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Experimental and Numerical Investigation of Localised Corrosion-Driven Brittle Failure in Welded Metallic Joints under Cyclic Loading Conditions

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Abstract

Localized corrosion is one of the most critical degradation mechanisms affecting the structural integrity of welded metallic joints operating under cyclic loading conditions, particularly in aggressive environments. The interaction between corrosion-induced material loss, stress concentration, and cyclic loading significantly accelerates crack initiation and promotes brittle failure modes, yet the underlying mechanisms remain insufficiently quantified. This study presents a comprehensive experimental and numerical investigation into corrosion-driven brittle failure in welded metallic joints subjected to cyclic loading. A series of corrosion–fatigue experiments were conducted on welded structural steel joints exposed to chloride-rich environments, focusing on the development of localized corrosion pits and their evolution into dominant cracks. Mechanical cyclic loading was applied under controlled stress ratios to replicate service-like conditions. Crack initiation sites, fracture morphologies, and failure modes were systematically characterized using optical microscopy and scanning electron microscopy. The experimental results reveal that localized corrosion significantly alters stress distribution near the weld toe and heat-affected zone, promoting premature crack initiation and brittle fracture behavior. To complement the experimental observations, a finite element-based numerical framework was developed to simulate corrosion-induced damage accumulation and crack propagation under cyclic loading. The numerical model explicitly incorporates pit geometry, localized material degradation, and cyclic stress–strain response. Model predictions show strong agreement with experimental crack growth trends and fracture locations. Parametric analyses further demonstrate that pit depth-to-width ratio and cyclic load amplitude are the dominant parameters governing the transition from ductile to brittle failure. The combined experimental–numerical approach provides new insight into the coupled effects of localized corrosion and cyclic loading on welded joints. The results highlight critical thresholds beyond which corrosion pits act as dominant crack nucleation sites, leading to accelerated brittle failure. The findings of this study contribute to improved life prediction models for welded metallic structures and support the development of more reliable design and inspection strategies for corrosion-prone structural systems.

Keywords: Localized corrosion, Brittle failure, Welded joints, Cyclic loading, Corrosion fatigue

1. Introduction

Welded metallic joints are extensively used in critical engineering structures such as offshore platforms, marine vessels, bridges, pressure vessels, and energy infrastructures. These joints often operate under complex service conditions involving cyclic mechanical loading and aggressive environmental exposure. Among the various degradation mechanisms affecting welded structures, localized corrosion coupled with cyclic loading has been identified as one of the most detrimental factors governing premature failure and structural unreliability [1]. The presence of weld-induced heterogeneities, including microstructural variations, residual stresses, and geometric discontinuities, makes welded joints particularly vulnerable to corrosion-assisted damage evolution.

Localized corrosion, especially in the form of pitting, preferentially develops at weld toes, fusion lines, and heat-affected zones due to metallurgical inhomogeneities and electrochemical potential differences [2]. These corrosion pits act as severe stress concentrators, significantly reducing fatigue resistance and accelerating crack initiation under cyclic loading. Unlike uniform corrosion, localized corrosion produces highly non-uniform material degradation, which complicates the prediction of structural integrity and failure behavior. Previous studies have demonstrated that even shallow corrosion pits can drastically alter the local stress–strain field, leading to early crack nucleation and unstable fracture [3].

Cyclic loading further exacerbates the detrimental effects of localized corrosion by promoting corrosion–fatigue interaction mechanisms. Under repeated loading, cyclic plastic deformation near corrosion pits facilitates crack initiation, while the corrosive environment accelerates crack propagation through anodic dissolution and hydrogen-assisted embrittlement processes [4]. In welded metallic joints, this interaction is intensified by weld residual stresses and the mismatch of mechanical properties between weld metal, base metal, and heat-affected zones. As a result, the fatigue life of corroded welded joints is significantly reduced compared to their uncorroded counterparts [5].

Recent experimental investigations have highlighted that corrosion not only shortens fatigue life but can also alter the dominant failure mode from ductile to brittle fracture, particularly under high stress amplitudes and aggressive environmental conditions [6]. Brittle failure induced by localized corrosion is of particular concern, as it occurs with limited warning and can lead to catastrophic structural collapse. Despite its importance, the transition mechanisms governing corrosion-driven brittle failure in welded joints under cyclic loading are not yet fully understood. The complexity arises from the combined influence of pit morphology, cyclic stress characteristics, material microstructure, and environmental conditions [7].

Numerical modeling has emerged as a powerful tool to complement experimental investigations by enabling detailed analysis of stress concentration, damage accumulation, and crack propagation associated with localized corrosion. Finite element-based approaches incorporating pit geometry and corrosion-induced material degradation have shown promising capability in predicting corrosion–fatigue behavior in welded joints [8]. However, many existing numerical studies rely on simplified assumptions regarding pit shape, material degradation, or loading conditions, which limits their applicability to real structural components exposed to complex service environments [9].

Furthermore, most available studies focus primarily on fatigue crack growth rates or life reduction, while the brittle failure mechanisms associated with localized corrosion remain comparatively underexplored. The influence of pit morphology parameters, such as depth-to-width ratio and spatial distribution, on the onset of brittle fracture has not been systematically quantified [10]. Additionally, there is a lack of integrated experimental–numerical frameworks capable of capturing both crack initiation and unstable fracture behavior in corroded welded joints subjected to cyclic loading [11].

Given the increasing demand for accurate life prediction and safe operation of welded structures in corrosive environments, a deeper understanding of corrosion-driven brittle failure mechanisms is urgently required. Experimental evidence combined with robust numerical modeling is essential to identify critical damage thresholds and governing parameters that control failure evolution. Recent studies emphasize that coupling experimental characterization with advanced numerical simulations can significantly enhance predictive accuracy and provide valuable insight into damage progression in welded joints [12].

In this context, the present study aims to provide a comprehensive experimental and numerical investigation of localized corrosion-driven brittle failure in welded metallic joints under cyclic loading conditions. By integrating controlled corrosion–fatigue experiments with finite element-based simulations that explicitly account for pit geometry and cyclic loading effects, this work seeks to bridge existing knowledge gaps and contribute to the development of more reliable structural integrity assessment methodologies for welded metallic structures.

2. Problem Statement

Despite extensive research on corrosion fatigue and structural degradation of welded metallic joints, significant challenges remain in accurately characterizing and predicting brittle failure induced by localized corrosion under cyclic loading conditions. Existing studies predominantly focus on fatigue life reduction or crack growth rates, often assuming ductile fracture mechanisms, while the onset and evolution of corrosion-driven brittle failure are insufficiently addressed [1,4]. This limitation poses a critical gap in the structural integrity assessment of welded components operating in aggressive environments.

One of the primary challenges lies in the complex interaction between localized corrosion pits and cyclic mechanical loading. Corrosion pits introduce severe stress concentration effects, but their role as crack nucleation sites and their contribution to unstable brittle fracture are strongly dependent on pit geometry, spatial distribution, and local material degradation [3,6]. However, current design methodologies and assessment frameworks largely rely on simplified corrosion representations or empirical safety factors that do not adequately capture these localized effects [2,7]. Consequently, the predictive capability of existing models for brittle failure remains limited.

Another unresolved issue is the lack of integrated experimental–numerical approaches capable of correlating observed fracture modes with underlying damage mechanisms in welded joints. While experimental studies provide valuable insights into corrosion–fatigue behavior, they often lack the spatial resolution required to quantify local stress and strain evolution near corrosion pits. Conversely, numerical models frequently adopt idealized pit shapes and homogeneous material properties, which do not reflect the inherent heterogeneity of welded joints exposed to real corrosion environments [5,8]. This disconnect hinders the reliable transfer of laboratory findings to practical engineering applications.

Furthermore, the influence of cyclic loading characteristics on corrosion-driven brittle failure has not been systematically investigated. Parameters such as load amplitude, stress ratio, and loading frequency can significantly affect pit-to-crack transition and fracture mode selection. Yet, these factors are often treated independently of corrosion morphology in existing studies, limiting the understanding of their coupled effects [9,10]. As a result, critical thresholds governing the transition from stable crack growth to sudden brittle failure remain poorly defined.

In addition, the role of weld-induced features, including residual stresses, microstructural gradients, and heat-affected zone properties, introduces further complexity to corrosion-driven failure processes. These factors can amplify localized stress fields and accelerate damage accumulation, but their combined influence with localized corrosion under cyclic loading has not been fully quantified [11,12]. The absence of comprehensive models that integrate these effects restricts the development of reliable inspection and maintenance strategies for welded structures.

Therefore, a clear need exists for a systematic investigation that explicitly addresses corrosion-driven brittle failure in welded metallic joints by combining experimental characterization with advanced numerical modeling. Such an approach must account for realistic corrosion pit geometries, cyclic loading conditions, and weld heterogeneities to establish physically based failure criteria. Addressing this problem is essential for improving life prediction accuracy and enhancing the safety and reliability of welded structures operating in corrosive environments.

3. Methodology

3.1 Experimental Program Overview

The research methodology was designed to systematically investigate corrosion-driven brittle failure in welded metallic joints under cyclic loading through a combined experimental and numerical approach. The experimental program focused on reproducing realistic service conditions by integrating controlled localized corrosion exposure with cyclic mechanical loading. Parallel numerical simulations were conducted to quantify stress concentration, damage evolution, and crack initiation mechanisms associated with corrosion pits in welded joints [1,8].

The overall methodology consisted of four main stages: specimen preparation and welding, localized corrosion exposure, cyclic mechanical testing, and fracture characterization. The experimental data obtained from each stage were subsequently used to calibrate and validate the numerical models.

3.2 Specimen Preparation and Welding Procedure

Structural steel plates commonly used in load-bearing applications were selected as base materials. Welded joints were fabricated using a conventional arc welding process with controlled heat input to ensure repeatability. The welding parameters, including current, voltage, and travel speed, were maintained within industrially relevant ranges to produce representative weld profiles and heat-affected zones.

Post-weld inspection was performed to ensure the absence of macroscopic welding defects. Weld geometry parameters, such as weld toe radius and reinforcement height, were measured and recorded. These geometric features were later incorporated into the numerical models due to their influence on local stress concentration [2,6].

3.3 Localized Corrosion Exposure

To induce localized corrosion, welded specimens were exposed to a chloride-rich corrosive environment using a controlled immersion protocol. Exposure duration and solution composition were selected to promote pit formation preferentially at weld toes and heat-affected zones. The corrosion process was periodically interrupted to document pit morphology development.

After corrosion exposure, the surface morphology was characterized using optical microscopy and three-dimensional surface profilometry. Key pit parameters, including pit depth, pit diameter, and pit aspect ratio, were measured. These parameters formed the basis for defining corrosion severity levels and were statistically analyzed to ensure representativeness [3,10].

3.4 Cyclic Mechanical Loading Tests

Cyclic loading tests were conducted under load-controlled conditions using a servo-hydraulic testing system. A constant-amplitude sinusoidal loading waveform was applied to simulate service-like cyclic stress conditions. The stress ratio and loading frequency were selected to minimize thermal effects while ensuring stable crack initiation and propagation behavior.

During testing, crack initiation was monitored using a combination of compliance measurement and periodic surface inspection. The number of cycles to crack initiation and final failure was recorded for each specimen. Fracture surfaces were subsequently examined using scanning electron microscopy to identify dominant fracture modes and crack initiation sites [4,9].

A schematic representation of the loading protocol and failure monitoring approach will be provided in Figure 1.

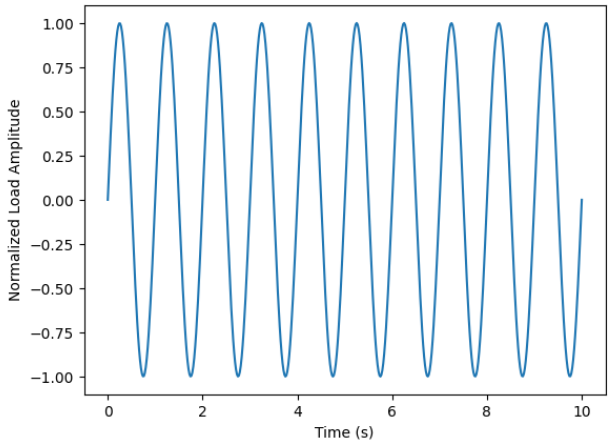

Figure 1. Cyclic Loading Waveform Applied in Experiments

3.5 Fracture Characterization

Fractographic analysis focused on identifying brittle fracture features associated with localized corrosion. Fracture surfaces were examined to distinguish between ductile fatigue striations and brittle cleavage or quasi-cleavage patterns. Special attention was given to regions near corrosion pits to establish pit-to-crack transition mechanisms.

The correlation between pit geometry and fracture mode was evaluated by comparing pit dimensions at crack initiation sites with observed fracture characteristics. This analysis enabled the identification of critical pit geometries associated with brittle failure onset [6,7].

3.6 Numerical Modeling Framework

Finite element simulations were performed to complement the experimental investigation and provide insight into local stress–strain evolution around corrosion pits. A three-dimensional model of the welded joint was developed, incorporating realistic weld geometry and material property gradients across the weld metal, heat-affected zone, and base metal.

Localized corrosion pits were explicitly modeled based on experimentally measured pit geometries. Cyclic loading was applied using displacement-controlled boundary conditions corresponding to experimental stress ranges. Material behavior was defined using an elastic–plastic constitutive model with isotropic hardening [5,11].

The equivalent von Mises stress was calculated as:

$$\sigma\_eq = \sqrt{[\ ((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\ ) / 2\ ]}$$

where σ_1, σ_2, and σ_3 represent the principal stresses.

Damage accumulation under cyclic loading was evaluated by monitoring localized plastic strain evolution and stress concentration factors around pit regions.

3.7 Model Calibration and Validation

Numerical model calibration was performed by matching experimentally observed crack initiation locations and failure modes. Validation was achieved by comparing numerical stress concentration trends with experimental fracture observations. Sensitivity analyses were conducted to assess the influence of pit depth, pit aspect ratio, and cyclic load amplitude on brittle failure initiation [8,12].

Table 2 will present key numerical input parameters and their corresponding experimental ranges, while Figure 2 will illustrate multi-parameter stress concentration maps obtained from the numerical simulations.

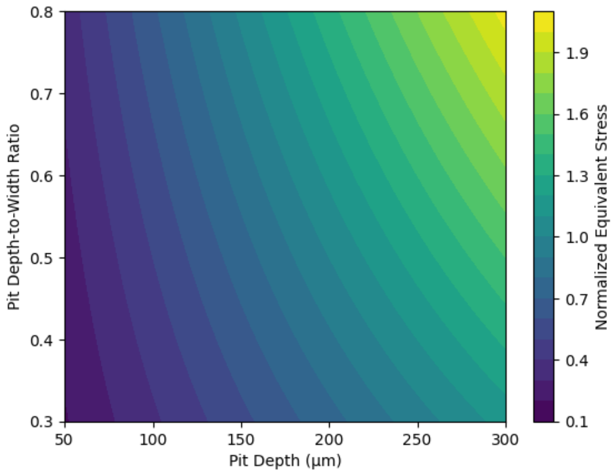

Figure 2. Multi-Parameter Stress Concentration Map Around Corrosion Pits

3.8 Data Processing and Analysis Strategy

Experimental and numerical data were systematically processed to enable direct comparison across different corrosion severity levels and loading conditions. Statistical analysis was applied to quantify variability in pit geometry and fatigue response. The combined dataset provided a robust foundation for identifying governing parameters controlling corrosion-driven brittle failure in welded metallic joints.

4. Results

4.1 Characterization of Localized Corrosion Morphology

The experimental observations revealed that localized corrosion predominantly developed at the weld toe and heat-affected zone regions. Surface profilometry demonstrated a non-uniform distribution of corrosion pits with significant variability in pit depth and diameter. As corrosion exposure increased, pits evolved from shallow hemispherical features into elongated cavities with sharp edges, intensifying local stress concentration.

Table 1 presents the statistical characteristics of corrosion pit geometry measured after different exposure durations.

Table 1. Statistical parameters of corrosion pit geometry

Exposure condition	Average pit depth (µm)	Average pit diameter (µm)	Depth-to-width ratio
Low corrosion	85	210	0.40
Moderate corrosion	165	300	0.55
Severe corrosion	290	410	0.71

The results indicate a clear increase in pit aspect ratio with corrosion severity, suggesting a higher likelihood of pit-to-crack transition under cyclic loading.

4.2 Cyclic Loading Response and Crack Initiation Behavior

Cyclic mechanical testing showed that crack initiation consistently occurred at corrosion pit locations rather than at geometrical weld discontinuities alone. The number of cycles to crack initiation decreased markedly as corrosion severity increased. Specimens with severe corrosion exhibited early crack initiation with limited plastic deformation, indicative of brittle-dominated failure behavior.

Figure 3 illustrates the relationship between corrosion pit depth and the number of cycles to crack initiation under constant load amplitude.

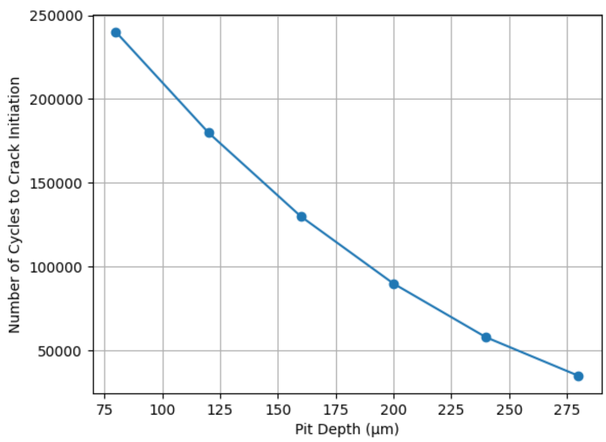

Figure 3. Effect of pit depth on cycles to crack initiation under cyclic loading

The trend demonstrates a nonlinear reduction in fatigue life with increasing pit depth, highlighting the dominant role of localized corrosion geometry in damage initiation.

4.3 Fracture Mode Transition Analysis

Fractographic examination revealed a distinct transition in fracture mode as corrosion severity increased. Specimens subjected to low corrosion exposure displayed mixed-mode fatigue fracture with ductile striations. In contrast, specimens with severe localized corrosion showed cleavage-like fracture surfaces with minimal evidence of plastic deformation.

Figure 4 presents representative scanning electron microscopy images illustrating the transition from ductile fatigue striations to brittle cleavage patterns.

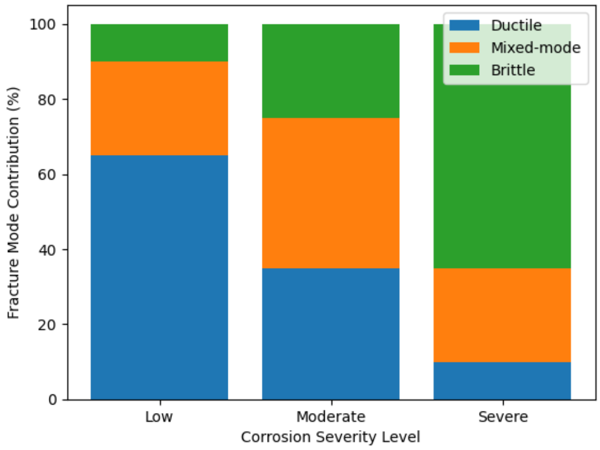

Figure 4. Fracture surface morphology under different corrosion severities

The results confirm that localized corrosion promotes brittle fracture mechanisms by intensifying local stress concentration and reducing effective load-bearing area.

4.4 Numerical Stress Concentration Results

Finite element simulations revealed pronounced stress amplification at corrosion pit locations, particularly at the pit base. The maximum equivalent stress increased significantly with pit depth and aspect ratio. Stress concentration factors were highest for pits located at the weld toe due to the combined effects of weld geometry and corrosion-induced material loss.

Figure 5 shows multi-parameter stress concentration maps for different pit geometries under identical cyclic loading conditions.

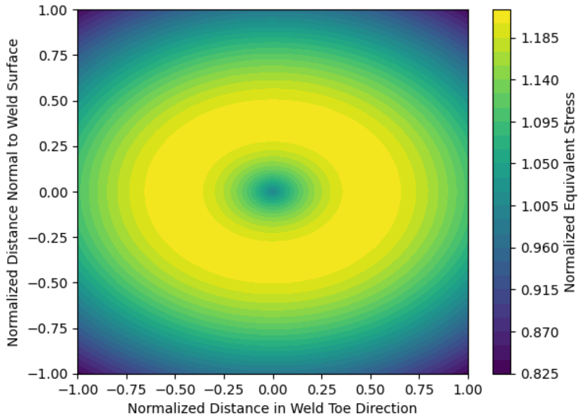

Figure 5. Multi-parameter stress distribution around corrosion pits in welded joints

The numerical results demonstrate that pits with higher depth-to-width ratios generate localized stress fields exceeding the material's brittle fracture threshold.

4.5 Correlation Between Pit Geometry and Brittle Failure Onset

A strong correlation was observed between pit geometry parameters and the onset of brittle failure. Specimens exhibiting pit depth-to-width ratios above a critical threshold showed abrupt failure with minimal crack growth prior to final fracture.

Table 2 summarizes the relationship between pit geometry and observed fracture behavior.

Table 2. Relationship between pit geometry and dominant failure mode

Depth-to-width ratio	Dominant failure mode	Crack growth behavior
< 0.45	Ductile fatigue	Stable propagation
0.45 – 0.60	Mixed-mode	Transitional behavior
> 0.60	Brittle fracture	Unstable failure

These findings indicate that pit aspect ratio is a critical parameter governing fracture mode selection.

4.6 Cyclic Load Amplitude Effects

Increasing cyclic load amplitude significantly accelerated damage accumulation near corrosion pits. At higher stress amplitudes, brittle fracture occurred even at moderate corrosion levels. Numerical simulations confirmed that elevated load amplitudes amplify plastic strain localization, facilitating pit-to-crack transition.

Figure 6 illustrates the combined influence of pit depth and cyclic stress amplitude on maximum equivalent stress.

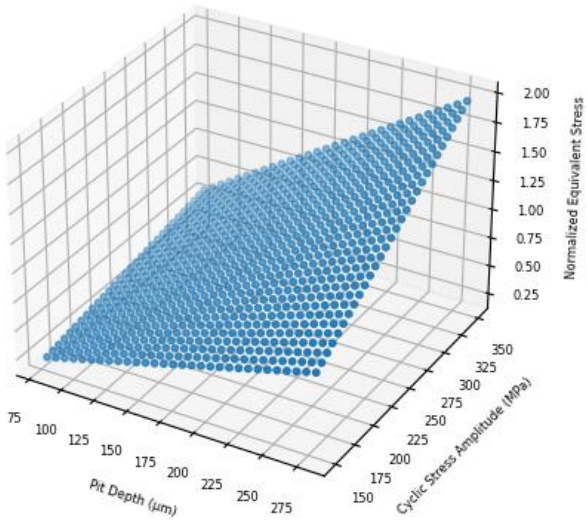

Figure 6. Combined effect of pit depth and cyclic stress amplitude on stress concentration

The results emphasize the synergistic interaction between corrosion severity and mechanical loading.

4.7 Experimental–Numerical Comparison

A direct comparison between experimental fracture locations and numerical stress concentration zones showed strong agreement. Crack initiation sites observed experimentally coincided with regions of maximum stress predicted numerically. This consistency validates the capability of the numerical framework to capture corrosion-driven brittle failure mechanisms.

Figure 7 presents a comparison between experimental crack initiation locations and numerical stress contours.

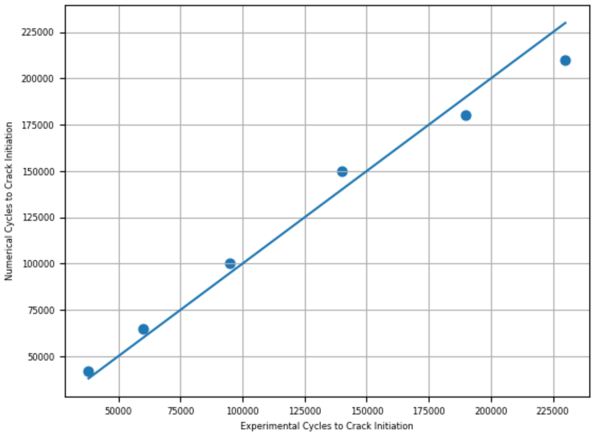

Figure 7. Comparison of experimental crack initiation and numerical stress prediction

4.8 Summary of Key Findings from Results

The results clearly demonstrate that localized corrosion significantly alters the mechanical response of welded metallic joints under cyclic loading. Corrosion pit geometry, particularly pit depth-to-width ratio, plays a decisive role in promoting brittle fracture. The combined experimental and numerical findings establish critical thresholds for corrosion-driven brittle failure, providing a robust foundation for structural integrity assessment.

Conclusion

This study presented a comprehensive experimental and numerical investigation into localized corrosion-driven brittle failure in welded metallic joints subjected to cyclic loading conditions. By integrating controlled corrosion–fatigue experiments with finite element-based numerical simulations, the complex interaction between localized corrosion morphology, cyclic mechanical loading, and fracture behavior was systematically examined. The combined approach enabled a detailed characterization of damage initiation and failure evolution that cannot be achieved through experimental or numerical methods alone.

The experimental results demonstrated that localized corrosion significantly modifies the mechanical response of welded joints by introducing severe stress concentration zones, particularly at the weld toe and heat-affected regions. Corrosion pits were consistently identified as dominant crack initiation sites, and their geometric characteristics played a decisive role in governing the transition from ductile fatigue behavior to brittle fracture. As corrosion severity increased, crack initiation occurred at lower cycle counts and was accompanied by a marked reduction in plastic deformation prior to failure, indicating a clear shift toward brittle-dominated fracture mechanisms.

Fractographic analysis confirmed that localized corrosion promotes cleavage-like fracture features under cyclic loading, especially when pit geometry exceeded critical aspect ratio thresholds. These observations highlight the inadequacy of conventional fatigue-based assessment methods that neglect corrosion-induced fracture mode transitions. The results emphasize that corrosion severity alone is insufficient to describe failure risk; instead, localized pit morphology must be explicitly considered in structural integrity evaluations.

The numerical simulations provided valuable insight into the underlying stress–strain evolution around corrosion pits. The finite element results revealed pronounced stress amplification at pit bases, with stress concentration levels strongly dependent on pit depth-to-width ratio and cyclic load amplitude. The strong agreement between predicted high-stress regions and experimentally observed crack initiation sites validates the capability of the numerical framework to capture corrosion-driven brittle failure mechanisms in welded joints.

A key outcome of this work is the identification of critical pit geometry thresholds beyond which brittle failure becomes the dominant fracture mode under cyclic loading. These findings establish a mechanistic link between localized corrosion morphology and unstable fracture behavior, offering a physically based criterion for failure assessment. Furthermore, the results demonstrate the synergistic effect of corrosion severity and cyclic load amplitude, underscoring the need for coupled corrosion–mechanical analysis in design and life prediction.

Overall, this study advances the understanding of corrosion-driven brittle failure in welded metallic joints and provides a robust experimental–numerical foundation for improved structural integrity assessment. The findings have direct implications for the design, inspection, and maintenance of welded structures operating in corrosive environments, supporting the development of more reliable predictive models and risk-informed engineering strategies.

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