12^{th} International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-12
B.L.A. Pichler, Ch. Hellmich, P. Preinstorfer (Eds)

https://doi.org/10.21012/FC12.1357
MS02-3:3

CORROSION FATIGUE IN REINFORCED CONCRETE BEAMS: ACCOUNTING FOR THE SYNERGISTIC EFFECTS OF CORROSION AND CYCLIC LOADING

MUNEEM AHMAD DAR*, **K. M. PERVAIZ FATHIMA** †

Indian Institute of Technology Jammu (IIT Jammu)
NH-44, PO Nagrota, Jagti, Jammu and Kashmir 181221
www.iitjammu.ac.in
*e-mail: muneem.dar@iitjammu.ac.in
†e-mail: pervaiz.khatoon@iitjammu.ac.in

Key words: Corrosion Fatigue, Reinforced Concrete, Fatigue Crack Growth, Fatigue Life Prediction.

Abstract. Corrosion fatigue can be more damaging than corrosion or pure fatigue alone in reinforced concrete (RC) structures. RC bridges in corrosive environments are exposed to coupled corrosion fatigue, potentially leading to an overestimation of the fatigue life of bridge structures. Understanding and modelling fatigue crack propagation in the context of corrosion is crucial for improving the durability and safety of RC bridges under cyclic loading in corrosive environments. In this study, a model is developed to predict the fatigue life of reinforcement bars in aging RC beams exposed to corrosive environments. The model is based on Paris' law, integrating fracture mechanics principles and corrosion growth kinetics. It evaluates the critical crack size by accounting for the combined effects of mechanical loading and corrosive exposure. A correlation has been developed to relate equivalent initial flaw size to the degree of corrosion. The model's fatigue life predictions are validated against experimental results for corroded RC beams reported in the literature.

1 INTRODUCTION

Due to its robustness, reinforced concrete (RC) is commonly used for constructing bridges and other structures subjected to cyclic loading, such as offshore buildings, wind turbine foundations, and dams. However, RC structures face the inevitable challenge of steel reinforcement corrosion, primarily caused by chloride ion infiltration from the surrounding environment [1]. RC bridges, in particular, are subject to repeated vehicle loads, causing damage to the steel reinforcement and the concrete due to high-cycle fatigue [2]. Previous studies have shown that the combination of corrosion and fatigue significantly accelerates structural degradation, shortens fatigue life, and often results in sudden, catastrophic failures [3]. The fatigue crack growth in RC structures affected by corrosion is a complex phenomenon, and its modelling involves corrosion kinetics and fracture mechanics [4]. Corrosion-fatigue interactions are particularly critical in chloride-contaminated reinforced concrete (RC) structures subjected to cyclic loading. Chloride ingress induces reinforcement corrosion, leading to cracking in the concrete cover and pitting of reinforcement steel bars. Cyclic loading accelerates these effects, increases concrete cover cracking, and residual stresses in reinforcement bars [8]. The penetration of chloride ions reduces the cross-sectional area of steel reinforcement and redistributes internal stresses that weaken the concrete and diminish the fatigue strength of RC elements [4].

Under combined chloride exposure and cyclic loading, the fatigue strength of RC structures can decrease by as much as $20\%–30\%$ [5, 9]. Given the critical nature of this problem, predicting the corrosion fatigue life of RC structures has become a focal point of research. Various methodologies have been developed, including the use of S-N curves and fracture mechanics approaches. However, while simple, traditional S-N curve methods do not capture the complete fatigue failure process. In contrast, the fracture mechanics-based methods, which analyse fatigue crack propagation, offer a more comprehensive understanding but still face challenges, such as accurately accounting for initial crack sizes. The concept of equivalent initial flaw size (EIFS) has emerged as a useful approach, simplifying the complex fatigue failure process by using virtual initial flaw sizes to better predict fatigue life [6]. The relationship between corrosion and EIFS, however, remains underexplored, highlighting the need for further research to improve the accuracy and reliability of corrosion fatigue life predictions for RC structures. Further, it has been observed experimentally that the critical crack size is a function of the degree of corrosion. However, the existing fatigue life prediction models available in the literature do not consider the critical crack size as a function of the corrosion mass loss.

This study aims to address the gap by investigating the effects of corrosion on the fatigue behaviour of RC beams. EIFS-based crack prediction methodology is used to account for short crack growth and a correlation between EIFS and mass loss due to corrosion is obtained. In this work, a relationship between corrosion degree and critical crack size is obtained by using experimental fracture toughness values for different degrees of corrosion. Based on the critical crack size and EIFS, the fatigue life of reinforced concrete beams in corrosive environments is predicted by using Paris' law and validated with existing experimental data from the literature.

2 EIFS-BASED FATIGUE LIFE PREDICTION

The propagation of large cracks is typically analysed using the principles of fracture mechanics and is given by Paris' law. The rate of fatigue crack growth ($\frac{\mathrm{d}a}{\mathrm{d}N}$), using Paris' law, is expressed as a function of the stress intensity factor range $\Delta K = K_{\text{max}} - K_{\text{min}}$, where K_{max} and K_{min} represent the maximum and minimum stress intensity factors, respectively. Crack growth below the threshold stress intensity factor range (ΔK_{th}) is characterised by rapid and irregular short crack propagation. The Paris' law, however, becomes applicable only when $\Delta K > \Delta K_{\text{th}}$. Also, in a corrosive environment, the influence of environmental factors on fatigue crack propagation is reflected in the relationship between $\frac{\mathrm{d}a}{\mathrm{d}N}$ and ΔK [7].

A key challenge in fatigue life prediction using fracture mechanics lies in determining the initial crack size for analysing crack growth. The initial crack size serves as a critical input for the prediction of fatigue life in materials with substantial pre-existing flaws. Metallic materials, in particular, often exhibit inherent defects smaller than typical microstructural features such as grain size. The propagation behaviour of small fatigue cracks at the microstructural level diverges significantly from that of larger cracks. The concept of the EIFS provides a pragmatic solution by estimating the initial flaw size, effectively bypassing the need for complex modelling of small crack growth. This approach allows an extended crack growth analysis that aligns with observed fatigue life. The EIFS is mathematically expressed as [6].

$$a_i = \frac{1}{\pi}\left(\frac{\Delta K_{\text{th}}}{\Delta \sigma_f \beta}\right)^2$$

where a_i is the EIFS, ΔK_{th} is the threshold stress intensity factor range, $\Delta \sigma_f$ is the fatigue limit, and β is a geometry correction factor dependent on crack configuration.

2.1 MODELLING OF FATIGUE LIFE PREDICTION

The propagation of fatigue cracks in RC steel bars subjected to cyclic loading is typically described by Paris' law as follows [4]:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\,(\Delta K)^m \tag{1}$$

In this equation, C and m are material-specific constants, $\mathrm{d}a$ represents the increment in crack growth per stress cycle increment of $\mathrm{d}N$, and ΔK denotes the stress intensity factor range. The ΔK depends on the applied stress range, crack size, and geometry of the crack, and can be expressed as:

$$\Delta K = \Delta\sigma\beta\sqrt{\pi a} \tag{2}$$

Here, β is a geometry correction factor, which accounts for the influence of crack geometry on the ΔK and is defined as [11]:

$$\beta = \lambda\left(0.752 + 1.286\psi + 0.37H^3\right) \tag{3}$$

The terms in the above equation are defined as follows:

$$\begin{aligned} \lambda &= 0.92\left(\frac{2}{\pi}\right)\sec\psi\left(\frac{\tan\psi}{\psi}\right)^{1/2} \\ H &= 1 - \sin\psi \\ \psi &= \frac{\pi}{2}\cdot\frac{d}{D} \end{aligned} \tag{4}$$

Here, D is the diameter of the reinforcing bar, and d represents the depth of the corrosion pit. The dependency of β on d indicates that the stress intensity factor range ΔK is directly influenced by the depth of corrosion pits.

Fatigue crack growth occurs when the stress intensity factor range ΔK exceeds its threshold value ΔK_{th}. This condition is expressed as:

$$\Delta K > \Delta K_{\mathrm{th}} \tag{5}$$

Thus from Equation (1), the relationship for $\mathrm{d}N$ in terms of $\mathrm{d}a$ is derived as:

$$\mathrm{d}N = \frac{1}{C(\Delta\sigma\beta\sqrt{\pi a})^m}\,\mathrm{d}a \tag{6}$$

To calculate the total fatigue life, the above expression is integrated from the initial crack size (a_0) to the critical crack size (a_c):

$$N = \int_{a_0}^{a_c} \frac{1}{C(\Delta\sigma\beta\sqrt{\pi})^m} a^{-\frac{m}{2}}\,\mathrm{d}a \tag{7}$$

This integral simplifies to:

$$N = \frac{1}{C(\Delta\sigma\beta\sqrt{\pi})^m}\cdot\frac{a_0^{1-m/2} - a_c^{1-m/2}}{1-m/2} \tag{8}$$

This equation illustrates the dependence of fatigue life on various parameters, including the material constants (C, m), the geometry correction factor (β), the applied stress range ($\Delta\sigma$), and the initial and critical crack sizes (a_0 and a_c). Substituting, EIFS for a_0, the analysis becomes more practical, offering a reliable method for predicting fatigue life in conditions influenced by corrosion.

3 MEASUREMENT OF FRACTURE TOUGHNESS OF REINFORCEMENT BARS

Standardized testing procedures, such as ASTM E399 [12] and ASTM E1304 [13], are recommended for accurately measuring the fracture toughness of steel bars. These tests involve applying tensile loading to specimens, ensuring that the crack orientation is perpendicular to the longitudinal axis of the bar. Key specimen dimensions include thickness (B), crack length (a), and width (W). According to the ASTM standards, the calculated fracture toughness (K_{IC}) is considered valid only if the following condition is satisfied:

$$B \text{ or } a \geq \frac{2.5K_{\mathrm{IC}}^2}{\sigma_y^2} \tag{9}$$

where a is the crack length, B is the sample thickness, σ_y is the yield stress of the material, and K_{IC} is the measured fracture toughness. This criterion ensures that the fracture toughness value corresponds to linear elastic behavior under small-scale yielding conditions.

The maximum value of K_{IC} consistent with small-scale yielding can be expressed as:

$$K_{\mathrm{IC}} = 0.632\sigma_y\sqrt{B} \quad (10)$$

For reinforcement bars with a diameter D, the fracture toughness K_{IC} is given as [14]:

$$K_{\mathrm{IC}} = Q\sigma_y\sqrt{D} \quad (11)$$

where Q is a constant dependent on the specimen type, with values of 0.385 for Compact Tension (CT) specimens and 0.432 for Single Edge Notched Bending (SENB) specimens.

3.1 EFFECT OF CORROSION ON FRACTURE TOUGHNESS

Fracture toughness K_{IC}, which measures a material's ability to resist crack propagation, decreases significantly with increased corrosion degree [19]. This reduction in K_{IC} results in a lower load-bearing capacity and premature failure under tensile and fatigue loads. Consequently, accurate prediction of K_{IC} degradation is essential for assessing corroded steel's remaining fatigue life. To quantify the effect of corrosion, the normalised fracture toughness which is defined as the ratio of fracture toughness of a corroded bar K_{IC}^{R} at a particular degree of corrosion R to the fracture toughness of an uncorroded bar K_{IC}. Table 1 shows the degradation in fracture toughness in steel plates with corresponding degrees of corrosion. An empirical relationship is fitted between the decrease in fracture toughness and the degree of corrosion, as given by Equation (12) and illustrated in Figure 1.

$$K_{\mathrm{IC}}^{R} = K_{\mathrm{IC}}\big(99.87R^4 - 118.7R^3 + 52.48R^2 - 10R + 1\big) \quad (12)$$

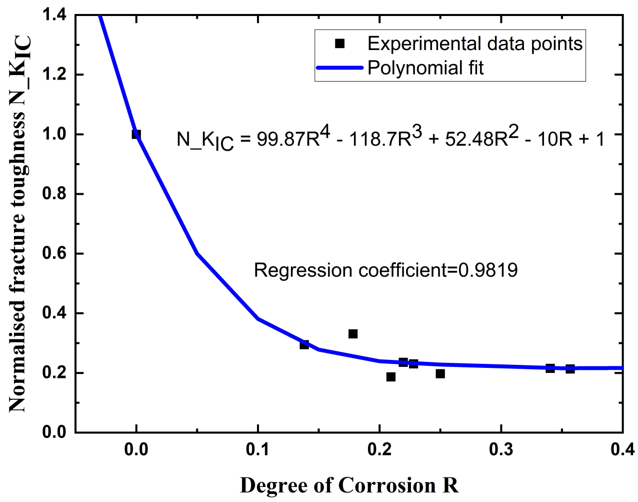

Figure 1: Decrease in fracture toughness with increasing degree of corrosion

4 CALCULATION OF CRITICAL CRACK SIZE

There is a direct correlation between the critical crack size and fracture toughness, and is given as follows:

$$a_c = \frac{1}{\pi}\left(\frac{K_{\mathrm{IC}}}{Y\sigma_y}\right)^2 \quad (13)$$

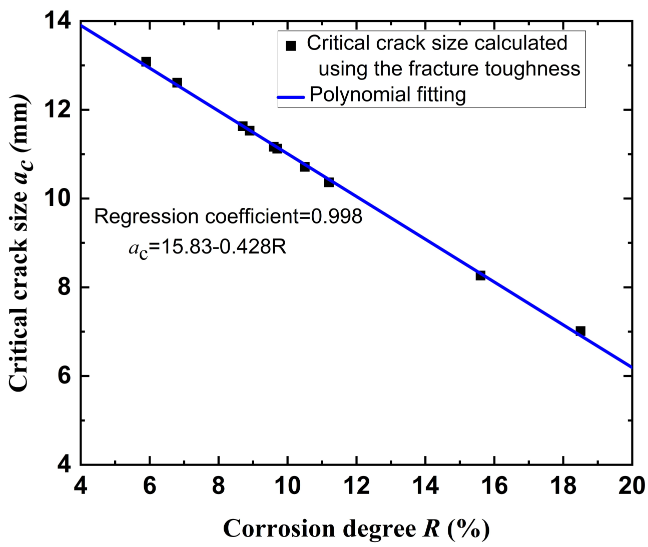

Figure 2: Relationship between critical crack size and degree of corrosion

For corroded steel bars under cyclic loading, the critical crack size a_c is significantly influenced by the degree of corrosion, K_{IC} decreases

Table 1: Fracture toughness degradation with corresponding degree of corrosion. [19]

$\left(\frac{K_{IC}^R}{K_{IC}}\right)$	**Degree of Corrosion (R)**
1.000000000	0.000
0.446280038	0.801
0.242769609	0.941
0.268322828	0.928
0.262803685	0.931
0.230119959	0.947
0.162938928	0.973
0.150230201	0.977
0.139879425	0.980

with increasing degree of corrosion. Figure 2 clearly shows that higher corrosion degrees results in reduced values of a_C, indicating that corrosion significantly decreases the critical crack size. This relationship demonstrates that as corrosion accelerates fatigue crack propagation, it substantially reduces the critical crack size, leading to an earlier onset of unstable crack propagation and fatigue fracture. Equation (14) shows an empirical fit between the degree of corrosion and critical crack size. This equation is valid for corroded reinforcement bars.

$$a_c = 15.83 - 0.428R \tag{14}$$

5 RELATIONSHIP BETWEEN EIFS AND DEGREE OF CORROSION

The need to obtain an estimate of the initial flaw size arises so that the Paris law, which describes the long crack growth behaviour, can be used to accurately calculate fatigue life by including the short crack regime as well. However, current EIFS estimation methods do not consider the effect of corrosion and are primarily based on the material's endurance derived from S-N curve data ($\Delta\sigma_f$ and ΔK_{th}).

To accurately determine the quantitative relationship between the EIFS and the degree of corrosion, the available fatigue life test results of corroded RC beams under similar loading conditions and failure modes were analyzed. This includes calibration of the model using a dataset of 11 experimental results from existing studies [15]. By using the analytical correlation for fatigue life prediction given by Equation (8), EIFS values at varying levels of corrosion mass loss were obtained. The resulting scatter plot and fitted expression, as depicted in Figure 3 and Equation (15) respectively, illustrate the correlation between EIFS and corrosion degree. This analysis shows that EIFS increases with higher degrees of corrosion, providing a clear and quantifiable link between the extent of corrosion damage and the initial flaw size.

$$a_{\text{EIFS}} = 0.328R - 1.25 \tag{15}$$

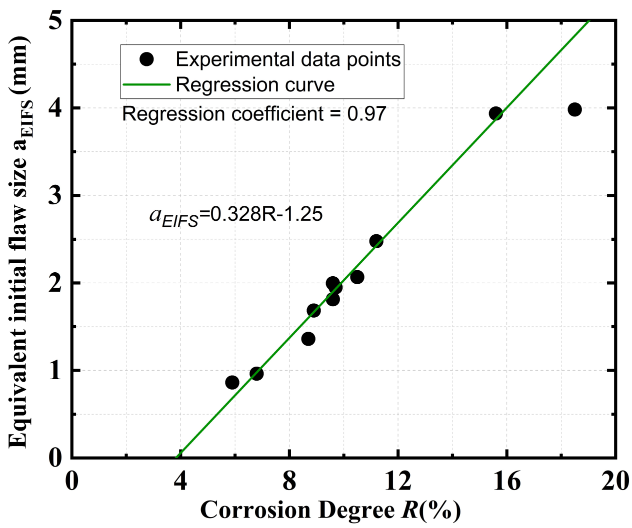

Figure 3: Correlation between EIFS and degree of corrosion

Table 2: Corrosion fatigue test results of corroded RC beams that are used to validate the proposed model

Author	No. of Beams	Dimensions of Beam	Reinforcement Properties	Fatigue Loading (kN)	Stress Ratio
Sun et al., 2019 [15]	12 beams	1800×150×250	f_y = 478 N/mm^2 f_u = 608 N/mm^2 D = 16 mm	Min. = 30 Max. = 70	0.42
Yi et al., 2010 [16]	8 beams	3600×150×300	f_y = 390 N/mm^2 f_u = 578 N/mm^2 D = 20 mm	Min. = 7 Max. = 33	0.21
Wang et al., 2004 [17]	2 beams	1700×120×200	f_y = 400 N/mm^2 f_u = 595 N/mm^2 D = 12 mm	Min. = 7 Max. = 36.5	0.19
Fernandez et al., 2015 [18]	140 corroded bars	310–320	f_y = 548 N/mm^2 f_u = 637 N/mm^2 D = 12 mm	Min. = 11.3 Max. = 33.7	0.33

6 VALIDATION OF THE PROPOSED MODEL

The results from accelerated and natural corrosion tests show only minor differences in the overall performance of corroded RC structures or their components. Therefore, data from accelerated corrosion tests can be effectively used to analyze and estimate the fatigue performance and lifespan of corroded RC beams. Using the above-proposed model, the fatigue life of corroded steel bars under various degrees of corrosion is predicted and verified by comparison of results with existing experimental data of corroded RC beams, given in Table 2.

The experimental data shows a significant decrease in the fatigue life of RC beams as the degree of corrosion increases. Fatigue life predictions using the proposed and available model [15] in the literature are compared to the experimental fatigue life of corroded RC beams, and illustrated in Figures 4(a) and 4(b), respectively. A 45° line signifies that the predicted values are exactly equal to the experimental values, and data points close to this line indicate the precision of the predictions. From Figure 4, it is clear that the proposed model outperforms the existing model. The predicted outcomes of the proposed model align more closely with the 45° line, showing an average percentage error of 1.39%, compared to the 4.97% error of the existing model. This indicates that the proposed model has a better agreement with the test results. This validation highlights the effectiveness of the proposed model in predicting the fatigue life of corroded RC beams, making it a reliable tool for future research and practical applications.

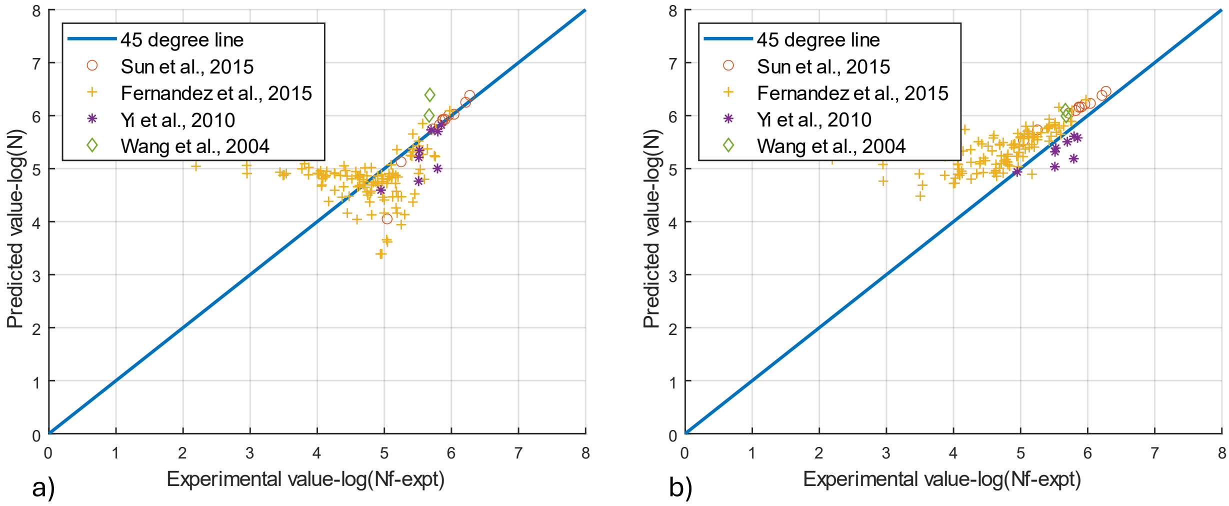

Figure 4: Comparison of the predicted fatigue life (N) and experimental fatigue life (Nf-expt) results of corroded RC beams (a) By using proposed model given in this study (b) Existing model in the literature.

7 CONCLUSIONS

1. This study investigates the effect of corrosion on the parameters governing fatigue crack growth life under the coupled corrosion-fatigue process. Using accelerated corrosion test data from the literature, a novel empirical relationship has been established to describe the degradation of fracture toughness as a function of the degree of corrosion.

2. This study examines the coupled effect of corrosion and fatigue loading by using EIFS as a substitute for the initial flaw size for corroded reinforcement in concrete beams. The EIFS approach eliminates the need for separate analysis of small crack growth and integrates the large crack growth model for predicting the fatigue life.

3. The validation of the proposed corrosion fatigue life prediction model demonstrated good accuracy when compared to existing models, as shown by the closer agreement of predicted results with experimental data. These findings emphasize the importance of explicitly accounting for corrosion-induced damage when evaluating the remaining fatigue life of reinforced concrete structures. The model offers practical utility for assessing the structural serviceability and safety of materials exposed to combined corrosive and cyclic loading environments.

REFERENCES

[1] Rodrigues, R., Gaboreau, S., Gance, J., Ignatiadis, I., & Betelu, S. 2021. Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring. *Construction and Building Materials*, 269, 121240.

[2] Herwig, A. 2008. Reinforced concrete bridges under increased railway traffic loads: Fatigue behaviour and safety measures. (No. 4010). *EPFL*.

[3] Devendiran, D. K., & Banerjee, S. 2023. Influence of Combined Corrosion–Fatigue Deterioration on Life-Cycle Resilience of RC Bridges. *Journal of Bridge Engineering*, 28(5), 04023014.

[4] Ma, Y., Xiang, Y., Wang, L., Zhang, J., & Liu, Y. 2014. Fatigue life prediction for aging RC beams considering corrosive environments. *Engineering Structures*, 79, 211-221.

[5] Gheorghiu, C., Labossiere, P., & Proulx, J. 2006. Fatigue and monotonic strength of RC beams strengthened with CFRPs. *Composites Part A: Applied Science and Manufacturing*, 37(8), 1111-1118.

[6] Liu, Y., & Mahadevan, S. 2009. Probabilistic fatigue life prediction using an equivalent initial flaw size distribution. *International Journal of Fatigue*, 31(3), 476-487.

[7] Madia, M., Vojtek, T., Duarte, L., Zerbst, U., Pokorný, P., Jambor, M., & Hutař, P. 2021. Determination of fatigue crack propagation thresholds for steel in presence of environmental effects. *International Journal of Fatigue*, 153, 106449.

[8] Yang, D. H., Yi, T. H., & Li, H. N. 2017. Coupled fatigue-corrosion failure analysis and performance assessment of RC bridge deck slabs. *Journal of Bridge Engineering*, 22(10), 04017077.

[9] Coca, F. O., Tello, M. L., Gaona-Tiburcio, C., Romero, J. A., Martínez-Villafañe, A. B. E. M., & Almeraya-Calderón, F. 2011. Corrosion fatigue of road bridges: A review. *International Journal of Electrochemical Science*, 6(8), 3438-3451.

[10] Xiang, Y., & Liu, Y. 2010. EIFS-based crack growth fatigue life prediction of pitting-corroded test specimens. *Engineering Fracture Mechanics*, 77(8), 1314-1324.

[11] Forman, R. G., & Shivakumar, V. 1986. Growth behavior of surface cracks in the circumferential plane of solid and hollow cylinders. In *Fracture mechanics: Seventeenth volume*. ASTM International.

[12] ASTM E399. Standard test method for fracture toughness of metallic materials; 1990.

[13] ASTM E1304. Standard test method for plane-strain (Chevron-Notch) fracture toughness of metallic materials; 2001.

[14] Elices, M., Perez-Guerrero, M., Iordachescu, M., & Valiente, A. 2017. Fracture toughness of high-strength steel bars. *Engineering Fracture Mechanics*, 170, 119-129.

[15] Sun, J., Ding, Z., & Huang, Q. 2019. Corrosion fatigue life prediction for steel bar in concrete based on fatigue crack propagation and equivalent initial flaw size. *Construction and Building Materials*, 195, 208-217.

[16] Yi, W. J., Kunnath, S. K., Sun, X. D., Shi, C. J., & Tang, F. J. 2010. Fatigue Behavior of Reinforced Concrete Beams with Corroded Steel Reinforcement. *ACI Structural Journal*, 107(5).

[17] Wang, H., Gong, J., & Song, Y. 2004. Experimental study on corrosion fatigue of RC beams. *Journal of Building Structures*, 25(5), 105-110.

[18] Fernandez, I., Bairán, J. M., & Marí, A. R. 2015. Corrosion effects on the mechanical properties of reinforcing steel bars. Fatigue and σ–ε behavior. *Construction and Building Materials*, 101, 772-783.

[19] Zhang, H., Xu, S., Nie, B., & Wen, Y. (2019). Effect of corrosion on the fracture properties of steel plates. *Construction and Building Materials*, 225, 1202-1213.