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A physically short fatigue crack growth approach based on low cycle fatigue properties

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ABSTRACT

This work proposes an improved and simplified fatigue life equation called LAPS, formulated from low cycle fatigue data of smooth specimens and the Rice-Kujawski-Ellyin asymptotic field, with proper crack opening functions for closure effects. The model captures both long and physically short fatigue crack growth behavior, but the emphasis of this contribution is on the modifications for physically short cracks based on empirical models found in the literature. The predictions for physically short cracks from this model coincide well with experimental data for the railway axle used steel 25CrMo4. The predictions for long cracks match well with data from a variety of different metals. This makes the model a suitable alternative, e.g. to NASGRO, for engineering applications.

1. Introduction

With increasing transport speed and capacity, progressive damage remains a concern in modern railway structures such as axles, brake discs, and the wheel truck [1–3]. However, nominal stress based infinite life design using stress-life (S-N) curve cannot adequately cope with this safety challenge. To ensure 30 years or more of safe service, railway axles therefore require strict monitoring and repair after inspections [2]. Damage tolerance approaches, as a very important complementarity to traditional nominal stress methods, have been recommended to evaluate the residual life and assess the resultant non-destructive testing interval [4].

One such damage tolerance approach is fatigue crack growth (FCG) modeling to describe the relationship between FCG rate, da/dN, and stress intensity factor range ΔK [5]. For instance, the NASGRO equation [6], which has been widely used in railway axles, can capture all three FCG rate stages by considering plasticity-induced crack closure (PICC) [7]. Recently, a modified NASGRO equation [8] was proposed to model physically short cracks (PSCs) [9,10] that can propagate even below the threshold SIF range (ΔK_{th}). Time-consuming and complex fracture toughness experiments are required to calibrate the model parameters. A preferable model would require fewer, simpler experiments.

This paper will employ a simplified and improved FCG rate model that uses information from the low cycle fatigue (LCF) response [11,12] and the Rice-Kujawski-Ellyin (RKE) [13,14] crack-tip stress-strain field, with very little recourse to parameters determined in terms of fracture mechanics. Naturally, it would be possible to make use of other crack tip fields such as the Hutchinson-Rice-Rosengren (HRR) field [15,16]; however the RKE allows us to base this model on a relatively small selection of readily available experimentally determined parameters. Modifications, based on some already made to the NASGRO model, will be made so this model captures PSC growth behavior, particularly relevant for high-speed railway axles. In order to verify this model, experimental fatigue cracking data for different engineering materials and stress ratios are compared to the model predictions.

The work is organized as follows: Section 2 will derive a FCG model with PICC effects. Section 3 adds modifications to account for physically small cracks. Section 4 presents comparisons to experimental results for physically short cracks for discussion and validation. Three appendices give: further detailed derivations (A), extended comparison with experimental results for a wide variety of load cases and engineering metals (B), and a MATLAB implementation of the model (C).

2. A LCF based FCG model with crack closure effect

Low cycle fatigue based models for long crack growth generally take the form:

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Nomenclature

da/dN	fatigue crack growth rate
ΔK	stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
U	portion of load cycle that crack is open
K_{IC}	Mode I fracture toughness
f	crack opening function
ΔN	cycles to penetrate the process zone
L_p	length of the process zone
C	cyclic constitutive parameters
C'	low cycle fatigue parameters
n'	cyclic strain hardening exponent
K'	cyclic strain hardening coefficient
ρ_{cb}	crack blunting radius
σ_{yc}	cyclic yield stress
ε_{yc}	cyclic yield strain
b	Coffin-Manson strain exponent
c	Coffin-Manson stress exponent
PSC	physically short crack
ε'_f	fatigue ductility coefficient
σ'_f	fatigue strength coefficient
σ_m	mean stress for Coffin-Manson
A_0, A_1, A_2, A_3	crack opening function fitting parameters
K_{max}	maximum SIF
Δa	crack extension for PSC
N	number of mechanisms for crack closure
a_0	initial crack length
a	crack length
l_i, v_i	fitting parameter for the i^{th} PSC mechanism
R	load ratio
K_{op}	SIF for fully open crack
Y	geometry factor for opening function
σ_{max}	stress at maximum load
σ_0	average of uniaxial and tensile strengths
α	constraint parameter for crack opening

Abbreviations

FCG	fatigue crack growth
SIF	stress intensity factor
PICC	plasticity-induced crack closure
LCF	low cycle fatigue

Subscripts

lc	long crack
in	intrinsic (where crack extension is 0)
eff	effective value

$$\frac{da}{dN} = \frac{L_p(\Delta K, \Delta K_{th}; C)}{\Delta N(\Delta K, \Delta K_{th}; C, C')} \tag{1}$$

where L_p is the size of a "process zone" ahead of the crack tip and ΔN is the number of cycles needed for a growing crack to penetrate this "process zone." Both terms are functions of the stress intensity factor range ΔK and the ΔK_{th}, formulated with the help of cyclic constitutive parameters C and low cycle fatigue parameters C'.

Although there is no clear definition of "process zone", it is generally thought that [17,18] (1) this zone exists in the vicinity of crack tip and within the cyclic plastic zone; (2) initial damage originates from this zone due to cyclic deformation. We assume that crack advance is governed by the blunting-resharpening mechanism, which would result in such a process zone. The mechanism has been observed in experiments for growing fatigue cracks at all the stages we consider [19–21]. A schematic of the various regions in front of a growing crack is shown in Fig. 1(a), where the blunted crack, with larger tip radius, is indicated by the dashed line. In the following derivation, we purposely define the process zone size L_p to be cyclic plastic zone size r_{cp} less the blunting radius ρ_{cb}. This may slightly overestimate crack growth rate and thus provide a conservative fatigue life prediction.

Under small-scale yielding and plane stress conditions, the crack process zone, L_p, and number of cycles required to penetrate that zone, ΔN, is given by

$$L_p = \frac{\Delta K^2 - \Delta K_{th}^2}{4\pi(n'+1)\sigma_{yc}^2} = \frac{\Delta K_{th}^2(\Delta K^2/\Delta K_{th}^2 - 1)}{4\pi(n'+1)\sigma_{yc}^2} \tag{2}$$

$$\begin{aligned}\Delta N &= \frac{1}{2}\left[\frac{K'\varepsilon_{yc}^{(n'+1)}}{(\sigma'_f - \sigma_m)\varepsilon'_f}\cdot\frac{\Delta K^2}{(\Delta K^2 - \Delta K_{th}^2)}\cdot\ln\left(\frac{\Delta K^2}{\Delta K_{th}^2}\right)\right]^{1/(b+c)}\\ &= \frac{1}{2}\left[\frac{K'\varepsilon_{yc}^{(n'+1)}}{(\sigma'_f - \sigma_m)\varepsilon'_f}\cdot\frac{\Delta K^2/\Delta K_{th}^2}{(\Delta K^2/\Delta K_{th}^2 - 1)}\cdot\ln\left(\frac{\Delta K^2}{\Delta K_{th}^2}\right)\right]^{1/(b+c)}\end{aligned} \tag{3}$$

for cyclic tensile loading (Mode I), as derived in [22,23]. Here, the cyclic strain hardening exponent is n', the cyclic strain hardening coefficient is K', the cyclic yield stress is σ_{yc} and the cyclic yield strain is ε_{yc}, which are cyclic constitutive parameters and $\varepsilon_{yc} = \sigma_{yc}/E$ where E is the Young's modulus; b, c, ε'_f, σ'_f and σ_m come from Manson-Coffin stress/strain-life relationship of low cycle fatigue

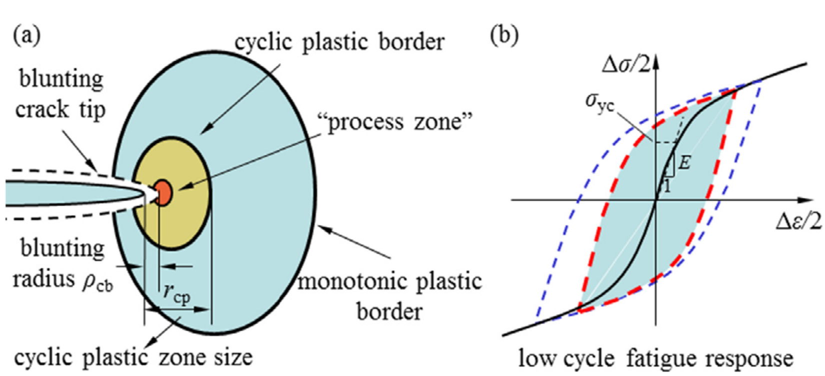

Fig. 1. (a) The cyclic plastic boarder delineates the region inside of which a "process zone" (shaded) ahead of a fatigue crack tip results in non-recoverable deformation during cyclic loading. The crack blunting zone is a small region where crack progress is impeded by highly localized deformation. (b) Cyclic stress-strain curve as described by a power law. The curve is given by the collected peak and valley values during cyclic loading.