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Fatigue Failure and Predictive Models for Welded Joints in Steel Truss Bridges Under Dynamic Loads

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ABSTRACT

Steel truss bridges, known for their high strength-to-weight ratio, face significant challenges from repeated traffic loading, environmental exposure, and dynamic stress, leading to potential fatigue failure. Fatigue damage in welded joints is especially critical, as they experience stress concentration and microstructural discontinuities. Recent studies, including those by Ye et al. (2026) and Giannella et al. (2025), emphasize the importance of advanced predictive models and fracture mechanics approaches to predict crack propagation. Despite improvements in experimental and computational methods, challenges persist, particularly with dissimilar welded joints and environmental effects. Understanding these factors is crucial for enhancing the durability and safety of steel truss bridges.

Keywords: *Steel Truss Bridges, Fatigue Failure, Welded Joints, Predictive Models.*

I. INTRODUCTION

Steel truss bridges constitute one of the most widely used structural systems in transportation infrastructure due to their high strength-to-weight ratio, efficient load distribution, and adaptability to long-span applications. However, despite their advantages, these structures are continuously subjected to repeated traffic loading, environmental exposure, and dynamic stress variations, which significantly influence their long-term performance and structural safety. Among various structural components, welded joints are recognized as the most vulnerable regions due to stress concentration, microstructural discontinuities, residual stresses, and fabrication-induced defects. Fatigue failure in welded connections has therefore emerged as a critical concern in bridge engineering, particularly as modern transportation systems experience increasing axle loads and traffic frequency. Ye et al. (2026) emphasized that fatigue crack initiation and propagation in orthotropic steel deck welds significantly affect bridge service life, highlighting the need for advanced predictive models to assess fatigue reliability under realistic loading conditions. Similarly, Lu et al. (2023) reported that stochastic traffic loading introduces randomness in crack growth behavior, making fatigue life prediction more complex and necessitating probabilistic approaches for accurate assessment of bridge deck weld performance.

Fatigue damage in welded joints is primarily governed by cyclic stress concentration at weld toes, weld roots, and heat-affected zones (HAZ), where microstructural heterogeneity and residual stresses accelerate crack initiation. The HAZ, in particular, is known to exhibit reduced toughness and localized softening, making it highly susceptible to crack nucleation under repeated loading. Giannella et al. (2025) demonstrated that fatigue life prediction using fracture mechanics-based approaches, such as the Paris law and equivalent initial flaw size (EIFS) concept, provides a more accurate representation of crack propagation behavior compared to conventional stress-based methods. Furthermore, Falodun et al. (2025) highlighted that residual stresses generated during welding due to uneven thermal cycles significantly contribute to fatigue failure, brittle fracture, and stress corrosion cracking, especially in thick structural components. These stresses cannot be completely eliminated, even with post-weld heat treatment

(PWHT), although such treatments improve ductility and reduce stress concentration effects. Additionally, microstructural variations and phase transformations in weld regions further complicate fatigue behavior, as observed by Zheng et al. (2026), who identified intergranular cracking in stainless steel welds caused by eutectic phase formation and grain boundary liquefaction. In corrosive or hydrogen-rich environments, the problem is further intensified, as hydrogen-assisted cracking mechanisms and corrosion fatigue accelerate failure processes (Park et al., 2021; Lu et al., 2024).

Recent advancements in experimental, numerical, and probabilistic methods have significantly improved the understanding of fatigue crack propagation in welded structures. Experimental techniques such as optical microscopy, beach marking, and slow strain rate testing have been widely used to observe crack initiation and growth behavior under controlled conditions. Meanwhile, computational approaches based on linear elastic fracture mechanics (LEFM), finite element analysis (FEA), and probabilistic fracture mechanics have enabled detailed simulation of crack propagation paths and stress intensity evolution. For instance, Ye et al. (2026) and Giannella et al. (2025) successfully applied Paris-based crack growth models combined with Monte Carlo simulations and finite element tools to predict fatigue life with improved accuracy. Similarly, Lu et al. (2023) integrated real-world weigh-in-motion traffic data into stochastic modeling frameworks to simulate realistic fatigue loading spectra in steel bridge decks. These studies collectively demonstrate that combining experimental observations with numerical modeling provides a robust framework for understanding fatigue mechanisms in welded joints. Furthermore, surface modification techniques such as laser shock surface patterning have been shown to enhance fatigue resistance by introducing compressive residual stresses and refining grain structures, thereby delaying crack initiation (John et al., 2024). Despite these advancements, challenges remain in accurately capturing multiscale damage evolution, environmental interactions, and material heterogeneity, particularly in dissimilar welded joints where mechanical and metallurgical incompatibilities significantly influence fatigue performance (Jambor et al., 2022). Therefore, fatigue life assessment and crack propagation analysis of welded joints in steel truss bridges remain an active and critical area of research aimed at improving structural durability, safety, and service reliability under complex loading environments.

II. RESEARCH BACKGROUND

Ye et al. (2026) had investigated the fatigue failure behavior of rib-to-deck (RTD) weld joints in orthotropic steel decks (OSD), recognizing it as a major factor influencing bridge service performance. In their study, eccentric tensile fatigue tests had been innovatively designed and conducted to simulate the combined tension-bending stress state experienced by RTD weld joints. The fatigue crack propagation process had been examined using an optical microscope and the beach marking method, through which crack length and depth were recorded and the propagation characteristics and patterns were analyzed. Furthermore, numerical simulations based on probabilistic fracture mechanics theory had been carried out to assess fatigue failure, and a two-stage Paris model had been established to represent the crack growth process. In addition, Monte Carlo simulation had been applied to evaluate probabilistic fatigue crack propagation while accounting for uncertainties in initial crack size and crack growth modeling. The findings had indicated that the proposed method had achieved acceptable efficiency and accuracy in analyzing fatigue crack propagation and failure in RTD weld joints of OSD.

Zheng et al. (2026) had investigated the cracking behavior of welded joints in thick-walled support beams made of 347 stainless steel used in slurry bed reactors, owing to the material's extensive application in large reactors and its otherwise excellent properties. Through detailed experimental analysis, the study had identified that the crack was located in the coarse-grained heat-affected zone near the fusion line. The fracture surface had exhibited typical intergranular cracking along with a considerable amount of secondary cracking. The initial fracture region had shown significant oxidation, while no dimples or cleavage microstructures had been observed. The base metal had demonstrated strong resistance to intergranular corrosion; however, low-melting-point Nb/Cr/Mo eutectic phases had been detected near the crack tip. Under the welding thermal cycle, these eutectic phases had induced grain boundary liquefaction, and with the expansion of the liquefied zone under thermal stress, intergranular cracks had formed. These microcracks had rapidly propagated along grain boundaries, coalesced into larger cracks, and ultimately caused fracture.

Falodun et al. (2025) investigated the influence of residual stresses on the service performance, reliability, and durability of welded carbon steel joints, noting that such stresses could increase susceptibility to brittle fracture, fatigue failure, and stress corrosion cracking, particularly in the heat-affected zone (HAZ). They explained that these stresses arose from uneven thermal expansion and contraction during welding, with thicker plates and constrained configurations being more vulnerable. The study emphasized that post-weld heat treatment (PWHT) played a crucial role in mitigating residual stresses by tempering martensitic structures, refining microstructures, and improving mechanical properties such as toughness and ductility. The authors reviewed mechanisms driving residual stress formation, assessed the effectiveness of various PWHT techniques, and highlighted advanced methodologies including neutron diffraction, computational modeling, and hybrid welding processes. Although PWHT was found to significantly reduce residual stresses, they concluded that complete elimination was unattainable, underscoring the need for innovative strategies to enhance welded joint performance and reliability in critical industrial applications.

Giannella et al. (2025) investigated the fatigue behavior of steel welded specimens in which a tube was inserted into a plate and joined by four intermittent fillet welds. In their previous work, fatigue tests under axial loading had been conducted on two geometries—longitudinal and transverse—where welds were oriented parallel and perpendicular to the applied load, respectively. Fatigue strength estimations based on the Peak Stress Method (PSM) had identified crack initiation locations but were found to underestimate the fatigue life of transverse joints due to extended crack propagation phases. In the present study, linear elastic fracture mechanics was employed to simulate crack propagation through finite element analyses using Abaqus® and FRANC3D® software. Material-specific Paris' law parameters were experimentally calibrated for 25MnCr6 Q&T (tube) and S355JR (plate) steels using Compact Tension specimens. Initial cracks of 0.1 mm radius were positioned at experimentally observed initiation sites, and simulations followed the Equivalent Initial Flaw Size (EIFS) approach recommended by IIW guidelines. Results showed that fatigue life estimations closely matched average experimental lifetimes, with deviations ranging from −34 % to +45 % for transverse joints and from −17 % to −12 % for longitudinal joints.

John et al. (2024) investigated stress corrosion cracking (SCC) failures in austenitic stainless steel (ASS)-based dry storage canister (DSC) weld joints, which were recognized as a potential safety hazard in nuclear applications. The study aimed to explore the influence of novel laser shock surface patterning (LSSP) on the SCC resistance of DSC welds. LSSP experiments were conducted at varying intensities across the fusion zone (FZ), heat-affected zone (HAZ), and base material (BM), while SCC tests were performed in boiling $MgCl_2$ on U-bend specimens. The laser-induced shock waves during LSSP were found to produce simultaneous strengthening and patterning effects via micro-indentation arrays, which promoted austenitic to strain-induced martensitic (α′-phase) transformation, residual compressive stress (RCS), and grain refinement. The surface hardness increased, whereas surface roughness and α′-phase volume fraction decreased significantly. SCC evaluation on LSSP-treated U-bend specimens demonstrated improved resistance compared to unpeened counterparts, which was attributed primarily to subsurface RCS and the minimal influence of surface roughness and α′-phase fraction.

Lu et al. (2024) investigated the corrosion fatigue behavior and underlying mechanisms of weld joints in Q690qE high-strength bridge steel within a simulated marine environment. They reported that the sub-critical heat-affected zone (SCHAZ) and the coarse-grained heat-affected zone (CGHAZ) were identified as the most susceptible regions for corrosion fatigue cracking. The study indicated that corrosion fatigue initiation in the CGHAZ primarily occurred due to micro-galvanic corrosion between the CGHAZ and the weld metal (WM), whereas failure in the SCHAZ was mainly attributed to local stress and strain concentration arising from weld softening. The researchers concluded that the ultimate fracture location was governed by the interplay and competition between these two mechanisms, highlighting the critical influence of weld microstructural heterogeneity on corrosion fatigue performance.

Hu et al. (2023) investigated surface cracking in butt welding joints of high manganese steel railway frogs, which was identified as a common failure mode. They emphasized that understanding the formation mechanism of such cracks could effectively prevent similar failures. Using a combination of macro- and micro-characterization tools, the study examined the causes of surface crack formation in flash butt welding joints. The findings indicated that the surface cracks were predominantly intergranular stress corrosion cracks (IGSCC) located near the fusion line between the carbon steel rail and the stainless steel medium on the stainless steel side. The researchers observed the presence of acicular martensite near the fusion line and noted significant residual stress. Additionally, continuous network chromium carbide precipitates were detected along the austenitic grain boundaries of the stainless steel. These factors were identified as the main contributors to crack initiation. The study suggested that optimizing the welding cooling rate to reduce martensite proportion and tempering the martensite to lower hardness and internal stress could mitigate intergranular cracks on the weld surface.

Lu et al. (2023) investigated the challenging issue of fatigue cracking in orthotropic steel bridge decks (OSDs), which was primarily driven by increasing traffic loads and inevitable truck overloading. They noted that stochastic traffic loading resulted in random fatigue crack propagation, complicating fatigue life evaluations of OSDs. The study developed a computational framework for fatigue crack propagation under stochastic traffic loads, integrating site-specific weigh-in-motion traffic data with finite element methods. Stochastic traffic load models were established to simulate fatigue stress spectra of welded joints, and the effects of transverse wheel track positions on the crack tip stress intensity factor were examined. The random propagation paths of cracks under various stochastic load spectra, including both ascending and descending patterns, were evaluated. Numerical results indicated that the maximum KI reached 568.18 $\mathrm{MPa\cdot mm^{1/2}}$ under the most critical transversal wheel load condition, decreasing by 66.4% when the load shifted transversally by 450 mm. Additionally, the crack tip propagation angle increased from 0.24° to 0.34°, and the crack propagation range remained largely within 10 mm, with the most pronounced migration observed under descending load spectra. The study’s findings were reported to provide theoretical and technical guidance for fatigue assessment and reliability evaluation of existing steel bridge decks.

Jambor et al. (2022) investigated the joining of dissimilar metals, a common engineering task in the power industry, emphasizing that the resulting joints are critical components that must endure various operational loads. They highlighted that, due to the differences in metal properties, the interface between the ferritic and austenitic sides was considered a critical zone for joint failure under static or cyclic loading. The study prepared two dissimilar joints using gas metal arc welding (GMAW) with different low alloy steels and extensively examined their microstructures via electron microscopy, focusing on the interface between low alloy steel and austenitic weld metal. It was reported that, under non-environmental fatigue conditions, the interface did not act as a preferential crack path; rather, cracks propagated through the heat-affected zones of the low alloy steel side. Significant differences in threshold stress intensity factors (5.8 MPa·m^1/2 vs. 8.7 MPa·m^1/2) were observed, indicating that the selection and microstructural variations of low alloy steel substantially influenced the fatigue crack propagation resistance of the dissimilar joints.

Aranđelović et al. (2021) conducted research that involved the numerical simulation of crack growth in a welded joint made of structural steel S235JR2, considering the presence of multiple welding defects—an aspect not addressed by the EN ISO 5817 standard. They analyzed several realistic defect combinations and identified the one exhibiting the least favorable combination of stress concentration and plastic strain as the representative model. Subsequently, a crack was introduced at a location where tensile loading induced stresses exceeded the material's yield stress. The study further performed numerical analyses under varying load magnitudes and crack lengths to determine the conditions under which the initial crack would begin to propagate.

Park et al. (2021) investigated the hydrogen stress cracking (HSC) behaviour in dissimilar welded joints (WJs) of duplex stainless steel (DSS) and carbon steel, emphasizing the influence of weld microstructure. They conducted in situ slow-strain rate testing (SSRT) with hydrogen charging on transverse WJs, which had fractured in the softened heat-affected zone of the carbon steel under hydrogen-free conditions. Their findings revealed that HSC initiated at the martensite band and at the interface between austenite and martensite bands in the type-II boundary, attributed to the accumulation of trapped hydrogen and high local strain during SSRT. The study highlighted that certain weld microstructures, such as austenite and martensite bands in type-II boundaries, were innocuous under normal conditions but became critical in a hydrogen atmosphere, promoting premature rupture. They concluded that the premature fracture in the type-II boundary occurred due to hydrogen-enhanced strain-induced void (HESIV) formation and hydrogen-enhanced localized plasticity (HELP) mechanisms, demonstrating the detrimental effect of specific microstructural features under hydrogen exposure.

III. KEY FINDINGS FROM STUDY

Author (Year)	Material / Structure	Methodology	Key Findings	Relevance to Current Study
Ye et al. (2026)	Rib-to-deck weld joints in orthotropic steel decks	Eccentric tensile fatigue tests, optical microscopy, Paris model, Monte Carlo simulation	Developed probabilistic fatigue crack growth model; accurate prediction of crack propagation behavior	Provides advanced probabilistic fatigue modeling framework for bridge weld joints
Zheng et al. (2026)	347 stainless steel welded beams	Experimental fracture and microstructural analysis	Intergranular cracking in HAZ due to eutectic phase formation and grain boundary liquefaction	Highlights microstructural failure mechanisms in welded joints
Falodun et al. (2025)	Carbon steel welded joints	Literature-based review on residual stresses and PWHT	Residual stresses significantly influence fatigue and cracking; PWHT reduces but does not eliminate stresses	Explains role of residual stresses in fatigue failure

Giannella et al. (2025)	Welded tube-to-plate steel joints	LEFM, FEM (Abaqus, FRANC3D), Paris law, EIFS approach	Accurate fatigue life prediction using crack propagation models; good agreement with experiments	Supports fracture mechanics-based fatigue life assessment
John et al. (2024)	Austenitic stainless steel welds	Laser shock surface patterning, SCC testing	Improved SCC resistance due to compressive residual stress and grain refinement	Demonstrates surface treatment impact on fatigue resistance
Lu et al. (2024)	Q690qE bridge steel weld joints	Corrosion fatigue testing in marine environment	CGHAZ and SCHAZ most vulnerable; micro-galvanic corrosion and stress concentration critical	Connects fatigue with environmental degradation
Hu et al. (2023)	High manganese steel railway welds	Macro-micro structural analysis	Cracks caused by martensite formation, residual stress, and carbide precipitation	Shows metallurgical influence on crack initiation
Lu et al. (2023)	Orthotropic steel bridge decks	Stochastic traffic modeling, FEM analysis	Traffic randomness significantly affects crack propagation and stress intensity factors	Supports probabilistic fatigue analysis of bridge loading
Jambor et al. (2022)	Dissimilar steel weld joints	Microstructural analysis and fatigue testing	Crack propagation mainly in HAZ of low alloy steel; interface not dominant failure path	Highlights role of material mismatch in fatigue behavior
Aranđelović et al. (2021)	S235JR welded joints with defects	Numerical simulation of crack growth	Defect combinations significantly influence crack initiation and propagation	Supports defect-based fatigue modeling
Park et al. (2021)	Duplex stainless steel–carbon steel welds	SSRT with hydrogen charging	Hydrogen-induced cracking due to HELP and HESIV mechanisms at type-II boundaries	Shows environmental effects on fatigue cracking

IV. CONCLUSION

The reviewed literature collectively indicates that fatigue life assessment and crack propagation in welded joints of steel truss bridges remain highly complex phenomena governed by the interaction of mechanical loading, microstructural heterogeneity, residual stresses, and environmental effects. Repeated traffic loading plays a dominant role in initiating and propagating fatigue cracks, particularly in heat-affected zones (HAZ), weld toes, and fusion boundaries where stress concentration and material discontinuities are prominent. Studies such as Ye et al. (2026) and Giannella et al. (2025) have demonstrated that fracture mechanics-based approaches, including Paris' law and equivalent initial flaw size (EIFS) methods, provide reliable predictions of fatigue crack growth when combined with numerical simulation tools. Additionally, probabilistic frameworks and stochastic traffic models, as highlighted by Lu et al. (2023), improve the realism of fatigue assessment under variable loading conditions. Microstructural investigations further confirm that weld-induced transformations, such as martensite formation, carbide precipitation, and eutectic phase development, significantly accelerate crack initiation and intergranular fracture (Zheng et al., 2026; Hu et al., 2023). Environmental factors, including corrosion, hydrogen exposure, and marine conditions, further intensify fatigue degradation, as reported by Park et al. (2021) and Lu et al. (2024). Although post-weld heat treatment and surface modification techniques such as laser shock peening enhance resistance by reducing residual stresses and improving microstructure, complete mitigation of fatigue damage remains unattainable (Falodun et al., 2025; John et al., 2024). Therefore, the integration of experimental analysis, fracture mechanics, probabilistic modeling, and environmental considerations is essential for accurate fatigue life prediction. Overall, a multidisciplinary approach is required to enhance the durability, safety, and reliability of welded steel truss bridges under long-term cyclic traffic loading.

V. FUTURE SCOPE

Future research in the fatigue life assessment and crack propagation analysis of welded joints in steel truss bridges should focus on developing more integrated and intelligent prediction frameworks that combine experimental, numerical, and data-driven approaches. While existing studies have successfully applied fracture mechanics, finite element modeling, and probabilistic methods, there is still a need to enhance predictive accuracy under real-world variability in traffic loading, material behavior, and environmental conditions. The integration of artificial intelligence and machine learning with classical fatigue models can significantly improve crack growth prediction by learning from large-scale structural health monitoring data. Advanced sensor technologies and digital twin systems may enable real-time tracking of fatigue damage evolution in bridge components, allowing proactive maintenance and improved service life estimation. Furthermore, multiscale modeling approaches that link microstructural changes in weld zones with macroscopic fatigue behavior should be developed to better understand crack initiation mechanisms. Environmental interactions such as corrosion fatigue, hydrogen embrittlement, and temperature variations also require deeper investigation, particularly for bridges in marine and industrial regions. In addition, future studies should explore improved welding techniques, advanced post-weld treatments, and novel surface engineering methods such as laser shock peening and ultrasonic impact treatment to enhance fatigue resistance. The role of dissimilar metal welding and high-performance steels in modern bridge construction should also be further evaluated under cyclic loading conditions. Finally, standardized probabilistic design guidelines incorporating uncertainty quantification in crack growth parameters are essential for improving reliability-based design of steel truss bridges. Collectively, these advancements will contribute to safer, more durable, and cost-effective bridge infrastructure systems under increasing transportation demands.

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