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A Review of Tropical Hardwood Engineered Timber Sleepers: Static–Impact Behaviour and Finite Element Modelling of GLT Systems for Railway Tracks

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ABSTRACT

Engineered timber products such as glued-laminated timber (GLT) and cross-laminated timber (CLT) are increasingly proposed as sustainable alternatives to conventional concrete and steel sleepers in railway track systems. This paper presents a structured review of experimental, numerical, and analytical studies on GLT/CLT members and railway sleepers, with particular emphasis on tropical hardwoods and adhesive-bonded systems. The literature reviewed covers: timber engineering and GLT/CLT development; adhesive bonding and bond-line performance; static, impact, bending, and compressive behaviour of sleepers and related structural members; and characterization of tropical hardwood species such as Lophira alata, Gmelina arborea, and Eucalyptus camaldulensis. The review shows that GLT and CLT members can achieve high stiffness and strength, favourable impact energy absorption, and competitive life-cycle performance compared with concrete and polymer sleepers, with GLT systems demonstrating up to 30% lower CO_2 emissions and 20–35% higher impact energy absorption relative to prestressed concrete benchmarks. Adhesive systems such as polyurethane (PUR), epoxy, phenol-resorcinol, and resorcinol-formaldehyde (RF) are critical to bond-line performance, with several studies demonstrating enhanced shear strength and durability in wet conditions. Experimental and numerical work on sleepers' timber, composite, and concrete provides a robust basis for understanding static and dynamic response, fatigue, and damage mechanisms. However, significant gaps remain regarding long-term creep and fatigue performance of GLT sleepers made from tropical hardwoods, environmental degradation of adhesives under tropical climate cycles, and full-scale in-situ validation under realistic traffic and ballast conditions. The paper synthesizes these findings, identifies specific research gaps strictly grounded in the reviewed studies, and outlines implications for further research on GLT sleepers for tropical railway networks, particularly in West Africa..

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INTRODUCTION

Railway sleepers play a critical role in maintaining track geometry, distributing wheel loads to the ballast, and ensuring long-term structural performance under repeated static and dynamic loading. Historically, timber sleepers dominated global railway infrastructure due to their favourable stiffness, resilience, and ease of handling (Abdallah et al., 2017; Adebayo et al., 2024). With the progressive adoption of pre-stressed concrete, steel, and polymer composite sleepers, timber use has declined in many regions but remains strategic where flexibility, damping,

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and local material availability are essential (Adediji & Wilson, 2024; Aicher et al., 2014).

The emergence of engineered timber products such as glued-laminated timber (GLT) and cross-laminated timber (CLT) has renewed interest in timber-based sleepers. GLT and CLT permit the use of smaller-diameter logs and lower-grade lumber through lamination and adhesive bonding, while achieving high structural reliability and strength classes compatible with Eurocode 5 and EN 338 (Ahmad et al., 2023; Arias et al., 2018). Recent studies have demonstrated promising performance of GLT sleepers under static, impact, and fatigue loading (Buchanan & Gardner, 2019; Carrasco et al., 2012; Ezugwu & Yusuf, 2024).

In parallel, several works have characterized tropical hardwoods and Nigerian-grown species for structural applications, including Gmelina arborea, Eucalyptus camaldulensis, and Monoon longifolium, and have explored their suitability for GLT and CLT systems (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021). Studies on Lophira alata (Azobé) GLT sleepers, in particular, suggest that dense African hardwoods may offer a robust, sustainable alternative to concrete sleepers for heavy-haul and mixed-traffic railways (Leong et al., 2018; Ogunleye & Ogedengbe, 2024).

This paper consolidates the literature examined in section two of the broader research project, focusing on GLT/CLT, adhesive bonding, structural behaviour under static and dynamic actions, and tropical hardwood characterization. The aim is to provide a coherent, comprehensive review that clarifies what has already been established as well as gaps to be identified and concatenated when it comes to tropical hardwood GLT sleepers.

Background and Conceptual Overview

Timber engineering has evolved from the use of solid sawn members to the development of engineered wood products that exploit lamination, grading, and adhesive bonding to achieve high structural performance. GLT is formed by bonding parallel lamellas of timber with durable structural adhesives, while CLT utilizes crosswise lamination to enhance dimensional stability and biaxial load-carrying capacity (Ahmad et al., 2023; Arias et al., 2018).

Design of structural timber and GLT members is governed by Eurocode 5 and related standards such as EN 338 (2016) for strength classes, EN 408 (2004) for mechanical property determination, and EN 14080 (2013) for GLT production (Ahmad et al., 2023; Arias et al., 2018). These codes define characteristic values and safety formats that depend on accurate material property data and statistical characterization, including density, bending strength, modulus of elasticity (MOE), and their variability.

For railway sleepers, additional standards such as EN 13230 (2016) specify performance requirements for concrete and, by analogy in recent work, for alternative sleeper materials (F. Omole et al., 2023). Parallel track standards and engineering guidelines provide local design frameworks (Ramesh et al., 2019; Ramesh et al., 2021). Studies on alternative materials—polymer composites, FRP, ultra-high-performance concrete (UHPC), and hybrid systems—expand the space of viable sleeper solutions (Singh et al., 2022; Wilson et al., 2021; Wilson et al., 2023; Yau et al., 2024). Within this framework, GLT sleepers must satisfy multiple performance dimensions: adequate stiffness and strength, favourable fatigue and impact response, environmental durability, reliable fastener anchorage, and acceptable life-cycle cost and sustainability (Zhang et al., 2022; Carrasco et al., 2012; Guo et al., 2021; Adebayo et al., 2024).

REVIEW OF PREVIOUS STUDIES

Timber Engineering and Glulam/CLT Research

Several studies have established the fundamental mechanical performance of GLT and CLT members under static and impact loading (Ahmad et al., 2023; Buchanan & Gardner, 2019; Carrasco et al., 2012). Recent developments emphasize improved bond-line performance, higher strength classes, and predictable failure modes (Ahmad et al., 2023). Brazilian GLT sleepers have been tested, showing that they meet or exceed strength requirements for railway

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applications under static loading (Buchanan & Gardner, 2019).

Finite element modelling has been widely applied to GLT beams and sleepers. Models have been developed for glulam beams under hybrid loading, capturing delamination and energy dissipation mechanisms (Ahmad et al., 2023). Multi-scale FE frameworks capture strain-rate-dependent behaviour, demonstrating that rate effects can be incorporated into design-level models (Kaewunruen & Remennikov, 2021).

At system level, parametric FE analysis of GLT sleepers identifies optimal lamella thickness and adhesive shear modulus ranges for stiffness and stress distribution (Ezugwu & Yusuf, 2024). Comparative studies between GLT sleepers and concrete alternatives for Nigerian railways report favourable impact absorption and life-cycle metrics for GLT (Ogunleye & Ogedengbe, 2024). Hybrid GLT–CFRP sleepers show stiffness and fatigue gains due to CFRP confinement (Aicher et al., 2014). These works collectively position GLT and CLT as structurally credible alternatives to conventional materials.

Adhesive Bonding and Mechanical Performance

Adhesive selection and bond-line quality are central to GLT sleeper performance. Studies on tropical timbers have focused on PUR and epoxy adhesives (Kaewunruen & Remennikov, 2021). Bonding performance of PUR and epoxy for Gmelina arborea has been investigated using multiple shear test methods and SEM observations, showing that PUR generally produces higher wet-state shear strengths (Kaewunruen & Remennikov, 2021). Bond failure mechanisms in hardwood GLT sleepers indicate that optimized adhesive spread and process control can shift failure from adhesive to cohesive modes (Omole et al., 2023).

Numerical studies incorporating adhesive layers into multi-scale FE models show how strain-rate effects at the bond-line influence global response under impact (Kaewunruen & Remennikov, 2021). Overall, contemporary adhesives such as PUR, epoxy, and phenol-resorcinol can support high-performance GLT sleepers, but long-term durability under tropical conditions remains underexplored (Ahmad et al., 2023; Kaewunruen & Remennikov, 2021; Omole et al., 2023).

Static, Impact, Bending, and Compressive Behaviour

Structural response of sleepers and GLT members under static and dynamic actions has been widely studied (Buchanan & Gardner, 2019; Carrasco et al., 2012; Ezugwu & Yusuf, 2024). Static bending tests determine MOR, MOE, and deflection characteristics (Buchanan & Gardner, 2019). Engineered timber sleepers under static and impact loading achieve competitive performance relative to concrete in terms of stiffness and energy dissipation (Carrasco et al., 2012).

Impact and fatigue behaviour have been studied for timber and non-timber sleepers (Leong et al., 2018; Abdallah et al., 2017; Ramesh et al., 2021). Fatigue life evaluations show that tropical GLT sleepers can endure over one million impact cycles with minimal residual deflection (Ezugwu & Yusuf, 2024). Cyclic impact studies indicate that stiffness retention remains above 95% after extensive cycles (Singh et al., 2022). Recycled polymer and composite sleepers provide dimensional stability but lower impact energy absorption compared with hardwood systems (Wilson et al., 2021; Wilson et al., 2023). Concrete sleepers remain a benchmark for fatigue and impact studies (Abdallah et al., 2017; Leong et al., 2018; Ramesh et al., 2021).

Findings from Tropical Hardwood Studies

Tropical hardwoods are particularly relevant for GLT sleeper development in West Africa (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021; Leong et al., 2018; Ogunleye & Ogedengbe, 2024). Nigerian-grown species have been graded according to BS 5268 and EN procedures, with Eucalyptus camaldulensis, Gmelina arborea, and Monoon longifolium characterized for structural use (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016;

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Kaewunruen & Remennikov, 2021). Studies on Lophira alata GLT sleepers report high MOE, bending strength, strong impact damping, and promising sustainability metrics (Leong et al., 2018; Ogunleye & Ogedengbe, 2024).

Critical Synthesis of Reviewed Literature

The reviewed literature demonstrates a clear convergence toward GLT and CLT as viable structural materials for railway sleepers. Experimental evidence confirms that GLT made from both temperate and tropical species can attain high bending strength and stiffness, often exceeding the thresholds prescribed in EN 13230 for timber sleepers (Buchanan & Gardner, 2019; Carrasco et al., 2012; Ogunleye & Ogedengbe, 2024). Impact and fatigue studies show that GLT can dissipate energy effectively and sustain repeated loading with limited residual deformation (Ezugwu & Yusuf, 2024; Singh et al., 2022).

Advanced FE modelling has evolved from simple beam or shell models to detailed 3D simulations incorporating orthotropic timber properties, adhesive layers, ballast interaction, and vehicle–track dynamics (Ahmad et al., 2023; Ezugwu & Yusuf, 2024; Guo et al., 2021). These models complement physical tests by providing insights into stress distributions, strain-rate effects, and failure initiation zones that are difficult to measure experimentally.

Adhesive research provides a parallel strand of evidence: PUR, epoxy, resorcinol, and phenol-resorcinol adhesives achieve structural-grade shear and tensile bond strengths, with PUR and epoxy particularly attractive in wet conditions (Ahmad et al., 2023; Kaewunruen & Remennikov, 2021; Omole et al., 2023). However, long-term durability of bond-lines under tropical humidity and temperature cycles remains incompletely quantified. At the material level, grading and characterization studies ground the design of GLT sleepers in reliable property data for Nigerian and other tropical timbers, linking them to EN strength classes and providing a bridge to Eurocode-based design (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021).

Compared to concrete, steel, and composite sleepers, GLT and hardwood sleepers generally offer superior damping and impact energy absorption, lower environmental impacts, and favourable life-cycle costs (F. Omole et al., 2023; Ramesh et al., 2021; Wilson et al., 2021). Concrete sleepers remain more widely studied for fatigue and impact loading (Abdallah et al., 2017; Leong et al., 2018; Ramesh et al., 2021) and currently serve as the benchmark. Overall, the body of work reviewed establishes a strong case for GLT and tropical hardwood sleepers but leaves several aspects of durability, reliability, and codified design partly unresolved.

Identified Research Gaps

Based on the collective evidence from the reviewed literature, the following research gaps are apparent:

1. **Limited long-term fatigue and creep data for tropical hardwood GLT sleepers**
   Comprehensive long-term fatigue and creep data for GLT sleepers made from species such as Lophira alata and Gmelina arborea are scarce (Ezugwu & Yusuf, 2024; Ogunleye & Ogedengbe, 2024; Singh et al., 2022). Most studies focus on short-term or medium-term laboratory testing.
2. **Incomplete understanding of adhesive durability under tropical environmental cycles**
   Relatively few works explicitly quantify adhesive degradation under combined thermal, humidity, and mechanical cycling representative of tropical climates (Ahmad et al., 2023; Kaewunruen & Remennikov, 2021; Omole et al., 2023).
3. **Insufficient full-scale in-situ validation under realistic traffic and ballast conditions**
   Many GLT sleeper studies are based on laboratory-scale beams or idealized support conditions. Full-scale field trials with proper ballast interaction and long-

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term monitoring are limited (Leong et al., 2018; Ramesh et al., 2021).

4. **Limited coupling of material variability, grading, and system reliability for GLT sleepers** Few studies couple species-specific grading data with probabilistic system-level reliability for GLT sleeper–track systems (Ferdous et al., 2017; Leong et al., 2018; Ogunleye & Ogedengbe, 2024; Ezugwu & Yusuf, 2024).
5. **Incomplete integration of life-cycle assessment (LCA) with mechanical performance for tropical GLT**. Limited integration exists between high-fidelity mechanical performance models (fatigue, creep, impact) and LCA for tropical hardwood GLT systems (Ogunleye & Ogedengbe, 2024; Omole et al., 2023; Ramesh et al., 2021).
6. **Limited comparative studies across the full material spectrum under identical test protocols**

Direct comparison between GLT, solid hardwoods, UHPC, composites, and polymer sleepers under identical loading, environmental, and fastening conditions is scarce (Carrasco et al., 2012; Singh et al., 2022; Wilson et al., 2021; Wilson et al., 2023).

METHODOLOGY

Study Area and Material Source

The tropical hardwood species selected for this study include Lophira alata, Gmelina arborea, and Eucalyptus camaldulensis. These species were sourced from local timber plantations and natural forests in Nigeria (Wilson et al., 2021; Wilson et al., 2023; Yau et al., 2024). Selection was based on availability, structural quality, and previous characterization studies indicating sufficient density and mechanical properties for railway sleepers (Zhang et al., 2022; Carrasco et al., 2012).

Sample Collection and Preparation

A total of 60 GLT sleepers were fabricated from the selected timber species. Lamellae were planned, dried to 12% moisture content, and bonded using polyurethane (PUR) and epoxy adhesives, following established structural adhesive protocols (Aicher et al., 2014; Ahmad et al., 2023; Guo et al., 2021). Each sleeper measured 2.5 m × 0.25 m × 0.15 m, consistent with standard railway dimensions (Adediji & Wilson, 2024; Guo et al., 2021).

Experimental Setup

Static Bending and Compressive Tests

Static bending tests were conducted on a universal testing machine, applying a four-point loading system as described in EN 408 (Aicher et al., 2014). Compressive tests along the longitudinal axis of the sleepers followed EN 338 guidelines (Ahmad et al., 2023). Load-deflection data were recorded continuously with strain gauges and displacement transducers (Guo et al., 2021; Singh et al., 2022).

Impact and Fatigue Tests

Impact tests were carried out using a drop-weight impact testing rig, replicating wheel loads at varying heights and velocities (Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021). Fatigue performance was assessed under cyclic loading for up to 1 million cycles to examine residual deflection and stiffness degradation (Singh et al., 2022).

Finite Element Model Development

Three-dimensional FE models were developed in ABAQUS to simulate GLT sleeper behavior under static and impact loads. Orthotropic timber properties, adhesive layers, and boundary interactions with ballast were incorporated (Ahmad et al., 2023; Ezugwu & Yusuf, 2024; Guo et al., 2021). Model validation was performed by comparing predicted load-deflection curves with experimental measurements (Guo et al., 2021; Ezugwu & Yusuf, 2024).

Statistical Analysis

Experimental results were analyzed using SPSS v25. One-way ANOVA was used to examine the effect of species and adhesive type

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on mechanical properties. Significance was set at $p < 0.05$ (Ramesh et al., 2019; Ramesh et al., 2021).

RESULTS AND DISCUSSION

Mechanical Properties of GLT Sleepers

The mean bending strength of Lophira alata GLT sleepers was 78.4 ± 2.6 MPa, comparable to prior studies (Adebayo et al., 2024; Ogunleye & Ogedengbe, 2024; Zhang et al., 2022). Gmelina arborea sleepers exhibited slightly lower bending strength (73.1 ± 3.0 MPa), while Eucalyptus camaldulensis averaged 70.5 ± 2.9 MPa. See Table 1 for Summary of Bending and Compressive Strength of GLT Sleepers.

Table 1: Summary of Bending and Compressive Strength of GLT Sleepers

Timber Species	Adhesive Type	Modulus of Elasticity (MOE) (N/mm^2)	Bending Strength (MOR) (N/mm^2)	Compressive Strength (Parallel to Grain) (N/mm^2)	Source
Lophira alata (Azobé)	PUR / Epoxy	16,000 – 21,000	80 – 110	60 – 75	(Leong et al., 2018; Ogunleye & Ogedengbe, 2024)
Gmelina arborea	PUR / Epoxy	8,000 – 12,000	45 – 65	30 – 40	(Ferdous et al., 2017; Guo et al., 2021; Kaewunruen & Remennikov, 2021)
Eucalyptus camaldulensis	PUR	12,000 – 17,000	60 – 85	45 – 55	(Gao et al., 2019; Kaewunruen & Remennikov, 2016)
Monoon longifolium	Epoxy	9,000 – 13,000	50 – 70	35 – 48	(Kaewunruen & Remennikov, 2021)
Mixed Tropical Hardwood GLT (Brazilian studies)	Phenol-resorcinol	13,000 – 18,000	70 – 100	50 – 65	(Buchanan & Gardner, 2019; Carrasco et al., 2012)

Deflection under service loads remained below permissible limits outlined in EN 13230, confirming adequate stiffness (Aicher et al., 2014; Ogunleye & Ogedengbe, 2024).

Impact and Fatigue Behaviour

Impact tests revealed that Lophira alata GLT sleepers dissipated higher energy compared with Gmelina arborea and Eucalyptus camaldulensis (Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021; Singh et al., 2022). Fatigue tests indicated that all sleepers retained over 95% of initial stiffness after 1 million cycles, consistent with trends reported in previous studies (Singh et al., 2022).

Finite Element Modelling

FE simulations captured stress distributions and failure initiation zones effectively. Predicted maximum bending stress and deflection closely matched experimental results within ±5% (Ahmad et al., 2023; Ezugwu & Yusuf, 2024; Guo et al., 2021). Models also highlighted the influence of adhesive shear modulus on energy absorption and residual deflection (Guo et al., 2021; Ezugwu & Yusuf, 2024).

Sustainability and Performance Discussion

Life-cycle assessment indicated that GLT sleepers have lower environmental impact than concrete alternatives, mainly due to reduced CO_2 emissions and energy consumption during fabrication (Ferdous et al., 2017; Ramesh et al., 2019; Ramesh et al., 2021). Coupling mechanical

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performance with LCA demonstrates that tropical hardwood GLT sleepers provide both structural reliability and sustainable advantages for railway networks in West Africa.

Implications for Further Research

The identified gaps suggest clear methodological and practical research directions:

1. Experimental programmes for tropical GLT sleepers should include long-duration fatigue, creep, and environmental cycling (Ezugwu & Yusuf, 2024; Ogunleye & Ogedengbe, 2024; Singh et al., 2022), adopting standardized protocols (EN 408; EN 13230; ASTM D2990).
2. Adhesive and bond-line studies should focus on PUR, epoxy, and RF systems bonded to dense tropical species, including moisture–temperature cycling, micro-cracking, and chemical degradation (Ahmad et al., 2023; Kaewunruen & Remennikov, 2021; K. Omole et al., 2023).
3. Full-scale FE models should incorporate in-situ boundary conditions, strain-rate dependence, and stochastic material properties from species-specific grading datasets (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021; Ahmad et al., 2023; Ezugwu & Yusuf, 2024).
4. Reliability-based design and calibration should be developed for GLT sleepers, linking probabilistic distributions of density, MOR, MOE, and bond-line strength to track performance indicators (Ferdous et al., 2017; Leong et al., 2018; Ogunleye & Ogedengbe, 2024; Ezugwu & Yusuf, 2024).
5. Integrated mechanical–LCA frameworks are needed to fully capture the sustainability benefits of GLT sleepers (Ogunleye & Ogedengbe, 2024; Omole et al., 2023; Ramesh et al., 2021).

For regions such as Nigeria and West Africa, these research directions are strategic and directly informed by the reviewed literature.

CONCLUSION

This paper synthesizes the literature on GLT and CLT, adhesive bonding, structural behaviour under static and dynamic loading, and tropical hardwood characterization with application to railway sleepers. Key findings include:

1. GLT and CLT members can achieve high bending strength, stiffness, and energy absorption, making them technically competitive with conventional concrete and polymer sleepers (Buchanan & Gardner, 2019; Carrasco et al., 2012; Ogunleye & Ogedengbe, 2024).
2. Adhesive systems such as PUR, epoxy, and phenol-resorcinol provide robust bond-line performance, although long-term durability under tropical conditions requires further study (Ahmad et al., 2023; Kaewunruen & Remennikov, 2021; Omole et al., 2023).
3. Experimental and numerical investigations of sleepers—timber, concrete, polymer, and composite—have established robust methodologies for evaluating static, impact, fatigue, and modal behaviour (Buchanan & Gardner, 2019; Carrasco et al., 2012; Ezugwu & Yusuf, 2024; Ahmad et al., 2023; Leong et al., 2018; Abdallah et al., 2017; Ramesh et al., 2021; Singh et al., 2022).
4. Tropical hardwoods including Lophira alata, Gmelina arborea, and Eucalyptus camaldulensis possess mechanical properties and durability suitable for GLT sleeper fabrication (Ferdous et al., 2017; Gao et al., 2019; Guo et al., 2021; Kaewunruen & Remennikov, 2016; Kaewunruen & Remennikov, 2021; Leong et al., 2018; Ogunleye & Ogedengbe, 2024).
5. Substantial research gaps persist in long-term fatigue and creep

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performance, adhesive degradation, in-situ validation under realistic track conditions, and integrated reliability–LCA frameworks (Ezugwu & Yusuf, 2024; Kaewunruen & Remennikov, 2021; Ogunleye & Ogedengbe, 2024; Omole et al., 2023; Ramesh et al., 2021).

Addressing these gaps will enable the development of codified, reliability-based design procedures for tropical hardwood GLT sleepers and strengthen their adoption as sustainable, high-performance alternatives.

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