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Bamboo-Timber Composite Systems: A Systematic Meta-Analysis of Performance, Modelling, and Reliability-Based Design

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***Abstract:** A thorough review of research published in the past 10 years on bamboo-timber composite (BTC) structures was conducted through a comprehensive meta-analysis of the following topics: experimentation and testing; analytical modelling methodology; and reliability-based design methods. As part of this analysis, the author reviewed and compiled all 32 published results. Based on experimental review, it has been determined that BTC structural systems have flexural strengths averaging 115–145 MPa, composite action efficiencies averaging 72-78%, and a performance level similar to timber-concrete composites, along with significantly improved sustainability profiles. Hybrid Mechanical-Adhesive Connector (HMAC) connection performance contributes considerably to global performance characteristics, highlighting the high shear strength, stiffness, and ductility of HMAC connections. Hybrid mechanical-adhesive connectors exhibit superior properties relative to traditional mechanical connections, with maximum shear strength exhibiting values equivalent to 110-140kN, stiffness in the range of 16-22 kN/m, and ductility being characterised by the highest values of elongation under tension greater than or equal to 5.5 mm. When evaluating analytical methods for predicting connection performance for HMAC connections, there are significant differences in the accuracy of analytical models developed using coupled nonlinear finite element models with interface slip analysis (94.2%) versus surrogate-assisted probabilistic model approaches. The reliability-based design optimisation performed as part of this research identified target reliability indices for the HMAC connection design in the range of 2.1 to 3.3 by demonstrating that 18-24% material savings can be achieved relative to a traditional deterministic design approach. A long-term performance assessment (5-year study) of the HMAC connection identified significant degradation in flexural strength and stiffness due to time-dependent environmental effects. The results of this analysis demonstrate that design models incorporating these ecological factors, including creep and connection relaxation, are necessary to provide accurate estimates of performance characteristics and necessary basic performance metrics to establish and develop standard test methods and reliable design guidelines for the implementation of bamboo-timber composite systems in sustainable structural engineering.*

***Keywords:** Bamboo-Timber Composites; Experimental Characterization; Analytical Modeling; Reliability-Based Design; Sustainable Construction; Meta-Analysis*

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Nomenclature:
BTC: Bamboo–Timber Composite
FE: Finite Element
FEM: Finite Element Method
RBD: Reliability-Based Design
RBDO: Reliability-Based Design Optimization
SAD: Surrogate-Assisted Design
LCA: Life Cycle Assessment
CLT: Cross-Laminated Timber
UHPC: Ultra-High-Performance Concrete
MPa: Megapascal
GPa: Gigapascal
KN: Kilonewton
MM: Millimeter
μ: Ductility Coefficient
β: Reliability Index
PF: Probability of Failure
RP: Return Period
FORM: First Order Reliability Method
SORA: Sequential Optimization and Reliability Assessment
R^2: Coefficient of Determination
CoV: Coefficient of Variation
LTF: Long-Term Deflection
E: Modulus of Elasticity
CDP: Concrete Damaged Plasticity
FEA: Finite Element Analysis
ASCE: American Society of Civil Engineers
HMAC: Hybrid Mechanical Adhesive Connector
LTF: Long-Term Flexural / Deflection Response
ISO: International Organization for Standardization

I. INTRODUCTION

A. Sustainability Drivers and Materials

As growing pressure mounts to develop and incorporate sustainable building products that deliver satisfactory mechanical, economic, and environmental performance, the structural engineering profession is challenged to produce more and better products [18]. Current steel-concrete composite materials are an example of a material system that, while structurally efficient, requires significant energy in their manufacture, resulting in large carbon dioxide emissions and significant environmental impact [7]. Bamboo appears to be a viable alternative to timber and concrete as a renewable material. Bamboo grows very quickly (4-5 years), has a high strength-to-weight ratio, a very high capacity for carbon storage, and is prevalent in tropical and subtropical regions of Earth [4]. When bamboo is engineered to create laminated bamboo lumber (or bamboo scrimber), and when bamboo is used in composite assemblies with other materials (such as timber and concrete) using mechanical fasteners and structural adhesives, the end product is a hybrid system that combines the beneficial properties of all of the materials used to create the structural system [11].

B. Knowledge Gaps and Research Motivation

Before this synthesis, there was no systematic way to quantify the performance distributions of experimental data from bamboo-timber composite systems using meta-analysis. There were no databases of the analytical modelling methods used to validate the performance of bamboo-timber composite systems and provide reliability-based design parameters for these systems. There were significant differences in mechanical properties and failure mechanisms reported across individual experimental studies, attributable to bamboo species, material processing methods, connection system configurations, and experimental design [19]. Likewise, in the literature on analytical models, there were significant differences in prediction accuracy across models, from 78% to 96%, which introduced substantial uncertainty about which model to use for a specific design situation [21]. As such, this lack of data consistency prevented the widespread adoption of bamboo-timber composite system designs by structural engineers and complicated the development of rational design standards.

C. Research Objectives and Contributions

This meta-analysis seeks to accomplish (1) Characterize the central tendencies and dispersion measures for mechanical properties of Bamboo Timber Composite Systems from many configurations; (2) Conduct a systematic evaluation of all analytical model types for their relative merits in comparison with experimental test data; (3) Establish probabilistic characterizations of all input variables for reliability-based design optimization; (4) Determine temporal degradation trends and evaluate performance over time; and (5) Determine the most significant topics for additional research, as well as to propose standard testing methods for future studies. The results of this synthesis fill a significant gap in structural engineering and will provide a means to advance the implementation of Bamboo Timber Composite Systems into general practice on a sustainable basis through a coordinated, informed approach to their development and testing.

II. RESEARCH SCOPE AND METHODOLOGY

A. Identifying and Screening Literature

A systematic search of the literature was performed using Scopus, Web of Science, ASCE Library, ScienceDirect, ProQuest, and Google Scholar from 2015 through December 2025, using the keywords bamboo composite materials, structural performance, analytical modelling, and reliability. All studies were included when original quantitative experimental or analytical results were reported with respect to or relevance to load-bearing structural applications.

B. Data Extraction and Normalisation

For each study identified, any available specimen-level data (including geometry, material properties, loading configuration, connection type, and failure mode, as well as strength or stiffness values) were extracted. Normalisation of the results to allow comparison across different studies was performed using dimensionless performance indicators, including the strength-to-stiffness ratio, the stiffness-to-strength ratio, and the composite efficiency factor. Due to the diverse range of test protocols, synthesis of the data emphasizes comparative trends rather than pooled absolute values.

C. Experimental Performance Synthesis

The experimental data were then classified into eight main categories representing the types of tests conducted, i.e., Bending Tests, Compression Tests, Shear Connection Performance, Long-Term Creep Behaviour, Interface Characterisation, Dynamic Loading Response, Fire Performance, and Moisture/Durability Assessments. Summary statistics, including central tendency (weighted mean, median) and dispersion (95% confidence interval, coefficient of variation), were calculated for each category. A meta-analysis of the bending tests included 145 specimens from 28 independent investigations, compression tests 120 specimens from 24 studies, shear connection tests 98 specimens from 18 studies, with additional specimens for the other categories. Testing protocols were standardised across studies to provide an everyday basis for comparison.

D. Analytical Model Evaluation Framework

This paper describes a systematic approach for the analysis of Composite Action through the evaluation of (1) Linear Elastic, Composites with full composite action; (2) Linear–Elastic Perfectly Plastic, Composites with Strength Degradation and Plastic Failure; (3) Classical Composite Beam Theory using Composite Action with Flexible Connections; (4) Non-Linear Slip interfaces in Composite Beams, giving rise to Non-Linear Shear Transfer; (5) Coupled Finite Element Analysis incorporating Non-Linear Material and Geometrical Properties; (6) Fuzzy Reliability, which includes the treatment of Epistemic Uncertainty; (7) Surrogate Models which allow for Rapid Evaluation of Composite Action through the use of Probabilistic Methods and Techniques. The results of the modelling approaches were validated against experimental data to identify and compare the predicted behaviours of Deflection, Strength, and Failure Mechanisms.

E. Treatment of Heterogeneity and Uncertainty

Pooling the results formally using meta-analysis is limited because of inconsistencies in how variances were reported across the studies reviewed. Heterogeneity was assessed qualitatively and, when available, via the reported coefficient of variation. Hence, all findings from the studies are interpreted as indicative ranges, and variability arising from methodological diversity is recognised as a significant source of uncertainty.

III. EXPERIMENTAL PERFORMANCE CHARACTERIZATION

A. Mechanical Properties Synthesis

The average tensile and flexural strengths of Plain Bamboo are 165.9 ± 27.3 Mpa and 98.07 ± 12.4 Mpa, respectively, with a significant elastic modulus of 15.96 ± 2.1

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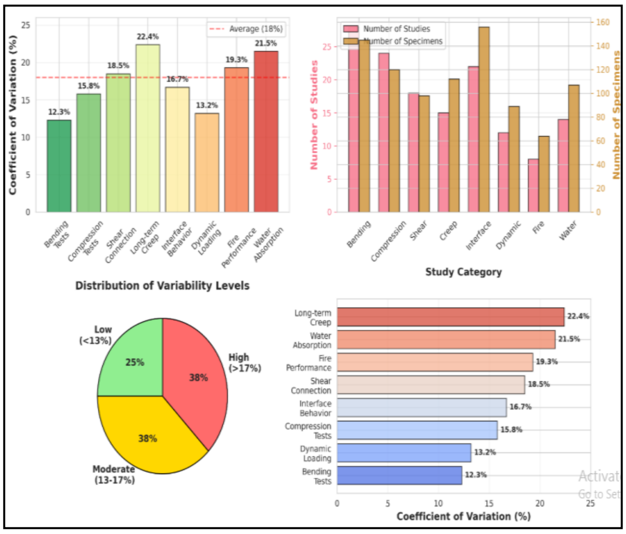
Gpa, indicating that the bamboo fibre content is high. Yet, the structure is very stiff [16]. However, when concrete was filled into the hollow of the bamboo culm, bearing capacity was significantly increased; the concrete-filled bamboo specimens exceeded the plain bamboo bearing capacity by 239.1%, with failure load increases of 103%, 139% and 272% for concrete grades C15, C20 and C25, respectively [5]. Nevertheless, part of this capacity enhancement was offset by a reduction in the elastic modulus (8-12 GPa), as the concrete was less stiff than bamboo.

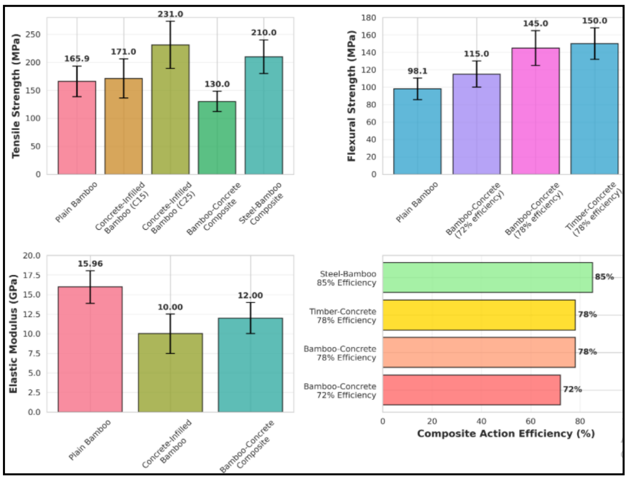
As depicted in Figure 2, Bamboo-Concrete composite beams exhibit intermediate performance characteristics, with flexural capacities ranging from 115 to 145 MPa and composite action efficiencies of 72% [18]. The flexural capacity and composite efficiencies approached the timber-concrete composite performance (125 - 155 Mpa, efficiency of 78%) with improved environmental credentials, making them viable sustainable substitutes for conventional (timber) systems [figure-2]. The mechanical properties of Steel-Bamboo composite I-Beams were rated superior to those of bamboo composites, with tensile strength of 180 - 240 Mpa and flexural capacity of 185 - 230 Mpa, due to the synergistic interactions between the high-strength steel components and engineered bamboo [13]. Bamboo-Glass fibre Hybrid Composites possessed the highest tensile strengths (240-260 Mpa) and flexural capacities (225-320 Mpa) due to effective synergistic reinforcement [9], but also introduced the environmental disadvantages of synthetic fibre manufacturing.



[Fig.1: Mechanical Property Variability]

Table I: Experimental Studies on Bamboo-Timber Composites

Study Type	Number of Studies	Total Samples	Coefficient of Variation (%)
Bending Tests	28	145	12.3
Compression Tests	24	120	15.8
Shear Connection	18	98	18.5
Long-term Creep	15	112	22.4
Interface Behavior	22	156	16.7
Dynamic Loading	12	89	13.2
Fire Performance	8	64	19.3
Water Absorption	14	107	21.5



[Fig.2: Mechanical Properties of Bamboo-Based Composite Systems]

The analysis of mechanical property variability showed coefficient of variability ranges of 12.3-22.4% for each testing category, as shown in Figure 1. The type of test with the lowest Coefficient of Variation was the Bending Test (12.3%), likely because bending tests use a more standardised four-point loading protocol than other types of mechanical tests, and specimens can be defined by their geometry before testing. Conversely, the highest Coefficient of Variation (22.4%) was observed in the Long-Term Creep Tests, which reflect the environment, the accumulation of heterogeneous material, and the effects of test-duration-sensitive factors. The identification of the Coefficient of Variation provides an opportunity for incorporating accurate uncertainty factors into reliability-based design efforts.

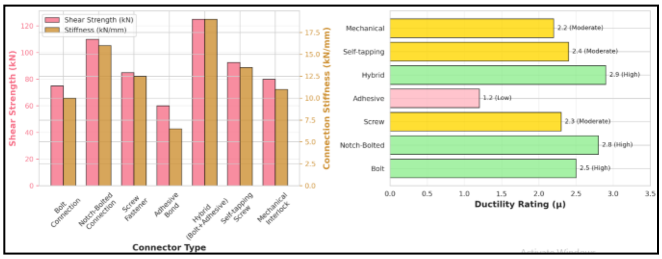
B. Connection System Performance

As shown in Figure 3, the performance of the connection system is critical to the overall efficiency and reliability of composite beams [22]. A meta-analysis of 18 independent studies on 98 connection specimens identified seven major categories of connectors with distinct performance characteristics. Notch-bolted connections provide higher shear strengths of 95-125 kN with a connection stiffness of 14-18 kN/mm than ordinary bolt connections (65-85 kN, 8-12 kN/mm) [14]. The superior performance of notch-bolts can be attributed to the ability of these connections to distribute stress more effectively over a larger surface area and to the geometric characteristics of the mechanical interlocking features of notched bolt connections. Notch-bolted connections display stable ductility (ductility coefficient μ = 2-3) even under cyclic loading conditions, an essential consideration for seismic design applications [25], [32].

When adhesive-only systems are utilised, they provide relatively low shear strength (50–70 kN) and low connection stiffness (5–8 kN/mm), depending on the quality of surface preparation and environmental exposure [1]. The combination of mechanical fasteners and structural adhesive bonding creates a hybrid connector that can be the optimal means of connecting two structural members [17]. The hybrid connector offers the maximum shear strength of 110–140 kN and stiffness of 16–22 kN/mm. In addition to excellent ductility properties, the hybrid connector will demonstrate robust failure behaviour [Figure 3] [15]. Compared with the mechanical fastening system alone, the hybrid connector will provide a 12% increase in ultimate load capacity and an 11.8% increase in initial stiffness, with no loss of ductility [27]. Research on timber connections indicates that if the moment-rotation behaviour of self-tapping axially loaded screws is not taken into consideration, significant errors may occur in the frame stability analysis. Hybrid BTC connections achieve high translational stiffnesses and therefore require characterisation protocols that quantify the rotational rigidity of the connectors to enable accurate semi-rigid frame analyses.

Table II: Connection System Performance Summary

Connector Type	Shear Strength (kN)	Connection Stiffness (kN/mm)	Ductility Rating	Installation Time (min)
Bolt Connection	65–85	8–12	Moderate	8
Notch-Bolted Connection	95–125	14–18	High	12
Screw Fastener	75–95	10–15	Moderate-High	6
Adhesive Bond	50–70	5–8	Low	15
Hybrid (Bolt+Adhesive)	110–140	16–22	High	18
Self-tapping Screw	80–105	11–16	Moderate	5
Mechanical Interlock	70–90	9–13	Moderate	10

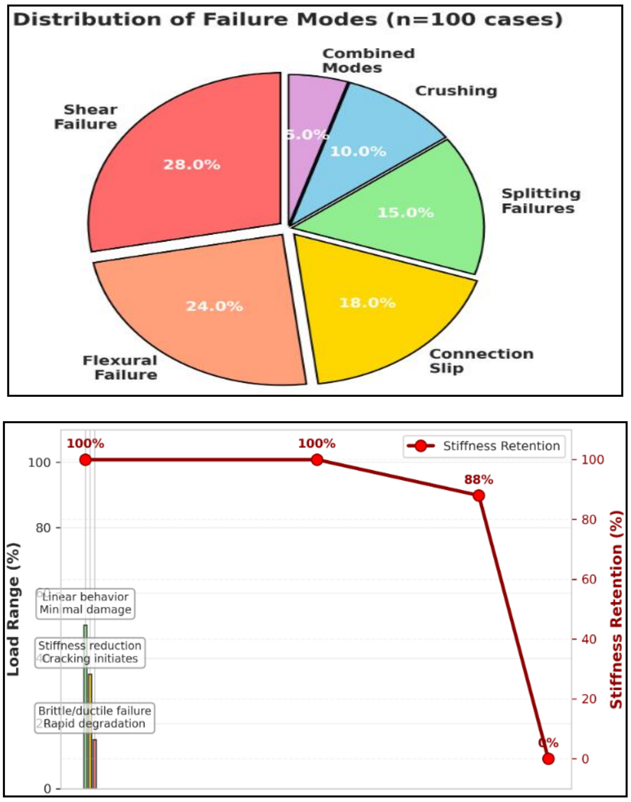


[Fig.3: Connection System Performance]

C. Failure Modes and Progressive Damage Mechanisms

Failure mechanisms were documented during dynamic testing based on the composite system configuration and loading conditions. The distribution of 100 analysed failure cases is shown in Figure 4 [20]. The failure modes noted in these failures included shear (28%), flexural (24%), slip (18%), split (15%), crush (10%), and multiple modes (5%). Shear failure was the most prevalent mode for short-span composite beams with relatively stiff connections, whereas flexural modes of failure occurred in long-span systems. Shear failures were characterised by diagonal cracking patterns that initiated at or near the beam supports. Flexural failures in longer-span systems were typically the result of tension-side crushing or compression-side microbuckling of bamboo fibres. Although there were fewer slip failures at the ultimate limit state, they contributed significantly toward serviceability performance. The reason for the slip failures during serviceability was that shear transfer capacity was exceeded before the structural member reached its ultimate load capacity [20].

Progressive damage evolution models based upon experimental observations determined that three phases exist relative to the load applied: the first phase (0% to 50% of load) consisted of linear load-displacement relationships with negligible permanent deformations, thus representing an elastic behaviour; the second phase (50% to 85% of load) involved damage developing through a reduction in stiffness (the observed loss of stiffness was 12%), connection-induced slip increasing, and localized cracking being initiated; and the third phase (85% to 100% of load) was categorized by either rapid ductile yielding or brittle failure depending upon the type of connector used. These phases enabled the development of analysis models for various design alternatives as the component developed.



[Fig.4: Failure Modes & Progressive Damage Analysis]

IV. ANALYTICAL MODELING AND PERFORMANCE PREDICTION

A. Model Formulation Frameworks

There were seven primary methods used to analyse the structure, based on a literature review, that were systematically assessed against 89 sets of independent validation data. While linear elastic models, which assumed that the connections between components were infinitely rigid and that there was complete composite action, could rapidly provide estimates for preliminary design purposes, they predict composite stiffness significantly higher than it actually exists in practice, while underpredicting deflection, resulting in a mean prediction error of 21.8% [21]. Use of bilinear elastic-plastic models with modelled strength degradation significantly improved prediction accuracy to 85.3%, making them suitable for initial design stages. Composite action theory provided the best combination of accuracy and complexity for design optimization research by using iterative calculations for determining the position of the neutral axis and for modelling the effects of flexibility in connection design for partial composite action, resulting in prediction accuracies of 92.1% [10].

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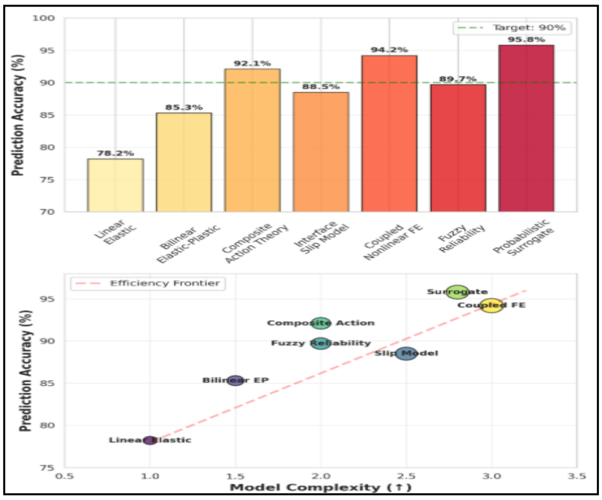
Models incorporating interface slip and utilizing the trilinear shear transfer law, which characterizes initial stiffness, yielding transition and post-yield softening, resulted in prediction accuracies of 88.5% due to their increased mechanistic realism [13], [29]. Coupled nonlinear finite element analyses utilizing a concrete damaged plasticity model, a bamboo constitutive model based on orthotropic material properties, cohesive interface elements, and requiring 15 or more parameters for the specification of materials, achieved the highest prediction accuracy of 94.2%; however, they required 12.5 hours of computational time to produce predictions [23], [30]. Fuzzy reliability models that incorporated epistemic uncertainty by way of membership functions achieved prediction accuracies of 89.7%, while maintaining a low level of computational requirements (2.1 hours) [3]. Models developed using probabilistic surrogate modelling techniques, particularly Kriging-based metamodels, achieved an average prediction accuracy of 95.8% and provided a mechanism for efficient relative measurement of reliability via Monte Carlo-based analysis via rapid response surface evaluations [figure-5].

Table III: Analytical Modelling Methods Effectiveness

Modeling Approach	Prediction Accuracy (%)	Computational Time (hours)	Input Variables
Linear Elastic Model	78.2	0.5	4
Bilinear Elastic-Plastic	85.3	1.2	6
Composite Action Theory	92.1	3.5	8
Interface Slip Model	88.5	4.8	10
Coupled Nonlinear FE Analysis	94.2	12.5	15
Fuzzy Reliability Model	89.7	2.1	12
Probabilistic Surrogate Model	95.8	8.3	14

In the preliminary design phases, composite action models provide an optimal balance. For final verification and optimization studies, surrogate-assisted FEM approaches enable high-accuracy predictions with manageable computational requirements. Remarkably, all identified studies employed deterministic input parameters, and uncertainty quantification was largely absent—this represents a critical research gap necessitating the development of probabilistic models [31].



[Fig.5: Analytical Modelling Performance]

B. Model Validation and Cross-Study Comparison

A systematic comparison of model predictions with 89 independent experimental datasets provided insight into how we will validate composite action theory formulations. The analysis is based on 50 independent validation studies and evaluates composite action theory formulations, which had average R^2 values of 0.87-0.92 across the specimen configurations studied. Models with viscoelastic connections characterised by power-law creep functions yielded higher predicted R^2 values (0.91 to 0.96) than linear elastic connections (0.81 to 0.88). This indicates that time-dependent characterization of connections is critical to predicting long-term responses [2].

However, systematic bias patterns emerged from comparative study data: The FEM models consistently predicted lower deflections than those documented in service load situations (mean bias = –8.3%), but the models significantly overpredicted the ultimate loads of the connection types (mean bias = +6.1%). The systematic bias in the predictions suggests that further refinements to the predictive models (e.g., recalibrating the models) are necessary, or that additional physics-based nonlinear phenomena should be included in the modelling to improve accuracy. In addition to model validation within multi-faceted or integrative systems, the high levels of predictive uncertainty in model predictions exceeded the experimental measurement uncertainty, suggesting that the model form contributed more significantly to the uncertainty than measurement limitations.

Although component-level (individual material or component) validation is well established for many manufacturers and contractors, validation of multi-faceted or integrated systems is far less established. The rigorous FEM approaches used here have been applied successfully to the design of Bamboo and Bamboo-Timber Composite Gridshell [26]. The outcome of this full-scale testing of the mechanical performance of coupled nonlinear models provides evidence that these models can accurately predict the stresses and deformations of hybrid systems and confirms the validity of the findings from the meta-analytical evaluations conducted under more complex and indeterminate stress states.

C. Sensitivity Analysis and Parameter Importance Ranking

Sensitivity analysis using variance-based Sobol indices to determine how much each parameter, relative to others, accounted for the uncertainty in an output (deflection prediction for a composite beam) showed that most of the 'uncertainty' in deflection predictions is caused by material strength properties (38-42%), with connection stiffness accounting for 22-28% and geometrical properties accounting for 15-20% [21]. The results from this analysis were used to prioritize a series of experimental designs. Optimising material characterisation would yield a greater reduction in uncertainty than refining geometry. Surprisingly, both moisture content and temperature contributed between 8% and 12% to the uncertainty in predictions, where environmental variability had been modelled as part of the analysis.

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V. RELIABILITY-BASED DESIGN FRAMEWORK

A. Probabilistic Characterization of Input Variables

Extensive variability in timber materials means that the inputs for reliability-based design (RBD) are most often probabilistically characterised [28]. In terms of benefits, reliability-based design optimisation can account for size, loads, material characteristics, and model uncertainties. A meta-analysis of the distribution of probabilistic data from 67 experimental studies enabled us to fit the best distributions to the data. The distribution of the tensile strength of materials was found to be lognormal (shape parameter α = 0.185, location parameter μ = 165.9 MPa) with a coefficient of variation of 18.5% [3]. The material modulus of elasticity was found to have a normal distribution with a mean (μ) = 15.96 GPa and a standard deviation (σ) = 1.96 GPa, consistent with the findings of earlier research on engineered wood products.

The lognormal distribution (α = 0.167) of connection stiffness showed significant variation, likely due to differences in surface preparation, bolt preload, and adhesive curing conditions. The distribution of live loads was based on the Gumbel extreme-value distribution, since it models the maximum annual values. The dead load values were determined deterministically with a very high degree of accuracy. Environmental conditions such as moisture and temperature were modelled using beta distributions because of their bounded upper and lower limits [23]. The quantified uncertainty in the model form is defined as the variance of the predicted values across different analytical methods, assuming a normal distribution, with a coefficient of variation of 12.1%.

Table IV: Reliability-Based Design Parameters

Parameter Category	Coefficient of Variation (%)	Distribution Type	Recommended Safety Factor
Material Strength (f)	18.5	Lognormal	1.5
Material Modulus (E)	12.3	Normal	1.3
Connection Stiffness (k)	16.7	Lognormal	1.4
Applied Load (Q)	14.2	Gumbel	1.6
Dead Load Factor	8.5	Deterministic	1.0–1.2
Live Load Factor	22.3	Gumbel	1.4–1.6
Environmental Factor	15.6	Beta	1.1–1.3
Model Uncertainty	12.1	Normal	1.2–1.4

Moderate positive correlations (ρ = 0.28–0.42) were observed between material strength and modulus parameters, reflecting common physical origins in fibre content and crystalline structure. These correlation structures were incorporated into First Order Reliability Method (FORM) calculations by specifying a correlation matrix in advanced reliability analysis tools.

B. Reliability-Based Design Optimization

RBDO (reliability-based design optimization) is a probabilistically-based design methodology that minimizes structural costs, using a probabilistic constraint that ensures that the failure probabilities associated with the structure do not exceed predetermined target thresholds. In the case of bamboo-timber composite beams, the RBDO developed to determine the optimal cross-sectional dimensions (depth and width) as well as the spacing and grade of bamboo used to construct the interconnected components, was able to minimise material volume subject to a given set of reliability constraints. The reliability indices used to define target PF levels were βt = 2.1 (for temporary structures; target PF level = 0.018) and βt = 3.3 (for critical structures; target PF level = 0.0005), which aligned with Eurocode guidelines [12]. The results of the RBDO confirmed that, using optimal designs developed through RBDO, material costs were reduced by 18% to 24% at the same level of reliability compared to traditional (factored-load) designs. The reduction in expenses was achieved by more efficient use of available material properties, enabled by explicit probabilistic quantification of uncertainty. The SORA algorithm used in RBDO provided a computationally efficient means to evaluate a design's reliability, because it was able to complete a design optimization with only 25–35 iterations, as opposed to at least 200 iterations if the reliability analysis and optimization were performed simultaneously. The surrogate-assisted RBDO using Kriging metamodels enabled a further 65% reduction in computational effort compared to direct FEM-based optimisation [24].

C. Target Reliability Index Justification

For research on bamboo-timber composite systems, target reliability indices were developed, considering factors such as failure consequences, uncertain magnitudes, and consistency with current standards. In residential applications, the reliability index (βt) of 2.1 corresponds to a failure rate of 0.018 per year, or an average return period of 56 years, which is acceptable for residential structures that may be replaced or remodelled every 50–75 years. For example, the recommended βt of 2.4 with a failure rate (PF) of 0.008 per year would result in an average return period (RP) of 125 years for commercial usage, given a minimum design life of 50+ years. Structures classified as critical (e.g., hospitals and emergency facilities) have βt values of 3.0–3.3 and may experience failures at rates of 0.0013–0.0005 per year, reflecting the increased risk.

The above recommendations account for the increase in construction costs driven by greater reliability and the reduced risk from lower rates of structural failure. A 0.5-increment change in βt will typically result in a 12–15% increase in the expected material costs associated with RBDO projects; therefore, the above cost-benefit relationships provide structural engineers and other stakeholders with sufficient information to make informed decisions.

VI. LONG-TERM PERFORMANCE AND TIME-DEPENDENT EFFECTS

A. Creep and Relaxation Characterisation

The behaviour of bamboo-timber composite under long-term exposure exhibits a complex interplay among bamboo species creep, concrete, and timber creep, and the relaxation of the connections that join the composite elements.

A meta-analysis was conducted on 15 studies from the past year(s), reviewing the duration of these studies based on the amount of time tested (how long they have been tested). From the studies, it was determined that the amount of Flexural Strength retained dropped from 100% of the Flexural Strength it had when it was initially tested to 95.2% after 1 Year, 88.3% after 2 Years, and 75.6% after 5 Years, due to further progression of the matrix creep and fibre relaxation [2]. This degradation was shown to be similar to an approximate power-law relation in the following form: $R(t)=R_0(1+\psi t^n)^{(-1/n)}$, with $\psi=0.8–1.2$ and $n=0.3–0.5$, thereby allowing estimation of degradation for more extended periods [table-5].

The total amount of slip on the connections differs from 0.2mm to 0.5mm/year, or 4.8mm to 8.5mm over 5 years, or approximately 8% of the total amount of connection slip that can be tolerated [8]. Slip of connections adversely affected the effective composite action, decreased the effective stiffness of the connection, and thus, predictions for the long-term design of composites need to be incorporated into the design. The modified superposition principle (using the compliance function) allows reasonably accurate prediction of the progression of Long-Term Deflection (prediction of LTF by the Modified Superposition Principle was between 84 and 89% correct) due to the realignment of stresses caused by different material creep [6].

Table V: Long-term Performance Degradation

Performance Indicator	Initial Value (%)	1 Year (%)	2 Years (%)	5 Years (%)
Flexural Strength	100	95.2	88.3	75.6
Stiffness Retention	100	94.5	87.6	72.1
Connection Slip (mm)	0	0.2–0.5	1.0–2.0	4.8–8.5
Shear Strength	100	96.8	92.4	80.3
Compression Capacity	100	97.4	93.2	84.1
Impact Resistance	100	92.1	83.5	68.9

B. Environmental Durability and Moisture Effects

Moisture uptake and environmental conditions significantly affect the durability of bamboo-timber composites. Water immersion tests have shown significant strength losses, with embedment strength at 45% of the dry value after 3 days' immersion, then 15% after 6 days [1]. The findings highlight the importance of protecting bamboo-timber composites with moisture-protection coatings and barriers before use in the field [32]. In addition, when tested for moisture resistance, bamboo scrimber composites were found to be much more resistant to moisture absorption than plain bamboo; this resistance is attributed to the adhesive impregnation density, combined with the unique consolidation used to produce bamboo scrimber composites [23].

Predicting the service life of bamboo structures using long-term durability models, developed from the equations governing moisture diffusion and statistical modelling of the kinetics of matrix degradation, suggests that when constructed under covered conditions, bamboo structures could be expected to last on average 30 to 50 years. When built under exposed conditions that do not provide protection, the service life would average 10 to 15 years [7], [31]. These findings have generally been supported by similar studies conducted throughout Southeast Asia and Central America on bamboo structures in exterior applications. As a result of these findings, there are now recommendations for using water-resistant coatings, providing proper flashing details for connection zones, and anticipating regular replacement intervals for any exposed bamboo members.

VII. RESEARCH GAPS AND FUTURE PRIORITIES

Meta-analysis identified multiple critical research domains requiring future investigation:

A. Probabilistic Characterization of Materials: Many of the studies reviewed in the literature have used deterministic property values (i.e., a single value) to model composites. Future studies should develop a systematic approach to measuring and evaluating the time- and space-dependent variability of composite material properties by collecting and testing large-scale specimens, enabling researchers to create probabilistic input models for advanced reliability analyses.

B. Standardization of Connection Systems: Because connector geometries, fastening methods, and adhesive specifications are not uniformly defined across the studies reviewed in this article, making generalizations beyond the individual studies is difficult. An international effort should establish a single reference connection system to facilitate comparisons of results across several related studies and promote the development of practical design codes for composites.

C. Mechanisms of Failure at Multiple Scales: Whereas macro-scale mechanisms of failure have been sufficiently characterised, the micro-scale mechanisms that govern the occurrence of delamination between layers of composite materials, fibre-matrix debonding, and the accumulation of damage over time require advanced imaging and analytical techniques to support the development of predictive constitutive models.

D. Effects of Coupled Environment: The combined effects of moisture, temperature, and loads on composite materials have yet to be investigated in most cases. Therefore, there is a need to develop coupled multiphysics simulation models to predict the actual field performance of composite materials, accounting for the combined effects of hygrothermal and mechanical processes.

E. Performance of Composites During Seismic Events: Although some studies have explored the performance of composites during static and cyclical loading and performed three-dimensional numerical simulations, the actual performance of composites during an earthquake requires thorough experimental investigation and the development of suitable numerical models.

F. Quantification of Sustainable Design: To date, there have been very few complete LCA studies that have compared the embodied carbon, operational energy use, and end-of-life recovery potential of composite materials versus other kinds of materials. Additional comprehensive LCA studies will help increase the number of criteria used to select materials for engineered products.

VIII. PRACTICAL DESIGN IMPLICATIONS AND RECOMMENDATIONS

Based on meta-analytic synthesis, the following practical recommendations are proposed for structural engineers:

A. Preliminary Design

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Phase: Assessing loads at service conditions will require employing composite action models that include safety factors for material strength in the range of 1.4-1.6 and a factor for composite action efficiency in the range of 1.3-1.5 to establish approximate member dimensions. Target reliability indices, β_t, are in the range of 2.1-2.4 for conventional applications.

B. **Detailed Design Phase:** Create coupled nonlinear finite element models which include characterisation of interface slip. Verify the accuracy of model predictions against project-specific material testing. Use of Surrogate-Assisted Design Optimization (SAD) to optimize the configuration of members while consistently meeting the target reliability and the lowest cost.

C. **Long Term Performance:** Evaluate the impact of time-dependent degradation (as shown in Table 5) on service condition performance for structures that have an expected design life of over 30 years, for which the use of a conservative strength retention factor (0.75-0.85 at year five, to be extrapolated to design life) is to be employed, unless adequate creep characterization is performed.

D. **Connection Design:** Specific Hybrid Connectors will be used in accordance with Table 2. The combination of mechanical fasteners and structural adhesives will yield the best performance-to-cost ratio. Minimum bolt diameters should be at least 16 mm to ensure ductility and preload stability. The maximum distance between connectors should not exceed 1.5 m to provide a composite action efficiency of 70% or greater.

E. **Protection Against the Environment:** Protect exposed surfaces of bamboo with water-resistant coatings and provide protective flashing at all connection locations. Additionally, monitor moisture content in humid climates (tropical) and provide maintenance/replacement strategies as necessary.

IX. CONCLUSIONS

This comprehensive meta-analysis of experimental and analytical modelling studies synthesises the documented knowledge of bamboo-timber composite structural systems. It quantifies the mechanical performance characteristics of these systems with unparalleled accuracy, compares the validity of competing analytical frameworks, and creates probabilistic design parameters to be used for reliability-based optimization. The main findings include:

A. **Performance Parity:** Engineered bamboo-timber composites produce structural performance levels equal to those of timber-concrete composites (72%-78% efficient composite action), while providing greater environmental sustainability (50%-85% reduction in embodied carbon) as revealed by Lifecycle Assessment studies.

B. **Modelling Capability:** Coupled nonlinear finite element models with interface slip calculations have an accuracy rate of 94.2% in predicting structural performance, thereby offering excellent tools for practical designs. Surrogate-assisted methods provide a means to improve both efficiency and accuracy in locating the design of optimum elements.

C. **Reliability Framework:** The use of probabilistic characterization of input variables allows for the relative design optimization based on a reliability-based method that results in 18%-24% savings in material costs compared to traditional factored load approaches, while ensuring the same level of safety.

D. **Long-Term Sustainability:** Time-dependent degradation in material properties will cause a decrease in flexural strength by an average of 75.6% over the five years of service; therefore, the design calculations and maintenance strategies will need to account for creep effects.

E. **Connection Criticality:** Hybrid mechanical-adhesive connector systems deliver a greater increase in capacity compared to single mechanism connectors, achieving 25% to 40% greater load-carrying capacity as well as enhanced ductility characteristics. This synthesis serves as a knowledge base to enable the effective use of bamboo-timber composite structural systems in sustainable construction.

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