

Design and Fabrication of a Gazebo Using Cross-Laminated Timber Beam and Column Made from *Mangifera Indica*

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Abstract

Senescent fruit trees have structural potential but are limited by short trunks and small girths, necessitating their use in engineered wood products (EWPs). However, information on their viability as EWPs for affordable housing is sparse. This study assesses the flexural performance of cross-laminated *Mangifera indica*. Samples were collected and air-dried. The manufacturing process involved crosscutting, planning, adhesive application, panel lay-up and assembly pressing. Preliminary tests were conducted. The samples were loaded in-plane, and their flexural properties were evaluated. ANOVA was performed on the flexural properties of solid wood, CLT (major axis), and CLT (minor axis) at $P = 0.05$. A gazebo was designed, and a scaled-down model was fabricated. The average MC and density were 10.03% (± 1.49) and 579.45 kg/m³ (± 70.99) respectively. The average MoE for the solid specimen was 23484.86 MPa (± 3238.83), and the average MoR was 64.91MPa (± 15.83). The average MoE of CLT samples loaded in the minor strength axis was 16945.821Mpa (± 2389.66), and the average MoR was 44.69MPa (± 22.62). The average MoE for the CLT in the major strength direction was 13981.72Mpa (± 8057.40), and the average MoR was 15.09MPa (± 10.41). ANOVA revealed significant differences: solid wood had the highest strength

and stiffness, while CLT (major axis) was the weakest. Although solid *M. indica* exhibited significantly higher strength and stiffness, attributable to weak interfacial bonding in glue lines, CLT values remained within the acceptable range for structural applications, indicating that CLT can increase span from short trunk *M. indica* trees without excessively compromising strength, suggesting promising applications for innovative construction.

Keywords: *Mangifera indica*, CLT, Construction, Affordable housing, innovative construction technologies

1. Introduction

The choice of construction material is determined by its availability, affordability, eco-friendliness, and low energy requirements for manufacturing (Breyer et al., 2006). Compared to concrete and metals, wood fits this category well and has consistently been a vital and sustainable building material for load-bearing structural elements. Different species of wood serve different purposes, and specific salient properties, such as wood's bending and mechanical properties, are of immense significance to their use in structural applications (Dinwoodie, 2000). This has created unparalleled exploitation of familiar economic wood species over the lesser-known species, the escalating decline in wood supply in Nigeria, driven by overreliance on traditional economic wood species and unsustainable logging practices, which have generated considerable concern for more than two decades (Adewole & Bello, 2013). The diminishing availability of familiar wood species encourages the exploration of non-traditional economic wood alternatives (Lucas et al., 2006; Adewole & Bello, 2013). using lesser-known but potentially viable wood species, such as wood sourced from fruit trees, could augment conventional construction materials (Olorunnisola, 2022).

In Nigeria, various trees produce fruits and wood, making them essential resources that offer economic advantages by producing fruits and Timber. (Areo et al., 2023), one such tree species is *Mangifera indica*. However, there is sparse information on its strength potential as an affordable building material. The mango tree species available in Nigeria are known for having a relatively short trunk with much branching, resulting in a wide-spreading tree structure. This morphological characteristic is common in

mango trees for a strong base and gradual taper along the trunk for stability and fruit production (Balamohan et al., 2010).

Although *Mangifera indica* are fast-growing and can survive for over 100 years before dying (Bally, 2006), with time, they become senescent and less viable in fruiting between 20 to 50 years of fruiting (Hiwale & Hiwale, 2015). Also, land clearing during building and infrastructure construction often results in the felling of *Mangifera indica* trees, which are typically disposed of or burned. Therefore, exploring ways to add value to this resource is important. According to Areo et al. (2015), the strength values of *Mangifera indica* were obtained compared with the strength values of other economic species, revealing properties similar to *Antiaris africana* and *Hildegardia bateri*. The researchers also observed a significant variation in strength properties along and across the tree (transversely). Rahmon et al., 2019 reported that *M. indica* timber with a modulus of elasticity of 20573.88MPa is viable in application as a structural member. However, the morphological characteristics of the species available in Nigeria, such as its short trunk, limit the spans that may be producible for structural members. It is therefore important to assess how this limitation of the use of *Mangifera indica* in construction can be addressed by engineering the material.

Engineered wood products (EWPs) are manufactured composite materials made from hardwoods and softwoods. These products undergo treatment to improve their quality. EWPs include various product categories, production techniques, and applications. EWPs include plywood, laminated veneer lumber (LVL), glued laminated Timber (GLT) and cross-laminated Timber (CLT) (New Nordic Timber, 2019). The traditional cross-section of CLT panels comprises at least three orthogonal layers of boards. Mass timber structures using CLT components are now commonplace for mid- to high-rise buildings up to 30 stories (Brandner et al., 2016).

The US CLT industry is growing, so the CLT product standard (ANSI/APA PRG 320) was created to provide guidelines for producing CLT panels.

Traditionally, softwood timber is used to make CLT panels. However, the forest products industry is working to establish a CLT manufacturing sector that spans the entire nation in response to the growing demand for CLT products in residential and

commercial construction. A range of Indigenous species will need to be used for this (Yunxiang et al., 2021). The possible use of hardwood species in CLT products has been the subject of several global investigations. Ehrhart et al. (2015) and Ehrhart & Brandner (2018) examined several European hardwood species using planar shear tests and demonstrated that they may be used in the production of cross-laminated Timber (CLT). These species included poplar (*Populus* spp.), silver birch (*Betula pendula* Roth), European beech (*Fagus sylvatica* L.), and European ash (*Fraxinus excelsior* L.).

Focusing on *Mangifera indica*, a deciduous tree primarily cultivated for its fruits, this research aims to engineer cross-laminated timber beams using this wood species that is not primarily utilised for that purpose. This study seeks to assess the properties of cross-laminated *Mangifera indica* with a view to expanding the obtainable span from the trunk and enhancing the structural properties of these species by cross-lamination, particularly when loaded in the plane. This study offers innovative solutions to the challenges of wood supply in Nigeria by investigating the viability of *Mangifera indica* as CLT structural elements. Ultimately, the study contributes to reducing the knowledge gap regarding the usage of deciduous trees for CLT production.

In this paper, Chapter 1 introduces the study's rationale and objectives. Chapter 2 outlines the methods used in constructing CLT and justifies their selection. Chapter 3 presents comparative findings between various CLT panels and solid wood of the same *M. indica* species, identifying optimal lamination configurations and potential applications for affordable housing. Finally, Chapter 4 summarises the findings, assesses the suitability of *M. indica* in affordable housing construction, and proposes recommendations for further research.

2. Research Methodology

This project was conducted in five stages to explore the potential *Mangifera indica* as CLT structural elements to address wood supply challenges in Nigeria and reduce the knowledge gap on deciduous tree use in CLT production and affordable housing construction. The first stage was harvesting senescent *Mangifera indica* wood from the University of Ibadan. The second phase was the processing of the *Mangifera*



indica cross-laminated and solid specimens, and the third phase involved the material's testing and the recording of results obtained. The fourth phase entailed the design of components of a typical simple Gazebo using available baseline data of *M. indica* wood. The fifth phase was fabricating a scaled-down model of the typical simple gazebo.

At the collection site, the logs were crosscut into billet sizes of 50.8mm thickness, 152.4mm width and about 1219.2 mm length for fabrication of CLT—also 152.4mm thickness, 152.4mm width and 1219.2mm long for the solid beam production. The lumbers were transported to the wood structures workshop at the University of Ibadan, which doubles as the drying site. The green M.C content was taken using the moisture meter and recorded at 26 °C until nearly uniform moisture content was obtained. This reduced moisture variation across samples, which could introduce strength variations. In compliance with PRG-320 (Standards for Performance-Rated Cross-Laminated Timber, ANSI/APA PRG 320, American National Standard, 2012), the moisture content (MC) was reduced to around 12%. The Timber was then visually graded in accordance with the grading rules established by the National Hardwood Timber Association (NHLA).

The density of *M. indica* wood at dry moisture content was conducted as per ASTM D198 using Equation 1.

$$p_i = \frac{M_i}{V_i} \dots \dots \dots (Equation 1)$$

Where P_i = density (Kg/m^3), M_i = Mass (kg), V_i = Volume (m^3)

CLT Manufacturing and Sample Production

The dimensions of the cross-laminated specimen were dimensionalised in compliance with ANSI/APA PRG-320 2019, “Standard for Performance-Rated Cross-Laminated Timber”. Altogether, three layers of laminates made the fabrication of CLT in both the major strength direction, which runs parallel to the laminations' strength direction in the panel's outer layer, and the minor strength direction, which runs perpendicular to the inner layers' grain direction and is the major strength direction of the CLT panel.

M. indica wood was cut into plies to enable CLT production. 45 sizes of 31.225 mm x 16.7 mm x 1080 mm and 255 sizes of 60.45 mm x 16.7 mm x 93.675 mm were cut. This produced 10 CLTs, five of which were in the major strength direction and another five in the minor strength direction.

Three 31.225mm x 16.7mm x 1080mm strips were glued edgewise using a one-component urea-formaldehyde adhesive, Top Bond®, to produce the laminates, which were held together using clamps. Ten replicates of this were made for the faces of CLTs. For the second layer, the core of the CLT production, five replicates of 17 pieces of 60.45mm x 16.7mm x 93.675mm were glued together and laid on the concluded faces, ensuring there was no slip during fabrication.

For the faces of the CLT production, 17 pieces of 60.45mm x 16.7mm x 93.675mm were edge glued using one-component top bond adhesive to form a laminate, and ten replicates were made. Three strips of 31.225mm x 16.7mm x 1080mm were held together using clamps, and five replicates were made for the core of the CLTs in this configuration.

Following the dimensioning of the cross-laminated timber specimen, *M. indica* wood was cut into dimensions of 93.675mm x 50mm x 1080mm. Five replicates were cut and planned to ensure surface smoothness.

2.1. Flexural Property Evaluation

The 4-point loading of the samples was conducted using an Instron® 3366 Universal Testing Machine. Edgewise bending tests were conducted at an average of 11.61% moisture content for test samples of Solid and Cross-Laminated Timber in both major and minor strength directions per the four-point load method at a 5mm/min loading rate. The on-central span length is approximately equal to 18 times the specimen depth. The process of loading continued until the specimen failed. The loading time, mode of failures and maximum load were recorded for each specimen according to the ASTM D198 (Gromala n.d).

Throughout the tests, the load-deflection data for both solid wood and CLT beams were also recorded. The data obtained were used to calculate the modulus of Elasticity and modulus of rupture.

The Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) were calculated using equations 2 and 3, respectively, according to BS 373:1957.

$$MOE = \frac{3P'a L^2}{4\Delta'bh^2} \dots \dots \dots (Equation 2)$$

$$MOR = \frac{3P_{max}L}{4bd^2} \dots \dots \dots (Equation 3)$$

Where:

P_{max} = the Maximum force (Load) obtained from the maximum load sustained at failure (N); = load at the limit of proportionality (N). L = the span of the test sample (mm), b = the breadth of the test samples (mm), and d = the breadth of the test samples (mm). a = the distance between the point of application of load and support.

An analysis of variance was carried out for the flexural properties of solid, cross lam (major axis), and cross lam (minor axis) at P=0.05.

An analysis of variance (ANOVA) was conducted on the flexural property values of solid wood, cross-laminated wood along the major axis, and cross-laminated wood along the minor axis at a significance level of P=0.05.



Figure 1: Edgewise loading of the Cross-Laminated Timber in the Minor

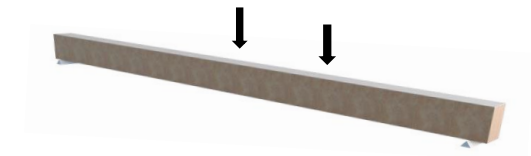


Figure 2: Model of the Edgewise loading of the Cross-Laminated Timber in the Minor Strength Direction

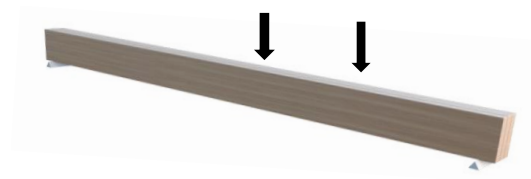


Figure 3.5: Model of the Edgewise loading of the Cross-Laminated Timber in the Major Strength Direction

2.2. Design and Construction of a Gazebo

Using the results of the elastic moduli of *M. indica*, a Gazebo was designed using the Allowable Stress Design (ASD) method according to Olorunnisola (2018). A 1/10 scaled-down model of the design was fabricated. To satisfy the deflection, bending, and shear criterion for the beam, equations 4, 5 and 6 were used, respectively, along with the baseline data of *M. indica* obtained from the Wood Database.

$$\frac{L}{180} \geq \frac{5WL^4}{384EI} \dots \dots \dots (Equation 4)$$

$$\sigma \geq \frac{M}{S} \dots \dots \dots (Equation 5)$$

$$F_v = \frac{1.5V}{A} \dots \dots \dots (Equation 6)$$

Where W = uniformly distributed load on the beam (N/mm), L = Span of the beam (mm), E = Modulus of Elasticity (N/mm²), I = Moment of inertia (mm⁴), S = Section modulus, F_v = Shear stress, M = Maximum moment, V = Maximum shear force, A = Area of the beam. As per Equation 5, must be greater than for the design to satisfy

the bending criterion. Otherwise, a greater trial section or shorter span will be selected, and the design process will be repeated until it satisfies the bending criterion.

Also, for the column calculation, using the modified Euler's formula, the equations used are:

$$\text{Slenderness ratio} = \frac{L_e}{d_{min}} \dots \dots \dots (\text{Equation 7})$$

$$k = 0.671 * \sqrt{\frac{E}{\sigma}} \dots \dots \dots (\text{Equation 8})$$

$$\sigma_c = \frac{0.3 * E}{\left(\frac{L_e}{d_{min}}\right)^2} \dots \dots \dots (\text{Equation 9})$$

$$\frac{P}{A} \leq \sigma_c \dots \dots \dots (\text{Equation 10})$$

where L_e = Effective length/span (mm), d_{min} = Least lateral dimension (mm), E = Modulus of Elasticity (N/mm²), σ = Compressive strength (N/mm²), P = load, and A = cross-sectional area.

As per Equation 10, must be less than for the design to be safe in compression. Otherwise, a greater trial section or shorter span will be selected, and the design process will be repeated until it satisfies the criterion. The design results were used to construct a scaled-down Gazebo model.

3. Findings and Discussion

The results of moisture content are presented in Table 1. The average green moisture content of the lumbers was computed and found to be 27.825%; the average dry moisture content was 10.03%. According to ANSI/APA PRG 320-2019, dry moisture content between $\pm 12\%$ is required to produce Cross-laminated Timber.

Table 1: Moisture Content Test Result

STATISTICAL DATA	Moisture Content (%)
Mean	10.02631579
Median	10
Maximum	12.5
Minimum	7.5
Standard Variation	1.409035172
Coefficient of Variation	14.053461

Table 2: summarises the density of *M. indica* wood at an average dry moisture content of 5.275%, as presented in Table 2. The average density was computed to be 579.45 kg/m³, which shows that *M. indica* wood is medium-density wood.

Table 2: Preliminary Density Test Result

STATISTICAL DATA	Density (kg/m ³)
Mean	579.455
Median	600.009
Maximum	662.622
Minimum	434.957
Standard Variation	70.9991
Coefficient of Variation	12.2527

For the densities of the solid and cross-laminated Timber produced, Table 3 summarises the results obtained. The density of the solid specimen is higher than that of the CLTs in both configurations. As reported by Rahmon et al., 2019, the higher the density of a material, the higher its strength characteristics; it can be inferred from the results that the flexural strength characteristics of the solid specimen will be higher than that of the Cross-laminated samples.

Table 3: Density Result of Solid and CLT Specimen

Material	Avg Mc (%)	Average Density (Kg/m ³)	Median	Max	Min	Standard Deviation	Coefficient of Variation
Solid	11.04	643.51	644.20	668.75	622.51	19.77	3.07
CLT (Minor)	11.86	602.82	612.82	618.66	569.88	20.83	3.46
CLT (Major)	11.92	593.22	592.83	600.77	583.12	7.70	1.30

3.1 Flexural properties of Solid and CLT Samples

The results of the Modulus of Elasticity and Modulus of Rupture for solid and CLT samples are presented in Table 4 and Table 5, respectively. The solid specimen results obtained tallies with Rahmon et al., 2019 which reported the modulus of elasticity of *M. indica* to be 20573.88Mpa. When compared to known species, *Xylopia aethiopica* has 11951 Mpa, *Terminalia ivorensis* 4686 Mpa, *Neem* 4338 Mpa, *Vitellaria paradoxa* 11136 Mpa, and *Hexalobus crispiflorus* 4564 Mpa; it was found to be satisfactory to be utilised as timber for utilisation in structural purposes. The results also show that the CLT in the minor strength direction has stronger flexural characteristics than the CLT in the major strength direction when loaded edgewise

(loaded in-plane). However, the solid specimen has higher stiffness than CLTs in both configurations.

Table 4: Modulus of Elasticity Result of Solid and CLT Specimen

Material	Avg Mc (%)	Mean MOE (N/mm ²)	Median	Max	Min	Standard Deviation	Coefficient of Variation
Solid	11.04	23484.86a	25073.49	25731.40	18033.02	3238.83	13.79
CLT (Minor)	11.86	16945.82b	16266.86	21076.05	14913.95	2389.66	14.10
CLT (Major)	11.92	13981.73c	14007.26	23479.60	1753.54	8057.40	57.63

Mean Moduli of Elasticity with different superscripts are statistically different at $P = 0.05$

Results presented in Table 5 revealed that solid *M. indica* exhibits higher bending strength properties than the Cross laminated variation when loaded edgewise. Also, the cross-laminated Timber in the minor strength direction exhibits higher bending strength properties than that in the major strength direction when loaded in an edgewise manner. An analysis of variance (ANOVA) was conducted using the flexural property values of solid wood, cross-laminated wood along the major axis, and cross-laminated wood along the minor axis at a significance level of $P=0.05$. The results indicated that there were statistically significant differences in the flexural properties among the tested specimens. Specifically, the solid wood exhibited the highest strength and stiffness, while the cross-laminated wood along the major axis demonstrated the weakest strength. CLT in the minor strength direction was reduced by 31.2%, and that of CLT in the major strength direction was reduced by 76.8%. The high percentage reduction in load resistance may be attributed to a weaker interfacial bonding along the glue line compared to the natural lignin bonding strength of the solid wood, the specific production techniques employed or the slightly higher moisture content of the CLT samples. Despite this, cross-lamination shows significant promise in enhancing the achievable span of structures made from *M. indica* wood. This potential makes cross-laminated *M. indica* wood a viable option for constructing simple structures, especially when loaded in the minor axis, where increased span without compromising too much on strength is advantageous. The application of cross-lamination opens new possibilities for utilising *M. indica* wood more effectively in construction, combining both its natural properties and the benefits of engineered wood products.

Mangifera indica exhibits promising potential to address housing affordability, foster advancements in construction techniques, and promote sustainability within the building sector by mitigating environmental impact and enhancing resource efficiency. Analysis of the investigated Cross-Laminated Timber (CLT) properties underscores M. indica's capacity to overcome inherent morphological constraints, albeit with associated processing costs, thus limiting its direct substitution for endangered and scarce timber species, which are progressively scarce and costly. Nonetheless, optimising laminar thickness, glue type, and other relevant processing parameters holds promise for enhancing its efficacy as a structural component in housing applications.

Table 5: Modulus of Rupture Result of Solid and CLT Specimen

Material	Avg Mc (%)	Average MOR (N/mm ²)	Median	Max	Min	Standard Deviation	Coefficient of Variation
Solid	11.04	64.91a	67.49	83.79	40.37	15.82	24.38
CLT (Minor)	11.86	44.69b	57.04	59.51	6.45	22.62	50.61
CLT (Major)	11.92	15.09c	16.27	27.34	2.50	10.41	69.02

Mean Moduli of Rupture with different superscripts are statistically different at P = 0.05

For the Gazebo design, all design calculations show that the components meet the requirements to carry the load safely.

Table 6: Beam Design Calculations

Beam Design Calculations	Long Span	Short Span
Load (N/mm)	1.77	1.77
Span (mm)	3657.6	3270
No of Elements	2	2
Factor of Safety	1	1
Width (mm)	125	125
Depth (mm)	150	150

Table 7: Column Design Calculations

Column Design Calculations	
Load (N)	6501.52
Span (mm)	2300
No of Elements	4
Ke	23.89
Effective Length (mm)	2300



Column Design Calculations	
Slenderness Ratio	30.67
Width (mm)	434.96
Depth (mm)	71.00

4. Conclusion and Further Research

This study has compared the bending strength properties of solid and CLT of *M. indica* in both strength directions. The solid specimens were of significantly better flexural properties than the CLT specimens. The flexural strength of the CLTs reduced significantly. Consequent to the results discussed, *M. indica* are suitable as structural members. It is also evident that solid specimens are more durable than the CLT based on the findings of this study. According to the values obtained from the computed result, *M. indica* can be classified as the N1 strength group of the NCP 2005, which is the highest strength; this is corroborated by Rahmon et al., 2019. Future studies should research the development of Standards for performance-rated cross-laminated timber made from hardwoods, as the present standard, the ANSI standard used, focuses on softwood species. Also, further research should be conducted on the influence of adhesive type on the strength of cross-laminated Timber made from *M. indica*. It is recommended that delamination tests be conducted to ascertain the glue line strength and how it influences the strength of the laminate. Hot pressing with more pressure and loading of *M. indica* out of the plane, that is, flatwise bending, could be experimented with.

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