EFFECT OF ORIENTATION AND ARRANGEMENT OF BAMBOO STRIPS ON STRUCTURAL STRENGTH OF LAMINATED BAMBOO BEAM

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ABSTRACT

This study evaluates the effect of orientation and arrangement of bamboo strips on structural strength of laminated bamboo beams, the study is motivated by the anatomical features of bamboo internode and earlier studies that has shown that strength properties increase from inner to outer layer of the culm and so is the concentration of the cellulose fibers. Mature Bamboo was harvested, split, treated and dried for the study; tensile test was carried out on strips with nodes, strips with outer skin removed and strips with outer skin intact. Laminated bamboo beams were made in various variations; two orientations, strips facing each other and strips facing same direction in respect to inner and outer face of culm, beams with coinciding nodes at mi point and beams made with jointed strips. Bending and compression tests were performed on the specimens. The results showed that orientation of bamboo beams and direction of loading has an effect on flexural strength of laminated bamboo beams, beams loaded on the edge had the highest flexural strength than beams loaded on the face, beams with strips facing the same direction and loaded on the inner face had the highest Modulus of Elasticity for the face loaded beams, nodes had a reducing effect on longitudinal tensile strength but had reinforced effect increasing flexural strength of beams while loaded on the face and on the edges, although having staggered joints in strips reduced the flexural strength of beams, the achieved values were sufficient for common construction works compared to commonly used timber species.

KEYWORDS: *Orientation, Tensile Strength, Flexural Strength, Nodes, Modulus of Elasticity.*

I. INTRODUCTION

Despite Bamboo processing superior structural properties especially its remarkable tensile strength, it has not been embraced in the construction industry for structural purposes. This is mainly due to its hollow tube natural occurrence and hence the limitation to be used structurally in construction unless it is engineered to suite the form of commonly used materials. As hollow tube, bamboo is efficient in resisting bending forces as a whole, it has large ratio of moment of inertia to cross-sectional area [1]. However it is difficult, to create connections for this shape, and furthermore tubes cannot be used in specific applications where flat surfaces are required. Laminated bamboo Beams comes in handy to resolve these deficiencies in the natural shape of bamboo as it is formed in rectangular sections that are more suitable and easier to use in the common traditional structural applications.

Studies on the anatomy of bamboo internode cross-section have revealed that the strength properties change (increase) from inner to outer layer of the culm. [3], this is as a result of concentration of cellulose fibers on the outer layer than on the inner layer that has less of the fibers and more of lignin (see figure 1). This means that the orientation of the bamboo strips and direction of loading has an effect on structural performance of laminated bamboo beams.

This study aims to evaluate the extent to which the orientation of bamboo strips in laminated bamboo beams, arrangement of the strips and direction of loading affects the structural strength and performance of laminated bamboo beams.

II. MATERIALS AND METHODS

2.1 Materials

2.1.1 Bamboo

Bamboo was the main raw material used in this study; ***Yushania alpina*** species was used; age and size were the most important factors considered. The bamboo harvested from Kamae, Kenya was three and half years old and the culms were selected from diameter greater than 80mm and wall thickness greater than or equal to 10mm in the lower section of the culm. Erect and straight culms were selected while withered, deformed or mildewed culms were rejected.

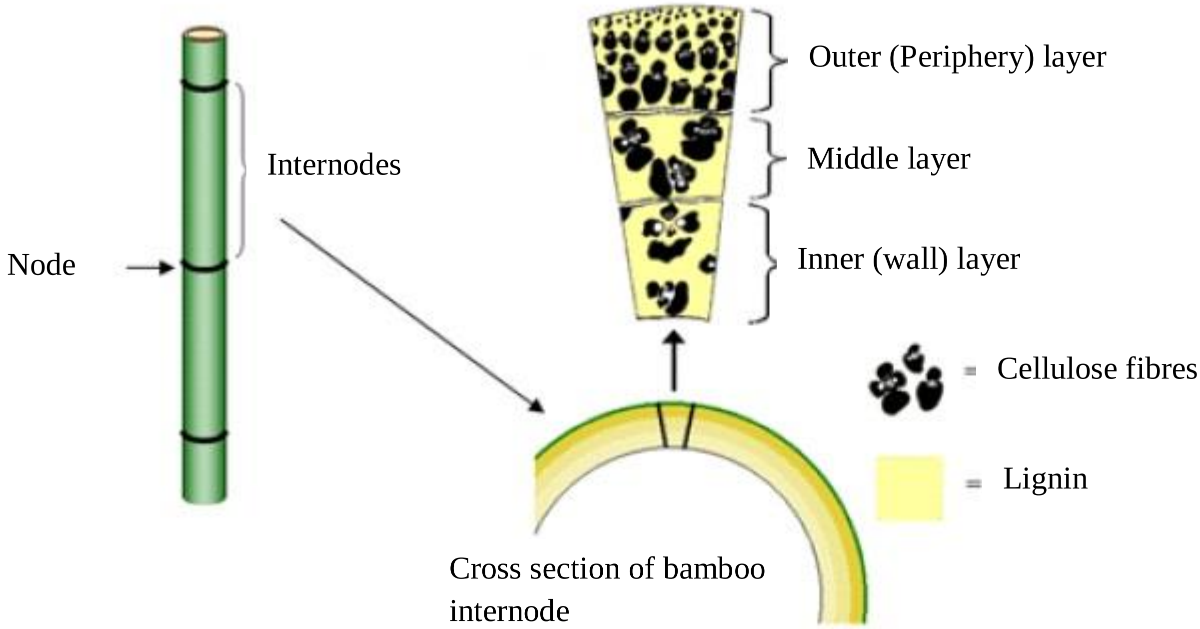

Figure 1: Anatomical Features of Bamboo Internode

2.1.2 Adhesive

High strength Polyvinyl Acetate Adhesive was used in this study, the adhesive is the most superior in the Kenyan market for structural and furniture works.

2.2 Material Preparation

The Study was conducted at Kenya Forestry Research Institute (KEFRI) using advanced machinery installed in the year 2012 as part of Bamcraft project at KEFRI Industrial Bamboo Processing & Training Centre at Karura, the latest state-of –art training center of bamboo applications in Eastern Africa

2.2.1 Cross Cutting

To obtain shorter and workable pieces, the culms were cut using the cross cutting machine to lengths of 2m to suite the dimensional requirements of the pressing machine that takes a minimum length of board of 1m and a maximum of 2m.

2.2.2 Splitting

Splitting was the first stage in the process of converting round bamboo poles into flat strips, the splitting machine with parallel rotary blades was used for this purpose. The hollow poles were longitudinally split into segments of 22mm.

2.2.3 Bamboo Strip 2 sides removal

The Bamboo strips were flattened and pre-shaped before being boiled and dried; shaping was done using the 2-side removal machine. Shaping involved removal of the shiny and silky outer skin and the inner knot of the strips, care was taken in removing the outer side of the strips (i.e. the culm epidermis) since it is the strongest part of the bamboo culm and hence only shaping and removal of the silky layer was done.

2.2.4 Preservation

The formed strips were disinfected and bleached, this was important for protecting bamboo materials and ensuring the quality of products. The strips were boiled in a tank for 3 hours to bleach them and protect them against pests in a single process using the following chemicals:-

Table 1: Preservation and Treatment Chemicals

Chemical Composition for preservation and Bleaching of Bamboo Strips		
Chemical Agent	**% in Solution**	**Quantity per 1000 L of Water**
Hydrogen peroxide (80%)	0.5	5 L
Borax oxide	0.8	8 Kg
Boric acid	0.2	2 Kg

Bleaching was achieved by boiling the strips for three hours in the solution containing hydrogen peroxide. Hydrogen peroxide is a strong oxidizer in both acid and alkaline media, and also functions as a reducing agent that extracts starch, protein and other nutrients thereby bleaching the surface of bamboo material.

The preservative agent was in the mixture of boric acid and borax oxide which resulted in the formation of disodium octaborate. Boron salts are dissolved in water and are effective against borers, termites and fungi. After treatment, the water evaporated leaving the salts inside the bamboo.

2.2.5 Drying

The bleached and treated bamboo strips were dried in air for 3 months while monitoring the moisture content until moisture content of below 12% was achieved.

2.2.6 4 Side Planning

Size of the strips and moisture content were most important in this stage to achieve stable laminated beams, the moisture content of the bamboo strips was rechecked to confirm it was below 12%. In order to achieve a stable laminated beam the strips had to be rectangular and flat on each side and hence ensure proper bonding of the strips on all the four sides.

A 4 side Moulding Machine was used to shape the strips into fixed width and thickness to ensure that they bonded into a solid beam after laminating; strips of half widths were also prepared for staggering the straight joints during lamination.

The Strips were marked on the outer side with red ink immediately after planning to ensure identification of inner and outer faces of the strips for the purpose of varying orientation during lamination.

2.2.7 Assembling and Pressing

After four sides planning, the bamboo strips were sorted in kept in order of the markings showing inner face/outer face, the bamboo strips were laminated horizontally while varying their orientation, a half width strip was introduced in each layer on alternating sides to break vertical straight joints on adjacent layers. The laminated bamboo panels were cold pressed at 200 tons top pressure and 100 tons side pressure and left overnight to bond at a room temperature of 22°C.

2.3 Test Specimens

2.3.1 Tensile Test Specimens

For Tensile test the specimens were prepared in accordance to BS 373:1957. Samples were prepared in three categories:-

i. Samples with node at the center.
ii. Samples with no nodes but with outer layer removed.
iii. Samples with no nodes and with outer layer.

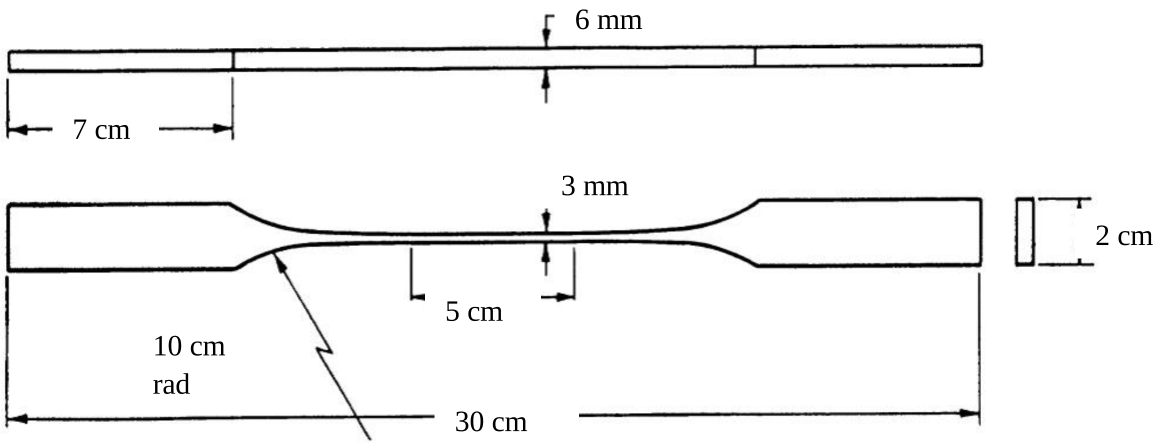

Figure 2: Tensile Test Specimen

2.3.2 Orientation 1

For orientation 1 the strips were laminated with inner sides facing each other and hence for every two layers the outer face of the bamboo culm formed the outer surfaces of the laminate.

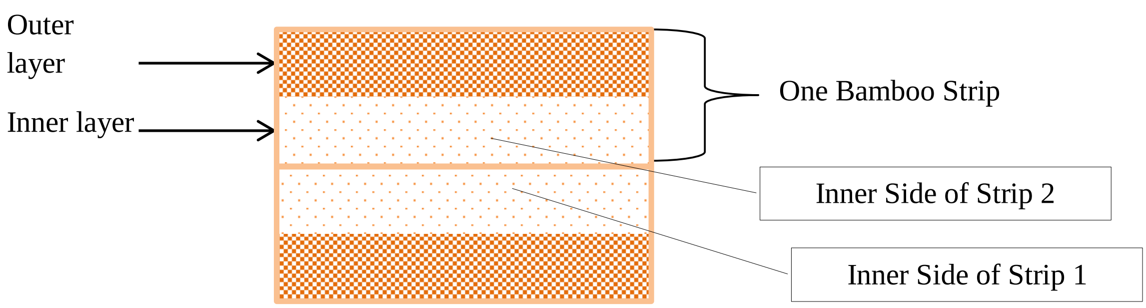

Figure 2: Orientation 1 – Bamboo Strips inner face glued together

2.3.3 Orientation 2

For Orientation 2 the strips were laminated facing the same side, the inner face of one layer glued to outer face of the adjacent layer.

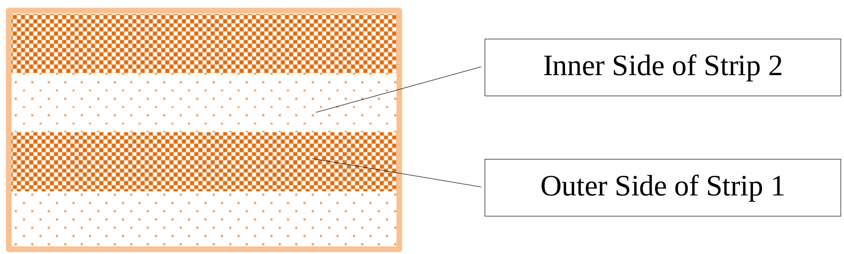

Figure 3: Orientation 2 – Bamboo Strips facing the same side

2.3.4 Coinciding Nodes at beam Mid-point

To establish the effect of coinciding nodes in laminated bamboo beams, specimens were made with coinciding nodes at the mid point of the beams.

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Figure 4: Bamboo Strips arranged with the nodes at the mid-point

2.3.5 Jointed Strips beam

To investigate the performance of jointed beams in cases of laminating longer beams than the available material length, specimens were made from strips pieces with staggered joints.

Figure 5: Bamboo Strips pieces with staggered joints

2.4 Test Set Up

2.4.1 Tensile Test

Tensile Test was done in accordance to BS 373:1957 using the Universal Testing Machine by applying the load parallel to the grain at a constant speed of 0.05in/min.

Figure 6: Tensile Test Set up

2.4.2 Static Bending Test

Static bending test for small clear specimens was carried out in accordance to BS 373:1957 using the central loading method. The Standard specimens of 2cm by 2cm by 30cm were placed on the universal testing machine with the distance between the points of support being 28cm; a dial gauge was fixed to measure deflection at mid length and loading was done at a constant speed of 0.26 in/min.

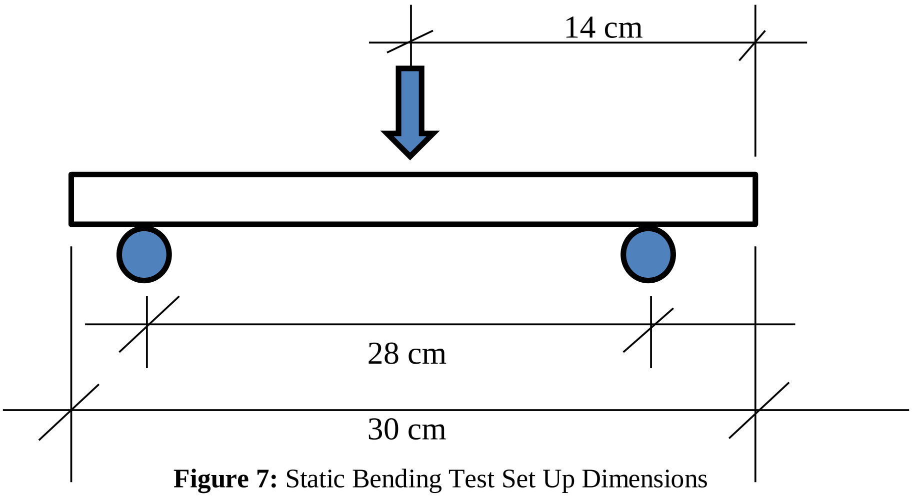

Figure 7: Static Bending Test Set Up Dimensions

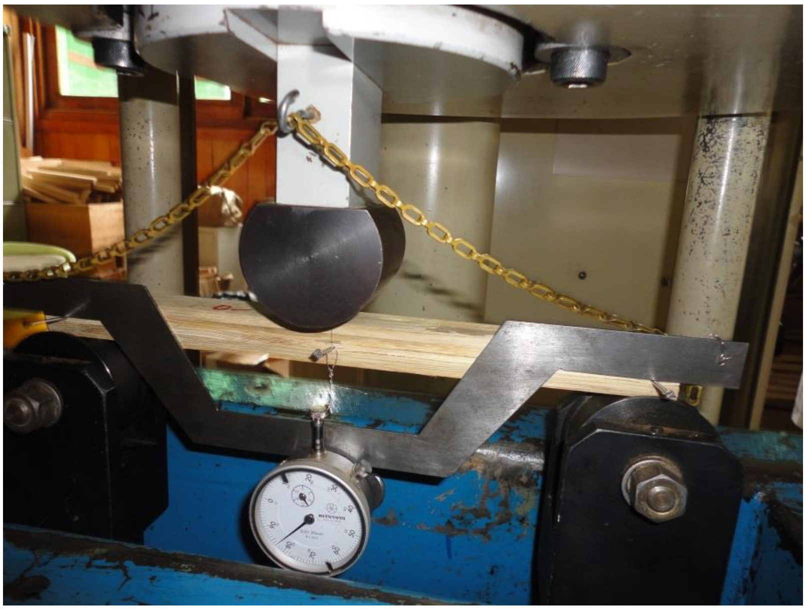

Figure 8: Static Bending Set Up, Dial Gauge measures deflection

Loading was done on two sides on the face and the edges for all specimens but for Orientation 2 loading was done on three sides, upper face, lower face and the edge

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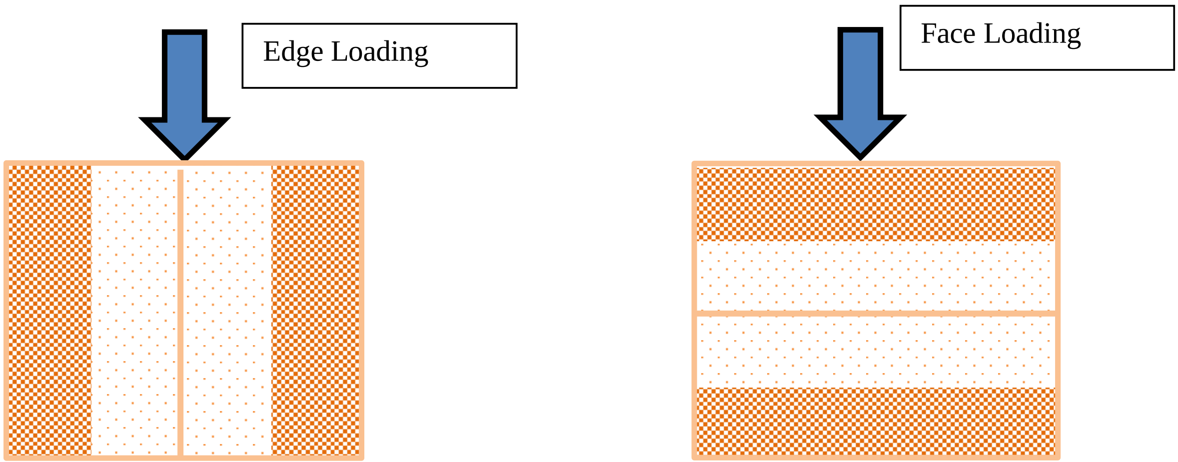

Figure 9: Direction of Loading for orientation 1

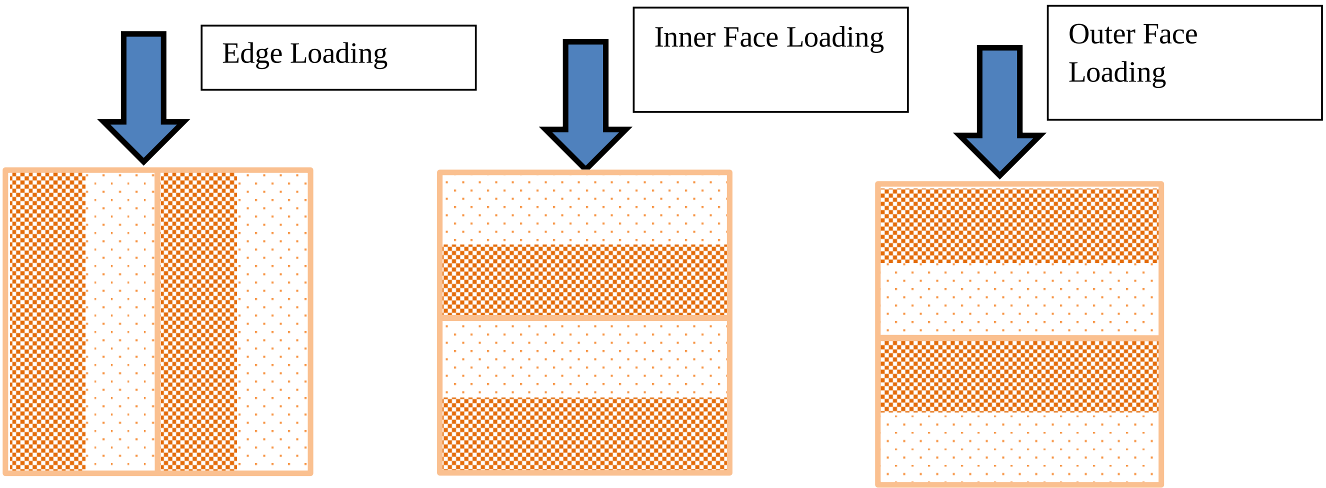

Figure 10: Direction of Loading for orientation 2

2.4.3 Compression Parallel to grain

Compression parallel to grain was carried out in accordance to BS 373:1957 on the Standard specimens of 2cm by 2cm by 6cm, loading was done at constant speed of 0.025 in/min.

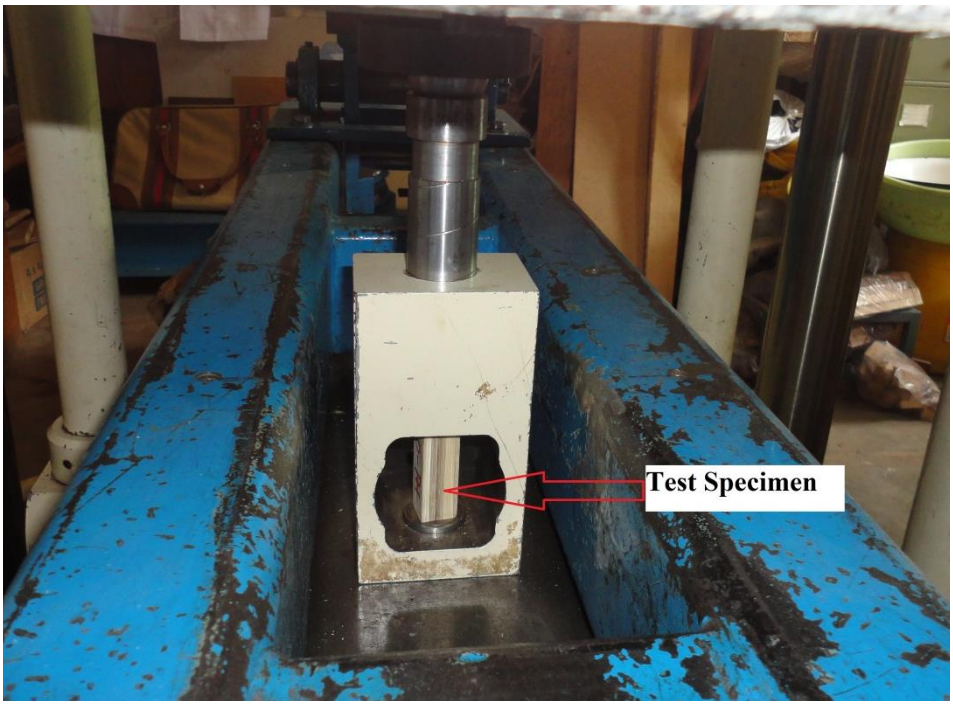

Figure 11: Compression Parallel to grain test Set Up

III. RESULTS AND DISCUSSION

3.1 Tensile Test

Specimens for each category were tested and the tensile stress at maximum load was calculated in accordance to BS 373:1957 and the mean tensile stress was tabulated in Table 2.

Table 2: Tensile Stress Results

Part of Bamboo Strip	Tension Parallel to Grain (N/mm^2)
Bamboo Strip With Node at Centre	151.67
Bamboo Strip with outer surface removed	253.06
Bamboo Strip with outer surface	363.89

Bamboo Strips with nodes at the center had the least tensile stress of 151.67 N/mm^2 compared to the others. Figure 12 shows the mode of failure was by separation of fibers, showing that the node is a point of fiber discontinuity, the fibers contribute to the high tensile strength of bamboo and hence the nodes forms a point of weakness in tension.

Figure 12: Tensile failure of a bamboo strip with node at the center

Strips with the outer surface removed failed by splitting and shearing diagonally as seen in Figure 13, the strips were much stronger than the strips with node at the center achieving a mean tensile stress of 253.06 151.67 N/mm^2 .

Figure 13: Tensile failure of a bamboo strip with outer skin removed

Bamboo strips with the outer skin intact and no nodes had the highest tensile stress of 363.89 N/mm^2 and failed by shearing parallel to the grains as seen in Figure 14. This confirmed that the outer skin of bamboo culm is the strongest in tension [3].

Figure 14: Tensile failure of a bamboo strip with outer skin intact and no node.

3.2 Static Bending Test

3.2.1 Bending for Orientation 1 and 2

3-Point flexural test was carried out and average of at least five specimens on each case reported, results for load and deflection on bending test for the various orientations and loading directions were plotted in Figure 15. A summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 3.

From the results, the maximum flexural strength was obtained for orientation 1 with a MOR of 103.5 N/mm^2 loaded on the edge, Orientation 1 also had the highest flexural strength while loaded on the face compared to orientation 2 by 2.5%, in this orientation the bamboo strips are arranged facing each other and therefore each pair of strips forms a beam with the strong outer layers on the extreme fibers which experience tension on the lower side and compression on the upper side while bending. Also when loaded on the edge, orientation 1 is more stable and achieves a little more strength than orientation 2.

While loaded on the face, orientation 2 had a major difference on flexural strength depending of the face loaded; loading on the inner face gave an increase in strength by 11% and a higher value of mid span deflection at maximum load as compared to loading on the outer face. When the beam in orientation 2 is loaded on the inner face, all the outer face of the strips are much closer to bottom axis of the beam and also the extreme fiber on the bottom is the outer face of the bamboo strip which is stronger in tension, in this case the beams performed better as compared to loading on the outer face which exposes the weaker inner face to tension on the bottom of the beam and also the arrangement places the outer stronger face of other strips further away from the bottom tension zone of the beams while bending.

In both orientations, it was noted that loading the beams on the edge gave higher values of Modulus of Rupture and Modulus of Elasticity, the beams are much stiffer while loaded on the edge and hence the increased load carrying capacity. However the balanced arrangement of orientation 1 gives it an advantage of less mid span deflection at the maximum load and slightly higher flexural strength as compared to orientation 2.

Even though orientation 1 has higher strength while loaded on the face as compared to orientation 2, orientation 2 has a higher modulus of elasticity when loaded on the inner face than orientation 1.

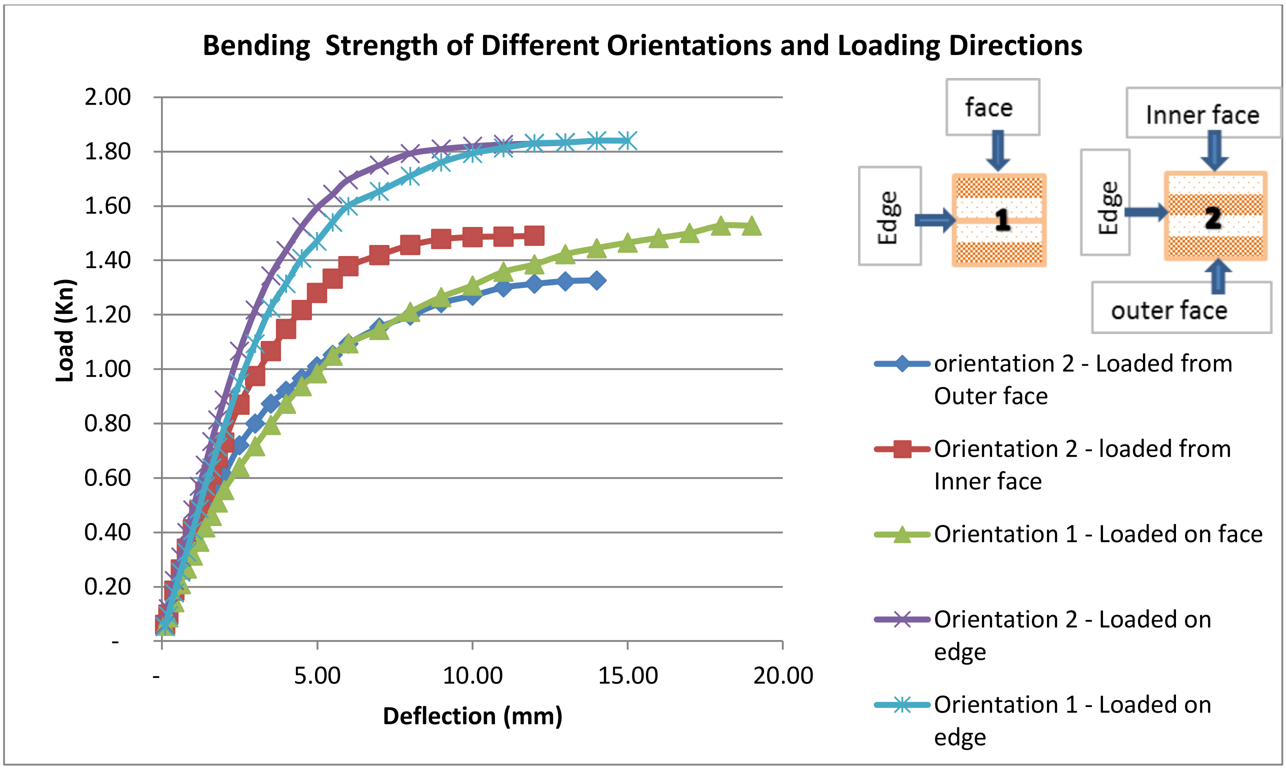

Figure 15: Load - Deflection Curves for orientations 1and 2 and different loading directions

Table 3: Summary of Bending Test Result for Orientation 1 and 2 beams

Beam	Loading Surface	Mid Span Deflection at Maximum Load (mm)	Modulus of Elasticity (N/mm2)	Modulus of Rupture (N/mm^2)
Orientation 1	face	*2.00*	12,656.25	85.92
Orientation 1	edge	*2.80*	15,066.96	103.50
Orientation 2	face - Outer	*2.00*	12,656.25	74.63
Orientation 2	face - Inner	*2.80*	13,560.27	83.81
Orientation 2	edge	*3.00*	16,875.00	103.13

3.2.2 Bending for Jointed beams and Central Nodes Beams

3-Point flexural test was carried out and average of at least five specimens on each case reported, results for load and deflection on bending test for the various orientations and loading directions were plotted in Figure 16 and Figure 18. A summary of loading surface, mid span deflection at maximum load, Modulus of Elasticity and Modulus of Rupture are given in Table 4.

The beams with coinciding nodes at the center performed better and had slightly higher values of Modulus of Elasticity and Modulus of Rupture compared to other beams in Table 3, this is despite the fact that strips with nodes at the center had the least tensile strength (Table 2) and the failure was at the nodes by separation of grains, a study done by Shao et al [3] indicated that in both planed and non-planed samples, the node did not have a reduced effect on bending strength, longitudinal shearing strength and compressive strength. Instead, the node had a reinforced effect of different degrees. However, the node reduced the longitudinal tensile strength. Occurrence of coinciding nodes in laminated bamboo beams is however not a possible case considering bamboo being a natural material that varies in internode length and very many strips are used in lamination process.

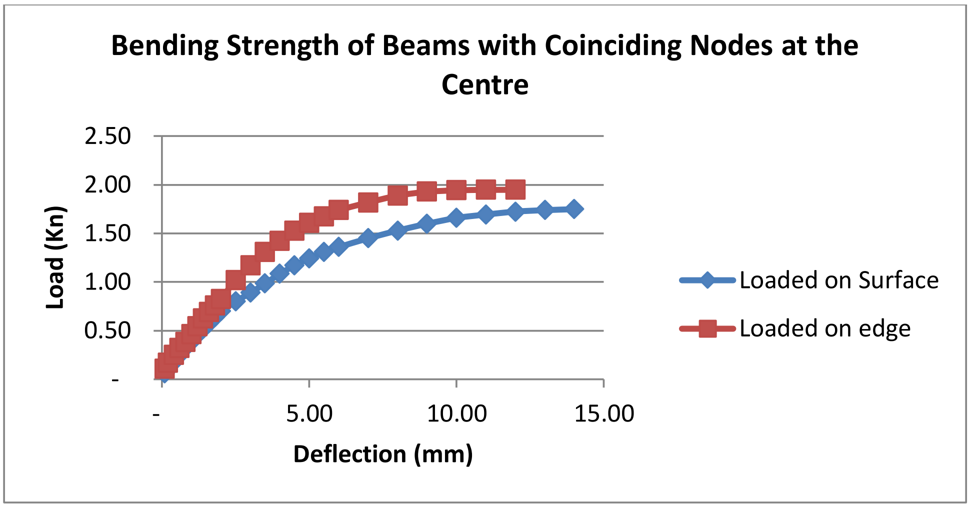

Figure 16: Load - Deflection Curves for Central nodes beams and different loading directions

The beams with jointed strips gave much lower flexural strength than other beams, however the figures obtained of Modulus of Rupture of 68.34 N/mm^2 compares well with commonly used timber like cypress timber [4] and can therefore be used in construction creating a possibility of using shorter strips to engineer a longer beam as required.

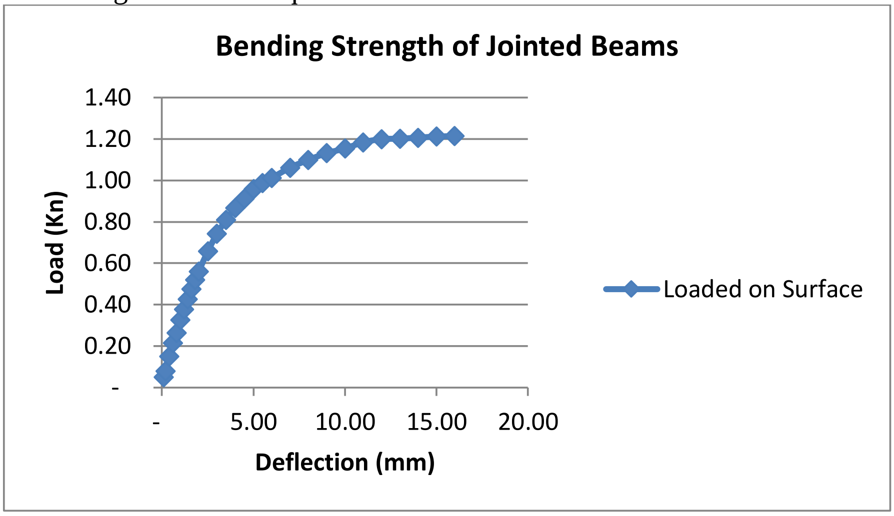

Figure 17: Load - Deflection Curves for Jointed beams

Table 4: Summary of Bending Test Result for Jointed and Central node beams

Beam	Loading Surface	Mid Span Deflection at Maximum Load (mm)	Modulus of Elasticity (N/mm2)	Modulus of Rupture (N/mm^2)
Central Node	face	*2.00*	14,765.63	98.44
Central Node	edge	*3.50*	15,669.64	109.69
Jointed Beam	face	*2.50*	11,812.50	68.34

3.2.3 Compression Strength Parallel to Grain for Orientation 1 and 2 beams

Compression parallel to grain was carried out in not less than 8 specimens for each case and an average of the maximum load presented in figure 19. Although orientation 2 had a higher maximum load by 7%, compression strength did not seem to depend on orientation of bamboo strips, bamboo outer skin is strong in tension and hence it's positioning in compression does not affect the compression strength.

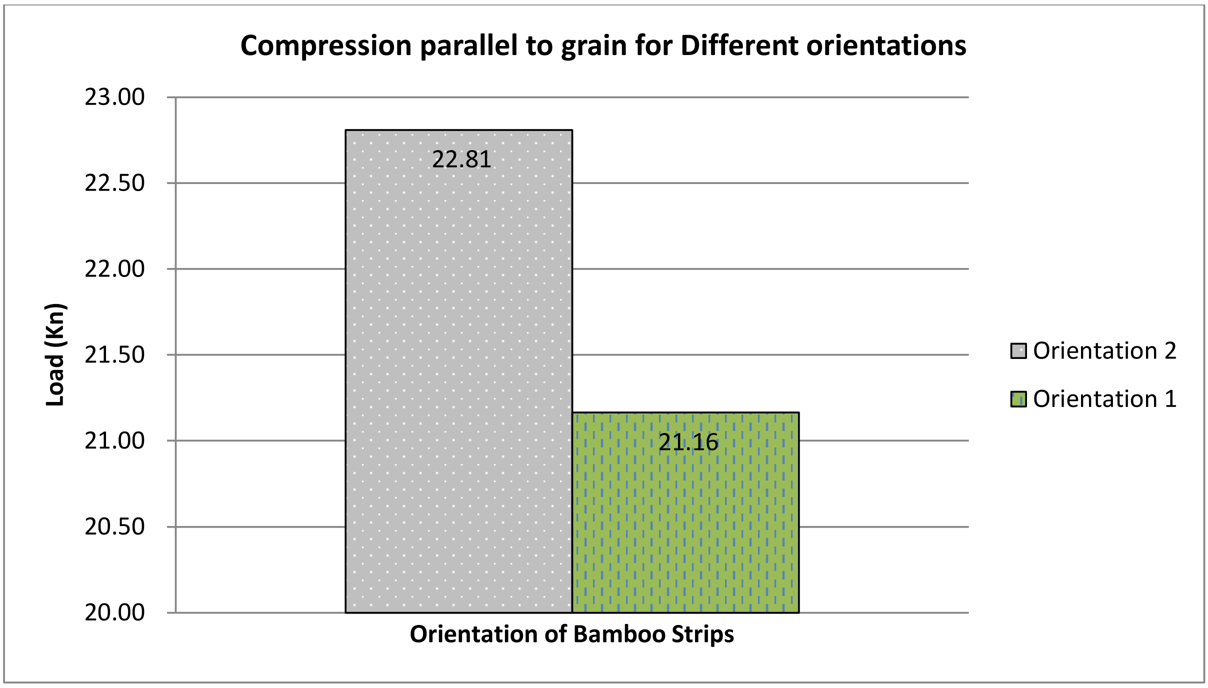

Figure 18: Compression Parallel to grain for different orientations 1 and 2.

IV. CONCLUSIONS

The following conclusions are made from the study:

(a) Orientation of bamboo strips in laminated bamboo beams and direction of loading affects the flexural strength of the beams; however the orientation has minimum effect on compression strength parallel to grain.

(b) Loading on the edge gives the highest flexural strength in either orientation of bamboo strips in laminated bamboo beams.

(c) When loading on the face, arranging strips facing the same direction and loading on the inner face gives the highest Modulus of Elasticity than arranging the strips facing each other and loading on the face.

(d) Nodes reduce the longitudinal tensile strength of bamboo strip, however presence of coinciding nodes at the midpoint of beam does not have a reduced effect on bending strength but instead the nodes has a reinforced effect increasing the flexural strength in both loading cases than other beams.

(e) Introduction of jointed strips in laminated bamboo beams reduces the flexural strength but the strength achieved is sufficient for normal construction works compared to commonly used timber species. Joining of staggered shorter strips can be adopted in engineering of longer laminated bamboo beams than available material.

(f) The outer skin of bamboo strip contributes the most in tensile strength, removal of the outer skin reduces the tensile strength by about 30%, and the outer skin should therefore have minimum disturbance in the making of laminated bamboo beams.

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