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Fatigue surface crack growth in cylindrical specimen under combined loading

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ABSTRACT

The subject for studies is a steel bar of circular cross-section with straight-fronted edge notch undergoing fatigue loads. Both the optical microscope measurements and the crack opening displacement (COD) method are used to monitor and investigate both crack depth and crack length during the tests. The variation of crack growth behavior is studied under cyclic axial and combined tension + torsion fatigue loading. Results show that cyclic Mode III loading superimposed on the cyclic Mode I leads to a fatigue life reduction. In parallel to the experimental activity, numerical calculations are performed based on three-dimensional DBEM analysis to determine the stress intensity factors along curvilinear surface crack front and fatigue life prediction. The experimental fatigue crack growth results obtained from round bar specimens have been compared with the numerical predictions. The computational DBEM results are found to be in satisfactory agreement with the experimental findings.

1. Introduction

In order to implement the operation with the constraint of a required fatigue life, it is necessary to carry out fracture mechanics assessment of a structural component under cyclic loading. The crack growth analysis of surface flaws is one of the most important parts for structural integrity prediction of the circular cylindrical metallic components (bars, wires, bolts, shafts, etc.) in the presence of initial and accumulated in-service damages. Fairly often, part-through flaws appear on the free surface of the cylinder and defects can be considered as semi-elliptical cracks. Multiaxial loading conditions including tension/compression, bending and torsion are typical for the circular cylindrical metallic components of engineering structures. The problem of residual fatigue life prediction of such type of structural elements is complex and analytical solutions are often not available because surface flaws are three-dimensional in nature.

In the present study, firstly, experimental results of fatigue crack growth are presented with reference to a crack starting from a straight-fronted edge notch in a cylindrical specimen under axial tension loading with or without superimposed cyclic torsion. The influence of different loading conditions on fatigue life of tested specimens is discussed. The relations between crack opening displacement and crack length on the free surface of specimens are determined and it is found that the position and change of the curvilinear crack fronts is dependent on the initial straight-fronted edge notch depth. Using the aforementioned experimental relations, the crack front shape and crack growth rate in the depth direction can be predicted. Secondly, crack growth numerical calculations are performed based on the Dual Boundary Element Method

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Nomenclature

a	crack length on the free surface
b	crack depth
C, m	paris equation constants
D	specimen diameter
E	Young's modulus
G	shear modulus
I_n	numerical constant
J	J-integral
K_1, K_2, K_3	Mode I , II and mode III elastic stress intensity factors
K^*	stress intensity factor at crack growth rate $da/dN = 10^{-7}$ m/cycle
M_P	Mode mixity parameter
n	strain hardening exponent
N	number of cycles
R	cyclic stress ratio
r,θ	polar coordinates
r_c	characteristic distance from the crack tip
S	strain energy density factor
u, v , w	displacement components
V	elementary volume
W	strain energy density
B	crack angle
θ^*	angle of crack propagation
η	biaxial nominal stress ratio
v	Poisson ratio
σ_e	Von Mises equivalent stress
$\tilde{\sigma}_e$	dimensionless angular function for Von Mises equivalent stress
σ_0	yield stress
FEM	finite element method
DBEM	Dual Boundary Element Method
SED	Strain Energy Density
MSED	Minimum Strain Energy Density
MPS	Maximum Principal Stress
SIF	stress intensity factor
COD	crack opening displacement

(DBEM) [1–3]. The simulations for the crack path assessment are based on the DBEM code BEASY [4]. DBEM is an extremely powerful approach for three dimensional fracture mechanics problems also in comparison with FEM [5–7] or XFEM [8,9], due to its intrinsic accuracy and flexibility (the three dimensional crack propagation proceeds in a fully automatic way), but the best results are nowadays obtained by a coupled usage of the two procedures [10–12].

The computational 3D fracture analyses deliver variable mixed mode conditions along the crack front [13,14]. Different criteria for the crack path assessment like the Minimum Strain Energy Density (MSED) [15], Maximum Principal Stress (MPS) [16] and Q-Plain [17]) are adopted. In the latter approach, the crack will propagate in a direction where the multiaxiality factor has a minimum value (the multiaxiality factor is defined as the ratio of the Von Mises equivalent stress to the hydrostatic stress). The stress intensity factor (SIF) evaluation is based on the J-integral approach [18,19].

2. Test material and specimens

The test material is carbon steel R2 M. Its main mechanical properties, including constants of the Paris equation (Eq. (1)), are listed in Table 1 where E is the Young's modulus, σ_b is the nominal ultimate tensile strength, σ_0 is the monotonic tensile yield strength, σ_f is the true ultimate tensile strength, n is the strain hardening exponent, C and m are the Paris constants which are determined using standard compact specimen.

Table 1
Main mechanical properties of steel R2M.

E (MPa)	σ_b (MPa)	σ_0 (MPa)	σ_f (MPa)	n	C ((mm/cycle)/(MPa mm$^{0.5}$)^m)	m
209000	810.3	540.8	890	6.134	4.1×10^{-13}	2.818