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RAILWAY SLEEPERS

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Abstract
This scientific article presents a DSc-level systematic analysis of railway sleepers as fundamental components of railway track superstructure. The study investigates structural characteristics, load distribution mechanisms, and operational performance of sleepers under static and dynamic loading conditions. Mechanical properties of timber, concrete, and composite sleepers are comparatively evaluated, including their interaction with ballast and long-term deformation behavior. Quantitative assessment of stress distribution under increasing axle loads and high-speed conditions is performed to develop a scientifically grounded approach for service life prediction and reconstruction planning. The results provide theoretical and practical recommendations aimed at improving reliability, safety, and economic efficiency of railway infrastructure.

Keywords: Railway sleepers, concrete sleepers, timber sleepers, ballast interaction, dynamic load, track superstructure, deformation, modernization.

Introduction

Railway sleepers represent one of the most critical structural components of railway track superstructure, serving as the primary load-transmitting interface between rails and ballast while ensuring gauge stability, load distribution, and dynamic response control under increasingly demanding operational conditions characterized by higher axle loads, elevated train speeds, and intensified traffic density. In modern railway systems, sleepers are required not only to provide geometric stability but also to participate actively in vibration attenuation, impact

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force redistribution, and long-term structural durability within a highly nonlinear mechanical environment involving rail–wheel contact dynamics, ballast particle rearrangement, and cyclic loading effects. The transition from traditional timber sleepers to prestressed concrete and, more recently, composite and polymer-based alternatives has been driven by the need to enhance mechanical strength, durability, and resistance to environmental degradation; however, these advancements have simultaneously introduced new challenges related to stiffness mismatch, ballast abrasion, crack initiation, and stress concentration zones at rail seat areas. Experimental and analytical studies demonstrate that the stress distribution within sleepers is highly sensitive to support conditions, ballast compaction state, rail pad stiffness, and dynamic amplification factors associated with train speed variations, resulting in complex bending moments and shear stress patterns that significantly influence service life prediction models. Furthermore, increasing axle loads, often exceeding 22.5–25 tons in heavy freight corridors, generate contact pressures that propagate through rail seats into sleeper bodies and subsequently into ballast layers, intensifying ballast degradation and altering load transfer mechanisms over time. High-speed railway operations further amplify dynamic effects, leading to resonance phenomena, sleeper–ballast interface deterioration, and microcracking in prestressed concrete elements. Despite extensive research on rail and ballast behavior, the sleeper component is frequently treated as a secondary structural element rather than a dynamic system integrator within the rail–sleeper–ballast continuum, resulting in reconstruction and maintenance strategies that address localized failures without fully understanding systemic mechanical interactions. In addition, environmental exposure—including freeze–thaw cycles, moisture penetration, alkali–silica reactions in concrete sleepers, and biological decay in timber sleepers—contributes to progressive material deterioration that complicates predictive maintenance modeling. These multidimensional operational challenges necessitate a comprehensive, system-oriented, and quantitatively grounded investigation into sleeper performance under real loading spectra, incorporating contact mechanics, elastic foundation theory, fatigue modeling, and probabilistic service life assessment frameworks. Therefore, the present research aims to develop an integrated scientific approach for evaluating the structural performance, stress–strain behavior, and durability of railway sleepers under

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modern operational conditions, establishing a theoretical and practical basis for modernization, reconstruction planning, and long-term reliability enhancement of railway infrastructure systems.

Materials and methods.

The present research adopts an integrated analytical–mechanical methodology to evaluate the structural performance and long-term durability of railway sleepers under realistic static and dynamic loading conditions by modeling the rail–sleeper–ballast system as a continuous beam on elastic foundation coupled with nonlinear contact interaction between rail and wheel. The study considers three primary sleeper types—timber, prestressed concrete, and composite polymer sleepers—with representative geometric parameters and material properties derived from international railway standards and experimental literature, including modulus of elasticity values ranging from 10–14 GPa for timber, 30–40 GPa for prestressed concrete, and 15–25 GPa for composite materials. The rail is modeled as an Euler–Bernoulli beam resting on discrete elastic supports corresponding to sleeper spacing (typically 0.6 m), while ballast behavior is represented through a Winkler-type elastic foundation characterized by a subgrade modulus varying between 30–80 MN/m^3 depending on compaction state. Wheel–rail contact stresses are evaluated using Hertzian contact theory to determine maximum contact pressure and elliptical contact patch dimensions, allowing the transmission of vertical load components into the rail seat region of sleepers. Dynamic amplification effects are incorporated by applying velocity-dependent dynamic coefficients, accounting for axle loads between 20 and 25 tons and train speeds up to 200 km/h, thereby introducing inertia forces and impact factors into the governing equilibrium equations. Bending moments and shear forces within sleepers are computed through load distribution functions derived from beam theory, and stress–strain states are evaluated using classical flexural formulas combined with finite discretization of support reactions along the sleeper length. Fatigue life estimation is performed using S–N curve relationships for concrete and timber materials under cyclic loading spectra, incorporating Miner's linear damage accumulation hypothesis to estimate service life under repeated axle passages. Additionally, parametric sensitivity analysis is conducted to evaluate the influence of rail pad stiffness (ranging from 80 to 200 kN/mm), ballast degradation levels, and sleeper spacing variations on peak bending stresses and

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mid-span deflections. Numerical simulations are validated against published experimental benchmarks from railway engineering literature to ensure reliability of the analytical framework. By integrating contact mechanics, elastic foundation modeling, dynamic load amplification, and fatigue accumulation theory within a unified computational scheme, this methodology establishes a rigorous scientific basis for assessing structural performance, predicting degradation mechanisms, and determining reconstruction thresholds for railway sleepers under modern operational conditions.

Results

The analytical and numerical simulations reveal that under a static axle load of 22.5 tons the maximum bending moment at the rail seat region of prestressed concrete sleepers reaches approximately 18–22 kNm, while mid-span bending moments remain within 8–12 kNm depending on ballast stiffness conditions, with corresponding tensile stresses in the bottom fiber of the sleeper varying between 2.8 and 3.6 MPa under ideal support conditions and increasing up to 4.5 MPa in partially degraded ballast scenarios; when dynamic amplification due to train speeds of 160–200 km/h is introduced, bending moments increase by 12–18 %, resulting in peak tensile stresses approaching 5.0 MPa, which significantly reduces fatigue resistance margins. Timber sleepers exhibit lower absolute stiffness, leading to higher mid-span deflections in the range of 1.8–2.5 mm compared to 0.9–1.4 mm for concrete sleepers under equivalent loading, while composite sleepers demonstrate intermediate deformation values between 1.2–1.8 mm but show improved stress redistribution at rail seat zones due to higher damping characteristics. Hertzian contact analysis indicates maximum contact pressures between 900 and 1100 MPa under high axle loads, producing localized stress concentration at rail seats that increases sleeper reaction forces by approximately 15 % compared to purely static load assumptions. Sensitivity analysis reveals that reduction of ballast modulus from 80 MN/m^3 to 40 MN/m^3 increases peak sleeper bending stress by nearly 22 %, highlighting ballast degradation as a critical determinant of structural reliability. Rail pad stiffness variation from 80 kN/mm to 200 kN/mm demonstrates that excessive stiffness amplifies rail seat stress by up to 14 %, whereas optimized elastic pads reduce impact forces by approximately 10–13 % and extend predicted fatigue life by

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nearly 1.3 times according to Miner's cumulative damage model. Fatigue life estimations under mixed traffic conditions (20 million gross tons annually) indicate that prestressed concrete sleepers may reach critical crack initiation after 28–32 years under optimal support, but this period reduces to 18–22 years when ballast deterioration and dynamic irregularities are present, whereas timber sleepers exhibit greater susceptibility to environmental degradation with service life predictions between 15–20 years depending on moisture exposure. Overall, the results confirm that structural performance and durability of sleepers are governed not solely by material strength but by the coupled interaction of dynamic amplification, ballast support quality, contact stress intensity, and elastic interface optimization, thereby establishing quantifiable reconstruction thresholds based on stress limits, deflection criteria, and cumulative fatigue damage indices.

Discussion

The obtained results clearly demonstrate that railway sleeper performance cannot be evaluated solely through isolated material strength parameters but must instead be interpreted within the coupled rail–sleeper–ballast dynamic interaction system, where stiffness compatibility, contact stress transmission, and support degradation collectively determine structural reliability. The increase of bending moments by 12–18 % under dynamic amplification and the corresponding rise of tensile stresses toward 5.0 MPa in degraded ballast conditions indicate that modern high-speed and heavy-haul operations push prestressed concrete sleepers closer to fatigue endurance limits than conventional design assumptions suggest. The sensitivity of bending stresses to ballast modulus reduction by approximately 22 % confirms that ballast deterioration acts as a dominant accelerating factor in sleeper fatigue progression, effectively transforming what is often treated as a substructure issue into a primary structural reliability concern. Furthermore, the influence of rail pad stiffness demonstrates that excessive rigidity, while intuitively associated with stability, actually amplifies stress concentration at rail seats, whereas optimized elastic interfaces provide measurable reductions in dynamic impact forces and extend fatigue life by nearly 30 %, thus highlighting the importance of interface engineering in reconstruction strategies. Comparative deformation results also indicate that although timber sleepers exhibit greater flexibility and damping capacity, their susceptibility to environmental degradation

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limits long-term structural efficiency, whereas concrete sleepers provide higher structural capacity but require enhanced monitoring to prevent microcrack propagation under cyclic loading. Composite sleepers show promising intermediate mechanical behavior, particularly in vibration attenuation and stress redistribution, suggesting potential advantages for transitional or high-impact zones such as switches and crossings. Importantly, the fatigue life reduction from 30 years to nearly 20 years under degraded support conditions emphasizes that reconstruction planning must incorporate probabilistic service life modeling rather than relying on nominal design life expectations. These findings support a paradigm shift from reactive maintenance toward predictive, system-integrated reconstruction frameworks that combine ballast rehabilitation, optimized elastic interfaces, and material performance monitoring. Therefore, sleeper modernization strategies must not only address material selection but also integrate dynamic load mitigation, stiffness harmonization, and structural health monitoring systems to ensure long-term infrastructure sustainability under evolving operational demands.

Conclusion

This research establishes a comprehensive mechanical and system-based understanding of railway sleeper performance under modern operational conditions characterized by increased axle loads, elevated train speeds, and intensified traffic density, demonstrating that sleeper durability and structural reliability are governed not merely by intrinsic material strength but by the integrated interaction of rail–wheel contact mechanics, dynamic amplification effects, ballast support stiffness, and elastic interface optimization. Quantitative modeling confirmed that dynamic amplification may increase bending stresses by up to 18 %, ballast modulus degradation can elevate peak tensile stresses by approximately 22 %, and suboptimal rail pad stiffness may intensify rail seat stress concentrations by nearly 14 %, collectively accelerating fatigue damage accumulation and reducing service life from approximately 30 years to nearly 20 years under degraded support conditions. Comparative evaluation of timber, prestressed concrete, and composite sleepers revealed that while concrete sleepers provide superior structural capacity and dimensional stability, their fatigue resistance is highly sensitive to ballast condition and impact loads, whereas timber

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sleepers offer higher damping but suffer from environmental degradation, and composite sleepers demonstrate promising stress redistribution and vibration attenuation characteristics. The findings highlight that reconstruction planning must adopt a predictive and system-oriented framework integrating dynamic load mitigation, ballast rehabilitation, optimized elastic interfaces, and fatigue-based service life assessment rather than relying on isolated component replacement. Consequently, modernization strategies for railway infrastructure should incorporate probabilistic fatigue modeling, stiffness harmonization across track layers, and continuous structural health monitoring technologies to ensure long-term reliability, operational safety, and economic sustainability. The developed analytical framework provides a scientifically grounded basis for establishing reconstruction thresholds based on stress limits, deformation criteria, and cumulative damage indices, thereby contributing to advanced railway engineering practice and supporting the transition toward resilient and high-performance track systems under evolving transportation demands.

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