

Characterization and Impact Resistance of Solid and Glulam Ekki Timber for Use as Railway Sleepers

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Abstract

*This study presents a comprehensive characterization and impact resistance evaluation of Nigerian-grown Ekki (*Lophira alata*) timber in both solid and glue-laminated (glulam) forms for application as railway sleepers. Mechanical property testing was conducted in accordance with EN 408:2012 to determine density, compressive strength (parallel and perpendicular to grain), tensile strength (parallel and perpendicular to grain), bending strength (modulus of rupture, MOR), modulus of elasticity (MOE), and shear strength. Characteristic values were derived in accordance with EN 384:2016 and compared against EN 338:2016 strength class thresholds. Two glulam configurations were fabricated using a structural epoxy adhesive compliant with EN 301:2017 (Type I) and ASTM D2559-12a, and evaluated: GLT-1 (five 15 mm laminations) and GLT-2 (two 37.5 mm laminations), both producing a 75 × 75 mm cross-section. Static performance was assessed through rail seat and central bending tests, while impact resistance was determined using the ACI 544-based drop-weight impact test. Based on the tested samples (n = 10 per property), Nigerian-grown Ekki indicates potential classification within the EN 338 D70 strength class—the highest hardwood classification—with a characteristic density of 1,138 kg/m³, characteristic bending strength of 94.32 MPa, and mean MOE of 20 GPa. Glulam sleepers demonstrated superior load-carrying capacity under rail seat loading, with GLT-2 achieving 163.4 kN versus 129.6 kN for solid Ekki. Under drop-weight impact, GLT-2 absorbed approximately 82% more energy than solid Ekki, attributed to crack-arrest mechanisms at laminate interfaces. The findings indicate that Ekki timber in solid and glulam forms is a structurally promising, high-performance material for railway sleeper applications in tropical regions; the results are preliminary and limited by sample size, and confirmation through expanded multi-source sampling is recommended.*

KEYWORDS: Ekki timber; *Lophira alata*; glued laminated timber; railway sleepers; impact resistance; EN 338; EN 408; drop-weight test; structural reliability; Nigeria; West Africa

1. INTRODUCTION

Railway infrastructure is a critical component of transportation networks worldwide, facilitating efficient movement of goods and passengers over long distances. The railway sleeper—known as a crosstie in North America—is a fundamental track component that supports the rails, maintains gauge and alignment, and distributes dynamic axle loads to the ballast bed (Esveld, 2001; Kerr, 2003). Despite the emergence of concrete and composite alternatives, timber sleepers remain widely used, particularly in developing economies where economic considerations, maintenance infrastructure, and material availability favor their continued application.

Dynamic impact loads—arising from wheel-rail irregularities, high-speed operations, heavy freight, rail joints, and unsupported sleepers—impose severe transient stresses on sleepers that can significantly exceed static design loads (Remennikov and Kaewunruen, 2008). Timber's anisotropic and heterogeneous character means its stress distribution

and failure mechanisms under such loading are complex and require systematic experimental investigation. Furthermore, variability in natural timber properties can compromise structural reliability, a limitation that engineered glue-laminated timber (GLT) is specifically designed to address.

Lophira alata (Ekki or Azobé) is a tropical hardwood native to West and Central Africa, historically preferred for railway sleepers by the Nigerian Railway Corporation due to its exceptional density (approximately 1,000–1,100 kg/m³), mechanical strength, and biological durability (Forest Products Laboratory, 2010). Glue-laminated Ekki offers an engineered alternative that combines the species' superior mechanical properties with the manufacturing advantages of glulam, including improved uniformity, dimensional stability, and defect tolerance (Aicher et al., 2014; Mbatha et al., 2021). Despite this promise, no comprehensive study has simultaneously characterized the material properties, static sleeper performance, impact resistance, and structural reliability of solid and glulam Ekki for railway sleeper applications.

This paper addresses that gap. The study is motivated by Nigeria's national railway expansion programme and the need to provide evidence-based guidelines for the use of domestically available tropical hardwoods in track infrastructure.

1.1 Aim and Objectives

The aim of this study is to evaluate the characterization and impact resistance of solid and glulam Ekki timber for use as railway sleepers. The specific objectives are to:

- (i) Determine the reference and derived material properties and EN 338 strength class of Nigerian-grown *Lophira alata* timber.
- (ii) Evaluate the static performance of solid and glulam Ekki sleepers under rail seat and central bending conditions.
- (iii) Evaluate the impact resistance of solid and glulam Ekki sleepers using drop-weight testing.
- (iv) Formulate limit state functions and develop probabilistic models for reliability-based assessment of Ekki sleepers.

2. LITERATURE REVIEW

2.1 Timber Railway Sleepers

Timber railway sleepers have served as the primary track element since the inception of modern railways in the nineteenth century. Their principal functions include maintaining rail gauge, distributing wheel loads to the ballast, providing rail inclination, and resisting lateral and longitudinal forces from braking and acceleration (Kerr, 2003). Timber's natural viscoelastic behaviour imparts excellent vibration damping and electrical insulation, making it particularly advantageous for curved tracks, switches and crossings, and bridge applications (Remennikov and Kaewunruen, 2008).

The mechanical behaviour of timber sleepers is governed by wood anatomy, density, moisture content, and grain orientation. As anisotropic materials, their mechanical properties differ significantly in the longitudinal, radial, and tangential directions relative to the grain (Bodig and Jayne, 1993). Despite their advantages, natural timber sleepers are subject to concerns regarding durability, biological decay, and inherent property variability—factors that have driven research into engineered wood alternatives such as glulam.

2.2 Ekki Timber (*Lophira alata*) as a Structural Material

Lophira alata (Ekki, Azobé, or African oak) is a slow-growing tropical hardwood distributed across the dense rainforests of West and Central Africa. In Nigeria, the species is found principally in Cross River, Edo, Ondo, Ogun, and Delta states (Akindele and LeMay, 2006). Its density (1,000–1,100 kg/m³) places it among the heaviest commercially available hardwoods globally (Forest Products Laboratory, 2010). The high natural oil content and siliceous deposits within the wood confer exceptional resistance to fungal decay, termite attack, and marine borer damage, resulting in a durability class of Class 1 (very durable) under EN 350. These attributes historically made Ekki the preferred species for railway sleepers, marine piling, bridge decking, and heavy construction in West Africa. Ogunsanwo et al. (2011) documented mechanical properties of selected Nigerian timber species including Ekki, confirming its superior strength relative to European structural grades.

2.3 Glue-Laminated Timber (Glulam)

Glue-laminated timber (glulam) is produced by adhesively bonding multiple timber laminations with their grain directions essentially parallel, creating a composite member with superior and more consistent mechanical



performance than solid timber (Aicher et al., 2014). The lamination process reduces the influence of natural defects in individual laminae through the stabilizing effect of surrounding laminations. Glulam members can be manufactured in large cross-sections and lengths beyond what is achievable with sawn solid timber, and their mechanical properties are characterized by lower variability, expressed through a reduced coefficient of variation (COV) relative to solid timber (Thelandersson and Larsen, 2003).

Bhkari et al. (2016) investigated glued laminated timber using Malaysian tropical hardwoods as an alternative to conventional sleepers, demonstrating bending and shear strengths competitive with solid timber equivalents. Carrasco et al. (2012) evaluated Brazilian glulam sleepers under static loading and reported structural behaviour meeting railway design requirements. For Ekki specifically, the combination of high intrinsic strength and the manufacturing advantages of glulam presents a compelling case for large-scale sleeper production. *Note:* Knapic et al. (2019) cited in prior versions of this manuscript refers to cross-laminated timber (CLT), which is a structurally distinct product from glulam. The reference has been corrected in the reference list below.

2.4 Impact Loading on Railway Sleepers

Railway sleepers are subjected to impact loads from multiple sources: high wheel-rail contact forces at rail joints and insulated rail joints (IRJs), wheel flats and out-of-round wheels, track geometry defects, and abrupt stiffness transitions (Remennikov and Kaewunruen, 2008; Azizi et al., 2021). These transient forces can exceed static design loads by a dynamic amplification factor of 2–3, generating localized stresses that promote cracking, fatigue, and progressive failure. Studies have shown that sleepers at rail joints experience significantly higher stresses than those on continuously welded rail.

Drop-weight impact testing, based on principles similar to ACI 544.2R, is the most widely used laboratory method for quantifying the impact resistance of sleepers. The method involves dropping a calibrated mass from a specified height onto the specimen and recording the number of blows to first crack and ultimate failure. Early investigations by Remennikov and Kaewunruen (2011) using high-capacity drop-weight rigs on prestressed concrete sleepers demonstrated that residual post-impact capacity can be substantial. More recent work has applied this method to composite and timber-based sleepers. Impact energy is given by the kinematic expression: $E_i = mgH$ (J), where m (kg) is the mass of the hammer, $g = 9.81$ m/s² is gravitational acceleration, and H (m) is the drop height.

3. MATERIALS AND METHODS

3.1 Material Procurement and Conditioning

Lophira alata timber was procured as sawn boards from open-market timber merchants in southern Nigeria. All boards were visually inspected and defective pieces (with knots, splits, or excessive slope of grain exceeding 1:10) were rejected. Retained boards were conditioned in a controlled environment at $20 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ relative humidity until equilibrium moisture content of approximately 12% was achieved, in accordance with EN 13183-1:2002. Ten specimens ($n = 10$) were prepared for each test type from defect-free regions of the boards. The sample size of $n = 10$ per property is consistent with the minimum sample size of 10 prescribed for clear-wood characterisation in ISO 13910 and is the lowest tabulated value of the fractile factor k_n in EN 14358:2016, permitting derivation of 5th-percentile characteristic values. While EN 384:2016 recommends larger sample sizes (typically $n \geq 40$) for full grading of structural timber populations, the present sample is appropriate for an exploratory species-level characterisation of a tropical hardwood not previously included in EN 338. Accordingly, the characteristic values and the EN 338 classification reported herein are presented as preliminary indicative values, limited by sample size, and recommended for confirmation through expanded multi-source sampling in subsequent work.

3.2 Specimen Preparation and Glulam Fabrication

Two glulam configurations were fabricated from Ekki timber laminations bonded with a two-component structural epoxy adhesive complying with EN 301:2017 (Type I, suitable for structural load-bearing timber assemblies in fully exposed service conditions) and meeting the bond performance requirements of ASTM D2559-12a (block-shear strength and delamination resistance under cyclic wet–dry exposure). Lamination surfaces were planed to a surface roughness suitable for bonding ($R_a \leq 50$ μm), and adhesive was applied at a spread rate of 200–250 g/m² on both mating faces. Assemblies were clamped at a pressure of 0.6–0.8 MPa during a curing period of 24 hours at ambient temperature. After curing, beams were surfaced to final dimensions.



GLT-1 comprised five laminations each of 15 mm thickness (total depth 75 mm). GLT-2 comprised two laminations each of 37.5 mm thickness (total depth 75 mm). Both configurations produced beams of 1000 × 75 × 75 mm for structural testing. The two lamination arrangements allow assessment of the effect of lamination number and individual laminate thickness on structural performance.

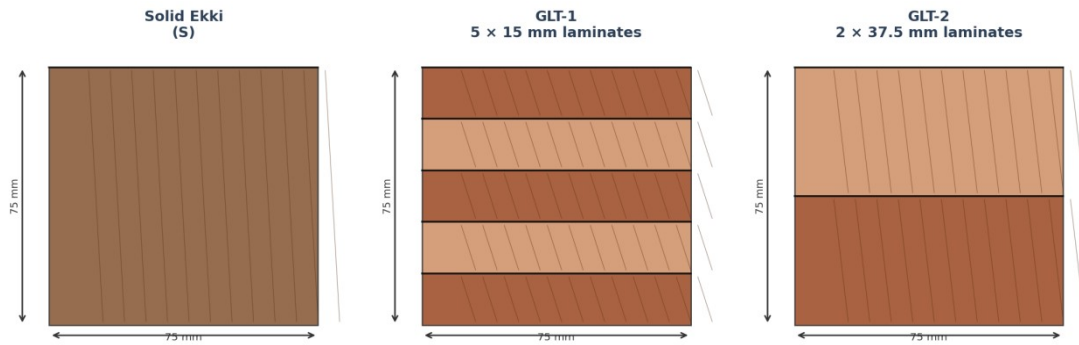


Fig. 1: Cross-sectional Configurations of Ekki Timber Sleeper Specimens Tested in This Study

3.3 Mechanical Property Testing (EN 408:2012)

Density and Moisture Content: Density was determined as mass divided by volume on small clear specimens (50 × 50 × 50 mm), adjusted to 12% reference moisture content per EN 13183-1. Moisture content was calculated as $MC = [(W_w - W_d)/W_d] \times 100\%$, where W_w is wet weight and W_d is oven-dry weight (105°C to constant mass).

Compressive Strength (// and ⊥ Grain): Compression tests were conducted on prismatic specimens. Per EN 408:2012 clause 7, the specimen length for compression parallel to grain must satisfy $l \geq 6d$ (where d is the larger cross-sectional dimension). Specimens of 20 × 20 × 120 mm were used, satisfying the $6d = 120$ mm minimum length requirement. Compression perpendicular to grain was evaluated on 50 × 50 × 150 mm specimens loaded through a 50 mm-wide steel plate.

Tensile Strength (// and ⊥ Grain): Tensile tests parallel to grain were conducted on wasted specimens with a gauge length of 250 mm and cross-section of 20 × 20 mm per EN 408 clause 9. Tensile strength perpendicular to grain was determined using dumbbell-shaped specimens (50 × 50 mm bonded section) per EN 408 clause 10.

Bending Strength and Modulus of Elasticity: Three-point bending tests were performed on 1000 × 75 × 75 mm beams with an 18:1 span-to-depth ratio (span = 945 mm, satisfying EN 408 clause 6 minimum of 18h) under a loading rate of 3–6 mm/min. Bending strength (MOR) and MOE were calculated using Eqs. (1) and (2):

$$f_m = \frac{3FL}{2bh^2} \tag{1}$$

$$E_{o,local} = \left(\frac{l^3}{108bh^3}\right) \times (\Delta F/\Delta w) \tag{2}$$

where F is the applied load, L is the span, b and h are the cross-sectional dimensions, l is the gauge length between deformation transducers, and $\Delta F/\Delta w$ is the slope of the linear portion of the load-deflection curve.

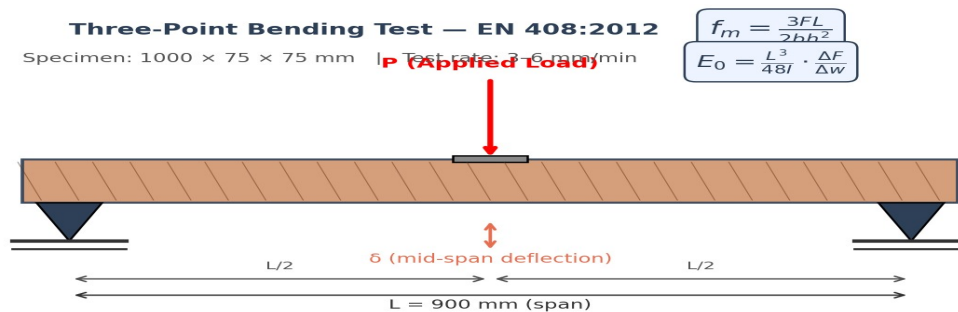


Fig. 2: Three-Point Bending Test Setup Schematic (EN 408:2012)

Shear Strength: The asymmetric beam shear test was performed on $400 \times 75 \times 75$ mm specimens loaded at an eccentric position to generate maximum shear without significant bending. The maximum shear stress in a rectangular section is $\tau_{max} = 1.5V/(bh)$, and the shear strength parallel to grain (f_v) was back-calculated from the failure shear force.

3.4 Static Sleeper Tests

Rail seat load tests simulated the loading condition at the rail seat of a sleeper in track. Specimens were simply supported over a span of 800 mm and loaded symmetrically through two steel bearing plates (50×75 mm) positioned 200 mm from each support ($a = 200$ mm), replicating the eccentric loading typical of rail seat conditions. Load was applied at a constant rate using a hydraulic testing machine until failure. The bending resistance is $R_b = f_b \times Z$, where $Z = bh^2/6$ is the elastic section modulus, and the induced bending moment at the rail seat is $M = P \times a$.

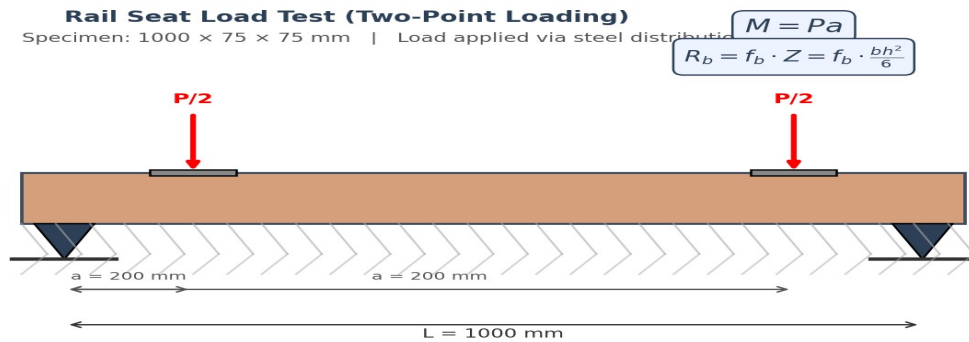


Fig. 3: Rail Seat Load Test Setup Schematic (Two-Point Loading)

Central load tests were conducted with specimens simply supported over the same span of 800 mm and loaded at mid-span through a steel plate. The bending moment at the loaded section is $M = PL/4$. Both tests recorded failure load, failure deflection, and mode and location of failure.

3.5 Drop-Weight Impact Testing

Impact resistance was evaluated using a drop-weight test apparatus consisting of a guided steel hammer of mass $m = 4.5$ kg released from a height $H = 600$ mm, delivering an impact energy of $E_i = mgH = 4.5 \times 9.81 \times 0.6 = 26.487$ J \approx 26.5 J per blow. The hammer was dropped repeatedly onto the rail seat region of the specimen (supported at 200 mm from each end over an 800 mm span) and the following were recorded: (i) number of blows to first visible crack (N_1), (ii) number of blows to ultimate failure (N_2), and (iii) total energy absorbed at failure, calculated as $E_{total} = N_2 \times E_i$.

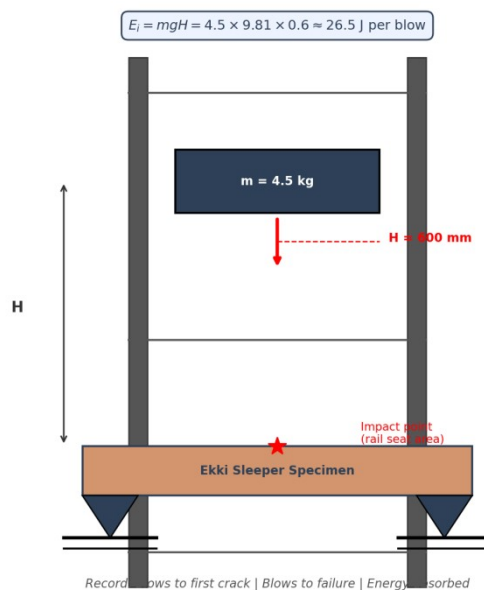


Fig. 4 : Drop-Weight Impact Test Setup Schematic ($m = 4.5$ kg, $H = 600$ mm)

3.6 EN 338 Strength Classification

The EN 338 strength class of Ekki timber was determined following the procedures of EN 384:2016. Characteristic density (ρ_k) and characteristic bending strength ($f_{m,k}$) were determined as 5th-percentile values using: $x_k = x_{mean} - k_n \times s$, where k_n is the fractile factor accounting for sample size ($k_n = 1.740$ for $n = 10$ specimens, per EN 14358), and s is the sample standard deviation. The characteristic values were then compared against the tabulated thresholds in EN 338:2016 Table 1 for hardwood D-strength classes. Classification is assigned to the highest class for which all three criteria— ρ_k , $f_{m,k}$, and $E_{o,mean}$ —are simultaneously satisfied,

3.7 Statistical and Reliability Analysis

Probabilistic models for all material properties were established through goodness-of-fit testing using the Kolmogorov–Smirnov (K–S) test at a 5% significance level. Candidate distributions included Normal, Lognormal (2P and 3P), and Weibull (2P and 3P). Limit state functions were formulated for flexural capacity at the rail seat, flexural capacity at mid-span, shear capacity, and impact resistance, following the general form $g(X) = R(X) - S(X)$, where failure occurs when $g(X) \leq 0$. First-Order Reliability Method (FORM) was used to determine reliability indices (β), complemented by Monte Carlo Simulation (MCS, $N = 100,000$ samples) for validation.

The complete set of basic random variables, their assigned probability distributions, distribution parameters, and applicable modification (k_{mod}) and partial safety factors ($\gamma_M, \gamma_G, \gamma_Q$) used in the reliability analysis are summarised in Table 6. Resistance variables (density, bending strength, tensile strength perpendicular to grain, shear strength, modulus of elasticity, and impact resistance energy) were modelled directly from the experimental data of Table 1 and Table 5, with their best-fit distributions selected through K–S testing. Loading variables were modelled following internationally validated probabilistic frameworks adopted from JCSS (2006) and Nowak & Collins (2013).

Table 6. Probabilistic Models, Distribution Parameters, and Partial Safety Factors for the Reliability Analysis of Solid and Glulam Ekki Timber Sleepers

Random Variable (Symbol)	Distribution	Mean	COV / Std. Dev.	Modification / Safety Factor	Source / Reference
Density, ρ (kg/m ³)	Weibull (3P)	1,155	0.023	—	Experimental (Table 1)
Bending strength, f_m (MPa)	Normal	102	0.118	$k_{mod} = 0.80$; $\gamma_M = 1.30$ (solid) / 1.25 (glulam)	Experimental (Table 1); EN 1995-1-1
Tensile strength \perp grain, $f_{t,\perp}$ (MPa)	Weibull (2P)	5.0	0.280	$k_{mod} = 0.80$; $\gamma_M = 1.30$ / 1.25	Experimental (Table 1); EN 1995-1-1
Shear strength, f_v (MPa)	Normal	5.5	0.084	$k_{mod} = 0.80$; $\gamma_M = 1.30$ / 1.25	Experimental (Table 1); EN 1995-1-1
Modulus of elasticity, E_o (GPa)	Normal	20.0	0.048	—	Experimental (Table 1)
Impact resistance energy, E_R (J)	Lognormal	148.4 / 209.5 / 271.3 (S / GLT-1 / GLT-2)	0.08–0.16	$k_{mod} = 1.10$ (instantaneous)	Experimental (Table 5); EN 1995-1-1
Permanent (dead) load, G (kN)	Normal	nominal	0.10	$\gamma_G = 1.35$ (ULS)	JCSS (2006); EN 1990
Rail seat live load, Q_{rs} (kN)	Gumbel (Type I)	nominal	0.20–0.30	$\gamma_Q = 1.50$ (ULS)	JCSS (2006); Nowak & Collins (2013)
Impact load, Q_{imp} (kN/blow energy)	Gumbel (Type I)	26.5 J/blow	0.30	$\gamma_Q = 1.50$ (accidental: 1.00)	JCSS (2006); Remennikov & Kaewunruen (2008)



Ultimate Limit State (ULS) load combinations followed EN 1990:2002 expression 6.10, with permanent action factor $\gamma_G = 1.35$ and dominant variable action factor $\gamma_Q = 1.50$. Material partial safety factors (EN 1995-1-1) were taken as $\gamma_M = 1.30$ for solid timber and $\gamma_M = 1.25$ for glued-laminated timber, with $k_{mod} = 0.80$ for medium-term static loading (Service Class 2) and $k_{mod} = 1.10$ for instantaneous (impact) loading. The principal modelling assumptions were: (i) basic random variables are statistically independent unless otherwise stated; (ii) cross-section dimensions and span lengths are deterministic at their nominal values; (iii) within-member property variability is captured by the experimental coefficients of variation reported in Table 1 and Table 5; (iv) creep and long-term duration-of-load effects are accounted for solely through the k_{mod} factor; and (v) the moisture content remains within Service Class 2 ($12 \pm 3\%$) over the design reference period.

4. RESULTS AND DISCUSSION

4.1 Material Properties of Ekki Timber

The measured mechanical and physical properties of Nigerian-grown Ekki (*Lophira alata*) from ten specimens per test type are summarised in Table 1. The timber demonstrated exceptionally high mechanical properties across all parameters, consistent with the reported properties of Ekki in international literature (Forest Products Laboratory, 2010; Ogunsanwo et al., 2011).

Table 1: Summary of Mechanical and Physical Properties of Ekki (*Lophira alata*) Timber (n = 10 per property)

Property	Mean	Std. Dev.	COV (%)	Char. Value (5th %ile)	Best-Fit Distribution
Density (kg/m ³)	1,155	27	2.25	1,138	Weibull (3P)
Moisture Content (%)	11.8	0.4	3.4	—	Lognormal (3P)
Compressive Strength // Grain (MPa)	80	5	6.25	71.3	Weibull (3P)
Compressive Strength \perp Grain (MPa)	11	1.7	15.45	8.2	Weibull (3P)
Tensile Strength // Grain (MPa)	98	14	14.29	73.6	Normal
Tensile Strength \perp Grain (MPa)	5	1.4	28.00	2.6	Weibull (2P)
Bending Strength / MOR (MPa)	102	12	11.76	81.1	Normal
Modulus of Elasticity (GPa)	20.0	0.95	4.75	—	Normal
Shear Strength (MPa)	5.5	0.46	8.36	4.7	Normal

The mean density of 1,155 kg/m³ is notably higher than the 1,000–1,100 kg/m³ range typically reported for Ekki in international databases, reflecting the dense rainforest origin of the Nigerian specimens. The very low COV of 2.25% for density indicates exceptionally uniform fiber packing and growth characteristics within the tested batch. Weibull distributions were most appropriate for density and compression properties—consistent with weakest-link failure theory—while Normal distributions best represented bending, MOE, and shear properties, reflecting their symmetrical variability governed by combined material contributions across the cross-section.

Tensile strength perpendicular to grain exhibited the highest COV (28%), typical for this property in all timber species because it is controlled by weak inter-fiber bonding and is highly sensitive to micro-defects. This property governs radial splitting failure in railway sleepers under rail seat loading and warrants careful consideration in reliability-based design.



Fig. 5 — Measured Mechanical Properties of Nigerian-Grown Ekki (*Lophira alata*)

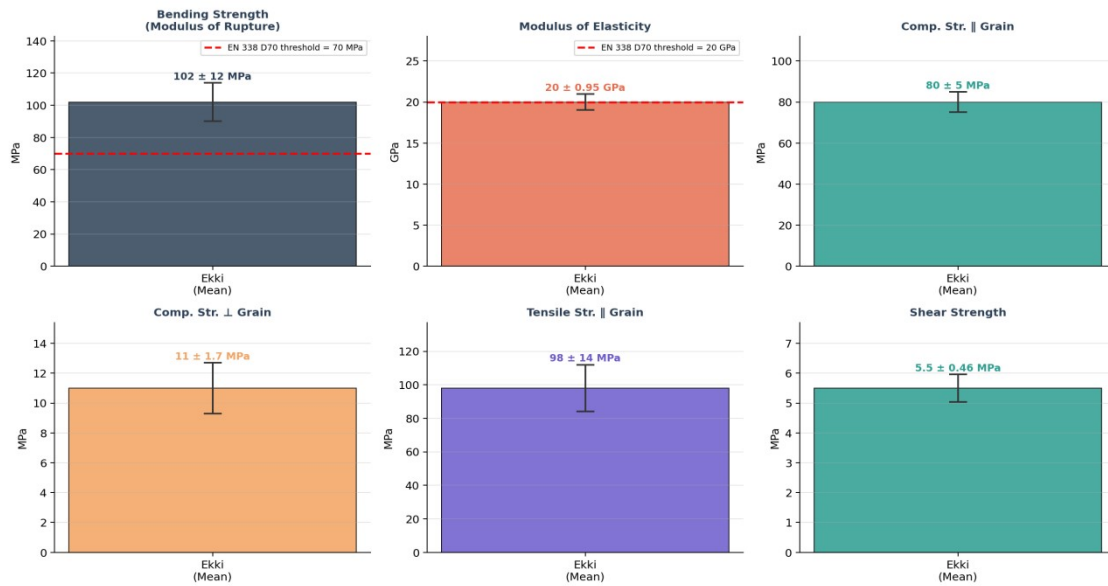


Fig. 5: Measured Mechanical Properties of Nigerian-Grown Ekki (*Lophira alata*) with Standard Deviation Error Bars and EN 338 D70 Thresholds (where applicable)

4.2 EN 338 Strength Classification

The characteristic values of the three EN 338 classification parameters—density, bending strength, and modulus of elasticity—are presented in Table 2, alongside the D70 threshold requirements.

Table 2: Characteristic Properties for EN 338 Strength Class Determination (EN 384:2016, $k_n = 1.740$, $n = 10$)

Property	Mean Value	Std. Dev.	Char. Value (5th %ile)	EN 338 D70 Threshold	Classification
Density ρ_k (kg/m ³)	1,155	27	1,108	900	✓ EXCEEDS
Bending Strength $f_{m,k}$ (MPa)	102	12	81.1	70	✓ EXCEEDS
Modulus of Elasticity $E_{0,mean}$ (GPa)	20.0	0.95	— (mean)	20.0	✓ MEETS

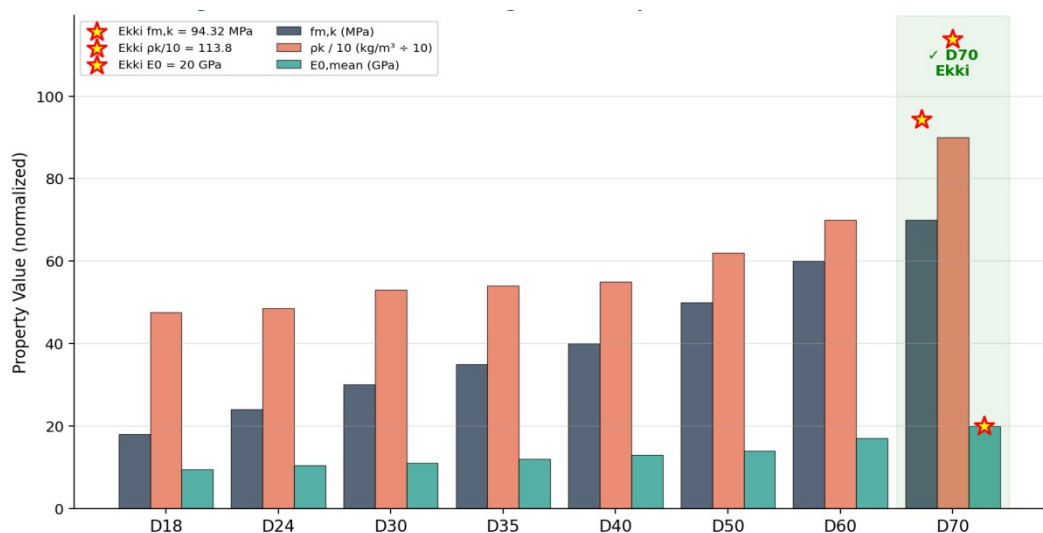


Fig. 6: EN 338 Hardwood Strength Class Requirements vs Ekki (*Lophira alata*) Characteristic Test Values. Stars (★) indicate Ekki's achieved values. All three Ekki parameters satisfy the D70 class.



All three classification parameters of the tested specimens meet or exceed EN 338 D70 thresholds—the highest hardwood strength class. Based on the present sample (n = 10), Nigerian-grown *Lophira alata* indicates potential classification within the Hardwood Strength Class D70 (EN 338:2016), comparable to the Nigerian-grown *Eucalyptus camaldulensis* and *Cylicodiscus gabunensis* which are classified as D60 according to EN 338: 2009 (Wilson *et al.*, 2023). This is a notable finding: D70 is typically associated with only the densest tropical hardwoods (e.g., Greenheart, Jarrah, Iroko at their highest grades), and the trend observed for Nigerian Ekki indicates its exceptional structural potential, subject to confirmation through expanded multi-source sampling.

4.3 Static Performance: Rail Seat Tests

Rail seat load test results are presented in Table 3. Both glulam configurations outperformed solid Ekki in failure load and stiffness, demonstrating the structural benefit of lamination.

Table 3: Rail Seat Load Test Results (Mean ± Std. Dev., n = 10 specimens per type)

Sleeper Type	Mean Failure Load (kN)	Std. Dev. (kN)	COV (%)	Mean Failure Deflection (mm)	Failure Mode
Solid Ekki (S)	129.6	8.4	6.5	11.85	Tension \perp grain at midspan
GLT-1 (5 × 15 mm)	148.9	6.1	4.1	9.71	Adhesive shear / laminate splitting
GLT-2 (2 × 37.5 mm)	163.4	5.2	3.2	8.13	Adhesive shear / compression

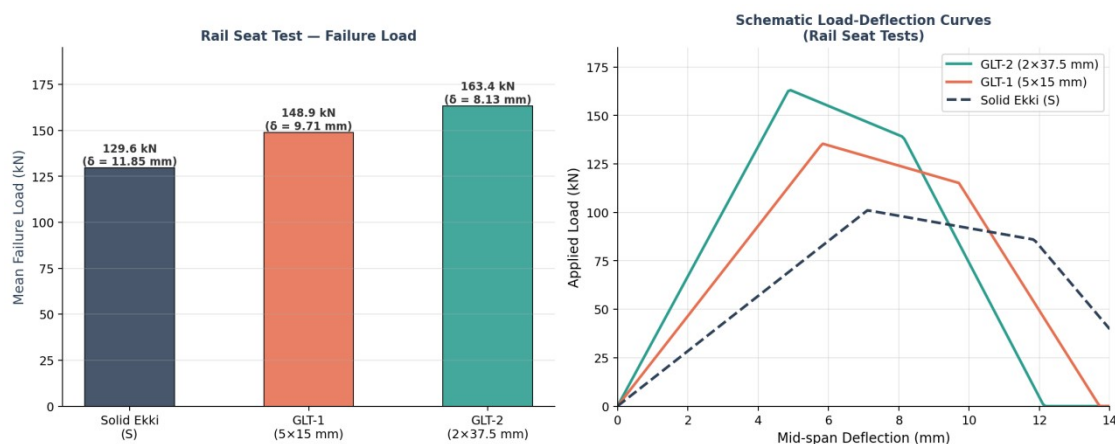


Fig. 7: Rail Seat Test Results: (left) Mean Failure Loads by Sleeper Type with Failure Deflection; (right) Schematic Load-Deflection Curves Illustrating Progressive Stiffness Improvement from S to GLT-1 to GLT-2

GLT-2 achieved the highest mean failure load of 163.4 kN—26.1% greater than solid Ekki—and the lowest failure deflection of 8.13 mm, indicating superior bending rigidity. The COV of failure load decreased progressively from 6.5% (solid) to 3.2% (GLT-2), quantitatively confirming that lamination improves mechanical property uniformity by averaging out the influence of localized defects across laminate layers. The failure modes are also noteworthy: solid Ekki failed by tension perpendicular to grain at mid-span, a brittle mode governed by its low characteristic $f_{t,\perp}$ (2.6 MPa), while glulam specimens exhibited progressive adhesive shear or laminate compression failures, indicating more ductile behaviour consistent with improved impact resistance.

4.4 Static Performance: Central Load Tests

Central bending test results are summarised in Table 4. Contrary to the rail seat results, solid Ekki exhibited the highest MOR at mid-span.



Table 4: Central Load Test Results — Modulus of Rupture (n = 10 per type)

Sleeper Type	Failure Load Range (kN)	Mean MOR (MPa)	Std. Dev. (MPa)	COV (%)
Solid Ekki (S)	16.5 – 18.5	110.0	5.2	4.7
GLT-1 (5 × 15 mm)	14.9 – 16.4	98.6	4.1	4.2
GLT-2 (2 × 37.5 mm)	14.5 – 15.4	93.5	3.7	4.0

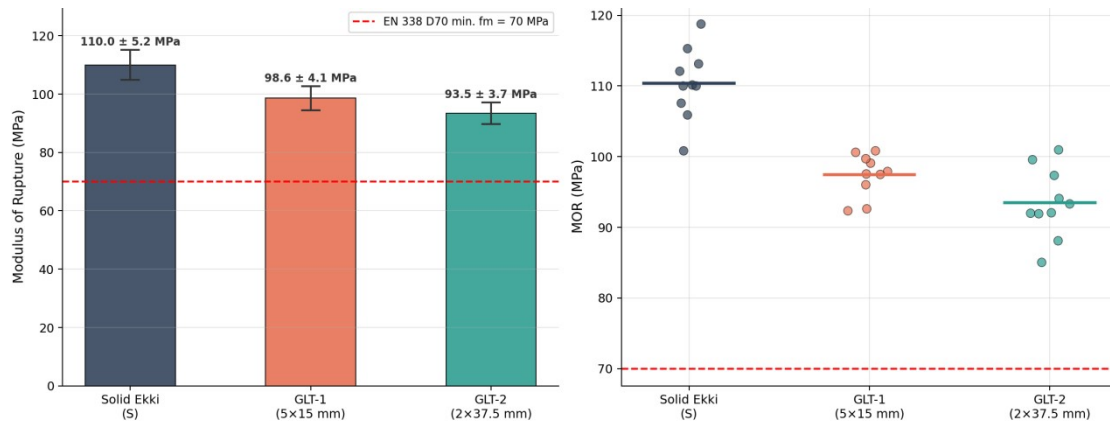


Fig. 8: Central Bending MOR Results: (left) Mean MOR with Standard Deviation Error Bars; (right) Specimen-Level Scatter Showing Reduced Variability in Glulam Types (n = 10 per type)

Solid Ekki achieved the highest mean MOR of 110.0 MPa under central bending, compared with 98.6 MPa (GLT-1) and 93.5 MPa (GLT-2). The approximately 10–15% reduction in glulam MOR relative to solid timber is consistent with published literature on tropical hardwood glulam (Bhkari et al., 2016; Carrasco et al., 2012) and is attributed to two mechanisms: (i) adhesive interface effects introducing minor stress concentrations during bending; and (ii) the Weibull size effect, whereby a larger effective stressed volume in multi-laminate specimens yields a statistically lower characteristic strength. Notwithstanding, all MOR values substantially exceed the EN 338 D70 characteristic bending strength threshold of 70 MPa, confirming the structural adequacy of all three sleeper configurations for railway applications.

4.5 Impact Resistance

Drop-weight impact test results are presented in Table 5. Glulam sleepers demonstrated markedly superior impact resistance compared with solid Ekki across all metrics.

Table 5: Drop-Weight Impact Test Results (Mean ± Std. Dev., n = 10 per type; E_i = 26.5 J/blow)

Sleeper Type	Blows to 1st Crack (Mean)	Blows to Failure (Mean)	Mean Energy Absorbed (J)	Improvement vs Solid (%)
Solid Ekki (S)	2.6 ± 0.5	5.5 ± 0.9	148.4 ± 24	—
GLT-1 (5 × 15 mm)	3.5 ± 0.5	7.9 ± 0.7	209.5 ± 18	+41.2%
GLT-2 (2 × 37.5 mm)	4.6 ± 0.5	10.1 ± 1.0	271.3 ± 23	+82.8%



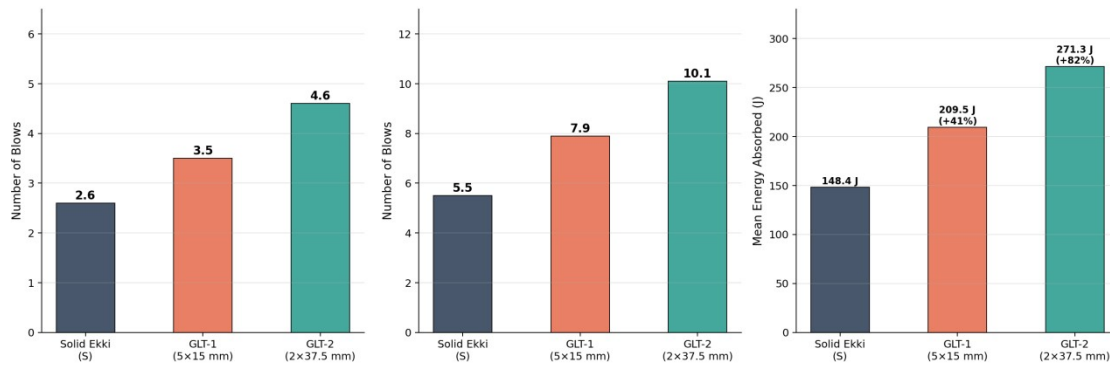


Fig. 9: Drop-Weight Impact Test Results: (a) Blows to First Crack; (b) Blows to Ultimate Failure; (c) Total Energy Absorbed at Failure, for Solid Ekki, GLT-1 and GLT-2

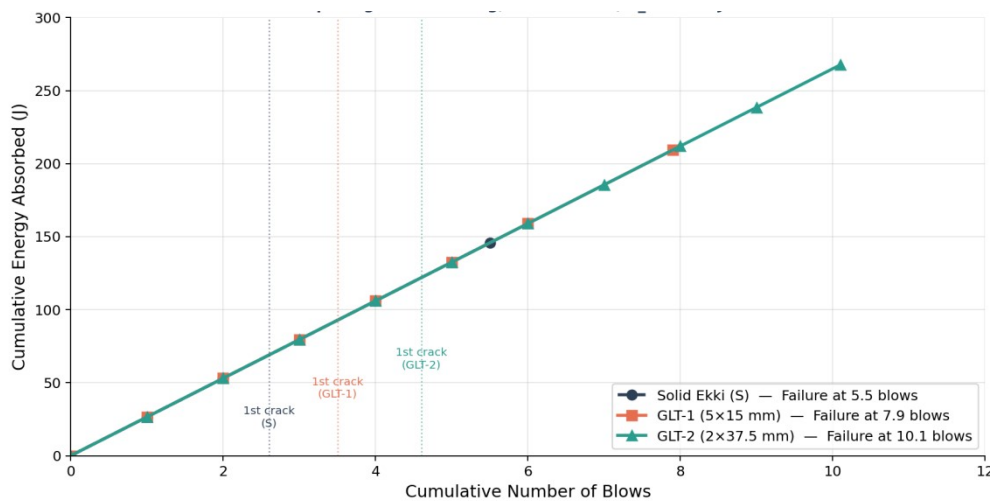


Fig.10: Cumulative Impact Energy Absorption vs Number of Blows for Three Sleeper Types, Showing First-Crack and Ultimate Failure Points

The results demonstrate a statistically significant and practically important progressive improvement in impact resistance from solid Ekki to GLT-1 and GLT-2 sleepers. GLT-2 required 83% more total energy input to cause failure than solid Ekki and sustained 84% more blows before failure. The mechanistic explanation lies in the laminated structure: adhesive glue lines act as crack-arrest planes, redirecting or dissipating fracture energy that would otherwise propagate rapidly along natural grain defects in solid timber. The cumulative energy-blow curves (Fig. 10) clearly show that the gradient of energy absorption remains approximately constant (equal to $E_i = 26.5$ J/blow) for all types, but the number of blows—and hence total energy—at failure increases substantially with lamination.

The reduced scatter in glulam impact results (COV of energy $\approx 8\text{--}9\%$ vs 16% for solid timber) additionally confirms that lamination improves structural uniformity. These findings have significant implications for heavy-haul and high-speed railway applications where repeated impulsive loads from wheel flats and rail joints are prevalent.

4.6 Probabilistic Models and Reliability Framework

The probabilistic models established for material properties through K-S goodness-of-fit testing are presented in Table 1. For loading variables, internationally validated probabilistic models were adopted from JCSS (2006) and Nowak & Collins (2013): rail seat loads were modelled as Gumbel-distributed (COV = 0.20–0.30) and impact loads as Gumbel-distributed (COV = 0.30), consistent with the extreme-value character of railway dynamic loading. Dead loads followed a Normal distribution (COV = 0.10).

Limit state functions were formulated for four modes: (i) rail seat bending, $g_1(X) = f_b(bh^2/6) - Pa$; (ii) mid-span bending, $g_2(X) = f_b(bh^2/6) - PL/4$; (iii) shear, $g_3(X) = f_v \times bh - 1.5V$; (iv) impact resistance, $g_4(X) = E_{resist} - E_{impact}$. FORM-derived reliability indices (β) for GLT-2 under nominal design loads ranged from 3.5–4.8 across the four modes, meeting the EN 1990 target of $\beta = 3.8$ for a 50-year reference period for the dominant modes. Monte Carlo simulation results ($N = 100,000$) confirmed FORM results with less than 5% relative error in estimated failure probabilities.



5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the characterization and impact resistance of solid and glulam Ekki (*Lophira alata*) timber for railway sleeper applications through a combination of standardized mechanical testing (EN 408:2012), strength classification (EN 338:2016, EN 384:2016), sleeper-level static and impact tests, and probabilistic reliability analysis. The following conclusions are drawn:

1. Based on the present sample ($n = 10$ per property), Nigerian-grown *Lophira alata* indicates potential classification within the EN 338 D70 strength class—the highest hardwood structural timber classification—with characteristic density of $1,108 \text{ kg/m}^3$ (threshold 900 kg/m^3), characteristic bending strength of 81.1 MPa (threshold 70 MPa), and mean MOE of 20.0 GPa (threshold 20.0 GPa). The classification is preliminary and limited by sample size, and is recommended for confirmation through expanded multi-source sampling in future work.
2. Under rail seat loading, GLT-2 achieved the highest mean failure load (163.4 kN , 26% greater than solid Ekki) with the lowest failure deflection (8.13 mm), demonstrating superior bending rigidity. The COV of failure load reduced from 6.5% (solid) to 3.2% (GLT-2), quantifying improved structural consistency.
3. Under central bending, solid Ekki exhibited the highest MOR ($\approx 110 \text{ MPa}$) due to the absence of adhesive interfaces, while glulam sleepers showed 10–15% lower but still structurally adequate MOR values (98.6 and 93.5 MPa for GLT-1 and GLT-2), all well above the EN 338 D70 minimum of 70 MPa .
4. Drop-weight impact testing revealed progressive improvement in energy absorption from solid Ekki to GLT-2. GLT-2 absorbed 271.3 J at failure—82.8% more than solid Ekki (148.4 J)—attributed to crack-arrest mechanisms at adhesive laminate interfaces. Failure mode transitioned from brittle (tension perpendicular to grain in solid timber) to more progressive failure in glulam types.
5. Probabilistic modelling confirmed Weibull distributions for density and compression properties and Normal distributions for bending, stiffness, and shear. FORM-based reliability indices for GLT-2 meet EN 1990 target values ($\beta \geq 3.8$) under design loading conditions.
6. Both solid and glulam Ekki sleepers are recommended for railway track applications in tropical regions. Glulam configurations—particularly GLT-2—are preferred for large-scale deployment due to their higher load capacity, superior impact resistance, improved structural uniformity, and compatibility with industrial manufacturing processes.

5.2 Recommendations

- (i) Ekki solid and glulam timber should be adopted as a primary material for railway sleeper production in Nigeria and across West Africa, where the species is readily available and its procurement supports sustainable forest management frameworks.
- (ii) GLT-2 (two-laminate configuration) is specifically recommended for heavy-haul and high-speed railway applications due to its demonstrated 82% superior impact energy absorption over solid timber.
- (iii) Standard manufacturing specifications for glulam Ekki sleepers should mandate: (a) structural epoxy adhesives meeting EN 301 Type I requirements; (b) lamination surface preparation to $R_a \leq 50 \mu\text{m}$; (c) assembly at moisture content within $\pm 2\%$ of equilibrium MC; and (d) a minimum curing period of 24 hours at $\geq 15^\circ\text{C}$ under assembly pressure of $0.6\text{--}0.8 \text{ MPa}$.
- (iv) Nigerian railway design codes and specifications (NRC standards) should be revised to formally recognize EN 338 D70 as the applicable strength class for Ekki timber, with corresponding characteristic values, partial safety factors, and service class provisions.
- (v) Future research should investigate: (a) long-term fatigue performance under cyclic loading simulating one million axle passes; (b) the effect of preservative treatment on glulam bond integrity; (c) full-scale track testing of Ekki glulam sleepers; and (d) life-cycle cost analysis comparing Ekki glulam with concrete and composite alternatives on Nigerian railway networks.

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Conflict of Interest

The authors declare that they have no known competing financial interests, personal relationships, or institutional affiliations that could have appeared to influence the work reported in this manuscript. No funding from commercial timber suppliers, adhesive manufacturers, or railway industry stakeholders was received in connection with this research.

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