STRUCTURAL EFFECTS OF STEEL LAMINATION MECHANISM ON AFRICAN BIRCH (*Anogeissus Leiocarpus*) TIMBER BEAMS

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ABSTRACT

Timber is a renewable, environmental friendly and economical structural material. However, it has a lower mechanical performance when compared with reinforced concrete. It has natural defects which causes brittleness. Thus, limits its usage in structural construction. This paper investigates the structural effects of steel reinforcement on African birch timber beams. The experimental test was a three point bending in a simply supported setup with a span of 0.7m. The samples were divided into three (3) groups: unreinforced, plate-reinforced and rod-reinforced timber beams with three (3) samples each. Each sample was loaded and tested until flexural failure occurred using universal testing machine (UTM). The reinforcement percentage ratio of plate-reinforced and rod-reinforced timber beams were 3.75% and 2.5% respectively as compared with unreinforced timber beam. Excluding an odd unreinforced timber beam sample labelled B3, the experimental test show that plate-reinforced beams and rod-reinforced beams increase in moment by 21.3% and 145.3% respectively; increase in deflection by 17.5% and 23.0% respectively, and increased in stiffness by -18.9% and 139.8% respectively. It was observed that bonding imperfections and grooving significantly affected the performance of the reinforced beams especially in the deflection and stiffness. The variability in structural performance of reinforced timber beams is lower than unreinforced timber beams in moment and deflection, except for stiffness. The variation in stiffness for the cases was due to bonding imperfection of the steel to timber at the elastic phase of the reinforced timber beams.

Keyword: - *timber, reinforced concrete, plate-reinforced, rod-reinforced, deflection, moment, stiffness*

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1. INTRODUCTION AND CONCEPT

Timber is a renewable, environmentally friendly, and economical structural material. This is because it is a naturally grown material. Despite its numerous advantages, it has relatively lower flexural strength and stiffness when compared with reinforced concrete. These lower mechanical properties are further negatively affected by the presence of natural defects [1]. The effort to overcome these natural defects of timber, improvement of mechanical performances while utilizing the other numerous advantages of timber pushes for various researches in timber reinforcements. [1,2,3]. These reinforcements are coupled to timber with either adhesive or bolts, resulting in a composite material [5].

Timber is a natural, anisotropic and inhomogeneous material. It exhibits natural defects such as misalignment of grain, presence of knots, among others [4]. These natural defects majorly affect their flexural strength negatively, which causes it to experience brittle failure when heavily loaded. Unlike its flexural strength, timber natural defects do not adversely affect its compressive strength. This is because the compressive strength increases with natural defects; since there are contacts between the timber elements. The characteristic compressive strength of timber is greater than the characteristic flexural strength though the inverse exists for the mean strength value [6]. In order to complement this timber natural defect for better structural performance, a reinforcing technique used for concrete is also introduced for timber. As in concrete, the method is adopted to take care of different failure modes of flexure, shear and compression. For timber reinforcing against these failures, several reinforcing materials, shapes and mechanisms have been investigated and successful. The reinforcing materials include steel, aluminum and fiber-reinforced polymers. Also, the reinforcement shapes include plate, rebar and cable. The reinforcement mechanisms also vary based on failure modes; it can be reinforced at the bottom, top, and/or sides. These reinforcing techniques have yielded positive results.

One of the critical areas of timber reinforcement is the transfer of stresses between the timber and the reinforcement. In several researches, delamination is one of the greatest challenges in timber reinforcement [7]. Different bonding materials have been adopted to join timber with reinforcement to overcome this challenge. These different bonding materials have peculiar usage based on the reinforcement material. Fiber-reinforced polymer is bonded to timber with epoxy resins, while steel is bonded with screw or epoxy resins. These bonding materials have been investigated and proven successful.

1.1 Arican Birch

African birch (Anogeissus Leiocarpus) is locally referred to as Ayin, Kojoli, Atara, Marke in Yoruba, Fulani, Igbo, and Hausa respectively [9]. It is a tall deciduous tree, which can grow up to a height range of 15 - 30m with a diameter of as much as 1m. It has a greyish and scaly bark and its branches are often dropping and slender. Its leaves are alternate, ovate-lanceolate in shape, 2-8cm long and 1.3-5cm across. Its flower clusters have globular head forms, 2cm across and yellow. These flowers as shown in Figure 1.0 are bisexual and are without petals. Its fruits are globular cone-like heads. Each fruit is broadly winged, dark grey and 3cm across. It can be replanted by seeds or vegetative propagation[9].

Figure -1: Trunk and branches of African Birch
(Source: Birnbaum, 2007)

1.2 Flexural strengthening of Timber Beams

Flexural deformation is a primary failure mode in timber beams, despite the stronger strength of mechanical properties in the direction parallel to grain. This is due to the direct loading on the longitudinal suspended structural element, and also the limited flexural capacity of the timber. The limited flexural capacity of the timber is further affected by the presence of natural defects in it. It is when this type of failure is forestalled that shear failure can occur under increased loading.

[7] examined the performance of pre-stressed structural timber beams. Three (3) series of samples were originally scheduled for the testing program. Series 1 consists of solid (unreinforced) glulam beams, which serve as the control beams. Series 2 is a set of sound glulam beams which is pre-stressed through cambering. Series 3 is the damaged

control beams (series 1) which are repaired and reinforced with passive CFRP strips, so as to evaluate the strength recovery provided by the rehabilitation procedures. The test showed that series 1 collapsed with a failure crack at a defect (knot) or finger joint on the tension zone. In series 2, as the load approaches the ultimate, fiber crushing was noticeable on the compression side. However, collapse failure occurs by shear failure (or delamination) at the timber-CFRP laminate interface. The pre-stressing enhanced the flexural strength by 26%, and the ultimate deflection more than doubles. In series 3, the failure mode was similar to series 2, however, it did not look as sudden as in series 2. The average strength enhancement towards the control beams was 19%. Series 4 and 5 (rehabilitated beams) recovered about 50% of the original solid glulam beam strength. The adhesive used was epoxy resin (sikacarbodur). [4][2]. studied CFRP which was used instead of steel plate. The experimental work was divided into two parts: Series 1 and Series 2. Series 1 was done using a nearly clear and relatively small specimen. In this series, the applied bending stress in the timber during the bonding of CFRP lamella was varied and three adhesives were tested. The most promising parameters of series 1 were used for series 2, which was produced using $GL24h^3$. Pre-stressing was achieved through cambering. For series 1, SD-330 was found to be the most promising adhesive out of the three and adopted for series 2. The first failure observed in series 1 was crushing on the compression side of the beam (before ultimate failure at tension). In series 2, the induced bending stress during the bonding of CFRP lamella was 20MPa. Its failure mode was a local failure in the compression zone before splitting (breaking) in the tension zone occurs, unlike non-reinforced beams.

2. MATERIALS AND METHODOLOGY

The materials used for this study includes:

- Timber (*Anogeissus Leiocarpus*)
- Steel plate
- Steel rod
- Screw

2.1 Material Selections and Criteria

Timber

From all available wood in Nigerian market, *Anogeissus Leiocarpus (Ayin)* was chosen because it is the commonest West African species of the Anogeissus genus. It has anti-feedants and physical toughness that makes it termite resistant [8]. The timber was sawn to approximately 2x2 inches size. This size was chosen from all standard market sizes for it to meet the standard span-to-depth ratio of 14 for wood, because the Universal Testing Machine used for the flexural testing has a maximum span capacity of one meter including the overhang as shown in Figure 2.

Figure -2: Sawing of Ayin Timber

Steel

For the reinforcement of the timber section, steel was chosen over fiber reinforced polymer (FRP) because it is the material that we are traditionally accustomed with. It is significantly cheaper, needs less expertise and is highly ductile unlike FRP [5]. The steel reinforcement geometry types used to reinforce the timber beams were either plates or rods. These geometry types were chosen due to their market availability and common usage in building construction. There is no standard for maximum or minimum steel reinforcement ratio for a timber cross-sectional area unlike reinforced concrete. In reinforced concrete, for a concrete cross-sectional area, the maximum steel ratio is 4%bh and minimum steel ratio are 0.13%bh and 0.2%bh for tension and compression reinforcement respectively. Where b and h represent cross-sectional breadth and height of the reinforced concrete section. Thus, full steel plates of approximately 2mm thickness (1.67mm precisely, equating to 3.75% of timber cross-sectional area) were screwed at 150mm spacing beneath the three timber beams of group BP, while an S410 steel rod of approximately 10mm diameter (9.55mm precisely, equating to 2.5% of timber cross-sectional area) were clamped (with U-shaped steel plate) and screwed at 150mm spacing beneath the three timber beams of group BR.

2.2 Material Procurement

Timber

The specie of timber sought was Ayin (*Anogeissus Leiocarpus*). It was procured and sawn into required sizes at Odo-Okun Sawmill Area, Ilorin as shown in Figure 2.1 above.

Steel: The steel plates and rods were obtained from metal place at Odo-okun and Surulere (Ilorin) respectively.

2.3 Material Preparation for the experiment

Timber: The stem was processed through the following steps:

Sawing and Grooving

The tree log was sawn into smaller sizes from which 1m long samples of approximately 2x2 inches (38x48mm) and 2x3 inches (42x68.5mm) cross-sectional area were extracted. These cross-sectional areas were used because they are two of the market standard sizes that is adequate for the required span-to-depth ratio. The numbers of 38x48mm and 42x68.5mm samples were six and three respectively. A length of 1m long timber beams was adopted because that is the maximum span capacity of the UTM (Universal Testing Machine). The 42x68.5mm timber section was increased from 38x48mm because the group is to be grooved. This increase is to prevent any reduction in the timber flexural capacity due to the grooving. The 3 test sample groups are shown in Figure 2.14. It was ensured that the timber prepared was straight and has fewer defects. A total number of nine (9) timber samples were prepared for this study.

2.4 Method

The methodology used to achieve the research objectives are as follows;

2.2.1 Preliminary Timber Property Test

Determination of the physical and mechanical properties of Ayin (*Anogeissus Leiocarpus).* The desired properties of the timber beams were tested following the procedures contained in BS 373 (1957).

Physical properties

The physical properties obtained from the samples are: geometrical dimensions, moisture content and density.

a) Geometrical dimensions

This is the measurement of sample cross-sectional and longitudinal specifications using a vernier calliper (see Figure 2).

Figure -3: Sample Measurement with Vernier Caliper

b) Moisture Content

This is the quantity of water contained in the timber. It is usually expressed as a percentage of the mass of oven-dried wood. Six samples of sizes 50x50x50mm were collected from the timber samples for this test. The same samples that were used for moisture content determination were also collected for density determination. Equation 1 and 2 were used to determine the moisture content and density of the tinber.

$$Moisture\ Content\ (\%) = \frac{Original\ mass - Oven\ dried\ mass}{Oven\ dried\ mass} \times 100 \qquad (1)$$

$$Density = \rho = \frac{Mass}{Volume}\frac{g}{cm^3} \qquad (2)$$

2.2.2: Preliminary Mechanical Property Tests

Timber

The determination of various mechanical properties was done in accordance with BS373:1957 standard code. The material tests were carried out with the use of 50kN Universal Testing Machine (UTM) at the Department of Mechanical Engineering, University of Ilorin. Samples were reduced from standard specification in BS 373:1957 to fit into UTM capacity.

a) Tension Strength Parallel to the Grain

Dog-bone-shaped samples as shown in Figure 4 were tested in UTM (see Figure 5) to obtain the tensile strength parallel to the grain. After the test, the tensile strength parallel to the grain was calculated using Equation 3.

$$Tensile\ Strength = \frac{Force\ at\ failure\ (N)}{Minimum\ cross - sectional\ area\ (mm^2)} \qquad (3)$$

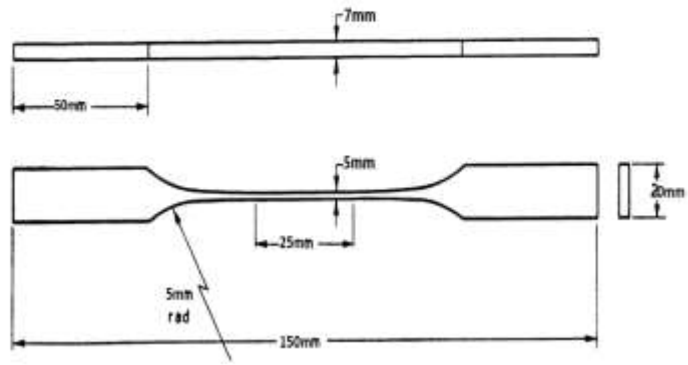


Figure -4: Typical Dog-Bone Sample Size

Figure -5*:* Tensile Test for Ayin Timber in UTM

c) Compression Strength Parallel to the Grain

8 Timber blocks were crushed in a direction parallel to the grain using the UTM, to obtain their compressive strength. The dimension of the blocks is 25x25x100mm as shown in Figure 6. This dimension is a reduction of the standard provision in BS 373:1957. The reduction was necessary because the 50kN capacity UTM could not crush the previously prepared standard size of 50x50mm cross-sectional area. After the test, the compressive strength parallel to the grain was calculated using Equation 4.

$$Compressive\ Strength = \frac{Force\ at\ failure\ (N)}{Cross - sectional\ Area\ (mm^2)} \quad (4)$$

2.2.3 Main Flexural Test of Steel Laminated Timber beams

Steel Coupling to Timber

After preliminary testing of the timber and steel, both were coupled to make a composite beam. This coupling was done with the use of bolt at 150mm intervals at a metal place in Odo-Okun area. Steel plates and rod are bolted to the bottom face of the timber beams as shown in the Figure 6. Figure 7-10 show the experimental setup of the flexural test, for the unreinforced and reinforced timber beams. This setup is a three-point flexural loading, which is in accordance with BS 373:1957. A Testometric FS300 universal testing machine was used for the test, with a load cell capacity of 300kN. The rate/speed of downward loading displacement was kept constant at 10mm/min until failure. The reinforcements used for the timber beams are steel plates and rods. Table 1 and 2 show the timber and steel information.

Figure -6*: Steel Reinforced Beam Samples*

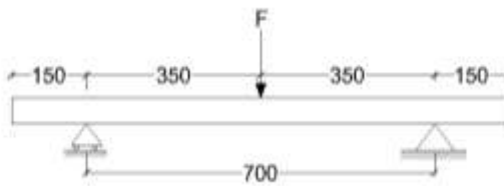


Figure -7*:* Flexural Test Setup

Table -1: Timber Specimen Information

Beam configuration	Beam names	Dimensional Properties (mm) Width (mm)	Height (mm)	Length (m)
Unreinforced Control Beam	B1	37.00	48.90	1
	B2	39.62	48.90	1
	B3	38.10	46.80	1
Steel Plate Reinforced Beam	BP1	40.21	47.65	1
	BP2	39.01	48.90	1
	BP3	38.19	47.97	1
Steel Rod Reinforced Beam	BR1	41.86	69.53	1
	BR2	40.73	67.43	1
	BR3	42.99	68.60	1

Table -2: Steel Reinforcement Information

Series reference	Numbers of replicate	Location of reinforcement	Shape/Type of reinforcement	Size of reinforcement	% reinforcement ratio	Reinforcement bond type
BP	3	bottom	Steel plate	1.67x38mm	3.75	Screwed
BR	3	bottom	Steel rod	9.55mm Ø	2.5	Clamped & Screwed

The average cross-sectional area of timber beams is $1824\,mm^2$ (38x48mm), with the exception of rod-reinforced beam that is grooved. The average cross-sectional area of rod-reinforced beam is $2877\,mm^2$ (42x68.5mm). The cross-sectional area of steel plate and rod are $63.5mm^2$ (1.67x38mm) and $71.6mm^2$ (9.55mm diameter) respectively.

3. RESULTS AND DISCUSSION

The result of moisture contained in the wood is presented in Table 3. Moisture content: The average moisture content of Ayin in the test is 24.55%, which falls below the fibre saturation point (FSP). The FSP is usually between 25-30% moisture content.

Table -3: Samples Moisture Content

Samples	Wet mass (g)	Oven dried mass (g)	Moisture Content (%)
A	134	107.5	24.65
B	155	124	25.00
C	112	90	24.44
D	164	132	24.24
E	170	137	24.09
F	147	117	25.64
G	129	102.5	25.85
H	122	98.5	23.86
I	138	111	24.32
J	129	104.5	23.44
Average			24.55

Density: The results of sample density are presented in Table 4. Density of Ayin timber: The average density of African birch timber is obtained to be 1080kg/cm3 (1.08g/cm3). As stated in BS 5268 (structural use of timber), the density ranges from 610 to 1150kg/m3 belongs to strength class of D30 – D70 (hardwood). This shows that the Ayin timber is a hardwood since the values obtained are greater than 640kg/m3. Also, according to Findlay (1975), African birch is classified as a very heavy wood.

Table -4: Density Results

Sample	Volume (mm3)	Weight (g)	Density (g/cm3)
A	480000	535	1.11
B	493500	525	1.06
C	494900	506.5	1.02
D	427500	467	1.09
E	499200	542	1.09
Average			1.08
SD			0.00099

Figure 8-10 show the graphs for the timber strengths. The maximum stress of Ayin is 63.760N/mm2 at 24.55% moisture content. This is about 16% strength of high yield steel and about 26% of the strength of mild yield steel. Which shows that Ayin is less ductile than any of the above mentioned steel. Maximum compression stress of timber: The maximum compression stress of Ayin is 54.477N/mm2. Compared to grade 25 of concrete, 218% strength of grade 25 concrete. Which shows that Ayin is compressively stronger than grade 25 concrete. The average compressive strain of Ayin is 5.38% while that of concrete is 0.35%, this shows that Ayin is less brittle than concrete.

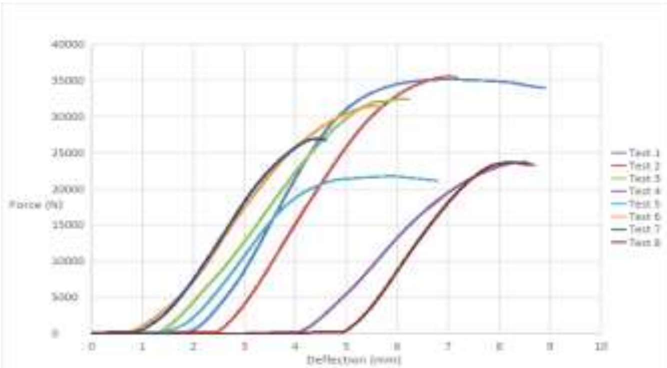


Figure -8: Compression Test Graph for Ayin

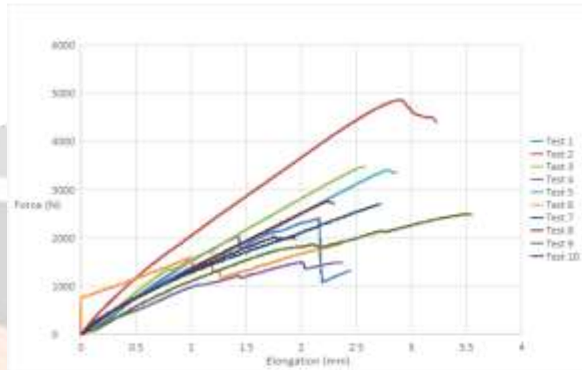


Figure -9: Tensile Test Graph for Ayin

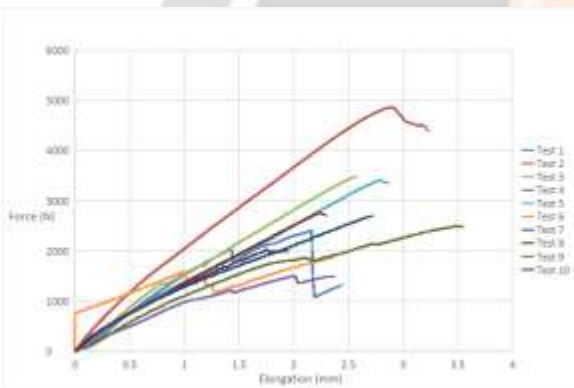


Figure -10: Tensile Test Graph for Steel Plates

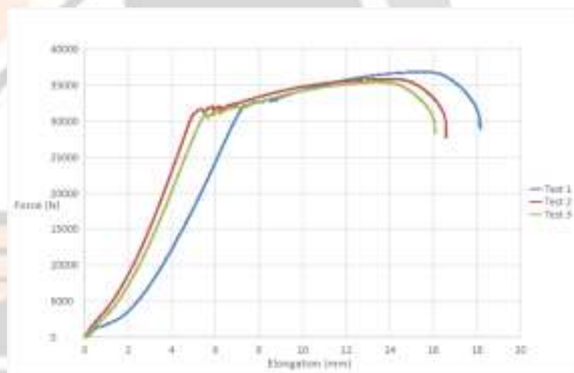
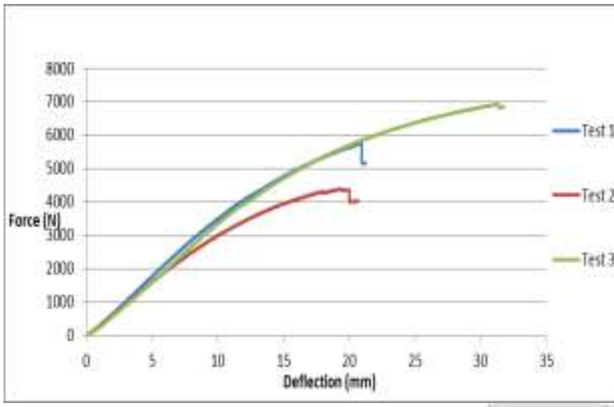


Figure -11: Tensile Test Graph For Steel Rod

Main Flexural Test Result on the Composite Beam

From Figure 12-16, the odd unreinforced beam B3 is excluded, the average experimental load/moment capacity increase is 21.3% and 145.3% for BP and BR series respectively. The experimental results show that the reinforced beams has lesser variability of load and moment when compared to unreinforced beams. Unreinforced, plate-reinforced and rod-reinforced timber beams has load standard deviation of 1.275kN, 0.113kN and 1.172kN respectively, while the moment standard deviations are 0.2232kNm, 0.0198kNm and 0.205kNm respectively. This shows that timber reinforcement reduces variability of failure load and moment induced of beams.



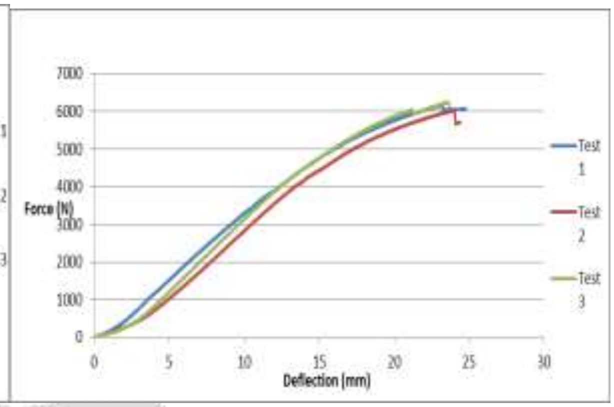


Figure -12: Steel Rod Unreinforced Timber Beams ***Figure -13:*** Plate Reinforced Timber Beams

The average experimental load and induced moment increased from B series by 8.1% and 118.5% for BP and BR series respectively. Excluding the odd unreinforced beam B3, the average experimental load/moment capacity increase is 21.3% and 145.3% for BP and BR series respectively. This shows the positive effect of the reinforcement on the load/moment bearing capacity of the beam. There is an average decrease in the experimental deflection of BP series by 0.931% and average increase in the deflection of BR series 3.726% of B series. Excluding the odd unreinforced beam B3, there is an average increase in the experimental deflection of 17.475% and 22.997% for BP and BR series respectively.

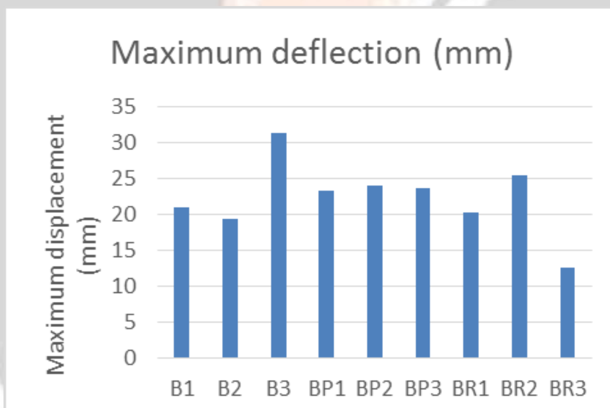


Figure -14: Load capacity at rupture of timber beams

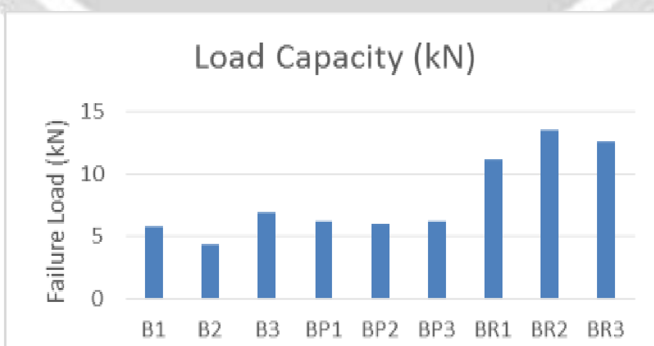


Figure -15: Load capacity at rupture of timber beams

From Figure 3.10, the stiffness capacity of the beams is a ratio of force to deflection. The force used to calculate the stiffness is the difference between 40% and 10% of the ultimate force (load) and their corresponding deflections. This is to calculate the elastic state of the beam and neglecting the plastic state. The experimental stiffness variability of reinforced beam is greater than unreinforced beam. The value is 0.0202, 0.0311 and 0.1117 kN/mm for B, BP and BR series respectively. This greater variability for reinforced timber at elastic phase can be due to bonding imperfection between the steel and timber (slightly wide screw spacing, screw punching, and slightly large groove sizes), which can influence the start and behaviour of reinforcement effect during the beam loading. Pre-cambering of reinforcement is a good solution to this problem.

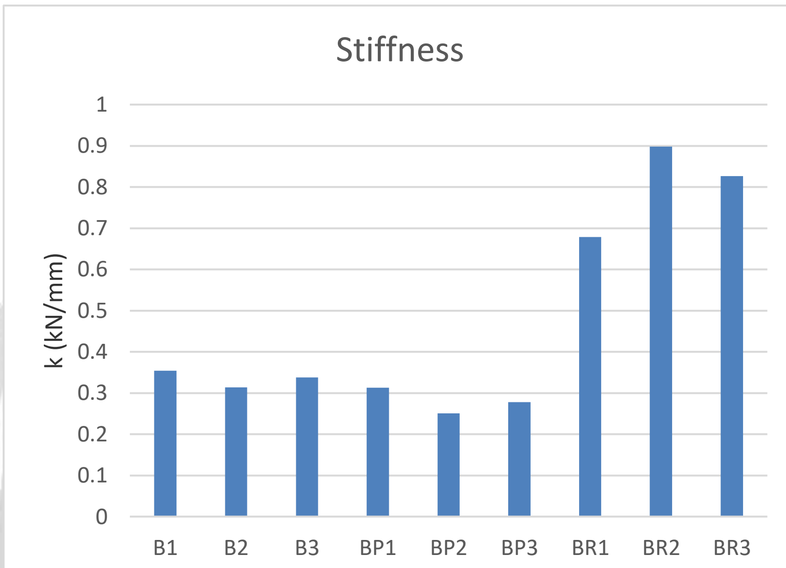


Figure -16: Stiffness Capacity of Timber Beams

4. CONCLUSIONS

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The following conclusion may be drawn from the research regarding reinforcement of African birch timber beams with steel plate and rod:

i. In the physical property test, the density of Ayin shows is 1.08g/cm^3 (1080kg/m^3) that it is a hardwood and its moisture content is 24.55% which falls below the fibre saturation point.
ii. For African Birch timber, the mechanical property test of Ayin timber reveals that the bending modulus is 6051.5N/mm^2. The maximum compression strain and stress is 5.38% and 54.477N/mm^2 respectively. The maximum tension strain and stress is 7.266% and 63.760N/mm^2 respectively.
iii. The average modulus of elasticity for steel plate and rod is 26095N/mm^2 and 18769N/mm^2 respectively.
iv. Plate-reinforced timber beams with 3.75% reinforcement ratio has an average percentage increase in ultimate load of 8.1%. The average percentage decrease in deflection of 0.931%. The average percentage decrease in stiffness is 16%.
v. Excluding odd unreinforced control beam B3, the plate-reinforced timber beams has an average percentage increase in ultimate load/moment and deflection capacity of 21.3% and 17.5% respectively, while the

stiffness has an average percentage decrease of -18.861%. The cause of unexpected decrease in plate-reinforced stiffness can be explained to emanate from imperfect reinforcement coupling to timber.

vi. Rod-reinforced timber beams with 2.5% reinforcement ratio has an average percentage increase in ultimate load/moment of 118.5%, average percentage increase in deflection of 3.726%, and average percentage increase in experimental stiffness of 134.4%.

vii. Excluding odd unreinforced control beam B3, the rod-reinforced beams has an average percentage increase in moment/load capacity, deflection and stiffness of 145.3%, 23% and 139.8% respectively.

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