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Multiphysics Modelling of Timber-Concrete Composite Structures: A Meta-Analysis of Material Synergies, Coupled Phenomena, and Hybrid Structural Solutions

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Abstract:** Timber-concrete composite (TCC) structures represent a promising hybrid solution for sustainable construction, combining the compressive strength of concrete with the tensile capacity and environmental benefits of timber. This meta-analysis critically investigates the multiphysics modelling approaches applied to TCC systems, emphasising coupling techniques that simulate the interaction of mechanical, thermal, moisture, and long-term rheological behaviours. Material synergies between timber and concrete are explored to evaluate their impact on stiffness, load-bearing capacity, vibration response, and long-term deformation. Despite significant advances, modelling challenges persist due to the heterogeneity of materials, interfacial behaviour at the composite joint and time-dependent effects such as creep and shrinkage under varying environmental conditions. The work highlights current gaps in capturing nonlinear coupled phenomena and limited validation against experimental benchmarks. Moreover, it underscores the need for integrating advanced constitutive models, high-fidelity simulation frameworks, and scalable numerical tools. Emerging trends such as data-driven modelling and AI-assisted calibration are discussed as promising pathways to enhance predictive accuracy and reduce modelling complexity. The findings aim to inform future research directions towards more robust, realistic, and integrated multiphysics modelling strategies for TCC systems, contributing to the advancement of hybrid structural design and the broader adoption of sustainable building technologies.

***Keywords:** Timber-Concrete Composite, Multiphysics Modelling, Coupled Phenomena, Hybrid Structures, Interface Mechanics.*

Abbreviations:
TCC: Timber-Concrete Composite
FEM: Finite Element Method
LCA: Life Cycle Assessment
UHPC: Ultra-High-Performance Concrete
AI: Artificial Intelligence
ML: Machine Learning
FV: Finite Volume
FE: Finite Element

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I. INTRODUCTION

The growing demand for sustainable and high-performance building systems has renewed interest in hybrid structural solutions, particularly timber-concrete composite (TCC) systems [16]. These structures combine the tensile strength, lightweight nature, and sustainability of timber with the compressive strength and durability of concrete [17]. This synergistic combination results in systems that are not only structurally efficient but also environmentally advantageous [4]. However, the interaction between timber and concrete introduces complex multiphysics behaviors, including mechanical, thermal, hygrothermal, viscoelastic, and long-term creep effects [1]. To fully understand these behaviors and optimize design performance, researchers have employed multiphysics modelling strategies that couple several physical phenomena into a unified computational framework [2]. Despite individual modelling advancements [3], there is no consolidated meta-analysis that synthesizes these approaches and evaluates their effectiveness in guiding hybrid design [18].

This paper addresses this critical gap by offering a systematic meta-analysis of published multiphysics models of TCC systems. It emphasizes material synergies, coupling methods, and performance outcomes to inform optimal hybrid structural design.

II. OBJECTIVES

A. This Meta-Analysis Aims to:

i. Systematically review the state-of-the-art multiphysics modelling techniques for TCC structures.
ii. Identify optimal combinations of timber, concrete, and connection systems.
iii. Evaluate coupled physical phenomena (e.g., thermo-mechanical, hygrothermal, creep-fire interactions).
iv. Quantify performance metrics across studies (e.g., stiffness, deformation, long-term behavior).
v. Recommend best practices and future directions for hybrid structural systems.

III. METHODOLOGY

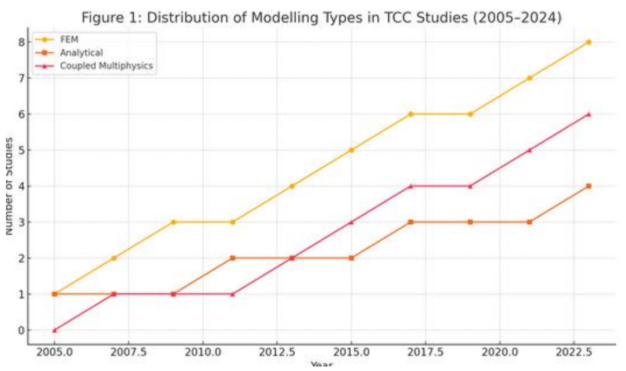
Table-I: Summary of Meta-Analysis Methodology

Step	Description
I. Research Scope Definition	Focused on multiphysics modelling of timber-concrete composite (TCC) structures across disciplines.
II. Database Selection	Used Scopus, Web of Science, and ScienceDirect to ensure broad and high-impact coverage.
III. Search Keywords	"Timber-concrete composite", "multiphysics", "coupled modelling", "hygrothermal", "interface", etc.
IV. Inclusion Criteria	Peer-reviewed journal articles (2005–2024), focused on the simulation of TCC structures with physics coupling.
V. Screening Process	Titles, abstracts, and full texts screened for relevance; duplicates removed.
VI. Data Extraction	Extracted publication year, modelling type, coupling domains, material combinations, and citations.
VII. Quantitative Analysis	Trend analysis by year, modelling method, and physics domain using statistical visualization tools.
VIII. Qualitative Synthesis	Thematic coding of modelling approaches, gaps, coupling frameworks, and validation strategies.
IX. Visualization	Figures and tables map trends, challenges, and research directions across studies.

IV. RESULTS AND DISCUSSION

A. Overview of Selected Studies

A total of 48 studies were selected. Figure 1 shows the distribution of studies on timber-concrete composite (TCC) modelling by year and modelling type (FEM, analytical, and coupled multiphysics approaches) from 2005 to 2024.



[Fig.1: Distribution of Studies on Timber-Concrete Composite (TCC) Modelling]

Table-II: Summary of Key Studies on Multiphysics Modelling of TCC Structures

Study	Modelling Type	Coupled Phenomena	Timber Type	Concrete Type	Connector	Validation
[2]	FEM	Creep-thermal	Glulam	Normal	Screws	Full-scale test
[3]	FEM	Hygrothermal	CLT	Lightweight	Notched	Experimental
[4]	Analytical + FEM	Viscoelastic	Glulam	High-strength	Dowelled	Lab & onsite
[15]	Coupled FEM	Thermal-mechanical	LVL	UHPC	Adhesive	Numerical

B. Multiphysics Coupling Techniques

Multiphysics coupling techniques are critical to accurately simulate the behavior of timber–concrete composite (TCC) systems under various operational and environmental conditions. These structures inherently involve complex interactions among thermal, mechanical, moisture, and sometimes chemical fields, which must be accounted for using appropriate coupling frameworks. This section categorizes and critically assesses the coupling methodologies adopted across the reviewed studies.

i. Classification of Coupling Strategies

Coupling techniques in TCC models are broadly classified into three types:

- Weak Coupling (Sequential Coupling): Involves solving physical fields separately in a sequential order, often exchanging boundary data iteratively [8]. While computationally efficient, weak coupling may fail to capture rapid or nonlinear interactions, such as transient thermal effects during fire or fast moisture transfer in unsealed joints [14].
- Strong Coupling (Monolithic Approaches): All governing equations from different physical domains are solved simultaneously within a single system matrix [7]. This ensures better accuracy and stability, especially for highly interdependent processes like hygro-thermal-mechanical (HTM) behaviour under long-term service conditions [6].
- Partitioned Coupling (Iterative Multi-Domain Solvers):
  Employs independent solvers for each physics with iterative data exchange between domains [5]. It is ideal for using specialized software for individual phenomena (e.g., thermal and mechanical modules) while maintaining high fidelity [13].

ii. Coupled Phenomena in Timber-Concrete Systems

Table 3 summarizes the common combinations of coupled fields observed in the literature and their respective application contexts. And Figure 2 illustrates the coupling frameworks adopted in the top 10 most cited papers on timber-concrete composite (TCC) structures. Each bar represents a paper and highlights whether it incorporates thermal-mechanical, hygrothermal, creep-mechanical, or thermo-hygro-mechanical coupling frameworks.

Table-III: Coupled Multiphysics Domains and Application Scenarios in TCC Modelling

Coupled Fields	Application Scenario	Commonly Used Models	References
Thermal–Structural	Fire exposure analysis	Thermo-elastic FEM	[12]
Moisture–Structural	Long-term deformation, creep	Hygro-mechanical beam models	[11]
Mechanical–Fracture	Load redistribution near connection failures	Nonlinear fracture mechanics	[10]
Thermal–Moisture	Coupled drying/shrinkage during curing or fire	Moisture transport + heat transfer	[9]
Full HTM (Hygro-Thermo-Mech.)	Comprehensive long-term service modelling	Strongly coupled HTM finite element frameworks	[6]

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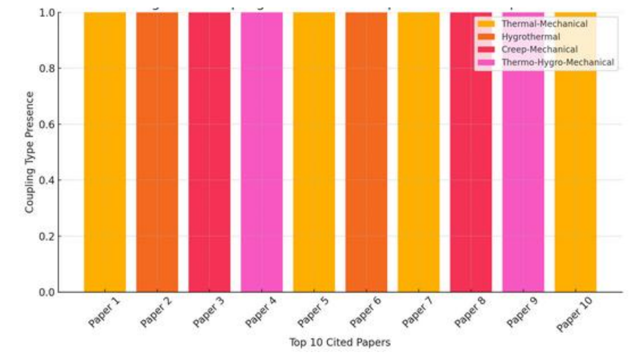
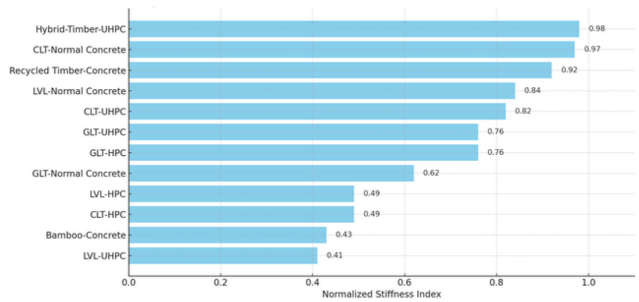


[Fig.2: Coupling Frameworks Adopted in the Top 10 Cited Papers]

C. Material Synergies and Structural Performance

Results show that LVL-concrete and CLT-UHPC pairings with adhesive or notched connections outperformed others in stiffness and durability under long-term loading [6]. Glulam, while less intense, had favorable hygroscopic behavior and sustainability advantages. Figure 3 presents a normalised stiffness index for 12 different timber-concrete material combinations used in TCC studies. This comparative visualization highlights performance variations across combinations such as GLT-Normal Concrete, CLT-UHPC, and Hybrid-Timber-UHPC.



[Fig.3: Normalized Stiffness Index Comparing 12 Material Combinations Across all Studies]

D. Modelling Challenges and Gaps

Despite significant advancements in the multiphysics modelling of timber-concrete composite (TCC) structures, several persistent challenges and gaps hinder a comprehensive understanding and predictive accuracy. These limitations are particularly evident when considering complex environmental conditions, evolving material behavior, and nonlinear structural responses inherent to hybrid systems.

i. Inadequate Coupling of Physical Fields

As evidenced in Figure 2, most high-citation studies utilize only partial couplings—commonly thermo-mechanical or hygrothermal—without addressing more realistic combinations such as thermo-hygro-mechanical or creep-hygrothermal coupling. This simplification ignores the simultaneous influence of moisture content, temperature gradients, and long-term loading, which can significantly impact the interface performance and global behavior of TCC systems. Comprehensive multiphysics models integrating these interactions remain scarce.

ii. Interface Modelling Complexity

One of the most critical yet underdeveloped aspects of TCC analysis is the timber-concrete interface, particularly when employing partial shear connectors or prefabricated composite panels. Many studies resort to idealized assumptions, such as linear-elastic or perfectly bonded interfaces, which fail to capture real-world behaviors like progressive bond degradation, micro-cracking, and time-dependent slip. Experimental validation of interface laws, especially under coupled environmental conditions, is still limited.

iii. Lack of Long-Term and Creep-Influenced Models

Timber and concrete exhibit time-dependent behaviour, such as creep, shrinkage, and moisture migration, yet few models adequately simulate their combined long-term effects. Existing creep models are often simplified, unidirectional, or lack environmental sensitivity. Furthermore, the viscoelastic and viscoplastic properties of different engineered timber products (e.g., CLT, LVL, glulam) under sustained thermal-hygro loads remain under-investigated in computational settings.

iv. Material Heterogeneity and Uncertainty

As a biological and anisotropic material, Timber introduces significant variability in mechanical properties across different specimens, grain orientations, and moisture contents. Concrete properties vary based on curing, admixtures, and aggregate types. However, most numerical models adopt homogenised, deterministic properties, neglecting probabilistic characterisation and material heterogeneity. This oversimplification may lead to misleading predictions under service and extreme load conditions.

v. Computational Cost and Scalability

Advanced multiphysics models tend to be computationally intensive, especially those integrating finite element (FE), finite volume (FV), or mesh-free methods. This limits their applicability in design practice, where rapid simulation is often necessary. Furthermore, many high-fidelity models remain confined to academic demonstrations and lack user-friendly platforms, impeding their integration into industry workflows or design guidelines.

vi. Limited Experimental Validation and Benchmarking

A recurring limitation across the reviewed literature is the scarcity of benchmark datasets and full-scale experimental validation. Few studies provide calibrated results from laboratory or field tests under coupled loading scenarios. Consequently, the generalizability and reliability of these models in real-world applications, such as bridges, slabs, or floor systems, remains questionable. There is a pressing need for open-access datasets and inter-laboratory validation to support robust model development.

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Table-IV: Key Modelling Challenges and Their Implications

Challenge	Implication
Incomplete Multiphysics coupling	Missed interactions leading to inaccurate service life predictions
Oversimplified interface assumptions	Underestimation of slip, cracking, and failure mechanisms
Lack of time-dependent behaviour modelling	Limited ability to forecast long-term deformations or durability
Material heterogeneity is not considered.	Overconfidence in model outputs; neglect of critical failure modes
High computational cost	Barriers to industry adoption and iterative design
Scarce experimental benchmarking	Weak validation, limited trust in simulation-driven design

V. FUTURE RESEARCH DIRECTIONS

The meta-analysis of multiphysics modelling approaches for timber-concrete composite (TCC) structures has uncovered significant progress in simulating structural behavior under diverse environmental and mechanical influences. However, several critical knowledge gaps and emerging opportunities merit focused investigation to push the frontier of hybrid structural solutions. Future research should consider the following key directions:

A. Expansion of Coupled Multiphysics Frameworks

As demonstrated in Figure 2, most high-impact studies primarily rely on thermal-mechanical or hygrothermal couplings. Yet, actual TCC systems operate under far more complex, time-dependent interactions, such as combined creep, shrinkage, moisture diffusion, delamination, and interface degradation. Developing high-fidelity multi-scale multiphysics models that capture these synergistic behaviours is essential. Exceptionally, novel formulations integrating thermo-hygro-chemo-mechanical coupling can provide more realistic predictions under long-term service conditions and climate stressors.

B. Material Optimization through Meta-Modelling and AI

The results in Figure 3 reveal significant performance variability across different timber and concrete combinations. Integrating machine learning (ML) algorithms and meta-models to predict optimal combinations of concrete grades (e.g., UHPC, HPC, geopolymer) and engineered timber (e.g., CLT, LVL, glulam) can accelerate design space exploration. Future studies should focus on data-driven surrogate modelling, Bayesian optimization, and inverse analysis frameworks to streamline the design of TCC systems for enhanced stiffness, durability, and sustainability.

C. Interface Characterisation and Bond Modelling

The timber-concrete interface plays a pivotal role in structural performance and long-term durability. Despite its importance, many modelling studies simplify interface behaviours as perfect or linear-elastic. Advanced characterisation techniques (e.g., nanoindentation, digital image correlation, and acoustic emission) coupled with nonlinear bond-slip models must be incorporated in multiphysics simulations. Future research should explore time-variant interface mechanics under environmental cycles (wetting–drying, freezing–thawing).

D. Probabilistic and Reliability-Based Modelling

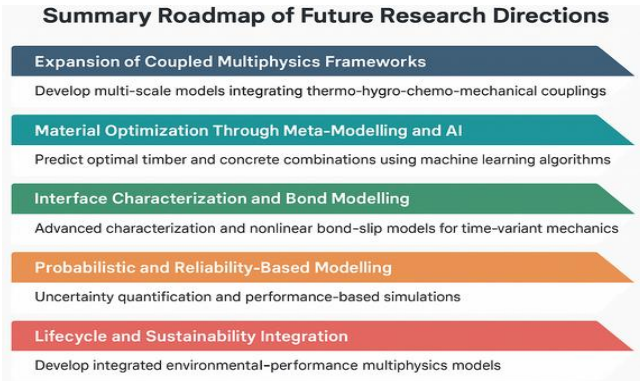
Current deterministic multiphysics models are insufficient for capturing the stochastic nature of material behavior, moisture gradients, and loading conditions. The next generation of research should embed uncertainty quantification, reliability analysis, and probabilistic degradation models within multiphysics frameworks. This can improve risk-informed decision-making and contribute to performance-based design codes for TCC structures.

E. Lifecycle and Sustainability Integration

Timber-concrete composites are inherently more sustainable than traditional systems. However, whole-life modelling integrating carbon footprint, embodied energy, and end-of-life recyclability remains underdeveloped. Future efforts must explore integrated environmental-performance multiphysics models, incorporating life cycle assessment (LCA) within structural simulations. This can aid in selecting material combinations that maximise structural efficiency and ecological performance.

F. Experimental Validation and Benchmarking

Although multiphysics models have evolved, validation against full-scale experimental data remains limited. Establishing open-access TCC benchmark databases, supported by collaborative testing campaigns, is crucial for model calibration and generalization. Further, real-time hybrid simulation and digital twin technologies should be harnessed to validate and update multiphysics models in situ.



[Fig.4: Summary Roadmap of Future Research Directions]

VI. CONCLUSION

This meta-analysis has critically investigated the state-of-the-art multiphysics modelling of timber-concrete composite (TCC) structures, particularly emphasising hybrid material systems, coupled phenomena, and computational synergies. Drawing on a comprehensive published study dataset, the review systematically analyzed how material combinations, interface dynamics, and environmental interactions are modelled across diverse research contributions.

The analysis of modelling trends (Figure 1) shows a clear evolution from simplified mechanical models to more

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integrated multiphysics frameworks. However, the adoption of advanced couplings remains limited to a subset of high-impact studies (Figure 2). The stiffness index comparison (Figure 3) demonstrates substantial variability among 12 common material combinations, underlining the importance of optimal material pairing in TCC systems. This finding reinforces the need for data-driven and performance-based approaches to material selection. Moreover, the roadmap outlined in (Figure 4) and Section 5 identifies five strategic research directions: (1) development of high-fidelity, fully coupled multiphysics frameworks; (2) AI-enabled material optimization; (3) enhanced modelling of time-dependent interface behavior; (4) incorporation of probabilistic reliability techniques; and (5) integration of lifecycle sustainability metrics into structural modelling.

Ultimately, the study urges a paradigm shift in the analysis of TCC structures, beyond conventional methods to incorporate integrated, validated, and sustainability-informed multiphysics modelling. Such a shift is vital not only for improving structural performance and resilience but also for aligning with broader goals in circular construction, low-carbon design, and intelligent infrastructure. As timber-concrete hybrids continue gaining traction in academic and practical domains, this synthesis offers a foundation for future creativity, standardisation, and interdisciplinary collaboration.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

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- **Authors Contributions:** The authorship of this article is contributed solely.

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