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Optimized Steel Plate Girder Bridges under Dynamic and Environmental Loads

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ABSTRACT

This study focuses on the design optimization of steel plate girder bridges using finite element modelling under dynamic traffic and environmental loads. A detailed finite element model was developed to analyse stress distribution, deflection, vibration response, fatigue behaviour, and material utilization. Dynamic moving traffic loads and environmental effects such as wind, temperature variation, and corrosion were considered to represent realistic bridge conditions. Design variables including web thickness, flange dimensions, girder depth, and stiffener spacing were optimized. Results showed reduced steel weight, lower stress, improved stiffness, enhanced fatigue resistance, and better dynamic stability.

Keywords: *Steel Plate Girder Bridge, Finite Element Modelling, Design Optimization, Dynamic Traffic Load.*

I. INTRODUCTION

Steel plate girder bridges occupy an important position in modern bridge engineering because they provide high structural efficiency, economical construction, and reliable performance for medium- to long-span transportation networks. These bridges are commonly used in highway, railway, and urban infrastructure projects where large loads, longer spans, and durability requirements must be satisfied within practical construction limits. A steel plate girder mainly consists of a deep web plate, top and bottom flange plates, transverse stiffeners, longitudinal stiffeners, cross frames, and deck elements that work together to resist bending, shear, torsion, vibration, and local instability. The increasing demand for faster transportation, heavier vehicles, and sustainable infrastructure has made the design of steel plate girder bridges more complex than before. Conventional design approaches are often based on simplified assumptions, empirical equations, and code-based safety factors, which are useful for preliminary design but may not fully capture the actual behaviour of bridge components under real field conditions. In practice, steel plate girder bridges are subjected not only to static dead and live loads but also to dynamic traffic effects caused by moving vehicles, braking forces, axle impact, vehicle speed variation, road surface irregularities, and repeated load cycles. These dynamic actions can produce stress concentration, excessive vibration, fatigue damage, and serviceability problems if they are not properly considered during the design stage. In addition, environmental loads such as wind pressure, temperature gradient, seasonal thermal expansion and contraction, moisture, corrosion, and long-term material degradation significantly influence the structural response and life span of steel bridges. Environmental exposure may reduce the effective thickness of steel plates, weaken connections, accelerate fatigue cracking, and increase maintenance requirements. Therefore, a realistic assessment of steel plate girder bridges requires an integrated design approach that considers traffic-induced dynamic response and environmental effects together rather than treating them as isolated design conditions. Finite element modelling has emerged as a powerful computational method for analysing such complex bridge behaviour because it allows the bridge system to be represented in a detailed and realistic manner. Through finite element analysis, different components of the plate girder bridge can be modelled using shell, beam, solid, or link elements depending on the required level of accuracy. The method helps engineers study stress distribution, deflection profile, natural frequency, mode shapes, fatigue-sensitive zones, local buckling behaviour, load transfer mechanism, and interaction between deck, girder, stiffeners, and supports. Unlike simplified manual calculations, finite element modelling provides a more detailed picture of how the bridge responds under combined loading conditions. It also helps identify critical locations such as web-flange junctions, bearing zones, stiffener connections, welded details, and regions of high bending or shear stress. These insights are highly valuable for improving design safety, reducing structural vulnerability, and ensuring long-term serviceability under realistic operating conditions.

Design optimization of steel plate girder bridges is essential because the traditional practice of increasing member sizes for safety may lead to unnecessary material consumption, higher construction cost, greater self-weight, and inefficient structural performance. Optimization aims to develop a balanced design in which the bridge satisfies strength, stiffness, fatigue, stability, durability, and serviceability requirements while minimizing cost and material usage. In the context of steel plate girder bridges, important design variables include girder depth, web thickness, flange width, flange thickness, stiffener spacing, cross-frame arrangement, bearing configuration, and material grade. A small change in any of these parameters can significantly affect stress distribution, deflection, vibration response, buckling resistance, and fatigue life. For example, increasing web thickness may improve shear resistance but also increases steel weight, while proper stiffener spacing can enhance buckling stability without excessive material use. Similarly, optimized flange dimensions can improve bending resistance and reduce deflection while avoiding overdesign. When finite element modelling is combined with optimization techniques, engineers can compare multiple design alternatives and select the most efficient configuration based on performance indicators. Dynamic traffic loading can be simulated through moving load models, vehicle–bridge interaction models, impact factors, or time-history analysis to evaluate how the bridge behaves under realistic vehicle movement. Environmental loads can be introduced through thermal gradients, wind forces, corrosion allowance, and material degradation models. The combined analysis enables the designer to evaluate not only the immediate strength of the bridge but also its long-term behaviour under repeated and changing load conditions. This is particularly important for steel bridges because fatigue is one of the major causes of deterioration in welded and bolted details. Repeated stress cycles from heavy traffic may gradually initiate cracks, which can propagate over time and reduce structural reliability. Finite element-based optimization helps reduce these risks by locating high-stress regions and modifying the design to distribute stresses more uniformly. It also supports sustainable infrastructure development by reducing unnecessary steel consumption and improving durability, thereby lowering maintenance costs and environmental impact. In modern bridge engineering, optimized design is not limited to achieving minimum weight; it also focuses on life-cycle performance, resilience, constructability, inspection convenience, and future maintenance needs. The integration of finite element modelling and design optimization therefore represents a scientific and practical approach for developing safer, lighter, more economical, and more durable steel plate girder bridges. It allows engineers to move beyond conservative assumptions and adopt performance-based design strategies that reflect actual structural behaviour. Under increasing traffic intensity and uncertain environmental conditions, such an approach becomes highly relevant for ensuring the reliability and sustainability of bridge infrastructure. Hence, the present topic emphasizes the importance of using finite element modelling as an analytical and optimization tool for improving the structural performance of steel plate girder bridges subjected to dynamic traffic and environmental loads.

II. RESEARCH BACKGROUND

Xiao et al. (2026) had investigated the importance of stress time-history prediction at rib-to-deck (RTD) connections in orthotropic steel bridge decks (OSBDs) for near-real-time safety assessment and early warning of highway bridges. They had developed a hybrid Temporal Convolutional Network–Long Short-Term Memory (TCN-LSTM) model to improve the accuracy and efficiency of stress prediction. The training dataset had been constructed mainly from finite element simulation results, which had been supplemented with real-world vehicle and temperature data obtained through the Weigh-in-Motion (WIM) system and temperature sensors installed in the structural health monitoring system of the Nanxi Yangtze River Bridge. The model had utilized vehicle volume, speed, axle weight, and ambient temperature data to capture both local features and long-term temporal dependencies. Its performance had been compared with BP, LSTM, CNN, RBF, and RF models using MAE, MSE, RMSE, and R^2 metrics. The findings had shown that the TCN-LSTM model had delivered the most accurate and stable stress predictions, significantly reducing prediction errors and improving R^2, while also offering an efficient and cost-effective approach for stress prediction in OSBDs.

Luo et al. (2026) had investigated the multidimensional relationship between axle loads and U-rib weld strains in steel bridge decks incorporating Resin-Bonded Ultra-High-Performance Concrete (RBPC) pavement under actual service conditions. Unlike earlier studies that had primarily depended on laboratory experiments or isolated numerical simulations, the study had integrated long-term structural health monitoring (SHM) data from a cable-stayed bridge with validated finite-element (FE) simulations. Numerous vehicle-passage events had been examined to assess the effects of temperature, vehicle speed, and axle configuration on weld-strain responses through a controlled-variable approach. The findings had revealed a strong linear correlation between strain and axle load, with the coefficient of determination (R^2) improving by 5.88% under fixed operational conditions. It had further been observed that higher temperatures and multi-axle configurations amplified strain responses, whereas increased vehicle speeds reduced them due to shorter load durations. In comparison with conventional double-layer epoxy asphalt overlays, the RBPC pavement system had significantly reduced temperature-induced strain amplification from approximately 12% to less than 2%, demonstrating superior thermal–mechanical stability. Comparative analysis using data from the Jiangyin Bridge had also confirmed that the RBPC deck maintained better stability, with less than 2% strain variation compared to over 10% in epoxy asphalt systems. Overall, the combined SHM–FE framework had provided one of the earliest field-based evaluations of strain–axle-load behavior in RBPC systems, offering important implications for fatigue assessment, performance prediction, and maintenance planning of orthotropic steel decks.

Chen et al. (2025) highlighted that while laser scanning had been widely recognized for capturing bridge geometry, the automation of information extraction and finite element model (FEM) generation remained constrained by manual intervention. They proposed an automated FEM framework for bridges by integrating point cloud data with intelligent recognition techniques. The study developed a high-precision external dimension extraction algorithm based on bridge-specific features and secondary segmentation, combining projection density, adaptive thresholding, and region-growing RANSAC. Additionally, an internal drawing extraction framework was established using deep learning-based search, optical character recognition (OCR), and large language models to automate the retrieval of structural information. They further implemented a FEM generation process by aligning internal and external data through component naming conventions, employing a three-step algorithm involving segmentation, element creation, and boundary and load assignment. The framework was validated on an arch bridge model and a pedestrian bridge, providing an initial exploration toward automated digital modeling in bridge engineering.

Deng et al. (2025) conducted a study in which they employed finite-element analysis of steel–concrete composite subassemblages to formulate design recommendations for composite steel bridges using 29-mm diameter shear studs. They investigated the influence of partial-depth precast concrete panels on stud performance and adopted a modeling approach that incorporated key nonlinear behaviors, including concrete cracking, compressive inelasticity, steel stud yielding, rupture, and contact interactions at the steel–concrete interface. Their modeling scheme was validated against data from 11 experimental tests and subsequently applied in a numerical parametric study covering various configurations of 29-mm shear studs and precast concrete panels. The findings indicated that both the stud penetration depth into the concrete deck and the clear spacing between studs and partial-depth precast panels significantly affected shear connection strength. Based on these observations, they proposed minimum values for stud penetration and clear spacing to ensure safe application of partial-depth precast panels with 29-mm shear studs in composite steel bridges.

Smith (2025) was reviewed for providing a comprehensive overview of the application of Finite Element Method (FEM) in modern bridge engineering. The study was noted to have emphasized how FEM had become integral for analyzing complex bridge structures with high precision. It was reported that the paper discussed the capabilities of leading FEM software, including MIDAS Civil, SAP2000, ANSYS, LUSAS, and CSI Bridge, and highlighted their advanced modeling tools, comprehensive load analyses such as moving loads, seismic and wind effects, compliance with design codes, and construction stage simulations. Real-world case studies of major bridges were presented to demonstrate the practical employment of FEM, while modeling techniques—including element selection, level of detail, and load application methods—were examined alongside procedures for verifying designs against engineering standards. The advantages of FEM, such as accurate representation of geometry and load effects, were weighed against limitations like modeling assumptions and computational demands. The paper was also observed to have explored recent developments, including AI integration for design optimization and digital twin technology for bridge health monitoring, with discussions structured professionally and supported by figures, tables, and references.

Hossain et al. (2024) examined the increasing interest in applying the controlled rocking concept in seismic-resisting systems over recent decades, noting that unlike conventional systems—where lateral deformation occurs through plastic hinge formation—rocking systems achieved deformation via a gap opening mechanism. They observed that such systems exhibited self-centering behavior due to gravity loads and/or post-tensioning forces. They highlighted that continuum finite element analyses for investigating the seismic response were computationally expensive, while simplified two-spring macro models failed to accurately capture the dynamic behavior. To address this, they employed a multi-spring model to simulate the nonlinear seismic response of circular tubular steel piers and developed an efficient genetic algorithm-based optimization procedure to calibrate the spring parameters. Their findings indicated that the multi-spring model, when validated against continuum finite element results, provided an accurate simulation of bridge seismic responses under multi-directional ground motions, effectively capturing hysteretic force-displacement relationships and dynamic response time histories.

Kumar and Nallasivam (2024) examined double-deck cable-stayed bridges, noting that such structures were suitable for high traffic volumes and limited space, as they combined road and rail transit to optimize bridge utilization and mitigate traffic issues. They investigated fluctuations in the modal properties arising from various factors influencing bridge dynamics, aiming to determine the system’s inherent frequencies, natural periods, and mode shapes. The modal analysis was conducted using a finite element method (FEM) model, where the bridge deck slab, cables, piers, and pylons were discretized using SHELL 181, CABLE 280, and BEAM 188 elements. The model’s reliability was validated through mesh convergence analysis and comparison with prior studies. Their cumulative mass participation factor analysis indicated that vibrations involved approximately 90% of the mass within the first five modes. They reported that applying prestressing forces significantly increased the natural frequencies, whereas higher damping ratios reduced them. The study concluded that factors such as prestressing and damping variations affected free vibration results and provided a basis for subsequent fatigue analyses under dynamic loads.

Szirbik and Virág (2023) investigated the challenges arising from increased lignite production in open-pit mining, which necessitated the cost-effective transport of overburdened rock. They highlighted the potential of reusing existing equipment, specifically a bridge frame from a conveyor belt system, to facilitate this process. The study presented a 3D finite element stress analysis of the steel bridge structure, modeled as a 3D frame using beam elements, to assess its suitability in supporting the conveyor belt under full operational loads. Their analysis focused on loads derived solely from the masses being transported, deliberately neglecting the effects of transverse belt vibrations on the structure. The simulation results suggested that the bridge frame possessed sufficient structural reserves, remaining within the proportional stress limit, thereby supporting its reuse in the mining operation.

Shi et al. (2023) investigated the seismic performance of a novel self-centering (SC) hollow-core (HC) fiber-reinforced polymer (FRP)-concrete-steel (SC-HC-FCS) bridge column through both experimental and numerical approaches. They fabricated the new column by integrating external energy dissipators (ED) and unbonded post-tensioned (PT) basalt FRP (BFRP) tendons into a conventional HC-FCS column, which comprised an outer FRP tube, an inner steel tube, and concrete filling in between. The study highlighted that the SC-HC-FCS column combined the benefits of accelerated bridge construction with self-centering capabilities. The authors examined the influence of initial prestress force and the configuration of energy-dissipated aluminum bars on column performance. Their findings indicated that the SC-HC-FCS column demonstrated sufficient self-centering and energy dissipation capacities, although they suggested that careful selection of aluminum bar configuration and material properties was necessary to optimize the seismic resistance of the system.

Zeng et al. (2023, July) investigated the corrosion fatigue life of steel bridges and highlighted its significant practical implications. They reported that the remaining life of corrosion-induced fatigue crack propagation was shorter than that of ordinary fatigue cracks. A finite element model was developed, with key points meshed at small sizes, to analyze the fatigue crack damage of local components. The study proposed a crack propagation life evaluation method for corrosion fatigue in orthotropic steel deck bridges using a multi-scale finite element approach. It was found that stress intensity and corrosion were the primary factors influencing crack propagation life, with the stress intensity factor affected by diaphragm spacing, diaphragm thickness, and roof thickness, where diaphragm thickness was particularly influential. Additionally, temperature, humidity, and the morphological characteristics of corrosion pits were observed to impact corrosion rates. Overall, their analysis demonstrated that corrosion significantly reduced the remaining life of fatigue crack propagation.

Xu and Liu (2022) investigated the increasing incidence of fire-induced bridge failures, noting that accurate prediction of bridge behavior under fire conditions was critical. They argued that existing numerical methods, typically using temperature curves designed for building structures, could significantly misestimate fire effects on bridges. To address this, they developed a framework that coupled computational fluid dynamics (CFD) with finite element methods (FEM) to predict the thermomechanical performance of fire-exposed bridges. The study simulated fire combustion using Fire Dynamic Simulator to generate thermal boundary conditions for the FEM model, after which adiabatic surface temperatures and heat transfer coefficients were applied to the bridge girder model. A sequentially coupled thermomechanical FEM analysis was then conducted to evaluate structural and thermal performance. The methodology was validated against experimental fire tests on a steel beam, and simulations of a simply supported steel box bridge showed that the framework could replicate the inhomogeneous thermomechanical response observed in real fires. The authors reported that girder failure occurred due to central diaphragm buckling within 10 minutes of ignition, and they concluded that the proposed CFD-FEM framework was user-friendly and applicable for estimating bridge performance under varied fire scenarios.

Ji and Shao (2021) proposed a practical and fast finite element (FE) model updating method in which the response surface method (RSM) and the fmincon algorithm (FA) were employed to modify the FE model of a newly improved box girder bridge with corrugated steel webs. They compared two three-dimensional FE bridge design models to develop a reasonable initial FE model for updating. The RSM was applied for optimal experimental design of the updated parameters, which served as the basis for numerical analyses to obtain explicit relationships between the structural responses from FE results and the parameters themselves. A comparison between genetic algorithm and FA indicated that FA yielded more stable and efficient optimization results. Using FA, the parameters were updated by minimizing an objective function constructed from residuals between measured and predicted structural responses. A numerical example of a simply supported composite girder was presented to demonstrate the procedure's effectiveness, and the method was subsequently applied to the FE model updating of the Jingzhong Bridge using in situ static and dynamic data, showing satisfactory agreement between measured and predicted responses.

III. METHODOLOGY

The methodology of this study was based on finite element modelling and performance-based optimization of a steel plate girder bridge subjected to dynamic traffic and environmental loads. First, a representative steel plate girder bridge was selected with defined span length, girder depth, web plate thickness, flange dimensions, transverse stiffeners, cross frames, bearing supports, and deck slab arrangement. The geometric model was prepared in finite element software by using suitable shell elements for steel plates and beam elements for stiffeners and bracing members. Material properties such as modulus of elasticity, Poisson's ratio, yield strength, density, and damping ratio were assigned according to structural steel behaviour. After model development, boundary conditions were applied at the bearing locations to represent realistic support conditions. Dead load, live load, moving traffic load, impact load, wind load, temperature variation, and corrosion-related section reduction were considered in the analysis. Dynamic traffic loading was simulated through moving axle loads at different vehicle speeds to examine stress, deflection, vibration, and fatigue response. Modal analysis was also performed to determine natural frequency and mode shapes of the bridge. In the optimization stage, key design variables such as web thickness, flange width, flange thickness, girder depth, and stiffener spacing were modified systematically. Each design alternative was analysed and compared on the basis of maximum stress, vertical deflection, fatigue stress range, natural frequency, vibration amplitude, steel weight, and material utilization. The final optimized design was selected by ensuring reduced material consumption, improved structural stability, better fatigue resistance, and compliance with strength and serviceability requirements.

IV. RESULT

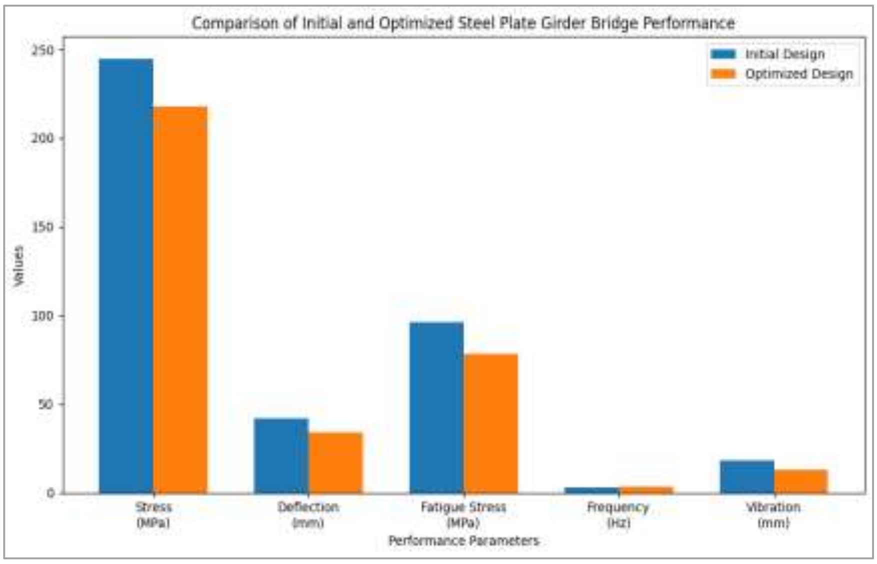
The finite element-based optimization of the steel plate girder bridge showed a clear improvement in structural performance under dynamic traffic and environmental loading conditions. The initial bridge model produced higher stress concentration near the web–flange junction, bearing region, and transverse stiffener connections. After optimization of web thickness, flange dimensions, girder depth, and stiffener spacing, the stress distribution became more uniform and the overall structural response improved. The optimized design reduced steel consumption while maintaining adequate strength, stiffness, fatigue resistance, and serviceability performance. The results indicate that finite element modelling is effective for identifying critical zones and improving bridge design efficiency.

Table: Comparative Results of Initial and Optimized Steel Plate Girder Bridge Design

Performance Parameter	Initial Design	Optimized Design	Improvement
Total Steel Weight	100%	86%	14% reduction
Maximum Von Mises Stress	245 MPa	218 MPa	11.02% reduction
Maximum Vertical Deflection	42 mm	34 mm	19.05% reduction
Fatigue Stress Range	96 MPa	78 MPa	18.75% reduction
Natural Frequency	2.8 Hz	3.4 Hz	21.43% increase
Maximum Vibration Amplitude	18 mm	13 mm	27.78% reduction
Estimated Fatigue Life	35 years	50 years	42.86% increase
Material Utilization Efficiency	72%	88%	16% increase

The optimized bridge model performed better than the initial design in almost all measured parameters. The reduction in maximum stress from 245 MPa to 218 MPa shows that the optimized section reduced stress concentration and improved load distribution. Maximum vertical deflection decreased from 42 mm to 34 mm, indicating improved stiffness and better serviceability under moving traffic loads. The fatigue stress range also decreased from 96 MPa to 78 MPa, which suggests a lower risk of crack initiation under repeated axle loading. The natural frequency increased from 2.8 Hz to 3.4 Hz, showing improved dynamic stability and reduced susceptibility to traffic-induced vibration.

Bar Graph



The graph compares the initial and optimized steel plate girder bridge performance under dynamic traffic and environmental loads. It shows that the optimized design reduced maximum stress from 245 MPa to 218 MPa, indicating better stress distribution. Vertical deflection decreased from 42 mm to 34 mm, improving serviceability and stiffness. Fatigue stress also reduced from 96 MPa to 78 MPa, suggesting better resistance against repeated traffic loading. Vibration amplitude declined from 18 mm to 13 mm, while natural frequency increased from 2.8 Hz to 3.4 Hz. Overall, the optimized bridge design is safer, lighter, and dynamically more stable.

V. CONCLUSION

The design optimization of steel plate girder bridges using finite element modelling proved to be an effective approach for improving structural efficiency under dynamic traffic and environmental loads. The study showed that the initial bridge design had higher stress concentration, larger deflection, greater vibration response, and increased fatigue stress range. After optimization of web thickness, flange dimensions, girder depth, and stiffener spacing, the bridge performance improved significantly. The optimized design reduced steel weight while maintaining adequate strength, stiffness, and serviceability. Maximum stress, vertical deflection, fatigue stress, and vibration amplitude were reduced, whereas natural frequency and material utilization efficiency increased. These improvements indicate better load distribution, enhanced dynamic stability, and improved fatigue resistance under repeated traffic loading. Overall, finite element-based optimization supports the development of safer, lighter, economical, and durable steel plate girder bridges. It also helps engineers identify critical structural zones and make design decisions based on realistic bridge behaviour. Therefore, FEM-based optimization can be considered a reliable method for modern bridge design and long-term infrastructure sustainability.

REFERENCES

1. Xiao, X., Liu, Z., Luo, Y., Chen, F., & Zhang, H. (2026). Stress time series prediction for orthotropic-steel-bridge-decks welds using a TCN-LSTM neural network. *High-speed Railway*.
2. Luo, R., Xie, J., Zhang, H., Gao, A., AL-Qadri, M., & Wei, D. (2026, March). Multidimensional influence analysis on the strain–axial load relationship in U-rib welds of steel bridge decks with resin-bonded UHPC (RBPC) pavement systems. In *Structures* (Vol. 85, p. 111258). Elsevier.
3. Chen, Y., Gao, C., Chen, Q., & Zhang, J. (2025). Automated finite element modeling method for steel bridges integrating 3D point clouds and intelligent drawing recognition technology. *Automation in Construction*, *179*, 106466.
4. Deng, X., Koutromanos, I., Engelhardt, M., Helwig, T., & Williamson, E. (2025). Design Considerations for Composite Steel Bridges Using 29-mm Diameter Shear Studs and Partial-Depth Precast Concrete Panels: A Finite-Element Study. *Journal of Bridge Engineering*, *30*(6), 04025024.
5. Smith, H. (2025). Bridge Design Using Finite Element Method (FEM) Software.
6. Hossain, F., Rahmzadeh, A., Tremblay, R., & Alam, M. S. (2024). Multi-spring model for tubular rocking steel bridge piers subjected to earthquake loading. *Engineering Structures*, *315*, 118449.
7. Kumar, S., & Nallasivam, K. (2024). Modal analysis of natural dynamic frequency for a double deck cable-stayed steel bridge by using finite element method. *Discover Civil Engineering*, *1*(1), 115.
8. Szirbik, S., & Virág, Z. (2023). Finite element analysis of a steel bridge frame for belt conveyors. *Geosciences and Engineering*, *11*(1), 110-116.
9. Shi, X., Guo, T., Song, L., & Yang, J. (2023). Cyclic load tests and finite element modeling of self-centering hollow-core FRP-concrete-steel bridge columns. *Alexandria Engineering Journal*, *70*, 301-314.
10. Zeng, Y., Zhou, J., Shu, H., Zhang, X., & Zhou, J. (2023, July). Study on crack propagation life of corrosion fatigue in orthotropic steel deck in steel bridges. In *Structures* (Vol. 53, pp. 731-741). Elsevier.
11. Xu, C., & Liu, Z. (2022). Coupled CFD-FEM Simulation of Steel Box Bridge Exposed to Fire. *Advances in Civil Engineering*, *2022*(1), 5889743.
12. Ji, W., & Shao, T. (2021). Finite element model updating for improved box girder bridges with corrugated steel webs using the response surface method and fmincon algorithm. *KSCE Journal of Civil Engineering*, *25*(2), 586-602.