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THREE-DIMENSIONAL FATIGUE FRACTURE IN COMPLEX ENVIRONMENTS

W. Guo[1,2]   Ping Wang[2]

[1]Departmant of Aircraft Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, 210016, CHINA
[2]Key Laboratory of Mechanical Structural Strength and Vibration, Xian Jiaotong University, Xian, 710049, CHINA

ABSTRACT

Some important problems in fatigue fracture of metal materials and structures under complex loading conditions and corrosion environments are analyzed on the basis of three-dimensional (3D) elastic-plastic fracture theory and experimental results. Special emphases are given for corrosion fatigue crack growth which is shown to be independent of stress ratio and geometry of specimen when represented by use of the three-dimensional theory. A 3D method for fatigue life prediction was established and life prediction under spectrum loading in corrosion environment can then be performed without requirement of any empirical parameter or extra-parameter to be determined by no standard tests. The prediction of whole fatigue life of structures and the calendric life of machines are discussed along this line. The efforts have been made in this direction by the fatigue fracture community in China are addressed briefly.

KEYWORDS

Three-dimensional constraints, fatigue crack growth, corrosion fatigue, life prediction, calendric life

INTRODUCTION

Fatigue fracture of structures is always analyzed or predicted on the basis of standard material test data obtained in laboratory. From standard specimens to real structures there exist significant differences in geometry configuration, size, stress state, loading configuration as well as environmental factors. Therefore, the reliability of the analysis and prediction is determined by the ability of the applied theory to eliminate these differences. Some of the efforts we have made in this direction are introduced in this paper and researches of the fatigue fracture community in China are addressed briefly.

THEORETICAL FUNDAMENT

For ideally two dimensional sharp crack, the near tip stress field in strain hardening material can be obtained from the HRR solution and the recently developed *J-Q* theory or higher order solutions[1]

$$\sigma_{ij} = \left[\frac{J}{\alpha\varepsilon_0\sigma_0 I(n) r}\right]^{1/(n+1)} \tilde{\sigma}_{ij}(\theta) + Q\delta_{ij} \cdot \tag{1}$$

3D studies show that crack tip fields are not only dependent on J-integral and in-plane constraint, but also dependent on out-of-plane constraint and in the case of $\partial Tz/\partial z < \infty$, a *J-$T_z$-$Q_T$* description can be proposed [2]

$$\sigma_{ij} = \left[\frac{J}{\alpha\varepsilon_0\sigma_0 I(n,Tz) r}\right]^{1/(n+1)} \tilde{\sigma}_{ij}(\theta, Tz) + Q_T\delta_{ij} . \tag{2}$$

Here, the *x-y* or *r*-θ plane is coincided with the normal plane at any point P of the crack front line, z is along the tangent line of the crack front and *y* perpendicular to the crack plane at P. Then the constraint in the *x-y* plane is the in-plane constraint that can be determined by the *K-T* or *J-Q* theory. The out-of-plane constraint in *z*-direction can be expressed by $T_z=\sigma_{zz}/(\sigma_{xx}+\sigma_{yy})=\sigma_{zz}/(\sigma_{rr}+\sigma_{\theta\theta})$. In the front of through cracks or notches in finite thickness plate under mode I loading, empirical expression of T_z has been obtained in [2] and [3] respectively.

For a through cracked plate with thickness of $B=2h$, the average tensile stress in the plastic zone ahead of the crack can be expressed as $\sigma_{yy}=\alpha_s\,\sigma_{ys}$ in a ideally-plastic material obeying Von Mises rule with the stress constraint factor

$$\alpha_s = \frac{1}{\bar{r}_p B}\int_{-h}^{h}\int_0^{r_p} \frac{\sigma_{ys}}{\left[(1-T_z+T_z^2)(1+k^2)-(1+T_z-2T_z^2)k\right]^{1/2}} drdz \, . \tag{3}$$

Where, $k=\sigma_{xx}/\sigma_{yy}$ is dependent on the in-plane constraint *T* or *Q*, σ_{ys} is the yield stress, r_p is the plastic zone size and $\bar{r}_p$ is the through-thickness average of r_p. α_s is found to be a function of $\bar{r}_p/B$ and for strain hardening material of *n* as well. In plane stress state, $T_z = 0$, $k = 0.5$ and $\alpha_s=1.155$ in perfectly plastic solution. In plane strain state, $T_z = 0.5$, $k = 0.611$ and $\alpha_s=2.97$ in the perfectly plastic solution.

In corrosion environment, the influence factors on fatigue crack growth are complex. Generally, material degradation caused by the corrosion and the change in effective driving force for crack growth caused by fatigue crack closure are the most important factors. For aluminum alloys, it has been shown that the corrosion environment has no effect on fatigue crack closure [4]. Thus the effective stress intensity factor can be obtained as in laboratory ambient.

It has been proven that plasticity induced fatigue crack closure is dominated by a combining constraint factor α_t [5]:

$$\frac{\alpha_t}{\beta} = \frac{\mu\pi}{(\kappa+1)\beta\sigma_{ys}}\frac{\delta_0}{r_p} . \tag{4}$$

Where, μ is the Lame constant, $\kappa = \frac{3-\nu-4\nu Tz}{1+\nu}$, β is the stress constraint factor in the reverse yield zone, δ_0 is the crack tip opening displacement. By use of the 3D constraint theory and the Budiansky-Hutchinson model it can be obtained that [5]

$$\frac{K_{open}}{K_{max}} = 1 - \frac{1}{\pi}\int_0^{\eta} \frac{f_1(\xi) - f_2(\xi)}{\sqrt{\xi}} d\xi \,, \tag{5}$$

where f_1 and f_2 are known functions and η is a parameter which can be determined as a function of stress ratio R and α_t/β by the following equation set,

$$\begin{cases} R\pi = \dfrac{\beta\pi}{2\alpha_t}\displaystyle\int_0^{\eta}\sqrt{\frac{\eta-\xi}{\xi(\xi-\gamma)}}d\xi + \int_{\eta}^{1}\sqrt{\frac{\xi-\eta}{\xi(\xi-\gamma)}}f_1(\xi)d\xi \\ R\pi = -\dfrac{\beta\pi}{2\alpha_t}\displaystyle\int_0^{\eta}\sqrt{\frac{\xi-\gamma}{\xi(\eta-\xi)}}d\xi + \int_{\eta}^{1}\sqrt{\frac{\xi-\gamma}{\xi(\xi-\eta)}}f_1(\xi)d\xi \end{cases} . \tag{6}$$

Solve the integral equations (5) and (6) and fitting the results can lead to an empirical expression of the opening stress ratio:

$$\frac{K_{open}}{K_{\max}} = 1 - \sqrt[3]{\eta} \tag{7}$$

$$\eta(R,\alpha_t) = (1-R^2)^2(1+10.34R^2)\left[(1+1.67R^{1.61}) + \frac{\beta}{0.15\pi^2\alpha_t}\right]^{-4.66} . \tag{8}$$

For a large range of β/α_t ($1.0 < \beta/\alpha_t < 3.0$) and $R \geq 0$, the fitting error of expression (7) and (8) is less than about 3%. For R<0, a linear relationship between the opening stress ratio and R can be assumed.

Under small scale yielding condition, $\alpha_s \approx \alpha_t$. Assume β=1 and $\alpha=\alpha_t=\alpha_s$, it can be found that the expression (7) and (8) coincides very well with Newman's empirical equation of crack closure [6]. So that Newman's equation is a special case of the present solution. When R<0, Newman's equation can be used.

Consequently, under small scale yielding condition the fatigue crack growth rate can be expressed as a function of equivalent stress intensity factor range

$$\Delta K_{eff} = (1 - K_{open} / K_{\max})K_{\max} \,, \tag{9}$$

or

$$\frac{da}{dN} = \begin{cases} f\left(\Delta K_{eff}\right) & \text{for} \quad \Delta K_{eff} > \Delta K_0 \\ 0 & \text{for} \quad \Delta K_{eff} \leq \Delta K_0 \end{cases} . \tag{10}$$

Where, ΔK_0 is a material constant.

MATERIAL BASE LINE FOR CRACK PROPAGATION

Material Base Line in Laboratory Ambient

Life prediction is always based on the da/dN-ΔK test curve under constant amplitude loading with standard specimens. This curve changes with stress ratio as well as specimen thickness and is not a material base line as shown in Figure 1. In the figure the da/dN-ΔK curve is obtained from standard compact tension specimens of 2mm and 10mm-thickness machined from a thick LY12-CZ aluminum mother plate. To avoid other influence factors the specimens take from the same position of the mother plate and have the same in-plane geometry with width of 60mm. When ΔK_{eff} obtained from the above 3D closure model is used a unique da/dN-ΔK_{eff} is obtained for both thicknesses. Such da/dN-ΔK_{eff} curve is also independent of stress ratio so that it can serve as the material base line for fatigue crack propagation.

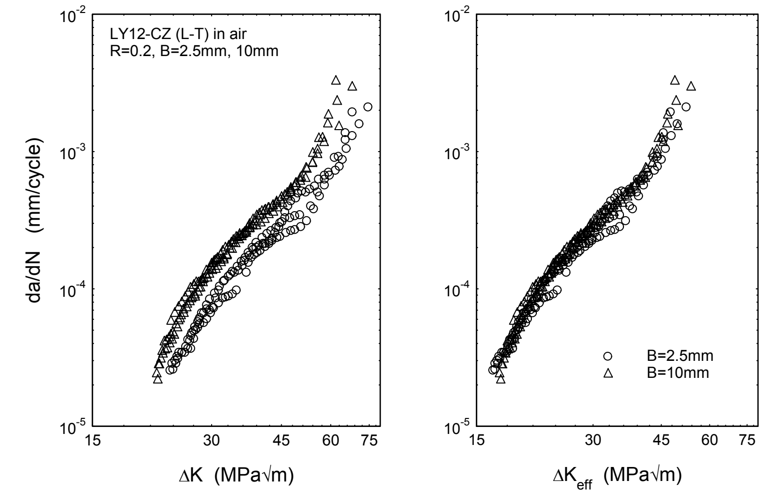
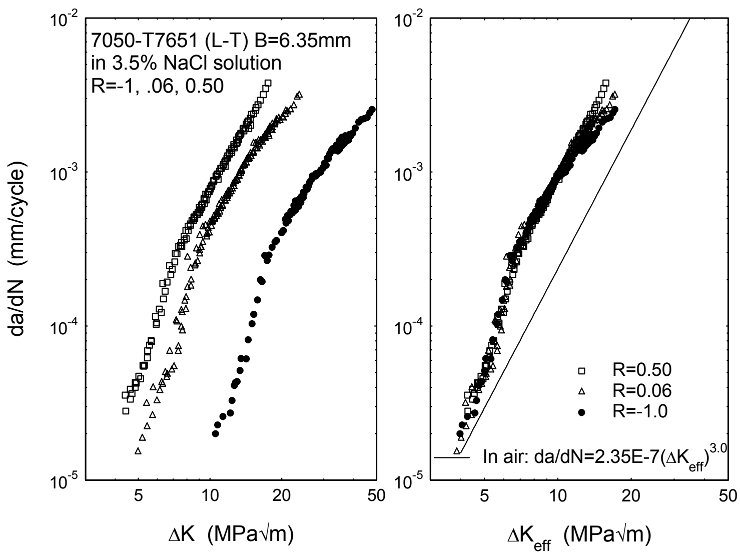


Figure 1: Effect of thickness on fatigue crack growth of LY12 aluminum alloy

Material Base Line for Corrosion Fatigue Crack Growth

Corrosion fatigue curve of da/dN-ΔK is generally higher than that in laboratory ambient and changes with the combination of material-environment-loading-geometry. When the above theory is used the da/dN-ΔK_{eff} curve become independent of loading and geometry parameters and unique for given combination of material-environment. In Figure 2 some typical results are presented for an aluminum alloy. It is shown that corrosion fatigue crack closure can be explained very well by plasticity-induced closure theory.

Figure 2: Effect of stress ratio on corrosion fatigue crack growth curve of 7050 aluminum alloy



For Al-alloys and Ti-alloys, the effects of frequency is very weak and the expression (10) can be used for given material-environment system. In steels, however, corrosion fatigue crack growth is very sensitive to loading frequency. As the plasticity induced crack closure will not change with frequency (λ), so the da/dN-ΔK_{eff} curve is still free from the stress ratio and geometry. So the crack propagation rate can be expressed in form of variable separation

$$\frac{da}{dN} = \begin{cases} f\left(\Delta K_{eff}\right) \times f_H(\lambda) & \text{for} \quad \Delta K_{eff} > \Delta K_0 \\ 0 & \text{for} \quad \Delta K_{eff} \le \Delta K_0 \end{cases}. \tag{11}$$

$f_H(\lambda)$ can be determined by experiment.

CORROSION FATIGUE LIFE PREDICTION UNDER SPECTRUM LOADING

Service life of structures can be reduced in corrosion environment mainly for two reasons: reduction of initiation life of a micro-crack by corrosion pitting and rise in crack propagation rate as shown above. The former influence can be represented by a large initial crack size a_0, while the later can be simple predicted by use of the corrosion fatigue crack growth base line (10) or (11). The effective initial crack size $a_{0\mathrm{eff}}$ in corrosion environment is a function of time that has to be determined by experiment or survey of aging structures. $a_{0\mathrm{eff}}$ is a statistic parameter having close relation with materials, environments, lasting time, interaction of environment and mechanical loading, *et al.*

As the plasticity induced crack closure is not affected by the corrosion environment, load interaction in spectrum corrosion fatigue caused by plasticity can be predicted by the plasticity-induced crack closure model. By use of the corresponding corrosion fatigue curve of da/dN-ΔK_{eff} and the modified FASTRAN-II life prediction code [6], the initial defect size dependent limit stress-life (S_L-N) curve of an aluminum alloy in sump-tank water under fighter spectrum is predicted and the results are presented in Figure 3. In the bi-logarithm coordinates the S_L-N curve is shown to be a linear line for different a_0.

Experiments have been performed on fastener specimens of 7475-T761 aluminum alloy in 3.5% NaCl solution under another kind of fighter spectrum. Specimens with straight hole as well as 90° dimple rivet hole are tested by MTS880 system. It is found that crack initiation always occurs at the intersected corner of the dimple with the hole in form of corner crack in the rivet hole specimen. Stress intensity factor for this kind of crack is calculated by 3D finite element code of ANSYS®. The present life prediction method and the da/dN-ΔK_{eff} curve of long crack of the material in the same environment are used to calculate crack growth life. When the initial defect size a_0 are determined in air and the salt solution by use of the straight hole test data in a manner of trial-and-error, the same a_0 is used to predict the life of the rivet hole specimens. The experiment results as well as the predicted results are drawn in Figure 4. Pretty agreement between the experiment and predicted results can be found.

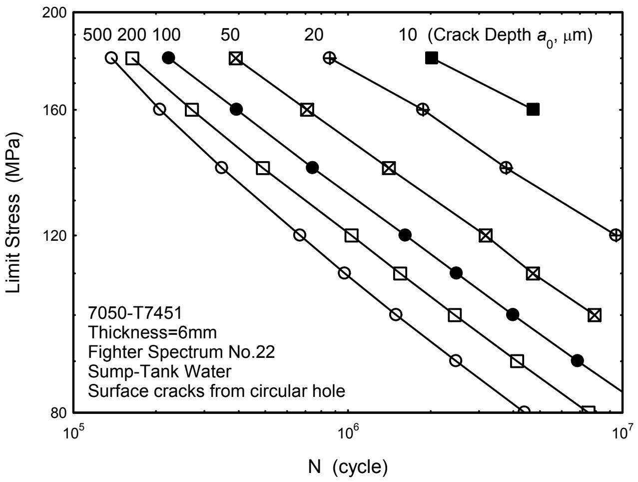


Figure 3: Effect of initial defect size on limit stress-life curve of 7050 Al in sump-tank water

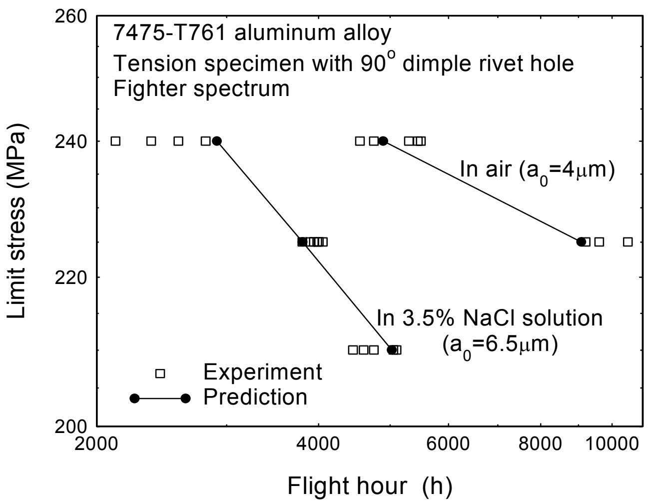


Figure 4: Life prediction for 7475-T761 under spectrum loading in air and 3.5% NaCl solution

It is shown that life of aluminum alloy can be remarkably reduced by the salt solution. The lower the stress level applied, the greater the reduction in life can be found. The initial crack size a_0 in the salt solution is also larger than that in air for the same material. From the viewpoint of life prediction, corrosion environments affect the structure by means of increasing both of the size of defects or corrosion pits and crack growth rate. The essential contents for life prediction in complex environments are illustrated in Figure 5.

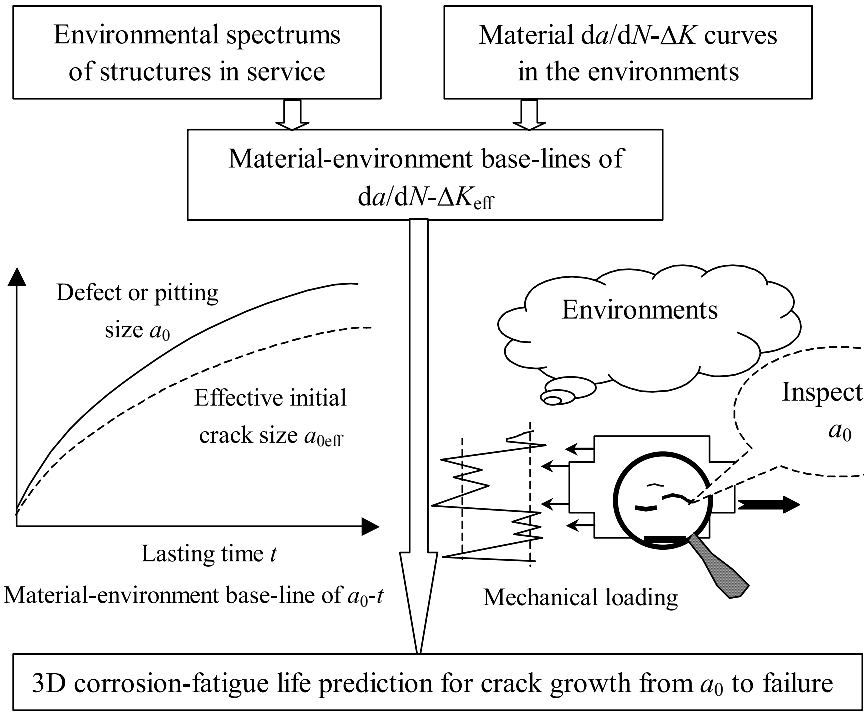


Figure 5: Illustration for life prediction in complex environments

The China community has paid great efforts toward solving the problem mainly in the following areas: 1) Compilation of environmental spectrums for mechanical systems used in different region of China and for different task. A wide range of environments has been surveyed. 2) Material degradation, especially reduction in fatigue strength in out-door air and other natural environments in different region of China has been studied for more than 20 years and it is shown that the reduction in fatigue strength in the first few years may be significant in some regions but the degradation rate slows down with time lasting. Structural materials for aircrafts, pipelines, sea structures and cars are studied extensively. Speeded simulation and damage equivalent study in controlled artificial environment in laboratory are important parts in the program. Inspection and survey of aging aircrafts, sea structures have been in processing. 3) Material base-lines for corrosion fatigue, creep fatigue are in accumulating. New materials and special details of structures such as welds and fasteners are widely studied. 4) Corrosion protection, repair and other surface engineering are studied and widely applied in both civil and defense engineering. 5) Based on these researches, calendric life of aircrafts and other important mechanical systems is intensively studied at present stage in order to extend the service life of aging structures.

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REFERENCES

1 O'dowd.N.P and Shih.C.F. (1991) *J. Mech. Phys. Solids* **39,** 989-1015.
2 Guo W. (2000) *Key Engineering Materials* **183,**193-198.
3 Li Z.H. and Guo W. (2001) *Int.J.Fract.* **107**, 53-71.
4 He B., He J. and Fan W. (1997) *J. Nanjing Univ. Aero-& Astronautics* **29**, 786.
5 Chang T. and Guo W. (1999) *Int.J.Fatigue* **21,** 881-888.
6 Newman J.C.Jr. (1992) FASTRAN-II. *NASA TM* 104159.