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Experimental Study on Shear Properties of *Gmelina Arborea* Cross-laminated Timber Panels by Short Span Bending

Yusuf Yau[1], Tasiu Ashiru Sulaiman[1], Aliyu Mani Umar[1], Ibrahim Bello[1], Isah Garba[1], Ashiru Mohammed[1], Adam Ado Sabari[1], Musa Abdullahi[1]

[1]Department of Civil Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria

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Corresponding Author:
Yusuf Yau
Department of Civil Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
yyau@abu.edu.ng

ABSTRACT

This study examines the shear strength properties of cross-laminated timber (CLT) panels fabricated from Nigerian-grown *Gmelina arborea* using polyurethane (PUR) and epoxy resin (ER) adhesives. Eight (8) CLT panels were fabricated and tested according to ANSI/APA PGR 320 and BS EN 16351 standards, with rolling shear strength assessed through short-span testing configurations across span-to-depth (S/d) ratios of 4, 5, and 6, per BS EN 408 guidelines. Results showed that PUR-bonded specimens had superior rolling shear strength, with mean values of 2.85 N/mm², 2.38 N/mm², and 2.14 N/mm² across S/d ratios 4, 5, and 6, respectively, compared to 1.97 N/mm², 1.74 N/mm², and 1.59 N/mm² for ER-bonded specimens. Rolling shear strength values decreased as S/d ratios increased, indicating typical structural responses. The ER-bonded specimens exhibited an increasing trend in MOR as the S/d ratio increased from 4 to 6, though the MOR values were consistently lower than those of PUR-bonded panels. These findings contribute essential data on *Gmelina arborea* CLT's mechanical properties, supporting its potential as a sustainable, high-performance material in the Nigerian timber industry. The study establishes a foundation for the development of value-added timber products, promoting sustainable construction practices in Nigeria.

Keywords: *Rolling shear strength · Polyurethane and Epoxy resin adhesives · Gmelina arborea timber · Short-span test · Cross-laminated timber*

1. Introduction

Cross-laminated timber (CLT) is composed of layers of solid-sawn lumber boards, stacked crosswise and glued together, which enhances its structural rigidity and dimensional stability. CLT is a construction material consisting of a minimum of three layers of bonded boards or lumbers derived from coniferous or deciduous wood, with each layer oriented at a right angle to the adjacent layer. This configuration allows CLT panels to bear heavy loads, making them suitable for use in large-scale buildings such as multi-story residential and commercial structures. CLT is increasingly used in structural applications due to its advantageous properties, including high strength-to-weight ratio and sustainability. The evaluation of shear strength properties of CLT panels is a critical area of research, as it influences design guidelines and safety standards for timber structures and also due to its implications for structural performance. Several studies have contributed to understanding the mechanical properties and behaviour of CLT in such conditions. The adoption of CLT technology has brought significant advancements in structural applications, combining the inherent benefits of wood with modern engineering techniques. This technology has not only revolutionised the construction industry but has also extended its influence to allied sectors, including the forest and adhesives industries, by promoting the utilisation of wood as a sustainable resource [1, 2].

The increasing adoption of mass timber products (MTPs) like CLT, laminated veneer lumber (LVL), and glulam in tall timber buildings requires a deep understanding of adhesive functions and their long-term performance. This understanding should consider the types of loads applied, environmental influences, and the in-service conditions of the materials [3]. Reference [4] conducted an extensive study to assess the bonding performance of polyurethane (PUR) and epoxy resin (ER) adhesives using *Gmelina arborea*, a timber species commonly grown in Nigeria, under various testing conditions and methods. Although *Gmelina arborea* is frequently used for general timber applications, its suitability for engineered wood products like cross-laminated timber (CLT) and glulam has not been thoroughly investigated, especially regarding adhesive bonding. Their research uniquely integrates multiple testing standards (EN 302-1, ASTM-D5868, and ASTM-D905) and examines adhesive performance across different environmental conditions (dry, soaked, heated), offering a deeper insight into how these adhesives function in real-world scenarios.

The literature on CLT primarily emphasises on the mechanical performance of panels made from various wood species under different loading conditions, with an emphasis on understanding the factors that influence their strength and stiffness. For instance, studies by [5-7] have evaluated the rolling shear strength of CLT through short-span bending tests, highlighting the importance of shear properties in determining the overall structural performance of CLT panels. Similarly, [8] explored the rolling shear properties of CLT made from Australian Radiata Pine, emphasising the variability in shear strength across different species and manufacturing processes. In terms of CLT production, research has emphasised the importance of optimising manufacturing parameters, such as pressing pressure and adhesive type, to enhance mechanical properties [1, 9]. The effect of adhesive performance on the durability and mechanical properties of CLT has also been extensively studied. Studies have shown that CLT's bending strength and stiffness are influenced by factors such as layer arrangement, adhesive type, and wood species [10, 11]. The study by [12] presents an in-depth analysis of the stiffness and deformation characteristics of cross-laminated timber (CLT) panels made from Nordic spruce. The research employs a combination of experimental testing, analytical methods, and numerical modelling to evaluate the structural performance of these CLT panels under various loading conditions. Also, the study by [13] focuses on evaluating the mechanical properties (bending, shear, and compressive strength) of CLT panels made from black spruce. The research investigates three- and five-layer CLT configurations, examining how the number of layers and the orientation of the wood affect the structural performance of the panels. Reference [14] examined the relationship between material stiffness and CLT element performance, particularly focusing on out-of-plane bending and rolling shear. Their findings underscore the importance of selecting wood species with high stiffness properties to enhance the structural integrity of CLT panels. Additionally, [15] provided insights into the characteristic values and testing configurations of CLT, focusing on selected properties that are critical for ensuring the reliability of these engineered wood products in construction. Collectively, these studies contribute significantly to the body of knowledge and offer valuable insights into the mechanical behaviour of CLT under compression perpendicular to the grain. The findings underscore the influence of factors such as wood species, grain orientation, layer configuration, adhesive type, and moisture content on the compressive strength of CLT. Understanding these parameters is essential for optimising CLT designs, ensuring structural reliability, and developing robust building standards for timber structures.

Despite the global adoption of CLT, its use in regions such as Nigeria is still limited, primarily due to the lack of comprehensive research and data on local wood species suitable for CLT production. *Gmelina* *arborea*, a locally available hardwood species in Nigeria, is a promising candidate for CLT production due to its favourable growth characteristics, mechanical properties, and dimensional stability [16, 17]. Traditionally, *Gmelina arborea* has been mainly used for pulp and paper production, furniture, and other low-value applications [18]. However, its potential for engineered wood products, especially CLT, has yet to be fully explored [4]. This research aims to assess the shear strength properties of CLT panels made from *Gmelina arborea* timber grown in Nigeria. The study seeks to address a gap in the current literature by presenting empirical data on the structural performance of CLT produced from locally sourced *Gmelina arborea*. This information could contribute to the development of value-added products in Nigeria's timber industry.

2. Materials and Methods

2.1 Material

2.1.1 Timber

Gmelina arborea timber logs were sourced from a local sawmill in Old Panteka Timber Market in Kaduna. The logs were processed into lumber, seasoned, and conditioned for approximately 14 weeks to achieve a moisture content (MC) of around 12% determined according to EN 13183 [19], which is the reference MC. The Gmelina timber has an average basic density and green MC of 505 kg/m^3 and 141% respectively. The timber was classified as C30 according to BS EN 338 [20]. All the CLT specimens were produced from visually graded planks or lumbers (with different cross-sectional) sawn from this timber species, as shown in Figure 1.

Figure 1: Lumbers sawn from *Gmelina arborea* timber specie

Some of the basic material properties of the lumber boards used in this study are presented in Table 1 and were determined in accordance with BS EN 408 [21].

Table 1: Properties of *Gmelina arborea* lumber boards

M C	Density	Bending Strength	MOE	Compressive Strength (‖)	Compressive Strength (⊥)	Shear Strength
10.85%	548 kg/m^3	52.86 MPa	12 GPa	35.8 MPa	5.9 MPa	7.65 Pa

2.1.2 Adhesives

Two commercial adhesives, one-component polyurethane (PUR). This adhesive (FV1KPUR1.1KGBTE716A) was manufactured by Pidilite Industries Ltd. According to the specifications for "DIN EN 204/D4" and as per "WATT91" provided by the manufacturer, the product is boiling water and high temperature resistant, respectively. It reaches final bond strength after 24 hours. Two-component epoxy resin (ER) adhesives (SUA-8714). It is resistant to heat, water, oil, acid, and alkali, according to the manufacturer. The initial curing time is 90 minutes, and subsequently reaches maximum strength after 24 hours. Some of the properties of the adhesives according to the manufacturers are presented in Table 2.

Table 2: Properties of PUR and ER adhesives

Adhesive type	Appearance	Specific Gravity	Viscosity	Resistance to high temperature
PUR	Clear Light Brown	1.15	40 - 80 Pa.s	Yes
ER	Transparent (R)* Pale yellow (H)*	1.13 (R)* 1.12 (H)*	40 Pa.s	Yes

(R)* = Resin and (H)*= Hardener

2.1.3 Clamping Device

A fabricated manual clamping device for mounting pressure on the bonding specimens was used in this study. The clamping device, also referred to as a pressing device**,** is used to press pieces of wood together after adhesive application. The improvised device shown in Figure 2 was used as an alternative to a vacuum or hydraulic press. However, for bonding large-scale specimens**,** a vacuum or hydraulic press is preferred. According to BS EN 302-1 [22], a manual pressing device is acceptable for use with small-scale specimens.

Figure 2: Improvised clamping device for pressure application

2.2 Methods

2.2.1 Materials Selection and Preparation

Visually graded *Gmelina arborea* lumber boards (Figure 1) in accordance with EN 14081-1 [23] were selected and then planed to uniform cross-sectional dimensions of 20 mm x 120 mm for 3-layer CLT panels. The length of longitudinal and transverse lumbers used is 1000 mm and 480 mm, respectively.

2.2.2 CLT Panels Fabrication and Test Specimens Preparation

To fabricate the 3-layer CLT panel, a total of 17 lumber boards were used. The first layer consisted of 4 longitudinal lumbers, followed by 9 transverse lumbers for the second layer, and another 4 longitudinal lumbers for the third (final) layer. The layers were assembled as shown in Figure 3 and glued together using the improvised clamping device (Figure 2) and pressed for 24 hours. Polyurethane (PUR) and epoxy resin (ER) adhesives were used to bond the layers. To ensure quality control during the manufacturing process, specific measures were implemented and are discussed in detail in the subsequent sections. The measures include precise visual grading of timber in compliance with EN 14081-1 [23], adherence to moisture content standards, careful monitoring of the adhesive application process (using both PUR and ER adhesives), and maintaining strict press times and constant pressure, ensuring consistent product quality.

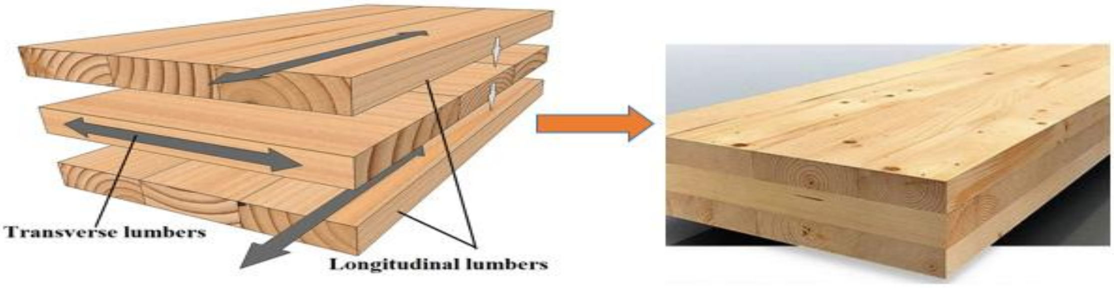

Figure 3: Conventional assembly layup and gluing of lumbers to produce CLT panels

2.2.2.1 Application of Adhesives

The adhesive application rate for both PUR and ER adhesives was 150 g/m², in accordance with the manufacturer's specifications (150 to 350 g/m^2). For the longitudinal lumbers (120 mm x 1000 mm), 21g of adhesive was uniformly applied over the surface area, while 10.5g was used for the transverse lumbers (120 mm x 480 mm). The mixing ratio for the two-component ER adhesive was 1:1. For the longitudinal lumbers, 10.5g of both resin and hardener were used, while 5.25g of each component was applied to the transverse lumbers.

2.2.2.2 Pressing of CLT panels (pressure application)

Four (4) improvised clamping devices were used for applying pressure during the bonding process. To ensure consistent pressure, the remaining length of the bolt above the device adjuster was measured (L) and recorded after the device was effectively tightened and pressed as shown in Figure 4. For subsequent clamping, this measurement was maintained to ensure uniform pressure application across all the CLT panels produced. After 24 hours pressing, the CLT panels were cut and surface-machined to the final dimensions specified in Table 3. The fabrication process followed the guidelines of ANSI/APA PRG 320 [24].

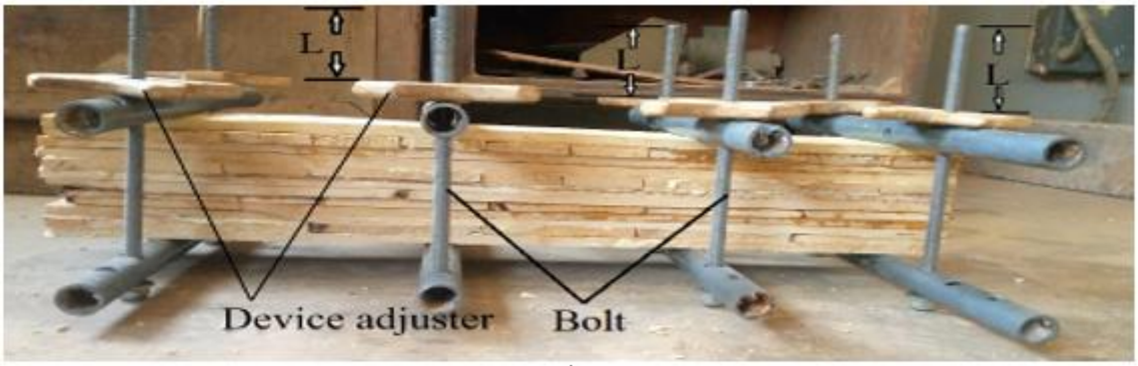

Figure 4: Clamping of CLT panel

Table 3: Dimension and number of CLT panels and specimens bonded with PUR and ER adhesives

CLT size	CLT - Panel		CLT Specimens		
	Dimensions	No.	Dimensions	No.	Span/depth
CLT - 60	60mm x 460mm x 980mm	8	60mm x 65mm x 420mm	20	6
			60mm x 65mm x 360mm	20	5
			60mm x 65mm x 300mm	20	4

A total of 8 CLT panels were produced, and 60 CLT specimens were extracted from the panels (Table 3), for use as shear strength test specimens. Figure 5 shows two samples of 3-layer CLT panels produced and some of the extracted specimens.

Figure 5: The 3-layer CLT panels and the extracted specimens

2.2.3 Experimental Testing of CLT Specimens: Determination of Shear Strength

The CLT specimens are subjected to out-of-plane bending conditions in a short-span testing configuration in accordance with BS EN 408 [21]; ANSI/APA PGR 320 [24]; and BS EN 16351 [25]. The failure load (F_{max}) was recorded for all the tested specimens. The experimental methods involved determination of the maximum shear force (V_{max}), maximum bending moment (M_{max}), modulus of rupture (MOR), and rolling shear strength (τ_v) at various span-to-depth ratios. The test setup and instrumentation as shown in Figure 6 were designed according to BS EN 408 [21].

Figure 6: Experimental set-up for three-point short span bending test

2.3.4 Theoretical Methods and Data Analysis

The experimental data were analysed in order to determine the structural response of the CLT panels made with *Gmelina arborea* timber. The theoretical formula used to compute the maximum shear force (V_{max}), maximum moment (M_{max}), MOR, and rolling shear strength are given in equations 1 to 4, respectively, based on the concept of the isotropic method.

$$V_{max} = \frac{\mathrm{F_{max}}}{2} \quad (1)$$

$$M_{max} = \frac{\mathrm{F_{max}}\, l}{4} \quad (2)$$

$$f_v = \mathrm{MOR} = \frac{3\ \mathrm{F_{max}}\, l}{2\ \mathrm{b}\ h^2} \quad (3)$$

$$\tau_v = \frac{3\ \mathrm{F_{max}}}{4\ \mathrm{bh}} \quad (4)$$

Where: *l* is the span of the CLT specimens
b is the width of the CLT specimens
h is the depth of the CLT specimens

3. Results and Discussions

The experimental results (mean values and standard deviations) for PUR and ER-bonded CLT specimens considering span-to-depth ratios of 4, 5, and 6 are presented in Tables 4 to 9. The study found that PUR-bonded CLT panels consistently outperformed ER-bonded panels in terms of shear strength, with average shear strength values for PUR specimens at 2.85 N/mm² (S/d = 4), 2.38 N/mm² (S/d = 5), and 2.14 N/mm² (S/d = 6), compared to ER values of 1.97 N/mm², 1.74 N/mm², and 1.59 N/mm², respectively. Shear strength decreased as the span-to-depth (S/d) ratio increased, as can be observed in Tables 4 to 9 and Figure 7, indicating a typical structural response where larger span-to-depth ratios yield lower shear performance. Furthermore, using a higher adhesive rate may improve PUR and ER performance. In existing literature, such as the work of [4], the superior bonding and load transfer capabilities of PUR adhesives are well-documented.

Table 4: Details of results obtained at S/d = 4 for PUR bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	4	60x65x300	14.5	7.25	0.87	22.31	2.79
2	4	60x65x300	15.1	7.55	0.906	23.23	2.90
3	4	60x65x300	14.7	7.35	0.882	22.62	2.83
4	4	60x65x300	14.8	7.4	0.888	22.77	2.85
5	4	60x65x300	14.6	7.3	0.876	22.46	2.81
6	4	60x65x300	14.5	7.25	0.87	22.31	2.79
7	4	60x65x300	14.9	7.45	0.894	22.92	2.87
8	4	60x65x300	14.4	7.2	0.864	22.15	2.77
9	4	60x65x300	15.8	7.9	0.948	24.31	3.04
10	4	60x65x300	15	7.5	0.9	23.08	2.88
	Mean		14.83	7.42	0.89	22.82	2.85
	SD		0.41	0.21	0.02	0.63	0.08

Table 5: Details of results obtained at S/d = 4 for ER bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	4	60x65x300	9.8	4.9	0.588	15.08	1.88
2	4	60x65x300	11.1	5.55	0.666	17.08	2.13
3	4	60x65x300	11	5.5	0.66	16.92	2.12
4	4	60x65x300	9.5	4.75	0.57	14.62	1.83
5	4	60x65x300	10.3	5.15	0.618	15.85	1.98
6	4	60x65x300	10.5	5.25	0.63	16.15	2.02
7	4	60x65x300	10.2	5.1	0.612	15.69	1.96
8	4	60x65x300	10.4	5.2	0.624	16.00	2.00
9	4	60x65x300	9.7	4.85	0.582	14.92	1.87
10	4	60x65x300	10	5	0.6	15.38	1.92
	Mean		10.25	5.13	0.62	15.77	1.97
	SD		0.53	0.26	0.03	0.81	0.10

Table 6: Details of results obtained at S/d = 5 for PUR bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	5	60x65x360	12	6	0.9	23.08	2.31
2	5	60x65x360	11.9	5.95	0.8925	22.88	2.29
3	5	60x65x360	12.3	6.15	0.9225	23.65	2.37
4	5	60x65x360	12.5	6.25	0.9375	24.04	2.40
5	5	60x65x360	12.8	6.4	0.96	24.62	2.46
6	5	60x65x360	12.4	6.2	0.93	23.85	2.38
7	5	60x65x360	12.7	6.35	0.9525	24.42	2.44
8	5	60x65x360	11.8	5.9	0.885	22.69	2.27
9	5	60x65x360	12.7	6.35	0.9525	24.42	2.44
10	5	60x65x360	12.8	6.4	0.96	24.62	2.46
	Mean		12.39	6.20	0.93	23.83	2.38
	SD		0.38	0.19	0.03	0.73	0.07

Table 7: Details of results obtained at S/d = 5 for ER bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	5	60x65x360	9.2	4.6	0.69	17.69	1.77
2	5	60x65x360	9.1	4.55	0.6825	17.50	1.75
3	5	60x65x360	8.5	4.25	0.6375	16.35	1.63
4	5	60x65x360	8.8	4.4	0.66	16.92	1.69
5	5	60x65x361	9.5	4.75	0.7125	18.27	1.83
6	5	60x65x362	9.4	4.7	0.705	18.08	1.81
7	5	60x65x363	9.4	4.7	0.705	18.08	1.81
8	5	60x65x364	9.2	4.6	0.69	17.69	1.77
9	5	60x65x365	8.7	4.35	0.6525	16.73	1.67
10	5	60x65x360	8.6	4.3	0.645	16.54	1.65
	Mean		9.04	4.52	0.68	17.38	1.74
	SD		0.36	0.18	0.03	0.70	0.07

Table 8: Details of results obtained at S/d = 6 for PUR bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	6	60x65x420	11	5.5	0.99	25.38	2.12
2	6	60x65x420	11.2	5.6	1.008	25.85	2.15
3	6	60x65x420	11.3	5.65	1.017	26.08	2.17
4	6	60x65x420	11.2	5.6	1.008	25.85	2.15
5	6	60x65x420	11.5	5.75	1.035	26.54	2.21
6	6	60x65x420	10.8	5.4	0.972	24.92	2.08
7	6	60x65x420	10.9	5.45	0.981	25.15	2.10
8	6	60x65x420	11.1	5.55	0.999	25.62	2.13
9	6	60x65x420	11.2	5.6	1.008	25.85	2.15
10	6	60x65x420	11.3	5.65	1.017	26.08	2.17
	Mean		11.15	5.58	1.00	25.73	2.14
	SD		0.21	0.10	0.02	0.48	0.04

Table 9: Details of results obtained at S/d = 6 for ER bonded specimens

S/N	Span/depth	Size	Fmax (kN)	Vmax (kN)	Mmax (kNm)	MOR (N/mm^2)	Shear (N/mm^2)
1	6	60x65x420	8	4	0.72	18.46	1.54
2	6	60x65x421	8.2	4.1	0.738	18.92	1.58
3	6	60x65x422	8.1	4.05	0.729	18.69	1.56
4	6	60x65x423	8.3	4.15	0.747	19.15	1.60
5	6	60x65x424	8.5	4.25	0.765	19.62	1.63
6	6	60x65x425	7.8	3.9	0.702	18.00	1.50
7	6	60x65x420	8.5	4.25	0.765	19.62	1.63
8	6	60x65x420	8.4	4.2	0.756	19.38	1.62
9	6	60x65x420	8.3	4.15	0.747	19.15	1.60
10	6	60x65x420	8.5	4.25	0.765	19.62	1.63
	Mean		8.26	4.13	0.74	19.06	1.59
	SD		0.24	0.12	0.02	0.55	0.05

Studies on CLT made with different adhesives have found similar patterns [5-8], with PUR-bonded timber providing improved shear resistance due to its flexibility and better integration with wood fibres. However, the performance of ER adhesive, while lower, was still within acceptable ranges, supporting its potential use where specific application criteria permit, for example in regions with very low humidity and temperature fluctuations. For applications in high-humidity regions, choosing adhesives and wood species tested for resilience under these conditions can ensure long-lasting and structurally sound CLT panels.

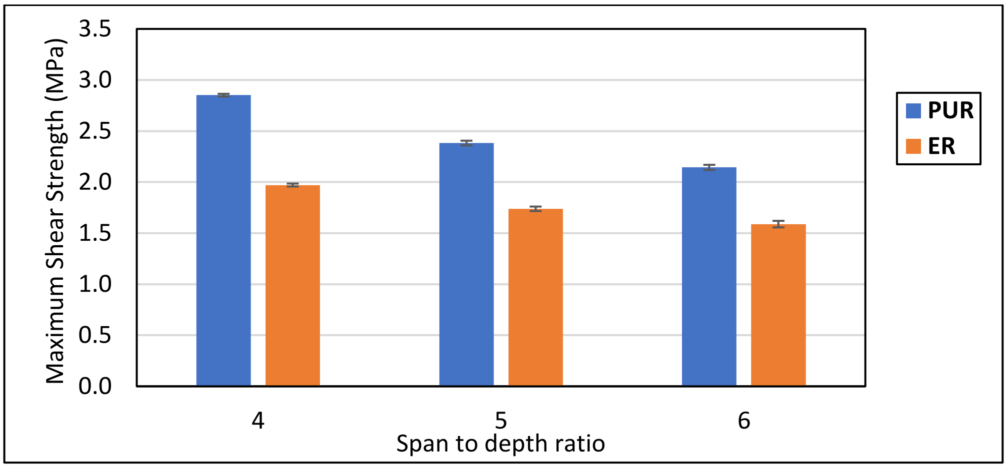

Figure 7: Mean shear strength at various span-to-depth ratio

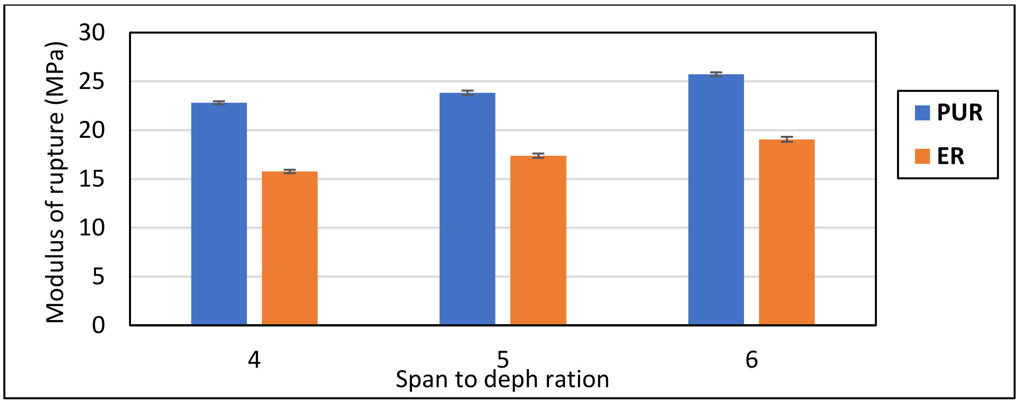

Figure 8: Mean MOR at various span-to-depth ratio

The modulus of rupture (MOR) values in this study, as shown in Figure 8 and Tables 4 to 9, reflect the bending strength of the Gmelina CLT panels bonded with either PUR or ER adhesives across different span-to-depth (S/d) ratios. For PUR bonded specimens as can be observed in Tables 1, 3, and 5 for S/d ratios of 4, 5, and 6, respectively, the mean MOR was 22.82 N/mm², with values ranging from 22.15 to 24.31 N/mm²; 23.83 N/mm², with individual results spanning from 22.69 to 24.62 N/mm²; and the highest MOR mean was observed at 25.73 N/mm², with a range from 24.92 to 26.54 N/mm² respectively. The MOR increased as the S/d ratio rose from 4 to 6 for the PUR-bonded specimens. This trend suggests that as the span increased relative to depth, the bending stress distribution became more favourable for higher MOR values in the PUR-bonded panels. The uniform bonding properties and effective stress distribution of PUR adhesive likely contributed to this improvement, aligning with its established performance in other timber studies such as [4]. However, for ER-bonded specimens, as can be seen in Figure 8 and Tables 2, 4, and 6 for S/d = 4, the mean MOR was 15.77 N/mm², with MOR values between 14.62 and 17.08 N/mm². For S/d = 5, the mean MOR was slightly higher at 17.38 N/mm², with values from 16.35 to 18.27 N/mm², and for S/d = 6, the MOR mean reached 19.06 N/mm², with a range from 18.00 to 19.62 N/mm². The ER-bonded specimens also exhibited an increasing trend in MOR as the S/d ratio increased from 4 to 6, though the MOR values were consistently lower than those of PUR-bonded panels. The observed difference between ER and PUR adhesives aligns with existing literature, which suggests that epoxy resins, while effective, may not provide a uniform bond as PUR in bending scenarios due to differing stress transfer efficiencies, which conforms with [4].

The provided cumulative probability graphs, as shown in Figures 9 and 10, for both PUR and ER adhesives bonded to *Gmelina arborea* timber panels display the distribution of shear strength values across different span-to-depth (S/d) ratios (S/d = 4, 5, and 6).

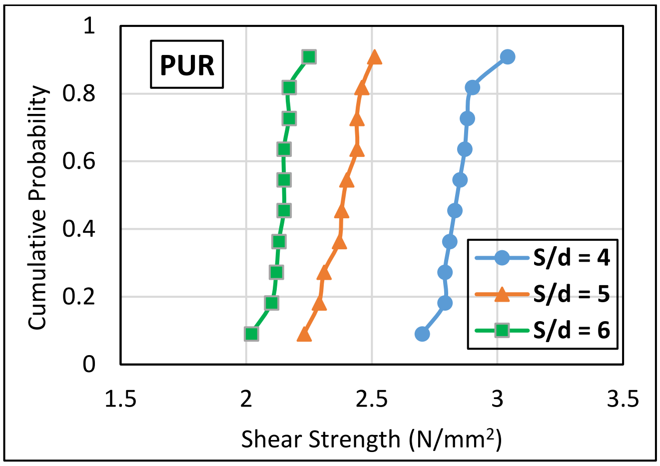

Figure 9: Cumulative probability curve for PUR bonded specimen at various span-to-depth ratio

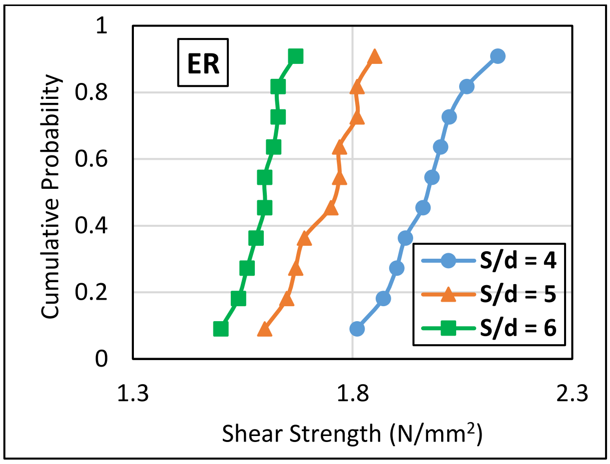

Figure 10: Cumulative probability curve for ER bonded specimen at various span-to-depth ratio

The shear strength values for PUR adhesive appear to be higher overall compared to ER adhesive, as can be observed in Figures 9 and 10, respectively. This suggests that PUR adhesive provides better bonding performance in terms of shear resistance. The S/d = 4 ratio shows a shift towards higher shear strength values. Most specimens have shear strengths within the range of 2.79 to 2.9 N/mm^2. This indicates that a lower span-to-depth ratio results in higher shear strength for the PUR adhesive-bonded specimens. For S/d = 5, the distribution is more moderate, with shear strengths ranging from 2.3 N/mm^2 to 2.51 N/mm^2, suggesting that increasing the span-to-depth ratio reduces the shear strength. At the highest span-to-depth ratio, S/d = 6, the shear strength values are distributed between 2.0 N/mm^2 and 2.25 N/mm^2, further indicating that increasing the S/d ratio leads to lower shear strength. The results of regression modelling to determine the correlation between MOR and maximum bending moment, rolling shear strength, and maximum shear force for PUR-bonded specimens are presented in Figures 11 and 12.

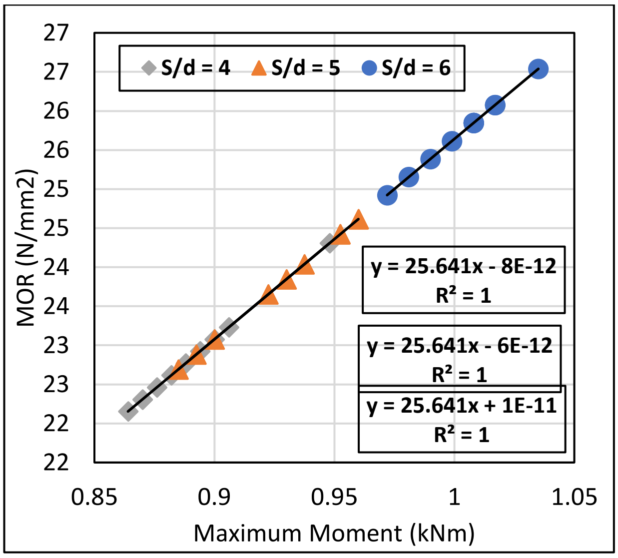

Figure 11: Correlation between MOR and Maximum bending moment

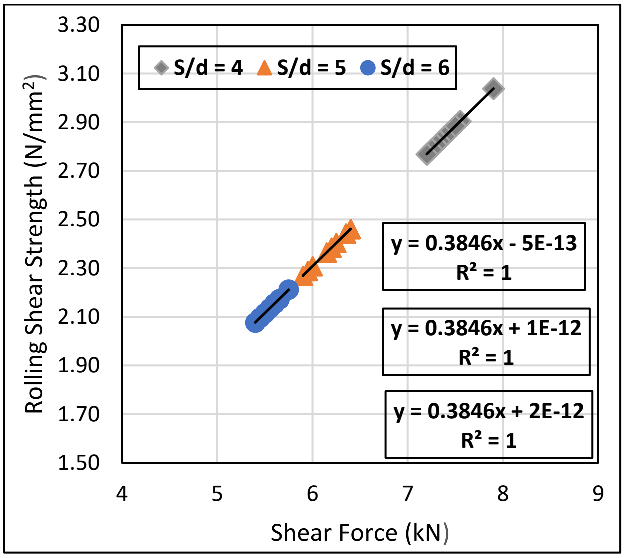

Figure 12: Correlation between Rolling Shear strength and Maximum shear force

All the regression equations (shown in Figs. 11 and 12) have an R^2 value of 1, which indicates a perfect positive correlation between the strength properties considered. The equations could be used as predictive models for MOR and rolling shear strength for PUR-bonded CLT specimens.

4. Conclusions

For both adhesives, increasing the span-to-depth ratio leads to a reduction in shear strength. This trend is more pronounced with ER adhesive than with PUR, which aligns with the expectation that as the span increases, the internal stresses due to rolling shear become more significant, leading to reduced shear strength.

However, increasing the span-to-depth ratio leads to an increase in MOR. The PUR adhesive shows better overall performance in terms of shear strength across all span-to-depth ratios when compared to ER adhesive. This suggests that PUR adhesive creates a stronger bond with Gmelina arborea timber, likely due to better penetration and uniformity of bonding, as indicated by SEM analysis findings in [4]. These results suggest that while both adhesives experience a decline in performance with increasing span-to-depth ratio, PUR adhesive provides significantly better shear strength across different test configurations. The higher MOR values in PUR-bonded panels across all span-to-depth ratios emphasise PUR's superior compatibility with Gmelina timber for applications requiring high bending strength. The findings highlight that while both adhesives support acceptable structural performance, PUR-bonded CLT panels have enhanced bending resistance, making them more suitable for applications involving significant bending stresses. These MOR values provide essential empirical data supporting the adoption of *Gmelina arborea* CLT panels in load-bearing applications. They also demonstrate that Gmelina, when bonded with PUR adhesive, can yield bending strength values comparable to CLT products made from more widely used wood species, broadening its potential use in sustainable construction projects in Nigeria and similar regions. Generally, for performance of adhesives, PUR adhesive yielded higher shear strength in Gmelina CLT panels than ER, confirming its suitability for load-bearing applications. Considering span-to-depth ratios, increasing S/d ratios correlated with decreasing shear strength, aligning with standard structural behaviour and previous studies. This study's results contribute essential data on the use of Nigerian Gmelina arborea in CLT applications, supporting its viability as a local, eco-friendly alternative for structural timber. Overall, these findings indicate that CLT panels fabricated from Gmelina arborea and bonded with PUR adhesive can meet structural demands, with the results setting a precedent for broader application in Nigerian construction and the development of sustainable building materials.

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