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Appendix XXIV

Appendix XXIV is not available with this version.

Compressive Strength of Nigerian *Gmelina Arborea* Cross-laminated Timber: A combined experimental and probabilistic approach for polyurethane and epoxy resin adhesive bonding

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ABSTRACT

Cross-laminated timber (CLT) is gaining recognition as a sustainable alternative to traditional building materials like steel and concrete, offering enhanced structural rigidity and dimensional stability. However, its performance depends heavily on the wood species used. This study explores the potential of *Gmelina arborea*, a fast-growing hardwood widely cultivated in Nigeria but underexplored for CLT applications. The research evaluates the compressive strength of CLT panels made from Nigerian-grown *Gmelina arborea* under in-plane and out-of-plane loading conditions. Panels were fabricated using visually graded planks bonded with one-component polyurethane (PUR) and two-component epoxy resin (ER) adhesives. Compressive strength tests were conducted following the BS EN 408:2010+A1:2012 standard, and reliability analysis was performed using Python and MATLAB to compute reliability indices (β) and probabilities of failure (P_f) via the first-order reliability method (FORM). Results revealed that compressive strength perpendicular to the grain ranged from 11.37 to 13.38 N/mm², while parallel strength ranged from 14.30 to 30.26 N/mm², with PUR-bonded panels exhibiting slightly higher values. PUR-bonded panels achieved a mean perpendicular strength of 12.47 N/mm² compared to 12.24 N/mm² for ER-bonded panels. Parallel strength in the minor direction was higher than perpendicular strength, with PUR and ER panels averaging 18.19 N/mm² and 15.80 N/mm², respectively. The major strength direction showed the highest values, with PUR at 27.86 N/mm² and ER at 26.79 N/mm². Reliability analysis indicated that PUR adhesives outperformed ER, with higher reliability indices ($\beta = 3.6637$, $P_f = 0.0243\%$) compared to ER ($\beta = 3.1646$, $P_f = 0.077641\%$). These findings highlight the superior structural reliability of PUR-bonded CLT panels.

KEY WORDS: Cross-laminated timber (CLT); In-plane and Out-of-plane compression; Major and Minor strength direction; Reliability analysis, *Gmelina arborea* Timber; PUR and ER Adhesives.

1. Introduction

Cross-laminated timber (CLT) has emerged as a revolutionary material in the construction of mass timber buildings, offering an eco-friendly option to conventional building materials such as steel and concrete. CLT is composed of layers of solid-sawn lumber boards, stacked crosswise and glued together, which enhances its structural rigidity and dimensional stability. 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. A major benefit of CLT in mass timber

production is its eco-friendliness. CLT panels are manufactured from renewable wood resources, which not only reduces the carbon footprint of buildings but also sequesters carbon dioxide for the lifespan of the structure (Brandner, 2013; Olsson et al., 2023). Additionally, CLT construction can lead to faster build times due to the prefabrication of panels, which are transported to the construction site and assembled with precision (Karacabeyli and Douglas, 2013). CLT's fire performance is also noteworthy. Contrary to traditional wood products, CLT panels char on the outside when exposed to fire, forming an insulating barrier that delays the combustion process and preserves the building's structural integrity for an extended time (Sharifnia, 2017). This property has made CLT an attractive option for developers aiming to meet stringent fire safety regulations in mass timber buildings. Furthermore, the versatility of CLT allows for innovative architectural designs, enabling the construction of tall timber buildings, some reaching up to 18 stories or more. The structural capabilities of CLT, combined with its environmental benefits, have positioned it as a key material in the growing trend of sustainable urban development (Sikora et al., 2016).

The use of CLT in mass timber buildings represents a significant advancement in sustainable construction, offering environmental, structural, and aesthetic benefits that make it a compelling choice for modern architecture. The continued development and adoption of CLT technology is expected to be vital in the future of green building practices worldwide. 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 (Shirmohammadi and Leggate, 2021). Initial studies indicate that *Gmelina arborea* has moderate mechanical properties, with compressive strength ranging from 10 to 30 N/mm² and bending strength similar to that of

softwoods (Yau et al. 2024a; Okon and Ogbonnaya, 2019). Yau et al. (2024b) 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 evaluation of cross-laminated timber (CLT) under compression perpendicular to the grain 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. However, according to Jeleč et al. (2018), research on compressive strength of CLT parallel to grain is scarce. Halili (2008) and Salzman (2010) conducted foundational research at the Institute of Timber Engineering and Wood Technology, Graz University of Technology, focusing on determining the mechanical characteristics of CLT under compression perpendicular to the grain. Both studies employed experimental techniques to derive parameters that describe the compressive behaviour of CLT, with results indicating that the orientation and type of wood layers significantly influence the mechanical properties under perpendicular load. In another study, Serrano and Enquist, (2010) extended this research by presenting their findings at the 11th World Conference on Timber Engineering (WCTE2010). Their work explored the compressive strength of CLT

perpendicular to the grain and highlighted the importance of considering grain direction and layer arrangement to optimize load-bearing capacity. Their results showed variability in compressive strength based on different wood species and layer configurations, emphasizing the need for standardized testing methods. Bogensperger et al. (2011) further analysed the properties of CLT panels exposed to compression perpendicular to their plane. Their study, presented at the 44th CIB-W18 Meeting, detailed how factors such as moisture content, wood density, and layer orientation impact the mechanical performance of CLT panels. They concluded that enhancing the layer adhesion and choosing appropriate wood species could significantly improve the compressive strength. 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 (Dong et al., 2021; Hematabadi et al., 2020). The study by Dobeš et al. (2023), 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 He et al. (2020) focuses on evaluating the mechanical properties (including 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. The impact of borate treatment on the durability of CLT was investigated by Bagheri et al. (2022), findings suggested that such treatments can significantly enhance the longevity of CLT structures in humid environments. Furthermore, Zelinka et al. (2019) conducted small-scale tests to assess the effectiveness of adhesives used in CLT under high-temperature conditions, concluding that

adhesive choice plays a critical role in the fire resistance of CLT panels. In terms of structural optimization, Mayencourt et al. (2018) emphasized the importance of panel configuration in maximizing the strength and stiffness of CLT. Their work suggests that the arrangement of layers within the panel significantly affects its load-bearing capacity, which is critical for both in-plane and out-of-plane performance. This is further supported by studies on the influence of layer configuration on bending strength by Hafkhani and Hematabadi (2022), who found that optimizing the orientation of layers can lead to significant improvements in the mechanical properties of CLT panels. The effect of wood species on the stiffness and deformation characteristics of CLT has been explored in various studies. The relationship between material stiffness and CLT element performance was examined by Olsson et al. (2023), 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, Unterwieser and Schickhofer (2013), provided insights into the characteristic values and testing arrangements of CLT, focusing on selected properties that are critical for ensuring the reliability of these engineered wood products in construction. In summary, the existing literature provides a solid foundation for understanding the factors that influence the strength and stiffness of CLT panels. CLT has become increasingly popular as a sustainable and adaptable construction material, providing benefits in structural integrity, environmental sustainability and aesthetic appeal. However, the evaluation of CLT's strength and stiffness properties is crucial for its safe and efficient application in construction. Despite the global uptake of CLT, its application in regions like Nigeria remains limited, largely due to the lack of comprehensive research and data on local wood species suitable for CLT production.

Gmelina arborea, a hardwood species locally available in Nigeria, presents a promising candidate for CLT production, owing to its favourable growth characteristics and mechanical properties (Muñoz et al., 2022). The *Gmelina* timber showed volumetric shrinkage and swelling of 8.71% and 8.26%, respectively, with tangential values at 5.19% and 4.96%, radial values at 3.72% and 2.82%, and longitudinal values at 1.19% and 0.48%. It absorbed 94.7% water over 53 days to reach full saturation, then lost 83.18% moisture during drying to an equilibrium moisture content of 12%. The timber's low shrinkage and swelling align with its low water absorption, enhancing dimensional stability and making it less prone to decay, mold, and fungal growth—ideal for outdoor and high-moisture applications (Yau et al., 2024c). Historically, *Gmelina arborea* has been primarily utilized for pulp and paper production, furniture, and other low-value applications (Ekundayo et al., 2022).

This research aims to evaluate the in-plane and out-of-plane compressive strength properties of CLT panels made with Nigerian-grown *Gmelina arborea* timber. The study seeks to fill the gap in existing literature by providing empirical data on the structural performance of CLT made from locally available *Gmelina arborea*, which could contribute to the development of value-added products in Nigeria's timber industry. This study focuses on 3-ply CLT panels with a lamination thickness of 35 mm, bonded using one-component polyurethane (PUR) and two-component epoxy resin (ER) adhesives.

2. Materials and Methods

2.1 Materials

2.1.1 Timber

Nigerian *Gmelina arborea* timber logs were sourced from a local sawmill in Old Panteka Timber market in Kaduna. The logs were processed into lumbers, seasoned, and conditioned for

approximately 14 weeks to attain a moisture content (MC) of approximately 12% according to EN 13183 (2002), which is the reference MC. The *Gmelina* timber has an average basic density and green MC of 505 kg/m³ and 141 % respectively. The timber was classified as C30 according to BS EN 338 (2016). All the CLT specimens were produced from visually graded planks or lumbers (with different cross-sectional) sawn from this timber specie (Fig. 1).



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

Some of the basic material properties of the lumber boards used in this research are presented in Table 1 and were determined in accordance to BS EN 408 (2012).

Table 1: Some basic properties of the lumber boards

MC (%)	Density (kg/m ³)	Compressive Strength (N/mm ²)		Strength Class BS EN 338
		Perpendicular to grain	Parallel to grain	
10.85	528.53	5.89	35.82	C 30

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 24hours. Two-component Epoxy Resin (ER) adhesives (SUA–8714), which is 100% synthetic resin. It is resistant to heat, water, oil, acid and alkali according to the manufacturer. The initial curing time is 90 min, and subsequently reaches maximum strength after 24hours. 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)*	1.13 (R)*	40 Pa.s	Yes
	Pale yellow (H)*	1.12 (H)*		

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

2.1.3 Clamping Device

A fabricated manual clamping device for mounting pressure on the bonding specimens was used and adapted from Yau et al. (2024d). 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 (2013), a manual pressing device is acceptable for use with small-scale specimens.



Figure 2: Improvised clamping device for pressure application (Yau et al., 2024d)

2.2 Methods

2.2.1 Material Selection and Preparation

Visually graded *Gmelina arborea* lumber boards (Fig. 1) in accordance with EN 14081-1 (2016), were selected and then planed to uniform cross-sectional dimensions of 35mm x 120 mm for 3-layer CLT-105. The length of longitudinal and transverse lumbers used is 750 mm and 380 mm respectively.

2.2.2 CLT Panels Fabrication and Test Specimens Preparation

To fabricate the 3-layer CLT panel, a total of 15 lumber boards were used. The first layer consisted of 4 longitudinal lumbers, followed by 7 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 (Fig. 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 (2016), 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.

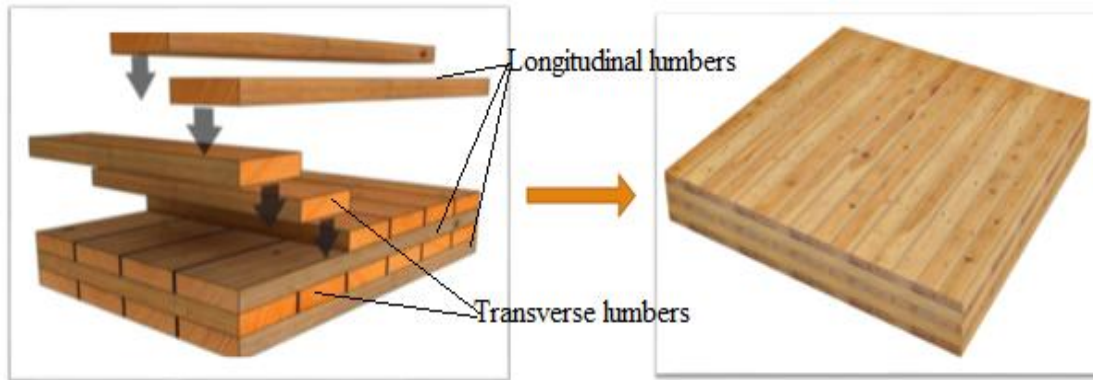


Figure 3: Conventional assembly layout and gluing of lumbers to produce CLT panels

Application of Adhesives: The adhesive application rate for both PUR and ER adhesives was 350 g/m², in alignment with the manufacturer's guidelines. For the longitudinal lumbers (120 mm x 750 mm), 32g of adhesive was uniformly applied over the surface area, while 16g was used for the transverse lumbers (120 mm x 380). The mixing ratio for the two-component ER adhesive was 1:1. For the longitudinal lumbers, 16g of both resin and hardener were used, while 8g of each component was applied to the transverse lumbers.

Pressing of CLT panels (pressure application): Four (4) improvised clamping device 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 hrs. 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 (2012).

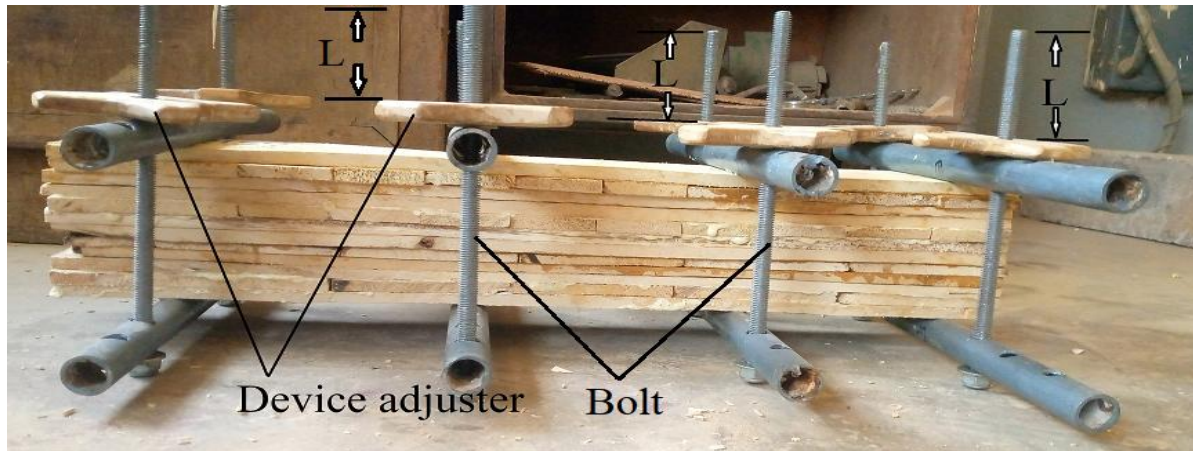


Figure 4: Clamping of CLT Panel

Table 3: Dimensions and number of CLP panels and specimens produced

Adhesive type	CLT-105 Panel		CLT- Specimen	
	Dimensions	Number	Dimensions	Number
PUR	105mm x 360mm x 720mm	2	105 mm x 90 mm x 90 mm	36
ER	105mm x 360mm x 720mm	2	105 mm x 90 mm x 90 mm	36

A total of 4 CLT panels were produced and 72 CLT specimen were extracted from the panels (Table 3), for use as compressive strength and density 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 Determination of Density and Compressive Strength

Density Test: The mass and volume of all the 72 CLT test specimens were measured and recommended before subjecting the specimens to compression. Equation (1) was used to compute the density results for each tested specimens and the average result for specimens tested perpendicular to grain (out-of-plane), parallel to grain in major strength direction (in-plane), and parallel to grain in minor strength direction (in-plane) was recorded respectively.

$$\rho = \frac{\text{Mass}}{\text{Volume}} \quad (1)$$

Compressive Strength Test: The CLT specimens were subjected to both in-plane (considering major and minor strength direction) and out-of-plane loading conditions using the specification in BS EN 408 [30]. The test configuration as illustrated in Figure 6, and instrumentation were also configured in compliance with BS EN 408 (2012), ANSI/APA PGR 320 (2012); and BS EN 16351 (2015). Equation (2) was used to compute the compressive strength properties of the tested specimen bonded with PUR and ER adhesives.

$$f_{c,90}, f_{c,0,minor}, f_{c,0,major} = \frac{F_{\max}}{\text{Area}} \quad (2)$$



(a)



(b)

Figure 6: Test setup for compressive strength (a) in-plane, and (b) out-of-plane conditions

For the in-plane compressive strength, major and minor strength directions as shown in Figure 7 are considered. The major strength direction consists of two outermost layers parallel to grain, while in the case of minor strength direction only the inner layer is aligned parallel to grain direction.

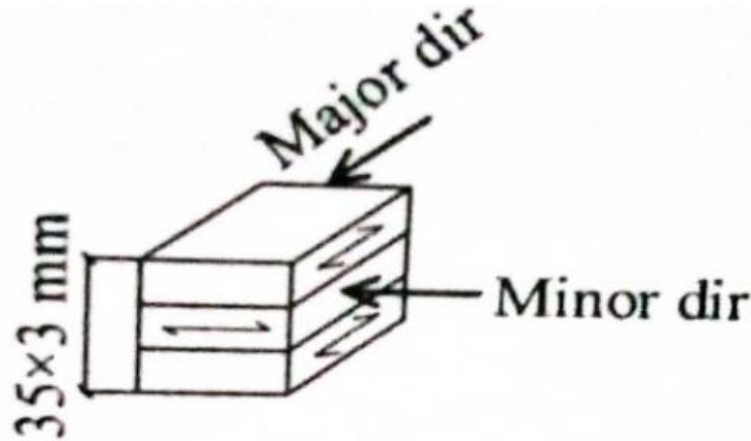


Figure 7: A prismatic CLT-specimen showing the two strength directions (He et al., 2020)

2.2.4 Reliability Analysis

Reliability analysis using the First Order Reliability Method (FORM) was conducted in MATLAB and Python to evaluate the probabilistic structural response of the Gmelina CLT panels. Compression failure criteria derived from the structural response of the CLT panels were adopted. Below are the detailed and complete procedures for conducting FORM:

1. Problem Definition, which involves the following:
 - i. Problem identification, by defining the structure and outlining the failure mode and consequently defining the limit state function (LSF) as shown in Equation (3).

$$g(x) = R(x) - S(x) \quad (3)$$

Where; $R(x)$: Resistance or capacity of the system and $S(x)$: Applied load or stresses.

Failure occurs when $g(x) \leq 0$, and the system is safe when $g(x) > 0$.

- ii. Random variables definition, by identifying the input variables $X = X_1, X_2, \dots, X_n$ and specifying the probability distribution (e.g., normal, lognormal, Weibull) and statistical parameters (mean, standard deviation, etc.) for each of the variables.
2. Transformation of Variables to Standard Normal Space
 - i. Conversion of all random variables X to standard normal variables $U = \{U_1, U_2, \dots, U_n\}$ using appropriate transformations.
 - ii. Provision of correlation matrix if the variables are correlated. Otherwise, set as the identity matrix. Using techniques like Cholesky decomposition to transform correlated variables into independent ones.
3. Find the Most Probable Point (MPP): The MPP is the point on the limit state surface ($g(U) = 0$) that is closest to the origin in standard normal space. Use optimization techniques such as Hasofer-Lind method, Gradient-based methods, and Newton-Raphson method to solve the optimization problem as shown in Equation (4) iteratively. Starting with an initial guess for U and compute the gradient $\nabla g(U)$. Finally updating U iteratively until convergence as shown in Equation (5).

$$\text{Minimize: } \|U\| = \sqrt{U_1^2 + U_2^2 + \dots + U_n^2} \quad (4)$$

Subject to: $g(U) = 0$

$$U^{(k+1)} = U^{(k)} - \alpha \cdot \frac{\nabla g(U^{(k)})}{\|\nabla g(U^{(k)})\|} \quad (5)$$

Where α is the step size.

4. Find the Reliability Index (β): Once the MPP U^* is found, the reliability index is computed using Equation (6). A higher β value indicates higher reliability (lower probability of failure).

$$\beta = \|U^*\| = \sqrt{(U_1^*)^2 + (U_2^*)^2 + \dots + (U_n^*)^2} \quad (6)$$

5. Computation of the Probability of Failure (P_f): Using the reliability index β , the probability of failure is calculated as shown in Equation (7).

$$P_f = \Phi(-\beta) \quad (7)$$

Where Φ is the standard normal cumulative distribution function (CDF). P_f gives the probability that the system will fail under given conditions.

6. Sensitivity Analysis (Optional): The sensitivity coefficients are calculated using Equation (8) for each random variable to understand their influence on reliability. Variables with higher $|\alpha_i|$ have greater influence on the system's reliability.

$$\alpha_i = \frac{\partial g(U)}{\partial U_i} \cdot \frac{1}{\|\nabla g(U)\|} \quad (8)$$

The limit state function for compression capacity is give in Equation (9)

$$g(x) = 0.89F_c A_{parallel} - P_{parallel} \quad (9)$$

Where; F_c is the allowable compressive strength, $A_{parallel}$ is the area of layers with fibres running parallel to the direction of the load and $P_{parallel}$ is the maximum load applied parallel to the direction of the fibres.

2.2.5 Data Analysis

The test data were analysed using statistical techniques in Excel to determine the mean values, standard deviation, and coefficient of variation (COV). Additionally, linear regression modelling and analysis of variance (ANOVA) were employed for further analysis.

3. Results and Discussions

The study evaluated the compressive strength of Cross-Laminated Timber (CLT) panels made with *Gmelina arborea*, under both in-plane and out-of-plane loading conditions. Two adhesives, polyurethane (PUR) and epoxy resin (ER), were used to bond the CLT panels. The results from compressive strength tests parallel and perpendicular to the grain as presented in this section, reveal important insights about the mechanical behaviour of Gmelina CLT and the influence of adhesives on its performance.

3.1 Density and Compressive Strength Perpendicular to Grain

The experimental results for 24 CLT specimens tested for compressive strength perpendicular to grain and density are presented in Table 4.

Table 4: Details of the compressive strength perpendicular to grain

S/N	PUR				ER			
	Area (mm ²)	F _{max} (kN)	$f_{c,90}$ (N/mm ²)	Density (kg/m ³)	Area (mm ²)	F _{max} (kN)	$f_{c,90}$ (N/mm ²)	Density (kg/m ³)
1	8094.44	92	11.3658	520	7560	90	11.9048	523
2	8149.06	107	13.1303	538	8007.55	98	12.2385	533
3	7858.98	95	12.0881	526	8176.68	103	12.5968	534
4	8128.82	97	11.9329	533	8130.63	90	11.0693	519
5	8129.72	105	12.9156	538	8137.84	98	12.0425	526
6	8118.91	98	12.0706	525	8131.43	96	11.806	533
7	8098.18	105	12.9659	536	8115.28	98	12.076	534
8	8094.58	108	13.3423	544	8126.09	97	11.9369	527
9	8068.47	96	11.8982	528	8153.15	108	13.2464	540
10	8147.77	103	12.6415	533	8165.81	100	12.2462	528
11	8249.83	109	13.2124	551	8071.99	108	13.3796	548
12	8247.28	100	12.1252	520	8095.48	100	12.3526	537
Mean	8115.5	101.25	12.47	532.67	8072.66	98.83	12.24	531.83

COV	1.22%	5.59%	5.12%	1.77%	2.08%	5.77%	5.10%	1.48%
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From Table 4, the mean compressive strength perpendicular to the grain for PUR-bonded CLT panels was 12.47 N/mm², with a coefficient of variation (COV) of 5.12%, while for ER-bonded panels, the strength was 12.24 N/mm², with a COV of 5.1%. These values show that both adhesives performed similarly in terms of strength, with a slight edge for PUR. The COVs indicate a relatively consistent performance, reflecting stable adhesive bonding and uniform material behaviour. In terms of strength range, the panels exhibited values between 11.37 N/mm² and 13.38 N/mm², which aligns with the expected performance for timber in this strength class (C30, according to EN 338). The close similarity between the performances of the two adhesives suggests that both PUR and ER are viable for CLT panel production with respect to out-of-plane loading.

3.2 Density and Compressive Strength Parallel to Grain (Minor Strength Direction)

The experimental data for density and compressive strength parallel to the grain in minor strength direction of 24 CLT specimens is shown in Table 5.

Table 5: Details of the compressive strength parallel to grain (minor strength direction)

S/N	PUR				ER			
	Area (mm ²)	F _{max} (kN)	f _{c,90} (N/mm ²)	Density (kg/m ³)	Area (mm ²)	F _{max} (kN)	f _{c,90} (N/mm ²)	Density (kg/m ³)
1	9665.44	158	16.3469	510	9323.73	135	14.4792	512
2	9349.79	169	18.0753	538	9364.17	141	15.0574	516
3	8994.88	156	17.3432	523	9161.16	155	16.9193	550
4	8996.71	158	17.562	531	9048.97	150	16.5765	545
5	8994.01	188	20.9028	551	9384.84	148	15.7701	537
6	9319.22	176	18.8857	536	9217.35	139	15.0803	528
7	9230.29	175	18.9593	524	9241.9	142	15.3648	522

8	9188.6	148	16.1069	527	9271.62	158	17.0413	553
9	9299.1	175	18.819	546	9437.82	135	14.3042	514
10	9675.28	158	16.3303	523	9172.7	147	16.0258	532
11	9048.26	165	18.2356	537	9044.65	150	16.5844	543
12	9096.06	188	20.6683	543	9035.43	148	16.38	541
Mean	9238.14	167.83	18.19	532.42	9225.36	145.67	15.8	532.75
COV	2.60%	7.65%	8.66%	2.19%	1.49%	5.06%	5.93%	2.68%

As can be seen in Table 5, the compressive strength parallel to grain in the minor strength direction was higher than the perpendicular strength, with mean values of 18.19 N/mm² for PUR-bonded panels and 15.80 N/mm² for ER-bonded panels. The PUR-bonded panels exhibited a COV of 8.66%, while the ER-bonded panels showed a COV of 5.93%. This indicates more variability in the PUR-bonded panels, though they performed better in terms of absolute strength. The range of values for compressive strength in the minor direction (from 16.11 N/mm² to 20.90 N/mm² for PUR and 14.30 N/mm² to 17.04 N/mm² for ER) suggests that the PUR adhesive provides better bonding and load transfer efficiency in the minor direction, which could be beneficial in applications requiring higher stiffness and strength along this axis.

3.3 Density and Compressive Strength Parallel to Grain (Major Strength Direction)

Considering the strength parallel to grain in the major strength direction, the experimental data obtained for 24 CLT specimens tested is shown in Table 6.

Table 6: Details of the compressive strength parallel to grain (major strength direction)

S/N	PUR				ER			
	Area (mm ²)	F _{max} (kN)	<i>f_{c,90}</i> (N/mm ²)	Density (kg/m ³)	Area (mm ²)	F _{max} (kN)	<i>f_{c,90}</i> (N/mm ²)	Density (kg/m ³)
1	9594.91	253	26.3681	512	9031	248	27.461	547
2	9493.05	248	26.1244	523	9205.52	242	26.2886	523
3	9085.41	235	25.8657	534	9090.4	245	26.9515	527

4	9086.98	275	30.2631	552	9140.74	254	27.7877	543
5	9196.85	265	28.8142	543	9165.9	245	26.7295	532
6	8857.19	248	27.9999	539	9125.55	257	28.1627	552
7	8696.82	243	27.9412	542	9190.51	248	26.9844	530
8	9115.53	248	27.2063	522	9091.22	245	26.9491	534
9	8840.83	258	29.1828	538	8883.6	238	26.7909	531
10	9439.83	248	26.2717	515	9028.21	245	27.1372	536
11	8912.4	268	30.0705	553	9054.78	230	25.4009	526
12	9026.62	255	28.2498	530	9077.67	225	24.7861	523
Mean	9112.2	253.67	27.86	533.58	9090.42	243.5	26.79	533.67
COV	3.05%	4.45%	5.48%	2.52%	0.96%	3.71%	3.51%	1.75%

The compressive strength in the major strength direction was the highest among all tests, as can be seen in Table 6 and Figure 8, with mean values of 27.86 N/mm² for PUR-bonded panels and 26.79 N/mm² for ER-bonded panels. The COVs were 5.48% for PUR and 3.51% for ER, indicating slightly more consistent performance with the ER adhesive in this direction. The strength range for compressive strength in the major direction (from 25.87 N/mm² to 30.26 N/mm² for PUR and 24.79 N/mm² to 28.16 N/mm² for ER) confirms that Gmelina arborea CLT panels offer robust structural performance when loaded in-plane, with values comparable to other hardwood CLT systems. Both adhesives performed well in this test, though PUR again showed a slight advantage in absolute strength. The densities of all CLT-specimen bonded with PUR and ER adhesives as shown in Table 3, remain nearly similar and identical, ruling out density as a factor for the strength differences observed. The significant difference in compressive strength between the major and minor directions is primarily due to the difference in wood grain orientation and how fibres resist compressive forces. Understanding these differences is crucial for structural design, especially for load-bearing applications where the direction of load application relative to the grain orientation can significantly affect the performance of CLT panels.

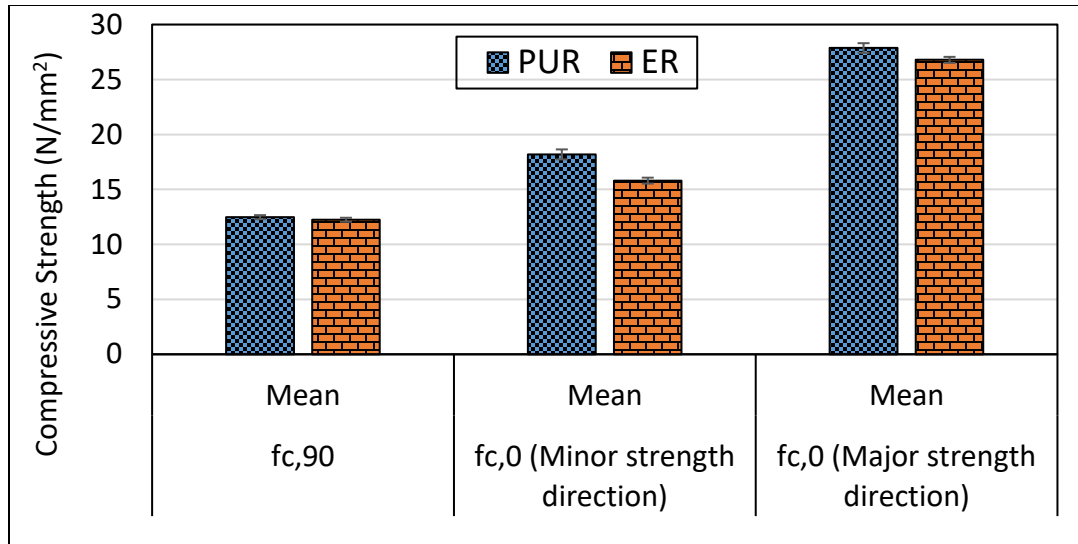


Figure 8: Mean values of the compressive strength properties of Gmelina CLT panels

Generally, the study reveals that both PUR and ER adhesives are suitable for bonding Gmelina arborea CLT panels, with PUR showing slightly better strength in both the minor and major grain directions as shown in Figure 9 (a & b).

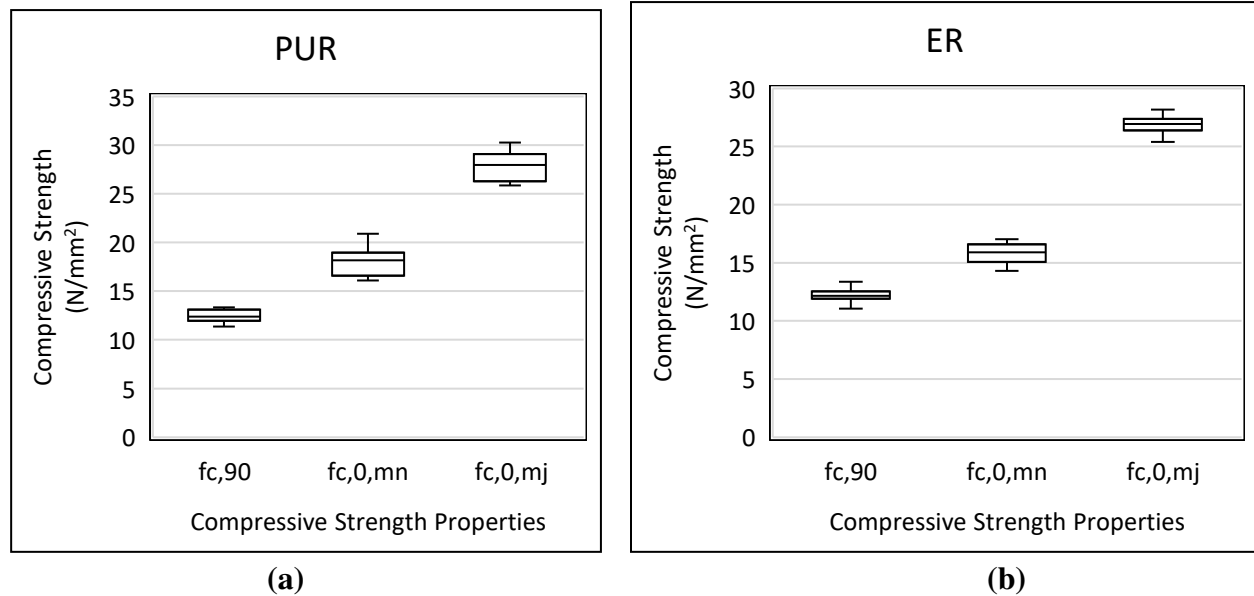


Figure 9: Comparison between compressive strength properties for specimens bonded with PUR and ER adhesives

The differences observed might be attributed to the high bonding efficiency of PUR, which is known for its excellent penetration into the wood fibres, resulting in stronger adhesion. The

compressive strength values obtained in this study are comparable to those found in other hardwood-based CLT systems. For instance, in traditional softwood CLT systems (like C24 spruce), compressive strength values parallel to the grain typically range from 20 N/mm² to 28 N/mm², making Nigerian *Gmelina arborea* CLT a competitive alternative for structural applications. The compressive strength perpendicular to the grain, though generally lower, is still within acceptable limits for CLT panel systems. This property is crucial for load-bearing elements subjected to compression from floors or other elements, indicating that *Gmelina arborea* can perform well in both in-plane and out-of-plane loading scenarios.

3.4 Analysis of Variance (ANOVA)

The results of two-factor ANOVA, which assessed the effects of adhesive type, strength properties (compressive strength perpendicular to grain, parallel to grain in minor strength direction, and parallel to grain in major strength direction), and their interaction on the CLT specimens' compressive strength are presented in Table 7.

Table 7: Two-factor ANOVA for Adhesive Type and Compressive Strength Properties

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Adhesive type	27.34728	1	27.34727712	22.25535*	1.28E-05	3.986269
Strength properties	2817.894	2	1408.946879	1146.608*	5.54E-52	3.135918
Interaction	14.14784	2	7.073921944	5.756792*	0.00496	3.135918

***Significant at P = 0.005 level**

From Table 7, looking at adhesive type as one of the sources of variation, the F-value of 22.26 is much greater than the critical F-value (3.986), and the P-value is significantly smaller than the 0.05 significance level. This indicates that adhesive type has a statistically significant effect on the compressive strength of the CLT specimens. The choice of adhesive contributes meaningfully to

the variation in the results. For the strength properties, the F-value of 1146.61 is dramatically larger than the F-critical value of 3.136, and the P-value is practically zero. This shows that strength properties (compressive strength perpendicular to grain, parallel to grain in minor strength direction, and parallel to grain in major strength direction) have an extremely significant effect on the results. This suggests that the direction in which the compressive strength is measured plays a major role in determining the overall performance. Considering interaction between adhesive type and strength properties, the F-value of 5.76 exceeds the critical F-value (3.136), and the P-value is less than 0.05. This means that there is a statistically significant interaction effect between adhesive type and strength properties. In other words, the effect of adhesive type on compressive strength depends on which strength property is being measured. This suggests that the performance of the adhesives may vary depending on whether the strength is measured perpendicular to the grain or parallel to the grain (in either direction). Conclusively, adhesive type has a significant impact on the compressive strength results of CLT specimens. Strength properties (whether compressive strength is measured perpendicular to grain or parallel to grain) show a highly significant effect, meaning the direction of the force greatly influences the results. There is also a significant interaction between adhesive type and strength properties, indicating that the performance of the adhesives varies depending on the direction in which the compressive strength is measured. This suggests that choosing an adhesive need to consider the specific strength requirements (e.g., perpendicular or parallel to the grain), as the adhesives do not perform equally across all strength directions.

3.5 Regression Model for the Compressive Strength Properties

The graphs in Figure 10 to 12, display the relationship between compressive strength (N/mm^2) and density (kg/m^3) for CLT specimens bonded with PUR and ER adhesives. Two set of data points

are represented on each graph, data for CLT specimens bonded with PUR adhesive and data for CLT specimens bonded with ER adhesive. Both adhesives show a positive correlation between density and compressive strength as can be observed in all the Figures (10 to 12).

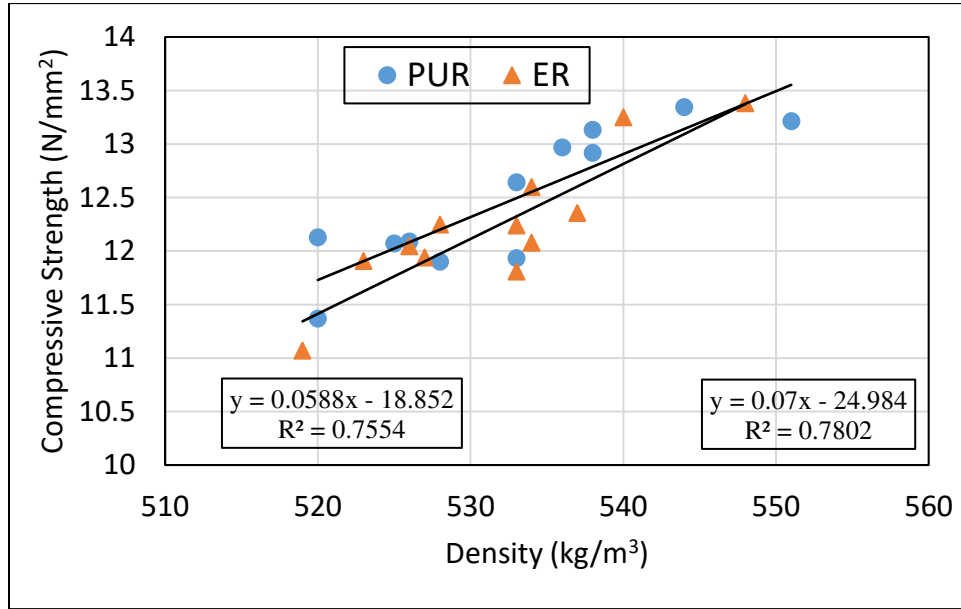


Figure 10: Correlation between Compressive Strength Perpendicular to grain and Density

From the regression equation in Figure 10, the slope (0.0588) indicates the rate at which compressive strength increases per unit increase in density for PUR adhesive. The R^2 value of 0.7554 suggests that approximately 75.54% of the variation in compressive strength can be explained by the variation in density for PUR-bonded specimens. While for ER-bonded specimens, the slope (0.07) shows that the increase in compressive strength per unit increase in density is slightly higher for ER adhesive than for PUR. The R^2 value of 0.7802 indicates that about 78.02% of the variation in compressive strength is explained by the variation in density for ER-bonded specimens. Both R^2 values are relatively high (above 0.75), meaning the relationship between density and compressive strength is strong for both adhesives. However, ER ($R^2 = 0.7802$) shows a marginally better fit than PUR ($R^2 = 0.7554$). In conclusion, for the remaining regression equations in Figure 11 and 12 respectively, similar explanations could be adopted.

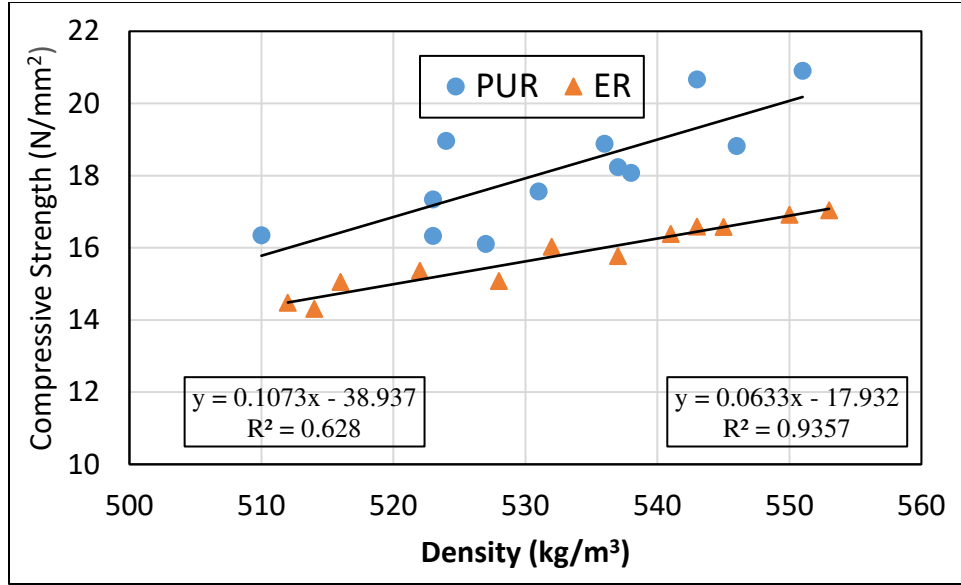


Figure 11: Correlation between Compressive Strength in Minor direction and Density

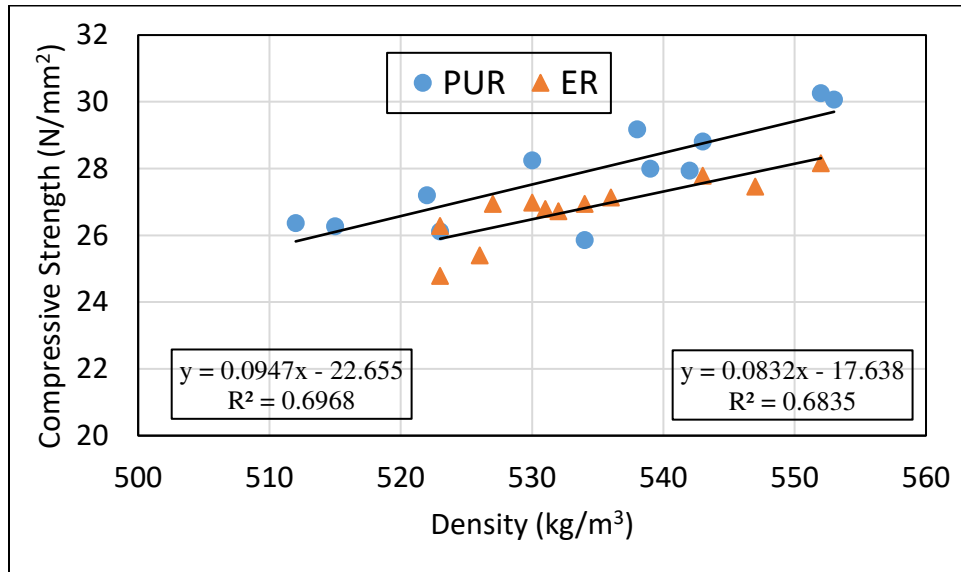


Figure 12: Correlation between Compressive Strength in Major direction and Density

3.6 Reliability Analysis Results

The design variables for the limit state function of in-plane compression (Eqn. 9), including the allowable compressive strength and maximum applied load parallel to the fibre direction, are provided in Tables 8 and 9. The areas of the layers with fibres aligned parallel to the applied load

($A_{parallel}$) are 6120 mm² and 3060 mm² for compression in the major and minor strength directions, respectively.

Table 8: Allowable compressive stress for different grain orientation

Grain Orientation	PUR-bonded specimens		ER-bonded specimens	
	Mean	SD	Mean	SD
	(N/mm ²)	(N/mm ²)	(N/mm ²)	(N/mm ²)
Parallel (Minor Direction)	15.587	3.76	14.25	4.2
Parallel (Major Direction)	25.34	1.53	24.23	1.73

Table 9: Maximum compressive force for different grain orientation

Grain Orientation	PUR-bonded specimens		ER-bonded specimens	
	Mean	SD	Mean	SD
	(kN)	(kN)	(kN)	(kN)
Parallel (Minor Direction)	135	24.2	120	25.7
Parallel (Major Direction)	188	10.8	175	9.8

The Python scripts used for the reliability analysis are presented in Appendix XXIV. The reliability analysis results for the compression capacity of CLT panels are summarized in Table 10 and illustrated in Figure 13. Table 10 provides the reliability indices (β) and probabilities of failure (P_f) for compression capacity of CLT panels bonded with polyurethane (PUR) and epoxy resin (ER) adhesives, considering grain orientation in the minor and major strength directions.

Table 10: Reliability index and probability of failure for in-plane compression failure

Grain Orientation	Reliability index (β)	Probability of failure (P_f)
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	PUR	ER	PUR	ER
Parallel (Minor Direction)	3.5228	2.8862	0.00021352	0.0019493
Parallel (Major Direction)	3.6637	3.1646	0.0001243	0.00077641

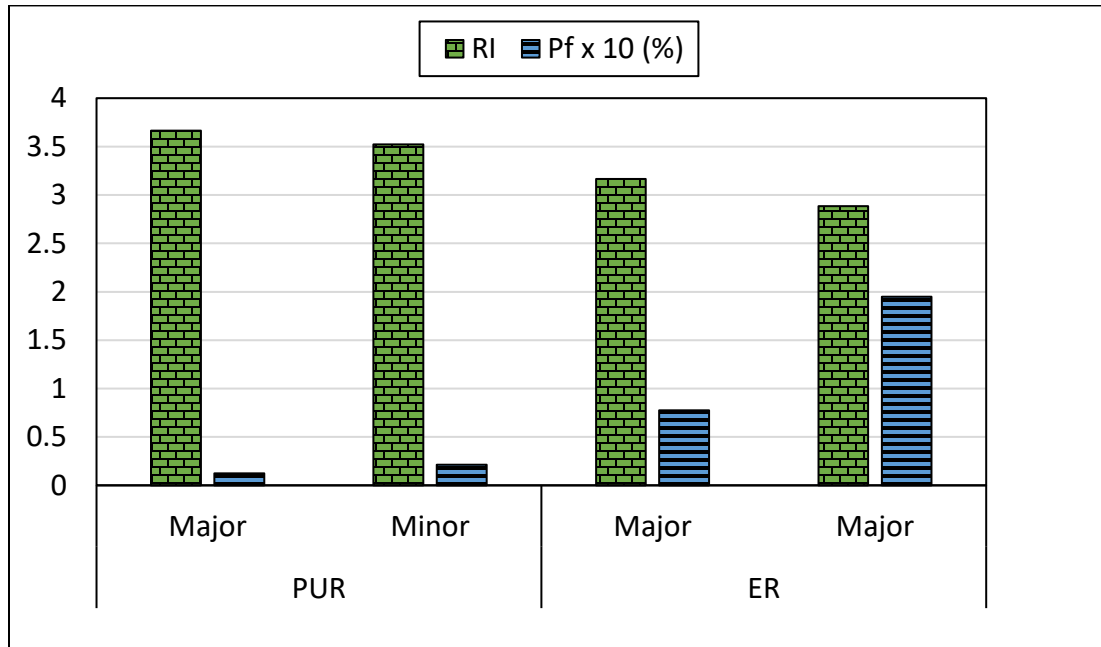


Figure 13: Reliability indices and probabilities of failure for varying span-to-depth ratios

The reliability indices for PUR-bonded panels are consistently higher than for ER-bonded panels in both grain orientations as can be observed in Figure 13. Panels bonded with PUR have lower P_f indicating better performance and safety compared to ER-bonded panels. The major strength direction yields higher reliability (β) and lower failure probabilities (P_f) for both adhesive types. Furthermore, a 2D reliability surface plot, shown in Figure 14, provides a visual representation of the reliability results for PUR-bonded CLP panels in major strength direction.

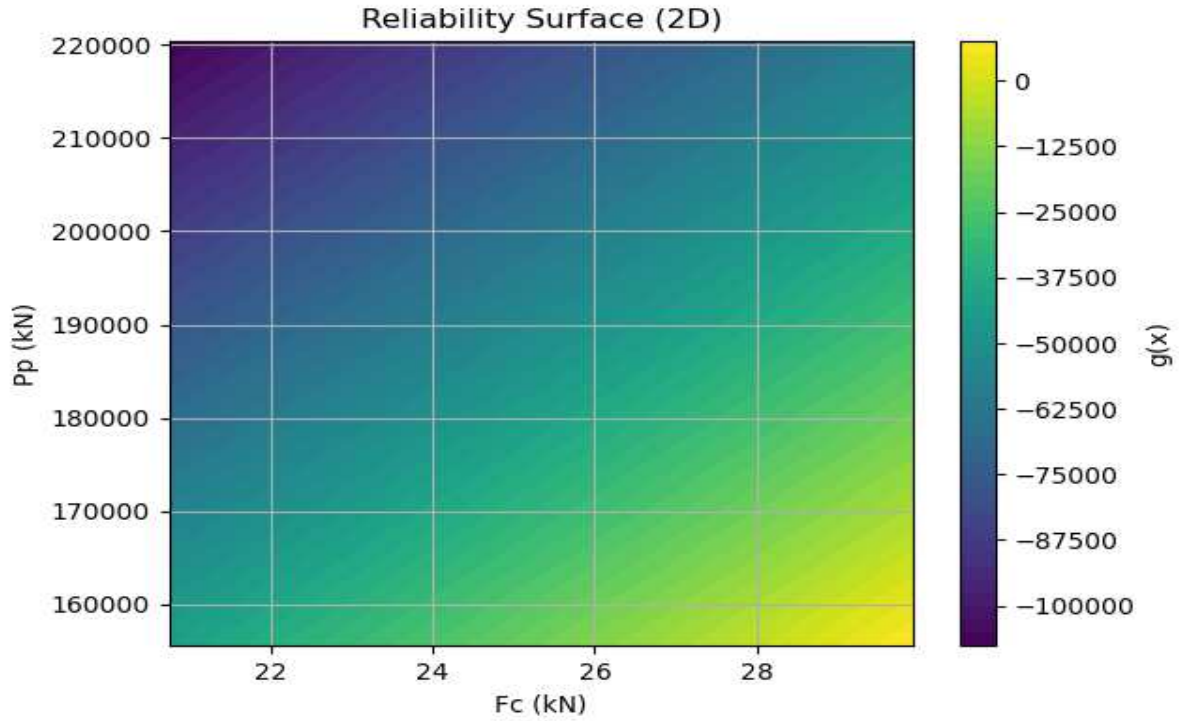


Figure 14: Reliability surface plot for CLT panels subjected to compression (major direction) bonded with PUR adhesive

In Figure 14, the blue region represents the failure zone, where combinations of variables lead to system failure. The yellow region denotes the safe zone, indicating combinations of variables under which the system operates safely. The boundary separating these zones is referred to as the limit state boundary, representing the critical combinations of variables at which the system reaches its maximum capacity.

4. Conclusions

The compressive strength perpendicular to grain ranged from 11.37 N/mm² to 13.34 N/mm² and 11.10 N/mm² to 13.38 N/mm² for PUR and ER respectively. For compressive strength parallel to grain in minor strength direction the value ranged from 16.11 N/mm² to 20.90 N/mm² and 14.30 N/mm² to 17.04 N/mm² for PUR and ER respectively. However, for compressive strength parallel to grain in major strength direction ranged from 25.87 N/mm² to 30.26 N/mm² and 24.79 N/mm²

to 28.16 N/mm² for PUR and ER respectively. The study confirms the potential of *Gmelina arborea* for use in CLT panel production, with favourable mechanical properties under both in-plane and out-of-plane loading. Generally, PUR provides superior compressive strength for CLT specimens, particularly in parallel-to-grain directions, making it an ideal choice for applications requiring high load-bearing capacity. ER, while slightly less strong, offers more consistent performance, making it a potential choice for applications where uniformity is more critical. The results indicate that the species is suitable for structural applications, particularly in mass timber construction. The slight advantage of PUR adhesive in terms of compressive strength suggests that it may be the preferred adhesive for applications requiring maximum strength. Moreover, there is a strong, positive correlation between density and compressive strength for both adhesives. As the density of the CLT panels increases, compressive strength increases as well. Also, from the ANOVA results, adhesive type has a statistically significant effect on the compressive strength of the CLT specimens. There is also a significant interaction between adhesive type and strength properties. The study introduces reliability analysis for CLT panels, revealing that PUR adhesives yield higher reliability indices and lower probabilities of failure for compression capacity ($\beta = 3.6637$), making them more reliable for structural applications as compared to ER's reliability indices ($\beta = 3.1646$), with corresponding probability of failure of 0.000243 and 0.00077641, respectively. These findings contribute to the broader field of sustainable construction and promote the use of local wood species in high-performance building materials. From a sustainability perspective, the use of locally grown *Gmelina arborea* offers significant advantages. This species is fast-growing and widely available in Nigeria, making it an excellent candidate for value-added timber products. The study provides crucial data that supports the development of local,

sustainable CLT production, which could reduce reliance on imported wood and promote the use of renewable building materials.

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Statements and Declarations

Conflict of interest: The authors have no competing interest to declare that are relevant to the content of this article.

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