Fatigue Life Prediction of Corroded Specimen

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Abstract: A new methodology of fatigue life prediction for corroded specimens is proposed in this paper based on an equivalent initial flaw size (EIFS) methodology and a corrosion pit growth function. The proposed EIFS methodology is based on the Kitagawa diagram and the El Haddad model. Life prediction for smooth specimens is performed by employing the crack growth analysis starting from an assumed crack size determined by the EIFS. A growing semi-circular notch is assumed to exist on the specimen surface caused by the corrosive environments. An asymptotic solution is used for the stress intensity factor solution of a crack at the notch root. Fatigue life can be predicted using the crack growth analysis, in which a crack propagates from the notch root. Various experimental data for aluminum alloys and steels are used to validate the proposed methodology.

1. Introduction

It is well known that corrosion introduces corrosion pits on the specimen surface and fatigue cracks usually initiate at and propagate from these pits. During the service life of a rotorcraft or aircraft structure, it experiences corrosive environments between flights and fatigue cyclic loading during flights [1]. The effect of the “pre-corrosion” environments between flights on the structural integrity is a critical issue for the damage tolerance design and analysis and need to be carefully investigated. It has been reported that “pre-corrosion” reduces the fatigue life of aluminum alloys [1-4] and also on steels [4, 5]. Active corrosion is a more complicated process, during which both corrosion pits and fatigue crack grows. Active corrosion fatigue life is the combination of corrosion and fatigue. The key point for pre-corrosion and active corrosion life prediction is how pit grows under these two conditions.

Several methodologies have been proposed to model the effect of corrosion on the material surface. Henshall [6] developed a computer model, which can successfully simulate the pits initiation, growth and cessation depending on time and environment. Statistical model is another method to simulate pit growth kinetics. Some factors including solution temperature and electrolyte composition do big effects on pitting formation. Park and Pyun [7] claimed that statistical variation of time to pit formation rate has been neglected and needs to be paid attention to. Goddard Hp[8] found that the depth of corrosion pit of unstressed aluminum alloy in water can be written as an exponential function of time:

$$d(t)=At^B \tag{1}$$

where t is exposure time, A and B are parameters related to corrosion process. W.Zhang [9] verified this model for AA2024 by forcing $B=0.5$. Kondo [10] proved the applicability of the equation by carrying out corrosion fatigue test on low alloy steels, 2.5Ni–Cr–Mo–V and 3.5Ni–Cr– Mo–V, in ion-exchanged water at 363 K. The parameter B equals to 0.33 in that equation. Nakajima and Tokaji et al. [11] performed a test on carbon steel, JIS S45C, in 3% NaCl aqueous solution. They found the constant A is a function of stress amplitude and B is a number between $0.2-0.22$. Valor [12] built a new stochastic model which can be used to simulate the pitting corrosion, which combines two stochastic process: pit initiation and pit growth.

Most of the researchers considered the corrosion pit as an initial crack on the surface. Sankaran et al [1] followed this assumption and used the commercial software AFGROW to predict the fatigue life of corroded specimen of Al 7075. Bray et al [13] performed crack growth analysis for Al 2024 and Al 2524 alloys. Nan [14] also perform corrosion fatigue life prediction for AZ31 by dividing the whole range in two pars: one is the corrosion initiation period and the other is the crack growth until failure.

However, due to the complex geometries of corrosion pits, such as aspect ratio and corner sharpness, modeling corrosion pit as an initial crack may not satisfy the requirement of a crack in the fracture mechanics, i.e. mathematically sharp crack. In this paper, a general fatigue life prediction methodology for corroded specimens is proposed, in which the effect of pre-corrosion and active corrosion is modeled as a notch on the specimen surface. Different pre-corrosion conditions will introduce different notch depth. An initial crack with length of the characteristic crack length determined by the fatigue limit of smooth specimen and the long crack threshold stress intensity factor range of the material is assumed to locate at the notch root and the crack analysis can be used to predict the fatigue life. Plasticity correction factor is included into the proposed methodology for both medium cycle and high cycle fatigue analysis.

This paper focuses on life prediction for both pre-corrosive and active corrosive specimen and is organized as follows. First, a life prediction methodology using fracture mechanics-based crack growth analysis is briefly discussed, which has been proposed for smooth specimens. Following this, an asymptotic solution for cracks at the notch root is introduced for notch crack growth analysis, which will be used for fatigue life prediction of corroded specimens. Then pit growth rate has been presented as a couple function of time and crack length. Methodology for corrosion life prediction has been proposed considering the pit as an initial notch. Next, a wide range of experimental data for Al 7075 and Steel 4340 are collected and compared with model prediction to validate the proposed methodology. Finally, several conclusions are drawn based on the obtained results.

2. Life prediction methodology

2.1 EIFS concept

A life prediction methodology using the Equivalent Initial Flaw Size (EIFS) concept has been developed. The procedures are summarized below. Detailed derivation and explanation can be found in [15]. Including the stress ratio effect, the material growth curve can be expressed as

$$da/dN = F(\Delta K) = ab^{R}(\Delta K - \Delta K_{th})^{m} \tag{2}$$

Where R is stress ratio, a, b, m and ΔK_{th} are fitting parameters. m controls the slope in the Paris regime. ΔK_{th}, is the threshold stress intensity factor estimated using a back-extrapolation method. It is also a function of the stress ratio and can be expressed as

$$\Delta K_{th} = (10^{-10}/a/b^{R})^{1/m} \tag{3}$$

For the high-cycle fatigue and VHCF problem of smooth specimen, ignoring unstable crack growth part will not result in significant error, because most of the fatigue life is spent in the near threshold crack growth. In the current study, the critical length a_c is assumed to be a constant. a_i is the EIFS and can be determined by Eq.(4), where Y is a geometry correction factor and depends on the crack configuration. $\Delta\sigma_f$ is the fatigue limit stress.

$$a_i = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_f Y}\right)^2 \tag{4}$$

In the proposed study, a semi-circular surface crack is assumed. The geometry correction factor for a surface crack can be expressed as [16-18]:

$$Y = \left[\frac{\left(\sin^2\phi + \left(\frac{a}{c}\right)^2\cos^2\phi\right)^{\frac{1}{4}}}{E(k)}\right]M_f \tag{5}$$

where a is the depth and $2c$ is the surface length of a semi-elliptical flaw. The term in square brackets represents the solution to the equivalent embedded elliptical flaw. The parameter Φ is the angle in the parametric equation of ellipse and $E(k)$ is complete integral of the second kind. M_f is the correction factor.

2.2 Plastic modification of EIFS

The above discussion is for elastic analysis and is appropriate for very high cycle fatigue analysis, in which materials are usually remaining elastic during the entire fatigue life. For medium and low cycle fatigue problems, materials will experience some plastic deformation. Elastic analysis is not sufficient for fatigue life prediction. To include the effect of plastic deformation, an elastic-plastic analysis using BCS model [19] is performed. Wilkinson [20] derived cyclic reversed plastic zone size also. It should be noted that Wilkinson's result is similar to Dugdale's model using continuum mechanics with elastic-perfect plasticity model. A modification is proposed as

$$\rho = a(sec\frac{\pi\sigma_{max}(1-R)}{4\sigma_0} - 1) \qquad (\quad \sigma_o = R_{HS}\sigma_y \quad) \tag{6}$$

Where ρ is the plastic zone size using dislocation theory, σ_o is the cyclic yielding strength, which represents the fatigue strength when the cycle number is one. R_{HS} is the hardening modification factor. The equivalent crack length a' considering plastic correction can be expressed as

$$a' = a + \rho \tag{7}$$

3. Asymptotic solution for SIF considering notch effect

Stress intensity factor (SIF) solution is required for fatigue crack growth and life prediction using the fracture mechanics-based approach. An asymptotic solution is used proposed in this study for notches. Jergeus [21] and Harkegard [22] proposed an asymptotic interpolation method for SIF solution of the crack at the notch root of an edge notched specimen. A similar approach was proposed by Wormsen [23]. All these approaches assume that the crack locates at an edge notch in a semi-infinite plate. The general idea is to match two extreme cases. One is for the short crack solution and the other is for the long crack solution. The SIF formula asymptotically matches these two extremes and the SIF solutions between these two extremes are interpolated. We first illustrate this approach assuming a through crack on the surface of an edge notch in a semi-infinite plate. Detailed derivation and verification of the asymptotic interpolation can be found in [23]. The general formula for the SIF solution is expressed as

$$K = 1.122\sigma\sqrt{\pi(a + d\{1 - \exp[-\frac{a}{d}(K_t^{\ 2} - 1)]\})} \tag{8}$$

where a is the crack length , d is the notch depth, and K_t is the stress concentration factor. 1.122 is the surface correction factor. The SIF solution (Eq. (8)) under several extreme conditions is discussed in [15]. A finite dimension correction factor of notched specimen is introduced to modify Eq. (8) as

$$K = 1.122\alpha\sigma\sqrt{\pi(a + d\{1 - \exp[-\frac{a}{d}(\frac{K_t^{\ 2}}{\alpha^2} - 1)]\})} \tag{9}$$

where α is the correction factor for an edge crack with length of *(a+d)* in a finite dimension specimen. The function of α can be found in the handbook of stress intensity factor solution for commonly used specimen types, such as those listed later in this paper. If the function is not readily available in the literature or textbook, numerical methods, such as finite element method, can be used to obtain this function.

4. Prediction for pre-corrosion and active corrosion fatigue life

4.1 Pre-corrosion fatigue life prediction

Notch fatigue life prediction methodology discussed in part 3 can be used for corroded specimens. Damage tolerance analysis assumes all materials contain initial defects (voids, inclusions, surface scratches and roughness, etc.). Environmental effects, such as corrosive pits, foreign object impact scratches and pits, etc, will change the initial damages, for example, exfoliation will scatter the depth on the surface [24]. This type of initial damage can be considered as notch on the surface, which leads to a reduced fatigue life. If all these damages can be represented by an equivalent surface notch, the proposed methodology can be used to predict the fatigue life under detrimental environments.

An assumption is introduced that corrosive environments will introduce an initial semi-circular notch with size d_e, which depends on the time and intensity of the corrosive environments and is obtainable from the following equation:

$$d_e = \alpha t + \beta \tag{10}$$

In this equation the parameter α is crack initiate rate, and β is material micro notch depth, therefore the initial notch depth has a linear relationship with time t. It is noted that the introduced equivalent initial notch represents the detrimental effects of the pre-corrosion. It is only a parameter to correlate with the fatigue life using the proposed life prediction methodology. And fatigue life of specimen is predicted by assuming the crack is propagated till the final fracture.

The general formula for the SIF solution Equation (8) can be rewritten as:

$$K = 1.122\sigma\sqrt{\pi(a + d_e\{1 - \exp[-\frac{a}{d_e}(K_t^{\,2} - 1)]\})} \tag{11}$$

Once the stress intensity factor solution is obtained for corrosive specimen, the life prediction can be performed following the methodology described as

$$N = \int_{a_i}^{a_c} \frac{1}{ab^R\left[\Delta K - \Delta K_{th}\right]^m} da \tag{12}$$

4.2 Active corrosion fatigue life prediction

It is common to perform corrosion fatigue test in a corrosive solution, and the equivalent initial notch depth

$$d_e = \alpha t + \beta = \alpha(N/f) + \beta \quad (13)$$

N is fatigue life and f is frequency of loading. In our preliminary research about active corrosion, we neglect loading effect on equivalent initial notch depth. d_e is still regarded as a linear function of time *(t)*, as shown in Eq. (13). Here a critical notch depth d_c is introduced; t_c is the corresponding time of d_c. When t is zero, the initial micro notch depth is β. If the loading is not big enough, in another word, the stress intensity factor $\Delta K < \Delta K_{th}$, crack does not grow, but micro notch depth d_e grows; when d_e is larger than d_c, $\Delta K > \Delta K_{th}$, crack grows from time t_c as well, the relation between crack and equivalent notch depth follow the line in the fig. 1 (b) ; for the other situation, loading is big enough and crack grows once loading added on specimen, just follow fig. 1 (a).

The general formula for the SIF solution Equation (8) can be rewritten as:

$$\Delta K = g(a,N) = 1.122\Delta\sigma\sqrt{\pi(a + (\alpha N/f + \beta)\{1 - \exp[-\frac{a}{\alpha N/f + \beta}(K_t^{\,2} - 1)]\})} \quad (14)$$

The material growth curve Equation (2) can be rewritten as a function of crack length (a) and fatigue life (N):

$$da/dN = F(\Delta K) = F(g(a,N)) \quad (15)$$

Equation (15) is the equation of crack length and fatigue life. Fatigue life can be gained by integrating Eq. (15) from the EIFS to the final critical crack size.

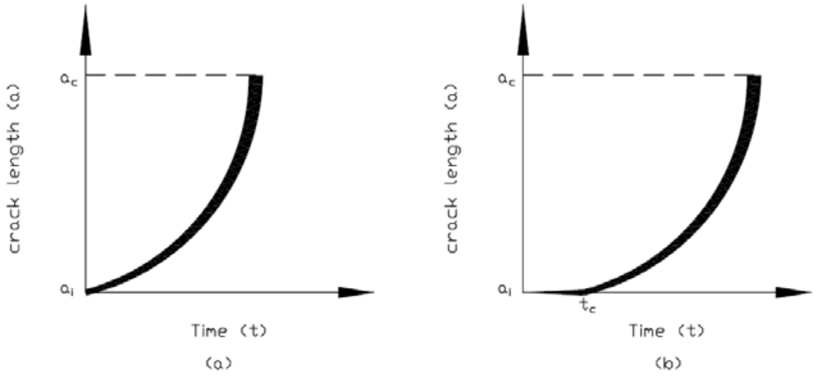


Fig. 1 crack length verse equivalent notch depth

5. Validation for corroded specimens

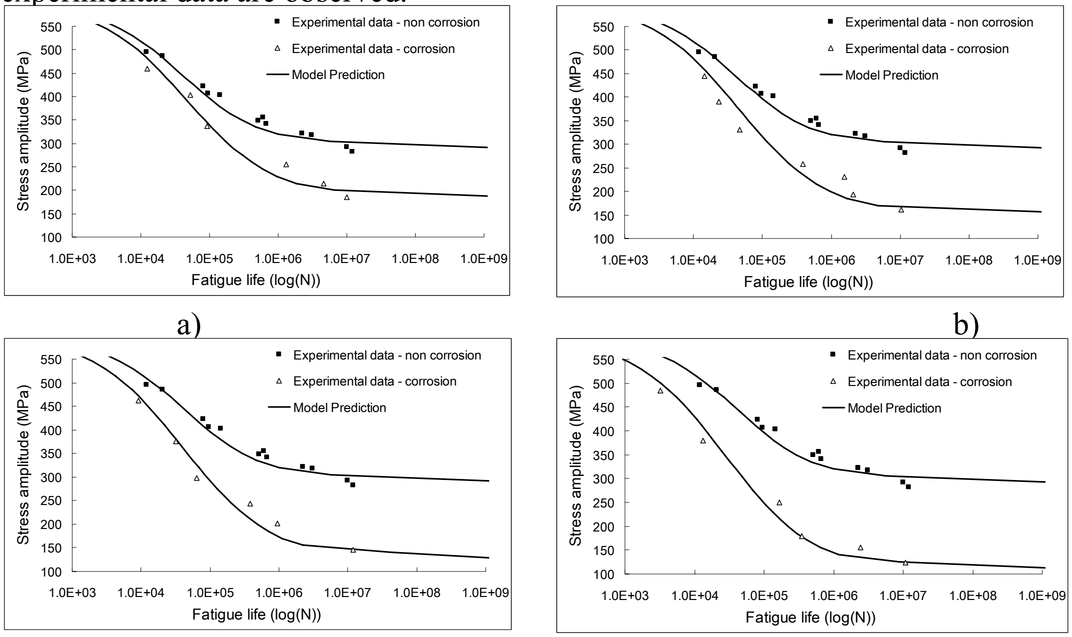
5.1 Validation for pre-corroded specimens

Experimental data on fatigue SN testing are collected for two materials under different corrosive conditions and different stress ratios. A summary of the experimental data is shown in Table. 1. In order to perform the crack growth analysis, crack growth rate curve is required has been collected from the FAA-FCGD data base for Al 7075-T6 and steel 4340.

Table 1. Summary of experimental data collection

Material	Corrosion conditions	Stress Ratio	α	β	References
Al 7075-T6	3.5% NaCl solution	R = -1	6e-7	-3e-6	[2]
Al 7075-T6	dilute electrolyte cyclic fog–dry spray	R = 0.02	5e-8	3e-6	[1]
Al 7075-T6	3.5 wt% NaCl solution	R = 0.1	——	——	[3]
Al 7075-T6	Salt fog to 2 mL/h of 5 ±1 w% NaCl	R = 0.1	6e-8	9e-6	[4]
Steel 4340	Salt fog to 2 mL/h of 5 ±1 w% NaCl	R = 0.1	2e-8	3e-21	[4]

Genel [2] performed experimental investigation on fatigue performance of both corroded and non-corroded specimens of 7075-T6 alloys. Corroded specimens were performed by immersing the samples in 400 ml of 3.5% NaCl solution for 6, 48, 96 and 240 h, respectively. S-N curves for corroded and non-corroded specimens are shown in Fig. 2 together with model prediction. It is noted that in each model prediction, the initial notch depth is calculated using equation (13) and finite life prediction is performed using the methodology described in Sections 4.1. An overall very good agreement between the model predictions and experimental data are observed.



a) b)

c) d)

Fig. 2 Comparison of experimental observations and model predictions for 7075-T6

Corrosion duration of a) 6h; b) 48 h; c) 96h; d) 120 h

5.2 Validation for active specimens

John.T [25] performed active corrosion experiment by wrapping a specimen with chemical-free tissue, which functions as a wick to maintain the salt solution in contact with the specimen. The tissue was saturated with 3.5-wt% NaCl solution. To avoid evaporation, it is sealed with polyethylene film and vinyl.

Fig. 3 shows comparison of experimental observations with model predictions for Al 7075 under active condition in 3.5% NaCl solution. Equivalent notch depth growth rate is 8e-8 and β is 2.573e-6. In very high cycle fatigue life, especially when fatigue life is larger than 1e5, model prediction match quite well with experimental data; however, when stress range is larger than 220 MPa, model prediction shows a little elastic trend. From the experimental data, a big drop of fatigue life can be seen when stress range is larger than 220 MPa, which corresponds to fatigue life larger than 1e5 cycles, however, there is no big difference between non-corrosion and active corrosion fatigue life when stress range is larger than 220 MPa, corresponding to fatigue life less than 1e5 cycles. This phenomenon can be explained by our proposed methodology. When stress range is smaller than 220 MPa, stress intensity factor is smaller than threshold ΔK_{th}. Then equivalent notch depth increase with fatigue life but crack does not grow, until notch depth reaches d_c. This process does big effect to the whole fatigue life. However, when stress range is larger than 220 MPa, crack grows once load added on the specimen. When fatigue life is 1e5 cycles, the total time of active corrosion is about 10 hours, which is very short to form a big notch on the surface. Therefore, the notch caused by active corrosion is not big issue for the whole fatigue life; the specimen under active corrosion performs no big difference with that under non-corrosion condition, the same trend shown in Fig.3.

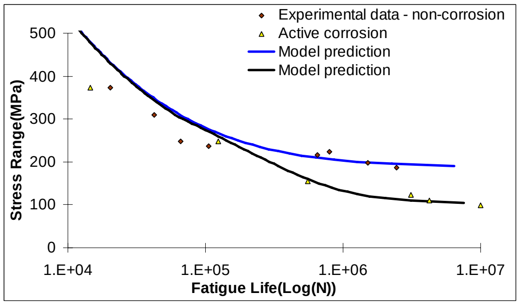


Fig. 3 Comparison of experimental observations and model predictions for Al 7075 under active condition

6. Conclusion

In this paper a general methodology for life prediction for both pre-corroded and active corroded specimens using notch crack growth analysis is proposed. This methodology is based on an asymptotic notch stress intensity factor solution and an assumption that the corrosive effect can be modeled as an initial semi-circular notch on the specimen surface. The fatigue life of both corroded and non-corroded specimens is predicted using the proposed methodology and compared with a wide range of experimental data available in the literature. Several conclusions can be drawn as below:

1. Corrosive environments have significant detrimental effects on the fatigue strength, which appears to be a highly non-linear function of the corrosion

duration. The initial reduction as the corrosion duration increases from zero, which indicates that a small amount of corrosion exposure can lead a large decrease of fatigue life.

2. Growth rate of equivalent notch depth is assumed as a linear function of time for pre-corrosion condition. For AL 7075, the growth rate A is a value between 1e-8 ~6e-7 m/h (1.5e-10 ~ 9e -11m/s) under different pre-corrosion condition. The growth rate for steel 4340 is 2e-8 m/h (3e -11m/s) under salt fog condition.
3. A good match has been got between experimental data and model prediction especially at very high cycle regime for Al 7075 under active condition. Linear relationship between equivalent notch depth and time t works well for very high cycle regime, but a little elastic for medium cycle regime.

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