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Fatigue Reliability Analysis of In-Service Pipelines using Fuzzy-Weibull approach to Reduce Epistemic and Aleatory Uncertainty in Stochastic Stress Loads

Muhammad Ali Khan[a,b], Salvinder Singh Karam Singh[a,b*], Shahrum Abdullah[a,b], Azli Arifin[a,b], M. Zaid Kamardin[c] & Musa Bashir[d]

[a]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, UKM Bangi, 43600 Selangor, Malaysia*

[b]*Computational and Experimental Mechanics (CEM) Research Group, Universiti Kebangsaan Malaysia, UKM Bangi, 43600 Selangor, Malaysia*

[c]*Group Technical Solutions (GTS), Petroliam Nasional Berhad (PETRONAS), 50088, Kuala Lumpur, Malaysia*

[d]*School of Engineering, University of Liverpool, L69 3BX, UK.*

[*]*Corresponding author: salvinder@ukm.edu.my*

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ABSTRACT

This paper integrates fuzzy logic with the Weibull distribution to improve fatigue reliability predictions for offshore steel pipelines under both aleatory and epistemic uncertainties. The existing durability assessments techniques mainly rely on deterministic material properties and simplified loading assumptions, which fail to account for epistemic uncertainty arising from limited data, corrosion-induced degradation, and operational variability. This study addresses that gap by incorporating stochastic modelling and epistemic uncertainties through realistic representations of material degradation and cyclic load variability. Stochastic modelling combined five years of in-service load data with experimental material properties, capturing degradation effects of corrosion on the API X65 Pipeline Steel material. Fuzzy logic quantified the epistemic uncertainty in Weibull parameters through low, medium, and high membership functions. The experimental results showed the yield strength variability (594 ~ 366 MPa) due to effects of corrosion and welding created an interference region, reducing structural integrity under random loading. The Fuzzy-Weibull Fatigue reliability assessment results showed mean cycles to failure ranging from 1.03 x 10^9 for operational stresses to 5.48 10^5 for interference region, with correlation of 90 % to the experimental S-N curve. Defuzzified reliability rose from 0.38 to 0.46, while the fatigue reliability index increased from 2.1 to 5.3 under operational stresses but declined from –0.6 to –2.25 in the interference region with the increase in Weibull shape parameter. Overall, the proposed method strengthens pipeline durability assessment by incorporating both random variability and epistemic uncertainty.

Keywords: Durability assessment; fatigue reliability; Fuzzy Logic; Weibull Distribution

INTRODUCTION

Offshore pipelines are critical infrastructure in the oil and gas industry, often subjected to cyclic loading from dynamic stresses such as waves, wind, ice, and internal pressure variations (Khan et al. 2025). These stresses can significantly threaten the structural integrity of pipelines, leading to fatigue-induced failures (Dong et al. 2021). Approximately 30–40% of pipeline damage results from material defects, corrosion, and welding flaws, which can accelerate failure mechanisms(Huang & Zhang 2021). Studies have shown that while welding and corrosion defects with a depth of up to 10% of the pipe diameter do not significantly reduce burst capacity, cyclic loading can still lead to the corrosion-fatigue failures resulting in significant degradation of the pipeline's structural integrity (Abdullah et al. 2024) . For accurate fatigue life prediction, real-time cyclic loading best reflects operational conditions, which include mean stresses that significantly impact fatigue behaviour, accelerating crack initiation and propagation (Chin et al. 2022). While empirical models such as stress-life, strain-life, and fracture mechanics approaches are widely used for low-cycle and high-cycle fatigue evaluations, they often fail to fully capture the dynamic nature of real-world loads and material degradation, introducing uncertainties (Chin et al. 2024). Given the uncertainties arising from material variability, load fluctuations, and modelling assumptions, a reliability-based approach is essential for more robust and probabilistic fatigue life predictions (Meng et al. 2024). This framework integrates these uncertainties, providing a more realistic evaluation of the pipeline's structural integrity and long-term performance.

Two primary methodologies for reliability-based assessment include limit-state-based(Song et al. 2018) and data-based approaches (Garbatov & Guedes Soares 2017). Recent studies have emphasised fatigue reliability evaluations under random loading conditions, using stochastic methods such as Monte Carlo simulations (Manouchehrynia et al. 2020) and Bayesian frameworks (Castillo et al. 2019). These methods typically assume Gaussian distributions for load-time histories, but selecting an appropriate probability distribution function based on experimental data remains critical for accurately characterising the probabilistic fatigue life of materials (Amiri et al. 2025). The statistical properties of these distributions can then be used to model the fatigue failure behaviour of pipeline steels, employing a bathtub curve approach to estimate key indicators such as mean cycles to failure, reliability, and hazard rates (Abdullah et al. 2023).

While these reliability models have provided valuable insights into pipeline deterioration, they suffer from limitations, including dependence on extensive failure data, assumptions of statistical distributions, and challenges in handling uncertain parameters in real-world conditions (Liu & Zhou, 2022). Additionally, fatigue reliability evaluation often requires multiple repeated assessments of limit state functions. For operational pipelines, the fatigue limit state function is typically implicit. However, conducting repeated simulations or physical experiments to evaluate these functions is impractical (An et al. 2024). Therefore, it is essential to develop a high-precision approximation model for assessing the fatigue reliability of operational pipelines (Liu et al. 2022). Moreover, in reliability analysis, uncertainty is generally classified into two types: stochastic uncertainty and epistemic uncertainty (Zhang & Zhou, 2013). Stochastic uncertainty is typically modelled using probability theory (Yang et al. 2019), while epistemic uncertainty is commonly represented through fuzzy theory (L. Wang et al. 2018). In practice, both types of uncertainties often coexist (Paci et al. 2021). However, most research on fatigue reliability in offshore pipeline structures primarily focuses on stochastic uncertainty, frequently neglecting the role of epistemic uncertainty (Bagheri et al. 2021). Lastly, in reliability evaluations regarding oil and gas pipelines, uncertainty arises from various factors, such as material properties, loads, and geometric variations(Karadeniz, 2001). Much of the existing research on fatigue reliability evaluation has not sufficiently addressed the impact of these uncertain factors on overall reliability (C. Wang et al. 2021).

To address the uncertainties in fatigue reliability evaluation, this study proposes a fuzzy logic-based fatigue reliability framework for offshore pipelines, particularly focusing on corrosion fatigue failures. The use of fuzzy logic offers an alternative computational approach that can handle imprecise and uncertain data in Weibull distribution-based fatigue analysis, enabling the integration of expert knowledge and uncertain parameters into the assessment process. This methodology utilises a Fuzzy Inference System (FIS) to model fatigue failure behaviour through fuzzy membership functions, rule-based systems, and defuzzification methods. The key objective of this study includes a fuzzy logic-based Weibull fatigue reliability framework that enables decision-making under uncertainty without requiring large-scale failure data. This is particularly useful for offshore pipelines, where experimental datasets are often limited. By bridging the gap between traditional probabilistic approaches and intelligent computational methods, this research enhances pipeline integrity assessment and provides a more flexible and robust tool for industry applications. The findings can support maintenance planning, risk-based inspections, and decision-making for long-term pipeline sustainability in offshore environments.

METHODOLOGY

METHODOLOGY FLOW

The detailed methodology of the current study is outlined in Figure 1. and further explained in the following steps.

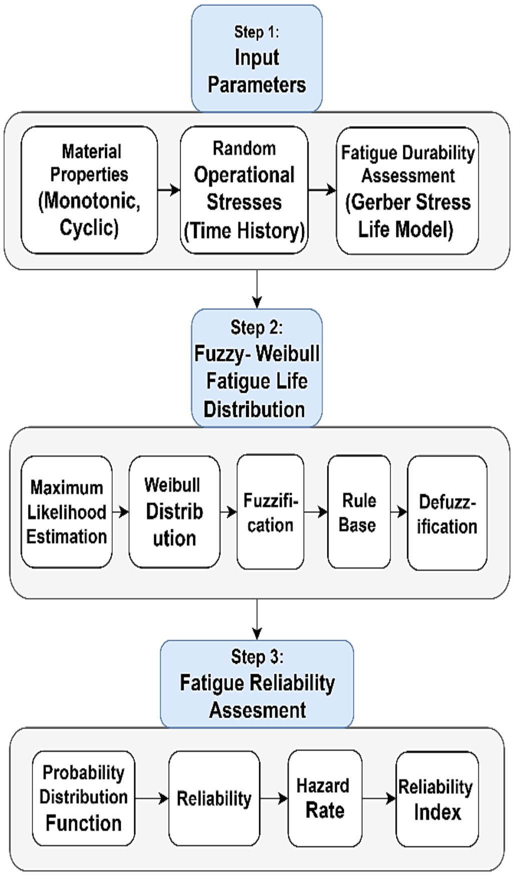


FIGURE 1. Three-step Methodology for Assessment of Fatigue Reliability of Steel Pipe under Random Cyclic Loads and Corrosive Environment

INPUT PARAMETERS

This study examined the uncertainties in monotonic and cyclic properties of API X65 longitudinal weld seam steel, widely used in pipelines (Kim et al. 2021). Mechanical testing was performed under four test conditions: standard tensile specimens, corroded specimens, welded specimens, and welded tensile specimens. The effect of corrosion aims to realistically incorporate the effects of environments on the material (Kim et al. 2021). Specimens' preparation was carried out using ASTM E8 and welded specimens using AWS class E7010 electrodes and the SMAW process (Figure 2). Tensile tests were conducted using a 100 kN machine at a crosshead speed of 0.02 mm/s and a strain rate of 1.0 x 10^{-3}, which was within the range from 1.0 x 10^{-5} to 1.0 x 10^{-2} for tensile tests as per ASTM E8 Standards [26].

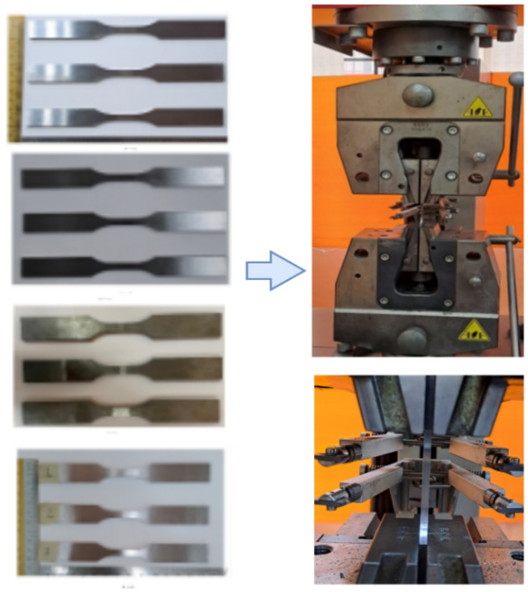


FIGURE 2. Monotonic Properties characterize samples original, corroded and welded test conditions

Fatigue characteristics of the base material were evaluated under seawater environments through uniaxial cyclic tests using a 100 kN servo-hydraulic machine at a stress ratio of -1 and a loading frequency of 10 Hz (Fatoba & Akid, 2022). Stress levels began at 90% of the experimental UTS and were progressively reduced to the fatigue limit, generating an experimental S-N curve for the corrosion environment. Specimens were prepared according to ASTM E466 standards (Figure 3). Stress was reduced until failure occurred beyond 10^6 cycles [32], establishing a correlation between stress levels and endurance limits (Adasooriya et al. 2020). To simulate corrosion, specimens were pre-soaked in seawater for 96 hours, resulting in pitting corrosion (~25 μm) (Yu et al. 2018). The fatigue behaviour was modelled using the Basquin equation, as follows:

$$S_a = AN_{f\_}^B \quad (1)$$

where S_a is the alternating stress, N_{f_sw} is the number of cycles to failure, and **A** and **B** are material constants. This investigation is necessary, as it provides insight into how the corrosion mechanism influences the fatigue behaviour of materials used in offshore pipelines, contributing to more accurate life predictions under real-world conditions.

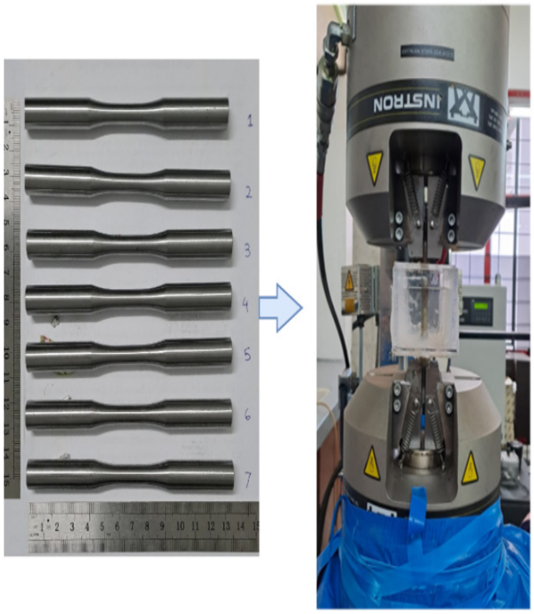


FIGURE 3. Cyclic Properties characterization of material samples under seawater conditions

The daily internal pressure data of an in-service offshore pipeline was recorded for five years, from 2014 to 2018, and showed oscillations due to pump suction and discharge. These pressure variations resulted in cyclic biaxial stresses (Amaya-Gómez et al. 2019). Using the Barlow equation, the internal pressure was converted to hoop stress, which accounts for the maximum stress component for thin cylindrical shells. The pipe thickness reduction factor was added in the empirical relation, and an average corrosion rate of 0.058mm/year was used to calculate the hoop stress time history(Khan et al. 2025). The random hoop stresses were then used operationally to assess fatigue life and durability.

The equation used to calculate hoop stress is:

$$\sigma_h = \frac{P.D}{2.(t_i - n.C)} \tag{2}$$

where P is the random internal pressure, D is the outer diameter, t_i is the initial thickness, n is the number of years, and C is the corrosion rate for the API X65 steel pipe.

Offshore structures like risers and pipelines are subjected to high-cycle fatigue (HCF), typically enduring 10^4 10^6 cycles before failure. Under HCF, materials operate near their endurance limit with mainly elastic stresses, making stress-life (S–N) methods suitable for analysis (Abdullah et al. 2024). S-N curves are generally derived from fully reversed loading, but in real applications, mean stresses significantly influence fatigue life. Tensile mean stresses reduce fatigue strength, while compressive stresses improve it (Gholami et al. 2021).Common mean stress correction models, such as Goodman, Soderberg, and Gerber, are widely used due to their simplicity and applicability (Dowling, 2004). Each assumes different material behaviour: Goodman suits brittle materials, Soderberg offers conservative estimates for ductile ones, and Gerber is more accurate for ductile materials under high mean stresses. More advanced models like Morrow and SWT are less generalisable due to specific material dependencies and suitability for low cycle fatigue calculations (Dowling et al. 2009).

Fatigue life is influenced by crack growth mechanisms either along shear or tensile planes depending on material properties and loading conditions (Latifi et al. 2025). No single correction model universally applies across all cases. This study adopts the Gerber model to estimate fatigue life under tensile loading:

$$\left[\frac{\sigma_{mean}}{\sigma_{UTS}} N\right]^2 + \left[\frac{\sigma_{alternating}}{\sigma_{endurance}} N\right] = 1 \tag{3}$$

Stress cycle counting, particularly the rain flow method, is used to analyse variable-amplitude loadings by identifying peaks and valleys in stress histories (Oyegbile & Muskulus, 2024). The average stress (σ) and mean stress (m) are calculated as follows:

$$\sigma = \frac{u - v}{2} \quad and \; m = \frac{u + v}{2} \tag{4}$$

Fatigue damage is evaluated using Miner's rule (Bjørheim et al. 2022), as shown in Eq. 5:

$$D = \sum_{i=1}^{f} \frac{n_i}{N_i} \tag{5}$$

where n_i is the number of cycles at a stress level, and N_i is the calculated fatigue life in each cycle. This study uses Rainflow cycle counting and the Palmgren-Miner rule to assess fatigue damage from random operational stresses, applying experimental material properties under corrosion conditions (Adam et al. 2025). The results from the Gerber fatigue life model form the basis for subsequent fatigue reliability analysis.

FUZZY WEIBULL FATIGUE LIFE DISTRIBUTION

The fatigue reliability of components under random stresses is often modelled using non-Gaussian distributions such as Weibull, Gumbel, lognormal, and gamma (Acitas et al. 2019). Maximum likelihood estimation (MLE) is applied to estimate log-likelihood (LL) values and select the best fit as given by:

$$LLF=\sum_{i=1}^{N_f} F(N_f;\sigma,\mu) \tag{6}$$

where the location and scale parameters are denoted by σ and μ, respectively. The Akaike Information Criterion (AIC) identifies the optimal model:

$$AIC=2k-2\log(L) \tag{7}$$

where k as the number of parameters in the model being evaluated and L, the maximum log-likelihood function, which measures how well the model fits the data. The Weibull distribution is adopted in the current study based on MLE and its PDF is:

$$F(N_f)=\frac{\beta}{\theta}\left(\frac{N_f}{\theta}\right)^{\beta-1}\exp^{\left[-\frac{N_f}{\theta}\right]^{\beta-1}} \tag{8}$$

The shape parameter β describes scatter in fatigue life: higher β values indicate fatigue failures, while lower values suggest life distribution with potential early random failures.

Fuzzy logic (FL), introduced by Zadeh (1968), is widely applied to handle uncertain data. It includes fuzzification, inference, and defuzzification (Saeed et al. 2025). Crisp inputs are converted into fuzzy sets by membership functions:

$$x_k \Rightarrow \mu_A(x_k) \tag{9}$$

where x_k represents the kth crisp input and $\mu_A(x_k)$ denotes the degree of membership of the input. Inference uses IF–THEN rules and engines, often Mamdani-type:

$$\wedge\mu_{A'_2}i(x_2)\ldots\ldots\ldots\mu_{A'_m}i(x_m)\wedge\mu_B i(y),\ i=1,2,\ldots,n \tag{10}$$

where in the i_{th} fuzzy rule, A'_m and B'_m are linguistic values defined by fuzzy sets, while x_m and y are the input and output linguistic variables, respectively (Hong et al. 2024). Finally, defuzzification (centroid method) yields a crisp output:

$$y'=\frac{\int \mu_{B'}(y)*y*dy}{\int \mu_{B'}(y)*dy} \tag{11}$$

where y' is the crisp value, given the fuzzy set $\mu_{B'}(y)$ (Yat Sheng et al. 2018).In the present study, fuzzy logic is used to include the effect of imprecise uncertainties in the stress's material properties and corrosive environments, which affect the overall shape and scale parameters of the Weibull distribution of calculated fatigue life. The membership functions were designed from low, medium, and high for three input fuzzy sets of operational stresses, tensile strength, and the corrosion rate. The rule base was assigned using the Mamdani fuzzy inference system to give the two output Fuzzy-Weibull shape and scale parameters (Zakikhani et al. 2020).

FATIGUE RELIABILITY ASSESSMENT

The output fuzzy sets were defuzzied using the centroid method to give the optimised values of the Weibull shape and scale parameter, which was further used to calculate the desired reliability based on the safe-life approach of the pipeline for the N_f number of cycles to failure, as can be determined using Eq. 13:

$$Reliablity_{N_f}=exp\left[-\frac{N_f}{\theta}\right]^{\beta} \tag{12}$$

The shape parameter is represented by β and the scale parameter is represented by θ. N_f represents the number of cycles to failure for the stress-life based fatigue model using the stress load history for the five years (Li et al. 2016). The random stress loads induce a structural reaction in the pipe and determine the operational state of the pipeline, which can be correlated with the hazard rate using the number of cycles to failure and optimised shape and scale parameters, as stated in Eq. 11:

$$HR_{N_f}=\frac{\beta}{\theta}\cdot\left(\frac{N_f}{\theta}\right)^{\beta-1} \tag{13}$$

The average duration until failure McTF is derived from the N_f, which is utilised to denote the specified time and is expressed in Eq. 12:

$$\mathrm{Mc}TF = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (14)$$

where Γ is the gamma function for $\left(1 + \frac{1}{\beta}\right)$.

For the assessment of the reliability index, the limit state function can be defined in Eq. 13, where Δ is the Miner's sum at failure and D is the accumulated fatigue total damage in the applied number of cycles. Failure of pipeline will occur when $D \geq \Delta$:

$$g(x) = \Delta - D \quad (15)$$

The probability of failure can be defined as:

$$P_f = \int_{g(x)} f_x dx \quad (16)$$

where $g(x) > 0$ indicates a safe domain and $g(x) < 0$ indicates a failure region (He & Zhou, 2021). Using the Weibull reliability and the design life of the pipeline material in the high cycle fatigue zone, we can calculate the reliability index as the inverse transformation of P_f, as indicated below, which is the inverse of the cumulative Weibull distribution function:

$$\beta = \phi^{-1}\left(exp\left[-\frac{N_f}{\theta}\right]^{\beta}\right) \quad (17)$$

RESULTS AND DISCUSSION

The results from experimental testing were used in the durability analysis to obtain fatigue life using three stress life models. The fatigue reliability assessment was carried out to calculate the suitable probability distribution for fatigue life data.

EXPERIMENTAL MECHANICAL PROPERTIES

Table 1 shows the monotonic properties of specimens under different test conditions. Specimens under normal conditions had slightly higher Young's modulus, yield, and tensile strength, suggesting corrosion reduces these properties. For welded specimens, those not exposed to corrosion had reduced strength, while those exposed to both corrosion and welding showed a significant strength reduction. The strain curve in Figure 4 indicated reduced toughness, particularly for welded specimens, pointing to welding defects and heat-affected zones as potential causes for crack initiation.

These findings suggest material degradation from corrosion and welding, leading to fatigue failure. While this study focused on corrosion, other factors like temperature fluctuations and biofouling could affect fatigue life but were not considered. Figure 5 shows the probability distribution function of variations in mechanical properties of the material under the effects of corrosion and welding. Future work could explore the sensitivity of results by further including the effects of these environmental factors. Additionally, while welding defects were examined, the influence of microstructure and residual stresses on fatigue behaviour was not addressed. These factors can affect material toughness and crack propagation, and future studies should consider their impact on pipeline fatigue life and durability. Figure 6 shows the fatigue characteristics of API X65 steel under cyclic load in seawater environments.

TABLE 1. Monotonic properties variation under four different test conditions

Test Condition	Young Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Standard Tensile Specimens	252	570	618
	225	594	630
	215	582	630
Corroded Tensile Specimens	252	593	631
	252	569	616
	261	547	597
Welded Tensile Specimens	215	381	575
	249	394	596
	279	375	590
Welded & Corroded Tensile Specimens	238	380	582
	239	385	582
	236	366	593

The S-N curve indicates that the endurance limit for corroded specimens is 50% of their average ultimate tensile strength (UTS), around 300 MPa, which shows that corrosion roughened the surface, promoting crack initiation and propagation, ultimately weakening the material.

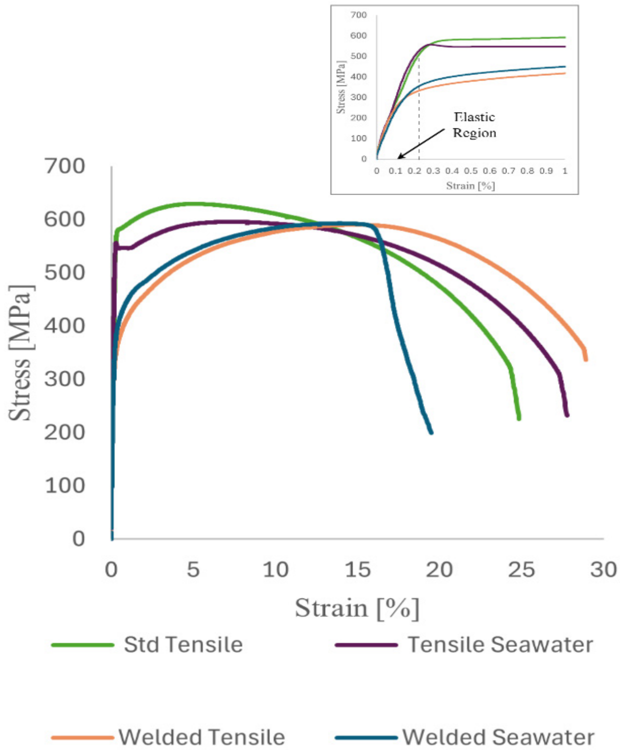


FIGURE 4 Tensile Test Results for the API X65 Steel Specimens under Four Test Conditions

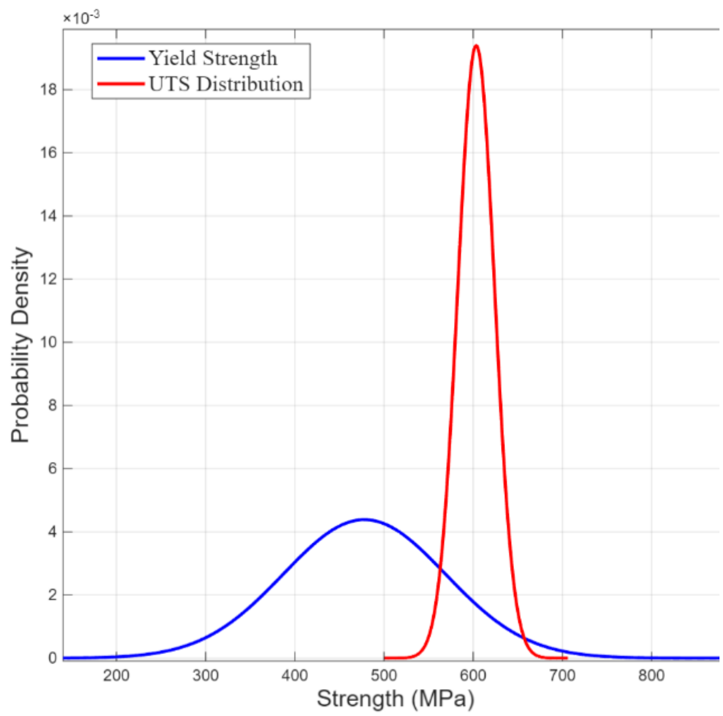


FIGURE 5. Experimental Tensile and Yield Strength Distribution under Four Test Conditions.

The fatigue life and parameters were calculated using the Basquin equation, and the fatigue strength coefficient (A) and exponent (B) were determined via the least squares method.

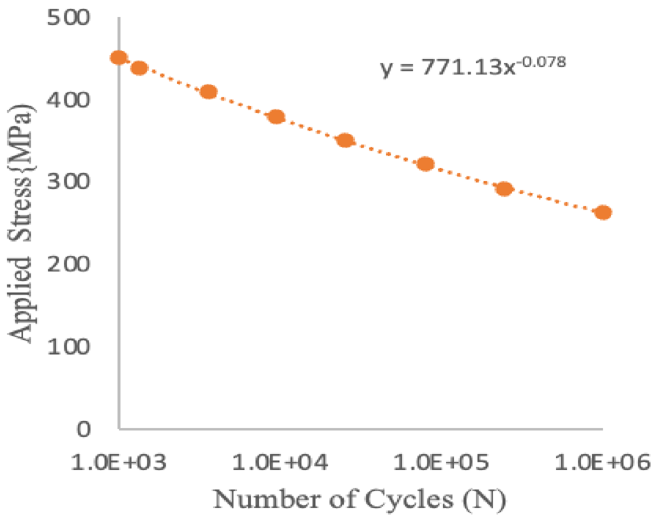
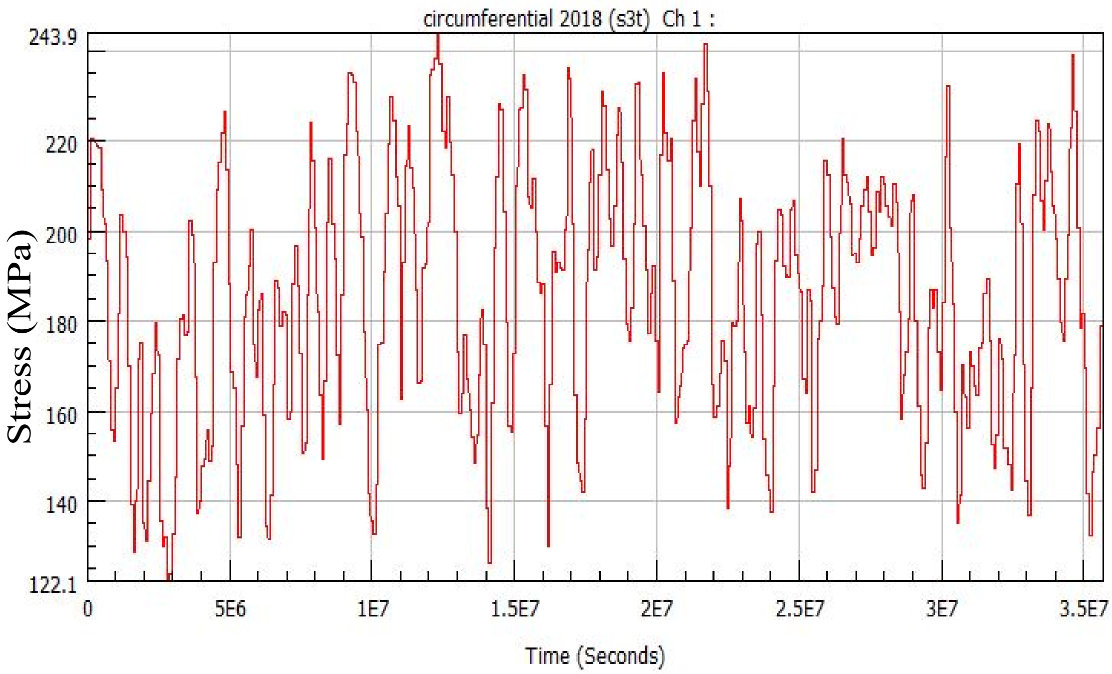


FIGURE 6. Fatigue Behaviour of API X65 Steel under Seawater Environment.

DURABILITY ASSESSMENT RESULTS

The circumferential stresses of an API X65 pipeline under internal pressure were determined using real-time history data of random internal pressure loads from 2014 to 2018. These stresses were then used to assess the pipeline's durability. Using the rain flow cycle counting method, the fatigue damage was calculated from the random circumferential stress cycles. The histogram revealed that high-cycle stresses remained within the elastic region, accounting for fewer damaging cycles. The range and mean of cycles observed were consistent across the five years of data. Fatigue damage was calculated using a stress-life-based model as shown in Figure 7. The fatigue life for the variable amplitude load data is shown in Figure 8. These results highlight the importance of accounting for mean stresses when estimating fatigue damage life under variable amplitude loading.



(a)

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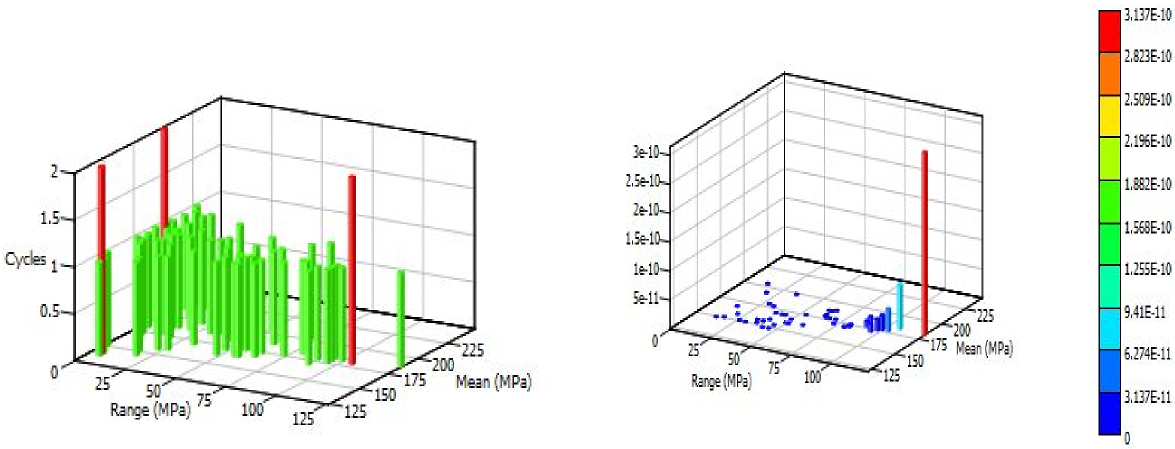


(b) (c)

FIGURE 7. Fatigue Durability Assessment (a) Random Operational Stresses (a) Rainflow Cycle Counting (b) Fatigue Damage Calculation.

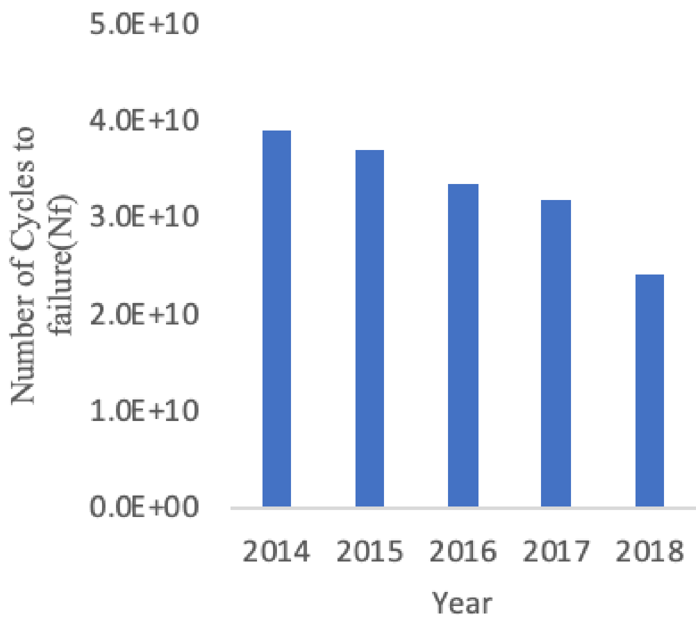


FIGURE 8. Stress-based Fatigue Life Assessment of Operational Stresses from 2014 to 2018.

FUZZY-WEIBULL FATIGUE RELIABILITY ASSESSMENT

Table 2 presents the values for the criteria of Akaike's information (AIC) and likelihood estimation log-likelihood (LL) for the stress life Gerber Fatigue Model using the results of the durability assessment of operational stresses. According to the LL value, the Weibull distribution had the lowest value, followed by the normal and lognormal distributions. Conversely, the AIC value indicates that the Weibull distribution yields the greatest value. The Weibull parameters-based distribution is a commonly used method for the reliability assessment of components and structures in terms of their lifespan probability.

TABLE 2. Log-likelihood and AIC Values for Five-Year Fatigue Life Data using Different Distributions

Distribution	Log Likelihood	AIC
Normal	-118.94	247.87
Exponential	-126.1	254.2
Weibull	-118.15	241.11
Lognormal	-119.24	244.48
Gamma	-119.07	245.13

The Weibull distribution for the operational stresses was plotted against the Weibull distribution of yield strength, as shown in Figure 9, which indicates the interference region of the higher operational stresses with the lower values of experimental yield strength, leading to the probability of failure.

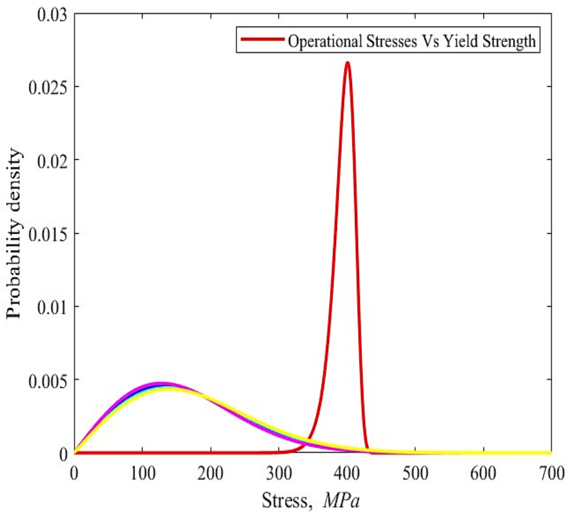


FIGURE 9. Distributions for Operational Stresses and Yield Strength Interference Region.

The Weibull distribution for the interference region, indicating higher stresses, was further used to include epistemic certainties in the Weibull shape and parameters. The Weibull fatigue life distribution was constructed based on operational Stresses and the stresses in the interference region using Monte Carlo technique. Figure 10 indicates the variation of probability distributions and mean cycles to failure by changing the shape parameter of the Weibull distribution, highlighting the imprecise data. The figure indicated that the operational stresses with higher statistical shape and scale parameters of the distribution showed to lower mean cycles to failure, leading to early fatigue failure. Additionally, the plots exhibited left-skewness, indicating a lower fatigue life for the pipeline with an increasing failure fate against the number of fatigue cycles Three membership functions for change in the Weibull shape parameters from low to high were formulated as 0.5, 1.5, and 2.5, with the spread of 5% to 25% assuming the epistemic uncertainty in the Weibull shape parameter, as shown in Figure 11. The Fuzzy Inference system was employed to calculate the defuzzified reliability for the three membership functions for Weibull fatigue life under operational stresses and for stresses under the interference region. Therefore, the Weibull distribution for fatigue life based on higher random loads was further studied using fuzzy logic to include the uncertainty in the Weibull shape parameter.

The plots depicted in Figure 12 correspond to the reliability of the pipe according to the Weibull distribution based on the number of cycles to fatigue failure using the stresses and higher stresses that fall under the interference region. The value of defuzzified reliability was calculated using fuzzy logic for three membership functions of low, medium, and high shape parameters of the Weibull distribution. The defuzzified reliability increased from 0.38 to 0.46 with an increase in Weibull parameters, indicating that the material can endure more cycles before failure, thus leading to an increased life expectancy of the material with an increasing shape parameter. The same trend of increasing reliability is observed for the stresses under the operational region.

The fuzzy-Weibull probability distribution and the defuzzified mean cycles to failure are indicated in Figure 13 for fatigue life of material using the operational stress and the stresses where the interference zone is created due to overlap of higher stresses and the material yield strength exhibiting left-skewness, indicating a lower fatigue life for the pipeline with an increasing failure rate against the number of fatigue cycles. The defuzzified hazard rate for the Fuzzy-Weibull model ranged from 8.56×10^{-7} to 3.38×10^{-6} at the mean cycles to failure under the high stresses falling under the interference region. The same trend of increasing hazard rate is observed for the stresses under the operational region, as shown in Figure 14, which presents the fuzzy rate surface plots for the operational stresses indicating the failure is caused by fatigue or wear-out failure mechanisms.

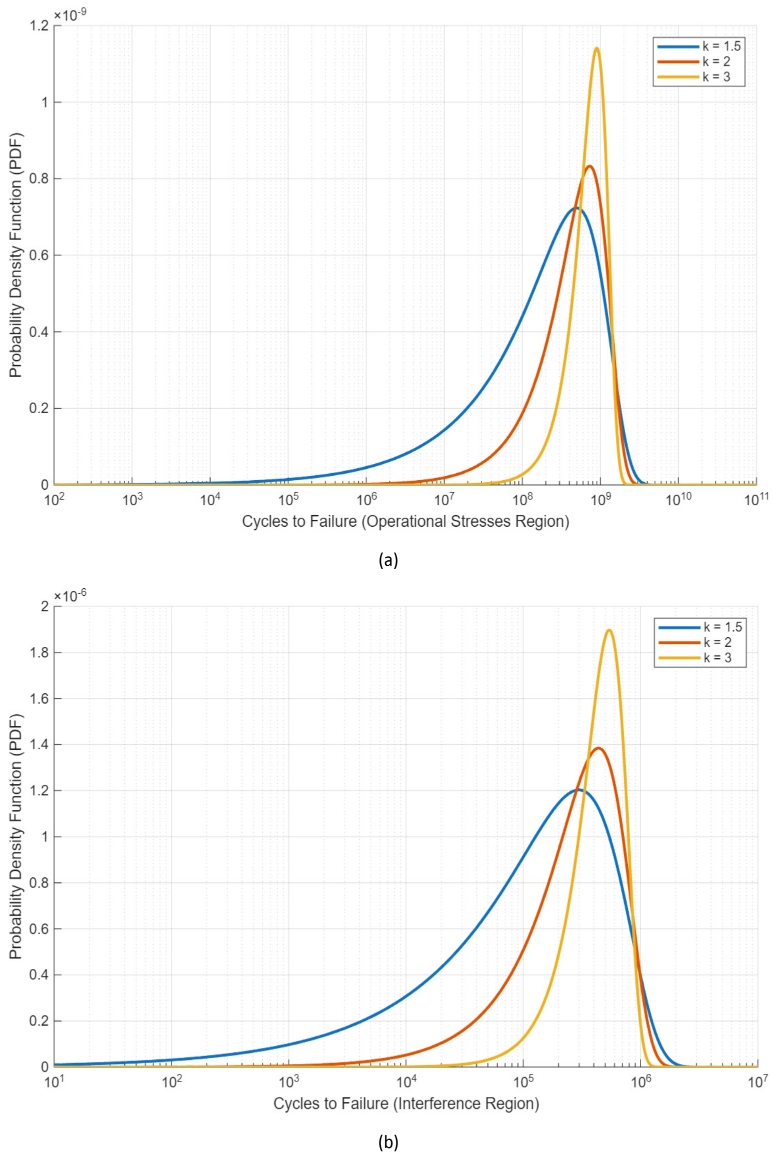


FIGURE 10. Effect of Variation in the Weibull Fatigue Distribution Parameters on (a) Operational Stresses Region (b) Interference Region

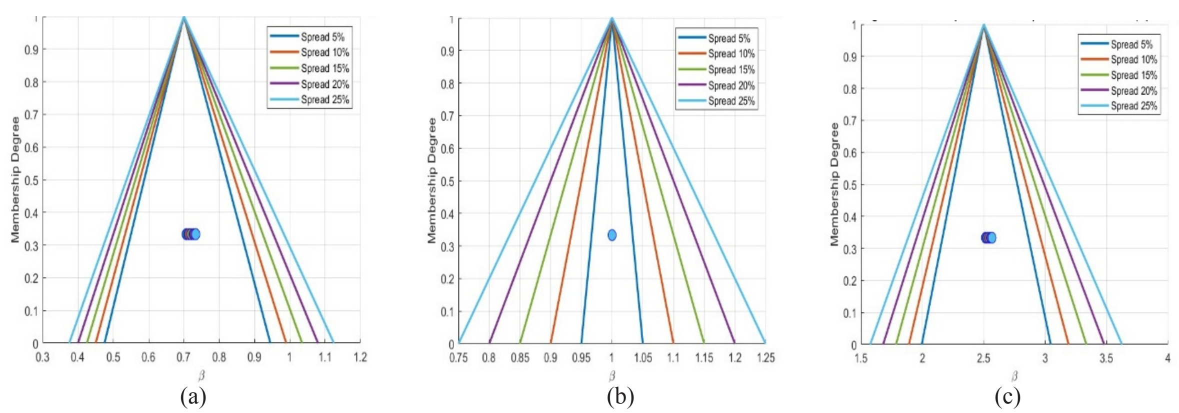


FIGURE 11. Triangular Fuzzy Membership Functions for Shape Parameter of the Weibull Distribution with 5 to 25% spread (a) Low $\beta < 1$ (b) Medium $1 \leq \beta \leq 2$ (c) High Medium $2 \leq \beta \leq 3$.

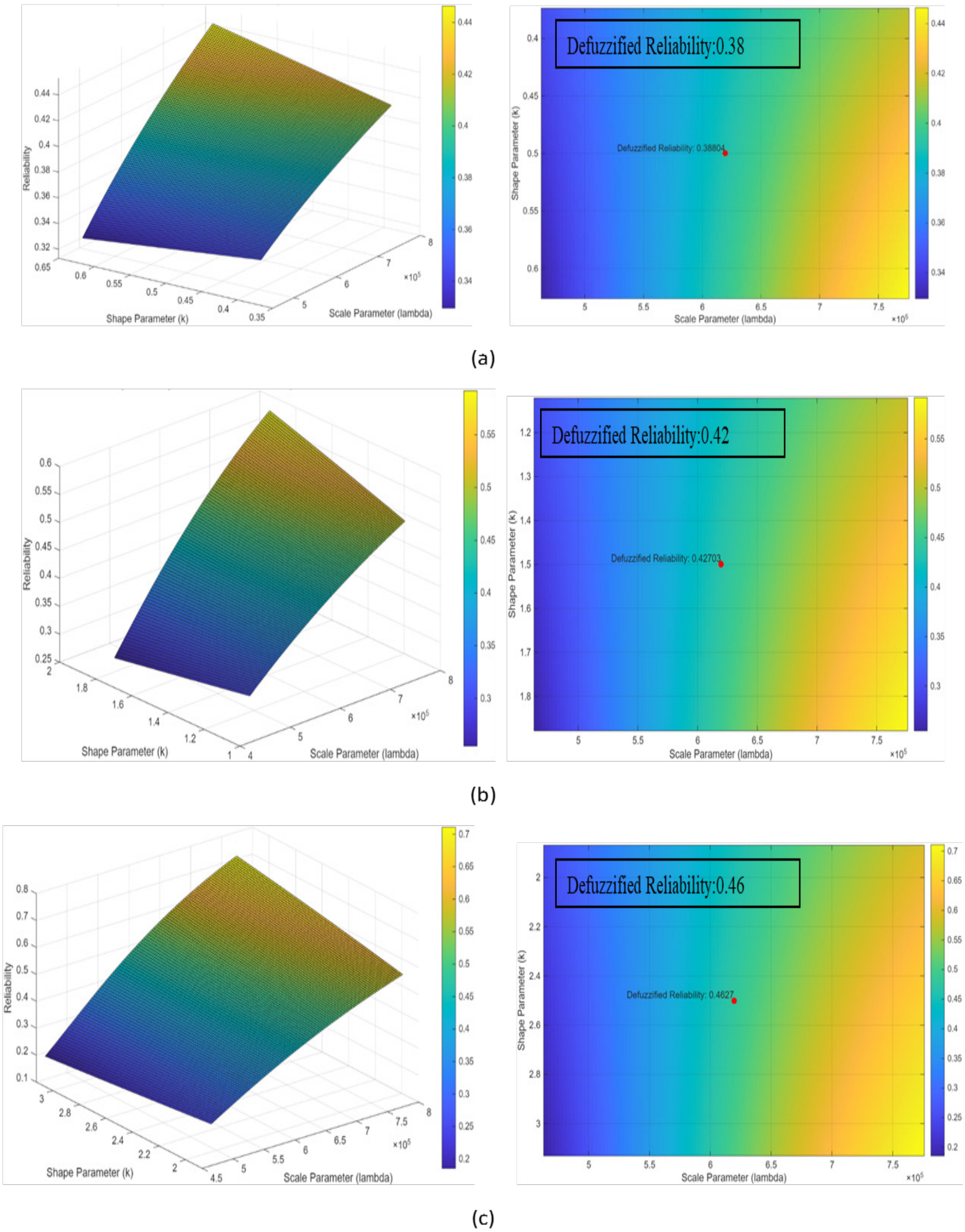
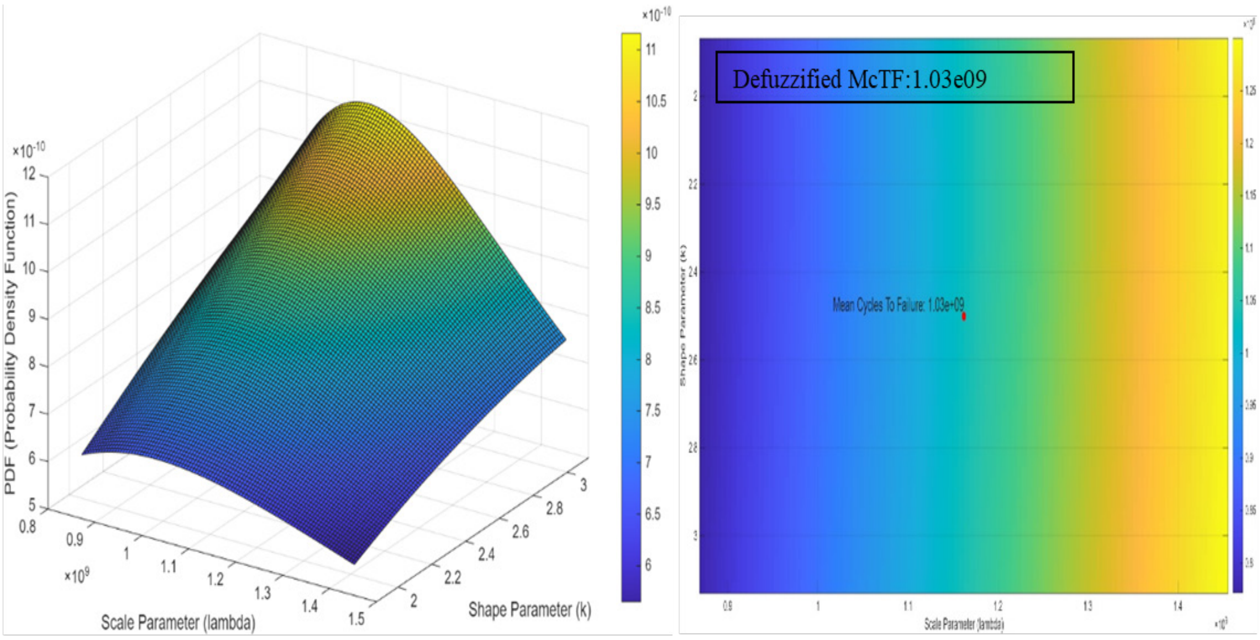
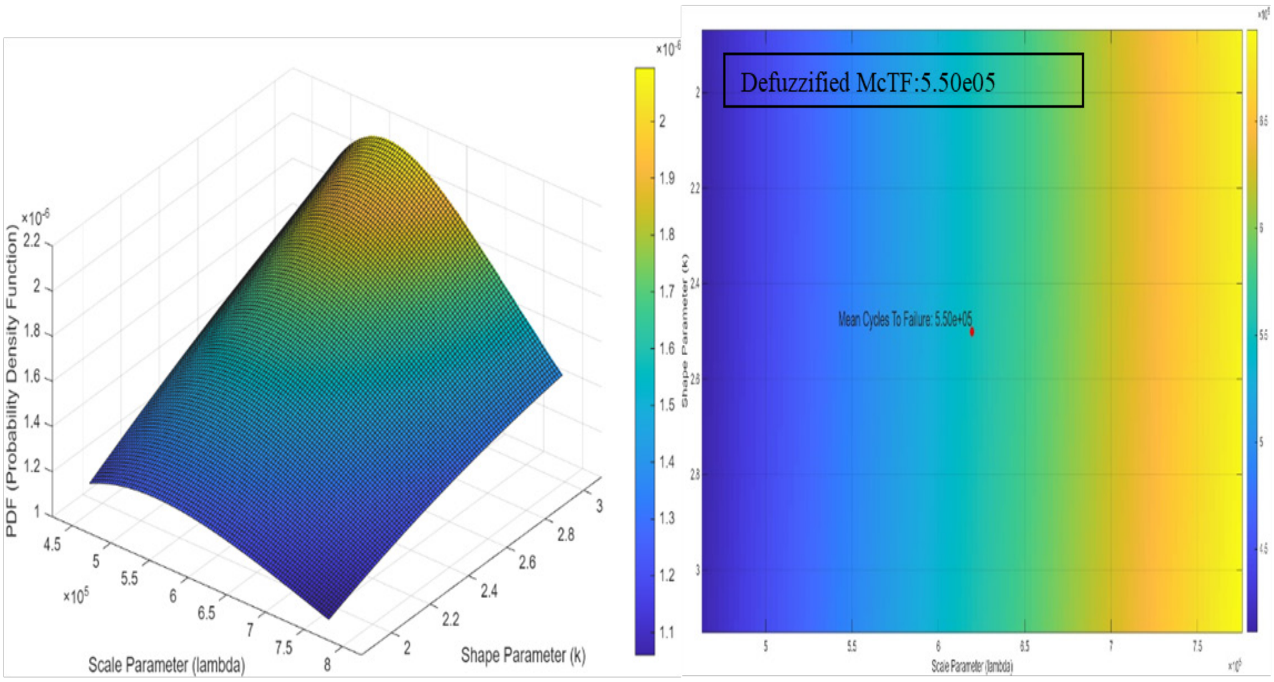


FIGURE 12: 3D Surface Plots for Fuzzy Fatigue Reliability and Defuzzified Reliability under Interference Region (a) Low Shape Parameter (b) Medium Shape Parameter (c) High Shape Parameter

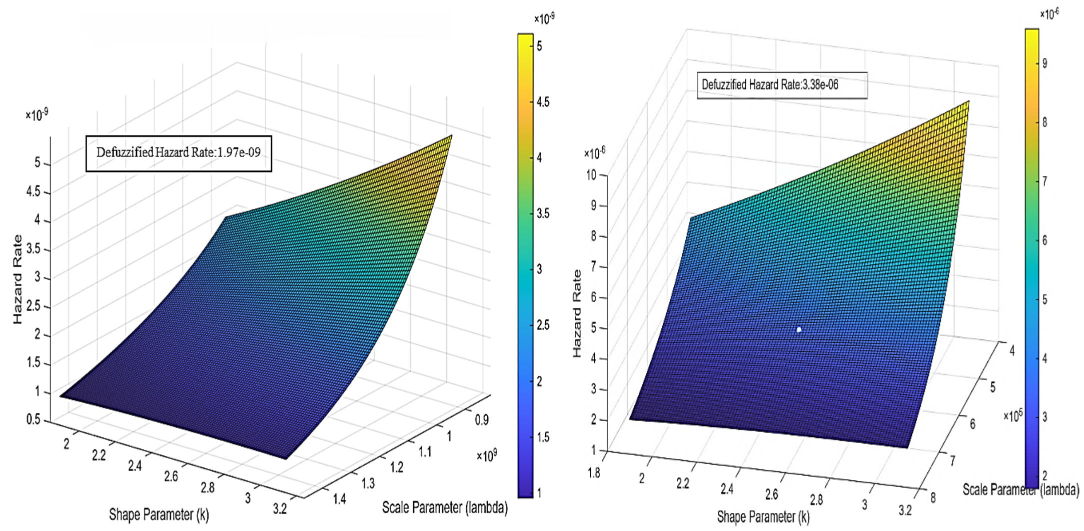


(a)



(b)

FIGURE 13. Three-Dimensional Surface Plot for Fuzzy-Weibull Probability Distribution Function under (a) Operational Stresses Region (b) Interference Region



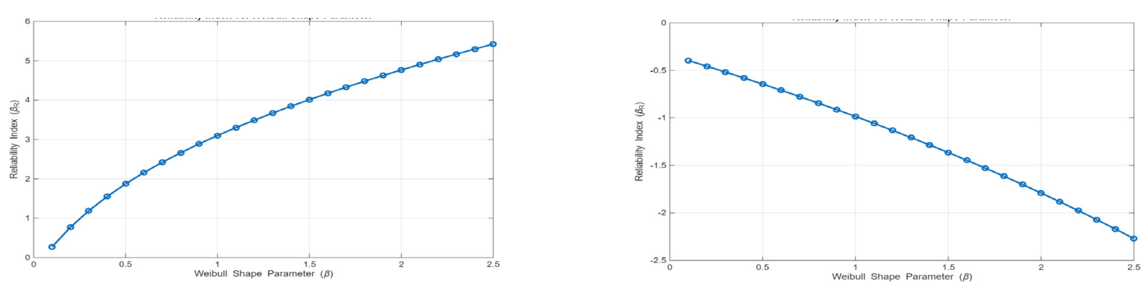
(a) (b)

FIGURE 14. Three-Dimensional Surface Plot and Defuzzification Plot for Hazard Rate for (a) Operational Stresses Region (b) Interference Region

The reliability indices for the predicted fatigue life using the Fuzzy-Weibull Fatigue Reliability model and the high cycle fatigue zone and 10^6 number of cycles to failure as the limit state function were plotted against increasing values of the Weibull shape parameter.

The results shown in Figure 15 indicate the increasing trend of the reliability index for Fuzzy-Weibull fatigue life under the operational stresses region, and the decreasing trend of the reliability index is indicated with an increase in the shape parameter of the Weibull distribution for the interference region. This indicates the fatigue reliability index of the in-service pipeline ranges from 2 to 5.5 for the operational stresses, and for higher stresses it drops from -0.6 to -2.25 with an increasing shape parameter. The results indicated that the pipeline is operating at the medium safety level for offshore pipelines, indicating the rescheduling of maintenance and inspection.

The correlation plot comparing the experimental cycles to failure and the Fuzzy-Weibull model shows a strong overall agreement, as shown in Figure 16. However, as the cycles to failure increase, the outliers are observed, especially at higher cycle values. These outliers indicate a deviation between the fuzzy model predictions and the experimental data, where the fuzzy model tends to overestimate the fatigue life compared to the experimental results.



(a) (b)

FIGURE 15. Trend of Reliability Index against the Increasing Weibull Shape Parameter (a) Operational Stresses Region (b) Interference Region

Moreover, obtaining the experimental results at a higher number of cycles also exhibits limitations. To address these limitations, future work could involve refining the fuzzy model to include machine learning techniques, which could improve the model's ability to predict fatigue life accurately in the high-cycle regime.

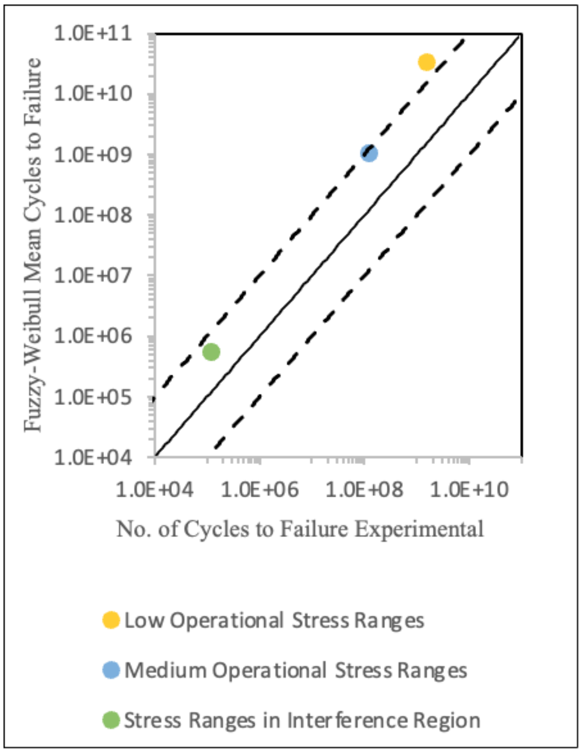


FIGURE 16. Correlation for Fuzzy-Weibull based Number of Cycles to failure to Experimental S-N Curve

CONCLUSION

This study combined fuzzy logic with the Weibull distribution to predict fatigue life, incorporating both experimental material properties and random operational stresses to improve fatigue reliability predictions for steel pipelines under aleatory and epistemic uncertainties. The random fluctuations in operational loading were used to address epistemic uncertainty, with fuzzy logic modelling the imprecision in Weibull distribution parameters (shape β and scale θ) and material properties. Fuzzy logic transformed uncertain and imprecise data into low, medium, and high Weibull shape and scale parameters for fatigue life, calculated using internal load fluctuations from an in-service offshore pipeline and the material's experimental mechanical properties. This approach allowed for a more flexible and accurate representation of uncertainties in pipeline fatigue life predictions. The scatter in operational stresses and the experimental material properties impacted by corrosion and welding ranged from 594 MPa to 366 MPa for yield strength and 618 MPa to 575 MPa for ultimate tensile strength, reducing the material's overall strength and creating an interference region under stochastic loading conditions. Fuzzy-Weibull fatigue reliability results, using the Gerber Fatigue Life model, indicated that the mean cycles to failure for operational stresses ranged from 1.06 x 10^8 to 1.03 x 10^9 cycles to failure and 5.48 x 10^{05} cycles to failure were calculated for higher stress levels in the interference region of load distribution with material strength. The defuzzified reliability increased from 0.38 to 0.46 as the Weibull shape parameter increased. The integration of fuzzy logic with Weibull fatigue life distribution improved reliability index calculations, showing an increasing trend with rising shape parameters in the mean operational stress region (2.2 to 5.1) and a decreasing trend in the stress-strength interference region, indicating a transition from high-cycle fatigue to low-cycle fatigue. The Fuzzy-Weibull mean cycles to failure demonstrated a better correlation with the experimental curve, enhancing pipeline durability by considering both random load variations and knowledge-based uncertainties.

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DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abdullah, L., Karam Singh, S. S., Abdullah, S., Ariffin, A. K. & Zainal, S. S. M. 2023. Fatigue reliability characterisation of effective strain damage model using extreme value distribution for road load conditions. *Materials* 16(1): 456.

Abdullah, L., Singh, S. S. K., Ariffin, A. K. & Abdullah, S. 2024. Probabilistic characterization for durability assessment under various road strain loads. *Journal of Mechanical Science and Technology* 38(7): 3441–3453.

Acitas, S., Aladag, C. H. & Senoglu, B. 2019. A new approach for estimating the parameters of Weibull distribution via particle swarm optimization: An application to the strengths of glass fibre data. *Reliability Engineering & System Safety* 183: 116–127.

Adam, M. A., Singh, S. S. K., Abdullah, S. & Muhamad, M. A. 2025. Strain-based fatigue reliability assessment of an automobile's lower arm for various road load conditions due to limited experimental data. *Jurnal Kejuruteraan* 37(1): 79–96.

Adasooriya, N. D., Pavlou, D. & Hemmingsen, T. 2020. Fatigue strength degradation of corroded structural details: A formula for S-N curve. *Fatigue and Fracture of Engineering Materials and Structures* 43(4): 721–733.

Amaya-Gómez, R., Sánchez-Silva, M., Bastidas-Arteaga, E., Schoefs, F. & Muñoz, F. 2019. Reliability assessments of corroded pipelines based on internal pressure: A review.

Amiri, A. A., Toor, I. U. & Shams, A. 2025. Understanding stress corrosion cracking (SCC), affecting variables and prevention strategies in nuclear power plants: A review. *Arabian Journal for Science and Engineering* 50(5): 2957–2990.

An, J., Hu, X., Gong, L., Zou, Z. & Zheng, L. R. 2024. Fuzzy reliability evaluation and machine learning-based fault prediction of wind turbines. *Journal of Industrial Information Integration* 40: 100606.

Bagheri, M., Zhu, S. P., Ben Seghier, M. E. A., Keshtegar, B. & Trung, N. T. 2021. Hybrid intelligent method for fuzzy reliability analysis of corroded X100 steel pipelines. *Engineering with Computers* 37(4): 2559–2573.

Bjørheim, F., Pavlou, D. G. & Siriwardane, S. C. 2022. Nonlinear fatigue life prediction model based on the theory of the S-N fatigue damage envelope. *Fatigue and Fracture of Engineering Materials and Structures* 45(5): 1480–1493.

Castillo, E., Muniz-Calvente, M., Fernández-Canteli, A. & Blasón, S. 2019. Fatigue assessment strategy using Bayesian techniques. *Materials* 12(19): 3239.

Chin, C. H., Abdullah, S., Ariffin, A. K., Singh, S. S. K. & Arifin, A. 2024. A review of the wavelet transform for durability and structural health monitoring in automotive applications. *Alexandria Engineering Journal* 99: 204–216.

Chin, C. H., Abdullah, S., Singh, S. S. K., Ariffin, A. K. & Schramm, D. 2022. Probabilistic-based fatigue reliability assessment of carbon steel coil spring from random strain loading excitation. *Journal of Mechanical Science and Technology* 36(1): 109–118.

Dong, Y., Garbatov, Y. & Guedes Soares, C. 2021. Strain-based fatigue reliability assessment of welded joints in ship structures. *Marine Structures* 75: 102878.

Dowling, N. E. 2004. Mean stress effects in stress-life and strain-life fatigue.

Dowling, N. E., Calhoun, C. A. & Arcari, A. 2009. Mean stress effects in stress-life fatigue and the Walker equation. *Fatigue and Fracture of Engineering Materials and Structures* 32(3): 163–179.

Fatoba, O. & Akid, R. 2022. On the behaviour of small fatigue cracks emanating from corrosion pits: Part I – The influence of mechanical factors. *Theoretical and Applied Fracture Mechanics* 117: 103154.

Firdaus, S. M., Arifin, A., Abdullah, S., Singh, S. S. K. & Nor, N. M. 2023. Fatigue life assessment of API steel grade X65 pipeline using a modified Basquin parameter of the magnetic flux leakage signal. *Materials* 16(2).

Garbatov, Y. & Guedes Soares, C. 2017. Fatigue reliability of dented pipeline based on limited experimental data. *International Journal of Pressure Vessels and Piping* 155: 15–26.

Gholami, H., Shahrooi, S. & Shishehsaz, M. 2021. Strain-based fatigue life analysis of pipelines with external defects under cyclic internal pressure. *Journal of Strain Analysis for Engineering Design* 56(5): 313–326.

He, Z. & Zhou, W. 2021. Fatigue reliability analysis of dented pipelines. *Journal of Pipeline Science and Engineering* 1(3): 290–297.

Hong, L., Li, S., Chen, M., Xu, P., Li, H. & Cheng, J. 2024. Non-probabilistic reliability analysis with both multi-super-ellipsoidal input and fuzzy state. *Computer Methods in Applied Mechanics and Engineering* 429: 117154.

Huang, Y. & Zhang, P. 2021. Re-rounding analysis of API X60 pipelines containing an unconstrained dent subjected to internal pressure using finite element method. *Journal of Mechanical Science and Technology* 35(10): 4467–4475.

Karadeniz, H. 2001. Uncertainty modeling in the fatigue reliability calculation of offshore structures. *Reliability Engineering & System Safety* 74(3): 323–335.

Khan, M. A., Singh, S. S. K., Abdullah, S., Arifin, A. & Bashir, M. 2025. Fatigue life characterisation of API X65 steel pipeline for internal vibrational loads under sea water condition. *Applied Ocean Research* 155: 104454. https://doi.org/10.1016/j.apor.2025.104454

Kim, J., Kang, S. C., Kim, J. K. & Song, J. 2021. Yield strength estimation of X65 and X70 steel pipe with relatively low t/D ratio. *Steel and Composite Structures* 38(2): 151–164.

Latifi, L. M., Mubasyir, M. M., Abdullah, S. & Singh, S. S. K. 2025. Effect of varying frequency of fatigue test on durability of AISI 1045 carbon steel plate under spectral loading. *Jurnal Kejuruteraan* 37(1): 369–381.

Li, H., Frangopol, D. M., Soliman, M. & Xia, H. 2016. Fatigue reliability assessment of railway bridges based on probabilistic dynamic analysis of a coupled train-bridge system. *Journal of Structural Engineering* 142(3): 04015158.

Liu, X., Hu, D., Wang, R., Wang, S. & Zou, Z. 2022. Calibration and validation of fatigue lifetime model in complex structures based on multi-level data. *International Journal of Fatigue* 159: 106783.

Liu, Y. & Zhou, W. 2022. Uncertainties in internal pressure of oil transmission pipelines and implications for the reliability analysis. *Journal of Pipeline Science and Engineering* 2(2).

Manouchehrynia, R., Abdullah, S. & Singh, S. S. K. 2020. Fatigue reliability assessment of an automobile coil spring under random strain loads using probabilistic technique. *Metals* 10(1).

Meng, D., Yang, S., Yang, H., De Jesus, A. M. P., Correia, J. & Zhu, S. P. 2024. Intelligent-inspired framework for fatigue reliability evaluation of offshore wind turbine support structures under hybrid uncertainty. *Ocean Engineering* 307: 118213.

Oyegbile, A. D. & Muskulus, M. 2024. Enhancing fatigue reliability prediction of offshore wind turbine jacket joints through individual uncertainties for each degree of freedom of stress concentration factor. *Marine Structures* 96: 103634.

Paci, A., Bualoti, R. & Çelo, M. 2021. Evaluation of distribution system reliability indices using fuzzy reasoning approach. *European Journal of Electrical Engineering and Computer Science* 5(3): 1–8.

Saeed, M. U., Elias, S. & Li, P. 2025. Novel adaptive intelligent control scheme with self-evolving genetic fuzzy BELBIC for enhancing the seismic resilience of smart building structures. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 11(2).

Song, L. K., Bai, G. C., Fei, C. W. & Wen, J. 2018. Reliability-based fatigue life prediction for complex structure with time-varying surrogate modeling. *Advances in Materials Science and Engineering* 2018.

Wang, C., Beer, M. & Ayyub, B. M. 2021. Time-dependent reliability of aging structures: Overview of assessment methods. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 7(4).

Wang, L., Xiong, C. & Yang, Y. 2018. A novel methodology of reliability-based multidisciplinary design optimization under hybrid interval and fuzzy uncertainties. *Computer Methods in Applied Mechanics and Engineering* 337: 439–457.

Yang, F., Ren, H. & Hu, Z. 2019. Maximum likelihood estimation for three-parameter Weibull distribution using evolutionary strategy. *Mathematical Problems in Engineering* 2019(1): 6281781.

Yat Sheng, K., Abdullah, S., Mohamed Haris, S., Zaidi Omar, M. & Schramm, D. 2018. Generation of artificial road profile for automobile spring durability analysis. *Jurnal Kejuruteraan* 30(2): 123–128.

Yu, J., Wang, H., Yu, Y., Luo, Z., Liu, W. & Wang, C. 2018. Corrosion behavior of X65 pipeline steel: Comparison of wet–dry cycle and full immersion. *Corrosion Science* 133: 276–287.

Zakikhani, K., Nasiri, F. & Zayed, T. 2020. Availability-based reliability-centered maintenance planning for gas transmission pipelines. *International Journal of Pressure Vessels and Piping* 183: 104105.

Zhang, S. & Zhou, W. 2013. System reliability of corroding pipelines considering stochastic process-based models for defect growth and internal pressure. *International Journal of Pressure Vessels and Piping* 111–112: 120–130.