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A comparative study of Bamboo reinforced concrete beams using different stirrup materials for rural construction

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ABSTRACT

This study aims at exploring ways of making the use of bamboo reinforced concrete beams simple, efficient and cost-effective for rural construction with Ghana as a case study. It is a comparative study of bamboo reinforced concrete beams with shear links made of different materials. The web materials considered were bamboo, rattan cane and steel. Sixteen (16) beams were tested to failure under four point bend tests. The highest and lowest failure loads were recorded for the cases of steel stirrups and no stirrups respectively. The experimental failure loads averaged 5.05 and 1.72 times the observed first crack and theoretical failure loads respectively. At failure, beams with low concrete compressive strength and small amount of bamboo tension reinforcement had wider cracks. The cheapest and most economical means of providing shear reinforcement for bamboo-reinforced beams was analysed using a performance model developed in this research. A beam performance index (BPI) in terms of energy absorbed per unit cost of beam, indicated the use of steel stirrups as the most economical. The most expensive means of shear reinforcement provision in bamboo reinforced beams is by rattan cane stirrups irrespective of the grade of concrete. It is therefore recommended that steel stirrups be used to enhance the performance of bamboo reinforced concrete beams.

Keywords: Bamboo, reinforced-concrete, shear links, bending, performance index, energy absorbed

1. Introduction

In recent times, the high cost and general shortage of reinforcing steel in many parts of the world has led to increasing interest in the possible use of alternative locally available materials for the reinforcement of concrete. This is the case especially in the developing countries where about 80% of the population live in villages. This has led to research on several non-ferrous reinforcing materials in structural concrete. In Ghana for an instance, a tall straggling shrub known as babadua (botanical: *thalia geniculata*) also reportedly found in parts of Africa, Asia and South America (Irvine, 1961; Lyman, 1965) has been used as a construction material in several rural areas where it is tied into a framework and daubed with mud (Schreckenbach and Abankwa, 1982). The local construction method of using babadua with mud was improved upon in an experimental program by the use of babadua as reinforcing material in concrete structural elements. The strength and deformation characteristics of concrete beams reinforced with babadua bars ranging from 2.87 to 12.13% were tested in bending (Kankam and Odum-Ewuakye, 1999). The experimental failure loads

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averaged 1.18 times the theoretical flexural strength of the reinforced concrete (RC) and 1.05 times the theoretical shear strength of the concrete sections taking into consideration the resistance of the tension reinforcement. In the case of one-way concrete slabs reinforced with babadua bars, the researchers (Kankam and Ewuakye, 2000) found experimental failure loads to average 175% of the theoretically predicted values. However, the experimental failure loads averaged only 67% of the design shear strength of the reinforced concrete section. Research work on two-way concrete slabs reinforced with babadua bars failed experimentally at loads that averaged 170% of the theoretically predicted loads (Kankam and Odum-Ewuakye, 2006). Raffia palm (rattan cane) was also used as both bending and shear reinforcement in concrete beams (Kankam, 1997). Fourteen simply-supported raffia palm reinforced concrete beams were subjected to four-point bend tests until failure. Collapse occurred mainly through the crushing of concrete and failure loads averaged 1.17 times the theoretically predicted values. Odera et al (2011) also demonstrated that raffia palm-fibre improves the compressive and flexural strength of ordinary cement-sand mortar composites for roofing tiles.

One natural material which has great appeal in terms of availability and ease of use in the rural and farming communities in the developing world is bamboo. Bamboos occur mostly in tropical and subtropical areas, from sea level to snow-capped mountain peaks, with a few species reaching into temperate areas. They are most abundant in south-eastern Asia, with some species in the Americas and Africa and none in Australia. A single bamboo that grows in clumps can produce up to 15km useable pole (up to 30cm in diameter) in its lifetime. The plant sways easily and snaps rarely due to the nodes and hollow stems. One of the major applications of bamboo is for construction and housing. It is estimated that one billion people live in bamboo houses. For ages bamboo has been used in construction and currently they are used as props, foundations, framing, scaffolding flooring, walls, roofs and trusses. Bamboos are tied together to make grid reinforcement and placed in soft clay to solve deformation problems in embankments (Maity et al., 2009). It is encouraged that bamboo be used as reinforcement material for construction of walls in place of mud walls since they have quite higher strength and they are environmentally sustainable.

There are about seven (7) species of bamboo in Ghana. These are; Bambusa *arundinacea*, Bambusa *bambus*, Bambusa *multiplex*, Bambusa *pervariabilis*, Bambusa *vulgaris*, Bambusa *vulgaris var vitata*, and Dendrocalamus *strictus.* Only Bambusa vulgaris is indigenous to Ghana while the others were introduced into the country from Asia. Bambusa vulgaris is the predominant bamboo species in southern Ghana constituting 95% of the stocks in this area (Oteng Amoako et al., 2005). In Ghana, the annual deficit in the building industry is about 200,000 housing units. The cost of building keeps increasing as inflation and material costs especially steel reinforcement increase. This limitation has adversely affected the provision of housing units in the rural and farming communities where adobe and mud house constructions are common. The use of bamboo strips as replacement for reinforcing steel rods is still not very common in Ghana.

In this paper, a summary of research by others on the mechanical properties of bamboo and its behaviour in structural concrete beams is presented as part of a study aimed at finding a cost-effective solution to the limited behaviour of bamboo reinforced concrete beams in shear behaviour for rural building construction in Ghana. Therefore a comparative study of sixteen reinforced concrete beams all with longitudinal bamboo reinforcement but shear links made of different materials was undertaken. The different stirrup materials considered were bamboo, rattan cane and steel. No special treatment was applied to the bamboo strips (eg in terms of asphalt emulsion treatment) to ensure that no extra cost in terms of the acquisition of additional materials and the use of preparation time would discourage the use of bamboo as reinforcement in structural concrete in rural areas. The beams were tested to failure by four point bend tests and their structural behaviour recorded. The aim of using local materials for construction is to ensure that we obtain a cost-effective solution to construction problems especially in the rural-farming communities. It is therefore imperative that a simple model to analyse the most cost effective solution to the problem of bamboo reinforced beams and their susceptibility to shear failure is employed. This is obtained by the introduction of a beam performance index (BPI) in terms of energy absorbed per unit cost at failure of a beam.

1.2 Mechanical properties of bamboo and its behaviour in structural concrete

The tensile strength of bamboo can reach up to 370 N/mm^2. This makes bamboo an alternative to steel in tensile applications. This is because the ratio of tensile strength to specific weight of bamboo is six times greater than that of steel (Amanda et al. , 1997). Ghavami (2005) found the strength distribution at the bottom of the bamboo culm to be more uniform than at the top. The strength of bamboo also increases with age and the maximum strengths are realized at age 3-4years, after which strength begins to decrease (Amada and Untao, 2001). In the nodes, the average fracture toughness is lower than the minimum value of the entire culm. Hence the fibres in the nodes do not contribute any fracture resistance. Lo et al (2004) also studied the mechanical properties of bamboo. They concluded that both physical and mechanical characteristics vary with respect to diameter, length, age, type, position along culm and moisture content of bamboo. Different bamboo species perform differently for the same set of test (US Naval Civil Engineering, 1966, 2000 and Iyer, 2002). Bamboo will perform differently depending on the specie and maturity. Unlike steel rods, bamboo can raise many issues with respect to durability. Bamboo may contain high nutrients to foster fungi growth and insect attack. It needs to be protected from several conditions including temperature, moisture and pest. Bamboo has strong water absorption, low resistance to fire than steel and show weak bond with concrete (Steinfield, 2001).
The behaviour of structural concrete elements reinforced with bamboo is reported in several research works (Glenn, 1950; Kankam et al, 1986; Kankam et al., 1988; Amadi and Untao, 2001; Ghavami, 1995; Ghavami, 2005; Khare, 2005). Laboratory tests were performed on ten simply-supported, one-way bamboo reinforced concrete slabs subjected to concentrated line loads. Three different modes of failure were exhibited in the slabs; concrete in compression, both shear and concrete in compression, and bamboo in tension. Experimental failure loads averaged 180 percent of the theoretically predicted values (Kankam et al. 1986).The authors in a follow-up work (Kankam et al. 1988) further tested ten bamboo-reinforced concrete simply supported beams to failure under monotonic short term loading whilst six other beams were subjected to long term loading. Collapse mostly occurred through diagonal tension failure of the concrete in the shear span. A method based on the analysis of the results was proposed for the design of such beams. Ghavami (1995) discussed the mechanical properties of bamboo used as reinforcement in structural concrete elements. The study showed that ultimate loads of the concrete beams averaged 400 percent of the unreinforced concrete beam capacity. Ghavami (2005) studied the mechanical properties of six different types of bamboo and their behaviour in concrete. The study concluded that bamboo can substitute steel satisfactorily and that there is the need to establish the characteristic strength of bamboo for

design purposes. Khare (2005) evaluated the performance of bamboo reinforced concrete. Tensile tests were conducted on the bamboo to obtain their constitutive relation. Four-point bending tests were performed on six concrete beams reinforced with bamboo to identify their behaviour compared to steel reinforced concrete beams. Tests results indicated that bamboo reinforcement enhanced the load carrying capacity by about 250 percent as compared to the initial crack load in the concrete beam.

1.3 Shear resistance of reinforced concrete beam

Figure 1 represents the shear transfer mechanism of a cracked concrete beam acted on by a shear force *V*. The directions of the principal compressive and tensile stresses are such that they tend to be parallel to the beam axis. At the mid-span of the beam shear stresses are low and the bending stresses dominate. Near the supports the shearing stresses are high and an element shown in figure 2 is subjected to both shear stresses and normal tensile stresses. Close to the neutral axis, the bending stress on an element is very small and can be neglected such that the shear stresses acting on an element are equivalent to the principal stresses also called diagonal tension.
Before the advent of diagonal cracking, loads are supported by concrete in tension. The major contributors to shear resistance *V*; are aggregate interlock across the diagonal crack V_a, dowel action effect of the longitudinal reinforcement V_d, un-cracked concrete action V_c and the web reinforcement V_w.

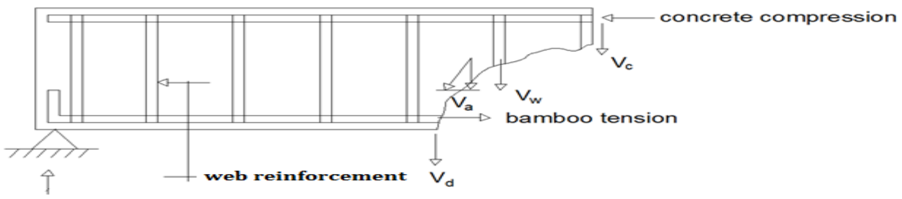


Figure 1: Shear transfer in beam with web reinforcement

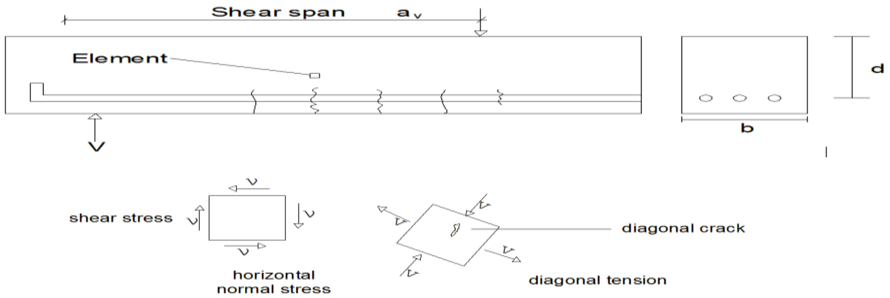


Figure 2: Stresses on an element in concrete beam

This results in an equilibrium equation described by:

$$V = V_a + V_d + V_c + V_w \quad (1)$$

In the case of non-existing web reinforcement, maximum shear strength occurs after diagonal shear crack. This means that before diagonal cracking, the shear force *V*, produces no shear stress in the web reinforcement. It is assumed that V_w is effective only when a diagonal crack is intercepted by the web reinforcement.

When shear cracks occur, the concrete in between the cracks isolate and cuts the incremental tensile flow in the longitudinal reinforcement. Compressive stresses due to V_a passes through the cracks. As the load increase, the V_a effect also decrease, allowing transfer of large shear force to the concrete compressive zone, increasing V_c and V_d. This may cause failure in one of two ways described by splitting of concrete along the longitudinal reinforcement or crushing of the concrete in the compression zone. The provision of web reinforcement functions to tie the longitudinal bars in place and the dowel action tends to transfer small portion of the shear to the webs. This is besides the major function that shear reinforcement are provided to;

(i) carry part of shear stresses

(ii) confine concrete to maintain interlock and resist growth of cracks

(iii) tie longitudinal bars in place and thereby increase their dowel capacity

Optimum amount of web reinforcement is needed to ensure that the concrete in the compression zone does not fail before yielding of bamboo in the case of excessive web reinforcement. On the other hand, web material may yield early if the shear reinforcement is very small. Web reinforcement is thus provided such that both the shear reinforcement and compression concrete carry substantial shear after the formation of inclined crack before the web material yields.

2.0 Experimental program

2.1 Materials and specimens

Fully grown bamboo samples seasoned for over three (3) months and rattan canes were obtained from a local market in Ghana. The bamboo used was of the specie *Bambusa vulgaris*. The rattan cane specie used was *Eremospatha spp* locally known as 'Mfea'. The bamboos were split along the horizontal axes into almost equal section to be used for longitudinal tension reinforcement. The concrete consisted of ordinary Portland cement, natural river sand and crushed granite rock. Sixteen beam specimens were cast with two different mix ratios (cement:sand:coarse aggregates:water ratio) of 1:2:4:0.6 and 1:1.5:3:0.45. The concrete for the reinforced beams with companion control cubes (100x100x100mm) and modulus of rupture prisms (100x100x500) were mechanically mixed in a paddle mixer placed and compacted by means of a shutter vibrator. Curing of the beams was done at 100% humidity and approximately 25^{o}C room temperature for 28 days. Each set of beams consisted of specimens without shear reinforcement, bamboo stirrups, steel stirrups and rattan cane stirrups. All sixteen (16) beams were reinforced with longitudinal tension and compression bamboo reinforcement. Details of individual specimen are given in Tables 3 and 4.

2.2 Test procedure

The beam specimens were loaded by third-point loading produced by a hydraulic jack supported on a rigid steel frame. A spreader beam transfer the load symmetrically to ensure pure bending in the mid-span of the beams. A dial gauge reading to 0.01mm was used to record the central deflection of the beams and crack widths were measured with a crack microscope that reads to 0.02mm on the surface of the beams. Length of cracks was measured with a rope which was transferred on a measuring tape. Appearance of cracks was visually inspected. A schematic setup of beam testing and instrumentation are shown in

Figures 3a and 3b.

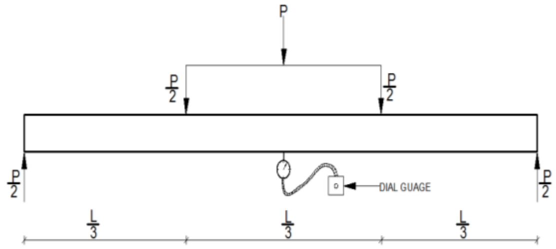


Figure 3a: A schematic beam testing setup **Figure 3b:** Experimental set-up

2.3 Flexural and shear strengths

A simply supported beam under third-point loading would yield an ultimate flexural load P_{ult} given as:

$$P_{ult} = 2(M_{ult} - \frac{wL^2}{8})/a_v \qquad (2)$$

where M_{ult} denotes ultimate moment of resistance; w is the self-weight per unit length of beam; L is the span of the beam and a_v is the shear span.
The theoretical shear strength of the beam was calculated per the British Standard BS8110: 1985 method of design considering the concrete section, tension reinforcement and shear reinforcement.

3. Theoretical and experimental results

The details of beam dimensions, reinforcement details and material strengths are shown in Tables 3 and 4. The physical and mechanical properties of the materials tested showed that the moisture content of the bamboo material and the rattan cane averaged 14.20% and 11.46% respectively**.** The average tensile strength of the stirrup materials was 105N/mm^2 for bamboo, 25N/mm^2 for cane and 250N/mm^2 tensile strength of steel stirrup. The bamboo and rattan cane were assumed to have material factor of safety of 3.0 and that of steel was 1.05. Table 5 presents the theoretical and experimental failure loads of all the beams. The lowest of beam strength in bamboo yielding, concrete crushing and shear failure governed the theoretical failure loads of a particular specimen. The deflection behaviour of the beams under ultimate loads is illustrated by typical load-deflection curves as shown in figure 4. The post cracking strain energy of all the beams are presented in Table 6.

Table 3: Description of beams

Beam No.	*B X DXL*	a_v/d	Percentage of bamboo		Concrete strength		Bamboo strength
			Tension	Compression	F_{cu}(N/mm^2)	F_t (N/mm^2)	F_b (N/mm^2)
BBR1	110 X 135x1800	4.64	6.94	0.39	27.30	3.31	126.72
BBR2	110 X 135x1800	4.64	7.83	0.39	27.30	3.31	126.72
BBR3	110 X 135x1800	4.64	7.22	0.39	27.30	3.31	126.72
BBR4	110 X 135x1800	4.64	7.04	0.39	27.30	3.31	126.72
BBR5	110 X 200x2000	3.33	6.46	0.25	28.20	3.21	126.72
BBR6	110 X 200x2000	3.33	6.28	0.25	28.20	3.21	126.72
BBR7	110 X 200x2000	3.33	5.49	0.25	28.20	3.21	126.72
BBR8	110 X 200x2000	3.33	6.20	0.25	28.20	3.21	126.72
BB1	110 X 135x1800	4.64	7.36	0.39	18.00	2.58	126.72
BB2	110 X 135x1800	4.64	7.07	0.39	18.00	2.58	126.72
BB3	110 X 135x1800	4.64	6.86	0.39	18.00	2.58	126.72
BB4	110 X 135x1800	4.64	6.80	0.39	18.00	2.58	126.72
BB5	110 X 200x2000	3.33	4.47	0.25	23.31	3.52	126.72
BB6	110 X 200x2000	3.33	4.69	0.25	23.31	3.52	126.72
BB7	110 X 200x2000	3.33	4.90	0.25	23.31	3.52	126.72
BB8	110 X 200x2000	3.33	4.17	0.25	23.31	3.52	126.72

B-breadth of beam , D-depth of beam, L-length of beam

Table 4: Details of shear stirrups

Beam No.	Stirrup Type	S_v (mm)	A_{sv}(mm^2)	F_m(N/mm^2)
BBR1	No stirrup	-	-	-
BBR2	Bamboo stirrups	80	40	105
BBR3	Steel stirrups	100	56	250
BBR4	Cane stirrups	60	155	25
BBR5	No stirrup	-	-	-
BBR6	Bamboo stirrups	60	40	105

BBR7	Steel stirrups	100	56	250
BBR8	Cane stirrups	50	155	25
BB1	No stirrup	-	-	-
BB2	Bamboo stirrups	80	40	105
BB3	Steel stirrups	100	56	250
BB4	Cane stirrups	60	155	25
BB5	No stirrup	-	-	-
BB6	Bamboo stirrups	60	40	105
BB7	Steel stirrups	100	56	250
BB8	Cane stirrups	50	155	25

S_v- shear stirrup spacing, A_{sv}-area of shear reinforcement,
F_m-average tensile strength of stirrup material

Table 5: Theoretical and Experimental loads

Beam	First crack	Experimental Failure	Theoretical Failure load P'_{ult} (kN)			P_{ult}/P_{cr}	P_{ult}/P'_{ult}
No.	load P_{cr}(kN)	load P_{ult} (kN)	Bamboo yielding	Concrete crushing	Shear failure		
BBR1	4	14	12.46*	22.21	43.03	3.45	1.12
BBR2	6	22	14.12*	22.21	49.65	3.70	1.56
BBR3	6	24	12.98*	22.21	54.43	4.00	1.85
BBR4	6	20	12.65*	22.21	48.19	3.33	1.58
BBR5	7	18	24.36*	49.38	58.35	2.56	0.74
BBR6	6	44	23.65*	49.38	67.94	7.14	1.86
BBR7	6	46	20.56*	49.38	72.22	7.69	2.24
BBR8	6	30	23.33*	49.38	66.85	5.00	1.29
BB1	4	8	13.24*	15.17	38.19	2.00	0.60
BB2	6	22	12.70*	15.17	44.16	3.70	1.73
BB3	4	24	12.31*	15.17	48.14	5.88	1.95
BB4	4	22	12.20*	15.17	43.14	5.55	1.80
BB5	6	36	16.62 *	41.22	48.44	5.88	2.17
BB6	6	40	17.45*	41.22	56.80	6.67	2.29
BB7	10	42	18.86*	41.22	67.40	5.26	2.23
BB8	4	38	15.45 *	41.22	55.08	9.10	2.46
					Average	***5.06***	***1.72***

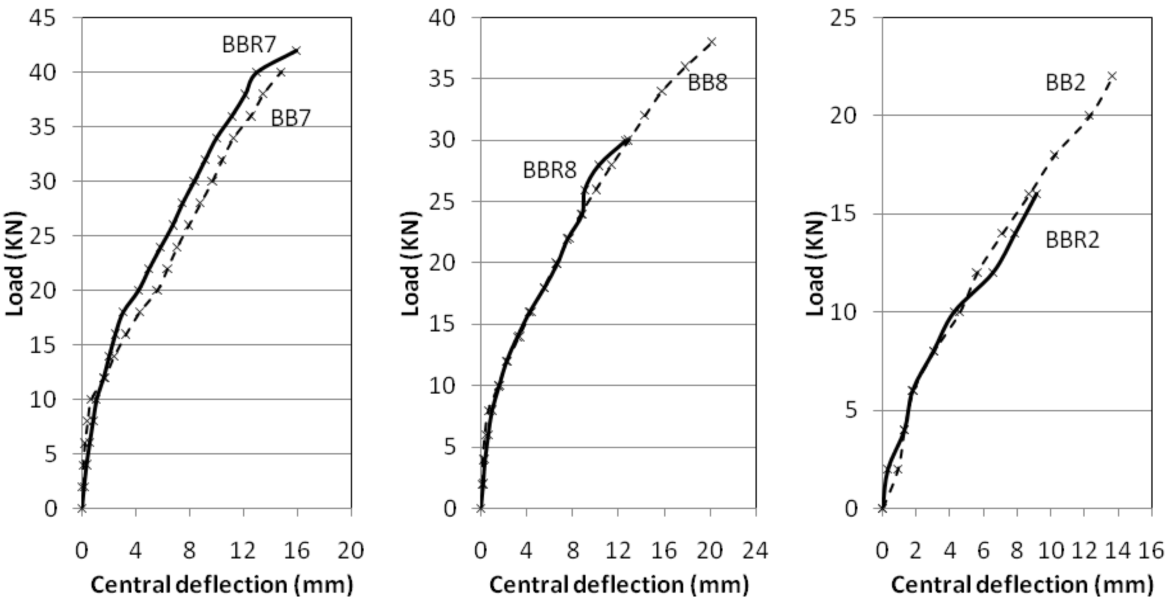
* Theoretical failure loads

4. Discussion of test results

4.1 Load-deflection behaviour

In a simply supported beam subjected to a four- point bend test, the middle third portion of the beam is subjected to maximum uniform bending and zero shear force assuming the self weight of the beam is negligible. The largest flexural strains therefore occur within this region, consequently, cracking initiates at the soffit of this region from where the cracks then spread rapidly towards the top of the beam with increasing applied load to collapse. The load-deflection curves (Figure 4) for reinforced concrete beams with longitudinal bamboo reinforcement show a similar behaviour to beams with longitudinal steel reinforcement. The load-deflection behaviour of reinforced concrete beams depend on the amount and type of reinforcement, concrete strength and the shear span-effective depth of the beam. In the sixteen beams tested to failure, the longitudinal tension reinforcement in bamboo varied from 4.17% to 7.83% of the gross concrete section.

The deflections of the beams when tested followed a fairly accurate straight line variation until the appearance of the first crack in the concrete. Immediately following the first crack, there was a pronounced flattening of the deflection curve (probably due to local bond slippage) followed by another period of fairly accurate straight line variation, but at a lesser slope, until ultimate failure of the member occurred. This flattening of the deflection curve was more pronounced in the members where the amount of longitudinal bamboo reinforcement was small. In all the beams tested, there was very little or no strain hardening observed. Beams prior to failure exhibited very short range of deflections indicating a low ductile behaviour of the bamboo. Beams with smaller amount of tension bamboo reinforcement deflected more at smaller loads than their corresponding beams with high tension reinforcement. This is typical in the case of two pairs of beams; BBR7/BB7 (Figure 4a) and BBR8/BB8(Figure 4b) which had the same amount of shear stirrups (in terms of size and spacing) but different tension bamboo reinforcements and concrete compressive strengths. It was observed that the beams with higher tension bamboo reinforcements and concrete compressive strengths (BBR7 and BBR8) did not necessarily produce the highest failure loads and displacements. Lower tension reinforcement resulted in higher failure load for beams with similar characteristics (Figure 4c). In terms of experimental failure loads and displacements, it was observed that beams BB5-BB8 which had tension reinforcements between 4-5% of the cross-sectional area of beam but low compressive strengths recorded the highest values when compared with other beam groups (BBR1-BBR4, BBR5-BBR8 and BB1-BB4). This confirmed earlier experimental reports that the optimum percent tensile reinforcement for bamboo in concrete is between 3-5% of the beam cross-section.

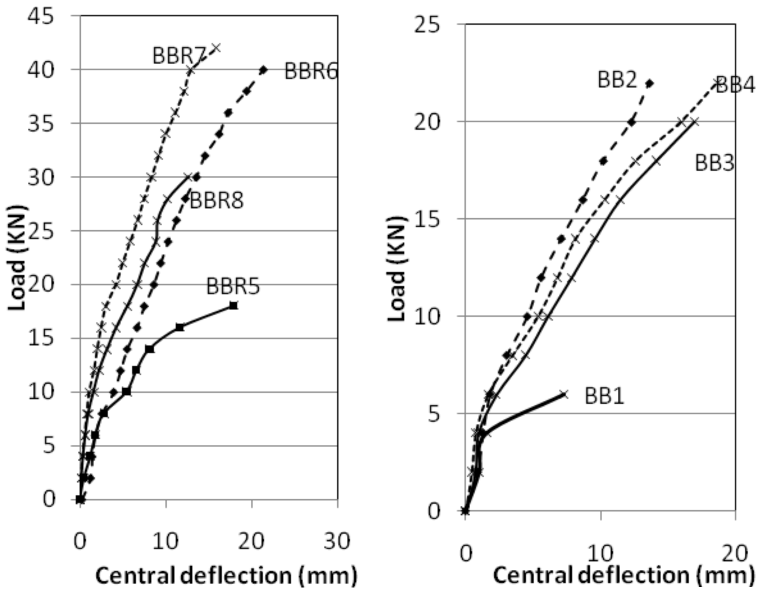


(a) (b) (c)

Figure 4: Typical load deflection curves of tested beam

4.2 Comparative study of shear behaviour

From Table 5, the observed first crack loads P_{cr} of the beams averaged 5.0 times the experimental failure loads (P_{ult}) . The ratio of ultimate load to the load at which the first crack occurred differed from 2.0 to 9.0 times and was very high (from 5.26-9.10) for beams in which tension reinforcement was optimum (ie 3%-5% tension reinforcement as in BB5-BB8). The type of stirrup material did not appear to have any effect on the first crack load. The experimental failure loads averaged 1.72 of the theoretical failure loads. This therefore implies that the average global overstrength factor of safety against failure for the woody materials in this research is about 5.0. This takes into consideration the fact that a material factor of safety of 3.0 had already been used in the theoretical calculations. It is worthy of note that the material strengths for the woody materials were measured from specimens without nodes and that those with nodes result in higher tensile strengths (Kankam et al, 1986, Kankam and Ewuakye 1999). The maximum bending moment positions coincided with the nodal positions resulting in failure loads higher than expected.



(a) (b)

Figure 5: Comparison of different web reinforcement

For BBR5 and BB1 which had no stirrups the ratios P_{ult}/P'_{ult} were 0.74 and 0.6 respectively. This suggests that bamboo reinforced beams without shear stirrups may not be safe for construction. The highest ratios of P_{ult}/P'_{ult} observed with consistency were for the steel stirrup beams which ranged from 1.85-2.24. The highest experimental failure load was 46 kN for BBR7 whilst the lowest experimental failure load was measured at 8 kN for BB1. The highest and lowest failure loads were recorded for the cases of steel stirrups and no stirrups respectively. Figure 5 compares the shear strength capacities of the different web materials as indicated by the load-deflection curves. It is evident that the inclusion of web reinforcement increased the shear capacity of the beams. This is because in all the beam groupings (BBR1-BBR4, BBR5-BBR8, BB1-BB4 and BB5-BB8), the beams without web reinforcement exhibited the lowest stiffness and failed at the lowest loads. For the higher strength concrete strength beams (BBR1-BBR8), the failure strength of the beam seemed to be dependent on the type of stirrup material. The failure strength of the beams with web reinforcement increased in order from rattan cane, bamboo and steel. A similar trend is observed in the low strength concrete beams (BB1-BB8) except that the failure strengths of BB2 and BB4 were found to be equal. It could therefore be inferred that the beams with steel stirrups showed the best performance with respect to strength followed by bamboo stirrups.

4.3 Mode of failure of beams

All the beams were theoretically designed against shear failure and were predicted to fail in flexural tension of longitudinal. Table 6 shows the theoretical and actual modes of failure, number and maximum widths of cracks in the beams. The mode of failure of the beam is usually influenced by the concrete compressive strength, the type of material and the ratios of main and web reinforcements and the shear span-effective depth ratio (a_v/d) of the beams. For reinforced concrete beams without adequate web reinforcement (Figure 6), a flexural crack a-b is propagated towards the loading point as the load V is increased. A further increase in load gradually results in a flexural shear or diagonal crack a-b-c. For beams with values of a_v/d ratio between 2.5 and 6.0 as in the case of this study the diagonal tension crack would end at j and random cracks would develop in the concrete region close to the longitudinal tension reinforcement (g-h). This crack will eventually destroy the bond between the concrete and the longitudinal reinforcement causing the splitting of the concrete along a-h. If the longitudinal reinforcement is hooked then a sudden collapse ensues. The diagonal cracks will extend into the concrete compression zone eventually causing crushing of the concrete.

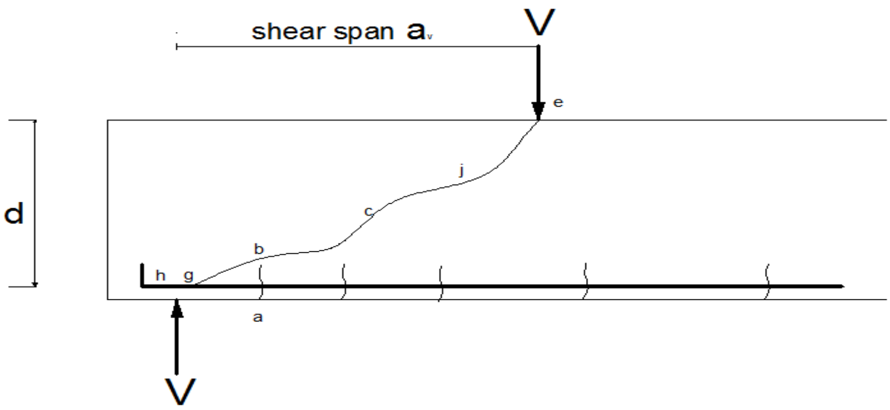


Figure 6: Crack development in beams

All the beams failed by a combination of some of the following failure modes; longitudinal bamboo in tension, concrete crushing, flexural shear, diagonal tension and shear bond with the exception of BB1 which failed by only bamboo in flexural tension. BB5 and BB8 failed by diagonal tension characterised by splitting of the concrete over the horizontal tension bamboo bars. The failure mode was irrespective of the type of stirrup material used. It is worthy of note that all the beams failed by brittle shear mode instead of the preferred ductile mode of flexure in tension reinforcement against the background that a material factor of safety of 3.0 for woody reinforcement has been used in theoretical calculations for both the bamboo and rattan cane materials. The largest crack widths were associated with the beams that failed in diagonal tension.

Table 6: Failure modes and cracking

Beam No	Failure mode: Predicted	Failure mode: Actual	Number and type of cracks	Max. Crack width (mm)
BBR1	Bamboo yielding	Diagonal tension and flexural shear	3 Diagonal +6 flexural shear	6.0
BBR2	Bamboo yielding	Flexural shear	4 flexural shear + 4 pure flexure	4.0
BBR3	Bamboo yielding	Concrete crushing and flexural shear	1 Diagonal and +3 flexural shear	4.0
BBR4	Bamboo yielding	Flexural shear	3 flexural shear + 4 pure flexure	2.5
BBR5	Bamboo yielding	Pure flexure and concrete crushing	1 Flexural shear + 3 pure shear	4.0
BBR6	Bamboo yielding	Diagonal tension	2 diagonal + 4 flexural shear	4.5
BBR7	Bamboo yielding	Flexural shear	2 flexural shear + 5 pure flexure	4.0
BBR8	Bamboo yielding	Diagonal tension	4 diagonal + 4 pure flexure	5.0
BB1	Bamboo yielding	Bamboo yielding in tension	3 pure flexure	2.0
BB2	Bamboo yielding	Diagonal tension	5 diagonal shear + 7 pure flexure	6.0
BB3	Bamboo yielding	Concrete crushing and tension failure	2 diagonal shear + 7 pure flexure	5.0
BB4	Bamboo yielding	Flexural shear	2 diagonal shear + 5 pure flexure	4.5
BB5	Bamboo yielding	Diagonal tension	4 diagonal shear + 4 pure flexure	8.0
BB6	Bamboo yielding	Diagonal tension and flexural shear	3 diagonal + 4 pure flexure	4.0
BB7	Bamboo yielding	Flexural shear	2 diagonal + 4 pure flexure	4.0
BB8	Bamboo yielding	Diagonal tension and shear bond	6 diagonal shear + 4 pure flexure	6.0

4.4 Post-cracking energy absorption and deflections

The post-cracking energy absorption which is a means of calculating the energy or work done per beam is a summation of the area under the load-deflection curve from first crack to failure. The post-cracking energy absorption calculated for the beams ranged from 36 to 492Nm (Table 7). These values are quite low as compared to those of reinforced concrete beams using reinforcing steel bars as both bending and shear reinforcement (Kankam and Adom-Asamoah, 2002). These very low values recorded for bamboo reinforced beams show that the bamboo has low ductility and will not give adequate warning prior to failure. Since the post-cracking energy absorbed is a function of the applied load and ultimate displacements, it is affected by factors that affect flexural behaviour in beams such as the span-depth ratio, grade of concrete, percent tension reinforcement and shear reinforcement. It therefore follows that beams with optimum tension bamboo reinforcement and higher grade of concrete will absorb higher post-cracking energy compared with those of similar characteristics but lower grade of concrete.

Cracks widths in low strength concrete were comparatively large with the larger crack widths recorded in beams with low amount of tension bamboo reinforcement that exhibited diagonal cracks. The maximum cracks measured ranged between 2 to 8mm. In all only two (2) of the beams (BBR4 and BB1) beams exhibited crack widths lower than the 3mm limit set by BS8110 for structural concrete. The range of crack widths at failure is indicative of the fact that the beams may be susceptible to termite attack if loaded beyond a certain threshold. The deflections at first crack and failure were in the respective ranges of 0.10-2.78mm and 7.3-20.15mm. There seemed to be no particular order in which the deflections varied for the different stirrup types even though the beams with steel stirrup appeared to perform better than beams made using bamboo and rattan cane stirrups.

Table 7: Post -cracking deflection and energy absorption of beams

Beam No	Deflection at first crack d_{cr} (mm)	Deflection at failure d_{max} (mm)	d_{cr}/d_{max}	Post cracking strain energy (Nm)
BBR1	1.230	10.71	0.11	79.486
BBR2	1.780	9.11	0.20	79.413
BBR3	1.372	13.15	0.10	162.809
BBR4	1.892	10.19	0.19	104.680
BBR5	2.780	17.89	0.16	206.943
BBR6	1.780	21.34	0.08	492.283
BBR7	0.820	15.88	0.05	431.261
BBR8	0.635	12.59	0.05	239.196
BB1	1.570	7.30	0.22	36.291
BB2	1.820	13.64	0.13	164.771
BB3	0.950	16.97	0.06	198.274
BB4	0.200	18.68	0.01	244.947
BB5	0.600	11.90	0.05	241.275
BB6	0.250	15.94	0.02	404.732
BB7	0.700	14.75	0.05	339.594
BB8	0.100	20.15	0.00	469.208

4.5 Beam Performance Index (BPI)

In structural engineering practice, performance has been made synonymous to strength for several decades when there seemed to be little understanding of structural behaviour. Therefore, the more strength a structure possessed, the higher the performance level attributed to it. This definition is not entirely true because a displacement parameter (eg. deflection, rotation, strains etc) is as important as the force parameter (eg. force, moment, torque etc). The inclusion of the displacement parameter helps capture the nonlinearity in the failure process. As observed from the experimental results (Tables 4 and 5), even though the beams with steel stirrups failed at the highest loads, the deflections at failure for those beams were not the highest in 3 out of 4 cases of the corresponding beam groupings (BBR2-BBR4, BBR6-BBR8, BB2-BB4 and BB6-BB8).

Therefore, the definition of performance in this research is a function of both the applied loads and the central deflections of the beams. This is measured as the work done or energy absorbed by the beams from the onset of cracking to failure which is the same as the post-cracking strain energy of the beams as shown in Table 5. The use of energy absorbed as a definition of performance is still insufficient. A more rationale definition in the opinion of the authors is one which incorporates the cost incurred in absorbing energy or doing work. A more practical measure of structural performance for the beams is introduced. This will be called the beam performance index (BPI) which measures the amount of energy absorbed or work done per unit cost of constructing the beam.

$$BPI = \frac{\int_{PcrDcr}^{PfDf} PD}{Cost\ of\ beam} \tag{3}$$

where; P-applied load; D-central deflection; P_{cr}-first crack load; P_f-failure load; D_{cr}-deflection at first crack; D_f-deflection at failure

The material and labour cost for the beams having web reinforcement are employed in estimating the total cost of beams shown in Table 7. Since the cost of concrete is the same for the same grade, the difference in cost of the beams is expected to come from whether the material is available locally or imported. This was however not the case. The cost of rattan cane was the highest as a result of the fact that it is used in the lucrative furniture industry and therefore was sold in the open market for four times the price of reinforcing steel bars. The bamboo trees were the cheapest. The cost of workmanship in terms of preparing the materials as stirrups increased in the order of steel, cane and bamboo. The availability of steel benders on the local market for steel bars used in reinforced concrete construction resulted in low workmanship costs for the steel bars. The time required to cut the bamboo tree into strips, cut the strips into pieces and tie the pieces into stirrups made the bamboo stirrups the most expensive in terms of time-input. The high cost of the rattan cane material was the most significant factor that made the rattan stirrup beams the most expensive to produce, followed by the bamboo stirrup beams with the steel stirrup beams the cheapest.

Therefore the total cost per beam (material and labour cost) in US$ (United States dollar) is shown in Table 8. The BPI values derived from the post-cracking energy absorbed and the cost per beam are such that for each group of beams (BBR1-BBR4, BBR5-BBR8, BB1-BB4 and BB5-BB8) the beams reinforced with steel stirrups (BBR3, BBR7, BB3 and BB7) obtained the highest BPI. The beams without stirrups (BBR1, BBR5 and BB5) surprisingly performed better in terms of BPI as compared to the corresponding beams having rattan cane as shear stirrups. Therefore the cheapest and most economical means of providing shear reinforcement for bamboo-reinforced beams according to the BPI is the use of steel stirrups and the most expensive is by rattan cane stirrups irrespective of the grade of concrete. The cheapest concrete also seemed to perform better in terms of cost-effectiveness when compared with a higher grade of concrete for beams of similar characteristics. The advantage of using the BPI is that it captures both the nonlinear behaviour in the structural performance and the cost of the beam. These two aspects of design and construction performance are important to both the designer and the client. The limitation of the BPI model in the opinion of the authors is that the nonlinear behaviour must be calibrated from project to project.

Table 8: Beam Performance Index (BPI)

Beam No.	Stirrup Type	Total Cost (US$)	BPI (J/US$)
BBR1	No stirrup	5.86	13.56
BBR2	Bamboo stirrups	9.06	8.76
BBR3	Steel stirrups	7.80	20.87
BBR4	Cane stirrups	15.40	6.79
BBR5	No stirrup	8.20	25.23
BBR6	Bamboo stirrups	15.96	30.84
BBR7	Steel stirrups	10.86	39.71
BBR8	Cane stirrups	18.46	12.95
BB1	No stirrup	5.00	7.25
BB2	Bamboo stirrups	8.00	20.59
BB3	Steel stirrups	6.80	29.15
BB4	Cane stirrups	14.46	16.93
BB5	No stirrup	8.20	29.42
BB6	Bamboo stirrups	11.20	36.13
BB7	Steel stirrups	9.00	37.39
BB8	Cane stirrups	16.86	27.83

5. Conclusions

A study of the shear strength of bamboo reinforcement concrete reveals that concrete members reinforced with sections of bamboo culms, which had been split along their horizontal axes, developed considerably higher load capacities than unreinforced concrete beams of similar sections. The ductility of tension bamboo reinforcement is low and failure of beams is characterized by splitting of concrete from the tension reinforcement and brittle failure. The shear capacity is enhanced by increased amount tension reinforcement and addition of web reinforcement. The strength of concrete influences the shear capacity and the failure mode of the concrete in a way that low strength concrete cause concrete crushing before the full shear capacity is reached. The predominant failure mode of bamboo reinforced concrete beams was shear even though they were all adequate in theoretical shear capacity. The highest and lowest failure loads were recorded for the cases of steel stirrups and no stirrups respectively. The cheapest and most economical means of providing shear reinforcement for bamboo-reinforced beams according to the BPI derived in this research is steel stirrups and the most expensive means is by rattan stirrups irrespective of the grade of concrete. It is therefore recommended that bamboo reinforced concrete beams are reinforced with steel stirrups to improve on its load carrying behaviour.

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