

Performance evaluation of cross laminated Timber from Coconut (*Cocos nucifera*) as sustainable resource in furniture industry

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Abstract

Coconut (*Cocos nucifera*) as a significant resource may provide a sustainable supply of engineered wood product, such as cross laminated timber (CLT), particularly in regions without sufficient conventional timber sources. This study aims to evaluate the performance of CLT made from coconut. The results revealed that coconut CLT had higher air-dry density, moisture content and water absorption due to its laminated structure compared with solid coconut beam. Meanwhile, modulus of rupture (MOR) of coconut CLT beam was 45.54 N/mm², 5.73% slightly higher than solid coconut beam with MOR value of 43.07 N/mm². As for modulus of elasticity (MOE), compressive properties (f_c) and compression modulus (E_c) of coconut CLT (10258.82, 31.84 and 840.93 N/mm², respectively) were higher compared to that of the solid coconut beam. (6687.67, 21.15 and 538.35 N/mm², respectively). Thus, coconut CLT fulfilled acceptable performance standards for structural and furniture usage that demonstrated a promising environmentally friendly material.

Keywords: *Cocos nucifera*; Cross laminated timber; Bending; Compression; Modulus of elasticity

Introduction

The continuous advancement in timber engineering technology has resulted in the development of numerous engineered wood products for structural and non-structural applications within the construction sector. Among these innovations is Cross-laminated timber (CLT), a modern two-way load-bearing panel system that emerged during the 1990s to serve both the building and furniture industries (FPInnovations 2013; Brandner *et al.* 2016; He *et al.* 2018). cross-laminated timber is a prefabricated engineered wood composite manufactured by arranging layers of lumber in alternating perpendicular directions, commonly at angles of 90°, before bonding them together using structural adhesives applied along the surfaces and edges of the timber elements. Typically, CLT panels are fabricated with an odd number of laminations, usually three, five, seven, or even more layers depending on the structural demand and intended application.

Commercial CLT products are commonly manufactured in widths of approximately 0.6 m, 1.2 m, 2.4 m and 3.0 m, with lengths extending up to 18 m and thicknesses reaching as much as 508 mm (FPInnovations, 2013; Hindman and Bouldin, 2015; Lim *et al.* 2020; Aicher *et al.* 2016; Thomas and Buehlmann, 2017; Yusof *et al.* 2019). Owing to its layered orthogonal arrangement, CLT has gained international recognition as an environmentally sustainable construction material capable of meeting increasing global housing and infrastructure demands. One of the major advantages of CLT is its ability to distribute and minimize the effect of defects naturally present in timber, thereby improving strength uniformity and reducing variability among production batches (Schickhofer, 2016). Furthermore, the multidirectional

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arrangement of laminations significantly enhances the dimensional stability of CLT compared with conventional solid timber products.

In recent years, global attention has increasingly shifted towards the utilization of renewable and sustainable resources in the production of CLT panels, including the use of coconut wood. This growing interest has largely been influenced by the increasing demand for environmentally friendly construction materials and sustainable manufacturing practices (Srivaro *et al.* 2022). In many regions of the world where conventional hardwood and softwood resources are becoming insufficient, researchers have explored alternative monocotyledonous species such as bamboo (Xing *et al.* 2019) and African oil palm (Srivaro *et al.* 2020; Srivaro *et al.* 2021) for CLT production based on their manufacturing feasibility and mechanical performance characteristics. Numerous studies have been conducted worldwide, including in Nigeria, on the structural performance and mechanical behaviour of cross laminated timber (CLT) and other engineered timber products. Karimi and Valipour (2022) investigated eleven different laminated veneer lumber (LVL) and glued laminated timber (GLT) beams subjected to three-point bending tests. The study generated benchmark experimental data for assessing the influence of web openings on the failure mechanisms, bending capacity, shear resistance and tensile stresses of proposed timber composite (TTC) beams.

In Nigeria, Oladunmoye (2024) evaluated the mechanical properties of CLT panels manufactured from Iroko (*Milicia excelsa*) and Omo (*Cordia platythyrsa*) timber species exposed to coastal environmental conditions. The properties examined included modulus of rupture (MOR), modulus of elasticity (MOE) and compressive strength before and after moisture exposure. The findings revealed that CLT panels produced from Iroko exhibited superior mechanical performance and durability compared with those fabricated from Omo timber under similar environmental conditions. Similarly, Hindman and Bouldin (2015) investigated CLT panels manufactured from Southern Pine and evaluated their bending strength, bending stiffness, and shear strength. Their results demonstrated the suitability of Southern Pine for structural CLT applications. Furthermore, the structural performance of CLT panels produced from Scottish Sitka spruce, providing valuable insights into the behaviour and engineering potential of CLT manufactured from plantation-grown softwood species. Collectively, these studies highlight the growing interest in engineered timber

products and underscore their potential for sustainable and high-performance structural applications. Danielsson *et al.* (2024) fabricated four cross-laminated timber (CLT) panels for each panel configuration, comprising three-layer and five-layer assemblies, using Sitka spruce boards graded to C16 and bonded with polyurethane (PUR) adhesive. The study focused on evaluating the shear force capacity of the CLT panels, employing a test setup with a low span-to-depth ratio ($L/h = 3.5$) to promote shear-dominated behaviour. During testing, the panels were loaded to failure and the ultimate load-carrying capacity and bending strength were determined. Observations revealed the development of cracks and eventual failure in the longitudinal laminations located on the tension side of the beams. The findings provided important insights into the shear performance and failure mechanisms of CLT panels manufactured from Sitka spruce, contributing to the understanding of their structural behaviour under loading conditions.

Nigeria has been recognized as favourable environmental conditions for coconut cultivation, but the extent of coconut plantation development within the country remains relatively low. Current estimates indicate that coconut plantations occupy only about 36,000 hectares in Nigeria, which is considerably small when compared with the nation's estimated 1.2 million hectares of land suitable for coconut cultivation (Owoyemi *et al.* 2022). This suggests substantial untapped potential for the expansion of coconut-based industries and value-added wood products within the country. Coconut palm, scientifically identified as *Cocos nucifera*, belongs to the family Arecaceae and remains the sole species within the genus *Cocos*. It is a tall perennial palm capable of attaining heights of approximately 30 m and trunk diameters ranging between 60 and 70 cm. The species is characterized by long pinnate leaves measuring between 4 and 6 m, with individual leaflets extending from 60 to 90 cm in length. Mature leaves naturally detach from the stem, leaving behind a relatively smooth trunk surface (Rana *et al.*, 2015; Mansoor *et al.* 2025; Owoyemi, 2022). Coconut palm is widely referred to as the "tree of life" because virtually every component of the plant, including the roots, stem, leaves, fruits and fibres, possesses economic and domestic importance (Lamidi *et al.* 2021; Sukanya *et al.* 2014).

Studies have shown that the compressive strength (CS), modulus of rupture (MOR) and modulus of elasticity (MOE) of coconut wood attain their highest values near the outer peripheral region of the trunk where fibre density is greatest (Srivaro *et al.* 2020). Suprobo and Santosa (2017), the high strength characteristics of coconut wood also make it highly

suitable for decorative and furniture applications including sculptures, picture frames, chairs and beds. Medium-density coconut wood is commonly utilized for wall studs, ceiling joists and lightweight framing applications, whereas low-density coconut wood is more appropriate for interior components such as ceiling boards, wall linings and roofing shingles (Anoop *et al.* 2011; Lamidi *et al.* 2021). According to Anoop *et al.* (2011) relates that coconut wood possesses several unique characteristics that make it attractive for structural and furniture applications (Srivaro *et al.* 2020). From above reviewed, it shows coconut solid wood is generally hard, durable, aesthetically appealing and demonstrates relatively low volumetric shrinkage compared with many conventional timber species. Despite that the coconut tree has a small girth which limits the dimensions of its board width and thickness into approximately 50 mm and 25 mm, respectively (Lamidi *et al.* 2021).

However, Coconut species can be introduced into a main stream of CLT markets at sufficient quality and quantity with adequate information of its structural properties, which are the major factors for its production and utilization. Therefore, the girth limitation associated with the small size of coconut tree species will be overcome and also serve a good source of CLT materials acquisition for sustainability of both civil

Materials and methods

Material collection

Mature coconut palm trees used for this investigation were sourced from Fashola Town, located within Oyo West Local Government Area of Oyo State in the south-western region of Nigeria. The study area is situated along the Oyo–Iseyin highway and lies approximately at latitude 6.8333°N and longitude 3.2833°E. The location is characterized by favourable tropical climatic conditions that support the growth and development of coconut palms. For the purpose of this study, two fully matured coconut trees were carefully selected based on their physical condition and availability within the plantation area. Information obtained from local farmers and plantation handlers indicated that the selected trees were estimated to be between 50 and 60 years old, suggesting that the stems had attained sufficient maturity for structural evaluation. The selected trees were subsequently felled and converted into logs for further processing, as illustrated in Figure 1.

Preparation of cross laminated timber (CLT) Specimens

The converted bottom and middle coconut logs were mechanically sawn into timber into two different groups,



Fig. 1. Coconut logs

engineering and furniture industries in the global world including Nigeria, at present and the nearest future (Lamidi, 2018). Therefore, this study focuses on evaluating the performance of coconut-based cross laminated timber beams and compared with solid coconut beams with respect to its physical and mechanical properties for possible utilization within the furniture industry.

namely 25 mm × 100 mm × 1000 mm strips for CLT specimens and 75 mm × 100 mm × 1000 mm, for solid coconut specimens, respectively, and thereafter transported to the Wood Processing Workshop of the Department of Wood Products Engineering, University of Ibadan, Nigeria, where they stacked and air-seasoning for approximately eight months in order to gradually reduce the moisture

content of the coconut wood to a range between 18% and 20% before the lamination process commenced as shown in Figure 2a.

Fabrication of CLT beam specimen

A total of five (5) CLT beams with nominal dimensions of 75 mm × 100 mm × 1000 mm (thickness × width × length) were fabricated in accordance with EN 317 (1993). A



2a



2b



2c

Fig. 2. (a) Coconut Specimens Stacked for Air-Seasoning (b) Fabrication of CLT Specimens and Adhesive Application (c) Clamping Arrangement of CLT Specimens

commercially available adhesive, Top Bond, was used as the bonding agent. Top Bond is a polyvinyl acetate (PVA) wood

adhesive manufactured by Purechem Manufacturing Ltd and produced in compliance with the requirements of NIS 341:2003. The adhesive is supplied as a white paste and is characterized by rapid drying, non-toxicity, and odourless properties. It develops handling strength within approximately 30 minutes and attains maximum bond strength after 24 hours. Owing to its widespread use among furniture makers, carpenters, and woodworkers in Ibadan and its environs, the adhesive was selected for this study. It was uniformly applied to the timber strip surfaces to ensure effective bonding between adjacent laminates, as shown in Figure 2b.

A cold-clamping method was employed during the fabrication process, as shown in Figure 2c. Three long sash clamps were positioned at equal intervals along the bottom side of the CLT specimens, while two short F-clamps were placed on the top side to provide additional support and ensure adequate and uniform bonding between the strip layers. Subsequently, the fabricated coconut CLT specimens were carefully arranged in stacked formations and allowed to cure under ambient conditions for another period of seven days. This curing duration was intended to ensure adequate adhesive setting, proper bonding development and sufficient drying prior to subjecting the specimens to physical and mechanical property evaluations. Following fabrication, the CLT and solid coconut timber specimens were finished to nominal dimensions of 65 mm × 100 mm × 900 mm using an iron jack plane.

Physical property testing method

Determination of moisture content of solid coconut timber and coconut CLT specimens

The moisture content of both solid coconut timber and Cross-Laminated Timber (CLT) specimens was determined in accordance with the procedures specified in EN317 (1993). Ten (10) air-dried CLT specimens with dimensions of 50 mm × 50 mm × 50 mm were prepared for the test. To obtain the green-state condition, the specimens were completely submerged in water for a duration of 24 hours to ensure sufficient moisture absorption.

Following immersion, the specimens were carefully removed from the water and subsequently oven-dried at a controlled temperature of $103 \pm 5^\circ\text{C}$ until a constant mass was attained. The drying process continued for several hours and repeated weighing was carried out at intervals until no significant change in weight was observed, indicating that the oven-dry condition had been achieved. Thereafter, the oven-dried specimens were reweighed using a digital weighing balance

and the moisture content (MC) of each specimen was expressed as a percentage and calculated using equation (1).

$$MC = \frac{W_w - W_o}{W_o} \times 100 \dots\dots\dots (1)$$

where MC is the moisture content (%), W_w is the green weight of specimen (g) and W_o is the oven-dry weight of specimen (g).

Determination of air-dry density

The air-dry density of the coconut CLT specimens was evaluated in accordance with EN323 (1993). Ten (10) air-dried specimens measuring 50 mm × 50 mm × 50 mm were utilized for the density assessment. Each specimen was weighed using a precision digital weighing balance to obtain its dry mass. Thereafter, the volume of each specimen was determined from the measured dimensions and the density values were calculated individually. The average density value obtained from all specimens was subsequently computed and reported as the representative air-dry density of the material and the air-dry density was determined using equation (2).

$$\text{Air-dry Density} = \frac{W}{V} \text{ (kg/m}^3\text{)} \dots\dots\dots (2)$$

where W is the oven-dry weight of specimen (kg) and V is the volume of specimen (m³).

Determination of water absorption of solid timber and coconut CLT specimens

The water absorption characteristics of the solid timber and coconut CLT specimens were determined following the procedures outlined in prEN 16351. Ten (10) air-dried specimens with dimensions of 50 mm × 50 mm × 50 mm were prepared for the test. Prior to immersion, the initial weights and dimensions of all specimens were carefully measured and recorded. The specimens were subsequently immersed completely in water for a period of 24 hours under ambient laboratory conditions. After the immersion period, the specimens were removed from the water and gently wiped with a dry cloth to eliminate excess surface water adhering to the specimen surfaces. Final weights and dimensions were then measured immediately after removal from water and the percentage water absorption (WA) of each specimen was calculated using equation (3).

$$WA = \frac{W_2 - W_1}{W_1} \times 100 \dots\dots\dots (3)$$

where WA is the water absorption (%), W_1 initial weight of specimen before water immersion (g) and W_2 final weight of specimen after 24-hour water immersion.

Mechanical property testing methods

Four-Point bending test for solid timber and coconut CLT specimens

The bending performance of both the solid coconut timber and coconut CLT specimens was evaluated in accordance with BS EN 408:2010, which specifies standard procedures for determining the bending strength and stiffness properties of structural timber members. The experimental setup and loading configuration were further conducted in line with the recommendations of prEN 16351, as illustrated in Figures 3a, 3b and 3c.

A four-point bending test configuration was adopted for the experiment in order to ensure uniform stress distribution within the constant moment region of the specimen. During testing, the load was applied continuously at a constant loading rate of through two loading points positioned symmetrically along the span length. An effective test span of 900 mm was maintained throughout the experiment.

A total of ten (10) specimens comprising five (5) solid coconut timber specimens and five (5) coconut CLT specimens were tested. Each specimen possessed nominal dimensions of 65 mm × 100 mm × 900 mm. During loading, the applied force and corresponding deflection values were continuously recorded until failure occurred. The Modulus of Rupture (MOR), which represents the bending strength of the material and the Modulus of Elasticity (MOE), which indicates the bending stiffness, were determined using equation (4) and (5), respectively, according to the BS EN 408:2010.

$$MOR = \frac{Fl}{bd^2} \dots\dots\dots (4)$$

$$MOE = \frac{(\Delta F)l^3}{4bd^3(\Delta \delta)} \dots\dots\dots (5)$$

where MOE is the modulus of elasticity or bending stiffness (N/mm²), ΔF is the increment of load within the linear elastic portion of the load–deformation curve corresponding to 0.5F and 0.1F(N), $\Delta \delta$ is the increment in deformation corresponding to 0.5 δ and 0.1 δ (mm), b is the width of

specimen (mm), d is the depth or thickness of specimen (mm), l is the span length between supports (mm), MOR is the modulus of rupture or bending strength (N/mm^2) and F is the maximum load sustained by the specimen before failure (N).

The bending test provided essential information regarding the load-carrying capacity, stiffness behaviour and structural suitability of coconut-based Cross-Laminated Timber for potential applications in furniture and structural systems.

Compression strength parallel to the grain for solid and Coconut CLT

The compression strength was carried out on a full cross-section and length of 5 times ($5 \times b$) the smallest side of the specimens. 90 mm x 60 mm x 300 mm specimens were loaded at the constant rate of 0.00001 mm/s in accordance with BS EN 408, as shown in Figure 4 and both compression strength and modulus of elasticity (MOE) of the specimens were also conducted using equations 6 and 7 respectively, according to the BS EN 408:2010.

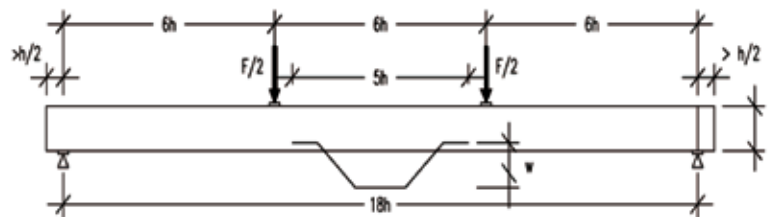


Fig. 3a. 4-Point bending test set-up



Fig. 3b. 4-Point bending test set-up for coconut CLT beams



Fig. 3c. 4-Point bending test set-up for solid coconut beams

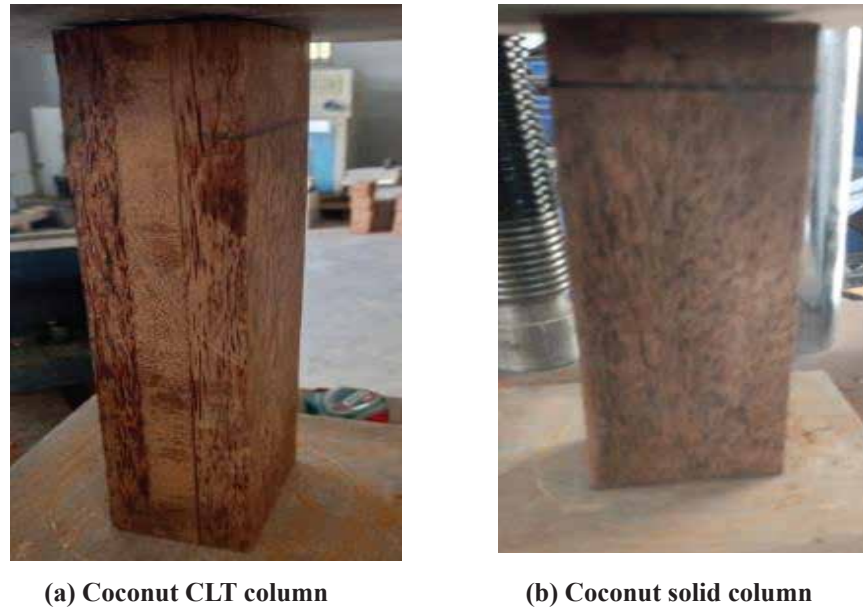


Fig. 4. Compression strength set-up for columns

$$\text{Compression strength} = \frac{F_{\max}}{h \times b} \text{ (N/mm}^2\text{)} \dots\dots\dots (6)$$

$$\text{MOE} = \frac{Fl}{\delta(h \times b)} \text{ (N/mm}^2\text{)} \dots\dots\dots (7)$$

where MOE is the modulus of elasticity of compression strength (N/mm), F is the maximum load at which the specimen failed under axial loading (N), δ is the deformation (mm), b is the width of specimen (mm), h is the depth of specimen (mm) and l is the length of the specimen (mm).

Results and discussion

Physical properties

Air-density

Table I shows the mean air-dried density (ρ) of the solid and coconut CLT specimens as 589.60 kg/m³ and 787.07 kg/m³, respectively. The corresponding standard deviations are 83.11 kg/m³ for solid timber and 183.04 kg/m³ for coconut CLT, while the coefficients of variation are 14% and 23%, respectively. The density value obtained for coconut solid timber falls within the range of 610–1150 kg/m³ specified for hardwood strength classes (D30–D70) in BS 5268. However, the observed densities are higher than the range of 400–460 kg/m³ reported by Rana *et al.* (2015). Conversely, the coconut CLT density aligns well with previously reported ranges of 580–850 kg/m³ (Kusnandar *et al.* 2018) and

640–960 kg/m³. If coconut CLT density is compared to the densities of Iroko and Omo CLT (614.60 kg/m³ and 411.53 kg/m³) by (Oladunmoye, 2024), coconut CLT is 21.91% and 47.71% higher than Iroko and Omo densities, respectively, but they are in closed range with solid coconut specimen. CLT variations in density values may be attributed to differences in origin, age, environmental conditions and cultivation practices.

Moisture content

As shown in Table II, the average moisture content of the solid and coconut CLT specimens are 16.16% and 19.12%, with standard deviations of 5.55% and 8.16%, respectively. The coefficients of variation were found to be 34% for solid timber and 43% for coconut CLT. The obtained moisture content values are below the Fibre Saturation Point (FSP), generally reported to range between 25% and 30% (Nabade, 2012). A higher moisture content was recorded in the coconut CLT specimens compared to the solid timber, which can be explained by the laminated configuration of the CLT. The presence of multiple layers and adhesive bonds increases the potential for moisture uptake. However, the recorded moisture content values for both specimens comply with the recommended limits of 6–15% for CLT according to EN 16351 (2015), 12% for solid timber under BS 5268 (2002) and 18% as specified by NCP 2 (1973).

Table I. Air-dried density (kg/m³) of solid and coconut CLT specimens

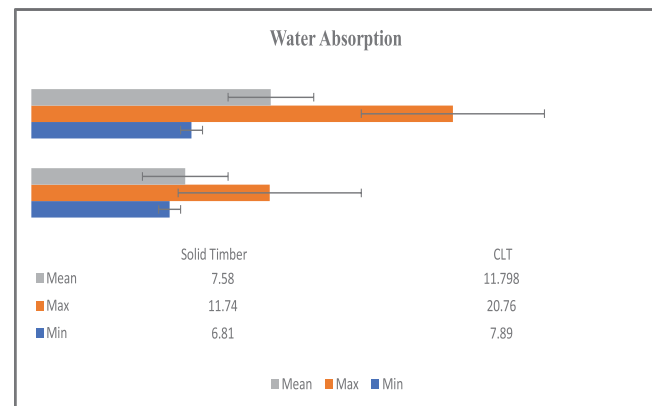
Parameter measured	Solid coconut specimen	CLT coconut specimen
Average	589.60	787.07
Minimum	440.00	547.72
Maximum	720.00	1149.35
Standard deviation	83.11	183.04
Coefficient of variation (%)	0.14	0.23

Table II. Moisture content (%) of solid and coconut CLT specimens

Parameter measured	Solid coconut specimen	CLT coconut specimen
Average	16.16	19.12
Minimum	7.59	10.31
Maximum	23.64	31.25
Standard deviation	5.55	8.16
Coefficient of variation (%)	0.34	0.43

Water absorption

Figure 5 presents the average water absorption values for both solid timber and coconut CLT specimens. The results indicate values of 7.58 % for solid timber and 11.798 % for CLT. The higher water absorption observed in CLT compared to solid timber suggests increased susceptibility to moisture uptake, which can significantly influence the texture and surface integrity of the material when exposed to humid conditions. This behaviour can be attributed to the laminated structure of CLT, which introduces multiple glue lines and interfaces that may facilitate moisture ingress, especially if bonding is not fully impermeable. According to EN 16351 (2015), the moisture performance of CLT is strongly influenced by adhesive type, bonding quality and layer orientation. Additionally, studies by Brandner *et al.* (2016) reported that engineered wood products such as CLT tend to exhibit higher moisture sorption compared to solid timber due to increased surface area and interlayer gaps. According to Frihart and Hunt (2010), higher water absorption may cause dimensional instability, swelling and a decline in mechanical properties, especially in bending and compression. Hence, the use of suitable adhesives, surface treatments and protective coatings is necessary to enhance the durability and moisture resistance of coconut CLT during service.

**Fig. 5. Water absorption properties of solid and coconut CLT columns**

Mechanical properties

Modulus of rupture and modulus of elasticity

The results summarized in Table III indicate that both solid and coconut CLT specimens exhibit comparable yet distinct mechanical performance. The mean MOR and MOE values were obtained as 43.07 N/mm² and 45.54 N/mm², respectively, demonstrating the material's capacity to resist bending stresses and deformation. Variability analysis shows standard deviations of 1.83 N/mm² for solid timber and 1.08 N/mm² for coconut CLT, with corresponding coefficients of variation of 4.2% and 2.4%. These relatively low COV values confirm good experimental repeatability, particularly

for the CLT specimens. The observed 5.73% increase in MOR for coconut CLT beams compared to solid beams can be attributed to the cross-lamination effect, which enhances stiffness, redistributes internal stresses and minimizes the impact of natural defects such as knots and grain deviations. By comparing, MOR for Iroko and Omo CLT (21.67 and 17.87 N/mm² by (Oladunmoye, 2024), coconut CLT is 49.69% and 58.51% higher than Iroko and Omo CLT.

Table IV shows a similar trend in the bending performance of the specimens. The average bending stiffness values for the solid timber and coconut CLT specimens were 6687.67 N/mm² and 10,258.23 N/mm², respectively, indicating a substantially higher stiffness in the CLT configuration. The corresponding standard deviations were 632.76 N/mm² for the solid specimens and 1334.51 N/mm² for the coconut CLT specimens, with coefficients of variation of 9.5% and 13%, respectively. When compared to MOE of Iroko and Omo CLT (10,061.04 N/mm² and 4091.91 N/mm²) reported by Oladunmoye (2024) and *Nordic spruce* CLT of MOE value of 11,243 N/mm² by Dobes *et al.* (2023),

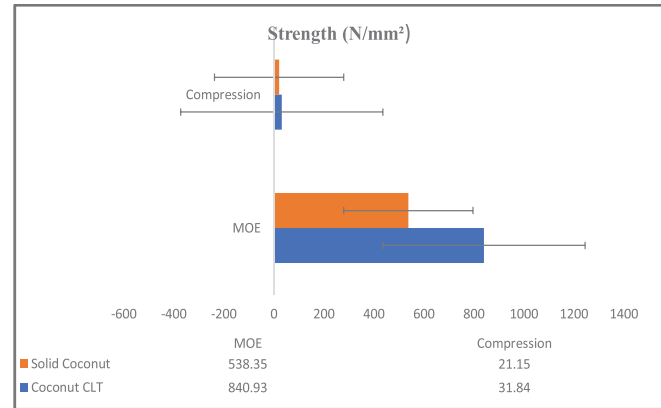


Fig. 6. Strength properties of solid and coconut CLT columns

the coconut CLT in this study is higher than that of Iroko and Omo CLT but slightly lesser than *Nordic spruce*. This suggests that coconut CLT beams possess enhanced structural capacity under imposed loads compared to their solid beam

Table III. Mechanical properties of coconut solid beams

Specimen	Force Max (N)	Deflection Max (mm)	Bending Strength (N/mm ²)	Force Elastic Limit (N)	Deflection Elastic Limit (mm)	Bending Stiffness (N/mm ²)
Solid -1	7000	20.10	44.79	2100	6.01	7168.00
Solid -2	6500	21.00	41.60	1950	6.30	6274.03
Solid -3	7100	19.00	45.44	2130	5.70	7653.05
Solid -4	6700	21.23	42.88	2010	6.40	6432.00
Solid -5	6350	22.06	40.64	1905	6.60	5911.27
Average	6730	20.68	43.07	2019	6.20	6687.67
S.D	285.66	1.05	1.83	85.70	0.315	632.76
C V (%)	0.042	0.051	0.042	0.042	0.051	0.095

Table IV. Mechanical properties of coconut CLT beams

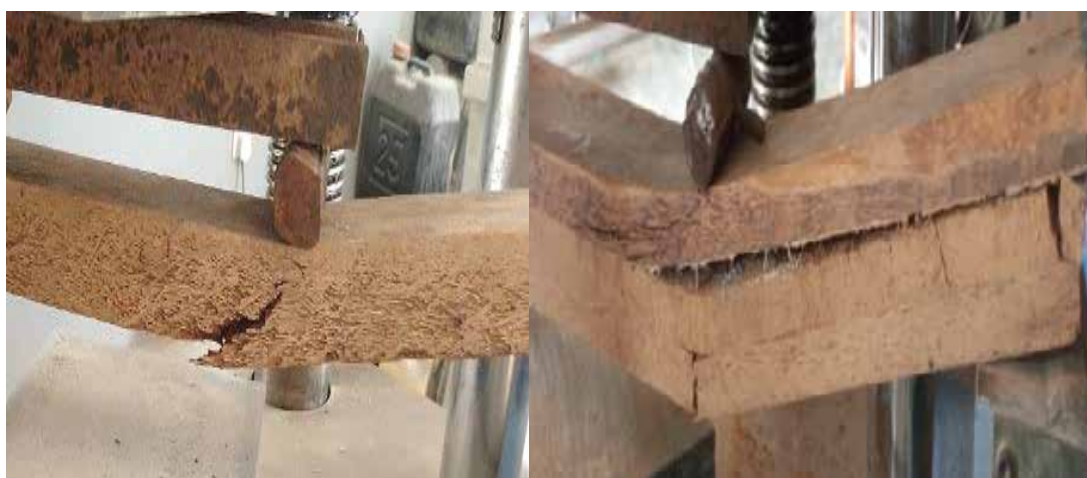
Specimen	Force Max (N)	Deflection Max (mm)	Bending Strength (N/mm ²)	Force Elastic Limit (N)	Deflection Elastic Limit (mm)	Bending Stiffness (N/mm ²)
CLT-1	18930	10.00	46.74	5679	3.0	12464.20
CLT-2	18500	11.20	45.68	5550	3.4	10,748.00
CLT-3	18000	12.56	44.44	5400	3.8	9356.73
CLT-4	18500	12.00	46.68	5550	3.6	10150.89
CLT-5	17890	13.06	44.17	5367	3.9	9061.10
Average	18364	11.76	45.54	5509.20	3.54	10258.23
S.D	378.03	1.078	1.081	113.41	0.32	1334.51
C V (%)	0.021	0.092	0.024	0.021	0.09	0.130



(a) Solid coconut beam failure



(b) Coconut CLT beam failure



(c) Failure details of solid beam

(d) Failure details of CLT beam

Fig. 7. Failure modes of tested beams

counterparts. Consequently, the use of cross-laminated timber (CLT) technology resulted in improved structural behaviour of the coconut CLT specimens.

Compression and elasticity of solid and coconut CLT specimens

Figure 6 presents a comparison of compressive strength and modulus of elasticity parallel to the grain for solid timber and coconut CLT columns. The results indicate that coconut CLT specimens consistently outperform solid timber columns, largely due to the absence of natural defects. A higher modulus of elasticity is also observed in CLT columns relative to solid coconut columns. However, compression parallel to the grain in solid columns may not be purely compressive because of localized rupture effects at the bearing ends. Coconut CLT columns exhibited increases of 50.54% in compressive strength and 56.26% in modulus of elasticity compared to solid columns. In comparison with Lamidi *et al.* (2021), who obtained 40.20 N/mm² and 1694.38 N/mm² for coconut columns measuring 50 mm × 50 mm × 300 mm, the values in this study differ by approximately 90.07% and 26.26% and 214.7% and 101.49% for strength and modulus, respectively. These variations are mainly due to differences in cross-sectional dimensions, emphasizing the significant influence of size effect on both strength and stiffness in timber structures.

Failure modes of both solid and coconut CLT beams

Figures 7 and 8 illustrate the failure modes observed in solid timber and coconut CLT beams during bending tests. When subjected to four-point loading, the coconut CLT beams

exhibited multiple interacting failure mechanisms due to their layered configuration. The bottommost layers failed primarily in tension, often accompanied by glue-line failure, which is attributed to high tensile stresses and potential weakness at the adhesive interface. The uppermost layers experienced compressive failure as a result of compressive stress concentration, typically manifested as crushing or localized buckling of fibres. The cross-layers in the CLT beams showed fine cracking and roller shear failure, particularly at the mid-span and near the supports. Roller shear is a well-documented failure mode in cross-laminated timber, especially in the transverse layers where shear strength is relatively low compared to longitudinal strength. This behaviour is consistent with findings reported in FPInnovations (2019), which noted that rolling shear often governs the failure of CLT panels under bending. Furthermore, the presence of multiple layers in CLT contributes to stress redistribution, resulting in a more gradual and progressive failure compared to solid timber (European Committee for Standardization, 2015). In contrast, the solid coconut beams exhibited predominantly tensile failure in the bottom fibres, accompanied by diagonal splintering along the grain. This type of failure is typical of solid timber under bending, where tensile stresses perpendicular to the grain initiate crack propagation, leading to sudden brittle failure (Forest Products Laboratory, 2010). Unlike CLT, solid timber lacks the capacity for stress redistribution, making it more susceptible to abrupt failure once the tensile strength is exceeded.

Failure modes of both solid and coconut CLT columns

Table V summarizes the experimental findings from the compressive strength tests, showing that both solid timber and coconut CLT columns predominantly failed through bending or



(S-1)

(S-2)

(S-3)

(S-4)

(S-5)

Fig. 8. Solid coconut failure modes



Fig. 9. Solid coconut failure modes

Table V. Failure modes for solid and coconut CLT columns

Column	Force Max (kN)	Deflection Max (mm)	Failure Modes	Column	Force Max (kN)	Deflection Max (mm)	Failure Modes
Solid -1	120.75	8.74	R/ B	CLT-1	167.92	14.25	R+ T+ S
Solid -2	104.92	15.95	R/B	CLT-2	180.49	8.31	B _b +D+C/H
Solid -3	110.65	13.74	R/ T-B	CLT-3	170.50	12.12	B _b +D+C/ O-T
Solid -4	115.95	11.50	R+S+C	CLT-4	165.60	15.25	R/T
Solid -5	118.87	11.98	S	CLT-5	175.1.2	10.15	R/T+R _s
Average	114.23	12.38		Average	171.13	12.02	
S.D	5.77	2.40		S.D	5.68	2.56	
C V (%)	0.051	0.20		C V (%)	0.033	0.21	

Note: R (rupture), S (splitting), B_b (bending/buckling), C (crushing), RS (rolling shear), D (delamination), TB (top bearing end), B (bottom bearing end), H (mid-height) and OT (one-third height).

buckling, crushing, splitting, delamination and rolling shear under axial loading conditions. Among the solid specimens (S-1 to S-5), S-1 and S-2 exhibited rupture at the bottom bearing end, S-3 failed at both top and bottom bearing ends, while S-4 and S-5 showed bending and buckling failures, respectively, as depicted in Figure 5. For the CLT specimens (CLT-1 to CLT-5), CLT-1, CLT-4 and CLT-5 experienced rupture at the top bearing end, with additional splitting and rolling shear observed in CLT-1 and CLT-5. Conversely, CLT-2 and CLT-3 failed due to buckling, delamination and crushing at mid-height and at one-third of the column height from the bottom, respectively, as illustrated in Figures 7 and 8. A comprehensive summary of all failure modes and their corresponding positions is provided in Table V.

Conclusion

In this study, some mechanical and physical properties of the three-layered coconut Cross-Laminated Timber (CLT) beam bonded with top bond adhesive and its properties were compared with the solid coconut beam. The following conclusion can be drawn:

1. The density, moisture content, and water absorption capacity of the coconut Cross-Laminated Timber (CLT) beams were found to be higher than those of the solid coconut timber beams.
2. Cross-Laminated Timber (CLT) demonstrated improved mechanical performance compared to solid timber, with higher MOE, MOR, and compressive strength parallel to the grain.

Consequently, CLT exhibits better resistance to bending and axial loads, making it suitable for structural applications subjected to various loading conditions.

3. The failure behaviour of the solid timber and coconut Cross-Laminated Timber (CLT) differed significantly. Under bending loads, the dominant failure modes observed in the solid timber and coconut CLT included tensile-zone cracking, rolling shear, and delamination. In contrast, specimens subjected to axial loading primarily failed through buckling, rupture, bearing-end crushing, and delamination.

4. The findings of this research indicate that coconut timber obtained from the bottom and middle portions of the stem is suitable for the production of Cross-Laminated Timber (CLT) products.

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