Mechanical Properties, Column Buckling Behaviour And Concrete Beam And Slab Reinforcement Behavior Of Bamboo

Mwero J. N

Department of Civil and Construction Engineering, University of Nairobi

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Abstract- The study focused on the use of Bamboo as reinforcement for reinforced concrete slab and beam samples. A comparison was also made on the use of bamboo as reinforcement against steel reinforcement in concrete. Both beams and slabs designed for bamboo tensile reinforcement equivalent to steel reinforcements resulted in significantly lower failure loads at 63% and 34% respectively of the steel beam and slab equivalents.

The mechanical and column buckling behavior in bamboo culms was also studied. The type of bamboo used here was *Bambusa vulgaris*(yellow bamboo). An average moisture content of 62.1% and 10% were observed for the green and dry bamboo samples used in the study respectively

Moisture content was found to have a significant influence in the physical and mechanical properties of bamboo with the strength and stiffness of bamboo being reduced with increase in moisture content.

For the column investigations the second moment of area against critical shear of dry bamboo were plotted for both theoretical and actual values measured in the laboratory. Variation factors of 1.50 and 0.48 were observed for green and dry bamboo samples respectively. In the case of second moment of area against critical load the variation numbers were 1.93 and 1.61 for dry and green bamboo respectively. The variation from theoretical values were slightly lower in both cases for green bamboo, this could be due to the effect of moisture content which lowers strength parameters of bamboo.

I. INTRODUCTION

Bamboo is a group of perennialevergreens in the true grass family Poaceae, subfamily Bambusoideae, tribe Bambuseae. Giant bamboos are the largest members of the grass family. There are more than 70 genera divided into about 1,450 species in the world (Gratani et al. 2008).

Bamboo is found in diverse climates, from cold mountains to hot tropical regions. Most of the bamboo resources in Kenya are found within government forests and in trust lands and farmlands, which were once within the Government forests but have since been degazetted. Another small proportion is found domesticated by farmers with *Bambusa vulgaris* as the dominant species (Ongugo et al, 2000). Some of the districts where reasonable amounts of bamboo are found in Kenya are; Mt. Elgon, West Pokot, Nakuru, Trans-Nzoia, Kiambu, Nyeri, Malindi/Kilifi, Nyandarua, Keiyo-Marakwet, Uasin Gishu, Narok, and Kakamega (Warinwa et al, 2016)

Bamboo's feasibility as reinforcement in precast concrete elements was investigated by the U.S Army Engineer Waterways Experiment Station in 1964(Brink F. E and Rush P. J, 1966). Bamboo is unique in that it is strong both in tension and compression. While its tensile strength remains the same, its compressive strength increases as it gets older. Its strength is in its culm (Y. Xiao et al 2007)

The bamboo culm, in general, is a cylindrical shell, divided by transversal diaphragms at the nodes. Bamboo is an orthotropic material with high strength along and low strength transversal to its fibres. The structure of bamboo is a composite material, consisting of long and aligned cellulose fibres immersed in a ligneous matrix. A close-up of a cross-section of a bamboo culm shows that the distribution of the fibres is variable along its thickness. This presents a functionally graded material, produced according to the state of the stress distribution in its natural environment. The fibres are concentrated more as they approximate the outer skin, in a way that the culm could resist wind forces, to which it is constantly subjected during its life as shown in Figure 1 (Y. Xiao et al 2007).

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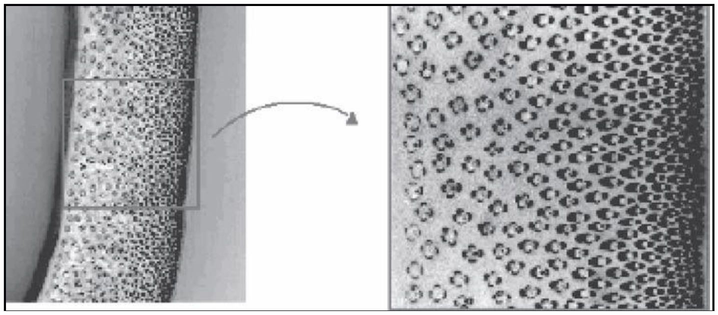

Figure 1: Concentration of fibres in bamboo culm (Y. Xiao et al 2007)

Culm, the primary product which is majorly used in construction, is the structure of bamboo that holds it up. The culm comprises of approximately 40% cellulose fibers, 10% vessels and 50% parenchyma tissue. The fibers which provide the culm's strength are grouped around vessels for water and sap transport in vascular bundles.

Figure 2: longitudinal and transverse sections of bamboo culm

2.3.5 Buckling

A perfectly straight column that is loaded with a normal stress at its ends deforms linearly until a certain load level, Pcr (critical load), where the structure cannot hold its initial straight line resulting in a transverse deflection. Buckling load for a slender column pinned at both ends;

Pinned at both ends $P_{cr} = \frac{\Pi^2 EI}{(LK)^2}$ (1)

Where, $P_{cr}$the Euler critical buckling load

E, the modulus of elasticity

I, the least moment of inertial of the column cross section ($I = \frac{\Pi(D^4-d^4)}{64}$ mm^4) (2)

L, the height of the column

K, the effective length factor (=1.0 for column pinned both ends)

$A = \frac{\Pi(D^2-d^2)}{4}$ mm^2 (3)

E_d = 17600 N/mm^2 for $MC < 20\%$

For moisture content, i.e. $MC > 20\%$ the modulus is modified for wetness by multiplying with a wetness factor K_2 (Timber design manual, 2006)

For a Value of K_2 = 0.8

E_g= 14080 N/mm^2

Critical stress $\tau_{cr} = \frac{P_{cr}}{A} = \frac{\Pi^2 EI}{A(L)^2}$ (4)

II. Materials and Methods

Reinforced Concrete Beams and Slabs

Pozzolana Portland cement 32.5N to (BS EN 197 Part 1) was used in casting all the beams and slabs. Clean natural river sand was used as fine aggregates, and natural crushed stone from local suppliers were used in preparation of the concrete. Concrete class 25 was designed to BS 5328: Part 2: 1997 and used in preparation of beam and slab samples Mature, well seasoned bamboo (*Bambusa Vulgaris*) showing pronounced yellow colour from University of Nairobi, Chiromo Campus was used. The whole bamboo culms were split into approximately 25mm to 35mm sizes. Small samples of the bamboo were taken for moisture content testing. Tensile strength test was carried out on the bamboo specimen to BS EN 4449:1997.

Beams and slabs were designed to BS8110-1:1997 to resist a maximum load of 50 kN using conventional square twisted main steel reinforcement. The tensile reinforcement was then replaced with equivalent bamboo reinforcement using relative tensile strength of bamboo to that of steel steel.

Beams were constructed with uniform dimensions of 300 x 150 x 1500 mm. Mild steel bars (R8) bars at 250mm spacing were used to offer shear resistance as shown in the Figure 3A. These beams were demolded after 24 hours and cured under wet rugs for a further 27 days prior to testing. The reinforced concrete beams were then subjected to three point loading to failure Figure 3B. Maximum load, deflection and crack patterns were noted

Figure 3A: Beam reinforcement arrangement

Figure 3B Three point beam loading arrangement

Concrete slabs were constructed of uniform dimensions of 500 x 500 x 100 mm with bamboo splits reinforcement as shown in the Figure 4A. The beams were demolded after 24 hours and cured further for 27 days covered by wet rugs before testing. These slabs were then loaded to failure using a load cell setup three point line loading (Figure 4 B). Maximum load, deflection and failure modes were also observed.

Figure 4: (A) Bamboo slab reinforcemen; **(B)** Bamboo slab line loading arrangement

Buckling

Bamboo specimens of length 1500mm and varying diameters were loaded using a load cell and hydraulic jack setup with pinned end supports. Longitudinal deformations were taken using an LVDT. Using the laboratory determined critical buckling load Pcr, the sample section property I, and the sample length L, the samples' modulus of elasticity E was determined.

The theoretical buckling of each specimen was calculated using Equation (1), with K = 1.0 and K = 0.8 for dry and green samples respectively, giving E_d = 17600 N/mm² for dry and E_g= 14080 N/mm² for green bamboo samples. The critical stress was calculated using Equation (4)

Figure 5: (A) Dry bamboo sample under compression testing; (B) Failed bamboo showing split of the stem following buckling

III. Results and Discussion

Bamboo

Moisture Content

The moisture content for the green bamboo was determined at 50.5% and dry bamboo at 22.7%

Beam and Slab Strength

The average ultimate measured loads for the beams and slabs was 31.5 kN and 17 kN respectively, these being 63% and 34% of the targeted design loads for the beam and slab respectively.

The main cause of this difference in strength was thought to have been caused by several reasons including loss of bond occasioned by the smoother bamboo reinforcement surface and a possible shrinkage of the bamboo reinforcement due to moisture loss during curing of the samples

The failure modes for the beams (Figure 6 A) was consistent with the three point load the beams were subjected to, this was expected as the beams were designed to be weakest in bending. Similarly, failure modes for the sabs (Figure 6 B) were consistent with the three-point line loading that the slab elements were subjected to. A closer inspection showed breaking of the bamboo reinforcement around the area of the element cracks suggesting at least partially failure of the reinforced concrete elements due to tensile failure of the bamboo reinforcement. It is also possible that some slip of the bamboo reinforcement might have occurred though this was not confirmed

Figure 6: (A) Beam failure mode and, **(B)** Slab failure mode

Bamboo Column

Second moment of area and shear stress of dry bamboo

Table 1: Second moment of area and shear stress of dry bamboo

L Mm	D mm	D mm	D-d Mm	A mm^2	I mm^4	τ (theory)	τ(empirical)	E N/mm^2	% Moisture
1500	52	40	12	113.1	233274.6	159.26	300.6	33218.62	9.2
1500	44	33	11	95.05	125786.8	102.20	178.86	30802.37	10.79
1500	35	25	10	78.55	54494.06	53.57	203.69	66917.69	11.32
1500	32	24	8	50.27	35190.40	54.06	79.56	25906.33	12.31
1500	24	17	7	38.50	12187.77	24.45	64.95	46750.47	11.56
1500	20	15	5	19.64	5369.63	21.12	76.38	63667.4	9.7
1500	15	10	5	19.64	1994.43	7.84	50.92	114274.80	10.23

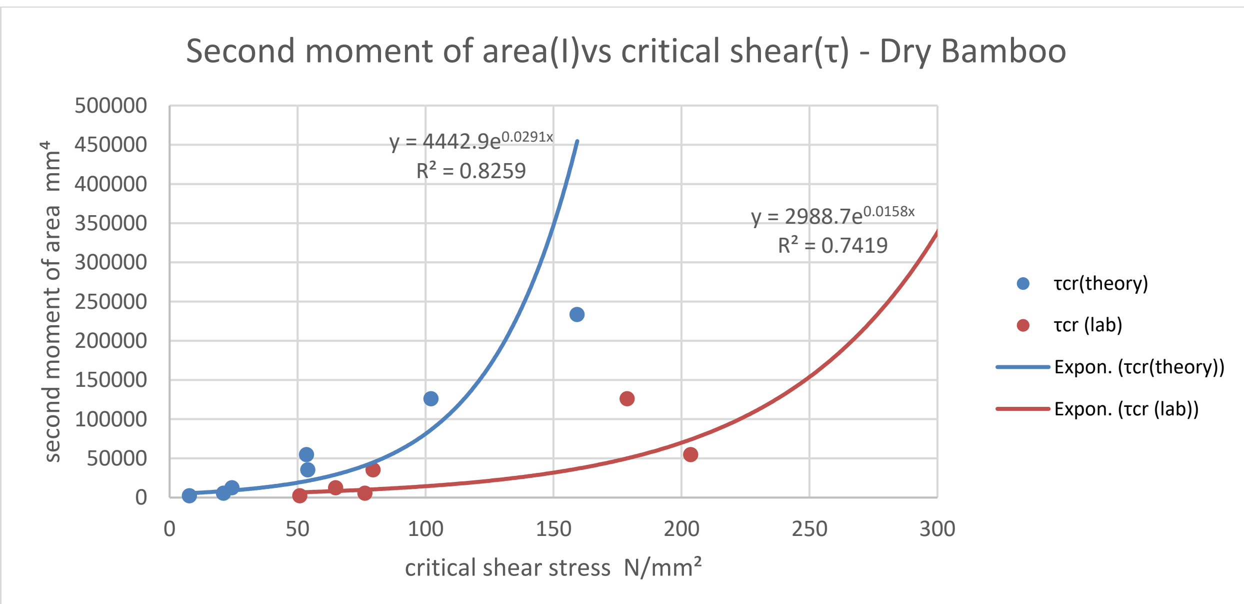

Figure 7: Second moment of area VS shear stress for Dry Bamboo

From Figure 7, as the second moment of area increases there's an increase in shear strength of the bamboo. The samples had an average moisture content of 10.73%. This moisture content of the culms was at equilibrium point.

The curve is steeper in the theoretical shear curve than that of the laboratory, this may be due to experimental errors and other non-factored conditions during the experiment. The theoretical curve had a percentage accuracy of 82.59% from the equation R^2 =0.8259, while that of the lab had an accuracy of 74.19 % from the equation R^2= 0.7419. A semi-empirical relation of the two curves can be determined such that, a factor when applied to the theoretical curve can map the curve to the empirical curve.

$$\frac{4442.9\, e^{0.0291x}}{2988.7 e^{0.0158x}} = 1.506$$

Hence when theoretical curve is factored by 1.506 it maps the curve to the empirical curve.

Second moment of area and shear stress of green bamboo

Table 2: Second moment of area and shear stress of green bamboo

L Mm	D Mm	D mm	D-d mm	A mm²	I mm⁴	T (theory)	T (empirical)	E N/mm²	% Moisture
1500	69	52	17	1615.74	753859.3	28.82	18.57	9069.87	64.8
1500	61	45	16	1332.20	478429.20	62.22	15.76	10003.96	62.22
1500	46	27	19	1089.50	193724.70	62.72	10.09	12941.30	62.72
1500	44	23	21	1105.20	170269.6	61.38	8.14	12046.9	61.38
1500	43	21	22	1105.20	158294	60.5	5.42	8638.87	60.5
1500	34	19	15	624.47	59207.8	63.2	7.21	17322.23	63.2
1500	30	21.5	8.5	343.85	29275.83	61.23	8.72	23355.13	61.23

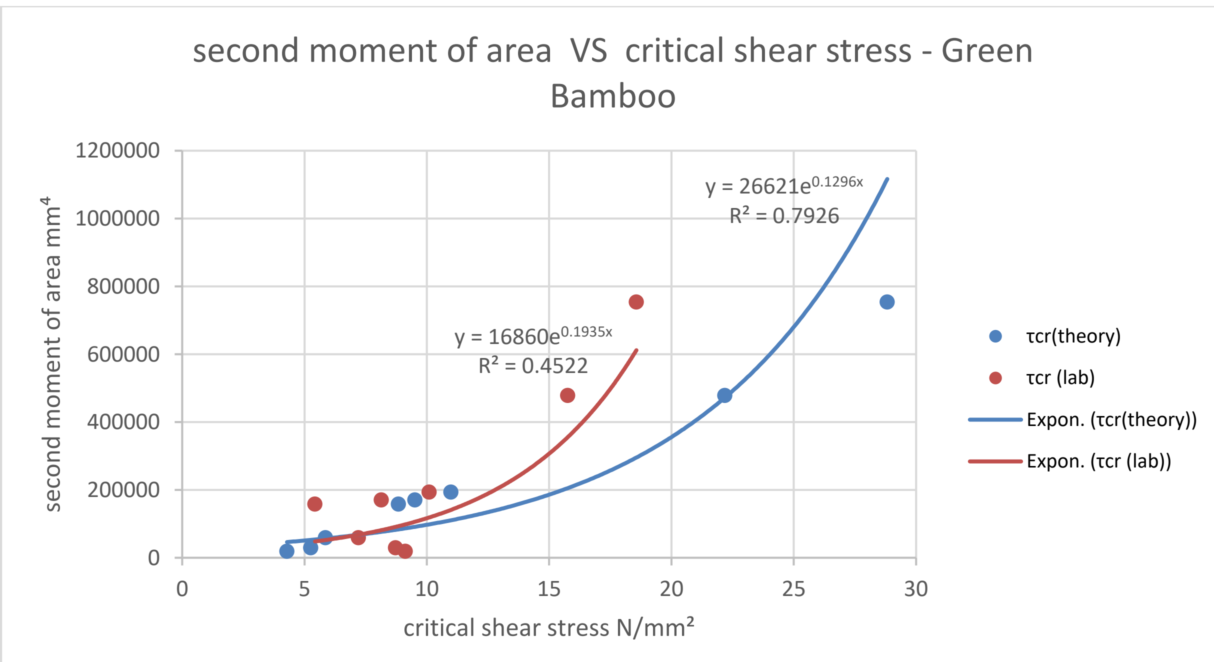

Figure 8: Second Moment of Area vs Shear Stress for Green Bamboo

From Figure 8 and analysis of the curves, there's an increase in shear strength of the bamboo as second moment of area increases. The curves are gentler and less steep than in the dry bamboo (Figure 7). This is due to the effect of high levels of moisture content, the samples had an average moisture content of 62.10%, moisture content therefore, clearly influences the strength and stiffness of these samples. Strength and stiffness of bamboo decrease with an increase in moisture content.

In addition to changes in strength and stiffness, dimensional changes also occur due to changes in moisture content. Shrinkage takes place with diminishing moisture content. The Timber design manual (2006) states that an average shrinkage of 4.6% occurs when the moisture content (M.C.) goes from 24% to 6%.

The curve is steeper in laboratory shear curve than the theoretical curve, this is a total opposite of the dry bamboo which was indicating that the theoretical curve is steeper than the lab one. This is clearly due to the high moisture content and also possibly experimental errors. The theoretical curve had a percentage accuracy of 79.26% while that of the lab had an accuracy of 45.22%. There's a significant variation in the accuracies of the dry and green bamboo data, 3.33% and 28.97 % respectively. This variation was caused by a high level of moisture content which affected other parameters of the bamboo. A semi-empirical relation can be determined to express the theoretical curve in form of the empirical one.

$\frac{26621e^{0.1296x}}{16860e^{0.1935x}} = 1.48$

Therefore, when a theoretical curve is factored by 1.48 it maps to the empirical curve. The factor is lesser than the one in dry bamboo, because moisture affects the strength properties of the bamboo.

Second moment of area VS critical load (dry bamboo)

Table 3: Second moment of area and critical load dry bamboo

L mm	D Mm	d mm	D-d mm	A mm²	I mm⁴	Pcr (theory)	Pcr (empirical)	E N/mm²	% Moisture
1500	52	40	12	113.1	233274.6	159.26	300.6	33218.62	9.2
1500	44	33	11	95.05	125786.8	102.20	178.86	30802.37	10.79
1500	35	25	10	78.55	54494.06	53.57	203.69	66917.69	11.32
1500	32	24	8	50.27	35190.40	54.06	79.56	25906.33	12.31
1500	24	17	7	38.50	12187.77	24.45	64.95	46750.47	11.56
1500	20	15	5	19.64	5369.63	21.12	76.38	63667.4	9.7
1500	15	10	5	19.64	1994.43	7.84	50.92	114274.80	10.23

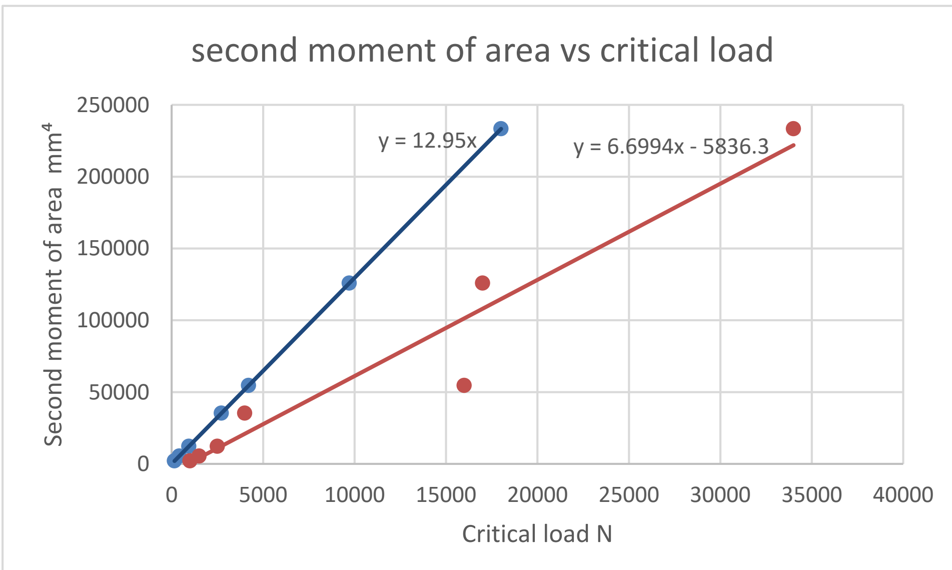

Figure 9: Second moment of area vs critical load for dry bamboo

From the curves (Figure 9) above its clear that as second moment of area increases there's an increase in the critical load of the bamboo samples. This is true in that a larger area moment of area increases the efficiency of a cross-sectional material to resist bending caused by loading. Therefore, critical load increases with an increase in second moment of area.

There's a variation in the curves of theoretical and the empirical. The theoretical curve is steeper than the empirical one, indicating that theoretical samples are stronger than the empirical samples. Hence there is need for a semi-empirical relation of the two curves to come up with a factor which can map the theoretical curve to the empirical curve.

$\frac{\mathbf{12.95x}}{\mathbf{6.6994x}} = \mathbf{1.933}$

Therefore, when 1.933 is factored to the theoretical curve it maps to the empirical curve.

Second moment of area VS critical load (green bamboo)

Table 4: Showing data for moment of area and critical load

L mm	D Mm	D Mm	D-d mm	A mm²	I mm⁴	Pcr (theory)	Pcr (empirical)	E N/mm²	% Moisture
1500	69	52	17	1615.74	753859.3	46571.78	30000	9069.87	64.8
1500	61	45	16	1332.20	478429.20	29556.31	21000	10003.96	62.22
1500	46	27	19	1089.50	193724.70	11967.89	11000	12941.30	62.72
1500	44	23	21	1105.20	170269.6	10518.89	9000	12046.9	61.38
1500	43	21	22	1105.20	158294	9779.05	6000	8638.87	60.5
1500	34	19	15	624.47	59207.8	3657.73	4500	17322.23	63.2
1500	30	21.5	8.5	343.85	29275.83	1808.59	3000	23355.13	61.23

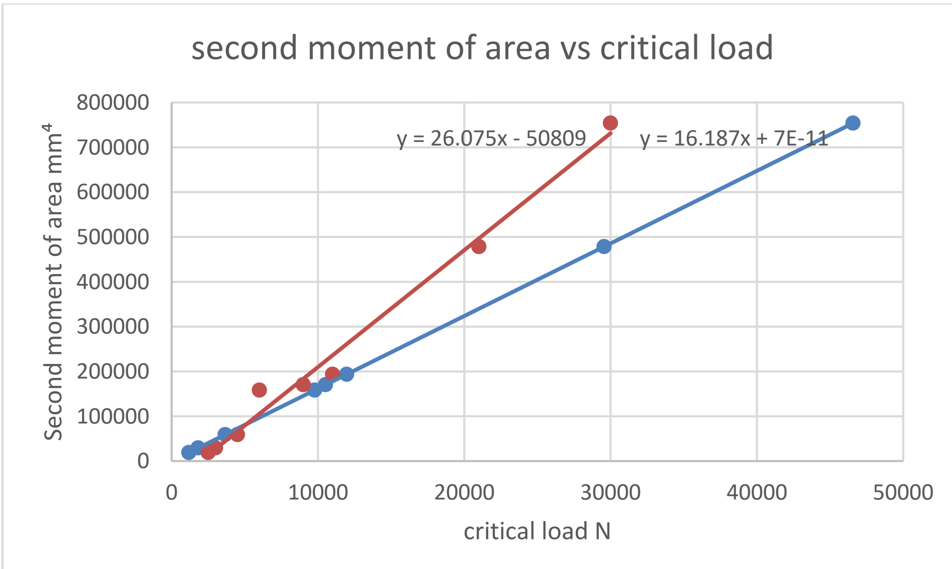

Figure 10: Second moment of area VS critical load for green bamboo

In the case of green bamboo (Figure 10), empirical curve is steeper than the theoretical one as shown from the graph. This is the total opposite of the dry bamboo curves which showed that, theoretical samples were much stronger than the empirical ones. This can be attributed to the high moisture content which has effects the strength of bamboo. The theoretical curve still needs to be factored to the empirical curve which is the correct representation of the relation above.

There is a need for a relation factor, to map the theoretical curve to the empirical one which is relatively accurate compared to the theoretical one.

$\frac{26.075x}{16.187x} = 1.61$

The factor 1.61 is slightly less than the factor in dry bamboo. This is due to high moisture content in the samples which adversely affects, the strength properties of bamboo. Therefore, there is need for seasoning of bamboo culms to the right moisture content before using them.

Critical load VS flexural rigidity

Table 5: Critical load and flexural rigidity of dry bamboo

L mm	D mm	d mm	D-d mm	A mm²	I mm⁴	τ (theory)	τ(empirical)	E N/mm²	% Moisture
1500	52	40	12	113.1	233274.6	159.26	300.6	33218.62	9.2
1500	44	33	11	95.05	125786.8	102.20	178.86	30802.37	10.79
1500	35	25	10	78.55	54494.06	53.57	203.69	66917.69	11.32
1500	32	24	8	50.27	35190.40	54.06	79.56	25906.33	12.31
1500	24	17	7	38.50	12187.77	24.45	64.95	46750.47	11.56
1500	20	15	5	19.64	5369.63	21.12	76.38	63667.4	9.7

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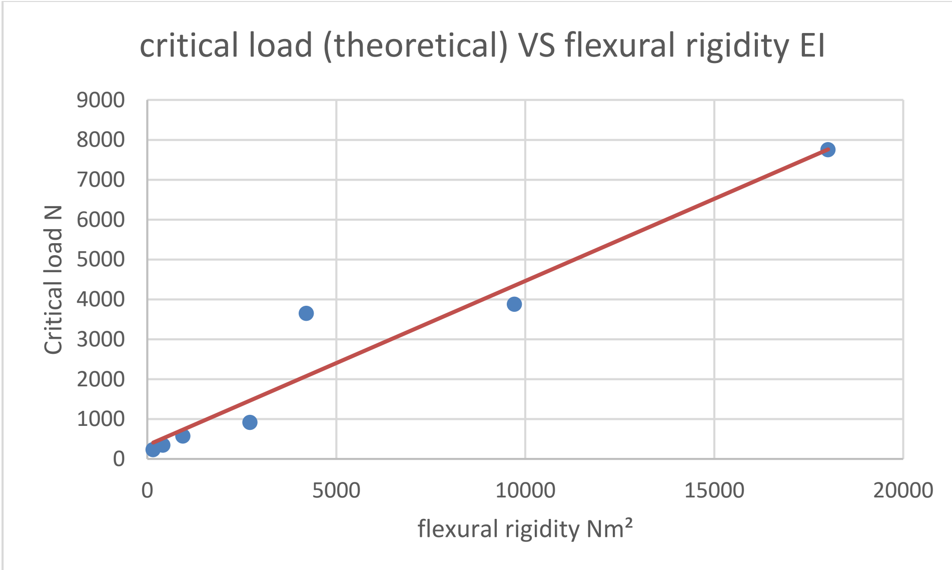

Figure 11: Theoretical critical load VS flexural rigidity for dry bamboo

Table 6: Data for critical load and flexural rigidity of green bamboo

L mm	D mm	D Mm	D-d mm	A mm^2	I mm^4	τ (theory)	τ (empirical)	E N/mm^2	% Moisture
1500	69	52	17	1615.74	753859.3	28.82	18.57	9069.87	64.8
1500	61	45	16	1332.20	478429.20	62.22	15.76	10003.96	62.22
1500	46	27	19	1089.50	193724.70	62.72	10.09	12941.30	62.72
1500	44	23	21	1105.20	170269.6	61.38	8.14	12046.9	61.38
1500	43	21	22	1105.20	158294	60.5	5.42	8638.87	60.5
1500	34	19	15	624.47	59207.8	63.2	7.21	17322.23	63.2
1500	30	21.5	8.5	343.85	29275.83	61.23	8.72	23355.13	61.23

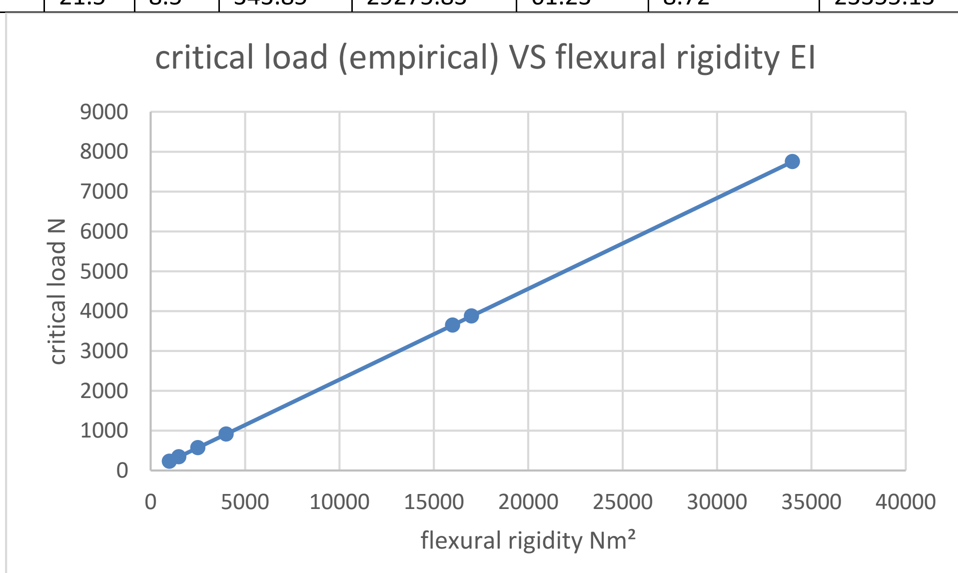

Figure 12: Critical load VS flexural rigidity for green bamboo

Flexural rigidity is the resistance offered by a structure while undergoing bending. From the graphs (Figures 11 and 12) it's clear that the critical load is proportional to the flexural rigidity of the samples. Moisture content has a significant effect on the flexural rigidity, as bamboo dries it shrinks hence second moment area and section modulus reduces this results in the reduction of the flexural rigidity. Increasing flexural rigidity leads to an increase in the strength property of a material as is observed in these figures.

Flexural rigidity is increased by using a stiffer material i.e. a material with larger modulus of elasticity or by distributing the material in such a way as to increase the moment of inertia I of the cross section. The moment of inertia is increased by distributing the material farther from the centroid of the cross section. Hence a hollow tubular member is generally more economical for use as a column than a solid member having the same cross-sectional area.

Reducing the wall thickness of a tubular member and increasing its lateral dimensions (while keeping the cross-sectional area constant) also increases the critical load because moment of inertia is increased. This process has a practical limit, however, because eventually the wall itself will become unstable. When this happens, localized buckling occurs in the form of small corrugations or wrinkles in the walls of column. This type of failure was also observed in some samples as is shown in Figure 5(B).

Critical stress VS slenderness ratio

Dry bamboo samples

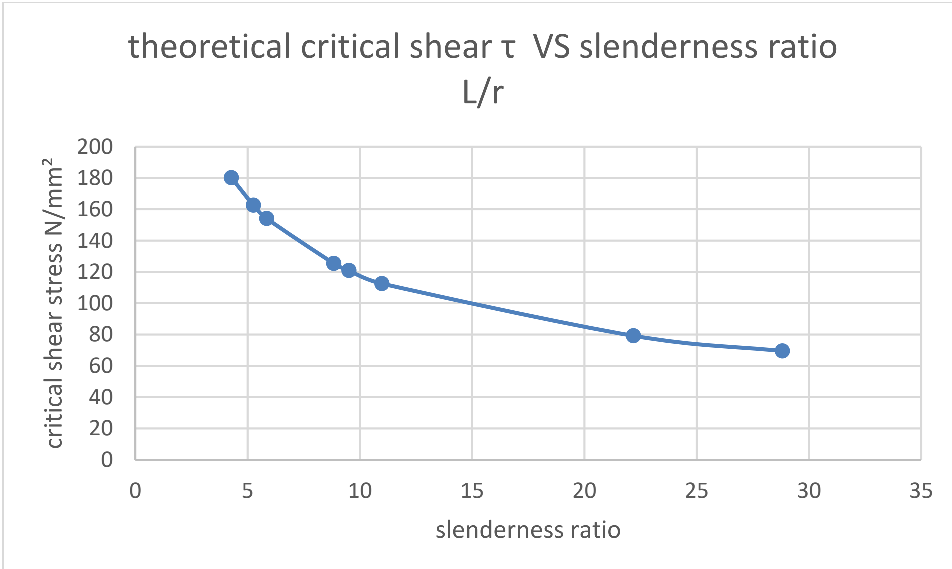

Figure 13: Theoretical critical shear VS slenderness ratio

Green bamboo samples

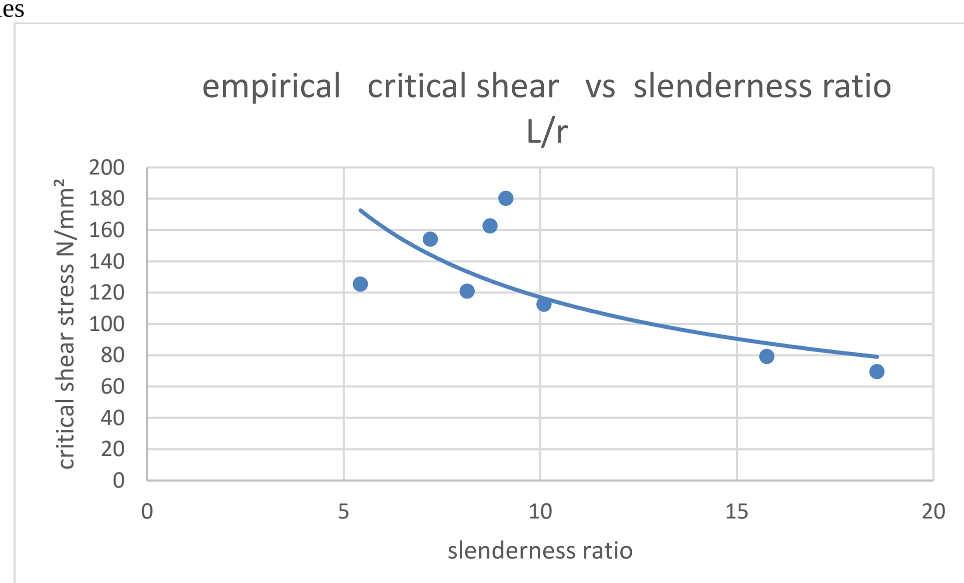

Figure 14: Empirical critical shear VS slenderness ratio

Slenderness ratio is the ratio of the length of a column and the least radius of gyration of its cross section. From the graph it's seen that an increase in the slenderness ratio results to a decrease in critical stress. Slenderness ratio depends on dimensions of the column of bamboo, a column that is long and slender will have a high slenderness ratio and therefore a low critical stress. While the column that is short will have a low slenderness ratio and will buckle at a high stress. This is the case in both the green and dry bamboo. The critical shear stress was observed to vary with the slenderness ratio for both dry and green bamboo columns (Figures 13 and 14)

Cross-sectional area VS critical load

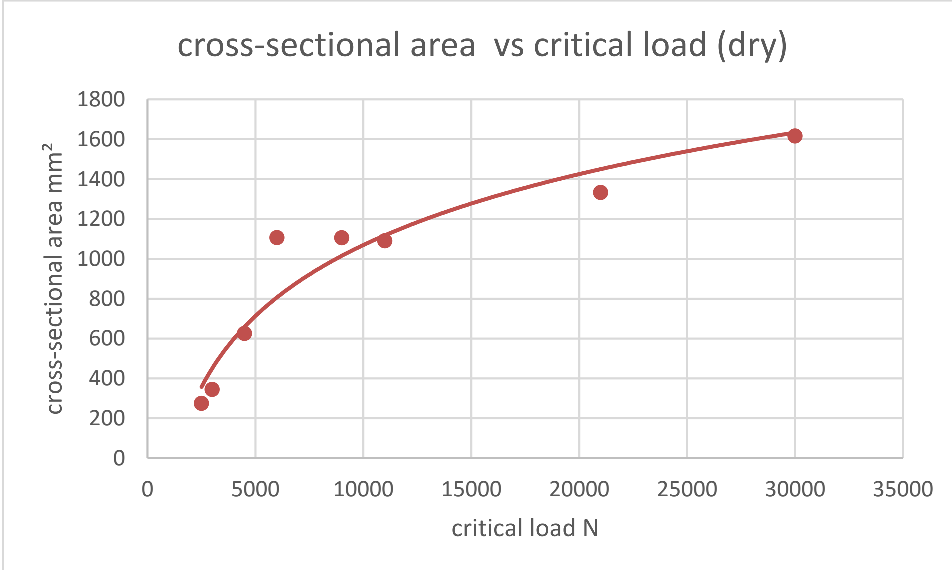

Figure 15: Cross sectional VS critical load for dry bamboo

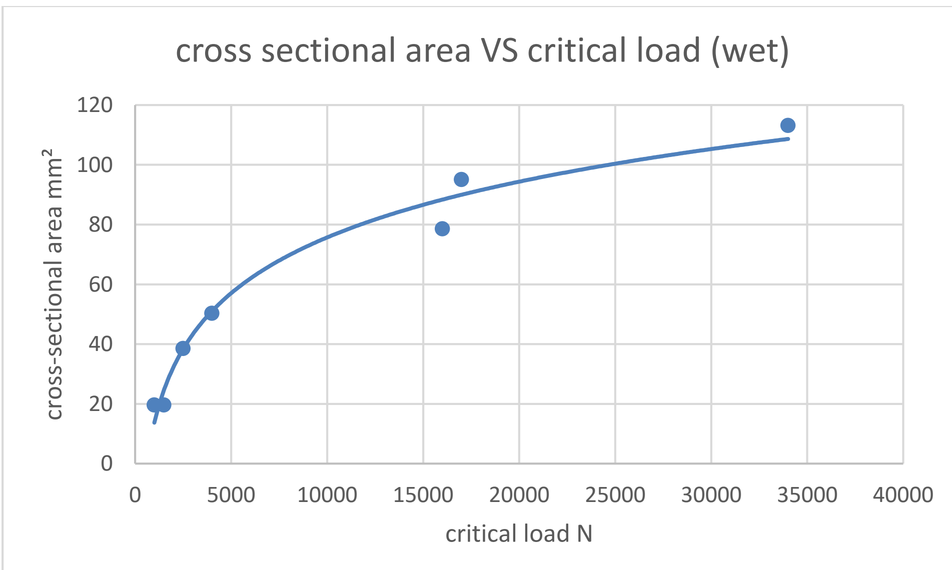

Figure 1Cross sectional VS critical load for green bamboo

From Figures 15 and 16, there is an increase in critical load as the cross-sectional area of the samples increases. The curve is steeper and then it gets less steep as the cross-sectional increases. For the same shape, the cross sectional area has a direct effect on second moment of area which in turn affects the bending and buckling properties of the bamboo column. A big cross-sectional area has a large second moment of area the reason why there’s an increase in critical load as the area increases. Hence columns of large cross sections are recommended in construction as they can effectively carry more loading with lower possibility of buckling. Also, from the two curves, Figures 15 and 16, the dry bamboo was found to be a lot stiffer than the green bamboo column

Moisture content VS modulus of elasticity

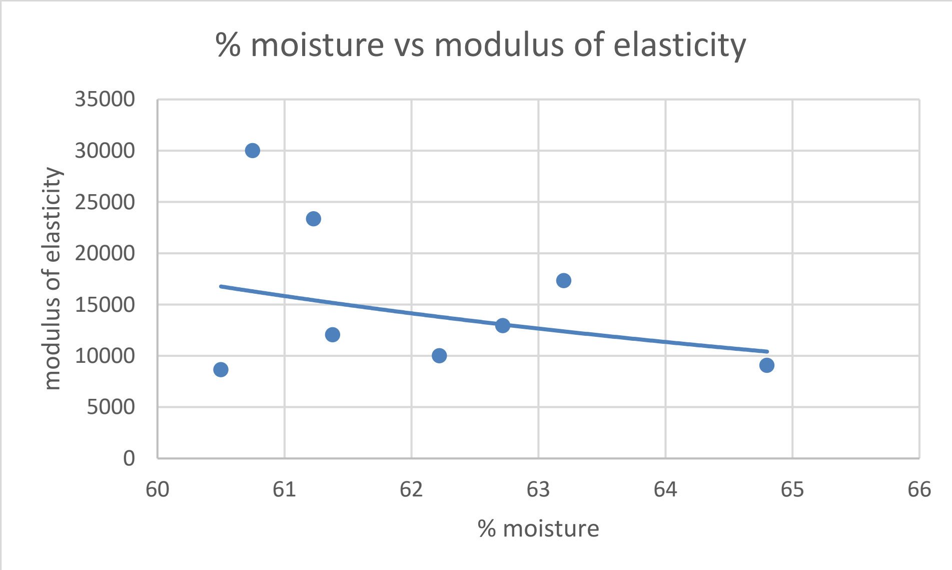

Figure 2Moisture content VS modulus of elasticity

From Figure 17 it can be seen that an increase in moisture leads to a decrease in modulus of elasticity. A decrease in modulus of elasticity, means even the strength and stiffness of bamboo is decreased, the right moisture content is significant in construction. Clearly moisture content is an important influence on the physical and mechanical properties of bamboo. This has to be taken into account when using bamboo in structural purposes. Therefore, the right amount of moisture content is required so as to ensure higher strength and stiffness of bamboo columns.

IV. Conclusions and Recommendations

In view of the results and analysis gotten above, these conclusions were arrived at

(i) Concerning bamboo as reinforcement in concrete:

- There is reduced bond between the concrete and the bamboo reinforcement. This causes a concern as it leads to low strength development in the beams and slabs leading to both failure under lower loading an also more brittle failure
- Curing and drying of the bamboo reinforcement is important as it can considerably increase the strength of bamboo reinforced concrete.

(ii) Concerning bamboo as column element

- The variation of diameter and thickness in bamboo columns had a considerable effect on their axial buckling resistances. It is important to incorporate the variation of diameter and thickness for bamboo columns when determining their axial buckling capacity.
- Local failure of the bamboo column as it buckles can occur and may need to be checked during design of such columns
- The lower the moisture content of a bamboo column, the higher the buckling resistance, when other factors are held constant

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AUTHORS

First Author – Mwero J. N, Department of Civil and Construction Engineering, University of Nairobi