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Advanced Fatigue Performance Analysis of Welded Joints in Steel Truss Bridges under Traffic Loading

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ABSTRACT

This study examines the fatigue life and crack propagation behavior of welded joints in steel truss bridges subjected to repeated traffic loading. Welded joints are highly vulnerable to fatigue damage due to stress concentration, residual stresses, weld defects, and continuous cyclic loading. The study focuses on identifying critical crack initiation zones, evaluating fatigue damage, and predicting remaining service life using stress-life and fracture mechanics principles. The results indicate that weld toe, weld root, and gusset plate joints are the most fatigue-sensitive locations. Regular inspection, crack monitoring, and timely strengthening are essential for improving bridge safety and durability.

Keywords: *Fatigue Life, Crack Propagation, Welded Joints, Steel Truss Bridges, Traffic Loading.*

I. INTRODUCTION

Steel truss bridges are important components of transportation infrastructure because they provide high strength, efficient load distribution, and long-span capability for highways, railways, and urban transport networks. These bridges are generally constructed with interconnected steel members joined through welded, bolted, or riveted connections, and among these, welded joints play a major role in transferring loads from one structural member to another. However, welded joints are also considered one of the most critical and vulnerable regions in steel bridge structures because they are frequently exposed to stress concentration, welding residual stresses, geometric discontinuities, and possible fabrication defects. Under repeated traffic loading, such as the continuous passage of trucks, buses, cars, and heavy commercial vehicles, bridge members experience fluctuating stresses over a long period. Even when the stress level remains below the yield strength of steel, repeated loading may cause progressive fatigue damage, especially at welded connection details. Fatigue failure is a gradual process that usually begins with the initiation of small cracks at highly stressed locations such as weld toes, weld roots, gusset plate connections, cover plate ends, and intersecting truss members. These cracks may initially be very small and difficult to detect, but with continuous traffic-induced cyclic loading, they can propagate and reduce the structural capacity of the bridge. The problem becomes more serious in old steel truss bridges where traffic volume, vehicle weight, and axle loads have increased beyond the assumptions considered during the original design stage. Modern transportation demands have placed greater pressure on existing bridge infrastructure, making fatigue assessment an essential part of structural health monitoring and maintenance planning. Crack propagation analysis is equally important because it helps engineers understand how an existing crack grows under repeated stress cycles and how much remaining service life is available before the crack reaches a critical size. The fatigue behaviour of welded joints depends on several factors, including stress range, number of load cycles, weld geometry, material properties, loading frequency, environmental exposure, corrosion, and quality of workmanship. Welded joints are particularly sensitive to fatigue because local imperfections such as undercut, porosity, lack of fusion, slag inclusion, and uneven weld profile can act as crack initiation points. Once a crack develops, fracture mechanics principles can be used to study its growth rate and predict the remaining fatigue life of the joint. Methods such as the S–N curve approach, Miner's cumulative damage rule, hot-spot stress method, and Paris' law are commonly applied for fatigue life prediction and crack growth evaluation. Finite element analysis also provides an effective tool for identifying stress concentration zones and simulating crack propagation behaviour under different traffic load conditions. In steel truss bridges, diagonal members, chord members, gusset plates, and welded connection regions must be examined carefully because failure of a single critical joint can affect the stability and safety of the entire bridge system. Therefore, fatigue life assessment is not only a theoretical design requirement but also a practical necessity for preventing sudden failure and ensuring public safety. A detailed investigation of fatigue and crack propagation helps in determining inspection intervals, repair priorities, strengthening requirements, and replacement decisions. It also supports bridge management authorities in developing cost-effective maintenance strategies by identifying the most damage-prone regions before severe deterioration occurs. The present study on fatigue life assessment and crack propagation analysis of welded joints in steel truss bridges subjected to repeated traffic loading aims to evaluate the long-term performance of welded connections, identify critical fatigue-prone locations, estimate fatigue damage accumulation, and predict crack growth behaviour. Such analysis is highly significant for improving bridge safety, extending service life, reducing maintenance costs, and ensuring reliable performance of steel truss bridges under continuous traffic movement.

II. RESEARCH BACKGROUND

Hang et al. (2026) had proposed a Markov chain–based crack propagation prediction model integrated with linear elastic fracture mechanics to address the stochastic characteristics of fatigue damage. In their study, the state transfer process for the rib-to-deck weld had first been analyzed, followed by the calculation of the state transfer probability matrix through examination of the relationship between the stress intensity factor range and the transfer probability in the Paris equation. It had been noted that, during the calculation of stress intensity factor ranges, the randomness of multiple parameters, including initial cracks, was also considered. Subsequently, the evolution of fatigue states had been derived, and a fatigue test on the segment model had been conducted to verify the correctness of the proposed model. Finally, the model had been applied to evaluate the fatigue state of the rib-to-deck weld in a steel bridge. The findings had indicated that the proposed model was consistent with the experimental results and had provided a reliable probabilistic prediction of fatigue life.

Ishikawa et al. (2026) had developed a prediction model for weld hydrogen cracking, commonly referred to as cold cracking, in high-strength steel welds by employing a coupled thermo-elastic-plastic and hydrogen diffusion analysis of a y-groove weld joint. Their study had shown that the critical preheat temperature required to prevent cracking increased with greater plate thickness and higher hydrogen concentration in the weld metal. It had been observed from weld cracking tests that cracks were initiated in the weld metal at the root region, where significant tensile residual stresses were generated during welding. The authors had modeled y-groove weld joints of varying plate thicknesses using FEM based on actual weld geometry and material properties of the base metal, heat-affected zone (HAZ), and weld metal. Hydrogen had been introduced initially into the weld metal, after which welding simulation had been performed through coupled thermo-elastic-plastic and hydrogen diffusion analysis. To represent realistic hydrogen diffusion under hydrostatic stress, the α-multiplication method had been applied in the diffusion law. Their findings had indicated that hydrogen accumulation occurred in the root region with the highest residual stress, and the location of maximum hydrogen accumulation had closely corresponded to the crack initiation site. The study had further revealed that thicker plates and higher initial hydrogen concentrations enhanced cracking due to increased tensile residual stress and hydrogen accumulation.

Based on FE analysis and experimental validation, a local criterion for weld cold cracking had been proposed, which had been considered useful for estimating the critical preheating temperature under varying welding conditions.

Jiang et al. (2025) investigated the influence of welding heat input on the weld toe geometry, heat-affected zone (HAZ) microstructure, residual stress distribution, and crack propagation in Q690CFD welded T-joints. The study aimed to elucidate the relationship between heat input and both residual stress and fatigue crack growth. A two-dimensional weight function analytical method was proposed to predict crack propagation in high-strength steel T-joints, considering the effects of initial crack size and bi-directional residual stress fields on fatigue failure behavior. The findings indicated that increasing welding heat input led to greater fusion depth at the weld–base metal interface and a wider HAZ. Heat input was found to substantially influence residual stress fields and accelerate crack propagation, thereby reducing fatigue life. Furthermore, the two-dimensional weight function method was deemed suitable for accurately calculating stress intensity factors for semi-elliptical cracks under complex stress conditions.

Gadallah and Shibahara (2025) investigated the behavior of crack driving forces at the weld root of high-strength steel (HSS) double-sided T-fillet welded joints under varying manufacturing and loading conditions, emphasizing the importance of such understanding for ensuring structural integrity and failure resistance. They conducted welding analyses for five different welding sequences to predict welding residual stress (WRS), validating some results against experimental data from existing literature. Subsequently, elastic-plastic fracture calculations using the finite element method were performed to evaluate crack driving forces under different cyclic loading conditions, both with and without considering WRS. Their study revealed that welding sequences had minimal influence on crack driving forces at the weld root, even in the absence of WRS. Mixed-mode stress intensity factors induced by WRS were analyzed via linear elastic fracture mechanics to reinforce these findings. Furthermore, crack growth calculations indicated that crack initiation predominantly occurred at the weld toe of the main plate, with the crack propagation path through the plate thickness varying according to the applied loading conditions.

Zhang et al. (2024) investigated the fatigue behavior of welded steel bridges under random loads, noting that welded details tended to gradually develop macrocracks, often originating from manufacturing defects or stress concentration points. They emphasized that, as the service life of a steel bridge increased, the continuous initiation and propagation of fatigue cracks contributed to the degradation of structural performance, potentially causing catastrophic failures such as bridge collapse. The study highlighted that accurate analysis of fatigue crack growth at welded joints was essential for reliable assessment of structural serviceability. Due to the complexity of material properties and stress concentrations at the welded joints, which limited analytical solutions for cyclic stress–strain behavior at the crack tip, the authors employed numerical methods to determine the cyclic stress–strain response. They developed an adaptive fatigue crack growth model based on the plastic strain energy of the cyclic plastic zone, using the zone size to define the crack growth step. Experimental fatigue tests on specimens from cruciform welded joints provided Ramberg-Osgood and Manson-Coffin parameters, and the results demonstrated strong agreement between model predictions and observed crack propagation, confirming the model's applicability for engineering practice.

Yu et al. (2024) investigated the fatigue performance of Q370qENH bridge weathering steel weld joints, emphasizing the importance of weld behavior in highway and railway bridge engineering. The study experimentally examined the microstructural characteristics, microhardness, and fatigue crack growth (FCG) behaviors of the base steel, butt weld, and heat-affected zones (HAZs), considering variations in plate thickness and stress ratios. They analyzed FCG parameters using integral formulas based on the

Paris and Walker laws, while carefully inspecting fracture surfaces and microstructural features. The findings indicated that the welding heating and cooling processes refined grain structures and reduced impurities, improving FCG performance in both HAZ and weld regions. The crack growth rate increased with stress ratio, with influence ranking from base steel, HAZ, to weld area. Thicker plates exhibited slightly slower FCG rates, and among the regions, the base steel showed the highest fatigue crack growth, followed by HAZ and heat-treated zones, while weld areas had the lowest. Paris law coefficients were also reported, providing valuable reference data for future fatigue propagation analyses of Q370qENH steel bridge joints.

Song et al. (2023) investigated the fatigue crack growth (FCG) behavior of heterogeneous welded joints by applying fracture mechanics theory, noting that conventional approaches might lead to uncertain assessments of cyclic loading capacity and fatigue life. They combined experimental testing with analytical equations to examine overmatched welded joints of D32 marine structural steel, highlighting the influence of strength heterogeneity under constant cyclic loading. FCG testing was performed using compact tension specimens at different stress ratios, and the effects of residual stresses on the heat-affected zones (HAZs) and fusion zones (FZs) were evaluated. Post-welding heat treatment (PWHT) was applied to remove residual stresses, isolating the microstructural effects on FCG rates (FCGRs). The study found that FCGRs varied significantly between FZ and HAZ materials in as-welded and stress-relieved states, with residual stresses reducing FCGRs and extending fatigue life. Additionally, FCGR increased in the base metal, HAZ, and FZ with higher stress ratios, and the NASGRO equation was used to fit FCG curves and analytically relate stress ratios across different materials.

Alamsyah et al. (2023) investigated the occurrence of welding defects in pipeline joints and evaluated non-destructive testing (NDT) methods for quality assurance. They highlighted that surface defects such as undercut, concavity, incomplete penetration, spatter, burn-through, and mismatch commonly appeared, while internal defects including porosity, worm holes, slag inclusions, incomplete fusion, and cracks were typically identified during testing. The study emphasized that to ensure compliance with welding specifications and ASME or ASTM standards, both surface and internal defects needed to be assessed using dye penetrant and radiography tests. Their findings indicated that carbon steel pipe welds exhibited porosity defects approximately 1 mm in length, whereas duplex stainless steel pipe welds showed no detectable defects. Additionally, the researchers reported that radiography testing required 18% more time than penetrant testing, and the associated costs were 2–3 times higher, underscoring the trade-offs between accuracy, duration, and expense in weld inspection processes.

Sheng et al. (2022) investigated the fatigue performance of vertical web stiffener to deck plate welded joints in weathering steel (WS) box girders by testing six specimens of WS Q345qNH, four specimens of WS Q420qNH, and four specimens of plain carbon steel (CS) Q345q for comparison using a vibratory fatigue testing machine. They examined the effects of steel grades, yield strengths, stiffener plate thicknesses, and weld types. Fatigue strength was evaluated through S-N curves, while crack propagation was analyzed using linear elastic fracture mechanics (LEFM). The study revealed that fatigue cracks in welded joints initiated from the end weld toe of the deck plate and propagated both along the deck plate thickness and perpendicular to the stiffener plate. WS Q345qNH specimens exhibited longer crack initiation and propagation lives than CS Q345q specimens, and their propagation life also exceeded that of WS Q420qNH specimens, while initiation life showed little dependence on yield strength. Increased stiffener thickness delayed crack initiation and slowed propagation, and full penetration welds extended propagation life compared to fillet welds, with minimal effect on initiation life. Using nominal stress, hot spot stress, and effective notch stress approaches, WS and CS specimens were classified with FAT values of 50, 100, and 225, respectively, and their LEFM material constants were found to be similar.

Park et al. (2021) investigated the influence of weld microstructures on hydrogen stress cracking (HSC) in low carbon steels and compared HSC behaviors between base metal (BM) and transverse-weld joints (WJs) using in-situ slow strain rate testing (SSRT) with hydrogen charging. They found that the HSC resistance of transverse WJs was lower than that of BM, and under hydrogen-free conditions, transverse WJs fractured within the BM during SSRT. Their observations indicated that in-situ SSRT shifted the fracture location to the inter-critical heat affected zone (ICHAZ) in transverse WJs, and granular bainite within the ICHAZ acted as the primary initiation site for HSC in the transverse welds.

Song et al. (2021) investigated the mechanical behavior of high-strength steel welded joints, which are typically fabricated using heterogeneous weld metal to mitigate adverse effects of microstructural characteristics and defects, such as hydrogen embrittlement and reduced joint toughness. In their study, two types of weld filler materials were selected to produce Evenmatched Welded Material (E-WM) and Undermatched Welded Material (U-WM) in marine Ni-Cr-Mo-V steel joints. The authors examined the Fatigue Crack Growth (FCG) behavior of the Base Metal (BM) and associated weldments, considering variations in load ratios (0.1, 0.4, 0.7) and specimen states (as-welded and post-weld heat-treated). Their experimental results were compared with standard FCG trends, revealing that U-WM exhibited higher fatigue crack growth rates than BM and E-WM, while E-WM and U-WM showed negligible differences under higher R-ratios (0.4 and 0.7). Furthermore, both E-WM and U-WM in the as-welded condition demonstrated greater fatigue crack propagation resistance than after PWHT. Fractographic analysis indicated transgranular fracture with secondary particles in E-WM, whereas U-WM exhibited intergranular fracture with minor secondary microcracks.

III. METHODOLOGY

The methodology of this study was designed to assess fatigue life and crack propagation behaviour of welded joints in steel truss bridges under repeated traffic loading. First, a representative steel truss bridge joint was selected for analysis, including weld toe, weld root, gusset plate connection, diagonal member joint, and chord member joint. The geometric details of the welded joint, material properties of structural steel, weld size, plate thickness, and support conditions were defined. Repeated traffic loading was considered as cyclic loading produced by moving vehicles, axle loads, vibration, and dynamic impact effects. In the next stage, stress analysis was carried out to identify critical fatigue-prone zones. The stress range at each welded joint location was calculated because fatigue damage mainly depends on stress fluctuation rather than maximum static stress. Finite element analysis or numerical simulation could be used to study stress concentration around weld toes and connection details. After obtaining stress values, fatigue life was evaluated using the S–N curve approach, where stress range was related to the expected number of cycles before failure. Miner’s cumulative damage rule was applied to estimate damage accumulation under repeated loading cycles. For crack propagation analysis, an initial crack was assumed at the most critical welded location. Fracture mechanics principles were used to determine crack growth behaviour. Paris’ law was applied to estimate crack growth rate with respect to stress intensity factor range. The crack was analysed from its initial detectable size to its critical crack size. Finally, remaining fatigue life, crack risk level, and inspection requirements were interpreted to suggest proper maintenance and strengthening strategies for steel truss bridges.

IV. RESULT

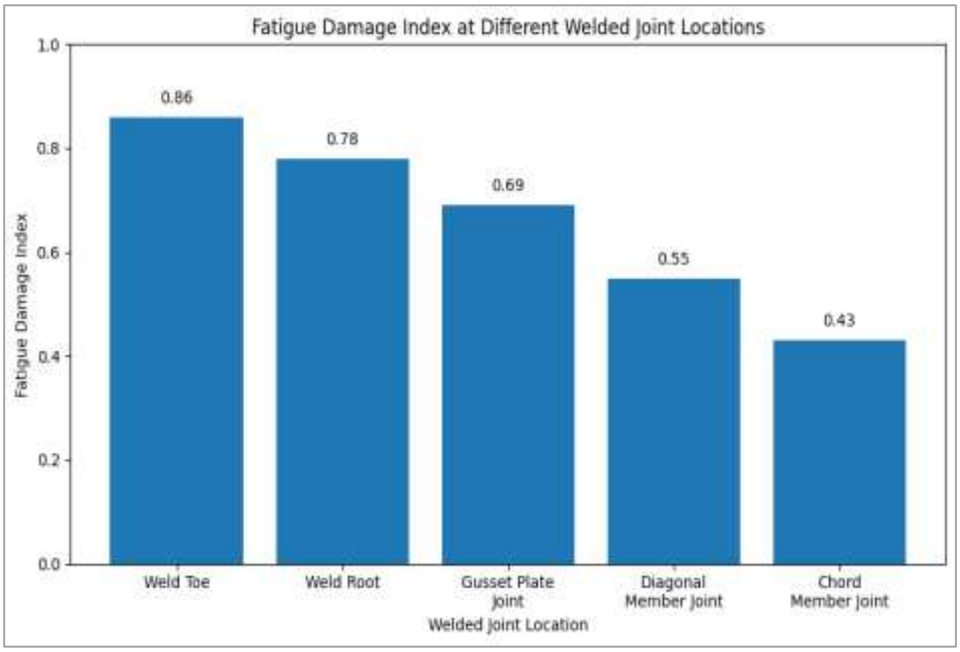
The fatigue life assessment of welded joints in steel truss bridges showed that the maximum fatigue damage occurred near the weld toe and gusset plate connection because these areas experienced high stress concentration under repeated traffic loading. The analysis indicated that fatigue damage increased continuously with the number of load cycles, even when the applied stress remained below the yield strength of steel. The weld toe region was found to be the most critical crack initiation point due to weld geometry, residual stress, and local discontinuity. Crack propagation analysis showed that cracks grew slowly during the initial stage, but the growth rate increased rapidly when crack length became larger. This confirmed that early detection of fatigue cracks is essential for preventing sudden fracture and improving bridge safety.

Table: Fatigue Performance of Welded Joint Locations

Welded Joint Location	Stress Range MPa	Fatigue Damage Index	Estimated Fatigue Life Cycles	Crack Risk Level
Weld Toe	145	0.86	1.20×10^6	Very High
Weld Root	132	0.78	1.55×10^6	High
Gusset Plate Joint	118	0.69	2.10×10^6	High
Diagonal Member Joint	104	0.55	2.85×10^6	Medium
Chord Member Joint	92	0.43	3.60×10^6	Medium

The result clearly indicates that welded joints with higher stress ranges have shorter fatigue life and greater crack propagation risk. Among all analysed locations, the weld toe showed the highest fatigue damage index of 0.86 and the lowest estimated fatigue life of 1.20×10^6 cycles. This means that the weld toe is the most vulnerable area and requires frequent inspection. The chord member joint showed comparatively lower damage and longer fatigue life, but it still needs monitoring under continuous traffic loading. Overall, the results confirm that fatigue failure in steel truss bridges is mainly governed by local stress concentration and crack growth behaviour at welded joints.

Bar Graph



The bar graph presents the fatigue damage index of different welded joint locations in a steel truss bridge under repeated traffic loading. The weld toe shows the highest fatigue damage index of 0.86, indicating that it is the most critical location for crack initiation. The weld root also shows high damage with a value of 0.78, followed by the gusset plate joint at 0.69. Diagonal member and chord member joints show lower damage values of 0.55 and 0.43. Overall, the graph confirms that fatigue damage is mainly concentrated near welded connection regions and requires regular inspection.

V. CONCLUSION

The study concluded that welded joints in steel truss bridges are highly vulnerable to fatigue damage when subjected to repeated traffic loading. The analysis showed that critical locations such as the weld toe, weld root, and gusset plate joints experience higher stress concentration, which increases the possibility of crack initiation and propagation. Fatigue damage was found to increase gradually with the number of load cycles, while crack growth became faster as the crack length increased. The weld toe showed the highest fatigue risk, indicating the need for frequent inspection and monitoring. Overall, fatigue life assessment and crack propagation analysis are essential for predicting remaining service life, preventing sudden structural failure, and improving bridge safety. Proper welding quality control, periodic non-destructive testing, timely repair, and strengthening of damaged joints can significantly enhance the durability and reliability of steel truss bridges under continuous traffic movement.

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