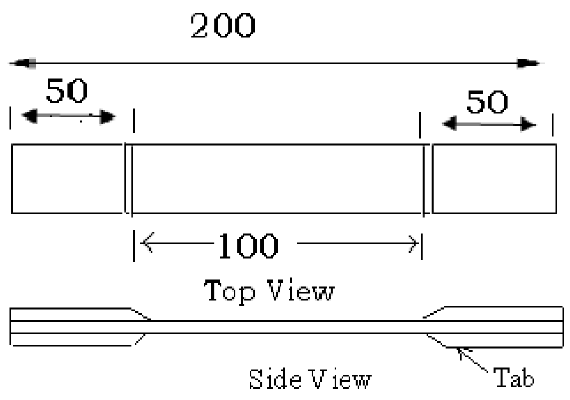

Fig.2. Sketch of lamina Specimens with tab.

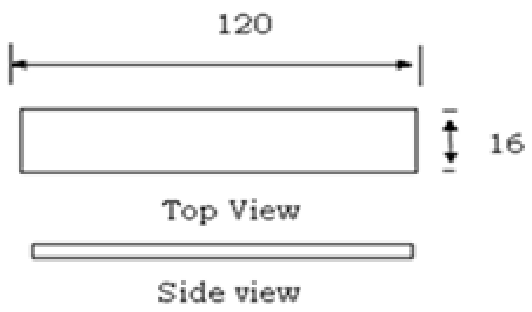

Fig. 3. Sketch of lamina specimens for compressive testing.

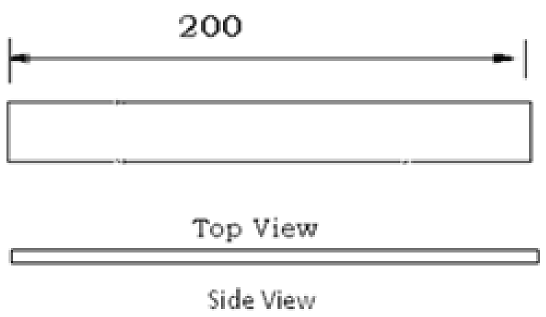

Fig. 4. Sketch of lamina specimens for flexural testing.

3. TESTING

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 during tensile and compressive tests. The stress - strain plots were obtained for each lamina specimen from the automatic computerized chart recorder with the help of software called testXpert inbuilt in machine. Typical recorded tensile stress - strain curve for inter nodal and nodal lamina are shown in Figs. 5.The linear slope of the line is referred to as modulus of elasticity or young`s modulus. It is a measure of stiffness of a given materials. When curve is non linear such as bi-linear or tri-linear, chord and tangent modulus is to be determined from stress-strain curves. Tensile failure strength and its young`s modulus were recorded from data obtained from computer inbuilt in Instron UTM machine for all laminas 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. 6A and 6B and with nodal numbers as shown in Figs. 7A and 7B respectively. Similarly a typical stress-strain curve and curves for variation of maximum compressive strength and modulus are shown in Figs. 8A, 8B, and 8C respectively under compressive loading. Further three point bend tests on lamina specimens were performed on UTM where outer roller were 100 mm apart. The ratio of distance between supports to thickness was 50: 1 so that failure occurs at the outer surface of the specimens due to bending moment only. The stress -strain plots were obtained for all specimens but a typical one is shown in Fig.9A. Using data’s obtained from computer of machine; graphs were prepared for variation of flexural failure stress and young modulus with intermodal number as shown in Figs.9B and 9C respectively.

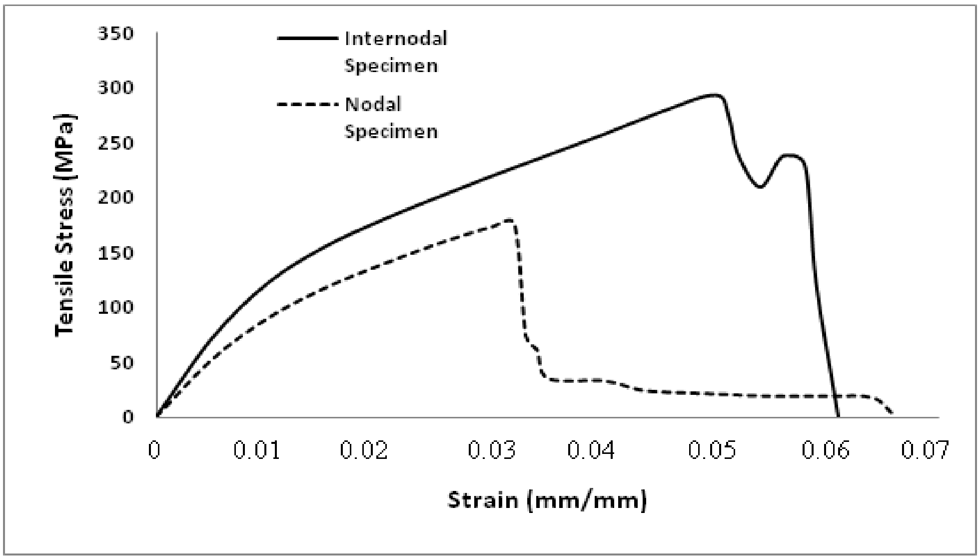

Fig. 5. Typical stress - strain curve for intermodal and nodal specimen in tension .

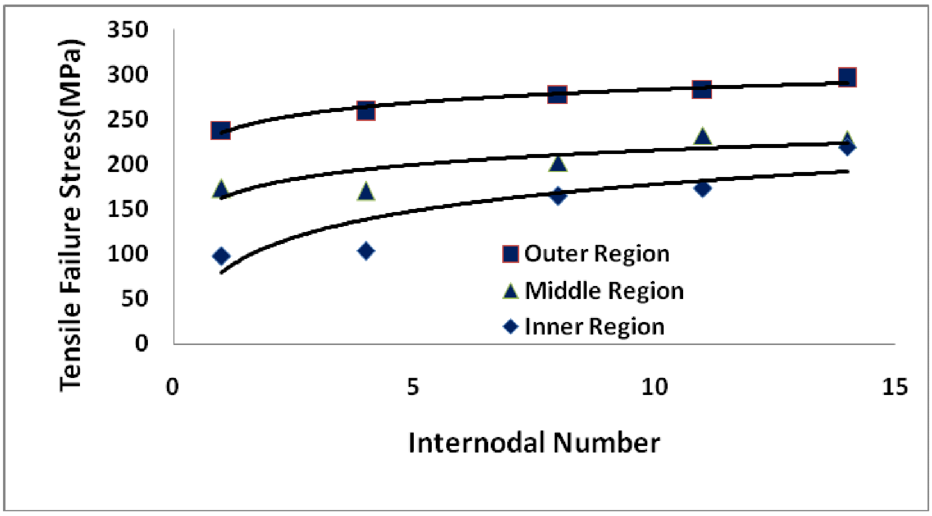

Fig .6A. Variation of tensile failure stress with inter nodal number (three specimens at each internodal).

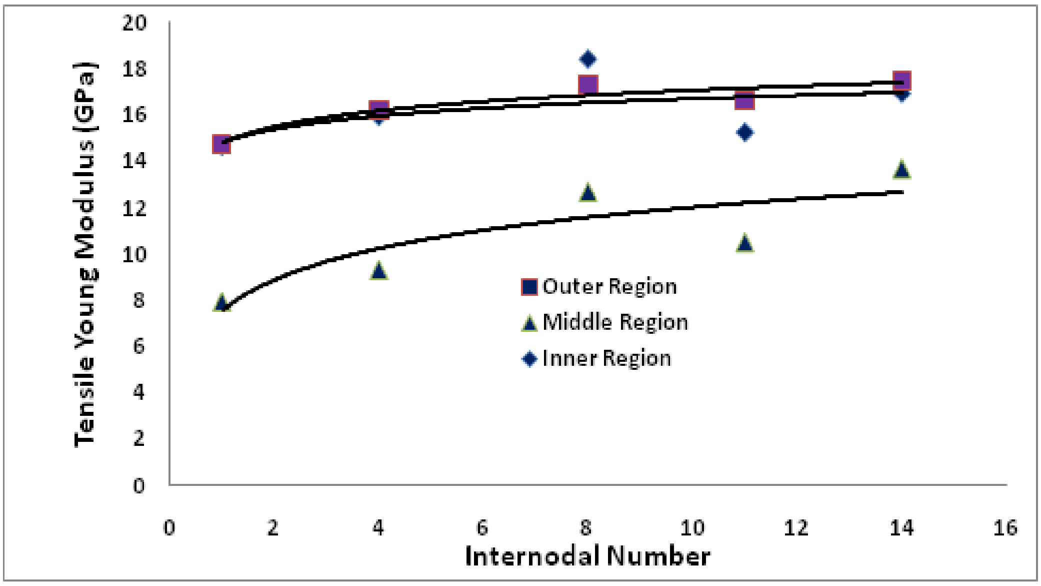

Fig .6B.Variation of Young modulus with Inter nodal Number (three specimens at each internodal).

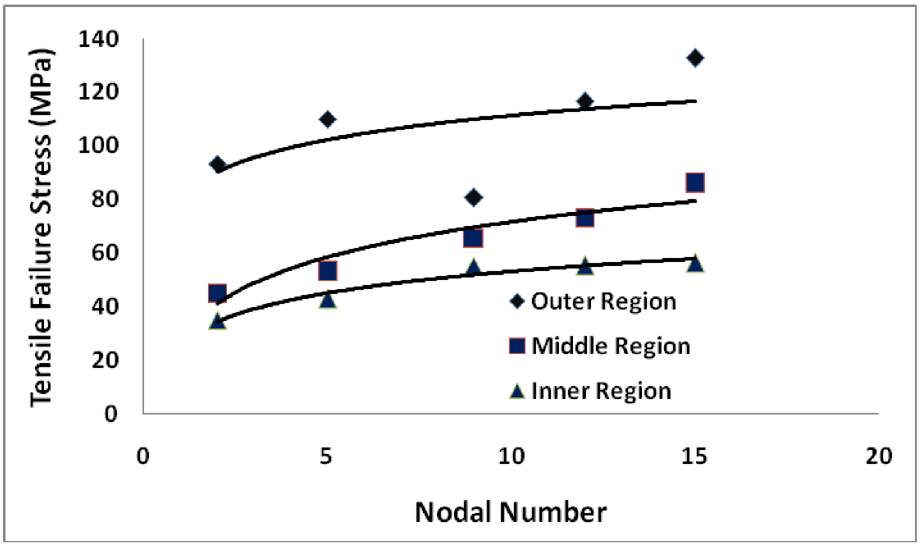

Fig .7A.Variation of Tensile Failure Stress with Nodal Number
(three specimens at each nodal).

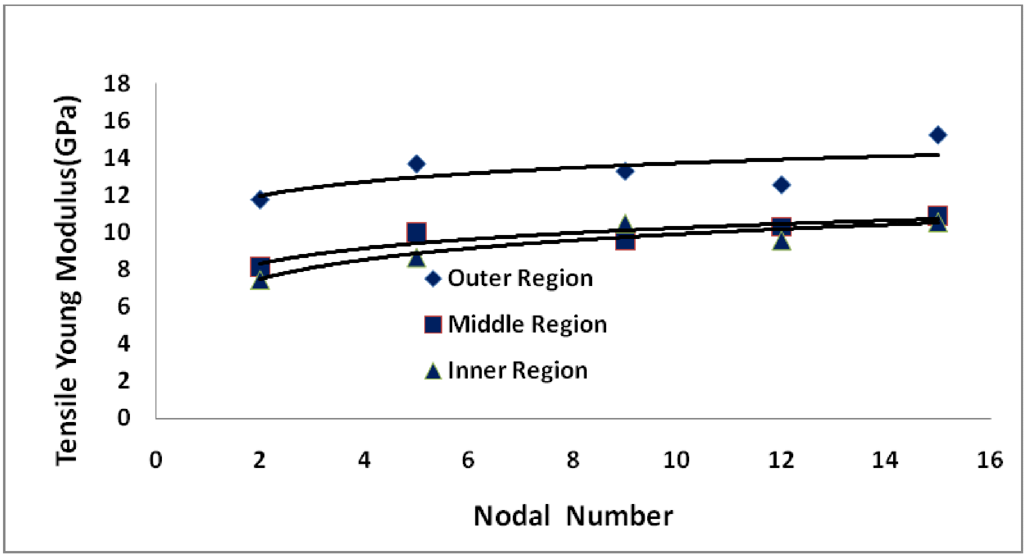

Fig .7B.Variation of Tensile Young Modulus with Nodal Number
(three specimens at each nodal).

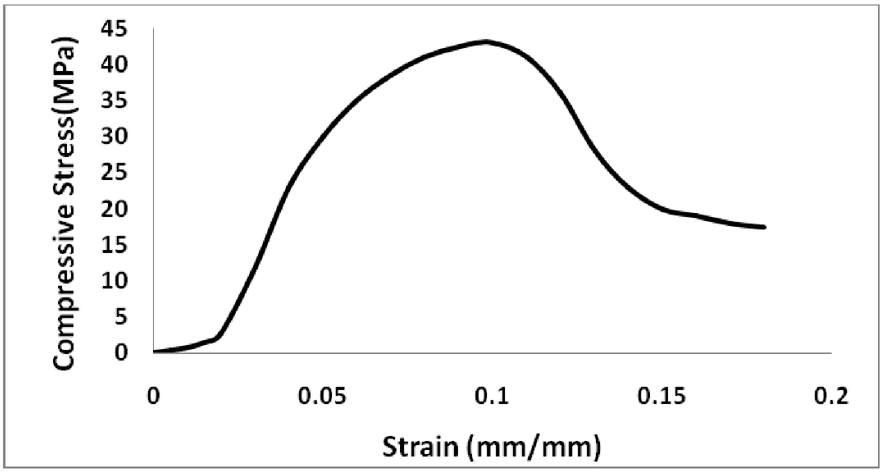

Fig. 8A. A typical stress-strain curve for internodal specimens under compressive loading.

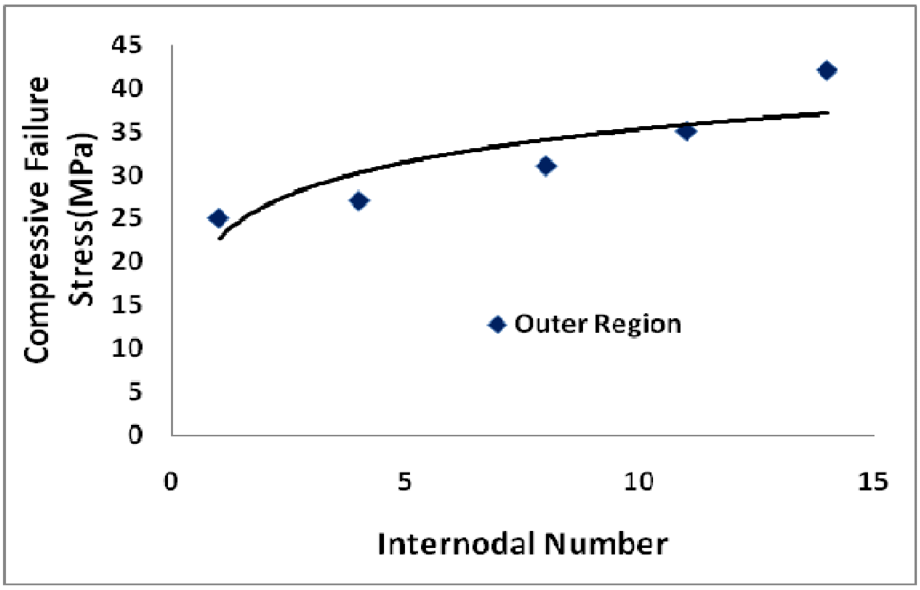

Fig. 8B.Variation of compressive failure stress with inter nodal number.

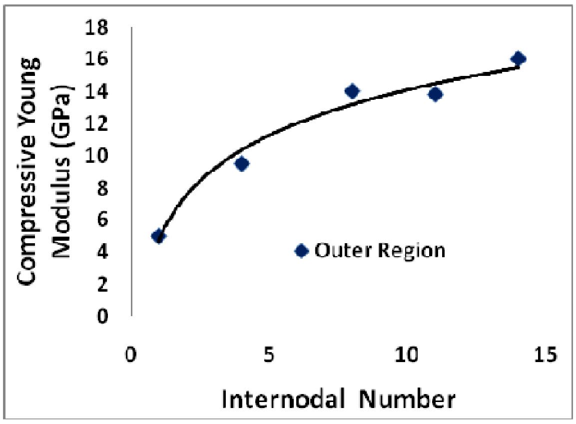

Fig. 8C. Variation of modulus with internodal number .

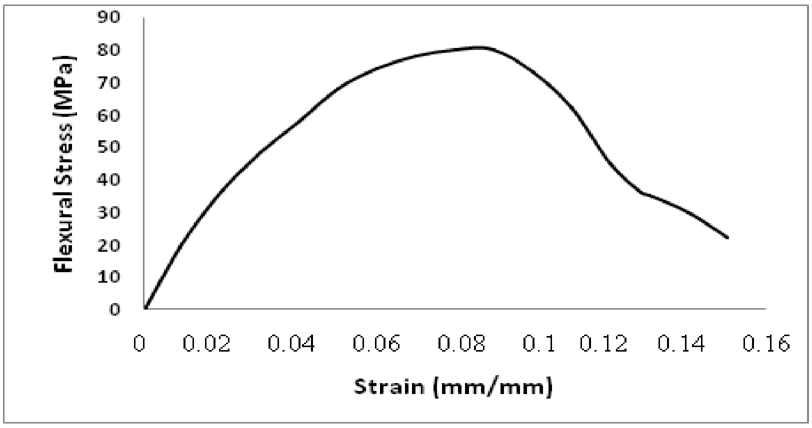

Fig.9A. A typical stress-strain curve for internodal specimens under flexural loading.

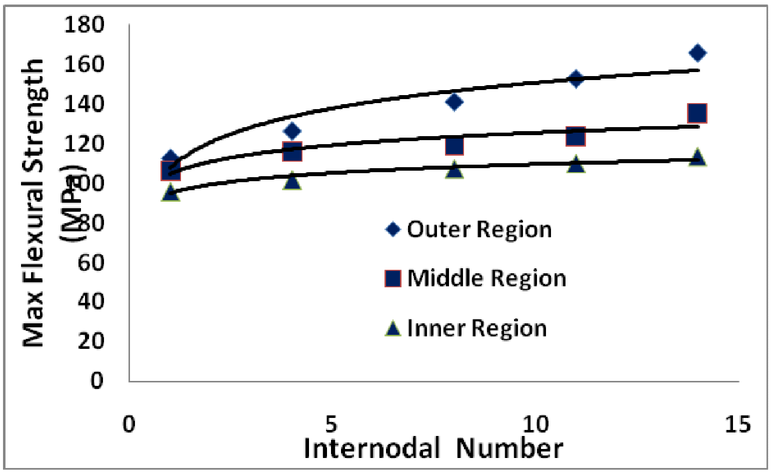

Fig.9B. Variation of flexural failure stress with inter nodal number.

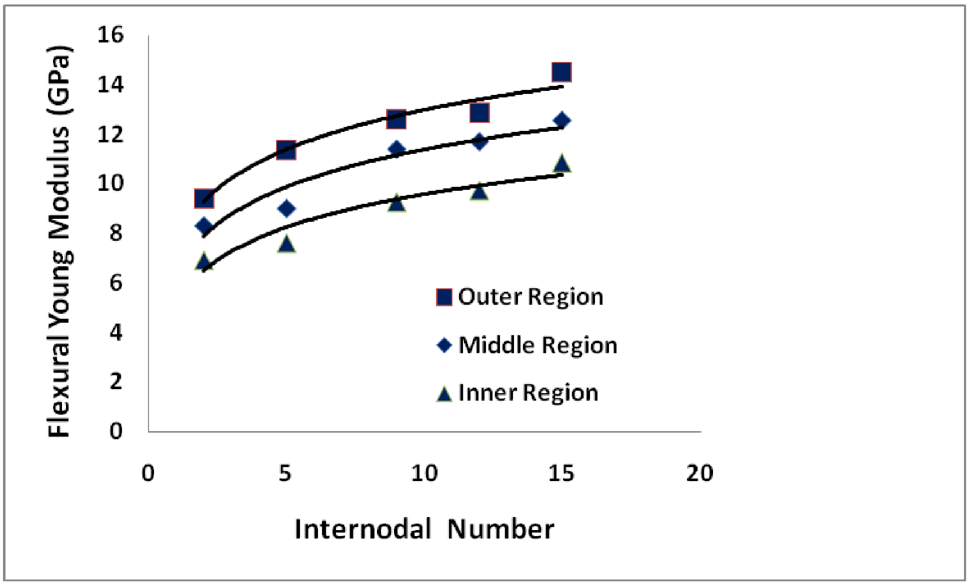

Fig.9C. Variation of flexural young modulus with internodal number.

RESULTS AND DISCUSSION

Fig. 5 shows that stress-strain curves for specimens are almost bi-linear up to ultimate load. The bi-linear curve implies that there is only one location where the change of slope occur called bifurcation point. The first change of slope location point in the slope is hypothesized to be due to matrix softening or cracking of laminae. First change of slope took place at about 45% of ultimate stress where transition of stress-strain curve from first linear to second linear behavior occurred at a strain level around 0.011-0.013 which corresponds to 110-125 MPa.(Fig.5). The stress-strain curves (Fig.5) 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 stress-strain 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. Value of failure stress and displacement at maximum load are much lower in case of nodal region than that of internodal 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 loads because of cushioning effect of matrix, but the ultimate stress reduced. Further, 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. 6A, 6B, 7A and 7B.Maximum tensile strength and modulus at the top of outer region for inter nodal specimens were observed as 324.1MPa and 16.6 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 138.4MPa 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 internodallaminae was 208.42MPa and 13.94 GPa respectively. Similarly, average failure strength and young`s modulus of outer regions inter nodal laminae of bamboo culms were 271.96MPa and 15.56 GPa respectively.

Similarly a typical stress-strain curve of lamina specimens under compressive loading is almost nonlinear up to ultimate load followed by a non linear segment along fiber direction (Fig. 8A). Above ultimate point, bamboo lamina appear slightly buckled. Compressive failure strength and young`s modulus of laminas increases with height and from inner to outer region due to increase in volume fraction of fibers as shown in Figs 8B and 8C. Tests were also conducted on specimens with nodes but there were two failure zones which were on either side of nodes of some samples. Thus test results with nodes are not reported. Average compressive failure strength and young`s modulus of outer regions laminae of bamboo culms were approx. 31.9MPa and 11.7 GPa respectively.

Fig. 9A shows a typical stress-strain curve of lamina specimens under three point bend tests which is also almost nonlinear up to ultimate load. During experimental investigation it was observed that above this load, matrix starts to fail and subsequently fibers at the middle region of the specimen because stress developed is high in middle region. The fracture starts at middle region and propagates slowly toward supports and the specimen breaks. Failure on the tension surface was due to fiber breakage or crack while the failure on the compression surface was due to local buckling. Buckling may be manifested as fiber micro buckling. About 75% of failure was on the tension side and the remainder failure was on the compression side. The maximum flexural strength and its modulus with the inter-nodal number increases with height since volume fraction of fibers increases with height as shown in Fig 9B and 9C respectively. For whole length of bamboo composite, average maximum flexural strength and modulus for samples from inter nodal was 121.58MPa and 10.27GPa respectively. Tests were also conducted on specimens with nodes but there were two failure zones which were on either side of nodes of some samples. Thus here test results with nodes are not reported. Further, average failure strength and young`s modulus of outer regions laminae of bamboo culms were app. 139MPa and 12.14 GPa respectively. Finally it was observed that some mechanical properties of laminas selected from outer regions is better than other regions due to availability of high volume fraction of fibers.

Failure modes of fractured specimens of laminas have been identified using a standard failure identification codes (three parts) used in ASTM standards. Mode of failure of fractured lamina specimens were compared with typical failure mode given in figures of ASTM standards manual and accordingly codes have been assigned. The summarized identification of failure modes under different loading conditions are presented in Table 2.When inter nodal laminae specimens were tested under tensile loading, the specimens failed by longitudinal splitting of fibers, starting at grips and edges and continued through the gage length as shown in Fig. 10A. 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. Due to this at nodes, transverse cracks were observed (Fig.10B). For all specimens, first matrix failure occurs followed by fiber failure with metallic sound. Fiber breaks when maximum strength is reached. These breaks in fibers cause damage in the form of de-bonding of bamboo fiber and micro cracking in the matrix i.e. lignin. . Fracture propagates spontaneously and the specimen breaks. Fractured specimens under compressive loading are shown in Fig. 11.

Compressive failure was mainly due to fiber buckling, and fiber misalignment**.** Fractured specimens under flexural loading are shown in Fig. 12. Flexural failure on the tension surface of specimens was due to fiber breakage while on the compression surface was due to buckling.

Figs. 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.13B).The SEM photographs (Fig.14) were taken for fractured surface of a specimens tested in compression where lateral surface of the fracture shows the source of the cracks and their subsequent propagation and enlargement. The SEM photographs (Fig.15) were taken for fractured surface of a specimens tested in flexure. Lateral view of fractured specimen under bending stress shows tension and compression in the upper and lower portions respectively. Fibers breaks due to tension and buckled due to compression.

Table 2

Mode of failures of laminas under different loading conditions

Loading Condition	**ASTM Standards/ Sections used for codes**	**Mode of failures identified in terms of codes (Figures)**
Tensile	D3039/11.9	DGM, GGT, MGM, MGT and XGM for intermodal (Fig.10A) and LGM and AGM for nodal Specimens (Fig.10B)
Compressive	D3410/11.10	TAT,MGM,AGM (Fig.11)
Flexural	D7264/11.7	CBB , TBT (Fig.12)

Fig.10A. Tensile failure mode of single laminas of intermodal.

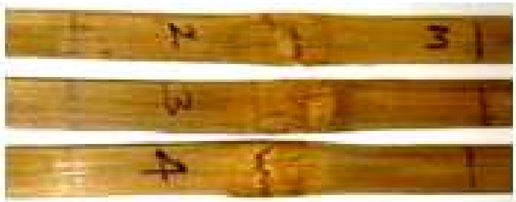

Fig.10B. Tensile failure mode of single laminas of nodal.

Fig.11. Fracture specimens under compressive loading.

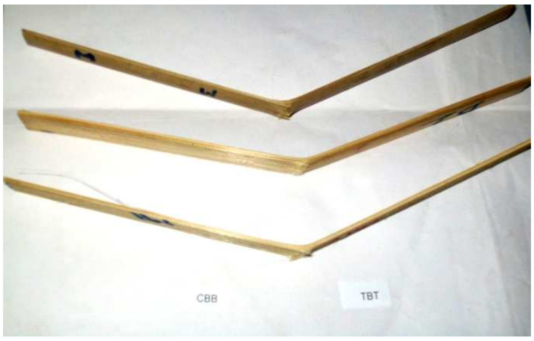

Fig.12. Fracture specimens under flexural loading.

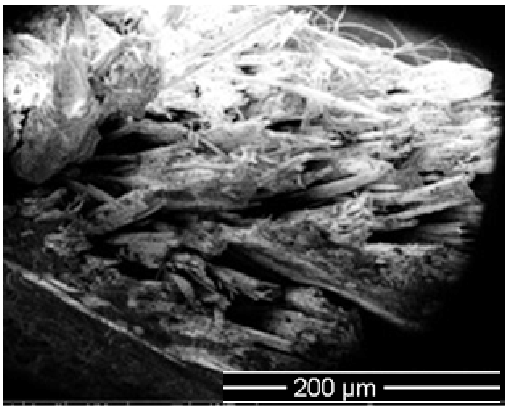

Fig. 13A.SEM photograph (x50) of fractured cross sectional surface under tensile loadingfor inter nodal lamina.

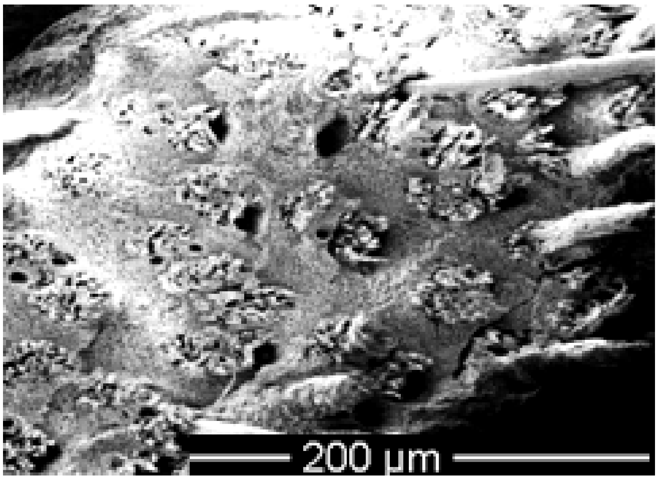

Fig. 13B.SEM photograph (x50) of fractured cross sectional surface under tensile loadingnodal lamina.

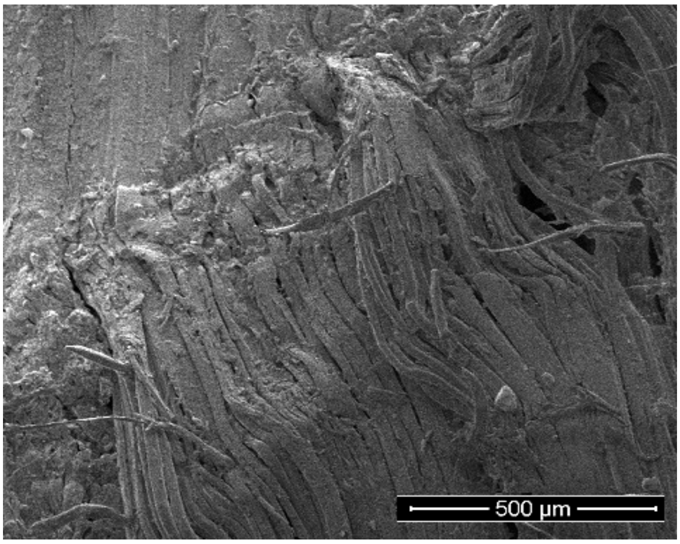

Fig.14. SEM photograph (x72) of fractured lateral surface under compressive loading.

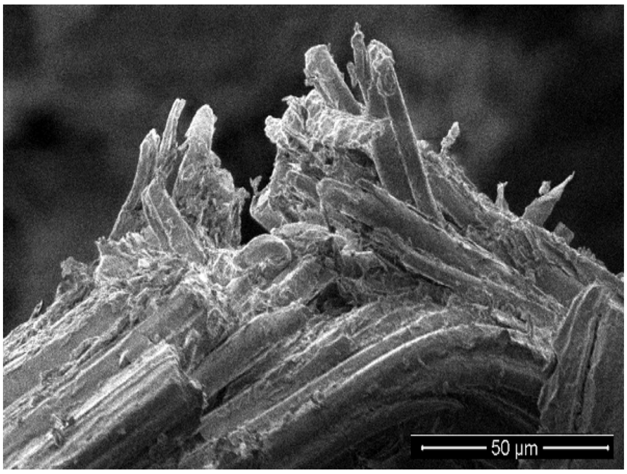

Fig.15. SEM photograph (x 500) of fractured lateral surface under flexural loading.

CONCLUSIONS

1. Mechanical properties such as tensile, compressive and flexural strength and their modulus of bamboo increases from inner to outer regions and with height of bamboo culms. The culms strength increases with height to compensate for the deterioration of rigidity due to the culms geometry.

2. Mechanical properties of laminas selected from outer regions are better than other regions due to availability of high volume fraction of fibers.

3. Bi-linear stress-strain response was observed in lamina under tensile loading. First change of slope took place at about 45% of ultimate stress. Nonlinear stress-strain response were observed in laminae under both compressive and flexural loading for which bifurcation points are difficult to find.

4. 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.

5. Longitudinal cracking is responsible for failure on single laminae. Mode of failure indicates that fibers presents in the laminae are brittle.

6. Investigations indicate that there are enough mechanical properties in bamboo lamina for preparing Engineered bamboo timber.

ACKNOWLEDGEMENTS

We are grateful to the Laboratory Incharge of Stress Analysis lab, Numericl Computation Lab and strength of material Lab of IIT Delhi and lab in charge, Material Testing Lab and central workshop , NSIT, New Delhi for assistance rendered in testing.

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FIGURE CAPTIONS

Fig. **1**. Bamboo culms and location of laminas on slats.

Fig.2. Sketch of lamina Specimens with tab.

Fig. 3. Sketch of lamina specimens for compressive testing.

Fig. 4. Sketch of lamina specimens for flexural testing.

Fig. 5. Typical stress - strain curve for intermodal and nodal specimen in tension.

Fig .6A. Variation of tensile failure stress with inter nodal number (three specimens at each internodal).

Fig .6B. Variation of Young modulus with Inter nodal Number (three specimens at each internodal).

Fig .7A. Variation of Tensile Failure Stress with Nodal Number (three specimens at each nodal).

Fig .7B. Variation of Tensile Young Modulus with Nodal Number (three specimens at each nodal).

Fig. 8A. A typical stress-strain curve for internodal specimens under compressive loading.

Fig. 8B. Variation of compressive failure stress with inter nodal number.

Fig. 8C. Variation of modulus with internodal number .

Fig.9A. A typical stress-strain curve for internodal specimens under flexural loading.

Fig.9B. Variation of flexural failure stress with inter nodal number.

Fig.9C. Variation of flexural young modulus with internodal number.

Fig.10A. Tensile failure mode of single laminas of intermodal.

Fig.10B. Tensile failure mode of single laminas of nodal.

Fig.11. Fracture specimens under compressive loading.

Fig.12. Fracture specimens under flexural loading.

Fig. 13A. SEM photograph (x50) of fractured cross sectional surface under tensile loadingfor inter nodal lamina.

Fig. 13B. SEM photograph (x50) of fractured cross sectional surface under tensile loadingnodal lamina.

Fig.14. SEM photograph (x72) of fractured lateral surface under compressive loading.

Fig.15. SEM photograph (x 500) of fractured lateral surface under flexural loading.