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Unified two-stage fatigue methodology based on a probabilistic damage model applied to structural details

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ABSTRACT

Fatigue cracks are often a result of incremental stable crack growths that can be described by fracture mechanics. Fatigue crack initiation, however, has been most often described using empirical relationships between an alternating stress or strain and the number of cycles at those loads until either a specimen fails or a crack is observed. There are, however, modern views that consider fatigue crack growth and crack initiation directly related phenomena, the former being repeated instances of the latter, localized at an existing crack tip. Models of this newer class allow for an integrated initiation and crack growth calculation process which is advantageous when dealing with notched details in elastoplastic strain conditions. Recently, Huffman developed such a model which relates Walker-like stress-life relation and fatigue crack growth behaviour. This paper expands upon this new approach in order to account for the expected statistical variation using probabilistic *S-N* and *ε-N* fields as per works of Castillo and Fernandez-Canteli. A unified local approach proposed to treat fatigue crack initiation and growth is used on notched geometries with the predicted probabilistic variations being accounted. Notched details made of puddle iron from the Eiffel bridge and P355NL1 pressure vessel steel are considered in this study.

1. Introduction

Fatigue crack initiation is traditionally described using empirical models, usually in the form of single and double power law relationships for stress-life or strain-life. Fatigue crack growth is most often described as a power law relationship between some rate of crack advancement and the applied load, in terms of fracture mechanics. Although these are often considered to be unrelated phenomena, recent work formulates fatigue crack growth as incremental repeating initiations. In these models the two phenomena are necessarily the same. Initiation naturally being taken as the formation of the fatigue crack, and then propagation is the successive re-initiation locally at the crack tip [1–9].

The fatigue crack propagation modelling using strain-based fatigue local relation was first proposed by Glinka [1], in 1985. Glinka postulated that the crack growth is assumed as the failure of the successive elemental blocks with the dimension of the notched tip radius, ρ^*. Others authors, as Peeker and Niemi [2], Noroozi et al. [3,4], Hurley and Evans [5], Correia et al. [6], Hafezi et al. [7] and De Jesus et al. [8], have used fatigue local models based on strain and SWT relations to model the fatigue crack propagation curves.

Peeker and Niemi [2] developed a fatigue crack growth model based on superposition of the near threshold and stable fatigue crack propagation regimes using the cyclic elastoplastic stress-strain constants [10] and Morrow's strain-life constants [11–13].

The authors, Noroozi and Glinka [3,4,14], presented a model for fatigue crack growth analysis based on the elastoplastic crack tip stress–strain history including the influence of the applied compressive stress. This approach is called the UniGrow model and uses the Smith-Watson-Topper (SWT) fatigue damage parameter [15].

A new methodology for predicting fatigue crack propagation rates relies on the assumption that a similar number of cycles is required to propagate a crack through the cyclic plastic zone as to initiate a crack in a plain strain-control specimen, where an equivalent stress–strain profile exists. This methodology to estimate the FCG curve considering the load ratio effects and using the Walker-life strain damage criterion was

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Nomenclature

b	fatigue strength exponent
$\vec{b}$	Burger's vector
B	thickness of the CT specimen
c	fatigue ductility exponent
C	fatigue crack growth rate coefficient
da/dN	fatigue crack growth rate
D	damage
Δa	crack increment or crack size
$\Delta\kappa$	fatigue crack growth driving force
ΔK	total stress intensity factor range
$\Delta K_{applied}$,ΔK	applied stress intensity factor range
$\Delta\varepsilon$	strain range
$\Delta\varepsilon/2$,ε_a	strain amplitude
$\Delta\sigma$	stress range
$\Delta\sigma/2$	stress amplitude
ε	strain
ε_f'	fatigue ductility coefficient
E	elasticity modulus
f	frequency
γ	fatigue crack growth rate exponent
γ_w	walker exponent
$K_{max,applied}$	maximum applied stress intensity factor
K_r,$K_{residual}$	residual stress intensity factor
K'	cyclic strength coefficient
L,L_1,L_2	width of the notched detail
$m(x,a)$	weight function
n'	cyclic strain hardening exponent
N	number of cycles
N_f,N_t	number of cycles to failure
N_i	number of cycles for the crack initiation phase
N_p	number of cycles for the crack propagation phase
N_0	threshold value for life
$2N_f$	reversals to failure
p	crack growth driving force exponent; probability to failure
υ	Poisson's ratio
R,R_ε	strain ratio
R,R_σ	stress ratio
ρ_c	critical dislocation density
ρ^*	notched tip radius
σ_a	stress amplitude
σ_{ar}	equivalent stress amplitude
$\sigma_{ar,0}$	corresponding value for the equivalent stress amplitude
σ_f'	fatigue strength coefficient
σ_{max}	Maximum stress
σ_x	elastoplastic stress distribution along the x direction
σ_y	elastoplastic stress distribution along the y direction
σ_r	residual stress distribution
t	thickness of the notched detail
U_d	strain energy density from dislocations
U_e	elastic strain energy density
U_p^*	plastic strain energy density
x	distance from the crack tip
W	width of the CT specimen

proposed by Hurley and Evans [5].

Recently, Correia [6], Hafezi [7] and De Jesus [8] proposed a residual stress-based crack propagation model using the assumptions of the UniGrow model [1,3,4,14] and considering the elastoplastic stress fields around the crack apex evaluated by elastoplastic finite-element (FE) computations. In addition, some probabilistic approaches to these FCG models based on local approaches have been suggested by Correia et al. [6,16,17] and Glinka et al. [18].

The fatigue crack propagation models based on local strain-based approach have been used in procedures to obtain the S-N curves for structural details. Correia et al. [16,19] proposed a general procedure for generating the probabilistic *p-S-*N_f*-R* fields for notched geometries. The procedure employs a modification of the UniGrow model which uses an elementary material block size, ρ^*, which is obtained from existing FCG data. Using the UniGrow method and the ρ^* parameter an initiation curve, *S-*N_i, is derived. Then *p-SWT-N* or *p-*ε_a*-N* material fields generated from experimentally determined material data are used to evaluate the *S-*N_i*-R* and *S-*N_p*-R* fields.

In this paper, an extension of the general procedure proposed by Correia et al. [16,19] to compute the probabilistic *S-*N_f fields for structural details is suggested. Thereby, this paper uses the probabilistic models proposed by Castillo and Fernandez-Canteli [20] to extend the strain energy based initiation and fatigue crack growth model proposed by Huffman [9]. The proposed model has intrinsic stress ratio behaviour which predicts Walker mean stress behaviour. This suggested approach is applied on notched details (side notched plate) made of P355NL1 pressure vessel steel [16,19] and a notched plate with circular hole made of puddle iron from the Eiffel bridge [21].

2. Overview of local stress/strain approaches

Fatigue crack growth behaviour such as that phenomenon that is typically characterized by the Paris law [22], uses Linear Elastic Fracture Mechanics (LEFM) to express the stress distribution in a material as a function of geometry and loading, and associate that with a crack growth rate. Local stress or strain approaches, however, take into account the stresses near the crack tip, as opposed to the entire distribution. The local stresses or strains are based on the strain energy distribution calculated by LEFM. Assuming that local stresses or strains can be used to calculate incremental failure in similar way that global stresses or strains are used to calculate initiation, damage parameters can be associated to the external loads for any geometry. The damage parameters that can be considered could be the SWT parameter [5,6] or the Huffman damage parameter [1].

The local approach mentioned above relates fatigue crack growth with stress or strain cycles at the crack tip. The stress or strain found near the crack tip is used to calculate a number of cycles until failure as if the crack tip itself was a specimen. The calculated failure is a crack growth extension of size Δa, which occurs after N_f cycles.

The damage parameter proposed by Huffman which is used for stress-life, strain-life, and fatigue crack growth, uses strain energy density calculated from cyclic stress-strain properties. The damage expression is derived from

$$\left(\frac{U_e}{U_d\rho_c}\right)\left(\frac{U_p^*}{U_d\rho_c}\right) = D = \frac{2N}{2N_f} \tag{1}$$

where U_e is the elastic strain energy density, U_p^* is the complementary plastic strain energy density, U_d is the strain energy density from dislocations, and ρ_c is the critical dislocation density. The strain energy

Table 1
Cyclic stress-strain properties for the P355NL1 steel [8,19,28] and the material from the Eiffel Bridge [6,16,26,27].

Material	Strain ratio, R_ε	E (GPa)	ν	K' (MPa)	n'
Eiffel bridge	−1	193.1	0.30	654.7	0.0946
P355NL1 steel	0	205.20	0.275	913.6	0.1459
	−1			1022.3	0.1682
	"−1" + "0"			948.35	0.1533