

# A Review of Research on Fatigue Performance of Steel-UHPC Composite Structures

Jingan Liu\*

School of Civil Engineering, Central South University of Forestry and Technology, Changsha  
410004, China

\*3219186762@qq.com

---

## Abstract

**Research on the fatigue performance of stud connectors in steel-UHPC composite structures is critical for ensuring engineering safety. This review demonstrates that: In fatigue life prediction, traditional fracture mechanics methods (e.g., the Paris formula), while well-established for steel-conventional concrete structures, exhibit limited accuracy for UHPC applications due to its ultra-high-performance properties and the complexity of fatigue mechanisms under cyclic loading; Weld geometry and dimensions significantly influence fatigue life through stress concentration effects, yet quantitative studies targeting steel-UHPC stud welding details remain scarce; For environmental degradation mechanisms, the synergistic effect between corrosion and concrete debonding has been proven to accelerate mechanical performance deterioration, but the coupled mechanisms of multiple factors remain unclarified; Recent advances in refined modeling and data-driven methods (e.g., machine learning) offer novel paradigms for fatigue analysis, though their deep integration in this field is still exploratory.**

## Keywords

**Steel-UHPC Composite Structure; Fracture Mechanics; Life Prediction.**

---

## 1. Introduction

Steel-UHPC composite structures are increasingly employed in modern bridge engineering owing to their exceptional mechanical properties and durability. As critical load-transfer components, the fatigue performance of stud connectors directly governs structural integrity. This systematic review synthesizes current research advances: Traditional fracture mechanics models (e.g., Paris formula), though well-established for conventional concrete structures, exhibit limited accuracy for UHPC applications due to material heterogeneity and mechanistic complexity under cyclic loading; Significantly influence fatigue life through stress concentration effects, yet quantitative studies on steel-UHPC stud welding details remain scarce; The synergistic effect between corrosion and concrete debonding has been proven to accelerate performance deterioration, while coupled multi-factor mechanisms lack quantitative characterization; Refined modeling and data-driven techniques show promise, but their deep integration in stud fatigue analysis remains exploratory.

This review aims to consolidate multidisciplinary research findings, identify theoretical constraints, and establish a scientific foundation for innovative assessment frameworks of stud fatigue performance.

## 2. Limitations of Fatigue Life Prediction Methods for Stud Connectors

Fatigue life prediction represents a critical research focus in fatigue studies, as structural component failures resulting from fatigue have inflicted immeasurable losses across industrial and construction

sectors worldwide. Consequently, scholars globally are dedicated to investigating bridge fatigue issues to mitigate losses caused by fatigue damage. From the perspective of fatigue damage progression, fatigue life can be divided into two distinct phases: crack initiation and crack propagation. The number of loading cycles from initial stress application until a crack reaches a specified length constitutes the crack initiation life. The subsequent cycle count required for the crack to extend to a critical crack length is termed the crack propagation life. The sum of crack initiation life and crack propagation life defines the total fatigue life. Based on the number of stress cycles leading to material failure, fatigue is categorized as either high-cycle fatigue (HCF) or low-cycle fatigue (LCF). Fatigue failure occurring above  $10^5$  stress cycles is classified as high-cycle fatigue, whereas failure below  $10^5$  cycles is designated as low-cycle fatigue.

Currently, four primary methodologies are internationally adopted for predicting the fatigue life of metallic components: the stress-life method, strain-life method, fracture mechanics approach, and damage mechanics approach.

The fracture mechanics approach is particularly applicable for assessing the strength of materials and structures with initial defects. By integrating modern non-destructive testing (NDT) techniques, this method overcomes limitations inherent in conventional methodologies.

In 1921, Griffith [1] proposed the fracture strength theory through analysis of low-stress brittle fracture in materials, laying the foundation for modern fracture mechanics. In 1957, Irwin [2] introduced the concept of the stress intensity factor by analyzing the stress field near crack tips, thereby establishing a crack growth criterion governed by this parameter.

During the period 1961-1963, Paris [3,4] applied linear elastic fracture mechanics (LEFM) theory to fatigue life prediction, proposing the Paris law (equation (1)) which establishes the relationship between fatigue crack growth rate and the stress intensity factor range ( $\Delta K$ ).

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

where:  $a$  = crack size;  $C$ ,  $m$  = material constants;  $\Delta K$  = stress intensity factor range.

Subsequent investigations into crack propagation mechanisms revealed the crack closure effect, wherein cracks do not propagate until fully opened. The driving force for fatigue crack growth is determined by the difference between maximum stress and opening stress, with effective stress intensity factor governing the process. In 1970, based on experimental evidence of crack closure, Elber [5] developed a model relating crack growth rate to effective stress intensity factor range. In 1975, Pearson [6] introduced the concept of short cracks during fatigue crack propagation studies, discovering their accelerated growth phenomenon. Through extensive testing, Miller [7] demonstrated the inapplicability of linear elastic fracture mechanics (LEFM) and Paris' law when crack lengths fall below critical thresholds, necessitating elastoplastic fracture mechanics formulations. McEvily et al. [8] modified LEFM equations to establish a model describing fatigue crack growth rates for both short and long cracks. Newman et al. employed short crack theory [9] and the Newman crack closure model [10] to predict short crack propagation fatigue life.

The successful application of fracture mechanics in steel-concrete composite structures has validated its accuracy for: Analyzing fatigue crack initiation and propagation in headed stud connectors; Predicting fatigue life of stud weld details; Investigating failure modes. This approach reveals the fatigue damage mechanism of shear connectors in composite structures. However, ultra-high performance concrete (UHPC) exhibits fundamentally distinct mechanical properties compared to conventional concrete. Most existing predictive methodologies, developed for normal concrete, inadequately capture UHPC's unique characteristics. Furthermore, the fatigue failure mechanism of stud connectors under cyclic loading remains incompletely characterized, resulting in predictive models lacking robust theoretical foundations.

### 3. Advances in the Influence of Weld Geometry and Dimensions on Fatigue Performance

The geometric discontinuity and complex stress states at headed stud weld details generate stress concentration zones, establishing these regions as critical determinants of fatigue life in steel-UHPC composite structures. Empirical observations indicate frequent deviations from welding specifications [11] in stud-to-steel plate connections (Fig. 1). Research [12] demonstrates that weld profile parameters-including height, width, fillet geometry, and macroscopic configuration-exert substantial influence on hot-spot stress distributions at weld toes. Consequently, weld dimensional and morphological characteristics significantly govern fatigue performance.



Fig. 1 Field-implemented headed stud weld details

Weld geometry and dimensions critically govern stress concentration intensity-the primary catalyst for fatigue crack nucleation. Systematic characterization of geometric features enables elucidation of crack initiation-propagation mechanisms, establishing foundations for fatigue life prediction models. Wang et al. [13] demonstrated through finite element analysis that incorporating weld profile parameters significantly enhances correlation between computational and experimental shear capacities of headed studs, validating the necessity of weld detail considerations. Nykänen et al. [14] conducted comparative fatigue testing on MAG and pulsed-MAG welded joints, documenting geometric imperfections and misalignments without examining their fatigue life implications. Chang et al. [15] pioneered an integrated reverse-engineering approach utilizing 3D laser scanning for precise quantification of fillet weld dimensions and surface topography, enabling objective geometric quality assessment. Employing linear elastic fracture mechanics, Nykänen et al. [16] quantified fatigue strength sensitivity to local geometric variations in non-load-carrying cruciform joints, identifying weld toe radius as the dominant influencing parameter. Bo et al. [17] verified the mesh-insensitive nature of structural stress methods in predicting fatigue cycles for T-joints under tensile loading. Crucially, fracture mechanics-based predictions require integration of microscopic weld ripple characteristics to ensure accuracy [18]. Livieri et al. [19] optimized fatigue-resistant weld configurations through implicit gradient methodology. Collective evidence confirms that morpho-dimensional weld attributes fundamentally modulate stress concentration effects and fatigue performance. However, research addressing geometric influences on fatigue life and failure mechanisms in steel-UHPC composite stud connections remains notably limited, revealing an imperative need for systematic investigation.

### 4. Synergistic Deterioration Mechanisms: Corrosion-Concrete Debonding Effects on Mechanical Performance of Shear Stud Connectors

In steel-UHPC composite structures, headed stud connectors constitute critical components enabling synergistic material interaction. These connectors fulfill essential functions including: shear transfer [20], interface separation prevention, structural stiffness enhancement [21], fatigue performance improvement, complex stress accommodation. The mechanical and durability performance of composite structures directly depends on stud design and condition. However, concrete cracking in negative moment regions [22] and design deficiencies permit moisture/chloride ingress, accelerating

stud corrosion. Corrosive deterioration not only compromises mechanical integrity but also jeopardizes structural continuity and long-term durability [23-25]. Empirical findings confirm that stud corrosion induces marked reduction in static strength [26] and substantial fatigue life diminution [27]. Corrosive degradation accelerates fatigue performance deterioration, where stress concentration at corrosion pits amplifies shear stress ranges, accelerates crack propagation, and establishes an exponential relationship between fatigue life and corrosion rate [28,29].

Research indicates that the steel-concrete interface in composite structures is highly susceptible to debonding and void defects [30]. Concrete voids reduce the bond strength between stud connectors and concrete, weakening the composite action between steel girders and concrete bridge decks. This deterioration causes studs to transition from a composite shear mechanism to single shear, thereby diminishing their mechanical performance [31]. The synergistic effect of corrosion and concrete voids accelerates the degradation of stud mechanical properties. Corrosion induces cross-sectional loss and increased surface roughness in studs, while concrete voids exacerbate unfavorable stress conditions. These combined factors significantly impair both the bearing capacity and fatigue performance of stud connectors.

## 5. Refined Modeling and Data-Driven Methods: Applications in Fatigue Analysis

In fatigue analysis of steel-ultra-high performance concrete (UHPC) composite structures, integrating refined modeling techniques with data-driven approaches can substantially enhance the accuracy and efficiency of fatigue life predictions. Refined modeling enables precise characterization of fatigue behavior by synergistically coupling macro-scale global structural responses with meso-scale local material interactions. Through refined finite element (FE) simulations, Liu et al. [32] demonstrated significantly enhanced static resistance and fatigue endurance in open steel-UHPC composite bridge decks lacking U-ribs. Qin et al. [33] established a refined steel box girder deck model, revealing that steel-UHPC lightweight composite decks exhibit 15%–46% lower stress amplitudes than conventional asphalt-surfaced steel decks under thermal gradients. Wang et al. [34] implemented co-simulation via Abaqus and FRANC3D, incorporating initial flaw assumptions into a stud weld detail submodel with locally refined meshing; their refined framework enabled systematic parametric quantification of stress intensity factors (SIFs). Employing fracture mechanics-based refined modeling, Li [35] investigated shear capacity and fatigue resistance of stud connectors in steel-UHPC composite decks, resolving critical issues including interfacial shear stress distribution, stud shear strength evaluation, and fatigue crack growth prediction at weldments.

The application of data-driven methodologies in fatigue analysis leverages extensive datasets—including experimental results, numerical simulations, and field monitoring—combined with machine learning (ML) and deep learning (DL) algorithms to efficiently predict material fatigue life [36,37], optimize design parameters, and elucidate fatigue damage mechanisms. Common data-driven approaches encompass conventional ML techniques, DL architectures, and optimization algorithms. Ma et al. [38] proposed a hybrid data-model driven framework for predicting crack propagation life in high-speed train bogies, integrating finite element analysis (FEA), the Paris' law, and Kriging surrogate modeling to achieve high-precision fatigue life predictions. Gan [39] developed a domain-knowledge-informed ML model (utilizing Random Forest, DL, and Symbolic Regression) for metallic fatigue life prediction, significantly enhancing generalization capability under complex loading conditions. Liu et al. [40] introduced a fatigue life assessment method based on energy-based criteria and artificial neural networks (ANNs), enabling accurate predictions for both uniaxial/multiaxial loading and high-cycle/low-cycle fatigue (HCF/LCF) regimes. Notably, research integrating refined modeling with data-driven methods for predicting stud fatigue life in steel-UHPC composite structures remains scarce. Therefore, this study establishes a ML-based predictive framework for stud fatigue life in steel-UHPC systems, leveraging high-fidelity simulation results from refined models.

## 6. Conclusion

This review synthesizes critical advances in fatigue performance research of stud connectors within steel-UHPC composite structures: Traditional fracture mechanics approaches exhibit limited accuracy for UHPC applications, necessitating novel models accounting for material heterogeneity; Weld geometry and dimensions govern fatigue life through stress concentration effects, yet quantitative studies targeting steel-UHPC stud welding details remain scarce; The synergistic corrosion-concrete debonding effect accelerates mechanical degradation, while multi-factor coupling mechanisms lack quantitative characterization; Refined modeling and data-driven methods offer innovative paradigms for fatigue analysis, though their deep integration requires further exploration. Future work should prioritize quantifying multiscale damage mechanisms, modeling environmental-loading coupling effects, and integrating multidisciplinary methodologies to establish robust frameworks for stud fatigue assessment.

## References

- [1] Griffith AA. The Phenomena of Rupture and Flow in Solids[J]. Philosophical Transactions of the Royal Society of London, Series A, 1921, 221: 163-199.
- [2] R. G I. Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate[J]. J. Appl. Mech, 1957, 24(3): 361-364.
- [3] PC P. A rational analytic theory of fatigue[J]. Trends Engin, 1961, 13: 9-14.
- [4] Paris P, Erdogan F. A critical analysis of crack propagation laws[J]. Journal of Fluids Engineering, 1963, 85(4): 528-533.
- [5] Suresh, S. Fatigue of Materials. Translated by Zhongguang Wang. Beijing: National Defense Industry Press, 1993. (In Chinese)
- [6] Person S. Investigation of fatigue cracks in commercial aluminum alloys and subsequent propagation of very short fatigue cracks[J]. Engineering Fracture Mechanics, 1975, 7: 235-47.
- [7] Miller K J. The behaviour of short fatigue cracks and their initiation part I-a review of two recent books[J]. Fatigue & Fracture of Engineering Materials & Structures, 1987, 10(1): 75-91.
- [8] McEvily A J, Eifler D, Macherauch E. An analysis of the growth of short fatigue cracks[J]. Engineering Fracture Mechanics, 1991, 40(3): 571-584.
- [9] Newman Jr J C, Phillips E P, Swain M H. Fatigue-life prediction methodology using small-crack theory[J]. International Journal of fatigue, 1999, 21(2): 109-119.
- [10] Newman Jr J C. A crack opening stress equation for fatigue crack growth[J]. International Journal of fracture, 1984, 24(4): R131-R135.
- [11] National Technical Committee on Fasteners of Standardization Administration of China. GB/T 10433-2002: Headed Studs for Arc Stud Welding [S]. Beijing: Standards Press of China, 2002. (In Chinese)
- [12] Weixin Liang. Fatigue resistance of modified shear stud connectors in UHPC [D]. Qingdao University of Technology, Qingdao: 2024. (In Chinese)
- [13] Xiaobi Wang, Ruinian Song, Yulin Zhan, et al. Effect of weld shape on shear bearing capacity of stud [J]. Industrial Construction, 2020, 50(12): 144-149+185. (In Chinese)
- [14] NYKÄNEN T, BJÖRK T, LAITINEN R. Fatigue strength prediction of ultra high strength steel butt-welded joints[J]. Fatigue & Fracture of Engineering Materials & Structures, 2013, 36(6): 469-482.
- [15] Chang C, Chen Y. Measurements of fillet weld by 3D laser scanning system[J]. The International Journal of Advanced Manufacturing Technology, 2005, 25(5-6): 466-470.
- [16] Nykänen T, Marquis G, Björk T. A simplified fatigue assessment method for high quality welded cruciform joints[J]. International Journal of Fatigue, 2008, 31(1): 79-87.
- [17] Bo H Y, Ping W, Liang H Q. Fatigue property of welded T-shaped joints using the structural stress method[J]. Materials Science Forum, 2021, 627068-73.
- [18] Shiozaki T, Yamaguchi N, Tamai Y, et al. Effect of weld toe geometry on fatigue life of lap fillet welded ultra-high strength steel joints[J]. International Journal of Fatigue, 2018, 116409-420.
- [19] Livieri P, Tovo R. Optimization of welded joints under fatigue loadings[J]. Metals, 2024, 14(6): 613-613.

- [20] Fangwen Wu, Yanpeng Feng, Jun Dai, et al. Study on mechanical properties of stud shear connectors in steel-UHPC composite structures[J]. *Engineering Mechanics*, 2022, 39(2): 222-234+243. (In Chinese)
- [21] Cong Li, Baochun Chen, Wenxu Hu, et al. Calculation of shear bearing capacity, slip and stiffness of headed studs in steel-UHPC composite slabs [J]. *Engineering Mechanics*, 2023, 40(6): 110-121. (In Chinese)
- [22] Xinhua Liu, Cong Zhou, Jianren Zhang, et al. Experimental study on mechanical behavior of steel-UHPC composite girders in negative moment regions [J]. *China Journal of Highway and Transport*, 2020, 33(5): 110-121. (In Chinese)
- [23] Lin Wu. Experimental study on the performance of steel-concrete composite beams with corroded studs [D]. Hangzhou: Zhejiang University, 2013. (In Chinese)
- [24] Wen Xue, Ju Chen, Lin Wu, et al. Experimental study on steel-concrete composite beams with corroded studs [J]. *Journal of Building Structures*, 2013, 34(S1): 222-226. (In Chinese)
- [25] Zhiwu Yu, Weihua Shi, Yachuan Kuang. Experimental study on mechanical properties of corroded stud connectors [J]. *Journal of Central South University (Science and Technology)*, 2014, 45(01): 249-255. (In Chinese)
- [26] Xueliang Rong, Qiao Huang. Experimental study on mechanical properties of corroded stud connectors [J]. *Journal of Civil Architectural & Environmental Engineering*, 2012, 34(02): 15-20. (In Chinese)
- [27] Chen J, Zhang H, Yu Q. Static and fatigue behavior of steel-concrete composite beams with corroded studs[J]. *Journal of Constructional Steel Research*, 2019, 156:18-27.
- [28] WANG Weilun, CHEN Ju, JIN Weiliang. Experimental investigation of corroded stud shear connectors subjected to fatigue loading[J]. *Journal of Materials in Civil Engineering*, 2016, 29(1): 04016175.
- [29] LIU Tai, NIE Xin, ZENG Jiahua, et al. Static and fatigue behaviors of corroded stud connectors in weathering steel-concrete composite beams[J]. *Engineering Structures*, 2022, 272: 115030.
- [30] Chengjin Qin. Study on nondestructive testing of interface void defects in steel-concrete composite structures [D]. Nanning: Guangxi University, 2023. (In Chinese)
- [31] Yue Li, Zhe Ning, Zhipeng Li, et al. Experimental Study on Seismic Performance of Concrete-Filled Steel Tubular Columns with Void Defects in Stud-Reinforced Zones [J]. *Journal of Building Structures*, 2023, 44(S2): 173-179. (In Chinese)
- [32] Yang Liu, Yongbin Li, Jinhua Tan, et al. Static-fatigue properties of open steel-UHPC lightweight composite deck structures [J]. *Engineering and Construction*, 2025, 39(1): 101-103, 215. (In Chinese)
- [33] Shiqiang Qin, Renjie Yang, Zhongcai Zhang, et al. Fatigue performance of steel-UHPC lightweight composite bridge deck under temperature effects [J]. *Journal of Wuhan University of Technology (Transportation Science & Engineering Edition)*, 2024, 48(2): 337-341, 346. (In Chinese)
- [34] Da Wang, Benkun Tan, Shengtao Xiang, et al. Fatigue Crack Propagation and Life Analysis of Stud Connectors in Steel-Concrete Composite Structures[J]. *Sustainability*, 2022, 14(12): 7253.
- [35] Guangyao Li. Shear strength and fatigue life analysis of stud connectors in steel-UHPC composite bridge decks [D]. Tianjin: Tianjin University, 2020. (In Chinese)
- [36] Lei Gan, Hao Wu, Zheng Zhong. Research progress on data-driven models for metal fatigue life prediction (in Chinese). *Advances in Mechanics*, 2025, 55(1): 30-79. (In Chinese)
- [37] Chao Feng, Lei Zhao, Lianyong Xu, et al. Fatigue life prediction model for welded joints based on integrated data-driven approach [J]. *Transactions of the China Welding Institution*, 2023, 44(11): 8-13, 51, 129. (In Chinese)
- [38] Jianyong Ma, Shuwen Ma, Haizhu Zhang, et al. A modeling and analysis method for crack propagation life prediction in digital twin-based structures [J]. *Machine Design & Research*, 2023, 39(5): 172-177. (In Chinese)
- [39] Lei Gan. Research on Data-Driven Fatigue Life Prediction of Metallic Materials [D]. Harbin: Harbin Institute of Technology, 2023. (In Chinese)
- [40] Zhizhuang Liu, Hao Wu. A parameter-influence-based data-driven method for fatigue life prediction [J]. *Journal of Mechanical Engineering*, 2023, 59(4): 71-79. (In Chinese)