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ORIGINAL CONTRIBUTION

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Fatigue strength degradation of corroded structural details: A formula for *S-N* curve

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Abstract

A formula is proposed to predict fatigue strength of corroded members and joints of steel structures. The concept of the formula is first studied from recently identified mechanism of corrosion fatigue. Hence, the corresponding fatigue strength curve (i.e. S-N curve) of corroded steel is presented. It is further improved to derive linear, bilinear or trilinear S-N curve for corroded constructional details of steel structures. The parameters of the corroded steel S-N curve are determined based on the corrosion fatigue testing results of different types of steel specimens in air, fresh water and seawater. Hence, the parameters for the derived S-N curve of corroded constructional details are predicted based on the above parameters and tabulated for the detail categories given in the Eurocode and DNVGL code. The proposed S-N curve formula is compared with full-scale fatigue test results of several constructional details, and the validity of the formula is confirmed.

KEYWORDS

corrosion fatigue, joints and connections, S-N curve, steel structures

1 | INTRODUCTION

Corrosion is one of the main structural degradation processes that affect integrity. Fractures due to cyclic stress in corrosive media are designated as corrosion fatigue (CF) which is a type of environmental assisted cracking. The forty percent failures in oil and gas pipelines and 8% of failures in offshore steel structures are reported to be caused degradation/deterioration due to corrosion. Corrosion commonly takes place in the splash zone area of offshore structures as the coating in this area disappears a few years after installation.[1] Recent collapses of steel bridges due to corrosion are reported and some examples are the Silver Bridge in 1967, the Mianus River Bridge in 1990 and the Minnesota Bridge in 2007.[2-4] Though many bridges are located onshore, de-icing salt may simulate marine environment to the bridges in snowy regions.[2] These failures emphasize the importance of more accurate simulation of CF strength of structural joints and connections (i.e. constructional details) in different corrosive environments.[3,5,6]

Corrosion pit induced stress concentration models and fatigue notch factor are commonly used to determine structures integrity.[7-10] Fatigue crack initiation life is determined when micro-cracks propagate to certain critical length. Fatigue crack propagation life is determined by fracture mechanics approach. Accurate determination of modified corrosion-fatigue stress intensity threshold and the critical length has been reported as challenging and difficult.[2-4] Therefore, limited amount of published works is found in the area of fatigue notch factor due to pitting corrosion.[9,10] Recent investigations of non-passive metals such as carbon steel reveals that CF cracks do not initiate at pits even though those are available. This statement concludes that CF crack initiation greatly occurs without the formation of pits (i.e. absence of pitting corrosion) and it may occur in any corrosive media.[11-14] This mechanism is proved by means of a slip-band preferential dissolution model and hydrogen embrittlement theory.[12-14] As these models are unable to represent CF crack initiation below yield stress and in the absence of hydrogen, Zhao et al[11] investigated the CF crack initiation and propagation mechanism of a carbon steel in details by stress controlled fatigue tests and microstructural analyses with scan electron microscopy, electron backscatter diffraction and transmission electron microscopy. The CF crack initiation and initial propagation mechanisms are highly governed by the peak stress level. In the high cycle fatigue region of steel, a high possibility of crack initiation in seawater is observed at the austenite grain boundaries than at the pits or from initial cracks.[11] A generalized model which precisely addresses the above mechanism is lacking in the literature for predicting life of the defect free (i.e. without cracks or pits) steel structural details. Therefore, further research is required to develop models to predict fatigue strength of the corroded steel members, joints and connections (i.e. constructional details) which are subjected to different types of corrosion.

As a result, a strain-life model was proposed based on the Smith–Watson–Topper model[2,3] to simulate the CF behaviour of metals. The model takes into account the state of corrosivity of environment, the stress level and the corrosive behaviour of the steel. Further verification of the proposed function is recommended in the same articles as future studies. The procedure for determining the model parameters requires a series of fatigue tests. The effect of pitting on the prediction of life is recommended for further studies.[2,3] To use the model, transformation of stress ranges into strain ranges is required to use the model by using cyclic properties of steel and fatigue notch factor. Due to mentioned complexities of the model and uncertainties of the model parameters, few applications are reported. A stress-life fatigue strength curve for corroded material is recently published.[4] The proposed curve depends on corrosion parameter, $\sigma_{\infty,cor,}$ which should be determined by CF tests in very high cycle fatigue (VHCF) region in relevant corrosive media. The determination of $\sigma_{\infty,cor}$ is complex as fatigue tests in the VHCF region is extremely time consuming. The discussed methods/models are limited for determination of the $\sigma_{\infty,cor}$ in the specimen scale. Therefore, it is required to have a simple formula/approach to model the fatigue strength of material, full-scale steel members and joints (i.e. constructional details).

Detailed provisions and models/formulas are not available in codes of practices to predict fatigue strength of corroded structural details of land-based structures/onshore structures.[2,3,15] Testing of different full-scale details in simulated corrosive environment is complicated especially in VHCF region (e.g. if the cyclic frequency is 1 Hz, for 10^8 cycles, it takes more than 3 years to finish a single test). Therefore, the test results are limited and the fatigue endurance of the majority of available results are reported in the range from 10^4 to 10^6 cycles. The obtained results are also scattered as the test process is subjected to many variables and uncertainties. Those results are not sufficient to warrant variable amplitude fatigue limits of the details. A few past studies recommend the endurance limit to be neglected (i.e. S-N curve should be used without cut off limit) to take into account the fatigue strength degradation due to the unexpected localized corrosion (i.e. mild pitting or crevice corrosion) near the corroded details.[15-18] The modified S-N curves do not match the available fatigue test results of corroded details.

Health and Safety Executive (HSE) provisions and guidelines for fatigue strength have been presented for the corroded structural details in offshore structures.[19] The fatigue strength curve for the welded tubular joints in seawater-free corrosion was obtained by applying environmental reduction factor (ERF) to the relevant curve in air. The ERF is determined by the ratio of the number of cycles to fatigue failure in air to that in seawater/marine environment for tubular joints at the same stress range. Average ERF value has been determined by very scattered CF test results (results varies from 0.8 to 5.2). The variation of defined test failure criteria (i.e. stopping criteria), damage histories of the joints and other environmental factors may scatter the obtained fatigue lives. The results were obtained in the range from 6×10^4 to 2×10^6 cycles and it does not include either constant amplitude fatigue limit (CAFL) or variable amplitude fatigue limit (VAFL) (i.e. 10^7 and 10^8 cycles respectively). A constant slope is proposed for the whole region of the corroded S-N curve. The same report has also mentioned the doubtfulness of the proposed ERF due to lack of data.[19] The modified corroded curve has the same slope with the air curve until 10^7 cycles. This violates CF behaviour of steels, which has negligible difference between fatigue lives in corrosive and non-corrosive environments in the low-cycle fatigue (LCF) region when compared to VHCF region.[2-4,19-22]

To overcome the previously mentioned problems, the main objective of this paper is to derive a generalized formula to determine the fatigue strength of structural joints/constructional details exposed to corrosive media/environment. The concept of the proposed formula has been studied by means of the fatigue test results of different types of corroded steel specimens in different corrosive environments. The parameters used in the formula are mainly dependent on corrosive environment (i.e. urban and marine) and the corresponding constructional detail (i.e. detail category), which can easily be found in the fatigue design codes. The corrosive environment dependent parameters have already been conservatively defined based on the corrosion fatigue testing results of different types of steel in different environments. The proposed formula can be easily used with the trilinear or bilinear fatigue curves/S-N curves of detailed categories provided in any fatigue design codes of steels structures only in the high cycle fatigue (HCF) region. Initially the mechanism and the concept of the fatigue strength degradation of the material is discussed and hence the proposed relation is derived for steels exposed to corrosive media. The verification of the corroded parameters is done by comparing CF tests of different types of steel specimens tested in air, fresh water and seawater. The relation for the fatigue strength curve is then developed for corroded constructional details. The verification of the proposed formula is done by comparing experimental results of many full-scale tests of corroded structural details.

2 | MECHANISM OF FATIGUE STRENGTH DEGRADATION OF CORRODED STEEL

Gliding can be seen in some of the grains due to alternating stresses. When dislocations reach a grain boundary, gliding is ceased.[22,23] When the stress is reversed, the movement of the grains retraces along the gliding plane. Slight irregularities may prevent the smooth gliding and it roughens along original gliding plane. Roughness restricts the movement and develops another parallel gliding plane. Finally, these disorganized bands of material cause separation between gliding planes while producing gaps and eventually developing cracks at high stress ranges (i.e. above the endurance limit) or cease the gliding at low stress ranges (i.e. bellow fatigue endurance limit). Under corrosion, disorganized atoms are moving along a gliding plane with less activation energy than without corrosion. The CF crack initiation can occur without the presence of pits and the corrosion-fatigue cracks are expanded by post reaction of corrosion for carbon steel.[11] The slip-bands preferentially dissolution model and the hydrogen embrittlement theory[11-14] describe this mechanism properly above the yield strength. The mechanism of CF crack initiation and propagation is mainly governed by the peak stress level and the stress range. Higher probability of crack initiation has been observed in parent austenite grain boundaries in HCF region. The crack propagation has been reported along the parent austenite grain and ferrite lath boundaries.[11] This phenomenon may be observed even below the fatigue endurance limit and hence there is no safe stress level at which the fatigue life is infinite. The cracks are usually transgranular[4,23] and, therefore, the specified number of cycles are stated as an endurance for the corroded steel by assuming the material will endure. The degraded fatigue strength/endurance of the corroded steel depends on the environmental, metallurgical and structural factors. These factors have direct effects on the corrosion rate which governs both strength degradation and the overall stiffness of the structure.[15,24] The fatigue endurance/strength of corroded material reaches a threshold after a certain period of exposure to corrosive environment. Fatigue test results of steel specimens show that the difference between fatigue lives in corrosive and non-corrosive environments LCF region is negligible and a significant larger difference is observed in VHCF region.[2,4,20-22]

3 | FATIGUE STRENGTH CURVE FOR CORRODED STEEL MATERIAL

A fatigue strength formula for corroded steel is presented based on previously published work.[4] Values for corrosive parameters used in the formula are proposed in this paper to further simplify the previously published formula. The validity of the proposed parameters is confirmed by comparing CF test results of different types of steel.

3.1 | Formula for high cycle fatigue region

The formula presented in this section exists in a previous publication[4] by the same authors. Based on Basquin's law, the S-N curve formula for corroded steel is proposed.[4] The concept of the proposed formula is based on the degradation mechanism discussed in the section 2 and the derivation is presented in a previous paper.[4] The final formula is shown in Eq. (1).

$$\sigma_{a.cor} = \left(\sigma_f' N_{f,LCF}^{c}\right) N_f^{(b-c)} \quad \text{where } c = {}^{log}\left[\frac{\sigma_\infty}{\sigma_{\infty,cor}}\right] \Big/ {}_{log}\left[\frac{N_{f,FL}}{N_{f,LCF}}\right] \tag{1}$$

where $\sigma_{a,cor}$ is the fatigue strength of corroded material, which corresponds to the number of cycles to fatigue failure, N_f. The term σ_f' is the fatigue strength coefficient and b is the Basquin's exponent. The endurance limit (i.e. fatigue limit for high-cycle fatigue) is σ_∞ and $\sigma_{\infty,cor}$ is the endurance limit for the corroded material, which corresponds to a specified number of cycles, $N_{f,FL}$. When the stress amplitude is the yield strength, σ_y, the number of cycles to fatigue failure of the uncorroded material is $N_{f,LCF}$.

3.2 | Proposed values of the parameters

The values of σ_f', b, σ_∞, $N_{f,FL}$ and $N_{f,LCF}$ are determined from the S-N curve of uncorroded materials. The value of $\sigma_{\infty,cor}$ has to be determined by fatigue testing in the VHCF region and it is a complicated process. Therefore, this section presents a reasonable accurate relation to obtain $\sigma_{\infty,cor}$ for structural steels in natural water (i.e. similar to urban environment) and sea water (i.e. similar to marine environment).

Revie and Uhlig[20,23,25] performed fatigue testing for several grades of medium and low strength corroded and uncorroded steels. Corrosive process was carried out in natural water. The values of σ_∞ and $\sigma_{\infty,cor}$ were determined corresponding to $N_{f,FL} = 10^7$ cycles. The ratios $\sigma_{\infty,cor}/\sigma_\infty$ are listed in Table 1a which shows that the ratio varies in the range of 0.53-0.70. The mean and coefficient of variation (COV) values of the ratio are 0.61 and 0.1. Taking into account the 5% failure probability (i.e. 95% safe prediction), the design value of the $\sigma_{\infty,cor}/\sigma_\infty$ ratio can be proposed as 0.5 for conservative prediction of fatigue strength of medium and low strength structural steels which are subjected to corrosion in natural water media. It is recommended to use mean and/or design value depending on the importance of the case studied.

Boyer[23] and Adasooriya et al.[4] presented previous fatigue test results in both air and saline/seawater. The related S-N curves were plotted for several grades of medium and low strength steels. The σ_∞ and $\sigma_{\infty,cor}$ were determined corresponding to $N_{f,FL} = 10^7$ cycles. The ratios $\sigma_{\infty,cor}/\sigma_\infty$ are tabulated in Table 1b which shows that the ratio varies in the range of 0.36-0.59. The mean and the coefficient of variation (COV) values of the ratio are 0.46 and 0.21. Taking into account the 5% failure probability (i.e. 95% safe prediction), the design value of $\sigma_{\infty,cor}/\sigma_\infty$ ratio can be proposed as 0.27 for conservative prediction of fatigue strength of medium and low strength structural steels which are subjected to corrosion in sea water media. The CF endurance limit of high strength steel reduces to 90% when it is exposed to sea water and hence the ratio is found to be 0.1.[26] Yantao et al.[27] concluded that the CF life was reduced to 1/2 to 1/3 of the life in air. This difference was greater when the stress level was low.

TABLE 1A Corrosion fatigue limits of steel tested in natural water[4,23,25]

Material	Fatigue endurance limit for uncorroded material, σ_∞ (MPa)	Fatigue endurance limit for corroded material, $\sigma_{\infty,cor}$ (MPa)	$\sigma_{\infty,cor}/\sigma_\infty$
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	0.53
13.8%Cr, 0.1%C steel, quenched and tempered	345	241	0.70
0.14%C,0.88%Cu steel, annealed	234	149	0.64
12.9%Cr, 0.11%C steel, hardened and tempered	379	264	0.70

3.3 | Experimental verification of the proposed parameters

The corrosion fatigue test results of three different steel types[23] and one type of aluminium alloy[28] have been compared with the predicted fatigue lives by the proposed formulae and published by authors.[4] The major objective of this section is to verify the fatigue strength formula related proposed parameters by comparing the experimental fatigue lives of the corroded specimens of different materials in different corrosive environments.

Figure 1 shows the comparison of predicted fatigue strength with test results of three types of carbon steel: the mild steel (MS), cold twisted deformed steel (CTD) and quenched and self-tempered steel (QST). The pre-corroded specimens were subjected to fatigue testing in 50Hz and stress ratio, R, equal to -1.[25] The surface of the uncorroded specimens were polished to a roughness of

TABLE 1B Corrosion fatigue limits of steel tested in sea water[4,23]

Material	Fatigue endurance limit for uncorroded material, σ_∞ (MPa)	Fatigue endurance limit for corroded material, $\sigma_{\infty,cor}$ (MPa)	$\sigma_{\infty,cor}/\sigma_\infty$
0.14%C,0.88%Cu steel, annealed	234	84	0.36
0.16%C steel, hardened and tempered	241	89	0.37
27%Cr, 0.2%C high chromium steel	309	183	0.59
12.9%Cr, 0.11%C steel, hardened and tempered	379	194	0.51

$R_z = 6$ μm and enclosed in the natural water for 60 days. Both the design and the mean values of the $\sigma_{\infty,cor}/\sigma_\infty$ ratio were used for these verifications as shown in Fig. 1.

Figure 2a shows the comparison of predicted S-N curves with the test results of E690 steel in air and simulated sea water.[11] The E690 steel was newly developed for marine structures. The chemical composition, mechanical properties and the test specification were clearly discussed by Zhao et al..[11] The round bar specimens were subjected to stress-controlled fatigue testing in simulated sea water (i.e. 3.5wt% NaCl solution) at 1 Hz frequency. The CF test results of medium strength shaft steel are compared with proposed S-N formula in Fig. 2b. The sample preparation, test specifications and the mechanical properties have been clearly presented else where.[29] The fatigue tests were conducted at R=-1 at the frequency of 22 Hz. The corrosive media has been simulated by 3.5 wt% NaCl and pH value 5 solution. The corrosion fatigue test results of butt-welded joints of steel which is commonly used for offshore platforms are compared with proposed *S-N* formula in Fig. 2c. The sample preparation, test specifications and mechanical properties have been clearly presented else where.[27] Four point bending cyclic loading test was performed in the frequency of 0.5 Hz and the R = -1. The sea water circulation system was used during the testing and 24.53 wt% NaCl solution was used. The pH value of the solution ranged from 7.5 to 8.5. Both the design and the mean values of $\sigma_{\infty,cor}/\sigma_\infty$ ratio were used for these verifications as shown in Fig. 2.

Figures 1 and 2 show a good match between the fatigue strength curve related proposed values of $\sigma_{\infty,cor}/\sigma_\infty$ and corrosion fatigue test results of different types of steel.

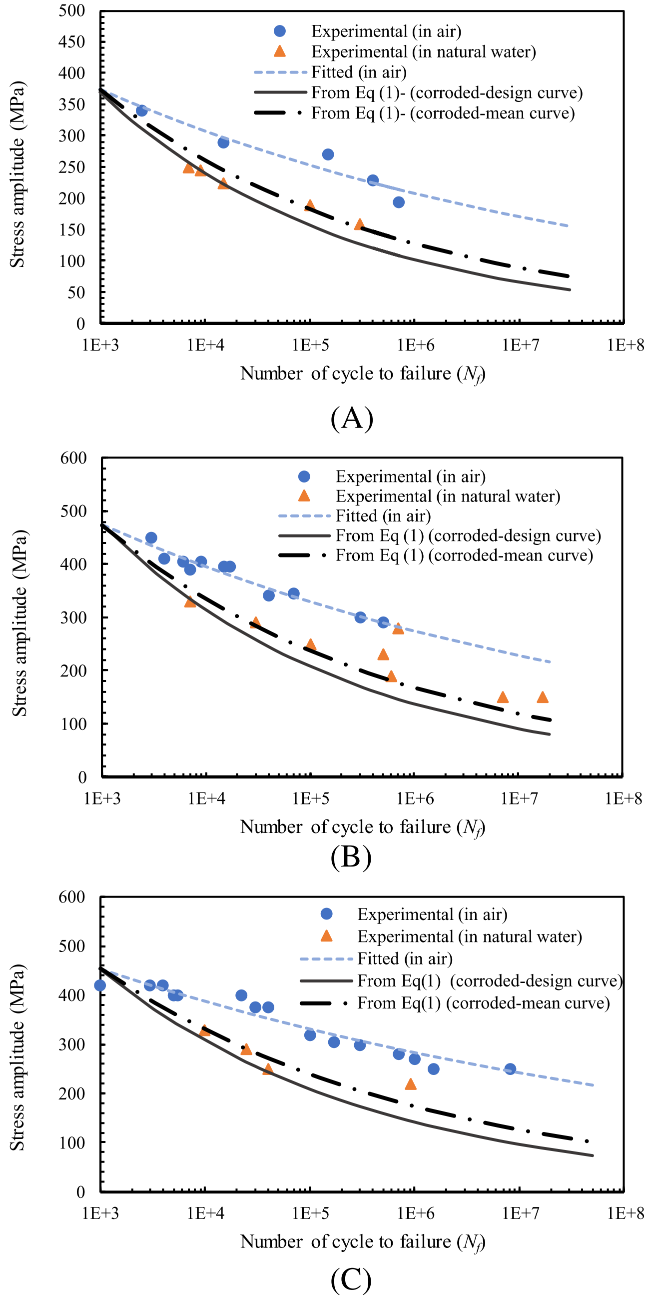

FIGURE 1 Comparison of the proposed S-N curve with experimental test carried out in natural water: (a) for mild steel (MS), (b) for cold twisted deformed steel (CTD), (c) for self tempered steel (QST) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | PROPOSED FATIGUE STRENGTH CURVE FOR CORRODED CONSTRUCTIONAL DETAILS

The corroded material fatigue strength curve described above was further improved to develop *S-N* curves for corroded constructional details/detail categories. The proposed curve is obtained by modifying the design fatigue strength curves of categories/detail class of connections.

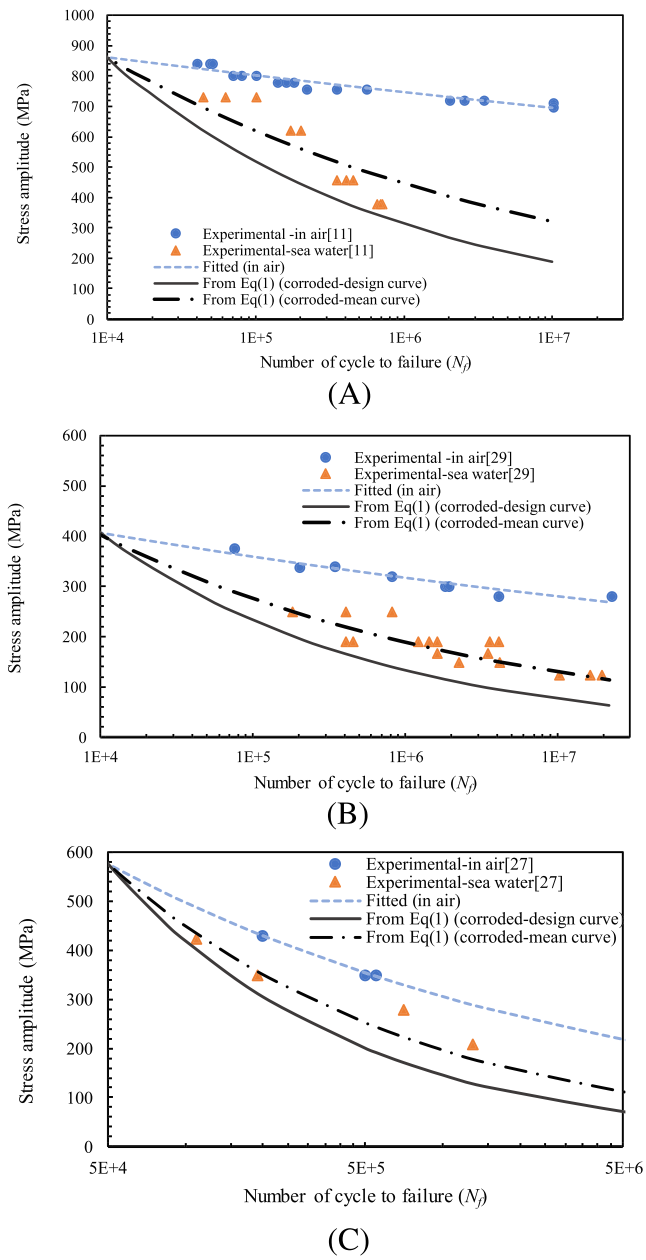

FIGURE 2 Comparison of the proposed S-N curve with experimental test carried out in simulated sea water: (a) for E690 steel, (b) for Shaft steel, (c) for steel butt welded joints [Colour figure can be viewed at wileyonlinelibrary.com]

The reduction factors, which represent environmentally assisted corrosion fatigue, are utilized for this modification. The linear, bilinear or trilinear design fatigue curves of details used in different fatigue codes can be modified to obtain the proposed fatigue curve for corroded details.

4.1 | Derivation of fatigue strength curve for corroded details

The trilinear fatigue strength curve of uncorroded constructional detail is presented in Fig. 3.[30] The relation between the stress range, $\Delta\sigma$ and the corresponding number of cycles to fatigue failure, N_R, presented by Eq. (2) for the uncorroded (i.e. fatigue design code given details) curve.

$$\Delta\sigma = \left(\Delta\sigma_D N_{f,CAFL}^{1/m}\right) N_R^{(-1/m)} \tag{2}$$

where $\Delta\sigma_D$ is the stress range at the fatigue curve slope changing point which corresponds to the $N_{f,CAFL}$ cycles. In some fatigue design codes, $\Delta\sigma_D$ is defined as the constant amplitude fatigue limit.[1,30] The slope of the fatigue strength curve is -1/m. According to the Eurocode[30] m is equal to 3 when $\Delta\sigma \geq \Delta\sigma_D$, is equal to 5 when $\Delta\sigma_D \geq \Delta\sigma > \Delta\sigma_L$ and it is infinite when $\Delta\sigma \leq \Delta\sigma_L$, where $\Delta\sigma_L$ is the fatigue endurance limit of the detail which corresponds to $N_{f,VAFL}$. This is also defined as the fatigue cut-off limit or variable amplitude fatigue limit in some fatigue design codes.[1,30] Some of the fatigue curves of the details do not have such a cut-off limit.

According to the verified mechanism and the concept of corroded fatigue endurance of steel mentioned in sections 2 and 3, the linear variation in the difference between the fatigue strengths of the uncorroded and corroded details has been observed as shown in Fig. 3. The relative difference in log scale is linearly deducted from the corrosion-free fatigue strength to obtain the fatigue strength of the corroded detail. Hence the fatigue strength range of corroded constructional detail, $\Delta\sigma_{cor}$, corresponding to N_R, can be derived, if $\Delta\sigma_{cor} \geq \Delta\sigma_{D,cor}$,

$$\log(\Delta\sigma_{cor}) = \log(\Delta\sigma) - {}^{\log}\left[\frac{\Delta\sigma_D}{\Delta\sigma_{D,cor}}\right] \Big/ {}_{\log}\left[\frac{N_{f,CAFL}}{N_{f,LCF}}\right] \left(\log N_R - \log N_{f,LCF}\right) \tag{3}$$

where $\Delta\sigma_{D,cor}$ is the stress range corresponding to $N_{f,CAFL}$ cycles at the intersection of the two corroded fatigue curves. Here, $N_{f,LCF}$ is the number of cycles to fatigue failure of uncorroded details at the intersection point of their HCF and LCF regions. This has been generally considered as 10^4 cycles, which is the lowest value of N_R given in fatigue design codes.[1,30] The proposed formula for the fatigue strength of corroded detail categories can be simplified as,

$$\frac{\Delta\sigma_{cor}}{\Delta\sigma} = \left(\frac{N_R}{N_{f,LCF}}\right)^{-c} \text{ where } c = {}^{\log}\left[\frac{\Delta\sigma_D}{\Delta\sigma_{D,cor}}\right] \Big/ {}_{\log}\left[\frac{N_{f,CAFL}}{N_{f,LCF}}\right] \tag{4}$$

By substituting $\Delta\sigma$ from Eq. (2), the proposed formula for the fatigue strength for the corroded detail can be obtained as

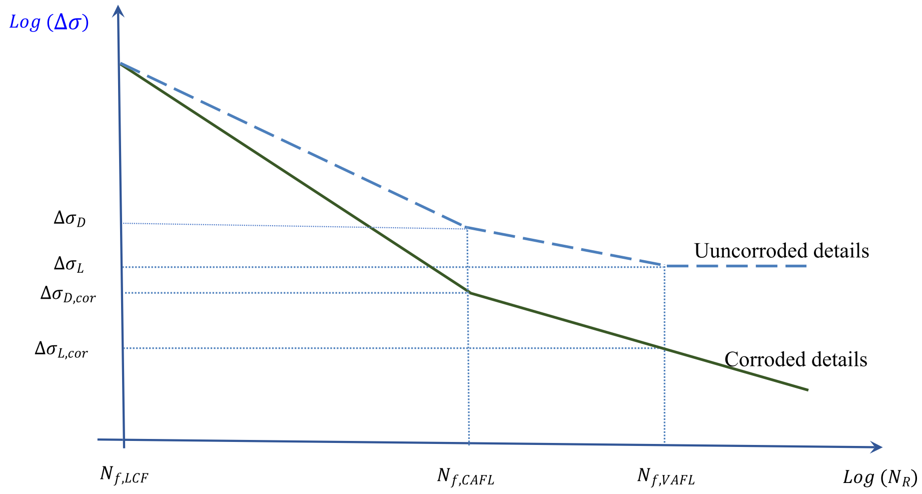

FIGURE 3 Schematic representation of fatigue strength curve of uncorroded and corroreded detail categories [Colour figure can be viewed at wileyonlinelibrary.com]

$$\Delta\sigma_{cor} = \Delta\sigma_D \left[N_{f,LCF}^{c} N_{f,CAFL}^{1/m} \right] N_R^{\left(-c-1/m\right)} \tag{5}$$

If $\Delta\sigma_{cor} \leq \Delta\sigma_{D,cor}$, the fatigue strength of corroded constructional detail can be obtained,

$$\log\left(\Delta\sigma_{D,cor}\right) - \log\left(\Delta\sigma_{cor}\right) = \frac{\left[\log\Delta\sigma_{D,cor} - \log\Delta\sigma_{L,cor}\right]}{\left[\log N_{f,CAFL} - \log N_{f,VAFL}\right]} \times \left(\log N_{f,CAFL} - \log N_R\right) \tag{6}$$

or,

$$\frac{\Delta\sigma_{cor}}{\Delta\sigma_{D,cor}} = \left(\frac{N_R}{N_{f,CAFL}}\right)^{\acute{c}} \quad \text{where} \quad \acute{c} = {}_{\log}\left[\frac{\Delta\sigma_{D,cor}}{\Delta\sigma_{L,cor}}\right] \Big/ {}_{\log}\left[\frac{N_{f,CAFL}}{N_{f,VAFL}}\right] \tag{7}$$

When $\Delta\sigma_{cor} \leq \Delta\sigma_{D,cor}$, the proposed formula for fatigue strength for corroded details can be obtained as,

$$\Delta\sigma_{cor} = \Delta\sigma_{D,cor} \left[N_{f,CAFL}^{-\acute{c}} \right] N_R^{\acute{c}} \tag{8}$$

The parameters c and $\acute{c}$ depend on the CF endurance of the construction details and their determination are discussed in the following sub section.

4.2 | Parameters used in the proposed curve

The values of $\Delta\sigma_D$,$\Delta\sigma_L$,m,$N_{f,LCF}$,$N_{f,CAFL}$ and $N_{f,VAFL}$ are directly obtained from the code providing fatigue strength/S-N curves of constructional details tested in air.[1,30] The $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ are the corrosive state and the environment dependent parameters of the detail. These parameters are commonly determined by full-scale fatigue tests in the VHCF region and it is costly in terms of both resources and time as the loading frequency is very low for full scale testing. The test results (i.e. experimental fatigue lives) are scattered as the test process is subjected to many variables and uncertainties. These $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ can be determined by fracture mechanics theories when there are corrosion pits. Recent investigations of carbon steel reveals that CF cracks initiate in any corrosive media due to a different mechanism and the presence of the pits is not necessary.[11-14] Therefore, this section proposes a reasonably accurate relation to obtain $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ for structural steels in fresh water (i.e. similar to urban environment) and sea water (i.e. similar to marine environment) based on the parameters used in the proposed formula for corroded material as described in section 3.2.

The values of $\Delta\sigma_D$,$\Delta\sigma_L$,m,$N_{f,LCF}$,$N_{f,CAFL}$ and $N_{f,VAFL}$ are presented in Table 2 to determine Eurocode[30] given fatigue curves. The following relations are obtained to determine the values of $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ by interpolations and extrapolations of $\sigma_{\infty,cor}/\sigma_\infty$ ratios corresponding to $N_{f,CAFL}$ and $N_{f,VAFL}$.

$$\frac{\Delta\sigma_{D,cor}}{\Delta\sigma_D} = \left(\frac{\sigma_{\infty,cor}}{\sigma_\infty}\right)^{0.9} \quad \text{and} \quad \frac{\Delta\sigma_{L,cor}}{\Delta\sigma_L} = \left(\frac{\sigma_{\infty,cor}}{\sigma_\infty}\right)^{1.33} \tag{9}$$

The corresponding mean and conservative values (i.e. design value= mean-2×standard deviation) are listed in Table 2. Similarly, for DNV code, the following relations can be derived. The corresponding values are listed in Table 2.

TABLE 2 Parameters used in the proposed fatigue strength curve of corroded details

Parameter	Constructional details in Eurocode				Constructional details in DNV code			
$N_{f,LCF}$	10^4				10^4			
$N_{f,CAFL}$	5×10^6				10^7			
$N_{f,VAFL}$	10^8				10^8			
$\frac{\Delta\sigma_L}{\Delta\sigma_D}$	0.549				0.631			
Corrosion parameters	Marine environment		Urban environment		Marine environment		Urban environment	
	Mean value	Conservative value	Mean value	Conservative value	Mean value	Conservative value	Mean value	Conservative value
$\frac{\Delta\sigma_{D,cor}}{\Delta\sigma_D}$	0.497	0.308	0.641	0.536	0.46	0.27	0.61	0.50
$\frac{\Delta\sigma_{L,cor}}{\Delta\sigma_L}$	0.356	0.175	0.518	0.40	0.356	0.175	0.518	0.40

$$\frac{\Delta\sigma_{D,cor}}{\Delta\sigma_D} = \frac{\sigma_{\infty,cor}}{\sigma_\infty} \text{ and } \frac{\Delta\sigma_{L,cor}}{\Delta\sigma_L} = \left(\frac{\sigma_{\infty,cor}}{\sigma_\infty}\right)^{1.33} \quad (10)$$

The proposed values in Table 2 are compared with environmental reduction factors (ERF), which are obtained from experimental results of welded plate and tubular joints in marine environment. The ERF is the inverse of the ratios $\frac{\Delta\sigma_D}{\Delta\sigma_{D,cor}}$ and $\frac{\Delta\sigma_L}{\Delta\sigma_{L,cor}}$. The value varies from 1 to 5.2. An average ERF value of 3 has been recommended for both 16 mm welded plate and tubular joints at 10^6 cycles of endurance in freely corroding environment.[19] The proposed values have a good match with the ERF values. Even though this paper only presents the parameters for the Eurocode and DNV codes, the same procedure can be applied to determine the parameters for obtaining corroded S-N curves in any detail category given in any fatigue codes.

4.3 | Experimental verification of the proposed curve

The corrosion fatigue test results of structural details exposed to corrosive media are compared with predicted fatigue lives by the proposed formula to confirm its validity in this section. Full-scale fatigue testing results of rolled plates fabricated from SMA weathering steel[2,31] are compared with the prediction of Eqs 5 and 8 as shown in Fig. 4. This steel is commonly used in Japan for bridges, agricultural vehicles, railway wagons, water pipes and etc. The tests were performed in tension compression constant amplitude loading. Corroded and uncorroded

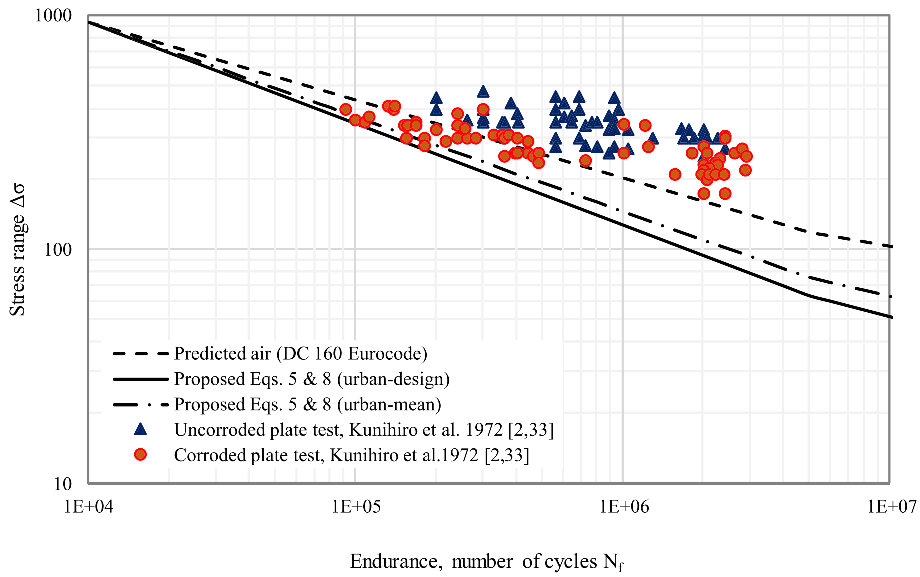

FIGURE 4 Comparison of proposed S-N curve with fatigue tests of 2 years weathered rolled SMA plates [Colour figure can be viewed at wileyonlinelibrary.com]

test results correspond respectively to plates taken after two years of weathering and unweathered plates. In lower stress levels, corroded specimens fatigue endurance is closer to uncorroded plates fatigue endurance as there were no severe rust pits formed after two years of weathering. The weathered steel is allowed to rust in order to form protection coating and the severity of rust pits governs the fatigue endurance.[3] Therefore, lower stress level is not sufficient to increase the stress concentration of rust pits and this is the reason why the same fatigue life for weathered and unweathered plates can be observed. The Eurocode detail category 160 represents fatigue strength of rolled steel plates.[30] As the plate was subjected to weathering in air and tests were performed in a sheltered environment, urban environment parameters conservatively were selected from Table 2 for predicting the S-N curves. The predicted S-N curve shows a good match with the test results as shown in the Fig. 4.

Fatigue test results of corroded bridge girders extracted from Trolley Bridge[32] are compared with the prediction of the proposed formula as shown in Fig. 5. The beams were standard rolled, 4.72 m long and made of carbon steel after 85 years of corrosion. The bridge was located urban environment and subjected to moderate corrosivity. The 22 beams which had not been subjected fatigue in service (i.e. operating stress were well below fatigue limit) were

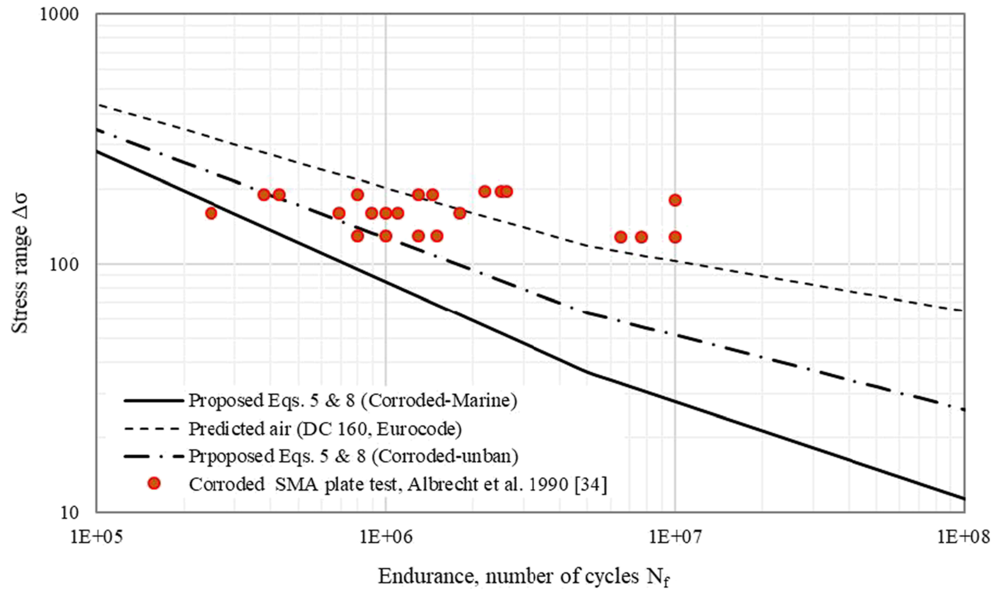

FIGURE 5 Comparison of proposed S-N curve with fatigue test of corroded carbon steel beams [Colour figure can be viewed at wileyonlinelibrary.com]

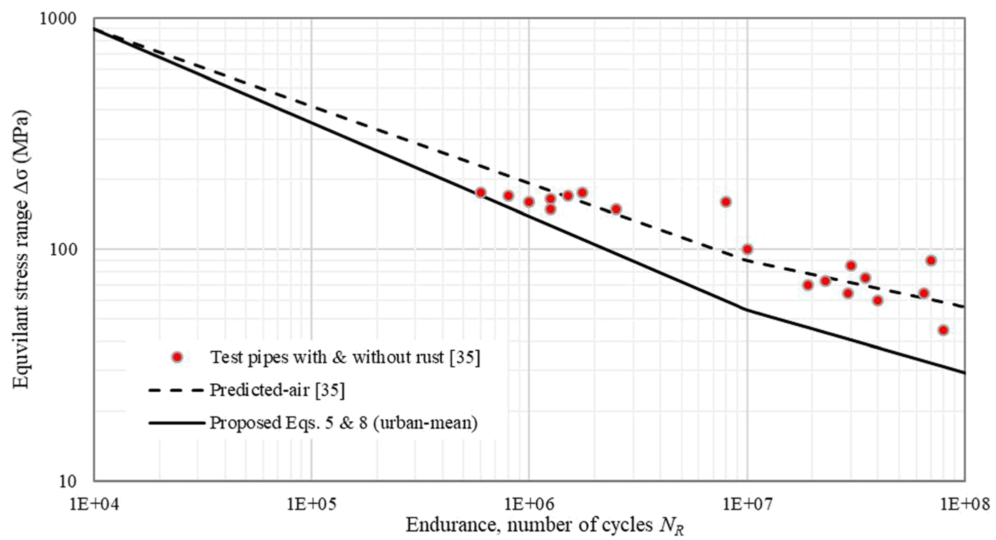

FIGURE 6 Comparison of proposed S-N curve with full-scale fatigue test of girth welded pipes under variable amplitude loading [Colour figure can be viewed at wileyonlinelibrary.com]

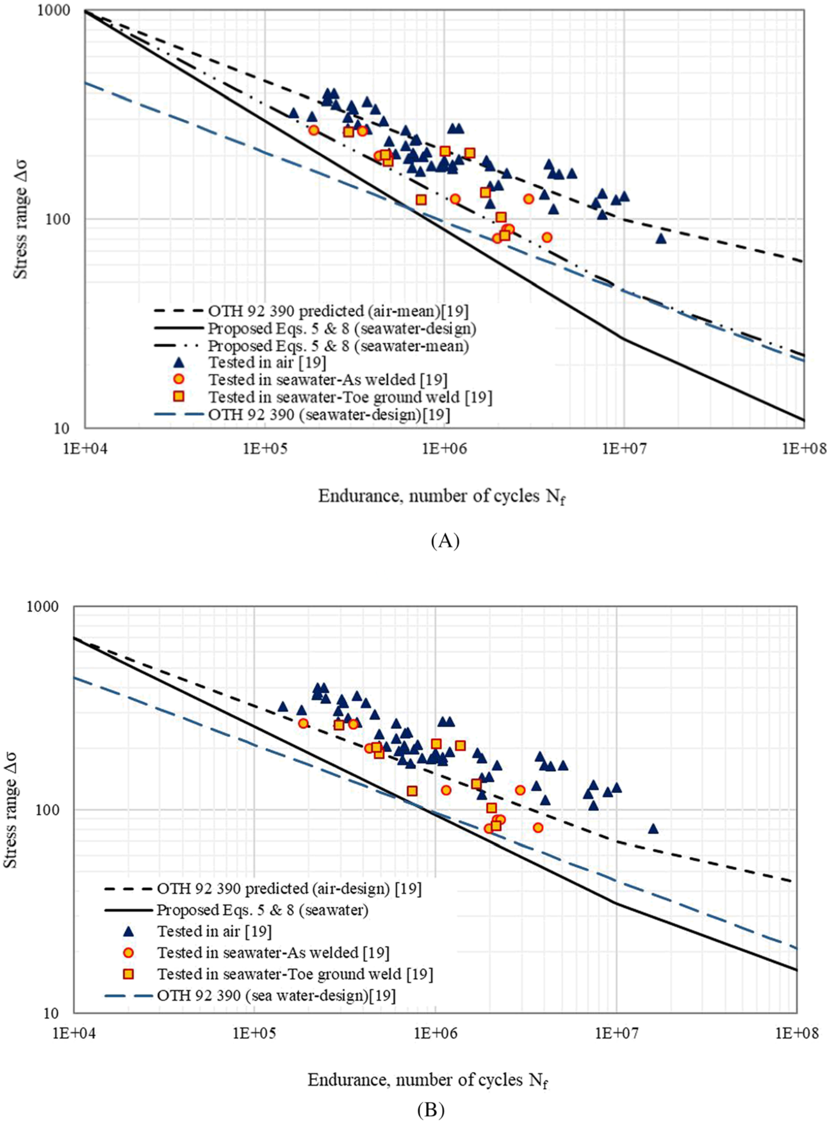

FIGURE 7 Comparison of proposed S-N curve with fatigue test of tubular joints in seawater-free corrosion, thickness 16 mm: (a). parameters obtained from mean S-N curve in air, (b). parameters obtained from design S-N curve in air [Colour figure can be viewed at wileyonlinelibrary.com]

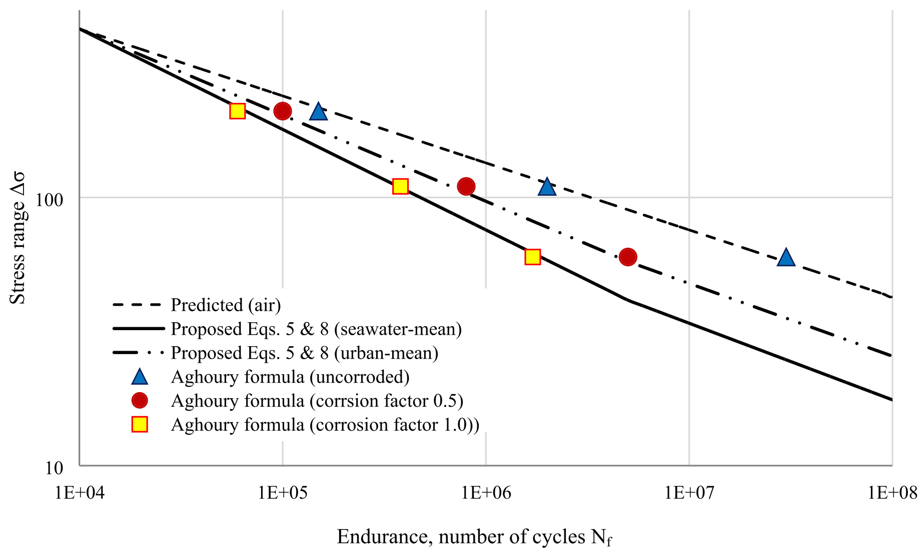

FIGURE 8 Comparison of proposed S-N curve with Aghoury's strain-life model [2,3] predicted fatigue endurances for different corrosion factors [Colour figure can be viewed at wileyonlinelibrary.com]

subjected to bending fatigue test. The Eurocode detail category 160 represents the fatigue strength of rolled carbon steel.[30] The proposed S-N curve for both marine and urban environments was plotted in Fig. 5 by using Eqs 5 and 8. The model parameters were selected from Table 2 to correspond detail category 160. Figure 5 shows a good agreement with the proposed formulae for 70% of the test results.

Figure 6 shows a similar verification with the fatigue testing results of full-scale girth welded pipes tested under variable amplitude loading.[33] The resonance fatigue testing technique was used for those full-scale pipes. Rotating redial force was applied to one end to excite the pipe close to its first mode of vibration. A bending moment was, then, generated to induce a variable amplitude stress state. Alternatively, girth welded pipe strips were also tested by ordinarily hydraulic test machine. Considerable amount of corrosion and rusting were observed in girth welded region only for few pipes and specimens. The S-N curve for uncorroded girth welded details were taken from the same reference and the predicted air curves are shown in Fig. 6. The model parameters for the proposed S-N curve of the corroded girth welded pipes were obtained from the predicted air curve and Table 2. Similarly, Eqs 5 and 8 are used to predict S-N curve of the corroded items as shown in Fig. 6 compared with the corresponding experimental results.

HSE offshore technology report[19] has provided free corrosion fatigue strength tubular joints used in offshore structures based on surveying some fatigue test results. The determination of ERF was also mentioned in the report. Fatigue tests of tubular joints with both the toe ground weld and as welded were considered for the test. Proposed S-N curves for the marine environment were

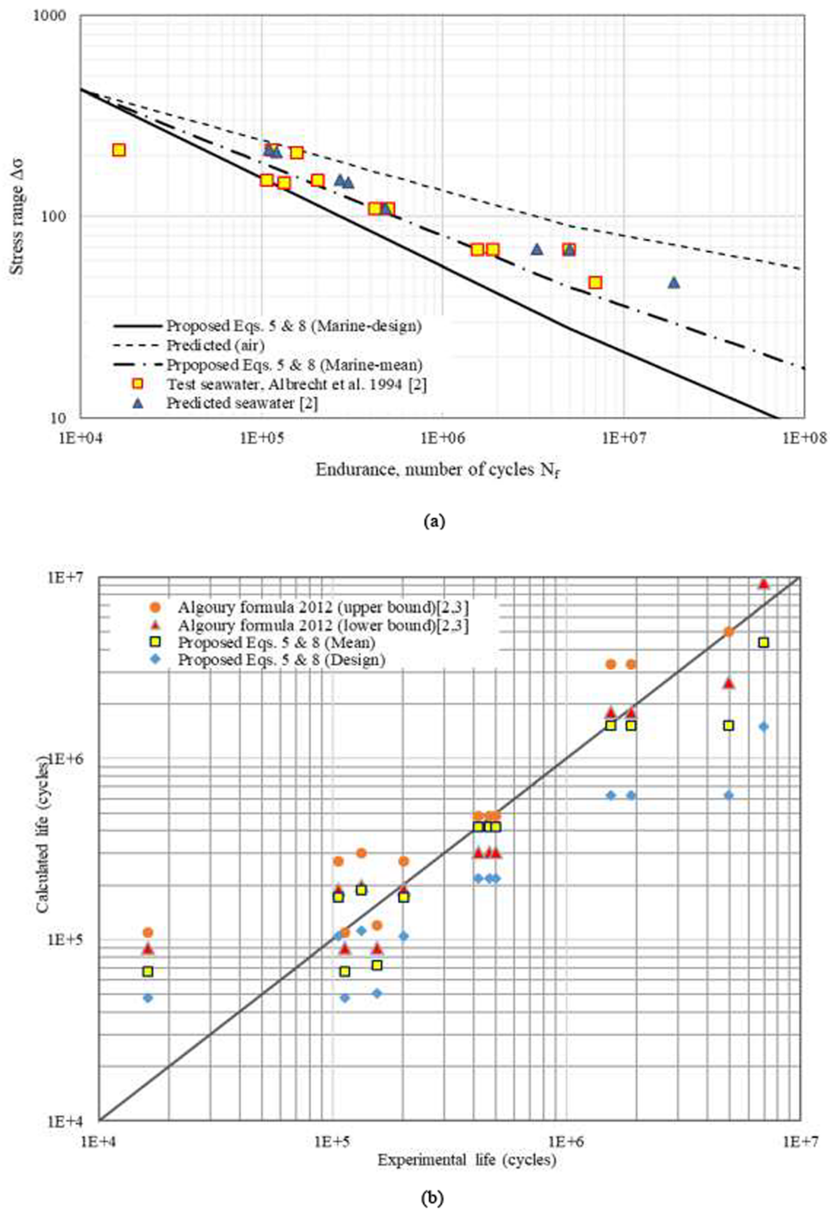

FIGURE 9 Comparison of Aghoury's strain-life model [2,3] predicted fatigue endurances and experimental fatigue lives of sheltered steel beams tested in moist saltwater environment with: (a). proposed S-N curve plots, (b). proposed S-N curve formula predicted fatigue lives [Colour figure can be viewed at wileyonlinelibrary.com]

plotted using the formulae given in Eqs 5 and 8 for thickness 12mm tubular joints as shown in Fig. 7. The proposed S-N curve in Fig. 7a was based on the parameters of mean S-N curve of tested tubular joints in air while Fig. 7b was based on the design curve. The marine environment model parameters were taken from Table 2 and hence both the design and the mean S-N curves are plotted for corroded tubular joints. Measured hot spot stresses were used for this comparison. The S-N curves has a very good agreement with the corresponding experimental fatigue lives. The previously proposed free corrosion (FC) fatigue curve[19] seems to be over conservative when the endurance is lower than 10^6 cycles. However, it is doubtful in VHCF region. The previous FC curve intersects the new curves between 10^5 and 10^6, where the test results were used for ERF determination. This indirectly indicates that the determined model parameters shown in Table 2 have a good agreement with the ERF values.[19]

As discussed in the introduction, Aghoury proposed a strain-life model based on the Smith–Watson–Topper model[2,3] to simulate the CF behaviour of metals. The S-N curves predicted by that model for three different corrosion rates are compared in Fig. 8 with the corresponding S-N curves predicted by Eqs 5 and 8 for marine and urban environments. The S-N curve for air was predicted based on corrosion factor zero. The figure shows good agreement between proposed models.

Aghoury[2,3] compared his model estimated fatigue lives with the experimental fatigue behaviour of the corroded rolled beams of A588 steel. The beams were boldly exposed for 67 months under metal deck in moist salt water (i.e. sheltered in marine environment). The fatigue lives predicted by both models are compared with experimental lives in Fig. 9. The figures confirm the validity of Eqs 5 and 8 and its parameters listed in Table 2.

5 | CONCLUSIONS

The comparisons of the predicted fatigue curves with fatigue test results of corroded steel in different corrosive media conclude the validity of a proposed formula and the validity of the proposed mean and conservative values for parameters used in the formula. The proposed curve does not require any material parameter or corrosive media specific parameter except the fatigue strength curve (i.e. S-N curve) obtained in air.

The S-N curves predicted by the derived formula are in a very good agreement with experimentally obtained fatigue lives of corroded constructional details considered in the present study. The physics behind the CF has been studied from the literature in a micro structural level, specimen scale and finally incorporated into structural member and joint scale. This is the main reason of having a good agreement with the full-scale fatigue test results. The values of the curve parameters have been proposed only for detail categories given by Eurocode and DNV code. The same procedure can be utilized with the values proposed for the corroded steel to determine the model parameters for any detail category given in any code. The main advantage of the proposed formula is that it requires only the fatigue strength curve of the constructional detail in air, which is given in relevant codes, to predict the corresponding S-N curve in a corrosive media.

NOMENCLATURE

b	Basquin's exponent
m	negative inverse slope of the *S-N* curve
N_f	number of cycles to fatigue failure
$N_{f,FL}$	endurance number of cycles
$N_{f,LCF}$	number of cycles to fatigue failure of the uncorroded materials at the yield strength
$N_{f,CAFL}$	number of cycles at constant amplitude fatigue limit
$N_{f,VAFL}$	number of cycles at variable amplitude fatigue limit
N_R	number of cycles to fatigue failure
$\Delta\sigma$	stress range
$\Delta\sigma_{cor}$	fatigue strength range of corroded constructional detail
$\Delta\sigma_D$	stress range at constant amplitude fatigue limit
$\Delta\sigma_{D,cor}$	stress range at intersecting points of two slopes of corroded fatigue at number of cycles at constant amplitide fatigue limit
$\Delta\sigma_L$	stress range at variable amplitude fatigue limit
$\Delta\sigma_{L,cor}$	stress range at number of cycles ar variable amplitude fatigue limit
$\sigma_{a,cor}$	fatigue strength of corroded material
σ_y	yield strength
σ_f'	fatigue strength coefficient
σ_∞	endurance limit (i.e. fatigue limit for high-cycle fatigue)
$\sigma_{\infty,cor}$	endurance limit for corroded material.

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