Stress-Dependent Dispersion of Corrosion–Fatigue Life in Aa 7075-T651 Under Multiaxial Loading: A Weibull-Based Analysis

Kingsley Obinna Iwuji

Opole University of Technology

DOI: https://doi.org/10.51583/IJLTEMAS.2026.150300033

Received: 14 March 2026; Accepted: 19 March 2026; Published: 04 April 2026

ABSTRACT

Corrosion–fatigue of high-strength aluminium alloys is governed not only by reductions in mean fatigue life but, more critically, by systematic changes in fatigue-life dispersion that directly affect structural reliability. In this study, the corrosion–fatigue behaviour of AA 7075-T651 under multiaxial loading is analysed from a dispersion-centred statistical perspective using a Weibull-based framework to quantify how variability evolves with stress level, corrosion exposure, and loading mode. Fatigue data obtained under uncorroded conditions and after 7-day and 14-day NaCl exposure were analysed for bending and torsional loading. Stress-level binning was employed to ensure statistically robust parameter estimation without extrapolation beyond the experimentally tested domain. Rather than treating scatter as experimental noise, the Weibull shape parameter is explicitly interpreted as a stress- and environment-dependent descriptor of fatigue-life variability. The results show that, under uncorroded conditions, fatigue-life dispersion increases significantly at lower stress levels for both bending and torsional loading, consistent with a transition toward initiation-controlled failure. Corrosion exposure produces a pronounced and persistent reduction in the Weibull shape parameter, indicating a fundamental broadening of the fatigue-life distribution that intensifies with increasing exposure duration. Loading mode is further shown to modulate this behaviour, with torsional loading exhibiting distinct dispersion characteristics relative to bending, particularly in corrosive environments. These findings demonstrate that fatigue-life dispersion in AA 7075-T651 cannot be characterised using stress-independent statistical parameters or inferred reliably from mean-life trends alone. Instead, dispersion evolves systematically with stress level, environmental degradation, and loading mode, necessitating stress- and environment-dependent probabilistic descriptions. By explicitly quantifying these effects, the present study provides a statistical basis for advancing corrosion–fatigue assessment beyond conventional deterministic and mean-life-based approaches toward reliability-oriented evaluation under multiaxial loading.

Keywords: Corrosion–fatigue, Weibull distribution, fatigue-life dispersion, multiaxial loading, AA 7075-T651

INTRODUCTION

Corrosion–fatigue of high-strength aluminium alloys is characterised not only by a reduction in fatigue life but also by a pronounced increase in life scatter. For alloys such as AA 7075-T651, this variability becomes particularly critical under multiaxial loading conditions, where complex stress states can substantially influence fatigue damage accumulation and failure probability [1]. Despite its direct relevance to structural reliability, fatigue-life scatter has traditionally received less attention than mean S–N behaviour, especially in corrosion–fatigue studies where design decisions are often based primarily on average trends.

Fatigue-life variability is increasingly recognised as a dominant factor in high-cycle and very-high-cycle fatigue regimes, where relatively small changes in stress level may lead to large differences in observed life [2]. In such regimes, deterministic descriptions based solely on mean behaviour become inadequate, particularly when multiaxial loading introduces non-proportional stress components, competing damage mechanisms, and heightened sensitivity to microstructural and surface-condition effects [3]–[5]. Under these conditions, scatter is no longer incidental but represents an intrinsic characteristic of the fatigue response, with direct implications for reliability-based design and assessment.

Probabilistic approaches provide a natural framework for capturing this behaviour. Among these, the Weibull distribution has been widely adopted for fatigue-life analysis due to its flexibility and its ability to represent the right-skewed life distributions commonly observed in metallic materials [6]. Importantly, several studies have demonstrated that Weibull parameters particularly the shape parameter are not constant material properties but exhibit systematic dependence on stress level, with fatigue-life dispersion often increasing as stress decreases [6], [7]. These findings indicate that variability itself evolves with loading conditions and should be treated as a stress-dependent response rather than as random experimental scatter.

For AA 7075-T651, extensive experimental investigations have been reported under uniaxial and multiaxial loading in non-corrosive environments, providing valuable insight into cyclic deformation behaviour, load-sequence effects, and fatigue damage mechanisms [8]–[10]. While these studies establish a robust understanding of baseline fatigue performance, they predominantly rely on deterministic or mean-life descriptions and do not explicitly quantify fatigue-life dispersion using probabilistic metrics. When corrosion is introduced, the interaction between environmental degradation and cyclic loading is expected to further amplify variability, making a systematic statistical characterisation of fatigue-life scatter particularly important.

The objective of the present study is therefore to quantitatively characterise corrosion–fatigue life dispersion in AA 7075-T651 using a Weibull-based statistical framework. Rather than focusing on mean-life degradation alone, this work examines how fatigue-life dispersion evolves as a function of stress level, corrosion duration, and loading mode under multiaxial loading conditions. Emphasis is placed on the interpretation of Weibull parameters as descriptors of variability, without recourse to mechanistic modelling of corrosion pits or crack initiation processes. By isolating stress-level-dependent dispersion effects, the study aims to provide a statistically grounded basis for reliability-oriented assessment of corrosion–fatigue behaviour that extends beyond conventional mean-life approaches.

METHODOLOGY

Statistical Framework

Experimental Dataset

The fatigue data analysed in this study were obtained from an experimental programme previously reported in detail in the literature [11]. The material investigated is the high-strength aluminium alloy AA 7075-T651. Prior to fatigue testing, specimens were subjected to controlled corrosion exposure, including an uncorroded reference condition and immersion in a sodium chloride (NaCl) solution for durations of 7 days and 14 days.

Fatigue tests were conducted under different loading modes, namely bending, torsion, and combined bending–torsion, in order to capture the influence of multiaxial stress states on fatigue-life behaviour. Fatigue life was defined as the number of cycles to failure. Run-out data were identified and treated consistently within the statistical analysis framework, as described explicitly in the methodology, to ensure unbiased estimation of fatigue-life dispersion.

To enable a unified statistical treatment of results obtained under different loading modes, an equivalent stress parameter σ_{eq}, was adopted. The definition of this parameter is deterministic and consistent with that employed in previous studies based on the same experimental dataset [11]. Detailed descriptions of specimen geometry, test rigs, corrosion procedures, and loading configurations are therefore not repeated here and can be found in the referenced work.

Although combined bending–torsion tests were included in the original experimental programme, the number of failed specimens under combined loading was insufficient to support statistically reliable Weibull parameter estimation. Consequently, combined loading data were intentionally excluded from the dispersion analysis. This restriction ensures that all reported Weibull parameters are based on adequately populated datasets and that subsequent statistical interpretations remain robust and defensible.

Choice of Distribution

Fatigue-life data are typically characterised by right-skewed distributions and substantial scatter, particularly under multiaxial loading and in corrosive environments where damage mechanisms are inherently heterogeneous. To capture this variability in a statistically consistent and interpretable manner, the Weibull distribution is adopted in the present study. The Weibull model is widely used in fatigue reliability analysis due to its mathematical flexibility and its ability to represent a broad range of dispersion behaviours using a limited number of parameters [12].

From a statistical standpoint, the Weibull distribution is well suited to life data analysis because it can accommodate increasing, constant, or decreasing failure rates depending on the value of the shape parameter. This capability is especially relevant for fatigue problems, where governing damage processes and failure probabilities may evolve with stress level, loading mode, and environmental condition [13]. Consequently, the Weibull framework provides a natural basis for probabilistic assessment of fatigue life in metallic materials.

In fatigue applications, the Weibull distribution has been successfully employed to unify the description of characteristic behaviour and statistical scatter within a single formulation. Unified statistical methodologies for fatigue modelling have demonstrated that Weibull-based representations can effectively describe experimental fatigue data across different stress regimes without requiring explicit assumptions regarding underlying damage mechanisms [14]. This feature is particularly advantageous when the objective is to quantify variability rather than to infer physical processes.

Previous studies have further shown that scatter in S–N data is not constant but varies systematically with stress level, especially in the high-cycle fatigue regime. Such stress-dependent dispersion has been linked to changes in crack initiation dominance and microstructural sensitivity, effects that are naturally reflected through variations in Weibull parameters [15], [16]. The Weibull distribution therefore provides a statistically robust framework for analysing fatigue-life dispersion as a function of stress level, corrosion exposure, and loading mode.

On this basis, the Weibull distribution is selected in the present study as the primary statistical model for quantifying corrosion–fatigue life dispersion in AA 7075-T651. The analysis focuses on comparative evaluation of Weibull parameters under different conditions, rather than on absolute reliability prediction or mechanistic interpretation, in full alignment with the defined scope of the work.

Weibull Parameters (β and η)

Within the Weibull framework, fatigue-life behaviour is characterised using two primary parameters: the shape parameter β and the scale parameter η. Together, these parameters provide a compact statistical description of both fatigue-life dispersion and characteristic life, with β governing the degree of scatter and η representing a characteristic fatigue life corresponding to a defined survival probability.

The Weibull shape parameter β is widely interpreted as a quantitative indicator of fatigue-life dispersion. Lower values of β correspond to broader life distributions and increased variability, whereas higher values indicate more concentrated fatigue-life data with reduced scatter. Importantly, β is not a fixed material constant but has been shown to depend on loading conditions, stress level, and failure probability, particularly when fatigue behaviour is examined at low probabilities of failure [6]. This sensitivity makes β especially suitable for assessing how corrosion exposure and multiaxial loading influence fatigue-life variability.

Recent developments in Weibull-based fatigue modelling have further emphasised the importance of appropriate parameter formulation for accurately representing experimental scatter. Modified Weibull parameterisations have been proposed to improve the fidelity of probability density functions and to reduce discretisation-related errors in fatigue applications, particularly when stress levels vary across test conditions [7]. Such formulations reinforce the interpretation of β as a physically meaningful descriptor of dispersion rather than a purely statistical fitting parameter.

The Weibull scale parameter η represents the characteristic fatigue life at which approximately 63.2% of specimens are expected to fail. In the present study, η is employed primarily as a reference quantity for comparing fatigue-life levels across different corrosion conditions and loading modes. Emphasis is placed on relative changes in η rather than absolute life prediction, in order to maintain consistency with the statistical focus of the analysis and to avoid extrapolation beyond the experimentally tested stress ranges.

In corrosion–fatigue applications, Weibull parameters have been successfully used to characterise reliability trends and life variability under environmentally assisted degradation. Previous Weibull-based reliability studies have demonstrated that both β and η can be significantly influenced by corrosion exposure, reflecting increased uncertainty and reduced characteristic life as environmental severity increases [14], [15]. These findings support the use of Weibull parameters as effective descriptors for analysing corrosion-induced changes in fatigue-life dispersion.

Accordingly, Weibull parameters are extracted in this study for each combination of stress level, corrosion condition, and loading mode. Their interpretation is intentionally restricted to comparative statistical behaviour within the tested domain, without extrapolation to untested stress ranges or attribution to specific microstructural or mechanistic processes, in full agreement with the defined scope of the work.

Stress-Level Binning Strategy

To examine the dependence of fatigue-life dispersion on stress level in a statistically consistent manner, the experimental data were grouped into discrete stress-level bins. This binning strategy enables Weibull parameters to be evaluated within comparable stress ranges while avoiding excessive fragmentation of the dataset, which can lead to unstable parameter estimation. Stress-level grouping is particularly important in fatigue analyses, as Weibull parameters—especially the shape parameter β—are known to vary systematically with applied stress level rather than remaining constant across the full S–N domain [6].

In the present study, the data were categorised according to corrosion condition, loading mode, and stress level. For each corrosion and loading configuration, stress levels were initially divided into low, medium, and high ranges. To ensure statistically meaningful estimation of Weibull parameters and to limit sensitivity to individual data points, a minimum of eight failure events per stress bin was targeted. Comparable binning strategies have been employed successfully in previous Weibull-based fatigue studies to capture stress-dependent dispersion while avoiding artificial trends associated with over-parameterisation [7].

Where the initial three-bin division resulted in insufficient failure counts for robust statistical inference, adjacent stress bins were merged to satisfy the minimum sample-size requirement. Consequently, uncorroded conditions were analysed using two stress groups (low and high), while corroded conditions were analysed using a single aggregated stress group. This adaptive binning procedure reflects a data-driven compromise between stress resolution and statistical reliability, ensuring that estimated Weibull parameters remain stable and interpretable.

Beyond facilitating parameter estimation, the stress-level binning strategy also defines the scope of statistical inference in the present work. By restricting the analysis to experimentally tested stress ranges and avoiding extrapolation beyond the available data, the study does not attempt to infer endurance limits, threshold stresses, or long-term service behaviour. Instead, Weibull parameters are interpreted as local descriptors of fatigue-life variability within defined stress groups, fully consistent with the objective of statistically characterising dispersion rather than predicting fatigue performance outside the experimental domain.

RESULTS

Fatigue-Life Dispersion under Uncorroded Conditions

The uncorroded fatigue data provide a necessary statistical reference for assessing fatigue-life dispersion in AA 7075-T651 prior to the influence of environmental degradation. Weibull shape (β) and scale (η) parameters obtained for bending and torsional loading under uncorroded conditions are summarised in Table 1 and serve as a baseline for evaluating corrosion-induced changes in variability.

Table 1. Weibull parameters for fatigue-life dispersion of AA 7075-T651

Corrosion condition	Loading mode	Stress group	β (shape)	η (cycles)	n
initial	bending	low	0.613	1.48×10^6	10
initial	bending	high	1.244	6.08×10^4	9
initial	torsion	low	1.361	1.34×10^6	9
initial	torsion	high	1.633	1.20×10^5	8
7days	bending	all	0.672	1.27×10^5	9
7days	torsion	all	0.497	3.53×10^5	12
14days	bending	all	0.703	8.38×10^4	11
14days	torsion	all	0.516	3.79×10^5	11

As shown in Table 1, uncorroded bending exhibits a pronounced dependence of fatigue-life dispersion on stress level. The Weibull shape parameter decreases from $\beta \approx 1.24$ at high stress to $\beta \approx 0.61$ at low stress, indicating a substantial broadening of the fatigue-life distribution in the low-stress regime. This increase in dispersion at lower stress levels reflects enhanced sensitivity to initiation-controlled fatigue processes, where local material heterogeneities and surface condition play a more dominant role than deterministic crack propagation. Similar stress-dependent increases in scatter have been reported in probabilistic fatigue studies employing Weibull statistics, particularly in high-cycle fatigue regimes [6], [16].

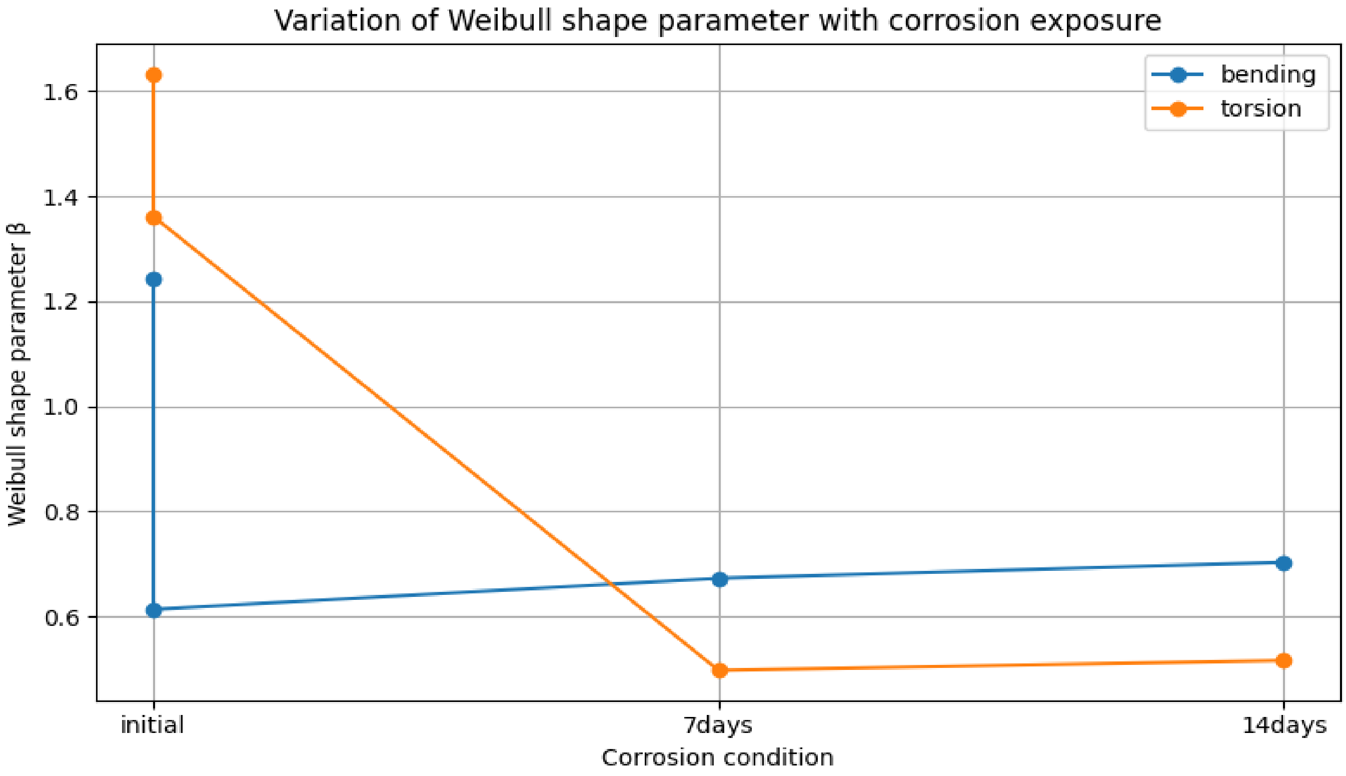

Figure 1: Variation of the Weibull shape parameter β with corrosion exposure for bending and torsional loading of AA 7075-T651.

In contrast, uncorroded torsional loading yields consistently higher Weibull shape parameters at both stress levels, with $\beta \approx 1.63$ at high stress and $\beta \approx 1.36$ at low stress. These values indicate comparatively narrower fatigue-life distributions and reduced scatter relative to bending. The reduced dispersion under torsional loading suggests a more stable fatigue response, likely associated with differences in stress state and damage accumulation mechanisms compared with bending-dominated loading. This observation is consistent with previous multiaxial fatigue investigations on AA 7075-T651, which reported more uniform fatigue behaviour under torsional loading conditions [1].

The variation of the Weibull shape parameter with loading mode under uncorroded conditions highlights that fatigue-life dispersion is inherently influenced by stress state, even in the absence of corrosion. As illustrated in Fig. 1, torsional loading consistently exhibits higher β values than bending across the investigated stress range, confirming lower intrinsic variability under torsion. Together, these results establish a quantitative statistical baseline for AA 7075-T651, against which the effects of corrosion exposure and loading-mode complexity on fatigue-life dispersion are examined in the subsequent sections.

Effect of Seven-Day Corrosion Exposure on Fatigue-Life Dispersion

The influence of short-term corrosion exposure on fatigue-life dispersion was evaluated using data obtained after seven days of NaCl exposure. The corresponding Weibull shape (β) and scale (η) parameters are reported in Table 1, while overall trends relative to the uncorroded condition are illustrated in Fig. 1, enabling assessment of the early statistical effects of environmental degradation on fatigue behaviour.

As shown in Table 1, seven-day corrosion exposure results in a pronounced reduction in the Weibull shape parameter for both bending and torsional loading compared with the uncorroded baseline. For bending, the estimated β value decreases to approximately 0.67, indicating a substantially broader fatigue-life distribution relative to uncorroded bending at comparable stress levels. This reduction in β demonstrates that corrosion-induced variability emerges rapidly, even over relatively short exposure durations, and cannot be regarded as a secondary or long-term effect.

An even more pronounced increase in dispersion is observed under torsional loading. After seven days of corrosion exposure, the Weibull shape parameter decreases to approximately $\beta \approx 0.50$ (Table 1), representing the lowest β value obtained among all investigated conditions. Such a low shape parameter indicates severe fatigue-life variability and highlights the strong sensitivity of shear-dominated stress states to early-stage corrosion damage. This behaviour is clearly reflected in Fig. 1, where the seven-day torsional data lie well below the corresponding uncorroded values across the investigated stress range.

The observed increase in dispersion with short-term corrosion exposure is consistent with previous corrosion–fatigue reliability studies, which have shown that environmental degradation amplifies fatigue-life variability by increasing sensitivity to surface condition, stress distribution, and local damage accumulation [2], [11]. Probabilistic analyses based on Weibull statistics further indicate that corrosion effects often manifest more strongly through increased scatter than through reductions in mean fatigue life alone [13]. The present results reinforce this observation by demonstrating that dispersion responds rapidly to corrosion exposure, even before longer-term degradation mechanisms develop.

Although the present study does not explicitly account for corrosion pit geometry or crack initiation mechanisms, the statistical trends observed after seven days of exposure are consistent with reported stress–corrosion interactions in fatigue, where corrosion-induced damage enhances life scatter across different stress states [12]. Taken together, these findings indicate that even limited corrosion exposure fundamentally alters the statistical distribution of fatigue life, underscoring the need to treat dispersion as a primary consideration in corrosion–fatigue assessment rather than as a secondary consequence of life reduction.

Effect of Fourteen-Day Corrosion Exposure on Fatigue-Life Dispersion

The effect of extended corrosion exposure on fatigue-life dispersion was assessed using data obtained after fourteen days of NaCl exposure. The corresponding Weibull parameters are summarised in Table 1, while comparative trends across corrosion conditions are illustrated in Fig. 1, enabling direct evaluation of how prolonged environmental degradation alters the statistical distribution of fatigue life. As shown in Table 1, fourteen-day corrosion exposure results in persistently low Weibull shape parameters for both bending and torsional loading, indicating a sustained and pronounced increase in fatigue-life dispersion relative to the uncorroded condition. For bending, the estimated shape parameter decreases to $\beta \approx 0.70$, remaining well below values obtained under uncorroded loading. This confirms that the increase in scatter observed after seven days of corrosion exposure is not transient, but instead reflects a stable shift toward broader fatigue-life distributions with increasing exposure duration.

Under torsional loading, the amplification of dispersion is even more pronounced. The Weibull shape parameter decreases further to β ≈ 0.52 after fourteen days of corrosion (Table 1), indicating a highly dispersed fatigue-life distribution. As illustrated in Fig. 1, torsional loading consistently exhibits lower β values than bending under corroded conditions, demonstrating that shear-dominated stress states are particularly sensitive to corrosion-induced variability. This behaviour highlights a strong interaction between loading mode and environmental degradation in governing fatigue-life dispersion.

The observed persistence and amplification of dispersion with increased corrosion duration are consistent with probabilistic corrosion–fatigue studies based on Weibull statistics, which report systematic reductions in the shape parameter as environmental severity increases [17], [18]. Importantly, similar trends have also been identified in data-driven fatigue-life analyses of aluminium alloys, where increased surface degradation leads to broader life distributions and reduced predictability even when mean-life trends remain comparatively smooth [7]. These findings indicate that prolonged corrosion exposure primarily degrades the predictability of fatigue performance rather than merely reducing characteristic life.

The combined influence of corrosion duration and loading mode on fatigue-life dispersion aligns with reliability-based corrosion–fatigue frameworks that emphasise the dominant role of statistical variability under sustained environmental exposure [2]. Within this context, the fourteen-day corrosion condition represents a regime in which variability becomes a controlling factor in fatigue behaviour, reinforcing the necessity of explicitly accounting for environment- and loading-dependent dispersion in probabilistic assessment of corrosion–fatigue performance.

Influence of Loading Mode

The influence of loading mode on fatigue-life dispersion was assessed through a statistical comparison of bending and torsional loading under uncorroded and corroded conditions. Weibull shape (β) parameters obtained for each loading mode are summarised in Table 1, while comparative trends across corrosion conditions are illustrated in Fig. 1, enabling direct evaluation of how stress state affects fatigue-life variability.

Under uncorroded conditions, torsional loading exhibits consistently higher Weibull shape parameters than bending at comparable stress levels, indicating narrower fatigue-life distributions and reduced scatter under torsion. This demonstrates that loading mode alone governs fatigue-life dispersion even in the absence of environmental degradation. The observed distinction reflects differences in stress state and damage accumulation associated with bending- and torsion-dominated loading. Similar loading-mode-dependent variability has been reported in probabilistic multiaxial fatigue studies of AA 7075-T651, where torsional loading was shown to exhibit more stable fatigue behaviour relative to bending [19].

Following corrosion exposure, the influence of loading mode on fatigue-life dispersion becomes more pronounced. Both seven-day and fourteen-day corrosion conditions result in systematically lower Weibull shape parameters for torsional loading compared with bending. As illustrated in Fig. 1, torsional data points lie consistently below those for bending under corroded conditions, indicating a broader fatigue-life distribution. This suggests that torsional loading is particularly sensitive to corrosion-induced variability, likely due to the interaction between shear-dominated stress states and surface degradation effects.

The observed loading-mode dependence of fatigue-life dispersion is consistent with Weibull-based probabilistic frameworks developed for multiaxial and notched fatigue problems, which demonstrate that variations in stress state and load path significantly influence the statistical distribution of fatigue life [20], [21]. Energy-based multiaxial fatigue approaches combined with probabilistic formulations further support the conclusion that loading mode plays a critical role in controlling fatigue-life scatter, even when mean-life predictions across loading configurations remain comparable [22], [23].

Within the scope of the present study, these results confirm that loading mode is a governing parameter in fatigue-life dispersion for AA 7075-T651. The systematically lower Weibull shape parameters obtained under torsional loading—particularly in corrosive environments—highlight that loading mode not only affects characteristic fatigue life but also fundamentally alters the uncertainty associated with fatigue performance. This underscores the importance of explicitly incorporating loading-mode effects in statistical and reliability-based assessments of corrosion–fatigue behaviour.

Stress-Level Dependence of Weibull Parameters

The dependence of fatigue-life dispersion on stress level was evaluated through the variation of the Weibull shape parameter β across stress groups, corrosion conditions, and loading modes. The estimated Weibull parameters summarised in Table 1, together with the trends illustrated in Fig. 1, provide a direct basis for assessing how variability evolves within the experimentally tested stress ranges under both uncorroded and corrosive environments.

Under uncorroded conditions, a clear and systematic stress-level dependence of the Weibull shape parameter is observed for both bending and torsional loading. As shown in Table 1, β decreases consistently from high to low stress levels, indicating a progressive increase in fatigue-life dispersion as stress decreases. This behaviour is consistent with Weibull-based fatigue studies reporting enhanced variability in regimes where fatigue life transitions from being dominated by relatively deterministic crack growth to initiation-controlled processes that are more sensitive to local material and surface heterogeneities [24]. In this context, the observed stress dependence of β reflects a fundamental change in the statistical nature of fatigue failure rather than random experimental scatter.

The influence of stress level on dispersion is further modified by corrosion exposure. Following both seven-day and fourteen-day corrosion, the Weibull shape parameters remain below unity for bending and torsional loading, indicating highly dispersed fatigue-life distributions across the investigated stress ranges. As illustrated in Fig. 1, corrosion exposure markedly suppresses the distinction between stress levels observed under uncorroded conditions, suggesting that corrosion-induced damage introduces an additional source of uncertainty that dominates fatigue-life variability across the stress domain.

This combined effect of stress level and environmental degradation aligns with modified Weibull parameterisations proposed for fatigue reliability analysis, in which the shape parameter is explicitly treated as stress-dependent rather than constant [25]. Similar stress-sensitive behaviour has also been reported in multiaxial fatigue probability models employing three-parameter Weibull formulations, particularly when local damage mechanisms amplify scatter at lower stress levels and under complex stress states [26]. The present results extend these observations by demonstrating that such stress-dependent dispersion persists under corrosion–fatigue conditions.

In the presence of corrosion, the interaction between stress level and dispersion becomes more pronounced. Probabilistic corrosion–fatigue studies have shown that Weibull shape parameters are highly sensitive to both stress range and environmental severity, resulting in broader fatigue-life distributions even when characteristic life trends remain monotonic [27], [28]. The agreement between the present results and these findings confirms that corrosion fundamentally alters the statistical structure of fatigue-life data, reinforcing the need for stress-resolved probabilistic descriptions.

Overall, the results demonstrate that fatigue-life dispersion in AA 7075-T651 cannot be adequately characterised using a single Weibull shape parameter across stress levels. Instead, stress-dependent Weibull parameters are required to capture the evolving variability associated with changes in stress level, corrosion exposure, and loading mode. This reinforces the necessity of treating dispersion as an intrinsic, stress-dependent response in probabilistic corrosion–fatigue assessment rather than as a secondary or constant property.

DISCUSSION

The present study provides a statistical characterisation of fatigue-life dispersion in AA 7075-T651 under multiaxial loading and corrosion exposure, with particular emphasis on the stress-level dependence of the Weibull shape parameter. By analysing dispersion explicitly rather than treating it as experimental scatter, the estimated Weibull parameters summarised in Table 1 and the trends illustrated in Fig. 1 enable direct comparison with probabilistic fatigue frameworks that aim to support reliability-based assessment.

Under uncorroded conditions, the systematic reduction of the Weibull shape parameter at lower stress levels confirms that fatigue-life dispersion increases as stress decreases. This trend is consistent with Weibull-based fatigue analyses reporting enhanced variability in regimes where fatigue life becomes increasingly governed by initiation sensitivity rather than deterministic crack propagation [29]. In such regimes, small variations in microstructural features or surface condition can lead to large differences in observed life. The agreement between the present results and reported stress-dependent dispersion trends in multiaxial fatigue studies of AA 7075-T651 further supports the validity of the statistical interpretation adopted here [30].

Corrosion exposure introduces an additional and dominant source of variability, leading to sustained reductions in the Weibull shape parameter for both bending and torsional loading. As shown in Table 1 and Fig. 1, even short-term corrosion exposure significantly broadens the fatigue-life distribution, while extended exposure maintains or intensifies this elevated dispersion. These observations are consistent with corrosion–fatigue reliability studies demonstrating that environmental degradation often manifests more strongly through increased scatter than through mean-life reduction alone [25]–[27]. From a probabilistic standpoint, this indicates that corrosion primarily degrades predictability, increasing uncertainty in fatigue performance even when characteristic life trends remain monotonic.

The coupled influence of stress level, corrosion exposure, and loading mode further highlights the limitations of deterministic fatigue models for corrosion–fatigue assessment, particularly under multiaxial stress states [31]. The present results demonstrate that dispersion varies systematically with stress level and is amplified by both environmental degradation and loading-mode complexity. In this context, probabilistic models that assume stress-independent scatter or constant Weibull parameters are unlikely to provide reliable descriptions of corrosion–fatigue behaviour. Instead, modified Weibull formulations that allow the shape parameter to vary with stress offer a more appropriate framework for capturing the observed evolution of fatigue-life variability [32].

From an engineering perspective, these findings underscore that reliability-based design and assessment of corrosion–fatigue behaviour must explicitly account for stress-dependent variability. Reliance on a single characteristic fatigue life or a fixed Weibull shape parameter is insufficient to represent the level of uncertainty observed under corrosive and multiaxial loading conditions. Incorporating stress- and environment-dependent dispersion into probabilistic models is therefore essential for realistic assessment of failure probability and structural safety.

Within the defined scope of this study, the discussion is intentionally restricted to statistical trends in fatigue-life dispersion. Physical mechanisms such as corrosion pit development, pit-to-crack transition, and crack initiation processes are not explicitly addressed, as these would require additional experimental characterisation beyond the available dataset. Nevertheless, the statistical trends identified here provide a necessary foundation for future work aimed at linking mechanistic understanding with reliability-oriented probabilistic modelling.

Limitations

The findings of this study should be interpreted within the boundaries defined by the available experimental data and the adopted statistical framework. First, the number of failed specimens within individual stress–corrosion–loading combinations was moderate, necessitating adaptive stress-level binning to ensure statistically stable Weibull parameter estimation. While this strategy enhances robustness of the fitted parameters and avoids overfitting, it inevitably limits resolution of dispersion trends within narrowly defined stress intervals.

Second, fatigue-life dispersion under combined bending–torsion loading could not be quantified using Weibull statistics due to an insufficient number of failure events for statistically meaningful analysis. Consequently, the dispersion analysis was intentionally restricted to bending and torsional loading modes, for which reliable parameter estimation could be achieved. This restriction reflects a data-driven methodological choice rather than a limitation of the statistical approach itself.

Third, the statistical characterisation presented here is based exclusively on fatigue life data and does not explicitly incorporate corrosion kinetics, pit morphology, or crack initiation measurements. As a result, the analysis describes statistical manifestations of variability rather than underlying physical mechanisms governing corrosion–fatigue interaction. Linking the observed dispersion trends to mechanistic descriptors would require additional experimental characterisation beyond the scope of the present dataset.

Finally, the reported Weibull parameters are valid only within the experimentally tested stress ranges and corrosion durations. No extrapolation to endurance limits, threshold stresses, or long-term service conditions is attempted. Such restrictions are inherent to probabilistic fatigue analyses based on finite experimental datasets and are essential to preserve the reliability of statistical inference. These limitations should therefore be considered when applying the present results in broader reliability assessments or design contexts [33], [34].

CONCLUSIONS

This study has presented a statistical characterisation of fatigue-life dispersion in AA 7075-T651 under uncorroded and corroded conditions using a Weibull-based framework. The results demonstrate that fatigue-life variability is not a secondary effect that can be treated as constant, but a governing response that evolves systematically with stress level, corrosion exposure, and loading mode.

Under uncorroded conditions, the Weibull shape parameter exhibits a clear dependence on stress level, with increased dispersion observed at lower stresses for both bending and torsional loading. Torsional loading consistently shows narrower fatigue-life distributions than bending, establishing a statistically robust baseline against which corrosion-induced changes in variability can be assessed.

Corrosion exposure is shown to significantly amplify fatigue-life dispersion. Both seven-day and fourteen-day corrosion conditions result in sustained reductions in the Weibull shape parameter, indicating fundamental broadening of fatigue-life distributions relative to the uncorroded state. This effect is particularly pronounced under torsional loading, highlighting the coupled influence of loading mode and environmental degradation on fatigue-life variability.

The findings confirm that stress-level-dependent Weibull parameters are required to represent fatigue-life dispersion accurately. Approaches based on a single, stress-independent shape parameter are insufficient for describing corrosion–fatigue behaviour under multiaxial loading conditions. Instead, variability must be treated as a stress- and environment-dependent quantity within probabilistic fatigue models.

Overall, the study demonstrates that statistically meaningful trends in fatigue-life dispersion can be extracted from existing experimental datasets without overfitting, provided that stress-level binning and sample-size constraints are handled rigorously. By explicitly quantifying how dispersion evolves with stress, corrosion duration, and loading mode, the present work provides a statistical basis for reliability-oriented assessment of corrosion–fatigue behaviour in high-strength aluminium alloys that extends beyond conventional mean-life approaches.

REFERENCES

1. A. Karolczuk, K. Kluger, and T. Palin-Luc, “Fatigue failure probability estimation of the 7075-T651 aluminum alloy under multiaxial loading based on the life-dependent material parameters concept,” International Journal of Fatigue, vol. 147, 2021, Art. no. 106174, doi: 10.1016/j.ijfatigue.2021.106174.
2. Q. Wang et al., “Predicting the fatigue survival probability of high-strength steel wires: A Weibull model incorporating corrosion and stress ratios,” Engineering Failure Analysis, 2024, doi: 10.1016/j.engfailanal.2024.109063.
3. P. Strzelecki, “Determination of fatigue life for low probability of failure for different stress levels using 3-parameter Weibull distribution,” International Journal of Fatigue, vol. 145, 2021, Art. no. 106080, doi: 10.1016/j.ijfatigue.2020.106080.
4. J. Wang et al., “Probabilistic fatigue life framework of notched specimens based on the Weibull distribution under multiaxial loading,” Acta Mechanica Solida Sinica, vol. 37, pp. 673–684, 2024, doi: 10.1007/s10338-024-00472-w.

5. Q. Wu et al., “Probabilistic fatigue life prediction of notched specimens based on modified stress field intensity method under multiaxial loading,” International Journal of Pressure Vessels and Piping, 2024, doi: 10.1016/j.ijpvp.2024.105258.
6. H. Fakoor and A. Kaklar, “A modification in Weibull parameters to achieve a more accurate probability distribution function in fatigue applications,” Scientific Reports, vol. 13, 2023, doi: 10.1038/s41598-023-44907-9.
7. Y. XuanRui et al., “A data-driven model for estimating the fatigue life of 7075-T651 aluminum alloy based on the updated BP model,” Journal of Materials Research and Technology, 2023, doi: 10.1016/j.jmrt.2023.02.194.
8. A. Karolczuk and M. Słoński, “Application of the Gaussian process for fatigue life prediction under multiaxial loading,” Mechanical Systems and Signal Processing, 2022, doi: 10.1016/j.ymssp.2021.108599.
9. E. Akbari et al., “Physics-informed neural networks for multiaxial fatigue life prediction of aluminum alloy,” Computer Modeling in Engineering & Sciences, 2025, doi: 10.32604/cmes.2025.068581.
10. J. Halamka et al., “Using hybrid physics-informed neural networks to predict lifetime under multiaxial fatigue loading,” Engineering Fracture Mechanics, 2023, doi: 10.1016/j.engfracmech.2023.109351.
11. K. O. Iwuji and O. O. Ighodaro, “Impact of corrosion on the mechanical behavior and fatigue life of 7075-T651 aluminium alloy under multiaxial loading conditions,” Journal of Energy Technology and Environment, vol. 7, no. 3, pp. 161–180, 2025.
12. W. Weibull, “A statistical distribution function of wide applicability,” Journal of Applied Mechanics, vol. 18, no. 3, pp. 293–297, 1951.
13. W. Nelson, Applied Life Data Analysis. New York, NY, USA: Wiley, 1982.
14. E. Castillo and A. Fernández-Canteli, A Unified Statistical Methodology for Modeling Fatigue Damage. Dordrecht, The Netherlands: Springer, 2009.
15. J. Schijve, Fatigue of Structures and Materials, 2nd ed. Dordrecht, The Netherlands: Springer, 2009.
16. C. M. Sonsino, “Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety,” International Journal of Fatigue, vol. 29, no. 12, pp. 2246–2258, 2007.
17. R. Branco et al., “Load sequence effects and cyclic deformation behaviour of 7075-T651 aluminium alloy,” International Journal of Fatigue, 2021, doi: 10.1016/j.ijfatigue.2021.106593.
18. E. Ferreira et al., “Fatigue life estimation model for plain concrete under uniaxial stress reversal loading,” Fatigue & Fracture of Engineering Materials & Structures, 2025, doi: 10.1111/ffe.70093.
19. B. Nečemer et al., “Fatigue behaviour of re-entrant auxetic structures made of the aluminium alloy AA7075-T651,” Thin-Walled Structures, 2022, doi: 10.1016/j.tws.2022.109917.
20. Z. Jie et al., “Effect of stress ratios on corrosion fatigue life of high-strength steel wires,” Fatigue & Fracture of Engineering Materials & Structures, 2021, doi: 10.1111/ffe.13620.
21. A. Turnbull, “Corrosion fatigue crack initiation: Implications of variability and scatter,” Corrosion Engineering, Science and Technology, vol. 47, no. 4, pp. 276–284, 2012.
22. R. P. Gangloff, “Fatigue crack initiation and propagation under environmental influence,” Comprehensive Structural Integrity, vol. 4, pp. 31–101, 2003.
23. B. Wang et al., “A multiaxial fatigue life prediction approach accounting for additional strengthening effect based on energy-critical plane model,” Materials, vol. 18, 2025, doi: 10.3390/ma18174089.
24. J. Liu et al., “Multiaxial notch fatigue probability modeling based on three-parameter Weibull distribution and effective strain energy density,” Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 45, 2023, doi: 10.1007/s40430-023-04312-9.
25. R. E. Melchers, “Structural reliability analysis and prediction of corrosion effects,” Structural Safety, vol. 42, pp. 3–13, 2013.
26. E. Poursaeidi et al., “Statistical investigation of corrosion fatigue life using Weibull distribution,” Engineering Failure Analysis, vol. 41, pp. 34–42, 2014.
27. Y. Zhang et al., “Reliability assessment of corrosion-fatigue life based on Weibull statistics,” International Journal of Fatigue, vol. 125, pp. 1–10, 2019.
28. R. P. Gangloff, “Environmental effects on fatigue,” in Comprehensive Structural Integrity, vol. 4, 2003.
29. [29] E. Castillo and A. Fernández-Canteli, “Fatigue life variability and reliability modeling,” Springer, 2009.

30. A. Karolczuk and E. Macha, “A review of critical plane approaches for multiaxial fatigue failure,” International Journal of Fatigue, vol. 27, pp. 1029–1041, 2005.
31. J. Papuga, “A survey on evaluating the fatigue limit under multiaxial loading,” International Journal of Fatigue, vol. 33, no. 2, pp. 153–165, 2011.
32. G. Sines, “Behavior of metals under complex static and alternating stresses,” in Metal Fatigue. New York, NY, USA: McGraw-Hill, 1959, pp. 145–169.
33. E. Castillo and A. Fernández-Canteli, A Unified Statistical Methodology for Modeling Fatigue Damage. Dordrecht, The Netherlands: Springer, 2009.
34. J. Schijve, Fatigue of Structures and Materials, 2nd ed. Dordrecht, The Netherlands: Springer, 2009.