Engineering Fracture Mechanics 158 (2016) 209–219

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

A prediction model for fatigue crack growth using effective cyclic plastic zone and low cycle fatigue properties

K.K. Shi *, L.X. Cai, S. Qi, C. Bao

Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu 610031, China

A R T I C L E I N F O

Article history:
Received 12 January 2015
Received in revised form 25 February 2016
Accepted 26 February 2016
Available online 2 March 2016

Keywords:
Crack closure
Effective cyclic plastic zone
Fatigue crack growth
Low cycle fatigue
Plastic strain energy

A B S T R A C T

Since there exists the crack closure phenomenon near the fatigue crack tip, it has an important role in the analysis of fatigue failure life. Considering the empirical crack closure expression, the effective cyclic plastic zone is developed in the present study. According to the fatigue failure criteria of plastic strain energy ahead of the fatigue crack tip, a theoretical model for fatigue crack growth rate is then established based on the effective cyclic plastic zone and the low cycle fatigue properties. The prediction results are compared with experimental data under the constant amplitude loading, and comparative results demonstrate that the fatigue crack growth rate estimated by the theoretical model closely approximates the experimental results.

1. Introduction

Fatigue crack growth (FCG) rate experiments for many engineering materials show that the fatigue crack surfaces exist the crack closure phenomenon near the fatigue crack tip under the constant amplitude (CA) loading [1]. The crack closure behavior was first found by Elber [2,3] and the characterization of crack closure is required in the accurate analysis of fatigue crack growth rate. The interaction of crack surfaces leads to a decrease of the stress intensity factor (SIF) range in the vicinity of the crack tip and to an increase of the fatigue life. There are a vast amount of experimental, numerical and theoretical works supporting the existence of crack closure near the fatigue cracking front and its significant influence on the FCG rate. The crack closure can be motivated by many different physical mechanisms, including roughness or oxides on the fatigue crack surfaces, extensive experimental and computational works have shown that the crack wake plasticity is commonly the dominant contribution to the closure phenomenon [4].

A crack initiation occurs followed by the FCG behavior. The FCG rate is one of the most important issues during both the design process and the subsequent monitoring stage for a critical engineering component. It is well-known that the FCG rate is statistically acquired through a pure curve fit of finite experimental data. As suggested by Paris and Erdogan [5], the FCG rate $\log(da/dN)$ is approximately linear with the SIF range $\log(\Delta K)$ in the intermediate range.

It has been realized for a long time that the nature of plastic deformation was strongly influenced by the constraint condition of the crack tip. Under plane stress condition, the out-of-plane deformation is not constrained in the vicinity of the crack tip [6]. Then, material elements within the cyclic plastic zone (CPZ) would be viewed as an assemblage of uniaxial cyclic loading. Besides, the low cycle fatigue (LCF) properties would be regarded as the representative volume element (RVE) of

* Corresponding author. Tel.: +86 28 87600850; fax: +86 28 87600797.
E-mail addresses: shikai1000@163.com (K.K. Shi), lix_cai@263.net (L.X. Cai).

http://dx.doi.org/10.1016/j.engfracmech.2016.02.046
0013-7944/

Nomenclature

b	fatigue strength exponent
c	fatigue ductility exponent
E	elastic modulus
I	non-dimensional parameter of cycle strain exponent
K_c	cycle strain hardening coefficient
n_c	cycle strain hardening exponent (N_c=1/n_c)
N_f	failure life
r	distance from the crack tip
r_c	cycle plastic zone (CPZ)
U	crack closure factor
α_c	cycle Ramberg–Osgood parameter
λ, ω	parameters in Eq. (4)
ΔK	stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
$\Delta\varepsilon$	strain range
$\Delta\varepsilon_e$	elastic strain range
$\Delta\varepsilon_p$	plastic strain range
$\Delta\sigma$	stress range
ε_f'	fatigue ductility coefficient
ε_{yc}	cycle tensile yield strain
v	Poisson's ratio
ρ_c	critical crack blunting radius
σ_f'	fatigue strength coefficient
σ_m	mean stress
σ_{yc}	cycle tensile yield stress
$\widetilde{\sigma}_\theta$, $\widetilde{\sigma}_r$	non-dimensional distribution functions

Abbreviations

CA	constant amplitude
CPZ	cycle plastic zone
FCG	fatigue crack growth
FPZ	fatigue process zone
HRR	Hutchinson–Rice–Rosengren
LCF	low cycle fatigue
PSE	plastic strain energy
RVE	representative volume element
SIF	stress intensity factor

cyclic strain behavior. So, the FCG and the LCF are the fatigue failure behavior under the cyclic loading. Based on the relationship between the LCF properties and the crack tip field, a number of FCG models [7–12] were developed over the past few decades. It is worth noting that the suitable fatigue process zone (FPZ) and the reasonable fatigue failure criteria ahead of the crack tip, such as the fatigue ductility, the plastic strain energy (PSE) and the weighted local strain, are adopted. Besides, Schwalbe [13] discussed two analytical models, model-A and model-B, with considering the different cracking assumptions for the fatigue crack growth rate. For model-A, the crack tip opening displacement is regarded as the fatigue crack growth size per load cycle. For model-B, the high strain zone x^* is viewed as the fatigue crack growth size per load cycle. Considering the threshold value and the fracture toughness influence on the fatigue growth rate model, the two parameters are used to modify the model-B. In the present study, the threshold value is considered by associating with the critical blunting formula.

The LCF properties, the PSE failure criteria under the effective cyclic plastic zone, and the conception of crack closure near the crack tip are taken into account in the proposed FCG model. The theoretical model is verified by open-published thirteen experimental data and the agreement is found to be fairly good.

2. Cyclic stress and strain field

The Hutchinson–Rice–Rosengren (HRR) field [14,15] is commonly used to describe the stress and strain field in the vicinity of the crack tip under the 2D condition (plane stress and plane strain), in which the crack is subjected to the remote tension load or the remote shearing load. However, the accurate solution of cyclic stress and strain field is not available in the classical fracture mechanics theory and is required in evaluating the fatigue life. To estimate the response to unloading,