

Design Optimization of Steel Plate Girder Bridges Using Finite Element Modelling

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ABSTRACT

Steel plate girder bridges are integral to modern transportation networks due to their high strength-to-weight ratio and versatility for medium to long-span applications. However, these bridges are under increasing stress due to rising traffic loads, environmental degradation, and aging infrastructure. To address these challenges, finite element modelling (FEM) has proven to be a critical tool in simulating the complex structural behavior of steel plate girder bridges under dynamic loads and varying environmental conditions. Advanced FEM techniques have enhanced the design, performance optimization, and durability predictions of these structures, ensuring their long-term serviceability and safety under demanding conditions.

Keywords: *Steel Plate Girder, Finite Element Modelling, Dynamic Loads, Structural Performance.*

I. INTRODUCTION

Steel plate girder bridges have remained one of the most widely adopted structural systems in modern transportation infrastructure due to their high strength-to-weight ratio, constructability, and suitability for medium to long-span applications. These bridges have been extensively used in highway and railway networks where heavy traffic loads, dynamic vehicle interactions, and varying environmental conditions continuously influence their structural performance. However, increasing traffic intensity, rising axle loads, and exposure to harsh environmental conditions such as temperature variation, corrosion, and fatigue loading have significantly challenged the long-term serviceability and safety of these structures. As a result, the need for accurate analysis, design improvement, and performance optimization of steel plate girder bridges has become more critical than ever. In this context, finite element modelling (FEM) has emerged as a powerful computational tool for simulating complex structural behaviour under realistic loading scenarios and has been widely applied in bridge engineering research to enhance design reliability and efficiency (Wang et al., 2025; López et al., 2025).

In recent years, significant advancements in finite element-based modelling techniques have enabled researchers to better understand the behaviour of steel bridge systems under dynamic traffic loads and environmental effects. Traditional design methods, which often relied on simplified analytical assumptions, were found to be insufficient in capturing localized stress concentrations, fatigue damage, and nonlinear structural responses. Advanced FEM approaches have allowed for detailed simulation of load transfer mechanisms, stress distribution patterns, and deformation characteristics in steel plate girder bridges. For instance, multi-scale modelling frameworks have been developed to integrate global bridge response with localized component behaviour, improving the accuracy of fatigue and serviceability assessments (Wang et al., 2026). Similarly, optimization studies using validated FEM models have identified efficient structural configurations that reduce material consumption while maintaining adequate strength and stiffness (Wang et al., 2025). Furthermore, research has also highlighted the importance of incorporating time-dependent effects such as creep, shrinkage, and thermal variations in composite bridge

systems to ensure long-term performance prediction accuracy (Huang et al., 2025). These developments demonstrate that FEM-based approaches are essential for capturing the complex interactions between traffic-induced dynamic loads and environmental influences in steel bridge structures.

Moreover, environmental degradation and structural deterioration mechanisms such as fatigue cracking, corrosion, and rutting in bridge deck systems have been widely studied using finite element modelling techniques. Studies have shown that repeated traffic loading combined with environmental exposure significantly reduces the fatigue life and load-carrying capacity of steel bridge components (Zeng et al., 2023). In addition, corrosion-induced deterioration has been identified as a major factor affecting the safety and durability of aging steel bridges, particularly in harsh climatic regions where de-icing salts and moisture accelerate material degradation (Zaghian et al., 2023). Advanced probabilistic and data-driven FEM approaches have also been introduced to incorporate uncertainty in material properties and loading conditions, thereby improving the reliability of structural assessment and maintenance planning (Barros et al., 2024). Furthermore, coupled modelling techniques such as DEM–FEM and thermo-mechanical simulations have enhanced the understanding of construction processes, pavement behaviour, and extreme loading scenarios in steel bridge systems (Liu et al., 2023; Zhang et al., 2026). Despite these advancements, challenges still remain in achieving fully integrated design optimization frameworks that simultaneously consider dynamic traffic loading, environmental effects, fatigue behaviour, and long-term structural degradation in steel plate girder bridges. Therefore, this study focuses on the design optimization of steel plate girder bridges using finite element modelling under dynamic traffic and environmental loads, aiming to improve structural efficiency, durability, and service life through advanced simulation and analysis techniques.

II. RESEARCH BACKGROUND

Zhang et al. (2026) had examined the increasing vulnerability of railway steel bridges to combined fire and explosion accidents, noting that most earlier studies had treated these hazards separately rather than in an integrated manner. They had proposed a comprehensive numerical framework that coupled the Fire Dynamics Simulator (FDS), the Finite Element Method (FEM), and the Coupled Eulerian–Lagrangian (CEL) technique to evaluate the sequential and combined effects of fire and blast loading. A key contribution of their study had been the development of a fully coupled thermo-mechanical-blast simulation model, which enabled the simultaneous representation of fire-induced material degradation and the subsequent dynamic response to blast forces within a unified computational platform. Using a 64-m railway steel truss bridge affected by an oil tanker fire as a case study, they had observed that structural members reached temperatures close to 1200 °C within 30 minutes, causing significant strength deterioration and severe thermal buckling. Their findings had further indicated that pre-fire heating substantially intensified blast-related damage, while longer fire duration and higher explosion equivalents had promoted progressive collapse. The study had thus provided important mechanistic insights into coupled fire-blast failure behaviour and had offered a valuable basis for the resilient and safe design of steel railway bridges under extreme multi-hazard conditions.

Wang et al. (2026) had examined the performance of steel bridge deck pavements (SBDPs) under complex mechanical and environmental service conditions and had observed that existing design approaches often failed to capture both global bridge behavior and local pavement responses simultaneously. To overcome this limitation, they had developed a multi-scale finite element modeling framework integrating a full-bridge model, a refined girder-segment model, and a detailed pavement submodel. The framework had been applied to an extra-long suspension bridge to assess the mechanical responses of five representative pavement structural configurations, including double-layer SMA, double-

layer epoxy asphalt (EA), EA-SMA combinations, and a composite system with a thin epoxy resin aggregate overlay. Their findings had shown that different pavement structures significantly influenced the stress and strain distribution within the deck system. It had been reported that the composite overlay configuration reduced interfacial shear stress but generated excessive tensile strain, thereby increasing the risk of fatigue cracking. In contrast, the double-layer EA system had exhibited the lowest fatigue-related strain and better deformation compatibility, while the optimized EA-SMA combination had provided a balanced performance in terms of fatigue resistance and interfacial stress control. Overall, the study had validated the effectiveness of the multi-scale modeling approach and had emphasized that appropriate selection of layer stiffness and thickness was essential for improving the durability and long-term service performance of steel bridge deck pavements.

López et al. (2025) had examined the vulnerability of steel truss bridges, emphasizing that bridges were among the most critical and costly assets within transportation networks, where the failure of even a single component could result in severe consequences for the entire structure. The study had highlighted the growing importance of vulnerability assessment, particularly as aging bridges made reliable structural evaluation increasingly difficult. To address this issue, the authors had proposed a component-based vulnerability assessment framework specifically for steel truss bridges. An index termed the State of Demand (SoD) had been introduced to quantify the demand condition of each structural element. The vulnerability level of all bridge components had been assessed through a finite element method (FEM)-based approach that incorporated uncertainties affecting structural behaviour. The proposed framework had been validated on a real steel truss bridge in Galicia, Spain. The study had integrated finite element modelling, uncertainty quantification and propagation, and probabilistic tools into a systematic methodology for component-level vulnerability evaluation. It had been concluded that the framework could support optimized inspection planning, cost reduction, and informed decision-making related to bridge safety, monitoring, and maintenance, while also offering potential for future automation in bridge management practices.

Huang et al. (2025, September) investigated the control of structural stresses and deformations in steel–concrete composite girder cable-stayed bridges during construction and operation phases. They proposed a comprehensive algorithm to account for shrinkage and creep effects, employing a recursive exponential function fitting method to derive a double-layer beam element algorithm. Subsequently, they developed a method for determining reasonable construction states of composite girder cable-stayed bridges using the unstressed cable length tension control approach, enabling effective structural modeling. A finite element model was constructed for the world’s largest span composite girder cable-stayed bridge, incorporating load history, and the effects of shrinkage and creep on the concrete deck were examined during both phases. They further analyzed curing age of precast bridge decks and isolated scenarios of shrinkage or creep, finding that shrinkage primarily influenced the construction phase, whereas creep dominated during operation, generating secondary internal forces that redistributed stresses in the concrete deck and steel girders. They recommended a minimum 180-day curing age and concluded that these findings offered guidance for mitigating long-term shrinkage and creep effects in bridge design and construction.

Wang et al. (2025) investigated steel box girder bridges, which are composed of mutually vertical stiffening ribs, including longitudinal and transverse ribs, that support vehicle loads. They emphasized that, due to the complexity and variability of external loads, the rational design of bridge components warranted further attention. The study aimed to determine the optimal range of certain design parameters to reduce costs while maintaining adequate stress-carrying capacity. A finite element model (FEM) was

developed using ABAQUS, and its reliability was confirmed through laboratory experiments. The researchers examined variations in the thicknesses of the bridge deck, diaphragm, and U-rib based on the validated FEM. The simulation results were found to align closely with experimental outcomes, indicating the FEM's accuracy. Stress analyses revealed optimal thickness ranges of 18–20 mm for the bridge deck, 14–16 mm for the diaphragm, and 8–10 mm for the U-rib. The study was considered to provide valuable guidance for the design and optimization of steel box girder bridge components and a theoretical foundation for future research in the area.

Zhu et al. (2024) investigated the rutting behavior of gussasphalt used in steel bridge deck pavements, highlighting its susceptibility to deformation during operation. They proposed a finite element-based method to predict rutting, drawing on the Nanjing Yangtze River Fourth Bridge project as a case study. Laboratory tests were conducted on prepared asphalt mixture specimens, and the viscoelastic-plastic constitutive model was calibrated using dynamic modulus and uniaxial repeated loading creep test results. Wheel track tests were performed to validate the numerical model, and temperature gradients were obtained from actual environmental data and verified against buried thermocouple measurements. By simplifying traffic loads and applying equivalent conversions, they calculated permanent deformation using both the viscoelastic-plastic and time-hardening creep constitutive models. Their findings indicated that the viscoelastic-plastic model provided more accurate predictions, with an average relative error of 25% and an absolute error of 0.57 mm, compared to 40% and 1 mm for the time-hardening creep model, suggesting its suitability for long-term rutting prediction.

Barros et al. (2024) highlighted that Finite Element (FE) modeling often required unavoidable simplifications or assumptions due to limited experimental data, modeling complexity, or high computational costs. They noted that one common simplification involved assuming uniform material properties or corrosion phenomena throughout structures, despite the local nature of corrosion and its severe impact on the behavior of steel structures. To address these limitations, they proposed a Gaussian Copula-based Bayesian Network (GCBN) approach to capture the spatial variability of structural element properties. They first conducted a study on the automatic generation process of Bayesian networks and subsequently applied the methodology to a severely damaged riveted steel bridge built in 1897. Their findings indicated that the approach offered excellent flexibility for generating property variability in FE models at low computational cost, demonstrating practical feasibility and robustness for accurate numerical modeling of aging steel bridges.

Liu et al. (2023) investigated the compaction mechanism and characteristics of steel bridge deck pavement (SBDP) under challenging construction conditions, noting that SBDP compaction was more complex and vulnerable compared with general highway asphalt pavement due to special supporting conditions and harsh construction environments. They highlighted that existing simulation models were inadequate for analyzing SBDP compaction and therefore generated particles using a random particle generation algorithm, simulating the asphalt mixture layer with the discrete element method (DEM) while representing the steel bridge deck with weld seams under unfavorable external conditions through the finite element method (FEM). Using a DEM-FEM coupling model, they tracked and examined the spatial movement and contact state of particles during compaction, demonstrating that this approach was effective and feasible for simulating the SBDP compaction process. Their findings were suggested to potentially improve SBDP compaction quality and provide a methodological reference for addressing other SBDP compaction issues, including temperature field variations and bridge vibrations.

Zeng et al. (2023) investigated orthotropic steel deck (OSD) structures, which were widely employed in the bridge deck systems of rail transit bridges, focusing on methods to improve fatigue life by reducing the amplitude of the stress intensity factor. They considered a cable-stayed urban rail transit bridge as the research object and designed a full-scale segment model of the OSD structure, conducting static and fatigue tests. Using linear elastic fracture mechanics and Paris' law for theoretical support, they simulated and predicted the fatigue life based on experimental data. Subsequently, ABAQUS and Franc3D were employed to analyze the effects of structural parameters, including U-rib thickness, roof thickness, and diaphragm thickness, on the stress intensity factor amplitude. Their findings indicated that diaphragm thickness and U-rib height had minimal impact on fatigue life, whereas appropriate increases in top plate and U-rib thickness positively influenced structural longevity. They further suggested that the study held reference value for sustainable development applications.

Zaghian et al. (2023) highlighted that corrosion of reinforcing steel in reinforced concrete infrastructure had been recognized as the primary cause of concrete deterioration in North America. They emphasized that piers, being the most critical bridge elements, were particularly vulnerable to reinforcement corrosion, especially in coastal regions and cold areas due to the use of de-icing salts. They noted that the combination of second-order effects and local nonlinearities governed the failure modes of slender and eccentrically loaded columns, and that degradation effects became more pronounced in the presence of corrosion, with nonlinear effects gaining dominance. The study adopted a comprehensive corrosion damage model from existing literature and proposed a stage-based corrosion scenario to evaluate the detrimental impact of corrosion on the ultimate capacity, rigidity, and ductility of bridge piers under eccentric loading through finite element analysis. Additionally, they generated interaction diagrams for corroded piers at various corrosion stages to define new safety margins and assessed the accuracy of their model by comparing results with available experimental data from the literature.

Rahmzadeh et al. (2022) investigated posttensioned (PT) rocking steel bridge piers through a finite-element (FE) study, in which each pier comprised a circular tubular column, welded end plates, PT strands, axially yielding steel energy dissipators (EDs), and corresponding chairs, configured to rock at the base. They summarized previously conducted experiments on five scaled rocking steel columns and generated three-dimensional continuum FE models of the specimens to verify the modeling approach for simulating both local and global responses. Strain-controlled cyclic coupon tests were performed to determine the kinematic and isotropic hardening material parameters, and a simplified method was proposed to model cyclic prestressing loss due to wedge seating in monostrand anchorages. The FE procedure was calibrated against experimental data at material, component, and global levels. They also conducted a parametric study to examine the influence of material models, P-Delta effects, base plate dimensions, column diameter-to-thickness and initial axial force ratios, ED chairs, and ED locations on lateral cyclic response. Their results indicated that local buckling and residual lateral deformations depended on column diameter-to-thickness and axial force ratios as well as ED configuration, and that proper selection of these factors enabled a stable self-centering response with minimal damage to the bridge pier.

Zhan et al. (2021) investigated the condition of joints in steel truss bridges, emphasizing their critical role in railway operational safety. They noted that existing methods for quantitatively assessing various types of joint damage were very limited. The study numerically explored the feasibility of applying a probabilistic neural network (PNN) in combination with a finite element (FE) model updating technique to evaluate joint conditions. A two-step identification procedure was developed to enable both damage localization and severity assessment. Multiple FE models representing single and multiple damage

scenarios were simulated to generate training and testing datasets and to validate the proposed approach. The researchers also examined the influence of noise on identification accuracy. Their findings indicated that the change rate of modal curvature (CRMC) could serve as a damage-sensitive input for the PNN, with preliminary damage localization achieving over 90% accuracy under suitable training patterns. They further reported that damaged members could be correctly localized within substructures even in the presence of noise, and that the FE model updating method could effectively quantify joint deterioration severity while remaining robust to noise.

III. KEY FINDINGS FROM STUDY

Author (Year)	Title / Focus Area	Methodology	Key Findings	Relevance to Present Study
Zhang et al. (2026)	Fire and explosion effects on steel bridges	Coupled FEM, FDS, CEL simulation	Fire significantly increases blast damage and collapse risk	Highlights multi-hazard FEM modelling for extreme load conditions
Wang et al. (2026)	Steel bridge deck pavement performance	Multi-scale FEM modelling	Pavement configuration affects fatigue and stress distribution	Supports FEM-based performance optimization under traffic loads
López et al. (2025)	Vulnerability assessment of steel truss bridges	FEM + probabilistic SoD model	Enables component-level damage and risk evaluation	Useful for reliability-based bridge design optimization
Huang et al. (2025)	Shrinkage and creep in composite bridges	FEM time-dependent analysis	Creep governs long-term deformation, shrinkage affects construction phase	Important for long-term service performance modelling
Wang et al. (2025)	Optimization of steel box girder bridges	ABAQUS FEM + experimental validation	Identified optimal thickness ranges for structural efficiency	Directly supports design optimization of steel girders
Zhu et al. (2024)	Rutting in steel bridge deck pavement	Viscoelastic-plastic FEM model	Improved prediction accuracy over traditional creep models	Enhances pavement durability modelling under traffic loads
Barros et al. (2024)	Spatial variability in steel bridges	Bayesian Network + FEM	Improved modelling of corrosion variability in aging bridges	Strengthens uncertainty-based FEM modelling approach
Liu et al. (2023)	Compaction process in SBDP	DEM-FEM coupling model	Improved simulation of pavement construction quality	Useful for realistic traffic-load interaction modelling
Zeng et al. (2023)	Fatigue life of orthotropic steel decks	FEM + fracture mechanics	Thickness influences fatigue resistance significantly	Relevant for fatigue-based optimization of plate girders

Zaghian et al. (2023)	Corrosion effects on bridge piers	FEM corrosion modelling	Corrosion reduces strength, stiffness, and ductility	Supports environmental degradation analysis in bridges
Rahmzadeh et al. (2022)	Rocking steel bridge piers	Nonlinear FEM simulation	Energy dissipation improves seismic performance	Useful for dynamic load resistance understanding
Zhan et al. (2021)	Damage detection in steel truss joints	FEM + probabilistic neural network	High accuracy in identifying joint damage	Supports integration of FEM with smart monitoring systems

IV. CONCLUSION

The reviewed literature clearly demonstrates that finite element modelling (FEM) has become an indispensable tool for the analysis, design, and optimization of steel plate girder bridges subjected to dynamic traffic and environmental loading conditions. Across the studies examined, it has been consistently observed that traditional analytical and empirical design approaches are insufficient to capture the complex structural behaviour of modern bridge systems, particularly under the influence of combined effects such as moving vehicular loads, temperature variations, fatigue accumulation, corrosion, and long-term material degradation. Advanced FEM-based methodologies have significantly improved the ability to simulate realistic load transfer mechanisms, stress distribution patterns, and nonlinear responses in steel bridge components. Research findings have shown that multi-scale and coupled modelling approaches provide a more accurate representation of both global structural performance and localized effects, thereby enabling better prediction of fatigue life and serviceability performance. Furthermore, optimization studies have demonstrated that careful selection of geometric parameters such as girder thickness, stiffener configuration, and deck composition can substantially enhance load-carrying efficiency while minimizing material usage and cost. Environmental effects such as shrinkage, creep, rutting, and corrosion have also been identified as critical factors influencing long-term structural integrity, and their inclusion in FEM frameworks has improved the reliability of durability assessments. In addition, the integration of probabilistic methods and data-driven techniques with FEM has enhanced uncertainty modelling, allowing for more robust decision-making in bridge maintenance and rehabilitation strategies. Studies involving advanced coupling techniques such as DEM–FEM and thermo-mechanical simulations have further expanded the applicability of FEM in capturing construction processes and extreme loading scenarios. Despite these advancements, it has been observed that challenges still exist in achieving fully integrated modelling frameworks that simultaneously address dynamic traffic loading, environmental degradation, fatigue behaviour, and real-time structural health monitoring. Therefore, it can be concluded that FEM-based design optimization represents a highly effective and evolving approach for improving the performance, safety, and sustainability of steel plate girder bridges. Continued research in this area is expected to further enhance predictive accuracy and contribute to the development of resilient bridge infrastructure systems capable of withstanding increasing operational demands and environmental uncertainties.

V. FUTURE SCOPE

- **Development of Fully Integrated Multi-Hazard FEM Frameworks:** Future research can focus on developing unified finite element modelling systems that simultaneously consider dynamic traffic loading, wind effects, seismic actions, corrosion, fatigue, fire, and blast scenarios. Such integrated frameworks will improve the realism of bridge performance prediction under combined extreme conditions.

- **AI-Enhanced Finite Element Modelling for Optimization:** The integration of artificial intelligence, machine learning, and deep learning with FEM can be further explored to automate design optimization of steel plate girder bridges. AI-assisted surrogate models can reduce computational time while improving accuracy in structural prediction and parameter optimization.
- **Real-Time Structural Health Monitoring Integration:** Future studies may incorporate sensor-based structural health monitoring (SHM) data directly into FEM models for real-time updating. This will enable continuous assessment of bridge health, early damage detection, and predictive maintenance planning.
- **Advanced Material Behaviour Modelling:** More refined constitutive models for steel and composite materials can be developed to capture nonlinear, time-dependent, and temperature-dependent behaviour under repeated loading cycles. This will enhance long-term durability prediction accuracy.
- **Probabilistic and Reliability-Based FEM Approaches:** Future research can expand probabilistic FEM techniques to better address uncertainties in material properties, loading conditions, and environmental exposure. Reliability-based design optimization will support safer and more economical bridge designs.
- **Digital Twin Technology for Bridge Systems:** The adoption of digital twin frameworks for steel bridges can enable real-time virtual replicas of physical structures. These models can continuously update using field data and FEM simulations for predictive analysis and lifecycle management.
- **Sustainability and Life-Cycle Optimization Studies:** Future work can focus on incorporating sustainability metrics such as carbon footprint, energy consumption, and life-cycle cost analysis into FEM-based design optimization of steel bridges.
- **High-Performance Computing and Cloud-Based FEM:** The use of high-performance computing (HPC) and cloud-based simulation platforms can significantly enhance the scalability of FEM analysis for large bridge systems under complex loading conditions.
- **Improved Fatigue and Fracture Mechanics Modelling:** Advanced fatigue crack propagation models combined with FEM can be developed to improve prediction of failure initiation and progression in steel plate girders under cyclic traffic loading.
- **Smart Infrastructure and Automation in Bridge Design:** Future research may explore fully automated bridge design systems where FEM, AI, and optimization algorithms work together to generate efficient and safe bridge configurations with minimal human intervention.

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