

Fatigue strength degradation of metals in corrosive environments

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Abstract. Structures exposed to aggressive environmental conditions are often subjected to time-dependent loss of coating and loss of material due to corrosion; this causes reduction in the cross-sectional properties of the members, increased surface roughness, surface irregularities and corrosion pits, and degradation of material strengths. These effects have been identified and simulated in different research studies. However, time and corrosive media dependent fatigue strength curves for materials have not been discussed in the design or assessment guidelines for structures. This paper attempts to review the corrosion degradation process and available approaches/models used to determine the fatigue strength of corroded materials and to interpolate corrosion deterioration data. High cycle fatigue and full range fatigue life formulae for fatigue strength of corroded materials are proposed. The above formulae depend on the endurance limit of corroded material, in addition to the stress-life fatigue curve parameters of the uncorroded material. The endurance limit of corroded material can either be determined by a limited number of tests in the very high-cycle fatigue region or predicted by an analytical approach. Comparison with experimentally measured corrosion fatigue behavior of several materials is provided and discussed.

1. Introduction

Corrosion is one of the principal deterioration processes that affect the integrity of structures. Major effects can be listed as thickness reduction, irregularities of the surfaces, surface roughness, and stress concentration due to the pitting and degradation of material due to the electrochemical process. The cracking of members especially starts at highly stressed locations. Thickness reduction, surface roughness and cyclic loading accelerate the crack initiation under different types of corrosion [1]. Cracks caused by corrosive media are mainly governed by environmental assisted cracking (EAC) such as stress corrosion cracking (SCC), corrosion fatigue (CF), sulfide stress cracking, etc. CF and SCC play a significant role in the degradation of metal structures. Fractures due to cyclic stress in corrosive media are designated as CF. SCC is generally defined as failure caused by continuously applied stress in corrosive media. Researchers are still highlighting the significance of further study on CF [2-4], due to the inherent nature of corrosion and its effects on random fatigue behavior.

Recent failures of key structures such as Silver Bridge in 1967, Mianus River Bridge in 1990, Minnesota Bridge in 2007, etc., emphasize the importance of more accurate simulation of CF in



different corrosive environments in respect to different structural materials. Therefore, the consideration of the corrosion effects on structural integrity is important [3,5].

This paper reviews the effects of CF in structural degradation. Initially, the paper describes the corrosion degradation process of metallic materials. Then methods for modeling CF are comprehensively reviewed. New formulae for determining the fatigue strength of corroded material are proposed as an original contribution of this paper. The proposed formulae are compared with published results of the experimentally measured CF behavior (i.e. fatigue test of corroded specimens) of several steel types.

2. Corrosion degradation process of metallic materials

Corrosion of steel is an electrochemical process, which starts with the presence of oxygen and water. Common agents such as carbon dioxide, sodium chloride and hydrogen sulfide affect this process. The corrosion mechanism of iron can be described as follows: oxidation of iron takes place when dissolution of iron produces ferrous iron (Fe^{2+}) at the anode with the presence of various impurities. At the cathode, oxygen produces hydroxide ions (OH^-). Then Fe^{2+} and OH^- iron combine to form ferrous hydroxide ($Fe(OH)_2$). Further oxidation of ferrous hydroxide produces rust ($Fe_2O_3 \cdot H_2O$). Corrosion pits, corrosion products on surfaces, uneven surfaces, loss of material and degradation of material strength can be seen as outcomes of the above electrochemical process [3,6]. Generally, structures are subjected to five of the most important forms of corrosion [6,7], the most common of which is general (uniform) corrosion, which is uniformly distributed on the surface. General corrosion often occurs in locations where water accumulates [6,8]. Pitting corrosion is a localized form of corrosion which is restricted to a small area and usually begins with an irregularity on the surface. This type is dangerous because it may cause local stress concentrations. Crevice corrosion is also a form of localized corrosion, occurring where different components of the structure are close together, leading to narrow spaces. Galvanic corrosion takes place when two different metals are placed in an electrolyte and are electrically connected, as is possible at bolted or welded connections. The last dominant form of corrosion is CF, which is the mechanical degradation of a material under the combined action of localized corrosion and cyclic loading [8]. Fractures due to corrosion fatigue are often transgranular. The effect of CF on structural integrity is reported as significant for most situations [2,3,6-8,10].

The effects of corrosion deterioration to metal structures yields; (i) reductions of the effective cross-sectional area, moment of inertia, torsional and warping constants [6,11-14]. This may change the overall stiffness of the structures and hence change the stress state in the remaining part of the material/member; (ii) Interaction of corrosion (i.e. mostly pitting and crevice) and cyclic loading affects the mechanical properties of metal and, hence, cracks initiate from the corrosion-induced surface (i.e. CF); thereby a significant decrease in the fatigue strength (i.e. degrade the S-N curve in air) can be observed [7, 15-17] as shown in Figure 1. Finally, these may cause a reduction of the fatigue life of metal structures which are subjected to loss of coating, rust or corrosion wastage.

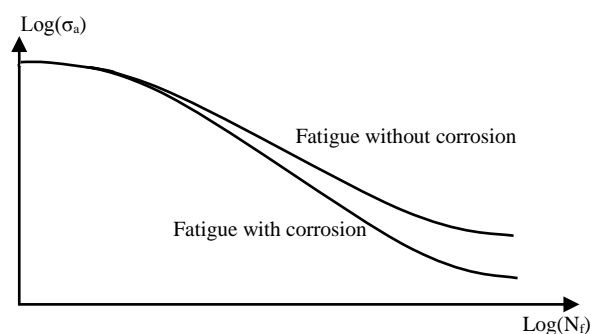


Figure 1. Fatigue behaviour of metals with and without corrosion

The behavior of the fatigue strength of corroded metals depends on various parameters such as types of corrosion, type and state of corrosive environment, rate of corrosion, chemical composition of the metal, etc. [18]. Generally, laboratory fatigue testing of corroded samples is popular for simulating the fatigue strength behavior of corroded materials [3]. However, it is obvious that testing corroded specimens is a time-consuming process, and it is still complicated to simulate a real corrosion situation in the environment. For this reason, a limited number of experimental studies are found, especially in the field of civil engineering, related to structural steels [2,3]. Therefore, there is a need for simple models or methodologies to model the fatigue strength of corroded materials. To fulfill this need, the major objective of this review paper is to illustrate/check the possibilities of proposing an interpolation formula for the fatigue strength of corroded material.

3. Modeling of fatigue damage due to corrosion

Approaches for modeling the fatigue damage of materials/structures due to corrosion can be mainly divided into two parts. The first is geometrical simulation of thickness loss and pitting. The other part is to model the degradation of material properties due to the corrosive environment (CF) by a stress-life fatigue model that simulates the fatigue strength of corroded material. The following subsections will review the aforementioned two parts of the modeling. At the latter part of this section, modeling of corrosion rate (i.e. intensity of corrosivity) is discussed, as it has a relation to the corresponding stress-life fatigue behavior of the corroded material.

3.1. Modeling of fatigue damage due to degradation of material properties

Fatigue damage due to corrosion pits and cracks is analytically modeled by fracture mechanics theories. Pitting corrosion damage models are widely used, based on stress intensity factor [19,20]. Moreover, fatigue crack propagation is determined by using stress intensity factor based fracture mechanics approaches [21, 22]. Using the modified corrosion-fatigue stress intensity threshold, ΔK_{th} , for the material to determine critical length L for corroded materials is reported as one method of modeling CF. Many researchers [2, 3] report that it is very difficult to get a clear value for ΔK_{th} in corrosive environments, in which the fatigue limit is not usually clear. The determination of critical length has not been well defined, as it is not clear in corrosive environments. Therefore, detailed research should be performed to fill this gap. A new strain-life model, based on the Smith–Watson–Topper model, was proposed in 2012 [2] to simulate the CF behavior of metals. The model takes into account the state of corrosive environment, the stress level, and the corrosive behavior of the material [2]. The parameters of the above CF model, which are modified Basquin's exponent and Coffin–Manson exponent, should be determined by a series of fatigue tests of materials in 3.5 wt/wt% NaCl which is a highly corrosive environment. As these model parameters are material dependent, and due to the complexity of fatigue tests, fewer applications of this model are found. This again emphasizes the importance of having a simple formula or methodologies to model the fatigue strength of corroded materials

3.2. Geometrical simulation of thickness loss and pitting

In order to estimate fatigue damage, it is essential to determine the stress histories generated by random loading of the structure. Therefore, it is necessary to know the stress cycles of all the corroded members in the past, present and future. The stress histories of the corroded members are evaluated by considering (i) past, present and future loadings and (ii) time-dependent change of cross-sectional shapes due to loss of material caused by the corrosion deterioration and related change in rigidities (i.e. change of axial, bending, torsional and warping rigidities), which finally cause change to the overall stiffness of the structure. These simulations associated fatigue damage/life assessment methods were discussed in recent literature [6, 11-14]. The proposed procedure with related theoretical formulae for structural elements has been comprehensively presented in recent literature [23]. For precise prediction of time-dependent stress histories, it is necessary to accurately model the time-dependent growth of corrosion wastage (i.e. rate of corrosion).

3.3. Modeling of corrosion rate

The environment makes a huge contribution to corrosion and changes the rate of corrosion. Corrosion rate is the speed of deterioration of material (loss of metal). It is the thickness reduction per year and can be calculated in general by metal loss divided by time. As corrosion rate is one of the key parameters, it is necessary to study the way corrosion effects in the integrity of steel structures and then the CF. Corrosion rate is one of the main factors affecting the service life of the structure. The intensity of the corrosivity depends on the corrosive environment. The corrosion rate is also presented for five categories of steel [23].

The experimental studies on corrosion rates include the following: (i) corrosion rates of low carbon steels in potable water conducted in this study, and (ii) effects of environmental factors on corrosion rates of previous research [24-29]. El Aghoury [2] proposed a new relationship between the logarithm of the penetration versus the proposed environmental corrosivity intensity factor (γ_{corr}). The corrosive environments of the materials have been divided into corrosivity categories in ISO 9224, based on average corrosion rate [2].

4. Proposed formulae for fatigue strength of corroded material

Two S-N curve formulae for corroded metals are proposed, based on Basquin's law [21] and the full-range curve proposed by Kohout and Vechet [30]. Conventional S-N curves for uncorroded steel have been used for assessing structures and components in a non-corrosive environment. Vacuum is the perfect non-corrosive environment. The difference in the fatigue strength of metals such as mild steel in the vacuum and in dry air is less than 5% [1]. Therefore, dry air can also be considered as non-corrosive and, hence, Basquin's law and Kohout and Vechet's proposed full-range S-N curve can be used in dry air without any modifications. It is necessary to use degraded S-N curves, when fatigue life is estimated for structures and components in a corrosive atmosphere (rain, various gases, water, marine, etc.).

4.1. Concept used for the proposed formulae

Gliding may occur in some of the grains when materials are subjected to alternating stresses. Gliding is halted when dislocation reaches a grain boundary. In the presence of corrosion, disorganized atoms are in motion along a gliding plane with less activation energy than in the absence of corrosion. This phenomenon may reasonably be expected, even below the fatigue limit. This means that there is no safe stress level at which the fatigue life is infinite, as shown in Figure 1 [18]. However, it is convenient to determine an endurance limit for corroded steel corresponding to a specified number of cycles by assuming the material will endure some specified number of cycles which must be stated. Previously experimentally obtained fatigue lives show that the difference between fatigue strengths in corrosive and non-corrosive environments in the low-cycle fatigue (LCF) region is very low, compared to the high-cycle fatigue (HCF) and very-high-cycle fatigue (VHCF) regions [1,9,22]. The difference is significantly large in the HCF and VHCF regions.

4.2. Proposed formula for high-cycle fatigue region

The relation between the applied stress amplitude, σ_a , and the corresponding number of cycles to fatigue failure, N_f , follows Basquin's law, as presented in (1), for uncorroded material when the stress is below the yield strength, σ_y [21],

$$\sigma_a = \sigma'_f N_f^b \quad (1)$$

where σ'_f is the fatigue strength coefficient and b is Basquin's exponent.

The linear variation in the difference between the fatigue strengths in the uncorroded and corroded materials has been observed in previous fatigue test results [18], and the relative difference in log scale

is linearly deducted, as shown in Figure 2, from the corrosion-free material fatigue strength to obtain the corroded material fatigue strength. The difference between corroded and uncorroded S-N curves at the stress amplitude just above yield strength (σ_y) can be neglected, when compared to the difference at the very-high-cycle fatigue region. Hence, it is assumed that corroded and uncorroded S-N curves are intercepted when stress amplitude is equal to yield strength, as shown in Figure 2.

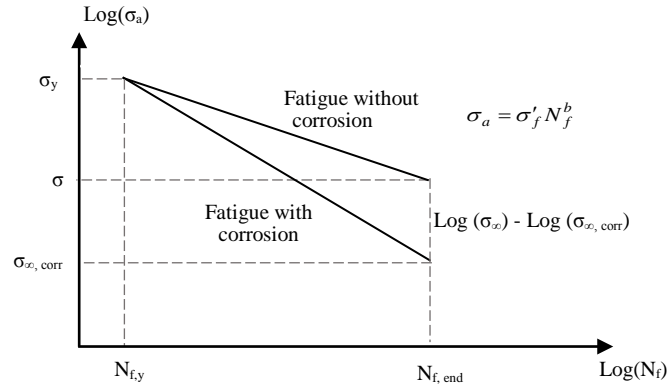


Figure 2. Schematic representation of fatigue strength degradation of corroded materials in HCF region

Hence, the fatigue strength of corroded material, $\sigma_{a,corr}$, which corresponds to number of cycles to fatigue failure, N_f , can be derived as,

$$\log(\sigma_{a,corr}) = \log(\sigma_a) - \frac{(\log \sigma_\infty - \log \sigma_{\infty,corr})}{(\log N_{f,end} - \log N_{f,y})} (\log N_f - \log N_{f,y}) \quad (2)$$

where σ_∞ is endurance limit (i.e. fatigue limit for high-cycle fatigue) and $\sigma_{\infty,corr}$ is endurance limit for corroded material, which corresponds to a specified number of cycles, $N_{f,end}$. The $N_{f,y}$ is the number of cycles to fatigue failure of uncorroded materials when stress amplitude is σ_y . The σ_a is fatigue strength of uncorroded material, which corresponds to the number of cycles to fatigue failure, N_f , as defined in Eq. (1). The proposed formula for fatigue strength of corroded materials can be simplified as,

$$\log(\sigma_{a,corr}) = \log(\sigma_a) - \frac{\log\left(\frac{\sigma_\infty}{\sigma_{\infty,corr}}\right)}{\log\left(\frac{N_{f,end}}{N_{f,y}}\right)} (\log N_f - \log N_{f,y}) \quad (3)$$

or

$$\log(\sigma_{a,corr}) = \log(\sigma_a) - c(\log N_f - \log N_{f,y}) \quad (4)$$

where c is constant for a given material corresponding to the current state of corrosion and is given as,

$$c = \frac{\log\left(\frac{\sigma_\infty}{\sigma_{\infty,corr}}\right)}{\log\left(\frac{N_{f,end}}{N_{f,y}}\right)} \quad (5)$$

The proposed formula for fatigue strength can be obtained as,

$$\sigma_{a,corr} = (\sigma'_f N_{f,y}^c) N_f^{(b-c)} \quad (6)$$

The only parameter required for the above formulae is the endurance limit for the corroded material, $\sigma_{\infty,corr}$, which can be either experimentally obtained by a limited number of tests in the VHCF region

or can be predicted if there is a relationship between fatigue endurance degradation and rate of corrosion of the material.

4.3. Proposed formula for full range

The relationship between the applied stress amplitude, σ_a and number of cycles to fatigue failure, N_f , in full range (i.e. S-N curve for ultra-low cycle fatigue, LCF, HCF and VHCF regions) for uncorroded material is given as [31],

$$\sigma_a = \sigma_\infty \left(\frac{N+B}{N+C} \right)^b \quad (7)$$

where B and C are the number of cycles corresponding to the points of intersection of the tangent for the region of finite life described by Basquin's law, with the horizontal line across the ultimate strength and horizontal line across the endurance limit, respectively.

The linear variation in the difference between the fatigue strengths of uncorroded and corroded materials has been observed in the previous fatigue test results as described in the previous section. The relative difference is then linearly deducted to obtain corroded material fatigue strength for full range as follows:

$$\sigma_{a,corr} = \sigma_a - \frac{(\sigma_\infty - \sigma_{\infty,corr})}{\log C} \log N_f \quad (8)$$

The only parameter which is required for this formula is also the endurance limit for corroded material, $\sigma_{\infty,corr}$, which can be determined in the same way as described in the previous sub-section.

5. Experimental Verification of Proposed formulae

The proposed fatigue strength formulae for corroded materials are verified by comparing the experimental fatigue lives of corroded specimens of different materials, as shown below. The corrosion fatigue test results of three different steel types [18] and one type of aluminum alloy [31] are selected and compared with the predicted fatigue lives by the proposed formulae, as shown in the following sections. The fatigue tests have been conducted for constant corrosion rate.

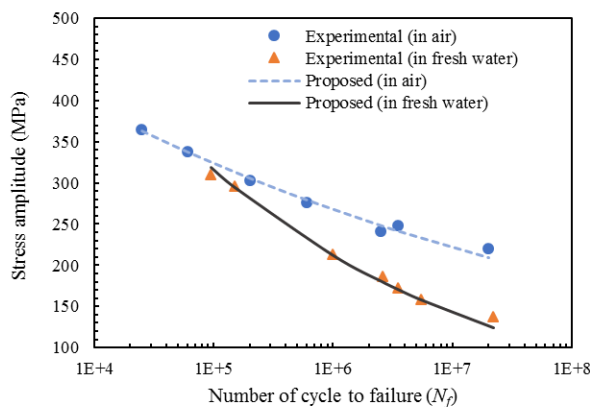


Figure 3. Comparison of proposed S-N curve with experimental test made in air and fresh water for annealed copper steel.

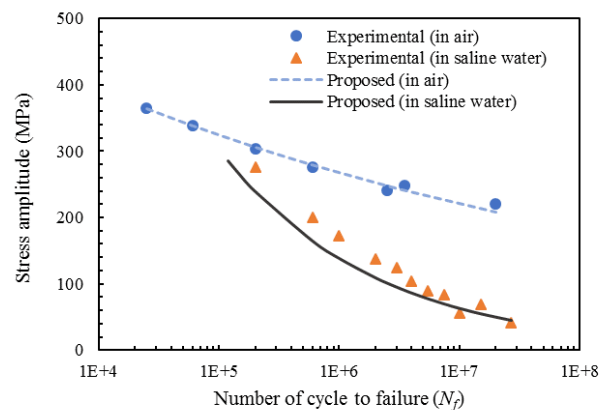


Figure 4. Comparison of proposed S-N curve with experimental test made in air and saline water for annealed copper steel.

5.1. Experimental verification of proposed formula for HCF

Figures 3 to 8 show the comparison of experimental fatigue lives of annealed copper steel (0.14% C, 0.98% Cu), hardened and tempered 0.16% carbon steel, hardened and tempered chrome-vanadium steel (0.88% Cr, 0.14% Va, 0.46% C) [18] and 6061-T6 aluminum alloy [31] specimens in different

corrosive environments with interpolated fatigue lives by the proposed interpolation formula for the high-cycle fatigue region shown in Eq (6).

Figures 3 to 7 show a good agreement between interpolated fatigue lives and experimentally observed lives for all three types of steel. This shows that the proposed formula in HCF provides a conservative rule regarding the fatigue strength of corroded steels. However, there are not conservative results for the aluminum alloy, as shown in Figure 8. One reason is the lack of an experimental data point to determine the endurance limit for corroded specimens. However, the proposed formula gives a better calculation of the mean fatigue strength of corroded aluminum alloy specimens.

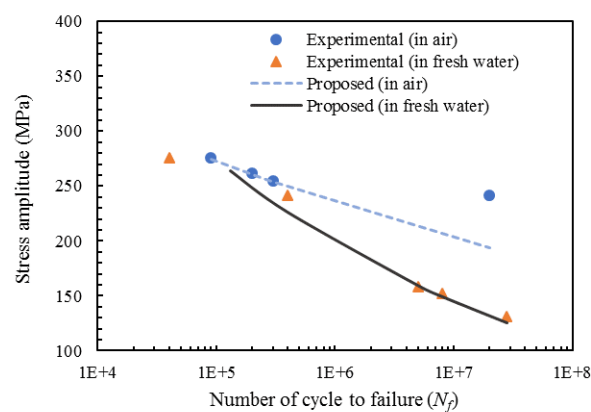


Figure 5. Comparison of proposed S-N curve with experimental test made in air and fresh water for 0.16% carbon steel (hardened and tempered).

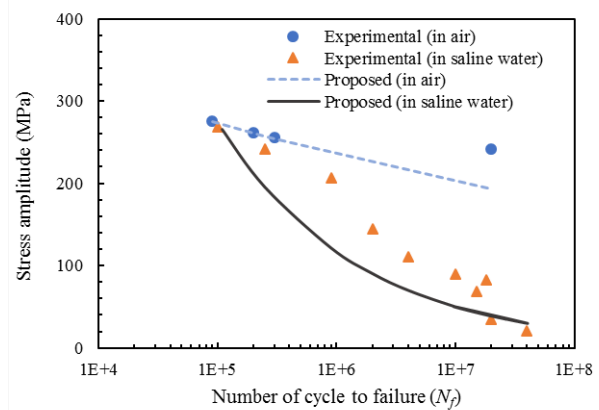


Figure 6. Comparison of proposed S-N curve with experimental test made in air and saline water for 0.16% carbon steel (hardened and tempered).

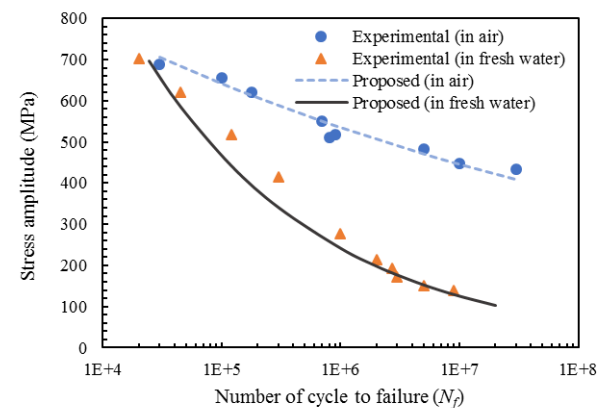


Figure 7. Comparison of proposed S-N curve with experimental test made in air and fresh water for chrome-vanadium steel (hardened and tempered).

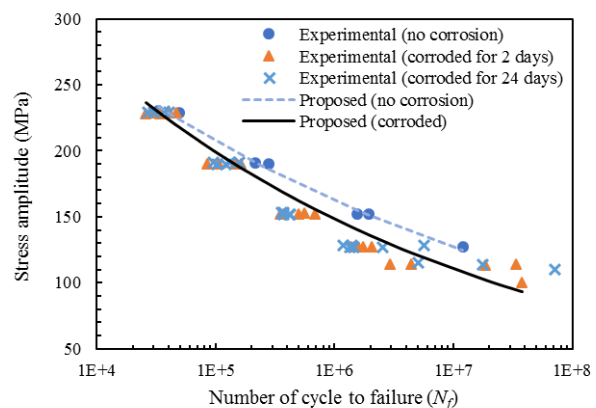


Figure 8. Comparison of proposed S-N curve with experimental test made with corrosive and non-corrosive situations of 6061-T6 aluminum alloy.

5.2. Experimental verification of proposed formula for full range

Figures 9 to 14 show the comparison of experimental fatigue lives of annealed copper steel (0.14% C, 0.98% Cu), hardened and tempered 0.16% carbon steel, hardened and tempered chrome-vanadium steel (0.88% Cr, 0.14% Va, 0.46% C) [18] and 6061-T6 aluminum alloy [31] specimens in different corrosive environments with interpolated fatigue lives by the proposed formula for full range shown in Eq. (8). Figures 9 to 14 show that the proposed formula for full range provides a conservative calculation of the fatigue strength of corroded materials. The proposed formula does not give better results when material is subjected to severe corrosion. This concludes that improvement of the proposed formula is required.

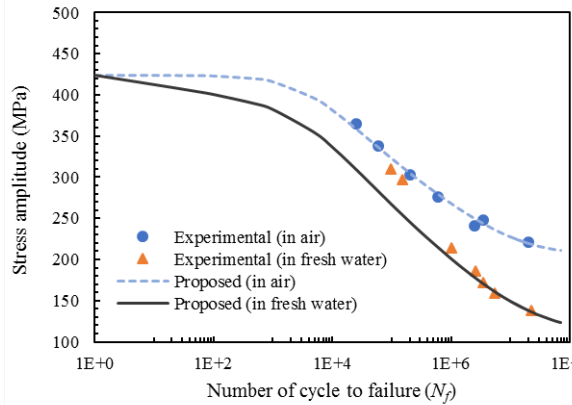


Figure 9. Comparison of proposed S-N curve with experimental test made in air and fresh water for annealed copper steel.

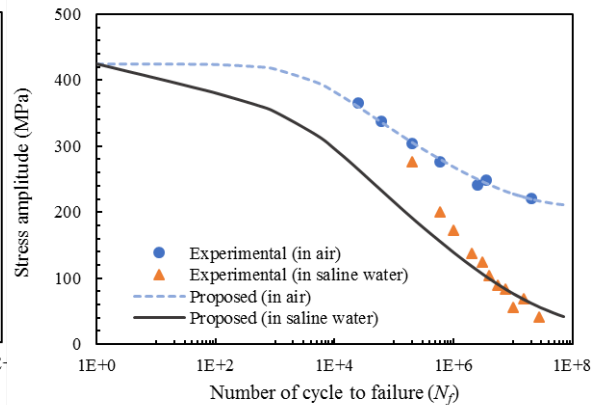


Figure 10. Comparison of proposed S-N curve with experimental test made in air and saline water for annealed copper steel

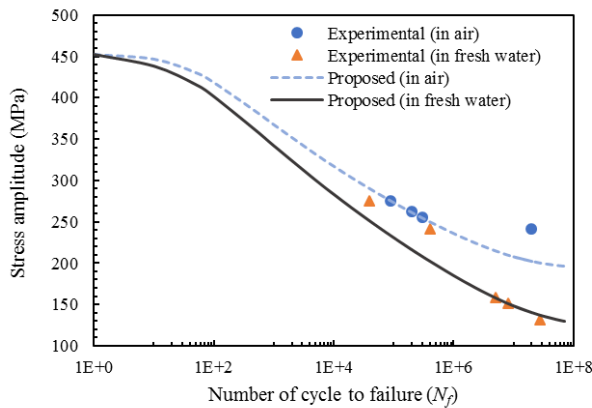


Figure 11. Comparison of proposed S-N curve with experimental test made in air and fresh water for 0.16% carbon steel (hardened and tempered).

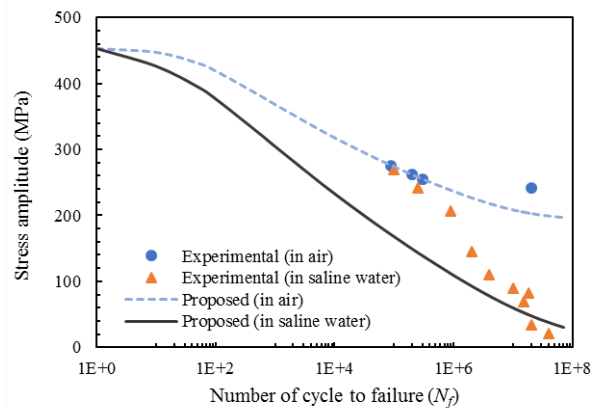


Figure 12. Comparison of proposed S-N curve with experimental test made in air and saline water for 0.16% carbon steel (hardened and tempered).

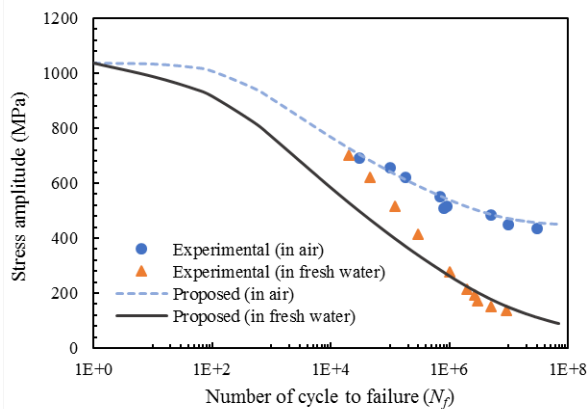


Figure 13. Comparison of proposed S-N curve with experimental test made in air and fresh water for chrome-vanadium steel (hardened and tempered).

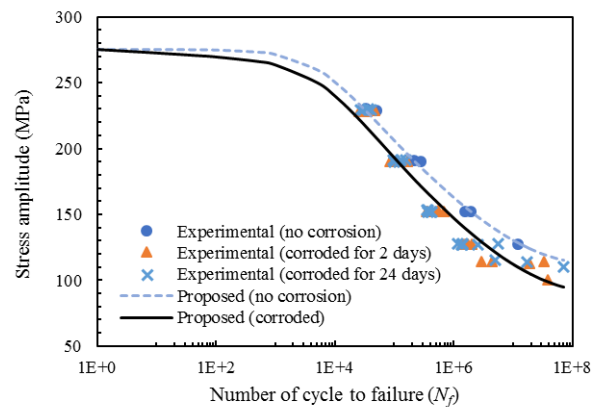


Figure 14. Comparison of proposed S-N curve with experimental test made with corrosive and non-corrosive situations of 6061-T6 aluminum alloy.

6. Discussion and conclusions

The corrosion degradation process of metallic materials has been reviewed by highlighting the mechanism of corrosion fatigue. Time-dependent geometrical changes in structural components and degradation of material strength are identified as key effects of corrosion. Corrosion fatigue, which is the degradation of materials under the combined action of localized corrosion and cyclic loading, significantly affects the integrity of structures. The fatigue damage due to corrosion pits and cracks can be modeled by fracture mechanics theories. Many researchers have reported the shortcomings of this approach in corrosive environments, as fatigue limit is not usually clear in corrosive environments. Generally, laboratory fatigue testing of corroded samples is popular for simulating CF. Testing corroded specimens is costly, and experimentally simulating the real corrosion situation in the environment is also complicated. A new strain-life model was proposed in 2012. Some of the model parameters should be determined by a series of complicated fatigue testing and, therefore, very few applications of this model have been reported.

Finally, new formulae for the fatigue strength of corroded materials were proposed in the paper. The proposed formulae only depend on the endurance limit of corroded material ($\sigma_{\infty,corr}$), in addition to the stress-life fatigue curve parameters of the uncorroded material. The $\sigma_{\infty,corr}$ can be either determined by a limited number of tests in the VHCF region or predicted by analytical approach. The interpolation formulae give fatigue lives were compared with experimentally obtained fatigue lives of a few materials in different corrosive environments. The comparisons show that the proposed formula for the HCF region gives a conservative calculation to the fatigue strength of corroded materials. It also reveals that the new formula for full range provides a better agreement with the fatigue strength of corroded materials. Knowledge of corrosion rates in the region where the structure is located is extremely important for damage assessments. Further verification of the proposed formulae is required for variable corrosion rates, as verification of the proposed formulae has been performed by comparing the results of fatigue tests conducted at a constant corrosion rate.

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