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Novel Method for Developing S-N Curves for Corrosion Fatigue Damage Assessment of Steel Structures

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Abstract: Corrosion is one of the main problems in steel structures. The combined effect of corrosion and fatigue caused by cyclic loading magnifies the damage severely reducing the fatigue life of the structure. Steel bridges in coastal and industrial zones are among the structures most vulnerable to corrosion fatigue. Up until now there have been no accurate methods introduced for assessing corrosion fatigue damage and predicting the future life of structures in a corrosive atmosphere.

In the S-N approach based fatigue damage assessment method S-N curves should include corrosion effects. If usual S-N curves that do not include corrosion effects are used, they should be modified or safety factors should be applied to account for the effects of corrosion. The present paper describes a study carried out for improving one of the existing full range S-N curve models for corrosion effects. Using adjustments to the existing S-N model a new corrosion based S-N model was proposed. Experimental results showed that the proposed S-N model can be efficiently used for assessing fatigue damage of steel structures located in corrosive atmosphere. The S-N model proposed remains a simple single formula. The only parameters necessary for the new corrosion based S-N model are the ultimate tensile strength, Vickers hardness and the high cycle fatigue strength in corrosive environment.

Keywords: corrosion fatigue, damage assessment, life evaluation, S-N curve, steel structures

1. Introduction

Structural failures of steel bridges and vessels due to corrosion fatigue has have made it a much discussed topic. The Silver bridge collapse in 1967, the Mianus river bridge collapse in 1983, the MV Kiraki vessel failure in 1990, the Aloha aircraft failure in 1998 and the Minnesota bridge failure in 2007 are some examples for corrosion fatigue failures in the past half century.

Corrosion fatigue occurs as a result of synergetic interactions between the environment, material microstructure and cyclic loading [1]. Corrosion fatigue damage accumulates with cyclic loading in four stages: (i) cyclic plastic deformation, (ii) micro-crack initiation (iii) micro-crack growth and coalescence and (iv) crack propagation [2]. Mechanisms behind the corrosion fatigue process in an aqueous environment (most common) can be described as: crack nucleation at corrosion pits due to high stress concentrations, reduction of crack closure, enhancement of slip irreversibility due to oxides in slip steps, electrochemical attack at plastically deformed regions (non-deformed regions act as cathodes), electrochemical attack when the protective oxide film is damaged and surface energy reduction due to the adsorption of environmental species that increase the micro crack growth [1]. It has been found that the combined damage of corrosion and fatigue is greater than the sum of their individual damage [3,4].

Corrosion fatigue is a complex process and there are no universal guidelines for assessing it [1]. The outcomes of this process on structural elements are: rough uneven surface, corrosion pits, reduction of thickness and deteriorated weak material microstructure [5]. All these outcomes raise the stresses due to stress concentrations and reduced cross-sections. Highly stressed locations then act as fracture origins in both static and cyclic loading. Fracture mechanic theories such as stress intensity based pitting corrosion damage models are widely used for assessing failures due to corrosion pits and cyclic loading [7,8]. It is a well accepted fact that corrosion related fatigue damage reduces the fatigue life of metallic materials [3,6]. Therefore, in the S-N approach based fatigue assessments, the S-N curve should contain the effects of corrosion.

Accordingly, the main aims of this study are: proposing a new two steps procedure for corrosion fatigue damage assessments and a simple full range S-N model that includes the effects of corrosion.

2. Hypothesis

In fatigue assessments, the reduction of thickness due to corrosion is usually taken into account by measuring the available thickness. Using the available cross-sectional area of sections, the actual stress is re-calculated. Then, using an S-N curve with a factor of safety to take into account the effects of corrosion and the past loading history of the structure the present fatigue damage is estimated [9]. When evaluating the future life of a structural element, the reduction of the thickness in the future should also be predicted. Corrosion rates of steels obtained from experiments and past studies may be useful for predicting the thickness reduction in the future [10]. Then, using the recalculated stress and the factored S-N curve the future life is evaluated. However, the S-N curve with safety factors is not economical and reliable all the time.

The main cause of failure due to corrosion fatigue is broadly divided into two: (i) Reduction in thickness that increases the stress in the remaining part of the material and (ii) Roughening of the surface and pitting that act as stress raisers due to which cracks initiate earlier and, weakening of the material due to micro-structural changes caused by the combined effects of corrosion and cyclic loading.

Then, the two steps proposed in the new damage assessment procedure are:

(i) Estimating the stress increment in the remaining material due to thickness reduction using thickness measurements.

(ii) Taking into account the effects of surface roughness, pitting and material weakening due to corrosion in the fatigue life by using an accurate SN curve.

The stresses estimated in step (i) can then be used with the S-N curve obtained in step (ii) to calculate the past, present and future damage of the structure due to corrosion fatigue.

As fatigue testing is difficult, costly and time consuming, analytical (or empirical) models and simple tests are necessary. Therefore, using an existing full range S-N model a new simple S-N curve that is able to account for the effects of surface roughness, corrosion pits and macrostructural changes is proposed in section 3.

3. Developing S-N curves with corrosion effects

The full range S-N model proposed by Bandara et al., [11] for assessing structures and components in the non-corrosive environment is given in Eq. (1),

$$\sigma(N) = a(N+B)^b + c \qquad (1)$$

where,

$a = \left(\frac{\sigma_{VHCF} - \sigma_k}{N_{VHCF}^b - N_k^b}\right)$, $B = \left(\frac{\sigma_u - c}{a}\right)^{1/b}$,

b = -0.2 and

$$c = \left(\frac{\sigma_k N_{VHCF}^b - \sigma_{VHCF} N_k^b}{N_{VHCF}^b - N_k^b}\right).$$

Here, σ_u is the ultimate tensile strength, N_k is the number of cycles at stress amplitude σ_k that represents the knee point of the S-N curve closer to 10^7 cycles. N_{VHCF} is the number of cycles concerned in the very high cycle fatigue (VHCF) region (> 10^7 cycles) and σ_{VHCF} is the fatigue strength amplitude in VHCF region [12] obtained from Eq. (2),

$$\sigma_{VHCF} = (155 - 7 log N_{VHCF}) \cdot \frac{(Hv+120)}{1000} (\sigma_u)^{1/3} \qquad (2)$$

where, Hv is the Vickers hardness.

Vacuum is the perfect non-corrosive environment. Due to the fact that the difference of the fatigue strength of metals such as mild steel in the vacuum and dry air is less than 5% [6], dry air can also be considered non-corrosive. Therefore, the proposed S-N curve can be used in dry air without any modifications. However, if the proposed fatigue model is used for structures and components in a corrosive atmosphere (rain, various gases, water, in the sea etc.,) a modification is necessary. Experiments have shown that the difference between the fatigue strengths in corrosive and noncorrosive environments in low cycle fatigue (LCF) region is low. This difference expands in the high cycle fatigue (HCF) and VHCF regions [2,6]. The expected modification for the full range S-N curve for corrosive atmosphere is as shown in Figure 1 [13].

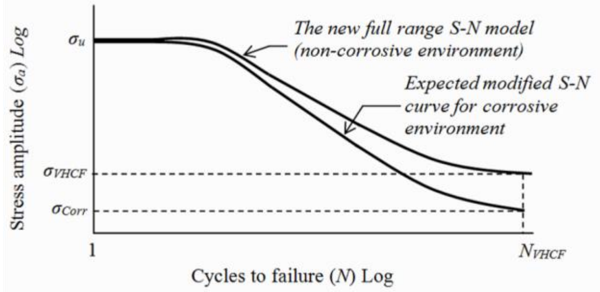

Figure 1: Proposed full range S-N model for corrosive environment. σ_{corr} is the VHCF fatigue strength of steel in the corrosive environment.

3.1 Modifications for corrosion effect

As illustrated in Figure 1, using a linear increase of difference between the non-corrosive and corrosive fatigue strength, the full range S-N curve can be modified to account for the corrosion effects. Eq. (3) shows this modification applied on the full range S-N model.

$$\sigma(\mathrm{N})_{\mathrm{corr}} = \sigma(\mathrm{N}) - \left(\frac{\sigma_{\mathrm{VHCF}}-\sigma_{\mathrm{corr}}}{\log(\mathrm{N}_{\mathrm{VHCF}})-\log(1)}\right)\{\log(\mathrm{N})-\log(1)\} \quad (3)$$

where, σ_{corr} is the VHCF fatigue strength of steel in the corrosive environment.

After simplifying some of the terms, the proposed full range S-N curve model for corrosive environment can be written as in Eq. (4),

$$\sigma(\mathrm{N})_{\mathrm{corr}} = \sigma(\mathrm{N}) - \mathrm{d}\cdot\log(\mathrm{N}) \quad (4)$$

where, $\mathrm{d} = \frac{(\sigma_{\mathrm{VHCF}}-\sigma_{\mathrm{corr}})}{\log(\mathrm{N}_{\mathrm{VHCF}})}$.

The only unknown (except σ_u and Hv) in this modified formula is σ_{corr}.

3.2 Experimental verification

Investigations for corrosion effects of steels on fatigue life is usually performed in two methods of tests; (i) Fatigue testing with low frequencies (5 - 25 Hz etc) using non-corroded specimens that are allowed to corrode during the test in corrosive media, and (ii) Fatigue testing with frequencies about 50 – 150 Hz using pre-corroded specimens.

The difference between the two tests is that the first test provides S-N curves for the combined effects of corrosion and fatigue while corrosion is taking place. The second test provides the effects of existing corrosion on the fatigue life. Test method (ii) is simple and the most relevant for existing structures and components. Therefore, in this study, pre-corroded steel specimens were subjected to fatigue testing.

Three low carbon steels, mild steel (MS), quenched and self tempered steel (QST) and cold twisted deformed steel (CTD) were used for fatigue testing. The mechanical properties of these steels are given in Table 1. The fatigue tester used was a rotating bending fatigue tester with a loading frequency of 50 Hz. The specimens were first polished and then left in contact with water for 60 days. The thickness reduction (60 days) calculated using weight measurements for MS, QST and CTD were 45.3, 36.7 and 39.8 μm respectively.

As mentioned in Section 3.1, predicting the full range S-N curve in a corrosive environment requires determining σ_{corr} in the VHCF region. This parameter should be found by conducting fatigue testing at very low stresses. In this study σ_{corr} at 10^7 cycles for medium and low strength steels was determined using experimental details provided by Revie and Uhlig [6] and given in Table 2. The testing has been done in air and in well water with the test frequency of 25 Hz.

Table 1: Mechanical properties of steels tested (σ_y is the yield strength and El is the percentage elongation)

Material	σ_u (N/mm²)	σ_y (N/mm²)	*El* (%)
Mild steel (MS-2)	426	249	37
Cold twisted deformed steel (CTD)	562	403	33
Quenched and self tempered steel (QST)	595	402	33

Table 2: High cycle fatigue (HCF) limit and corrosion fatigue strength σ_{corr} of steels [6]

Metal	HCF limit in air, σ_{HCF} (N/mm²)	σ_{corr} at 10^7 cycles	$\sigma_{corr}/\sigma_{HCF}$
0.11% C steel, annealed	172	110	0.64
0.16% C steel, quenched and tempered	241	138	0.57
1.09% C steel, annealed	289	158	0.55
3.5% Ni, 0.3% C steel, annealed	338	200	0.59
0.9% Cr, 0.1% V, 0.5% C steel, annealed	289	152	0.52
13.8% Cr, 0.1% C steel, quenched and tempered	345	241	0.70

Prediction of σ_{corr} was done as follows. As the VHCF fatigue strength and σ_{corr} at VHCF region were not available, σ_{corr} at 10^7 cycles and HCF limit σ_{HCF} were used in this study. The ratio ($\sigma_{corr}/\ \sigma_{HCF}$) for these steels was in the range 0.52 – 0.70 with an average of 0.60. For MS, CTD and QST steels, σ_{HCF} was calculated using the relationship $\sigma_{HCF} = 0.5\sigma_u$. Then, σ_{corr} for MS, CTD and QST steels were estimated from the relationship, $\sigma_{corr} = 0.6\sigma_{HCF}$. Accordingly, the estimated σ_{corr} values for MS, CTD and QST steels were 127.8, 168.6 and 178.5 N/mm² respectively. Then, full range S-N curves of MS, CTD and QST steels with corrosion effects were predicted using Eq. (4). A comparison of predicted S-N curves, experimental data and details for non-corroded steel tests are given in Figures 2, 3 and 4.

The comparison of experimental fatigue data for non-corroded and corroded specimens shows the increasing difference of fatigue strengths as expected. The new corrosion based S-N models for all three steels also show this increasing gap between non-corrosive and corrosive curves well aligning with the experimental data. This observation verifies the ability of the new model to produce S-N curves with corrosion effects well.

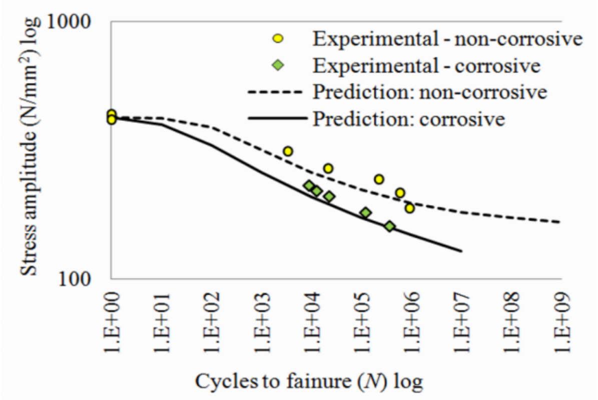

Figure 2: S-N curves for non-corroded and corroded specimens of MS with predictions

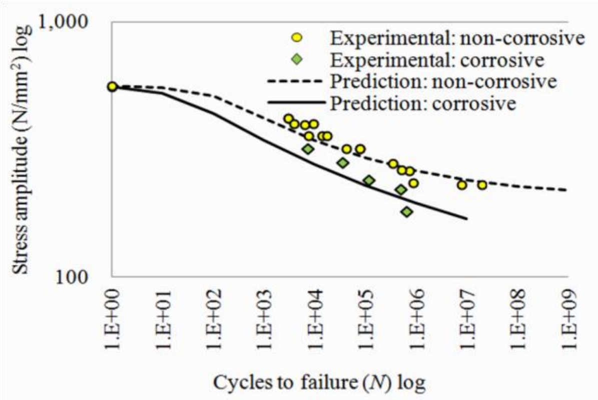

Figure 3: S-N curves for non-corroded and corroded specimens of CTD with predictions

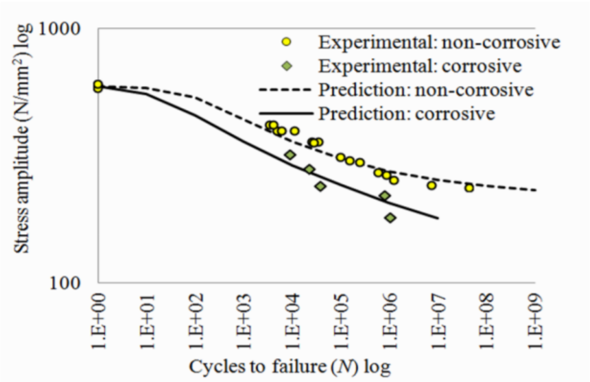

Figure 4: S-N curves for non-corroded and corroded specimens of QST with predictions

Though there are minor differences, experimental fatigue data of corroded specimens and the corresponding full range curves are mostly in good agreement. Reasons for these minor differences are; the difference between corrosion fatigue test data and fatigue testing of pre-corroded specimens and approximations used when estimating σ_{corr}. It should be noted that the method used for estimating σ_{corr} in this study may not always produce good predictions. Therefore, stress intensity and fracture mechanics based methods or experimental methods should be used for estimating σ_{corr}. These methods must be able to combine the effects of material factors, loading conditions and environmental factors.

4. Discussion

The effect of corrosion on steel structures and components creates many problems. Thickness reduction, increased surface roughness, surface irregularities and corrosion pits, and weakening of the material microstructure are some of them. Corrosion reduces the carrying capacity of structural elements. When thickness is reduced, stress in the remaining portion of structural elements increases. Due to surface roughness, surface irregularities and pitting, stresses in structural elements get concentrated, thus magnifying detrimental effects. Due to these many failures involved in corrosion fatigue, the assessment of corrosion fatigue damage is complicated. Therefore, in the present study, a simple two steps procedure was proposed.

In S-N approach based fatigue assessments, usual S-N curves that do not include corrosion effects should be modified and/or factors of safety should be applied. The full range S-N model with corrosion effects proposed in this study does not require any modifications and therefore, it is a valuable tool for fatigue damage assessments.

Due to the fact that fatigue in a corrosive environment (and fatigue in corroded elements) is caused by the combined effects of material, stress and environment, determining σ_{corr} using simple analytical methods is not successful. Therefore, the verification of the new S-N model with corrosion effects was done using both analytical methods and experimental data. It was observed that the new SN model performs well.

The new S-N model has many advantages. It is a simple formula that describes the entire stress – life region in a single function. Therefore this model can be easily used for assessing cumulative fatigue damage caused by both constant and variable amplitude loading. The material parameters needed for developing S-N curves from this model are σ_u, Hv and σ_{corr}. Here, σ_u and Hv are parameters that are obtained from simple tests.

5. Conclusions

The new two steps fatigue assessment procedure and the fatigue S-N model proposed in this paper that takes into account the effects of corrosion (corrosion due to water) is important in the fields of civil, structural and mechanical engineering. The conclusions of the study are as follows.

The procedure can easily be applied for structures once the S-N model is developed. The S-N model can be developed for low and medium carbon steels using three parameters, σ_u, Hv and σ_{corr}. Here too, σ_u, Hv can be found easily using common monotonic tests.

The S-N formula with corrosion effects proposed for carbon steels (in aqueous environment) is able to describe the full stress-life behavior of steel. Therefore, it can be used for both constant and variable amplitude loading to calculate the cumulative fatigue damage.

The average ratio $\sigma_{corr}/\ \sigma_{HCF}$ obtained from experimental results of six low and medium carbon steels is 0.60. This average ratio is a good approximation for determining σ_{corr} of carbon steels.

Acknowledgement

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