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Experimental assessment of fatigue life and fracture modes in MTS-based bolted joints

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Abstract

Purpose – This study aims to investigate the fatigue behavior and failure modes of bolted lap joints using Modified Tensile Specimens (MTS) under various cyclic load conditions. Emphasis is placed on identifying the relationship between load amplitude, fatigue life, and damage progression in low-carbon steel assemblies.
Design/methodology/approach – An experimental approach was adopted using MTS specimens fabricated from St 12 03 cold-rolled steel, joined with Grade 8.8 M4 bolts. Cyclic fatigue tests were conducted under zero-based loading at seven distinct force levels. Fracture surfaces were visually analyzed to identify dominant failure mechanisms.
Findings – The results revealed a strong inverse correlation between applied cyclic load and fatigue life. Three distinct failure modes were identified: bolt shear at high loads (5.4 kN), interface cracking and slippage at moderate loads (4.9–5.1 kN), and plate tearing or stable fatigue behavior at lower loads (=4.1 kN). The results highlight a progressive transition in failure mechanisms, from bolt shear at high loads to plate tearing and interface cracking at lower loads, providing essential insights for fatigue-resistant bolted joint design.
Originality/value – This study offers original insights into the fatigue behavior of bolted lap joints using MTS, a relatively underexplored configuration in fatigue assessment. By experimentally evaluating failure modes under varied cyclic load levels, the authors uncover critical transitions in damage mechanisms—from bolt shear to interface cracking and plate tearing—depending on the applied load. Unlike many existing studies focused on numerical modeling or bonded joints alone, this work provides empirical data rooted in real-world fastening conditions using cold-rolled low-carbon steel.

Keywords Fatigue life, Bolted joints, Modified tensile specimen (MTS), Failure modes, Cyclic loading, Fracture analysis, Lap joints, Low-carbon steel, Experimental fatigue testing, Shear failure

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1. Introduction

Bolted joints are vital across sectors such as automotive, aerospace, and infrastructure, primarily due to their ease of assembly, economic efficiency, and mechanical reliability. However, these joints are also prone to fatigue-related damage under cyclic loads, often leading to structural failure if not properly accounted for (Liu, Cui, Xiao, Lua, & Phan, 2020; Xu, Sun, & Zhang, 2016). To address this vulnerability, a wide body of research has evolved around fatigue prediction, joint optimization, material selection, and failure detection in bolted connections.

Bolted joints also play a critical role in ensuring the structural integrity and service reliability of railway components, particularly in high-load zones such as wagon wheels and suspension systems. Their modularity, ease of maintenance, and mechanical robustness make them indispensable in rail applications where repeated cyclic loading is prevalent. The schematic provided as an example (Figure 1) reinforces the practical significance of such joints in rail assemblies, emphasizing the need for fatigue-resistant designs. Therefore, understanding the load-dependent fracture mechanisms and optimizing joint configurations are vital for enhancing the fatigue life and safety of railway systems.

1.1 Fatigue life prediction and computational modeling

Accurate fatigue prediction remains a critical objective in the design of bolted structures. Finite Element Analysis (FEA) and damage mechanics models are now widely applied to simulate stress distributions and evaluate potential failure scenarios. Liu *et al.* (2020) combined Continuum Damage Mechanics with a critical-plane method to assess fatigue under multiaxial loading, while Yang *et al.* (2023) proposed a structural stress approach that aligns well with normalized S–N curves. Other studies (Abazadeh, Chakherlou, Farrahi, & Alderliesten, 2013; Esmaeili, Chakherlou, & Zehsaz, 2014; Pichon, Daidié, Paroissien, & Benaben, 2023; Venugopal Poovakaud, Jiménez-Peña, Talemi, Coppieters, & Debruyne, 2020) employed multiaxial criteria, preload analysis, and simplified fretting fatigue models to enhance predictive accuracy.

1.2 Crack initiation and material behavior

Fatigue cracks typically originate around bolt holes due to stress concentration and fretting wear. Xu *et al.* (2016) and Juoksukangas, Lehtovaara, and Mäntylä (2016) highlighted how preload and cyclic movement affect crack development. Material selection plays a key role, with studies showing that high-strength steels (Guo *et al.*, 2012), aluminum alloys (Sun, Voyiadjis, Hu, Shen, & Meng, 2017), and composite-metal hybrids (Hou, Qiao, Wang, & Zhang, 2023) respond differently under fatigue. Fretting and contact behavior remain major contributors to early failure (Ferjaoui, Yue, Abdel Wahab, & Hojjati-Talemi, 2015; Jiménez-Peña, Talemi, Rossi, & Debruyne, 2017).

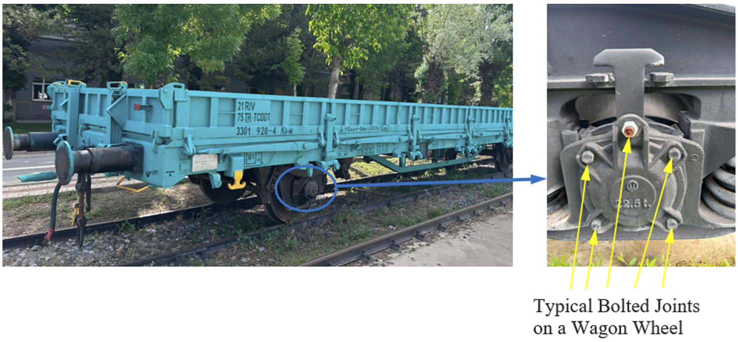

Figure 1. Schematic representation of a bolted rail-wheel joint. Authors' own work

1.3 Design optimization and structural improvements

Design parameters such as bolt spacing, joint geometry, and hybrid bonding significantly influence fatigue performance. Guo, Bhosale, Srikantan, Munson, and Mentley (2012) optimized automotive body joints under cyclic loading using FEA, while Gao, Du, Zhang, Feng, and Yu (2021) compared bolted, welded, and hybrid configurations in structural steel. Noda *et al.* (2016) showed that slight bolt-nut pitch mismatches could enhance fatigue resistance through improved anti-loosening behavior.

1.4 Fatigue life enhancement techniques

Various enhancement methods have been proposed, including cold expansion (Duncheva & Maximov, 2013), interference fits (Liu *et al.*, 2018), and hybrid adhesive-bolted joints (Samaei, Zehsaz, & Chakherlou, 2016; Emami Geiglou & Chakherlou, 2019). These techniques often work by introducing residual compressive stresses or distributing loads more uniformly across the joint. Maximov, Duncheva, and Ganev (2012) demonstrated up to a 40% increase in fatigue life with optimized hole treatment techniques.

1.5 Loading conditions and clamp effects

Tightening torque, clamping force, and load direction are among the most influential variables in fatigue damage progression. Excessive torque may cause fretting damage (Wagle & Kato, 2009), while insufficient clamp force accelerates crack initiation (Esmaeili *et al.*, 2014). Studies also investigated fatigue behavior under axial excitation (Li *et al.*, 2022; Liu *et al.*, 2018) and seismic-type loading (Zhang, Lv, Wang, Gao, & Srivatsan, 2021; Lim, Choi, & Sumner, 2012), emphasizing the complexity of real-world load spectra.

1.6 Environmental and temperature influences

Corrosive environments and elevated temperatures are known to degrade fatigue life substantially. Zampieri *et al.* (2017) and de Jesus, da Silva, and Correia (2015) analyzed fatigue in aged riveted joints, showing that corrosion leads to early microcracking. Yu, Zhou, Yu, and Yang (2018) introduced a temperature-dependent fatigue model, validated under 550°C and 650°C, while Zhang *et al.* (2021) highlighted chloride-induced shifts in crack location in aluminum joints.

1.7 Material and fastening type considerations

Material combinations, fastening configuration, and surface treatments heavily influence fatigue behavior. Sivaramakrishnan, Vasanthe Roy, Sevvel, and Abraham Anthony (2023) and Wang, Uy, Li, and Song (2020) showed improved fatigue performance with high-strength bolts and appropriate preload values. Hybrid bonded-bolted joints consistently outperform simple bolted connections, especially under shear loading (Chakherlou, Zehsaz, & Samaei, 2016).

1.8 Crack detection and smart monitoring

Recent studies focus on real-time crack monitoring systems. Coelho, Das, Chattopadhyay, Papandreou-Suppappola, and Peralta (2007) used piezoelectric sensors and Support Vector Machine (SVM) algorithms to detect and classify fatigue damage in joints, paving the way for predictive maintenance systems in high-risk applications.

1.9 Application-oriented investigations

1.9.1 Automotive applications. Studies like those by Liu *et al.* (2020), Jayaprakash, Mutoh, and Yoshii (2011), and Esmaeili *et al.* (2014) focused on high-cycle fatigue and fretting resistance in automotive joints. Innovations include the use of hybrid bonding (Emami Geiglou & Chakherlou, 2019) and S–N curve unification across bolt types (Nam, Kim, Kim, Choi, & Oh, 2022).

1.9.2 Aerospace applications. Precision preloads (Benhaddou *et al.*, 2018), laminate-metal combinations (Hou *et al.*, 2023), and high-strength alloy optimization (Jiménez-Peña *et al.*, 2017) were central to fatigue resistance improvements in aerospace joints.

1.9.3 Civil and bridge structures. Historic structures pose challenges due to material aging and outdated design codes. Pedrosa, Rebelo, Gervásio, da Silva, and Correia (2020) and Urban (2003) emphasized the need for updated models to predict fatigue in riveted joints from legacy materials.

1.9.4 Railway applications. Yin, Qian, Edwards, and Zhu (2018) investigated the link between train speed and rail bolt fatigue using FEA, concluding that geometric design and preload play more critical roles than operational velocity.

A summary of relevant studies discussed in the Introduction is provided in Table 1, outlining the focus, methodology, and main findings of each selected work.

The present study focuses on fatigue behavior relevant to railway bolted connections and is grounded in experimental investigations using modified tensile-shear (MTS) specimens. Fatigue tests were performed on these specimens to simulate structural joint conditions and analyze fatigue resistance under controlled cyclic loads (Ertas, Vardar, Sonmez, & Solim, 2009; Ertas & Akbulut, 2021). The tests evaluated both spot-welded and bolted joints in terms of fatigue life, crack initiation, and failure progression. The insights gained were pivotal in assessing the predictive capabilities of various general-purpose fatigue models.

Table 1. Summary of selected studies on fatigue behavior in bolted joints

Study reference	Focus area	Methodology	Key findings/contribution
Liu *et al.* (2020)	Fatigue life prediction using CDM	Numerical (FEA & CDM)	Proposed simplified model for cumulative fatigue in bolts
Xu *et al.* (2016)	Fretting fatigue in steel bolted joints	Experimental & FEM	Identified critical fretting zones and failure trends
Guo *et al.* (2012)	Automotive body joint fatigue estimation	FEA-based cyclic analysis	Developed a technique for life prediction under service loads
Duncheva and Maximov (2013)	Fatigue enhancement in rail bolts	Experimental	Demonstrated life extension via cold expansion
Abazadeh *et al.* (2013)	Multiaxial fatigue in lap joints	Numerical	Compared fatigue criteria for interference-fitted bolts
Samaei *et al.* (2016)	Hybrid (adhesive/bolted) fatigue analysis	Experimental & Numerical	Hybrid joints showed longer crack growth life
Hou *et al.* (2023)	Composite–metal bolted joint fatigue	Simulation (FEM)	Revealed plate-laminate interaction in fatigue damage
Jiménez-Peña *et al.* (2017)	Fretting fatigue in high-strength steel bolts	Experimental	Increased pre-tension improves resistance to fretting fatigue
Emami Geiglou and Chakherlou (2019)	Cold expansion in bonded-bolted joints	Numerical & Experimental	Cold expansion improved fatigue life in hybrid joints
Yin *et al.* (2018)	Rail joint fatigue vs train speed	Simulation (FEA)	Speed less critical than geometry/preload for fatigue life
Ertas and Akbulut (2021)	Fatigue of spot-welded joints	Experimental	Established fatigue resistance under variable loads in MTS setup
Ertas *et al.* (2009)	Measurement and assessment of fatigue life of spot-weld joints	Experimental & Simulation (FEA)	Established fatigue resistance under variable loads in MTS setup Validated finite element analysis for predicting stress and strain states

Source(s): Authors' own work

Rather than employing models tailored exclusively for spot welds—as has been common in earlier literature—the study explored the broader applicability of generic fatigue models across different joint types. This approach supports design practices where a single robust model applicable to both bolted and welded configurations is preferred for efficiency and standardization. Several fatigue models were thus comparatively assessed to identify the most accurate and versatile option for practical engineering use, particularly within the scope of railway and structural applications.

2. Materials and method

In this study, an experimental investigation was conducted to evaluate the fatigue performance of Modified Tensile Specimen (MTS) bolted lap joints under cyclic loading. The specimens were manufactured using low-carbon cold-rolled steel, St 12 03 (DIN 1623), a material commonly used in the automotive industry due to its formability, weldability, and cost-effectiveness. The steel used had an average tensile strength of 319.64 MPa, yield strength of 217.41 MPa, a reduction in area of approximately 35.59%, and a base metal hardness of 35 kgf/mm^2. Bolted connections were made using Grade 8.8 M4 bolts, which are characterized by a proof load of 580 MPa, a minimum yield strength of 640 MPa, and a minimum tensile strength of 830 MPa.

The fatigue testing was conducted on a servo-hydraulic machine under force control with a sinusoidal waveform at a frequency of 10 Hz. Specimens were mounted axially using hydraulic grips, and cyclic loads were applied until either fatigue cracks or full fracture was observed. The geometry of the MTS specimen, including bolt placement and gauge dimensions, is illustrated in Figure 2. This configuration replicates a modified tensile-shear load path commonly observed in bolted structural connections.

Throughout the testing process, critical parameters such as load levels, number of cycles to failure, and crack initiation sites were carefully recorded. The objective was to characterize the fatigue behavior and identify failure modes specifically associated with bolted interfaces.

This experimental procedure formed the basis for evaluating the structural performance of bolted joints, particularly in terms of their crack resistance and fatigue life under realistic service conditions.

3. Results

The fatigue life results presented in Table 2 and Figure 3 reveal a pronounced inverse correlation between cyclic load amplitude and fatigue life of the MTS bolted lap joint specimens. As the

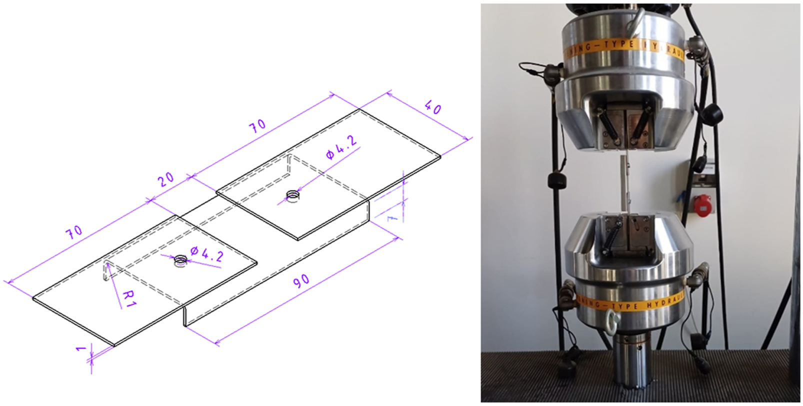

Figure 2. Schematic representation of the (a) MTS specimen geometry and (b) test setup used in fatigue testing of bolted lap joints. Authors' own work

Table 2. Experimental fatigue life results of MTS bolted lap joint specimens

Zero-based applied load (kN)	Fatigue life (cycles)
3.2	279,923
3.7	207,332
3.8	193,998
4.1	156,005
4.9	66,881
5.1	46,879
5.4	27,645

Source(s): Authors’ own work

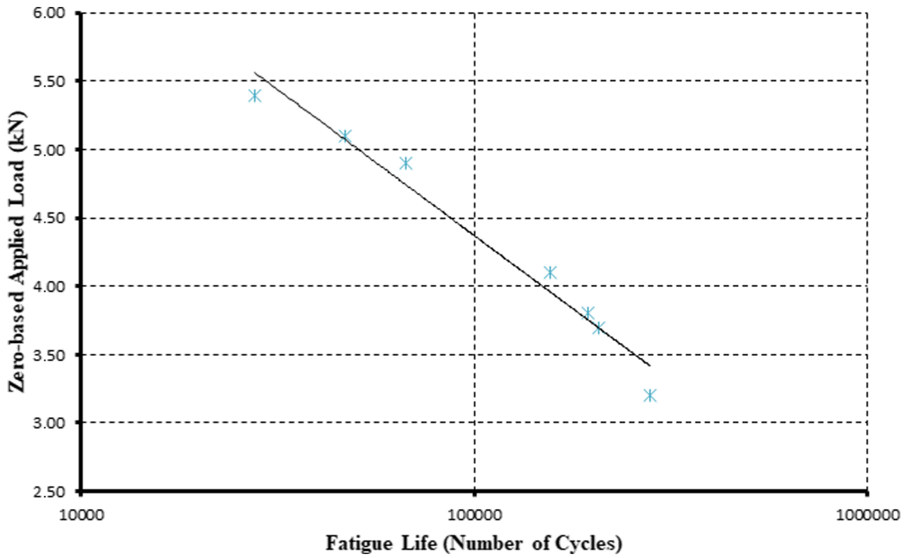

Figure 3. Fatigue life of bolted lap joints under varying applied loads. Authors’ own work

zero-based applied load increases from 3.2 kN to 5.4 kN, the number of cycles to failure decreases substantially, confirming a classical fatigue behavior consistent with the S–N (stress–number of cycles) relationship observed in metallic joints. The monotonic decline in fatigue life suggests that higher load amplitudes accelerate crack initiation and propagation, likely due to elevated local stress concentrations and cumulative damage mechanisms at the bolt–plate interface. This trend validates the structural sensitivity of bolted joints under cyclic loading and underscores the importance of load control in fatigue-critical applications. As shown in Table 2 (with Figure 3), increasing the applied zero-based cyclic load from 3.2 kN to 5.4 kN significantly reduced the number of cycles to failure, confirming the expected F–N behavior commonly observed in metallic joints under repeated stress.

Visual inspection of the fractured specimens revealed a range of failure modes that changed systematically with increasing load. These fracture patterns are illustrated in Figure 4, with each subfigure corresponding to a specific load level:

(1) At 5.4 kN (Figure 4d), a shear failure of the bolt was observed, resulting in complete fracture of the fastener. This mode indicates that at the highest load, the bolt itself becomes the weakest link under cyclic shear stress.

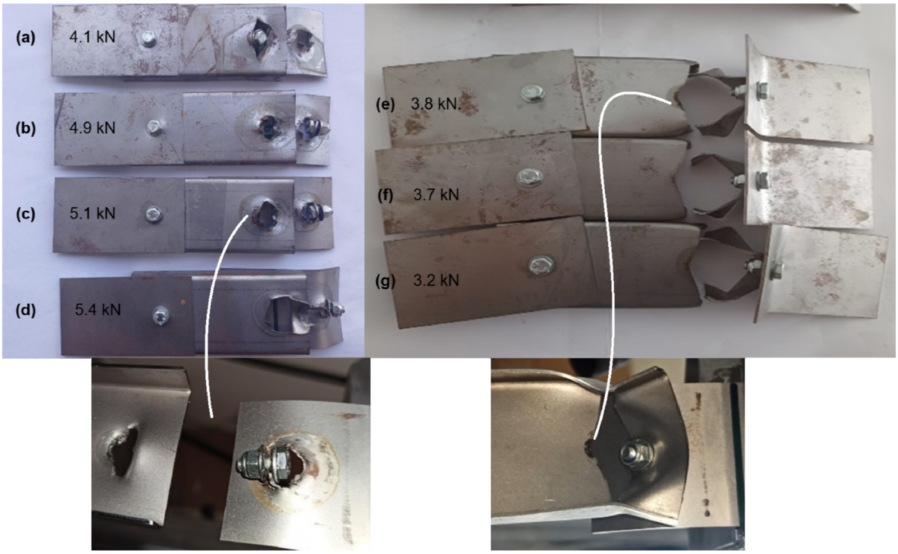

Figure 4. Fracture surfaces of MTS bolted lap joint specimens tested under different cyclic loads, highlighting the evolution of failure mechanisms from bolt shear at high loads to minimal damage at lower loads. Authors' own work

(2) At 5.1 kN (Figure 4c), the bolt remained unbroken, but circumferential cracking developed around the bolt hole, causing joint slippage. The plate began to deform, indicating damage localized at the interface.

(3) At 4.9 kN (Figure 4b), a similar interface cracking behavior occurred, with more pronounced deformation in the surrounding material compared to 5.1 kN, but the bolt remained intact.

(4) At 4.1 kN (Figure 4a), fatigue cracks initiated in the plate near the bolt and propagated through the bent sheet, eventually tearing off a section. This suggests plate-dominated failure under moderate loads and longer fatigue lives.

(5) At 3.8 kN (Figure 4e) and 3.7 kN (Figure 4f), cracking remained mostly localized and surface-level, showing minimal material separation. These cases suggest the onset of fatigue damage with long life but no catastrophic propagation.

(6) At the lowest load of 3.2 kN (Figure 4g), although the fatigue life reached nearly 280,000 cycles, no visible macroscopic cracks were observed. This indicates stable fatigue resistance in both bolt and plate under low stress amplitudes.

These observations confirm that as load decreases, not only does fatigue life increase, but the nature of failure also shifts—from bolt-dominated shear fracture at high loads, to interface cracking at mid-range loads, and ultimately to plate integrity preservation under low loads.

4. Discussion

The experimental findings clearly demonstrate the complex and load-dependent fatigue behavior of bolted lap joint assemblies. The fatigue life of the specimens showed a consistent inverse relationship with the applied zero-based cyclic load, aligning with classical S–N curve theory. However, beyond life expectancy alone, the evolution of failure modes across load levels offers deeper insight into the mechanical limits of bolted structures.

At the highest load level of 5.4 kN, the dominant failure mode was shear fracture of the bolt, indicating that under severe cyclic stresses, the bolt itself is structurally incapable of withstanding prolonged repetition. This catastrophic mode is critical in safety-relevant applications where bolt integrity is essential. The sudden and complete failure of the fastener in this case underscores the importance of bolt strength matching with surrounding joint components in high-stress environments.

As the load decreased to 5.1 kN and 4.9 kN, the failure mode transitioned toward circumferential fatigue cracking around the bolt hole, accompanied by slippage and localized deformation. This shift in damage location reflects a mechanical redistribution of stress—from bolt shear to contact and frictional stresses at the bolt–plate interface. Such transitions are frequently observed in hybrid stress states, where multiaxial fatigue influences failure initiation. These results emphasize the need for interface design improvements, such as washer inclusion or improved surface finish, in order to delay fatigue initiation around the bolt boundary.

At intermediate loads (4.1 kN), the fatigue damage extended across the sheet metal, with cracks propagating from the bolt zone into the bent region. Although the bolt did not fail, fatigue cracks initiated and propagated through the plate due to localized stress concentrations and material fatigue, highlighting the plate as the dominant failure site under intermediate loads. This behavior suggests that sheet geometry, including bending radii and thickness gradients, plays a crucial role in fatigue resistance, especially under extended loading durations.

At lower loads (3.8–3.2 kN), fatigue damage was minimal or absent, and life cycles extended significantly. The absence of macro-scale fractures at 3.2 kN—despite nearly 280,000 cycles—indicates that St 12 03 steel, when used under moderate stress amplitudes, offers sufficient resistance against fatigue crack initiation in both the bolt and the surrounding plate. This aligns with known behavior of low-carbon steels, which are more notch-tolerant and less prone to brittle crack propagation compared to high-strength alloys.

An important takeaway from these observations is that failure mode transitions are progressive, not abrupt. The shift from bolt shear to plate cracking occurs gradually across the stress spectrum, reflecting the interdependence of load amplitude, stress concentration, and local material behavior. This progression must be considered in design, particularly in structures subject to variable-amplitude loading over time (e.g., rail joints, automotive chassis, lightweight frame structures).

Additionally, the observed fracture morphologies—ranging from smooth sheared bolt surfaces to rough, branched plate cracks—suggest different underlying fatigue mechanisms, including shear-driven failure, out-of-plane bending fatigue, and fretting-induced micro-cracking. Such diversity underlines the necessity of combining experimental testing with microstructural and fractographic analyses in future studies to distinguish the dominant damage contributors.

5. Conclusion

This study experimentally investigated the fatigue behavior of Modified Tensile Specimen (MTS) bolted lap joints under varying cyclic load levels. The findings demonstrated a clear inverse relationship between applied load and fatigue life, with failure modes evolving from bolt shear at high loads to interface cracking and plate tearing at moderate levels. At lower loads, the joints showed minimal fatigue damage, even after extended cycles, confirming the suitability of low-carbon steel for moderate-stress applications.

The results emphasize the importance of load-adapted design in bolted joints, where both the bolt and surrounding material must be evaluated as potential failure sites depending on the expected stress regime. These insights are particularly relevant for structural applications such as rail systems, automotive frames, and thin-walled assemblies.

For future studies, the following recommendations are proposed:

1. Incorporating fractographic and microstructural analysis to understand the initiation mechanisms at the material level;
2. Extending the study to include variable amplitude loading to replicate real service conditions more accurately;
3. Comparing bolted joints with hybrid (bonded–bolted) or pre-tensioned configurations to evaluate enhancement strategies;
4. Developing data-driven fatigue models using the experimental results for integration into design software tools;
5. Investigating the impact of surface treatments, bolt coating, and lubrication on fatigue resistance and interface damage progression.

These directions would help bridge the gap between simplified laboratory testing and complex in-service conditions, improving the fatigue durability of bolted joints across industries.

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