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Material Degradation with Moisture Transport Mechanisms in Timber Bridge Decks: Finite Element Modeling

Simone Benedetti*

Department of Materials Science and Engineering, School of Engineering, University of Pisa, Pisa, Tuscany, Italy

Corresponding author: simone.benedetti@gmail.com

Abstract

The structural longevity of timber bridge decks is inherently governed by the complex interplay between environmental exposure and the fundamental hygroscopic nature of wood. Material degradation in these structures is rarely the result of immediate mechanical overload, but rather a progressive deterioration facilitated by long-term moisture transport mechanisms. This paper investigates the spatial and temporal distribution of moisture within timber bridge decks and evaluates the subsequent material degradation using advanced finite element modeling techniques. By simulating the anisotropic diffusion of water through the porous cellular network of the wood, the study captures the transient moisture gradients that develop under cyclic environmental loading. A coupled hygro-mechanical framework is employed to assess how localized elevations in moisture content initiate stiffness reduction and promote conditions conducive to biological decay. The computational results demonstrate that moisture accumulation is highly concentrated at connection points and interfacial gaps, creating persistent high-moisture zones that significantly accelerate localized degradation. The finite element modeling evidence underscores the necessity of considering non-Fickian diffusion characteristics and moisture-dependent mechanical properties in the structural assessment of timber bridges. These findings provide critical insights for optimizing preservation strategies, informing maintenance schedules, and enhancing the overall resilience and service life of sustainable timber infrastructure globally.

Keywords: Timber Bridge Decks; Finite Element Modeling; Moisture Transport; Material Degradation; Structural Reliability

1. Introduction

1.1 Background of Timber as a Construction Material

Timber has served as a foundational construction material for centuries, prized for its remarkable strength-to-weight ratio, aesthetic appeal, and widespread availability. In the context of civil infrastructure, timber bridges have historically provided critical transportation links across rural and remote regions. Despite the proliferation of steel and reinforced concrete in modern bridge engineering, timber remains a highly relevant material due to the increasing global emphasis on sustainable construction practices and carbon sequestration. The utilization of engineered wood products, such as glued laminated timber and cross-laminated timber, has further expanded the structural capabilities of wood, allowing for longer spans and heavier load-bearing capacities. However, the fundamental biological and chemical composition of timber introduces unique challenges not encountered with synthetic or highly processed structural materials. Wood is inherently hygroscopic, meaning it constantly exchanges moisture with its surrounding environment to achieve equilibrium. This continuous absorption and desorption of water vapor fundamentally dictate the physical, mechanical, and biological stability of the material [1]. In outdoor structural applications, such as bridge decks, the material is directly exposed to precipitation, fluctuating relative humidity, solar radiation, and wind, making moisture management the single most critical factor in ensuring structural longevity [2]. Without adequate understanding and mitigation of moisture ingress, timber structures are highly susceptible to premature failure, necessitating costly repairs or complete replacements.

2.2 The Problem of Moisture in Timber Bridges

The deterioration of timber bridge decks is primarily driven by moisture accumulation, which acts as a catalyst for a multitude of degradation mechanisms. When the moisture content of wood exceeds the fiber saturation point, typically around twenty-five to thirty percent of its dry mass, free water begins to fill the cellular lumens [3]. This state provides an ideal microenvironment for the proliferation of wood-decaying fungi, which metabolize the structural polymers of the wood cell wall, namely cellulose, hemicellulose, and lignin. Fungal degradation drastically reduces the density and mechanical strength of the timber, compromising the safety of the entire bridge structure [4]. Furthermore, fluctuations in moisture content below the fiber saturation point induce significant dimensional changes due to the swelling and shrinking of the cell walls. Because wood is a highly anisotropic material, these dimensional changes occur at vastly different rates in the longitudinal, radial, and tangential directions [5]. This differential movement generates internal stresses within the timber deck, particularly when constrained by mechanical fasteners or adjacent structural members. Over time, these cyclic hygro-mechanical stresses lead to the development of micro-cracks and deep checks, which in turn provide new pathways for liquid water to penetrate deeper into the cross-section, thereby accelerating the degradation cycle [6]. The bridge deck, being the horizontal surface directly exposed to traffic loads and weather events, is particularly vulnerable to water pooling and persistent dampness, making it the focal point of structural vulnerability in timber bridges.

1.3 Objectives and Scope of the Study

The primary objective of this research is to comprehensively assess the mechanisms of material degradation in timber bridge decks by quantifying moisture transport utilizing high-fidelity finite element modeling. Traditional methods of assessing timber decay often rely on empirical field inspections or simplified analytical models that fail to capture the complex, transient, and multi-dimensional nature of moisture diffusion in real-world environmental conditions [7]. By employing computational mechanics, this study aims to simulate the intricate pathways of moisture ingress, retention, and egress within the complex geometry of a bridge deck. The scope includes the formulation of an orthotropic diffusion model that accounts for the varying permeability of wood in different structural directions [8]. Additionally, the research seeks to couple the moisture transport analysis with a mechanical degradation model, enabling the prediction of structural stiffness reduction as a direct function of localized moisture content over prolonged environmental exposure cycles [9]. The ultimate goal is to provide a robust theoretical and computational framework that can predict degradation patterns with high spatial resolution, thereby informing more effective design protocols, protective detailing, and targeted maintenance interventions for timber bridge infrastructure.

2. Literature Review and Background

2.1 Historical Approaches to Timber Degradation Analysis

The study of timber durability and degradation has a long history, initially grounded in observational and empirical methodologies. Early approaches to timber bridge maintenance relied heavily on visual inspections, sounding techniques with hammers, and core drilling to identify areas of advanced rot or fungal decay. While these methods provided immediate, practical assessments of structural health, they were inherently reactive, identifying damage only after significant material degradation had already occurred [10]. Subsequent research sought to correlate environmental conditions, such as average annual rainfall and temperature, with the expected service life of timber components, leading to the development of empirical decay hazard maps [11]. These macroscopic models offered valuable geographic guidelines but lacked the resolution required to predict the performance of specific structural details or individual bridge configurations. In the realm of material science, laboratory experiments using climate chambers were extensively utilized to measure the equilibrium moisture content and the corresponding loss of mechanical properties under controlled steady-state conditions [12]. However, translating these steady-state laboratory findings to the dynamic, highly variable transient conditions experienced by a bridge deck in the field proved highly challenging. The necessity for predictive, rather than merely diagnostic, tools drove the academic community to explore more sophisticated mathematical representations of moisture dynamics in porous media.

2.2 Advances in Moisture Transport Modeling

The mathematical description of moisture transport in wood represents a complex challenge in the field of porous media physics. Early analytical models primarily relied on Fickian diffusion theory, which posits that the moisture flux is directly proportional to the moisture concentration gradient [13]. While Fickian models provided a useful approximation for steady-state scenarios or slow variations in ambient humidity, they often failed to accurately capture the rapid absorption of liquid water during rain events or the non-linear desorption profiles observed during drying phases. Researchers increasingly recognized that moisture transport in timber is a multi-phase phenomenon, involving the simultaneous movement of water vapor through the continuous void space, bound water diffusion within the dense polymeric matrix of the cell walls, and capillary transport of liquid water in the macro-pores [14]. Consequently, advanced multi-physics models were developed, utilizing thermodynamic potential or relative humidity as the driving potentials instead of simple mass concentration. These models incorporated moisture-dependent diffusion coefficients, acknowledging that the permeability of wood increases significantly as it absorbs moisture and the cell walls swell [15]. Furthermore, non-Fickian behaviors, such as sorption hysteresis and relaxation phenomena associated with the viscoelastic nature of the wood polymers, were integrated into the governing equations to improve theoretical accuracy [16]. Despite these theoretical advancements, solving these highly non-linear partial differential equations for complex structural geometries required substantial computational resources.

2.3 Finite Element Methods in Structural Timber Analysis

The advent of robust finite element modeling techniques has revolutionized the structural analysis of timber components, allowing for the numerical solution of complex hygro-mechanical problems that defy analytical resolution. Initially, finite element applications in timber engineering were confined to static stress analysis, treating wood as a simple linear elastic orthotropic material. As computational capabilities expanded, researchers began to implement transient thermal and moisture diffusion models to map the environmental state variables within the structural domain [17]. A critical breakthrough was the development of coupled hygro-mechanical formulations, which link the moisture transport solver directly to the mechanical solver. In these coupled analyses, the calculated moisture field is used to update the mechanical material properties in real-time, accounting for both moisture-induced swelling strains and the reduction in elastic moduli at elevated moisture levels [18]. Recent literature has heavily focused on modeling the local micro-climates at structural connections, such as steel-to-timber dowel joints, which are notorious for trapping moisture and initiating decay [19]. Furthermore, researchers have incorporated cohesive zone models and extended finite element methods to simulate the initiation and propagation of moisture-induced shrinkage cracks, thereby dynamically updating the domain geometry and internal moisture boundary conditions as the material fractures [20]. This ongoing integration of multi-physics modeling with advanced fracture mechanics represents the current frontier in predicting the long-term degradation of timber bridge decks.

3. Methodology and Modeling Framework

3.1 Material Characterization and Domain Definition

The foundation of the finite element methodology employed in this study rests upon the rigorous characterization of the timber material properties and the precise definition of the computational domain. The modeled bridge deck represents a typical longitudinally laminated timber structure, composed of individual dimensional lumber laminations compressed together to form a solid continuous slab. The material is designated as a standard structural softwood species, specifically engineered for load-bearing outdoor applications. Because wood possesses a cellular structure resembling a bundle of parallel microscopic tubes, its physical and mechanical properties are highly directional. The material model is therefore defined using an orthotropic constitutive matrix, requiring independent parameters for the longitudinal direction aligned with the grain, the radial direction extending outward from the pith, and the tangential direction aligning with the growth rings [21]. The computational domain encompasses a representative cross-sectional volume of the deck, capturing several adjacent laminations and the vertical interfaces between them. These interfaces are modeled with specific contact properties to simulate the microscopic gaps where capillary action can draw liquid water deep into the structure. The external boundaries of the domain are designated as environmental interaction surfaces, subject to convective mass transfer coefficients that simulate the exchange of moisture with the surrounding atmosphere.

Table 1: Material Properties and Hygro-mechanical Parameters for Finite Element Simulation

Property	Longitudinal Direction	Radial Direction	Tangential Direction
Elastic Modulus	12000 MPa	800 MPa	500 MPa
Diffusion Coefficient	0.005 cm2/s	0.001 cm2/s	0.0008 cm2/s
Moisture Expansion	0.001 per percent	0.15 per percent	0.25 per percent

3.2 Finite Element Formulation for Moisture Transport

The transient transport of moisture through the timber deck is simulated using a time-dependent mass diffusion analysis within the finite element environment. The governing principle is the conservation of mass, formulated mathematically such that the rate of change of moisture concentration within a differential volume is balanced by the net flux of moisture across its boundaries. To account for the multi-phase nature of water in wood, the model utilizes a normalized driving potential based on relative humidity, which seamlessly handles the transition between the hygroscopic range and the capillary over-hygroscopic range. The resistance to moisture flow is quantified by a diffusion tensor, which is fully populated with the orthotropic transport coefficients detailed in the material characterization phase [22]. Crucially, this tensor is programmed to be state-dependent, meaning the diffusion coefficients are continuously updated based on the local moisture concentration computed at the previous time step. This non-linearity captures the phenomenon where wet wood conducts water significantly faster than dry wood. The boundary conditions are applied as transient flux functions, driven by historical meteorological data encompassing hourly variations in ambient temperature, relative humidity, and precipitation intensity over a simulated multi-year period. A specialized surface boundary formulation is implemented to model the rapid absorption of liquid water during rain events, contrasted with the much slower desorption process during dry periods, effectively simulating the moisture trapping that plagues real-world timber decks [23]. The spatial domain is discretized using higher-order, three-dimensional solid elements, with extensive mesh refinement near the exposed surfaces and lamination interfaces where the steepest moisture gradients are anticipated to occur.

3.3 Implementation of the Degradation Model

To translate the simulated moisture fields into actionable data regarding material degradation, a phenomenological mechanical degradation model is coupled to the diffusion analysis. This model operates on the principle that prolonged exposure to high moisture levels intrinsically damages the structural integrity of the timber, both through immediate mechanical softening and cumulative biological decay. The finite element solver is configured to execute a sequentially coupled analysis. In the first phase, the transient moisture transport simulation computes the spatial distribution of moisture content at every integration point within the mesh at each specified time increment. In the second phase, these moisture values are mapped onto an identical structural mesh to perform a mechanical stress analysis under standard bridge loading conditions [24]. The degradation is implemented through a user-defined material subroutine that mathematically reduces the elastic moduli and strength parameters of the elements based on their specific moisture history. A critical threshold is established at a moisture content of twenty percent; elements that exceed this threshold for extended, continuous durations experience an exponential decay in their mechanical properties, simulating the onset and progression of fungal rotting [25]. Furthermore, the subroutine calculates the internal stresses generated by differential swelling and shrinking. If these hygro-mechanical stresses exceed the perpendicular-to-grain tensile strength of the timber, the element stiffness is permanently degraded to simulate micro-cracking. This continuous feedback loop between the environmental moisture loads, the internal moisture distribution, and the localized structural capacity provides a highly comprehensive assessment of the progressive deterioration of the bridge deck over its projected service life.

4. Results and Discussion

4.1 Spatiotemporal Moisture Distribution Profiles

The outputs generated by the finite element moisture transport simulation reveal complex, highly localized patterns of moisture accumulation that traditional analytical methods fail to predict. Analysis of the spatiotemporal distribution profiles over the simulated multi-year weather cycle demonstrates that the top surface of the bridge deck, directly exposed to precipitation, experiences rapid and severe fluctuations in moisture content. However, the most critical findings relate to the internal moisture dynamics. Due to the high longitudinal permeability of timber compared to its transverse permeability, moisture that penetrates the end grain at the abutments or through surface checks rapidly migrates deep into the core of the laminations. The simulation clearly illustrates the phenomenon of moisture entrapment. During subsequent drying periods driven by solar radiation and lower ambient humidity, the surface layers dry relatively quickly, forming a low-permeability barrier that effectively seals the elevated moisture within the interior core. Consequently, the internal moisture content remains consistently high, often hovering near the fiber saturation point, even during extended dry seasons. The vertical interfaces between adjacent timber laminations were identified as particularly severe pathways for moisture ingress [26]. Capillary action draws water down into these narrow gaps during rain events, creating persistent micro-environments of extreme humidity. The computational evidence demonstrates that these interfacial zones maintain moisture levels conducive to decay for durations significantly longer than the bulk material, highlighting them as the primary initiation sites for structural degradation.

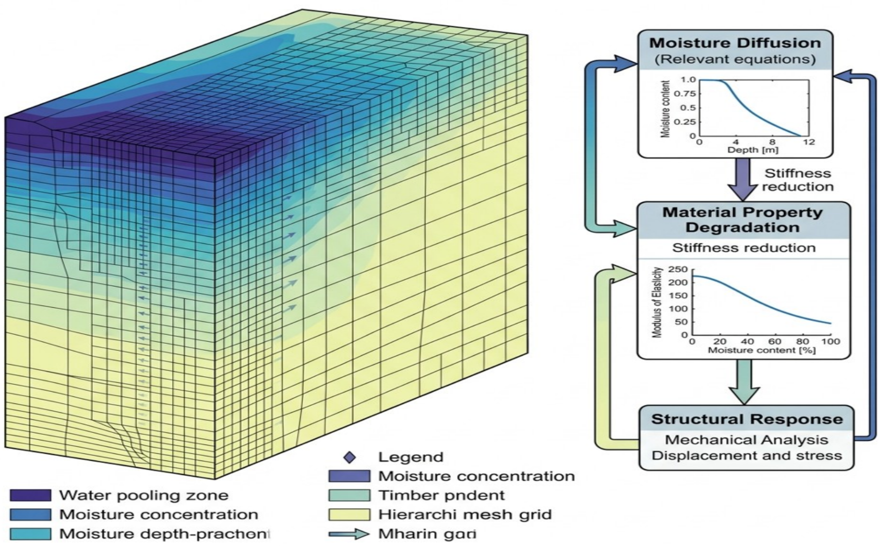

Figure 1: Comprehensive Finite Element Modeling Schematic of Moisture Transport and Subsequent Material Degradation in a Timber Bridge Deck Cross

4.2 Impact on Mechanical Performance and Degradation

The coupling of the moisture distribution data with the mechanical degradation subroutine provides profound insights into the structural consequences of prolonged environmental exposure. The results indicate that the global stiffness of the timber bridge deck undergoes a gradual but irreversible decline over the simulated period. This degradation is not uniform across the structure; rather, it is highly concentrated in the specific zones where moisture entrapment was identified. The elements representing the core of the deck and the regions adjacent to the lamination interfaces exhibited severe reductions in their elastic moduli, directly correlating with the cumulative time spent above the critical moisture threshold. This localized softening forces a redistribution of mechanical stresses when subjected to traffic loads, often shifting the burden to adjacent, less degraded laminations. Furthermore, the simulation highlighted the destructive impact of cyclic hygro-mechanical stresses. The rapid wetting and drying of the surface layers induced substantial swelling and shrinking strains, leading to high tensile stresses perpendicular to the grain. The model predicted the initiation of significant surface checking and internal micro-cracking, particularly near mechanical fasteners that restrain the natural dimensional changes of the wood. These simulated cracks essentially act as new boundary conditions in reality, allowing future precipitation to bypass the protective surface layers and deposit water directly into the vulnerable interior, thus creating an accelerating feedback loop of deterioration that drastically shortens the effective service life of the deck system.

4.3 Comparative Analysis with Field Observations

To validate the computational findings, the simulated degradation patterns were qualitatively compared against well-documented field observations of existing timber bridge structures. The finite element model successfully replicated the spatial locations where advanced decay is most frequently encountered during bridge inspections. Field data consistently shows that internal rotting is prevalent in the core of large timber elements and at the interfaces of laminated decks, locations that appear completely sound from external visual inspection. The simulation precisely captured this internal moisture pooling mechanism. Furthermore, the model predicted the highest rates of stiffness reduction in the immediate vicinity of penetrations, such as scuppers or the bolt holes used for attaching the deck to the supporting stringers. These locations are notorious in field maintenance reports for harboring aggressive fungal decay due to the exposure of the highly permeable end-grain. The alignment between the high-resolution computational predictions and historical field performance data validates the efficacy of utilizing coupled hygro-mechanical finite element modeling as an advanced diagnostic and predictive tool [27]. It confirms that accurately capturing the anisotropic transport properties and the non-linear desorption behaviors is absolutely essential for understanding the true mechanisms driving the failure of timber infrastructure.

5. Conclusion and Implications

5.1 Summary of Key Findings

This comprehensive study has successfully demonstrated the critical utility of finite element modeling in assessing material degradation mechanisms within timber bridge decks. By implementing a sophisticated, multi-physics computational framework, the research moved beyond traditional empirical assessments to rigorously quantify the complex spatiotemporal dynamics of moisture transport under cyclic environmental conditions. The simulations conclusively established that the primary driver of deterioration is not merely the total volume of water encountering the structure, but rather the localized entrapment of moisture within the internal core and along inter-lamination interfaces. The anisotropic permeability of wood, combined with hysteresis in the drying process, creates persistent internal micro-environments that remain well above the critical moisture threshold necessary for fungal propagation. The coupled mechanical degradation analysis further revealed that these high-moisture zones suffer profound and irreversible reductions in stiffness and structural capacity over time. Additionally, the modeling highlighted the significant role of cyclic hygro-mechanical stresses in generating micro-cracks, which perpetually create new pathways for moisture ingress and accelerate the overall degradation lifecycle.

5.2 Engineering Implications and Future Directions

The evidence generated by this computational modeling holds profound implications for the future of timber bridge engineering, design, and maintenance. Foremost, the results emphasize the absolute necessity of incorporating detailed hygro-thermal analysis during the preliminary design phase of timber infrastructure, shifting the engineering focus from purely load-bearing calculations to holistic environmental durability. The identification of critical moisture pooling zones provides engineers with targeted locations for implementing enhanced protective detailing, such as improved waterproof membranes, optimized drip edges, and the strategic application of breathable sealants that prevent liquid water ingress while allowing internal vapor to escape. For existing infrastructure, the predictive capabilities of this modeling framework can revolutionize maintenance strategies, enabling asset managers to transition from reactive repairs to proactive, targeted interventions based on simulated moisture accumulation data. Future research directions should focus on integrating this finite element methodology with large-scale structural health monitoring systems, utilizing embedded moisture sensors to continuously calibrate and validate the computational models in real-time. Furthermore, expanding the material subroutines to explicitly model the biological kinetics of specific fungal strains will provide even greater accuracy in predicting the ultimate service life of these vital, sustainable transportation structures.

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