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An Extended Engineering Critical Assessment for Corrosion Fatigue of Subsea Pipeline Steels

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Abstract

Engineering critical assessment (ECA) is widely used to assess the structural integrity in offshore industry. But industry standards provide limited guidance on ECAs of structures subjected to corrosion fatigue (CF). In this paper, a critical stress intensity factor (SIF) derived from a corrosion-crack correlation model is proposed to improve the traditional ECA for steel structures in seawater. The proposed critical SIF extends the traditional ECA for CF in that it accounts for the influence of load frequency and initial crack size on the model selection within current ECA guidelines for the ECA of marine structures under CF. The extended ECA is applied for X65 carbon pipeline steels subjected to CF. The crack growth curves are built using a three-stage CF crack growth model and the experimental data. Fatigue lives are calculated based on those curves as well as traditional ECA models. Results show that the critical SIF can effectively improve the ECA for X65 carbon pipeline steels under CF. The extended ECA provides a reasonable assessment with reduced conservatism in contrast to the traditional ECA for CF.

Keywords: Structural integrity, engineering critical assessment (ECA), corrosion fatigue, fracture mechanics

Abbreviations

AD	Anodic Dissolution
CF	Corrosion Fatigue
CP	Cathodic Protection
EAC	Environment Assisted Cracking
EAZ	Environment Affected Zone
ECA	Engineering Critical Assessment
FFS	Fitness For Service
HE	Hydrogen Embrittlement
HEDE	Hydrogen Enhanced De-cohesion
LEFM	Linear Elastic Fracture Mechanics
SCC	Stress Corrosion Cracking
SD	Standard Deviation
SIF	Stress Intensity Factor
SIM	Structural Integrity Management

1. Introduction

The structured programme for assessing the integrity condition of a structure is commonly referred as the structural integrity management (SIM) (ISO 19902, 2000). SIM as a maintenance strategy has been widely adopted for marine structures for a long time (API RP 17N, 2009; Chen et al., 2011). Various approaches are available for structural integrity assessment and the most popular nowadays is the fracture mechanics based approach, which is also known as engineering critical assessment (ECA) or fitness-for-service (FFS) assessment. The established philosophy behind the approach is to ensure that the material of which the component is made, is able to withstand the maximum applied load when a crack-like flaw exists.

ECA has been regularly performed in today's offshore oil and gas industry to ensure the safe operation of critical structures as well as to maximize their earning capabilities (Holtam, 2010). There are several industry standards that can provide guidance on conducting ECAs, such as BS 7910 (2013), API 579-1/ASME FFS-1 (2007), SINTAP (2000), FITNET (2008), etc. Although these guidelines have specified corrosion fatigue (CF) as an important damage mechanism, they are not able to provide as detailed, in depth and generality, and accurate assessments to CF as to failure modes such as fracture/collapse, fatigue, creep fatigue, etc. (BS 7910, 2013). And this insufficiency often leads to overestimation or underestimation of the damage by CF to structural integrity. Offshore structures, for instance subsea pipelines, are vulnerable to CF. The excessive conservatism can ensure safe operation, but also leads to unnecessary and costly underwater inspections; while the lack of conservatism will put the structure at a high risk of failure, which may result in enormous economic loss as well as catastrophic environmental disasters. There is thus a practical and pressing need to improve the traditional ECA for the marine structures suffering CF.

Based upon previous research work (Cheng and Chen, 2017a; Cheng and Chen, 2017b), a critical stress intensity factor (SIF) is proposed from the perspective of CF severity. It accounts for the influence of load frequency and initial crack size on the model selection for the ECA of marine structures under CF. The critical SIF is decided according to the specific CF cracking behavior pattern, and it is calculated invoking a corrosion-crack correlation model (Cheng and Chen, 2017a). While the subcritical crack growth is estimated using a three-stage CF crack growth model (Cheng and Chen, 2017b), with each stage involving both the cracking processes assisted by anodic dissolution (AD) and by hydrogen embrittlement (HE). Finally, the proposed ECA is applied to X65 grade pipeline carbon steels to demonstrate the capability of the extended ECA.

2. Corrosion Fatigue

The impact from environment on the structural integrity of marine structures is multi-aspect and complicated. Take subsea pipelines for example, in the aspect of mechanics, huge external hydrostatic pressure will be imposed in a deep-sea situation. Intervention vessels, current and other met-ocean events may also be a source of loads acting upon the structures. Additional attention is required to the possible thermal and pressure expansion and contraction. In engineering practice, the load frequencies, stress ratios and even temperatures related to subsea pipelines can vary in rather big ranges. In the aspect of materials, the presence of aggressive environment can severely degrade the material properties such as fracture resistance, while unfortunately subsea pipelines are exposed to aggressive service environments both internally and externally. In the aspect of chemicals, the contact of salts and water with the metal surfaces, either inside or outside the pipelines, gives corrosion a chance to happen. Potential carbon dioxide and hydrogen sulphide in the product flow makes the situation even worse. Under such severe service conditions, environment-assisted cracking (EAC) is very likely to occur and damage the integrity of subsea pipelines.

EAC describes the aggravated cracking process of metals by the presence of aggressive environment. Stress concentrations such as as-built pipeline defects or dents caused by interference as well as corrosion pits may act as initiating sites for EAC. Depending on the loading profile, EACs are sorted into two major categories, i.e. the stress corrosion cracking (SCC) and the corrosion fatigue (CF). CF is the environment enhanced cracking under fatigue loads and SCC represents the accelerated cracking synthetically induced by environments and static loads. In contrast to CF, researches on SCC are relatively extensive and fruitful (Parkins, 2000; Woodtli and Kieselbach, 2000; Beavers and Harle, 2001; Fang et al., 2003). SCC cracks are found to initiate from bottoms of surface blemishes, and then propagate into the material either transgranularly, intergranularly or sometimes in a mixed way,

depending on the interaction of corrosion reactions and mechanical stress. For high-pH (9-13) SCC, cracks often grow along intergranular paths. This is thought to be associated with the strong environmental influence it receives, manifesting as local corrosion at crack tips. The transgranular crack path of near-neutral pH (5-7) SCC has been suggested to be associated with the ingress of hydrogen, a byproduct of corrosion, and the local corrosion at the crack tip. While hydrogen is well known for its adverse effect on the material's fracture toughness which has the name of hydrogen embrittlement (HE), local corrosion is believed to be caused by anodic dissolution (AD). That is to say AD and HE should be mainly responsible for the crack-tip material damage in near-neutral pH SCC. Interestingly, CF cracks usually follow a transgranular path similar to that of near-neutral pH SCC. The similarity in crack morphologies implies a similarity in cracking mechanisms. Further studies confirm that the mechanisms, which have generally been proposed to explain near-neutral pH SCC, are also applicable for CF. Combining with the fact that practical operations commonly generate varying working stresses in engineering structures, some researchers even consider SCC as a special case of CF where the stress ratio reaches unity (Shipilov, 2002). BS 7910 (2013) suggests using CF threshold to assess the starting of SCC, as it has recognized that structures are seldom subjected to pure static loads and the threshold of SCC can be considerably reduced if a cyclic component, even of very small magnitude, is superimposed on the static loading. Hence, it is of significant necessity to reasonably assess the damage on structural integrity due to CF.

Experimental observations (Vosikovsky, 1975; Stephens et al., 2000; Holtam, 2010; Yu et al., 2015) have confirmed that CF can change the crack growth behaviour and lead to remarkably higher crack growth rate than that of fatigue in air for carbon pipeline steels such as X65 (shown in Fig. 1), and a few researchers have examined the CF damage in the view of the consequently lower overall fatigue life. For example, Baxter et al. (2007), based on their experimental results, found fatigue lives of steels in seawater, with or without cathodic protection (CP), at high stress range can be a factor of three lower than those in air.

Most of the researchers have been aware that load frequency has an important influence on the crack growth in the situation of CF, which is quite different from fatigue crack growth in dry-air environments. Holtam (2010) investigated the effect of crack size on CF crack growth. However, there is a lack of research performed on assessing the CF damage with respect to both initial crack size and load frequency. The main objective of the study is to fill this gap. Cheng and Chen (2017a) proposed a corrosion-crack correlation model for predicting the cracking behavior of HE-influenced fatigue. Based on this model as well as the physics of CF, Cheng and Chen (2017b) further established a two-stage crack growth model for CF. The previous research work has provided a solid

theoretical foundation for extending the traditional ECA of structures suffering CF to account for the influence from both load frequency and initial crack size.

3. Extended Engineering Assessment (ECA)

Since it was developed in the 1950s by Irwin (1957), linear elastic fracture mechanics (LEFM) analysis has been widely applied to ECA for steel structures. It introduces the concept of stress intensity factor (SIF) K to describe the crack growth under sustained loads,

$$K = YS\sqrt{\pi a} \quad (1)$$

where a is the crack size, Y stands for the geometry function, and S is the applied stress perpendicular to the crack plane. For the case of fatigue crack growth, the applied loading is characterized by an applied stress range ($\Delta S = S_{\max} - S_{\min}$) rather than a single value of stress, and in fracture mechanics terms, a given crack can then be considered to experience a SIF range (ΔK), which is calculated as

$$\Delta K = Y\Delta S\sqrt{\pi a} \quad (2)$$

where Y is the geometry function. ΔK also has a relationship with the maximum SIF $K_{\max}$ in each load cycle as shown below,

$$K_{\max} = \frac{\Delta K}{(1 - R)} \quad (3)$$

3.1 Traditional approach

For a component subjected to fatigue loading, creep, brittle fracture and general volumetric corrosion, procedures are given in industry standards for assessing the acceptability of cracks found in service in relation to their effects on fatigue strength, both in welded and unwelded parts, or for estimating the tolerable crack sizes based on FFS. The likelihood of failure from the operation of these failure modes and damage mechanisms can be predicted with varying degrees of confidence and accuracy. This is because the behaviour of components subjected to these failure modes and damage mechanisms is relatively well understood.

Yet traditional ECA in industry standards are not able to provide treatments for CF in the same depth and generality as is provided for the aforementioned failure modes. For example, BS 7910 (2013)

only offers brief guidelines in its clause 10 for the assessment of CF as a part of EAC. As in most other industry standards, the EAC defects are therein evaluated based on avoiding the phenomena by limiting the SIF, K . More specifically, BS 7910 (2013) describes a crack acceptance criterion for mode I cracking as follows

$$K_I < \frac{K_{ISCC}}{F} \quad (4)$$

where K_I is the applied SIF, F is a factor of safety to be agreed between the parties involved in the structural integrity assessment and K_{ISCC} indicates the point when SCC happens. Following such an idea, the corresponding characterizing parameter for CF should be the SIF range (ΔK) where CF starts. BS 7910 (2013) advises that the threshold range in SIF at $R = 0$, ΔK_0 , for the growth of fatigue cracks under the environmental and loading conditions of interest be chosen to assess the significance of cracks. And to assessment the subcritical crack growth before the crack size (length or depth) reaches the failure criterion, the simplified model, which is actually a plot of Paris law in a log-log scale, and the bilinear model, which is a plot of a two-stage Paris equation, are recommended. However, it is often challenging to use ΔK_0 for assessment, because the fatigue crack growth rate is very small and hard to measure in the very low ΔK regime, and such an assessment approach is actually in a preliminary level. While the simplified model and bilinear model are not always good descriptions of the specified CF crack growth. Thus it is often seen that traditional ECA for CF may result in unnecessary cost as well as high risk of failure arising through the structure's service life.

3.2 Extended approach

For normal fatigue cracking (i.e. fatigue cracking in an inert environment), in principle, crack propagation starts from the "stage I" (the "initiation" phase), mainly being "short crack", and continues with the "propagation" phase of stage II and stage III (fast crack propagation), being "long crack" towards final failure with the maximum SIF K_{max} in each load cycle approaching the fracture toughness K_{IC} (Pugno, 2006). Cracks detected at service are usually in the stage II. And it is generally agreed that LEFM can provide reasonable fatigue life prediction for long cracks (Stephens, 2000). Paris Law (Paris and Erdogan, 1963), which describes the relationship between cyclic crack growth rate da/dN and SIF range ΔK in stage II is the tool used in LEFM to predict the fatigue life, and has the expression as below,

$$\frac{da}{dN} = C(\Delta K)^m \quad (5)$$

where C and m are material constants.

However, the fatigue crack growth process will be different in the presence of corrosion. According to McEvily and Wei (1972), the CF crack growth of metals may be broadly categorized into three general patterns of behaviour as illustrated schematically in Fig. 2. The Type A behaviour pattern is typical as that of the aluminium-water system, and is characterized by a reduction in the apparent threshold for crack growth and increases in the rate of crack growth at given $K_{\max}$ levels. As $K_{\max}$ approaches K_{IC} , the environmental influence diminishes. The Type B behaviour is typical for the steel-hydrogen systems. An abrupt increase of crack growth rate occurs somewhere along the abscissa, which indicates the environmental effects are quite strong above some apparent critical SIF but they are negligible below this level. A broad range of material-environment systems such as seawater-steel systems exhibit behaviour that falls in the Type C behaviour pattern, with Type A behaviour at $K_{\max}$ levels below the apparent threshold and Type B behaviour above.

For steels freely corroding in a marine environment, current industry standards suggest the simplified or bilinear models to be used in the ECA of CF. Take BS 7910 for instance, it provides the simplified model, the mean bilinear model and the mean plus two standard deviations (mean+2SD) bilinear model for assessments of different accuracies. And two sets of parameters are available for the cases $R < 0.5$ and $R \geq 0.5$ respectively in the mean bilinear model as well as the mean+2SD bilinear model. However, as seen in Fig. 1, with the experimental data from Vosikovsky (1975) for fatigue crack growth of X65 pipeline carbon steels tested in seawater as the reference, the models are often not good descriptions of the whole CF crack growth. On the other hand, the experimental observation of fatigue crack growth curves of steels tested in seawater with and without CP clearly show that the HE induced degradation of fracture toughness is the reason causing crack behaviour features such as transition and plateau (Shipilov, 2002). But Paris law in itself doesn't link the crack growth behaviour with the fracture toughness degradation. In order to reasonably describe the HE influenced fatigue crack growth of pipeline steels, Cheng and Chen (2017a) developed a two-stage Forman equation model

$$\frac{da}{dN} = \begin{cases} \frac{B_1(\Delta K)^{n_1}}{[(1-R)K_{IH} - \Delta K]}, & K_{\max} < K_t \\ \frac{B_2(\Delta K)^{n_2}}{[(1-R)K_{IE} - \Delta K]}, & K_{\max} \geq K_t \end{cases} \quad (6)$$

where B_1 , B_2 , n_1 , and n_2 are material constants, f is the load frequency, K_{IH} is the saturated fracture toughness which is obtained with sufficient hydrogen supplement using procedures defined in ASTM E 1820 (2017), K_{IE} is the equilibrium fracture toughness, namely the final fracture toughness

displayed in the fatigue test conducted in hydrogen gas, and K_t is the transition SIF connecting the two stages, corresponding to the transition point in the CF crack growth curve.

This model is based on the fatigue cracking of steels in high-pressure hydrogen gas depicted by API 579 (2009). Accordingly, the typical HE influenced fatigue cracking process of steels with constant amplitude loading is divided into three stages, denoted as stage 1, 2 and 3 as shown in Fig. 3. In stage 1, the hydrogen delivered at the crack tip leads to an enhanced fatigue crack growth compared with the normal fatigue cracking, causing the crack grows along the sigmoidal curve dedicated by K_{IH} . However, when the crack growth rate goes beyond the hydrogen delivery rate, the crack propagates into the bulk material with less hydrogen delivered at the crack tip. As a consequence, larger cracking resistance is encountered, inducing a decrease in the growth acceleration which manifests as a transition in the crack growth curve and indicates the commencement of stage 2. Due to the continuity of hydrogen charging and crack growth, the cracking rate will not drop. But later as the equilibrium between the crack growth rate and hydrogen delivery rate is achieved, a plateau of crack growth rate appears in the crack growth curve and lasts over a range of K_{max} , denoted as K_{pl} . In stage 3, as K_{max} approaching the equilibrium fracture toughness K_{IE} , the crack growth curve merges into the sigmoid oriented by K_{IE} . The two-stage Forman model consists of two segments of sigmoidal fatigue crack growth curves oriented by K_{IH} and K_{IN} connected by the transition SIF K_t both plotted using dash lines in the same figure.

As previously stated, CF involves two damage mechanisms, i.e. AD and HE. Thus, based on the two-stage Forman model, Cheng and Chen (2017b) further established a two-stage CF crack growth model as shown below,

$$\frac{da}{dN} = \begin{cases} Af^{-0.36}(1-R)^2(\Delta K)^3 + \frac{B_1(\Delta K)^{n_1}}{[(1-R)K_{IH} - \Delta K]}, & K_{max} < K_t \\ Af^{-0.36}(1-R)^3(K_t)^3 + \frac{B_2(\Delta K)^{n_2}}{[(1-R)K_{IE} - \Delta K]}, & K_{max} \geq K_t \end{cases} \quad (7)$$

where the AD effect is considered by the former part while the HE assisted cracking process is represented by the latter part in each stage, and $A = 4.93 \times 10^{-12}$ was obtained by Endo et al. (1981) from their experiments. The other parameters have the same definition as in Eq. (6) but for CF in the seawater-steel system. As seen in Eq. (7), each stage involves both the cracking processes assisted by AD and HE.

However, as seen in Fig. 1, the plateau in the crack growth curves of carbon pipeline steels such as X65 in seawater is not evident, and most importantly, the SIFs of cracks detected at service usually locate within the range defined as long crack propagation. Thus it may be reasonable and convenient

to use Paris law for the specified range of ΔK , instead of Forman equation, from a view of practical engineering. Furtherly, a three-stage CF crack growth model, which has the expression shown below was built for CF of pipeline carbon steels in seawater,

$$\frac{da}{dN} = \begin{cases} Af^{-0.36}(1-R)^2(\Delta K)^3 + C_1(\Delta K)^{m_1}, & K_{\max} < K_t \\ Af^{-0.36}(1-R)^5(K_t)^3 + C_1[(1-R)K_t]^{m_1}, & K_t \leq K_{\max} < K_t + K_{pl} \\ Af^{-0.36}(1-R)^5(K_t)^3 + C_2(\Delta K)^{m_2}, & K_{\max} \geq K_t + K_{pl} \end{cases} \quad (8)$$

where A is set the same as in Eq. (7), C_1 , C_2 , m_1 , and m_2 are material constants, and the $K_{\max}$ range $K_{pl} = \Delta K_{tH}/(1-R)$ according to Cheng and Chen (2017a), with the SIF range threshold for CF $\Delta K_{tH} = 2 \text{ MPa} \cdot \text{m}^{1/2}$ from API 579 (2009).

Experimental observation shows that as $K_{\max}$ increases, before each K_t is achieved, the crack with load frequencies of 1 Hz, 0.1 Hz, and 0.01 Hz, grows almost along the same curve, however, their growth curves deviate after K_t , which has an obvious dependence on the load frequency. Such a deviation has a direct influence on the crack growth rate and therefore the fatigue life. For the reasons stated above, the transition SIF K_t is proposed to be the critical SIF value that should be particularly checked before conducting ECAs for critical structures under CF. And the expression of K_t is derived from the corrosion-crack correlation model which is used to explain the process of HE influenced fatigue cracking (Cheng and Chen, 2017a) and schematically plotted in Fig. 3.

In LEFM, the stress perpendicular to the crack plane in Mode I loading, σ_{yy} , is expressed by

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \quad (9)$$

where r is the distance in front of the crack tip, and K_I is the SIF in Mode I loading.

And the maximum principal stress happens at the elastic-plastic boundary as,

$$\sigma_{\max} = \sigma_{yy} = \omega \sigma_{ys} \quad (10)$$

where ω is a magnification factor accounting for the material's working hardening effect and it is usually considered to be in a range of value 3 ~ 5 (Wang et al., 2013).

Thus the plastic zone size r_p has the expression

$$r_p = \frac{1}{2\pi} \frac{K_I^2}{(\omega \sigma_{ys})^2} \quad (11)$$

The concept of environment-affected zone (EAZ) is introduced to define the damaged zone where material exhibits a property different from that of the bulk material due to the penetration of

chemical agents into a localized crack-tip region (Liu, 2005). Assuming that the hydrogen diffusion in the material of crack-tip region is primarily stress-driven, then r_{EAZ} has an expression as (Cheng and Chen, 2017a):

$$r_{EAZ} = \sqrt{\frac{DV_H\sigma_{ys}}{k_B T} \cdot \frac{1}{f}} \quad (12)$$

where D corresponds to the diffusion coefficient and is calculated from the ratio of hydrogen permeability and solubility for carbon steel (Gadgeel and Johnson, 1979), f is the load frequency, V_H is the partial volume of hydrogen, k_B is the Boltzmann constant, T is the temperature in Kelvins and σ_{ys} is the material's yield strength.

As can be seen from Eq. (11), r_p grows as K_I increases. In accordance with the corrosion-crack correlation model, the point where the crack propagation curve starts transition is the very point where r_p grows to an equilibrium with the environment-affected zone size r_{EAZ} , i.e.

$$r_p = r_{EAZ} \quad (13)$$

Combining Eqs. (9)-(13), it follows that

$$K_{tran} = \omega_H \sigma_{ys} \left(\frac{4\pi^2 DV_H \sigma_{ys}}{k_B T f} \right)^{1/4} \quad (14)$$

where ω_H accounts for the material's working hardening effect in the presence of hydrogen.

Note that fracture happens when K_I reaches the fracture toughness of the material, and the corresponding critical plastic zone size r_c keeps the same regardless of hydrogen ingress (Wang, et al., 2013), the following equation can be achieved

$$\frac{\omega}{\omega_H} = \frac{K_{IN}}{K_{IH}} \quad (15)$$

where K_{IN} is the inherent fracture toughness. Wang et al. (2013) gives an equation for calculating K_{IH} based on the theory of hydrogen-enhanced de-cohesion (HEDE),

$$\frac{K_{IH}}{K_{IN}} = 1 - \frac{\beta c}{\omega \sigma_{ys}} \exp \left[\frac{2(1+\nu)}{3} \frac{V_H}{k_B T} \frac{K_{IH}}{K_{IN}} \omega \sigma_{ys} \right] \quad (16)$$

where β is a parameter related to the loss of critical cohesive stress by hydrogen impurity, c refers to the hydrogen concentration in the material under a unstressed state, and ν is the Poisson ratio.

Inserting Eq. (15) into Eq. (14), the transition SIF can be obtained as

$$K_{\text{tran}} = \omega \sigma_{ys} \frac{K_{\text{IH}}}{K_{\text{IN}}} \left(\frac{4\pi^2 D V_H \sigma_{ys}}{k_B T f} \right)^{\frac{1}{4}} \quad (17)$$

To obtain a valid transition SIF K_t , the following formula is used

$$K_t = \min \left\{ \max \left\{ K_{\text{tran}}, \frac{\Delta K_0}{(1-R)} \right\}, K_{\text{IH}} \right\} \quad (18)$$

4. Application

For pipeline carbon steels, the frequency effect on the crack growth rate is normally negligible in dry-air environments. However, under CF, the frequency effect appears to be obvious for materials under constant-amplitude load. It is generally believed that in an environment with stable corrosiveness, the fatigue crack growth rate increases with the decrease of the frequency. But as mentioned in Yu et al. (2015), observations from fatigue tests in corrosive environments showed that there exists a critical frequency f_c , under which the material properties show the same level of degradation. According to the corrosion-crack correlation model, the lower cyclic load frequency extends the exposure time of the material to the corrosive environment, and this allows more hydrogen atoms to diffuse to a longer distance in front of the crack tip within each loading cycle and thus a higher K_t . When $f < f_c$, the whole CF crack growth maintains high crack growth rate, namely no transition appears in the growth curve. Thus, f_c is decided by the relationship below:

$$K_{\text{tran}} = K_{\text{IH}} \quad (19)$$

Combining Eqs. (17) and (19), it follows that

$$f_c = \frac{4\pi^2 D V_H \sigma_{ys}}{k_B T} \left(\frac{\omega \sigma_{ys}}{K_{\text{IN}}} \right)^4 \quad (20)$$

To validate the corrosion-crack correlation model, the results of an experiment conducted by Yu et al. (2015) are compared with the prediction by Eq. (20) for f_c . The experiment was performed on X60 pipeline steel and the measured critical frequency was 1.04×10^{-3} Hz. According to the experimental conditions and material properties provided, the f_c of X60 pipeline carbon steels is calculated to be in the range of 4.4×10^{-4} to 3.4×10^{-3} Hz, with a consideration of ω ranging from 3 to 5. While the measured f_c is 1.04×10^{-3} Hz that exactly falls in the predicted range of 4.4×10^{-4} and 3.4×10^{-3} Hz, which shows the critical frequency of the experiment is captured by Eq. (20). Similarly, using the material in Table 1, the f_c of X65 pipeline carbon steels falls in a range of 1.8×10^{-4} to 1.4×10^{-3} Hz, which is reasonable since it is well below the sample frequency 0.01 Hz. Furthermore, the validity of Eq. (17) can be confirmed by the experimental data from tests conducted by Vosikovsky (1975) for

API X65 pipeline steels freely corroding in seawater with a series of load frequencies. As the saturated fracture toughness is hard to be decided for a component with free corrosion in seawater, a degradation factor δ , with a value of $0 \sim 1.0$, is multiplied by the inherent fracture toughness to approximate the remaining fracture toughness, namely

$$K_{IH} = \delta K_{IN} \quad (21)$$

Assuming $\delta = 0.8$, i.e. 80 percent of the inherent fracture toughness is left providing a saturated diffusion condition, which corresponds to the worst CF case where pH=5, transition SIFs are calculated using the material property data provided in Table 1 and then plotted together with the experimental data in Fig. 4. Good agreement between the model prediction and experimental data is observed as shown in Fig. 4, which indicates that Eq. (17) is an effective formula to predict the transition SIF for CF crack growth curves above f_c . The results of the model prediction are summarized in Table 2.

The initial crack size a_i in this paper is defined as the size when the crack is detected using a reliable non-destructive technique. It characterizes the initial state of the crack in the ECA to be conducted. The initial size of cracks in pressure vessels may range from several millimetres to some centimetres (Visser, 2002). Three cases where the initial crack size (length of crack) $a_i = 1$ mm, 4 mm, 12 mm are investigated due to limited experimental data (Vosikovsky, 1975). Since the transition SIFs of CF crack growth curves of X65 pipeline carbon steels under various load frequencies have been acquired, the experimental data are regressed to follow the three-stage CF model. The parameter values from regression are summarized in Table 3. Crack growth curves generated by each model are plotted in Fig. 5, with the experimental data plotted as reference.

The fatigue life in cycles over the range of crack sizes a_i to a_f is calculated as:

$$N_{if} = \int_{a_i}^{a_f} \frac{1}{C(Y\Delta S\sqrt{\pi a})^m} \frac{da}{a^{m/2}} \quad (22)$$

Vosikovsky (1975) used specimens of single-edge notched type, with the width b being 76.2 mm and the half length of h being 580 mm, in his experiment. The specimen is plotted in Fig. 6. Accordingly, the geometry function for calculating the geometry factor Y is determined to be (Dowling, 2012):

$$Y = \left(1 + 0.122\cos^4\frac{\pi\alpha}{2}\right) \sqrt{\frac{2}{\pi\alpha} \tan\frac{\pi\alpha}{2}} \quad (23)$$

where α is the ratio of crack length a to the width of specimen. Eq. (23) is also plotted in Fig. 6. It is obvious that the geometry effect is relatively stable before α reaches 0.6, i.e. before the length of

crack grows to a length of 0.6 times the width. So the failure criteria in this case is set as the crack grows to a length of 45.7 mm, namely $a_f = 45.7$ mm. The ratio of applied stress to the material's yield strength is adjusted to 0.4 so that the SIF range for evaluation approximately equals that where experimental data are available and the small yielding assumption of LEFM is met.

To evaluate the influence from the load frequency as well as the initial crack size on the ECA model performance of CF life prediction, a comparison is made among each group in terms of load frequency and initial crack size. And conservatism is used as the evaluation parameter, which is defined as:

$$\text{Conservatism} = \frac{\text{Experimental prediction} - \text{Model prediction}}{\text{Experimental prediction}} \times 100\% \quad (24)$$

Negative conservatism means the ECA model predicts a larger life than that of the experiment, i.e. the ECA model prediction is unconservative, which is usually not allowed in engineering practices. So a negative conservatism indicates that the model should be rejected for the ECA. Conversely, positive conservatism stands for a redundancy in life prediction of the model, and the smaller the conservatism the better the performance of the model in the ECA. Only the simplified model and the bilinear model of mean plus two standard deviations (mean+2SD) are used for fatigue life prediction and comparison with experimental data, since the mean bilinear model is obviously short of conservatism for ECAs of CF, as indicated in Fig.1. And the parameter values of the simplified and bilinear models suggested in BS 7910 (2013) are summarized in Table 4 for the experimental case where $R = 0.2$. The calculation results for each case are summarized in Table 5.

The crack growth curves as well as the corresponding crack evolution curves are plotted in Fig.7, Fig.8 and Fig.9 respectively for cases where $a_i = 1$ mm, $a_i = 4$ mm and $a_i = 12$ mm. CF lives calculated based on the experiment data are plotted in Fig.10 and those predicted using ECA models from BS7910 are plotted in Fig.11.

Conservatisms calculated from Eq. (24) for each model are plotted in Fig.12 as histograms. The histograms are clustered in terms of load frequencies, and within each cluster the histograms are lined in a sequence of initial crack size 1 mm, 4 mm, and 12 mm from left to right.

It can be clearly observed from Figs.7-9 that the difference in initial crack sizes may result in different crack evolution behaviours and CF lives even though the overall crack growth behaviour keeps the same.

As shown in Fig. 10, the fatigue life of structures subjected to CF is tightly related with the load frequency f . The lower the frequency, the higher the crack growth rate and thus the lower the

fatigue life, represented by the experiment based prediction. This is believed to be caused by the increase in the value of ΔK_t resulting from the decrease of load frequency. However, the ECA models from industry standards such as BS 7910 (2013), ignore the load frequency effect in CF, causing either overestimation or underestimation of the structure's fatigue life. Fig.10 also implies that the CF life in low regime of ΔK occupies a much bigger fraction in overall fatigue life than that in high ΔK regime, which means more cycles are spent to drive the crack growth when the crack size is small. Combining the aforementioned two findings with the observation, it is found that the increase of fatigue life accelerates as f increases.

Fig.11 shows that among the CF lives predicted by ECA models using the parameter values provided by BS7910, the CF life predicted by the bilinear model (mean) is always the highest, and then comes that by the bilinear model (mean+2SD), and the CF life predicted by the simplified model is the lowest. All the three predicted values decrease as the initial crack size increases. And quite obviously, the difference among them decreases as well.

It can be seen from Fig.1 that there is some underestimation of the CF crack growth rate from the bilinear model in the high ΔK regime for low load frequencies, while the simplified model always overestimates the crack growth rate. But this doesn't mean the simplified model is better than the bilinear model. Because the underestimation of the CF crack growth rate for low frequencies such as 0.01Hz from the bilinear model in high ΔK regime can be balanced by the overestimation from the bilinear model in low ΔK regime. Keeping in mind that the crack growth in low ΔK regime contributes much more than that in high ΔK regime, the bilinear model may give a prediction that is overall conservative, but with a much better performance in the view of conservatism. For example, the conservatism of the prediction by bilinear model (mean+2SD) for a crack of the initial size 4 mm with a load frequency of 0.01 Hz is as low as 3.55%, as indicated in Table 5.

Fig. 12(a) shows that the simplified model always give a conservative life prediction for CF cracks with various initial crack sizes. And while the conservatisms in the life prediction by the simplified model remain relatively large, they decrease as the load frequency decreases. Additionally, the sensitivity of the conservatism to load frequency is higher for a larger initial crack size, and this is also true for Figs. 12(b) and (c). Fig. 12(b) implies that among all the possible 9 combinations of load frequencies and initial crack sizes, the bilinear model (mean) can only be used for ECAs of two cases, i.e. $f = 1$ Hz with $a_i = 4$ mm, and $f = 1$ Hz with $a_i = 12$ mm. In Fig. 12(c), only the case where $f = 0.01$ Hz with $a_i = 12$ mm is not fit for conducting ECA using the bilinear model (mean+2SD). In a general view, with the load frequency decreasing, the conservatisms of the simplified, bilinear (mean) as well as bilinear (mean+2SD) models decrease, and the bilinear model (mean+2SD)

performs best. The conservatism generated by the ECA models in life prediction accumulates with the crack growth. The inefficient performance of the simplified model, indicated by its large conservatisms on average, is due to the ignorance of the transition in the CF crack growth curve. As revealed by Eq. (17), the transition SIF is determined by the load frequency. Depending on both the load frequency and the initial crack size/SIF range, the CF life, as seen in Fig. 10, may be heavily influenced, and so is the conservatism. The transition SIF specified in the bilinear model (mean+2SD) happens to be close to that of the crack growth curve with a load frequency of 0.1 Hz, as seen in Fig.1, which makes the conservatism in life prediction by the bilinear model (mean+2SD) small overall. But for cases where the load frequencies are lower than 0.1 Hz, the bilinear model (mean+2SD) tends to underestimate the crack growth rate after ΔK_t , contributing a negative value to the overall conservatism afterward; while for the cases where load frequencies are higher than 0.1 Hz, the bilinear model tends to overestimate the crack growth rate after ΔK_t , contributing a positive value to the overall conservatism afterward. Based on the conclusion drawn for Fig. 10, the increase of the sensitivity of conservatism to load frequency with the increasing initial crack size, which has been shown in Fig. 12, is explained to be due to the increase in initial crack size reducing the portion of the low- ΔK crack growth in the predicted life.

Fig. 12 also shows that a large initial crack size combined with a low load frequency tend to provide small even negative conservatism. So caution is needed when the case to be assessed involves either low frequency or large initial crack size or both. When assessing cases where $f \leq 0.01$ Hz, the simplified model is suggested to be used. If more accuracy is required, it may work to use the bilinear model (mean+2SD) before ΔK reaches the transition SIF range value specified by BS910 (2013), and use the simplified model afterward. Large initial crack size actually implies a high ΔK . Even though most cracks found at service are in a scale of several millimetres, this doesn't equivalently mean that their ΔK usually falls in the regime of low ΔK range. It is also necessary to consider the stress history and future working load conditions. For cracks detected with high ΔK , the simplified model is suggested to be used for ECA since it can always provide positive conservatism. As shown in Table 5, in the case where the crack has an initial size of 12 mm under a load frequency of 0.01 Hz, the use of the bilinear model provides unconservative life prediction (conservatism = -59.1%), however, the use of the simplified model still provides conservative life prediction (conservatism = 40.7%).

In traditional ECAs, the effect of the load frequency and initial crack size (in long-crack domain) is ignored due to their little influence on fatigue crack growth in an inert environment. However, for a structure subjected to CF, the effect of the load frequency and initial crack size on the CF crack growth is important. Such an effect can be taken into account through the parameter K_t or ΔK_t .

According to Eq. (17), K_t or ΔK_t is directly related to the load frequency. The higher the load frequency, the smaller the value of K_t or ΔK_t . Meanwhile, the initial crack size may be well above the crack size corresponding to K_t or ΔK_t . As analysed before, conservatism accumulates as the crack grows, thus the crack growth curve after K_t or ΔK_t may impose a significant influence on the performance of the model. Eq. (17), which is derived from the corrosion-crack correlation model, provides an effective way of calculating K_t or ΔK_t . It is thus believed that the calculation of critical SIF K_t or ΔK_t and an analysis on the fatigue crack growth behaviour for the structures under CF would benefit the subsequent ECA.

5. Conclusions

An extended ECA was proposed in this paper, in which a critical SIF was developed for accounting for the influence of load frequency and initial crack size, and directing the model selection for assessing the integrity of structures suffering CF within current ECA guidelines. For the specific CF cracking behavior pattern, a three-stage fracture mechanics based CF crack growth model is used to predict the subcritical crack growth. This extended ECA was applied to X65 grade pipeline carbon steels and the results indicate that

- The load frequency and initial crack size impose significant impact on the CF crack growth.
- The proposed critical SIF K_t extends the traditional ECA for CF in that it accounts for the influence of load frequency and initial crack size on the model selection for the ECA of marine structures under CF.
- For X65 pipeline steels, the simplified model always give a conservative life prediction for CF cracks with various initial crack sizes
- When assessing CF cases of X65 pipeline steels where $f \geq 1$ Hz, the life prediction by the bilinear model (mean) from BS7910 (2013) is conservative only if the initial crack size is larger than the crack size corresponding to K_t or ΔK_t under the specified load history.
- When assessing CF cases of X65 pipeline steels where $f \leq 0.01$ Hz, the simplified model is suggested to be used. If more accuracy is required, it may work to use the bilinear model (mean+2SD) before ΔK reaches the transition SIF range value specified by BS910 (2013), and use the simplified model afterward.

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Table 1. Material properties of API X65 steel

Material	Yield strength (σ_{ys})	Poisson ratio (ν)	Diffusion coefficient (D)	Threshold SIF range (ΔK_0)	Inherent fracture toughness (K_{IN})	Partial Volume of Hydrogen (V_H)
API X65 Steel	458.5	0.3	5.3×10^{-9}	2.0	197.9	2.0×10^6
Unit	MPa	-	(mol H ₂)/m ³ · MPa ^{1/2}	MPa · m ^{1/2}	MPa · m ^{1/2}	m ³ mol ⁻¹

Table 2. Predicted transition SIFs for X65 pipeline carbon steels under CF

Material	Stress Ratio (R)	Load frequency (f)	Transition SIF (K_t)	Transition SIF range (ΔK_t)
X65	0.2	1	28.8	23.0
X65	0.2	0.1	40.3	32.3
X65	0.2	0.01	62.0	49.6
Unit	-	Hz	$\text{MPa} \cdot \text{m}^{1/2}$	$\text{MPa} \cdot \text{m}^{1/2}$

Table 3. Parameters of CF crack growth curves regressed from experimental data

Crack growth curve	$K_{\max} < K_t$		$K_{\max} \geq K_t$		K_t
	C_1	m_1	C_2	m_2	
X65, $f=1$ Hz	2.30×10^{-9}	3.69	2.67×10^{-8}	2.76	28.8
X65, $f=0.1$ Hz	4.01×10^{-10}	4.34	9.72×10^{-6}	1.36	40.3
X65, $f=0.01$ Hz	8.79×10^{-11}	4.58	4.15×10^{-7}	2.17	62.0
Unit	-	-	-	-	$\text{MPa} \cdot \text{m}^{1/2}$

Table 4. Parameters of ECA models for crack growth curves with $R < 0.5$ from BS7910 (2013)

Model	Stage 1		Stage 2		K_t
	C_1	m_1	C_2	m_2	
Simplified	2.30×10^{-12}	3	2.3×10^{-12}	3	-
Bilinear (mean)	3.0×10^{-14}	3.42	1.27×10^{-7}	1.30	1336
Bilinear (mean+2SD)	8.55×10^{-14}	3.42	1.93×10^{-7}	1.30	993
Unit	-	-	-	-	$N \cdot mm^{3/2}$ for da/dN in mm/cycle

Table 5. Prediction of simplified and bilinear models from BS 7910 (2013) and experimental results

Initial crack size (mm)	Crack growth curve	f = 1.0 Hz	f = 0.1 Hz	f = 0.01 Hz	Unit
1	Test	1.38×10^5	9.78×10^4	8.56×10^4	cycles
	Simplified model	2.98×10^4			cycles
	Conservatism	78.4%	69.6%	65.2%	-
	Bilinear model (mean)	1.67×10^5			cycles
	Conservatism	-21.0%	-70.5%	-90.4%	-
	Bilinear model (mean+2D)	6.37×10^4			cycles
	Conservatism	53.8%	34.9%	25.6%	-
4	Test	6.00×10^4	3.10×10^4	2.63×10^4	cycles
	Simplified model	1.23×10^4			cycles
	Conservatism	79.6%	60.5%	53.4%	-
	Bilinear model (mean)	5.77×10^4			cycles
	Conservatism	3.83%	-86.2%	-119%	-
	Bilinear model (mean+2D)	2.54×10^4			cycles
	Conservatism	57.7%	18.1%	3.55%	-
12	Test	3.04×10^4	1.55×10^4	8.14×10^3	cycles
	Simplified model	4.83×10^3			cycles
	Conservatism	84.1%	68.8%	40.7%	-
	Bilinear model (mean)	2.23×10^4			cycles
	Conservatism	26.7%	-44.0%	-174%	-
	Bilinear model (mean+2D)	1.30×10^4			cycles
	Conservatism	57.4%	16.3%	-59.1%	-

Figure 1. Comparison between model prediction (BS 7910, 2013) and experimental data

Figure 2. Corrosion fatigue behavior patterns: (a) Type A; (b) Type B; (c) Type C. (Note: Diagrams are plotted in log-scale)

Figure 3. Corrosion fatigue crack evolution

Figure 4. Prediction of transition SIFs for X65 under CF with various load frequencies

Figure 5. Crack growth curves of X65 under CF with various load frequencies

Figure 6. Geometry and the geometry function of the single-edge notched specimen

(a) (b)
Figure 7. CF crack curves for X65 steels with initial crack size $a_i = 1$ mm: (a) Crack growth; (b) Crack evolution.

(a) (b)
Figure 8. CF crack curves for X65 steels with initial crack size $a_i = 4$ mm: (a) Crack growth; (b) Crack evolution.

(a) (b)
Figure 9. CF crack curves for X65 steels with initial crack size $a_i = 12$ mm: (a) Crack growth; (b) Crack evolution.

Figure 10. Load frequency effect on CF life prediction for X65 steels under various initial crack sizes

Figure 11. Prediction by ECA models for CF life of X65 steels with various initial crack sizes

(a)

(b)

(c)

Figure 12. Comparison of life prediction for X65 under various load frequencies

Highlights

- An extended ECA was developed, in which a critical stress intensity factor (SIF) was proposed to improve the traditional ECA for steel structures in seawater.
- The influence of load frequency and initial crack size on the model selection for the ECA of marine structures subjected to CF was investigated.
- The extended ECA provides a reasonable assessment with significantly reduced conservatism in contrast to the traditional ECA.