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Unveiling the Critical Gap in Bamboo Furniture Durability: A Systematic Review and Science Mapping Analysis of Fatigue Performance and Stiffness Degradation in Connections

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Abstract

The adoption of bamboo as a sustainable material in furniture manufacturing has increased considerably in recent years. While the static mechanical behavior of engineered bamboo products such as laminated bamboo lumber and bamboo scrimber has been examined extensively, the long-term performance of knock-down (KD) connections under cyclic loading remains inadequately understood. This paper presents a systematic literature review combined with bibliometric analysis of 842 peer-reviewed publications from Web of Science and Scopus databases covering the period 2000–2024. A structured screening methodology following PRISMA guidelines was employed. The results demonstrate a substantial imbalance: approximately 68% of studies address static strength, whereas less than 5% investigate fatigue behavior. The analysis identifies stiffness degradation resulting from progressive crushing of parenchyma tissue and hole elongation as the predominant serviceability failure mechanism. Based on this synthesis, a hybrid diagnostic framework incorporating digital image correlation, acoustic emission monitoring, and machine learning is proposed for predicting fatigue life. The findings establish a foundation for future experimental investigations and support the development of performance-based design provisions for bamboo furniture connections.

Keywords; Bamboo furniture · Fatigue life · Knock-down joints · Stiffness degradation · Bibliometric analysis · Engineered bamboo · Serviceability.

INTRODUCTION

Background and sustainability context

The furniture industry has traditionally depended on slow-growth hardwoods and petroleum-based synthetic polymers, contributing to resource depletion and environmental degradation [1, 2]. Within the framework of the United Nations Sustainable Development Goals, particularly Goal 12 (Responsible Consumption and Production), pressure has mounted to transition toward renewable bio-based materials. Bamboo, a giant woody grass of the Poaceae family, has emerged as a promising alternative. Its growth cycle of 3–5 years to maturity, compared with 30–60 years for commercial softwoods, positions it as a strategically important renewable resource [3, 4]. The material exhibits favorable mechanical properties, including tensile strength values ranging from 100 to 400 MPa depending on species and processing, making it suitable for load-bearing applications [5].

Engineered bamboo products and modern furniture systems

Processing innovations during the past two decades have enabled the production of engineered bamboo products including glued laminated bamboo (GluBam), laminated bamboo lumber (LBL), and bamboo scrimber. These materials demonstrate improved homogeneity and mechanical performance relative to raw bamboo culms [6, 7]. Concurrently, consumer preferences have shifted toward knock-down (KD) furniture systems characterized by flat-pack designs, logistical efficiency, and user-assembled modularity [8]. However, KD systems rely on mechanical fasteners such as bolts, cam-locks, and screws, which introduce localized stress concentrations distinct from traditional woven or mortise-tenon joints [9]. The performance of these connections governs the overall stability and durability of furniture assemblies.

Problem statement: static strength versus dynamic durability

Current design standards for bamboo structures, including ISO 22156:2021, primarily prescribe safety factors based on static ultimate strength [10]. This approach fails to account for the repeated low-amplitude loading that furniture experiences during service. A dining chair, for instance, may undergo 100,000 or more load cycles throughout its service life, while bed frames may experience millions of cycles [11]. The primary failure mode in KD furniture is typically serviceability-related—manifesting as joint loosening or "wobble"—rather than catastrophic fracture. This phenomenon is particularly pronounced in bamboo due to its functionally graded structure: the outer cortex contains dense vascular bundles rich in silica, whereas the inner region comprises soft, porous parenchyma cells [4]. Under cyclic loading, steel fasteners progressively crush the parenchyma tissue, leading to hole elongation and eventual joint loosening [12].

Research objectives

This study addresses the identified knowledge gap through four specific objectives:

- Conduct a bibliometric analysis of bamboo furniture and connection research (2000–2024) to map thematic clusters and research trends.
- Quantify the disparity between static and dynamic research focus through systematic content analysis.
- Synthesize failure mechanisms of bamboo joints under cyclic loading.
- Propose an experimental and computational framework for fatigue characterization.

Novel contributions

This investigation provides four primary contributions: (i) a focused bibliometric synthesis of fatigue-related research on bamboo connections; (ii) quantitative evidence that less than 5% of published studies address cyclic performance; (iii) a mechanistic explanation linking parenchyma crushing to serviceability failure; and (iv) an integrated hybrid-diagnostic framework combining experimental and computational methods. These contributions establish a foundation for evidence-based standardization and design improvement.

MATERIALS AND METHODS

Review protocol and PRISMA framework

The review methodology was designed in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility [13]. The approach integrated quantitative bibliometric analysis with qualitative content synthesis, enabling identification of research gaps at the field level while extracting detailed technical information about failure mechanisms and testing methodologies.

Data sources and search strategy

Systematic searches were conducted in the Web of Science Core Collection and Scopus databases. These platforms were selected for their comprehensive coverage of peer-reviewed engineering and materials science literature. The search query employed Boolean operators:

("bamboo" OR "glubam" OR "laminated bamboo" OR "scrimber") AND ("joint" OR "connection" OR "furniture" OR "fastener") AND ("fatigue" OR "cyclic" OR "durability" OR "stiffness" OR "degradation")

The temporal scope was limited to January 2000 through June 2024, capturing the emergence and development of engineered bamboo products. This timeframe corresponds with commercial introduction of LBL and bamboo scrimber, which substantially altered the bamboo research landscape.

Screening and selection process

Figure 1 presents the PRISMA flow diagram documenting the screening process. The initial search identified 1,452 records (823 from Web of Science; 629 from Scopus). After removing 326 duplicates, 1,126 records underwent title and abstract screening. Full-text evaluation of 903 potentially relevant articles resulted in exclusion of 61 publications that did not meet eligibility criteria. The final sample comprised 842 publications for analysis.

Inclusion and exclusion criteria

Inclusion criteria: Peer-reviewed journal articles, conference proceedings, and graduate theses addressing mechanical behavior of bamboo joints, connection design, furniture durability, or structural fatigue. Studies on engineered bamboo products were explicitly included.

Exclusion criteria: Non-English publications, editorials, letters, and studies focusing exclusively on botanical anatomy or non-structural applications.

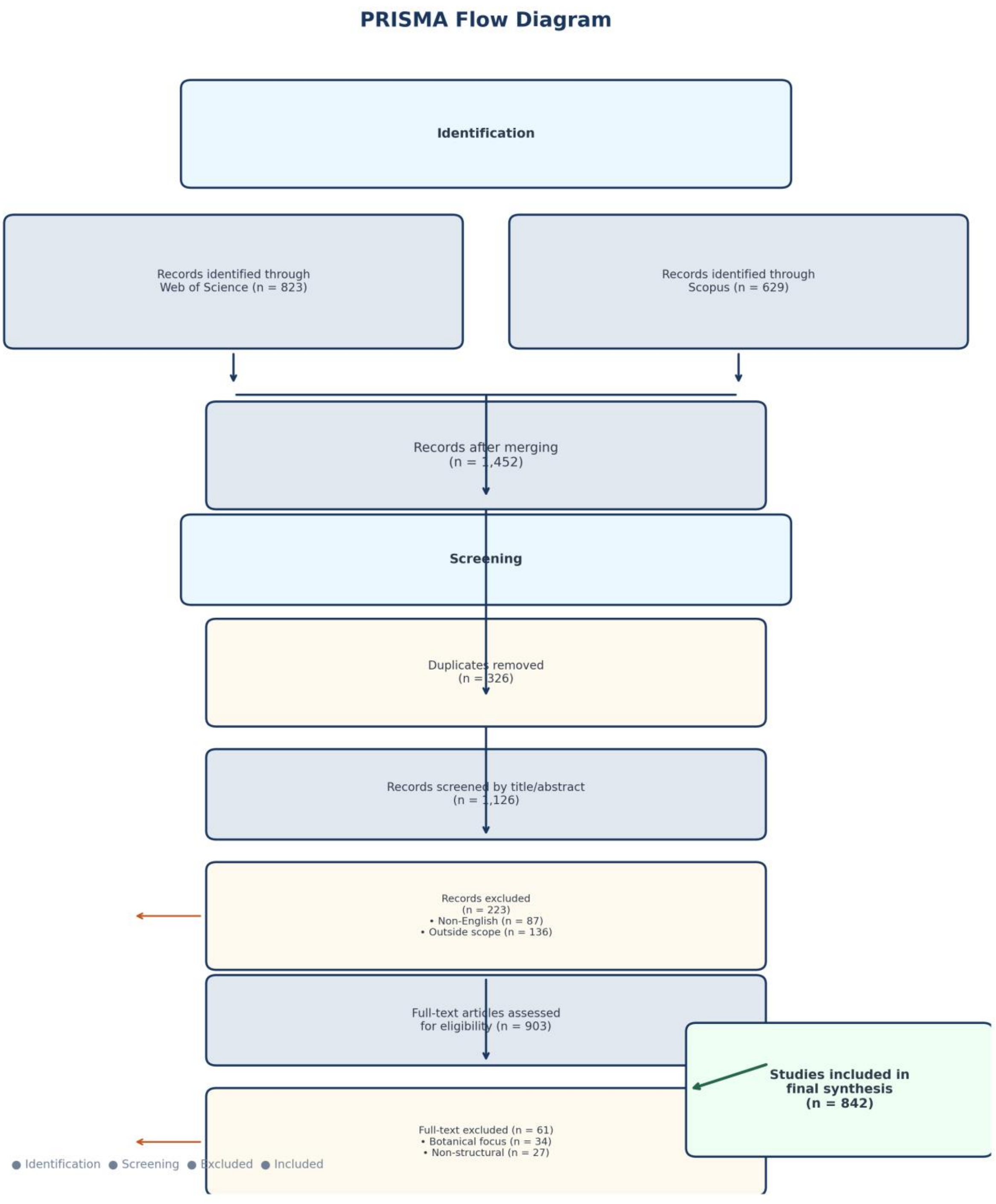

Figure 1 PRISMA flow diagram documenting the systematic screening process

Data extraction and classification

For each included study, the following data were extracted: publication year, material type (raw or engineered bamboo), joint configuration, loading condition (static or cyclic), and primary findings. Publications were classified into four categories: static strength, fatigue behavior, dynamic/seismic performance, and durability/treatment studies. Two reviewers independently conducted classification, with disagreements resolved through consensus discussion.

Bibliometric analysis methods

Bibliometric network analysis was performed using VOSviewer (version 1.6.20) to generate keyword co-occurrence networks and identify research clusters [14].

The bibliometrix package (version 3.0) in R was employed for thematic mapping based on keyword centrality and density metrics [15]. These tools enabled visualization of dominant research themes and emerging topics within the field.

RESULTS

Publication trends

The annual publication output exhibited consistent growth over the study period (Fig. 2). The compound annual growth rate (CAGR) was calculated as 14.2%, substantially exceeding the approximately 6–8% growth observed in timber connection research over the same period [16]. Three distinct phases were identified: a nascent phase (2000–2010) characterized by foundational material studies; a growth phase (2010–2018) marked by emergence of engineered bamboo products; and an acceleration phase (2018–present) driven by sustainability initiatives and circular economy policies.

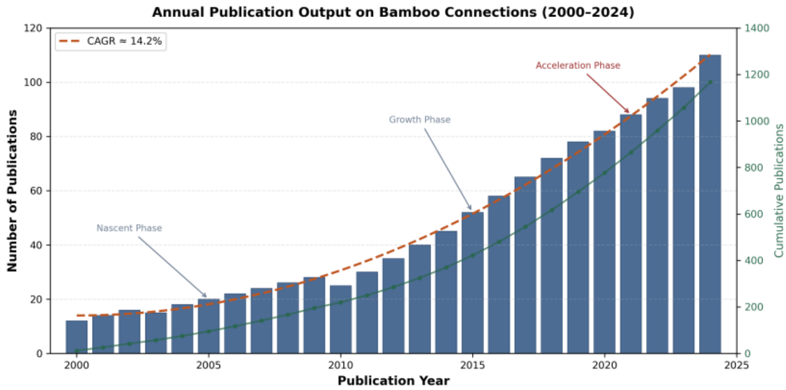

Figure 2 Annual publication output on bamboo connections (2000–2024) with cumulative trend line

Keyword co-occurrence network

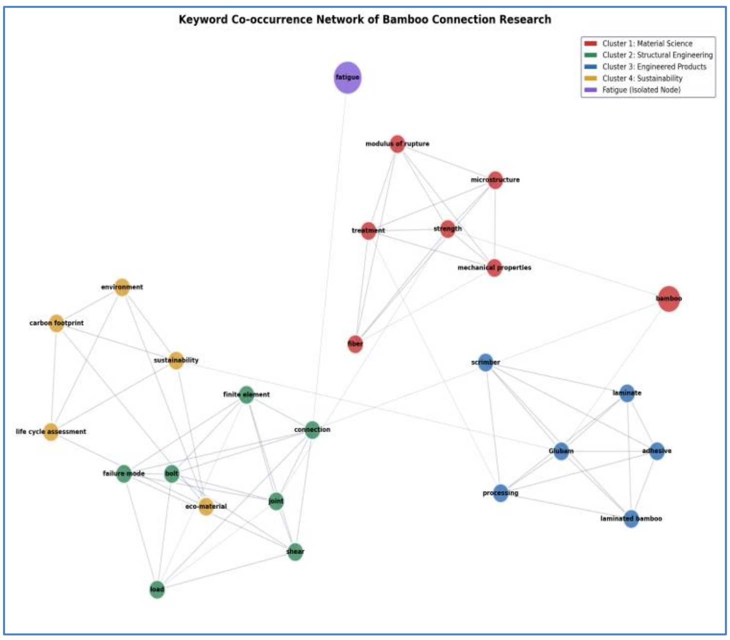

Figure 3 Keyword co-occurrence network visualization showing four thematic clusters

Network analysis of author keywords (minimum occurrence threshold: 5) revealed four primary clusters (Fig. 3). Cluster 1 (Material Science) encompasses terms related to microstructure, fiber, treatment, and mechanical properties. Cluster 2 (Structural Engineering) includes connection, bolt, joint, shear, and finite element analysis. Cluster 3 (Engineered Products) covers Glubam, laminated bamboo, scrimber, and processing. Cluster 4 (Sustainability) contains life cycle assessment, carbon footprint, and environment. Notably, the keyword "fatigue" appears as an isolated node with limited connections to the main network, indicating its peripheral position within current research.

Distribution of research focus

Content analysis of the 842 publications revealed a pronounced imbalance in research focus (Table 1). Static strength investigations constitute 68.0% of the literature, whereas fatigue-related studies account for only 5.0%. This distribution reflects a testing paradigm adopted from timber research, where ultimate capacity has traditionally been the primary design parameter. However, this approach inadequately addresses serviceability-limiting behavior that governs the functional lifespan of furniture products.

Table 1 Classification of research focus in retrieved literature (n = 842)

Research focus	Paper (n)	Share (%)	Trend	Key observations
Static strength	573	68.0	Decreasing	High ultimate capacity; splitting failure
Seismic/dynamic	143	17.0	Stable	Energy dissipation in traditional joints
Fatigue life	42	5.0	Increasing	Critical gap: lack of S-N curves
Durability/treatment	84	10.0	Increasing	Treatment efficacy; fatigue effects unknown
Total	842	100.0	—	—

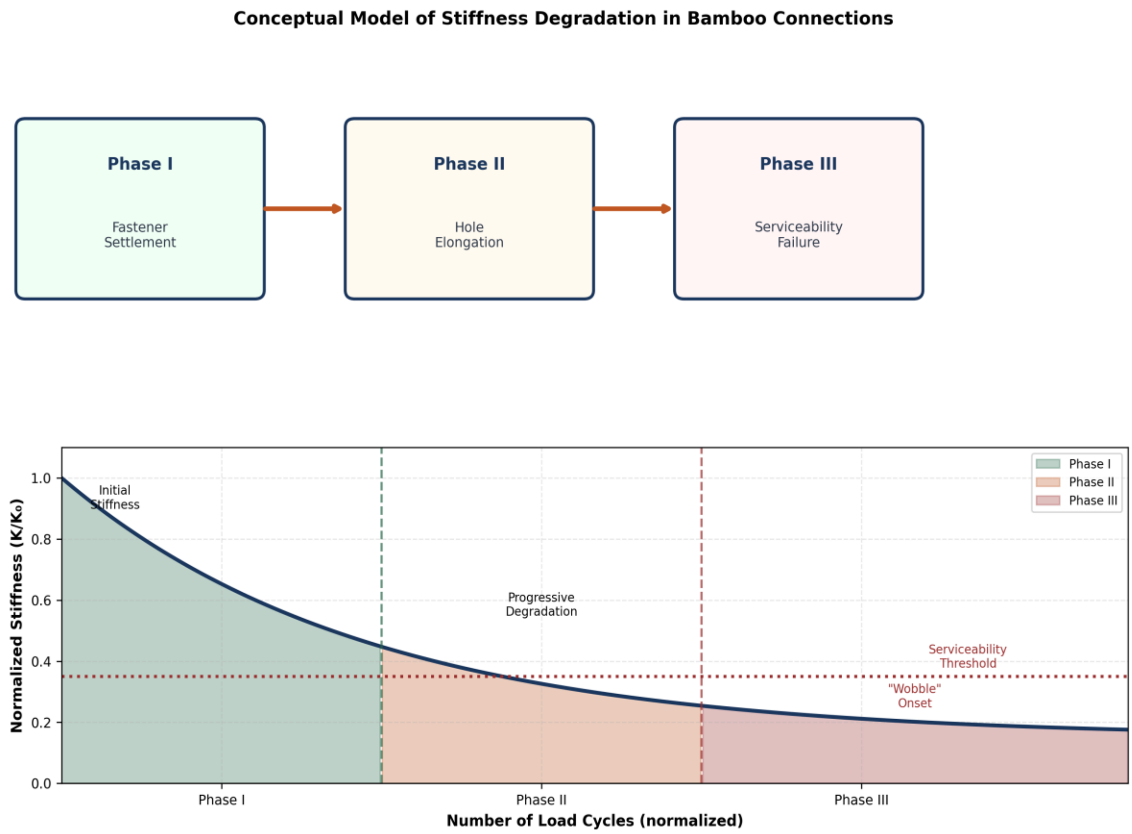

Figure. 4 Conceptual model of stiffness degradation in bamboo connections showing three phases

Failure mechanisms in bamboo connections

The review identified three phases of stiffness degradation in bamboo connections subjected to cyclic loading (Fig. 4). Phase I involves fastener settlement as the surrounding material compacts under initial loading. This settlement, often dismissed as "bedding-in," represents the initial stage of damage accumulation. Phase II is characterized by progressive hole elongation perpendicular to the grain, driven by crushing of the parenchyma matrix and micro-buckling of vascular bundles in the compression zone. Phase III manifests as serviceability failure, where excessive clearance between fastener and hole produces perceptible joint loosening. Importantly, this

PROPOSED FRAMEWORK FOR FATIGUE EVALUATION

To address the identified research gap, a standardized framework for fatigue characterization in bamboo connections is proposed (Fig. 5). This hybrid-diagnostic approach integrates advanced experimental techniques with computational modeling.

Experimental methodology

Digital image correlation (DIC) enables full-field strain mapping across the joint region, quantifying hole elongation, strain concentrations, and crack initiation with sub-pixel accuracy [17]. Acoustic emission (AE) monitoring provides real-time detection of micro-cracking events; analysis of signal frequency, amplitude, and energy content enables identification of damage accumulation mechanisms and correlation with failure modes [18]. These techniques are particularly valuable for bamboo joints due to their heterogeneous material properties and complex stress distributions.

Computational integration

A digital twin approach is proposed, integrating experimental observations with finite element modeling. Machine learning algorithms trained on combined experimental-simulation datasets can predict fatigue life under varying design and loading conditions [19]. This approach enables efficient evaluation of connection performance and supports development of design charts for practitioners.

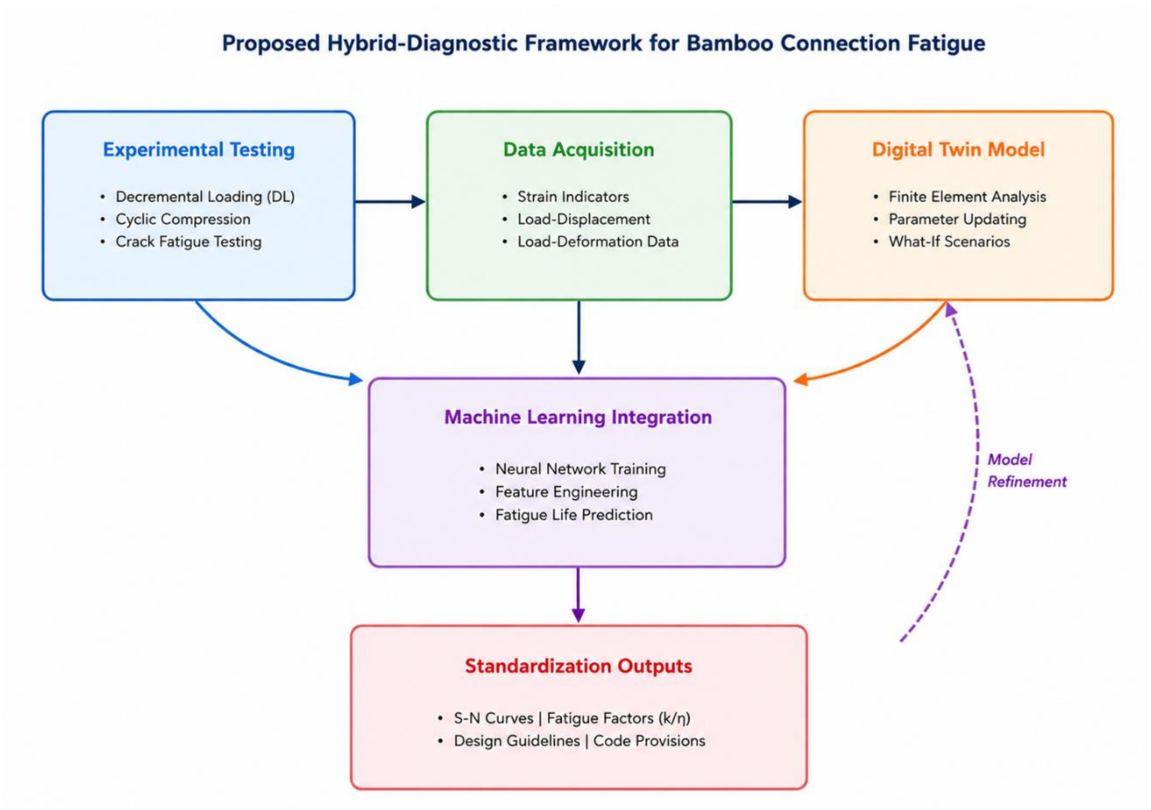

Figure 5. Proposed hybrid-diagnostic framework for bamboo connection fatigue evaluation

failure mode occurs at load levels substantially below ultimate capacity, often after several thousand cycles.

DISCUSSION

Comparison with timber design approaches

Timber design codes such as Eurocode 5 incorporate fatigue reduction factors accounting for strength degradation under cyclic loading. The absence of equivalent data for bamboo compels designers to adopt timber factors, which may be non-conservative given bamboo's lower perpendicular-to-grain compressive strength and unique functionally graded structure [20]. Research indicates bamboo's compressive strength perpendicular to grain can be 40–60% lower than comparable timber species, suggesting current approaches may substantially overestimate fatigue performance. Furthermore, timber's relatively homogeneous cellular structure yields predictable ductile yielding failure modes, whereas bamboo's gradient from dense outer cortex to soft inner parenchyma produces complex multi-mechanism failure progression.

Recommendations for standardization

Based on the analysis, two recommendations are proposed for inclusion in future bamboo furniture standards:

Fatigue reduction factor (k_{fat}): A preliminary factor of 0.60 should be applied to static connection capacity for furniture subjected to repeated loading. This value requires refinement through systematic testing programs implementing the proposed framework.

Washer dimensions: Minimum washer diameter of 3.5× bolt diameter is recommended to prevent localized parenchyma crushing, with minimum thickness of 3 mm to resist deformation under load concentration.

Limitations and future research needs

This review is limited to English-language publications and may have missed relevant studies in other languages. The proposed framework requires validation through experimental programs across multiple institutions. Development of S-N curves for various bamboo species, product types, and connection configurations represents a critical research need. Investigation of environmental effects (humidity cycling, temperature variations) on fatigue performance also warrants attention.

CONCLUSIONS

This systematic review of 842 publications demonstrates that while bamboo has received considerable attention as a sustainable furniture material, scientific understanding of connection durability under cyclic loading remains inadequate. The bibliometric analysis reveals "fatigue" as an isolated research node, disconnected from main clusters in material science and structural engineering. Static strength investigations constitute 68% of the literature, whereas fatigue-related studies account for less than 5%—a disparity requiring correction to support evidence-based standardization.

The predominant serviceability failure mechanism involves stiffness degradation caused by hole elongation, driven by progressive crushing of the parenchyma matrix under cyclic loading. This failure mode differs fundamentally from the ductile yielding observed in timber connections and requires distinct characterization approaches. The proposed hybrid-diagnostic framework, integrating digital image correlation, acoustic emission, and machine learning within a digital twin paradigm, offers a pathway to generate data necessary for standardization.

Addressing the fatigue knowledge gap is essential for transitioning bamboo furniture from niche eco-products to certified, durable mainstream commodities aligned with global sustainability objectives.

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DECLARATIONS

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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