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A study of fatigue crack growth with changing loading direction

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Abstract

Round compact specimens made of 1070 steel were experimentally tested under cyclic loading for crack growth. The specimen was first subjected to Mode I loading. After the crack reached a certain length, the external loading direction was changed 50° from the original loading direction. Right after the change of the loading direction, the specimen experienced the combined Mode I/II loading condition. Following a short transient period, the fatigue crack was found to grow in the direction approximately perpendicular to the external loading direction, indicating the recovery of Mode I cracking. A recently developed approach was used to predict the cracking behavior of the specimens. Detailed elastic–plastic stress analysis was conducted using the finite element (FE) method. Both crack growth rate and cracking direction were predicted by employing a critical plane multiaxial fatigue criterion based on the stress–strain response outputted from the FE analysis. The predictions made by using the approach were in excellent agreement with the experimental observations in terms of both crack growth rate and cracking direction. The material constants used in the approach were obtained from testing smooth specimens for crack initiation.

Keywords: Crack growth; Crack orientation; Elastic–plastic stress analysis; Mixed mode

1. Introduction

Many structures and machine elements are subjected to the mixed-mode loading conditions. It is important and necessary to understand and characterize the behaviour of a structure under mixed-mode loading. Very often, crack growth rate and cracking direction are considered separately with different criteria.

By testing the plates with an inclined crack, the crack grew away from its original direction [1–4]. From the experiments on 2024-T3 aluminum alloy sheets with a central inclined crack, Abdel-Mageed and Pandey [5] reported that the crack tended to grow into the direction perpendicular to the loading axis. The direction of the crack extension from the inclined crack was found roughly perpendicular to the tensile axis at stress ranges just above the threshold value for non-propagating cracks [6].

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Nomenclature

a	crack length measured from the notch root along the crack wake
a_n	notch depth measured from the notch root to the line of action of the externally applied load
A	damaging area in the fatigue model
b	material constant in the fatigue model characterizing cracking behaviour
d	differential or infinitesimal increment
$\mathrm{d}a/\mathrm{d}N$	crack growth rate
$(\mathrm{d}a/\mathrm{d}N)_1$	crack propagation rate right before the loading direction change
D	fatigue damage on a material plane
D_0	critical fatigue damage
Δ	prefix denoting range
ΔD	fatigue damage per loading cycle on a material plane
ΔD_1	pre-existing fatigue damage per loading cycle
D_i	accumulated pre-existing fatigue damage
G	energy release rate
ΔK	stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
m	material constant in the fatigue model
N	number of loading cycles
P_i	external load
$\Delta P/2$	amplitude of the externally applied load
r	polar coordinate in the radial direction starting from the crack tip
R	R-ratio (minimum load over maximum load in a loading cycle)
S	strain energy density factor
ΔS	strain energy density factor range
$\Delta S_{\mathrm{p,eff}}$	Effective strain energy density factor range
T_{D}	distortional strain energy
T_{V}	dilatational strain energy
$T_{\mathrm{V,cr}}$	critical dilatational component of the total strain energy
Y	plastic strain energy density on a material plane
β	loading angle
γ^{p}	plastic shear strain corresponding to the shear stress on a material plane
ε^{p}	plastic strain corresponding to the normal stress on a material plane
ε_{yy}	strain corresponding to the normal stress in the y direction
φ	angle made by the normal of the material plane and the z-axis
θ	angle made by the x-axis and the projection of the normal of the material plane onto the xoy plane
σ_0	endurance fatigue limit
σ_{f}	true fracture stress
σ_{mr}	material memory stress
σ_{yy}	normal stress in the y direction
τ	shear stress on a material plane

To predict the crack growth direction under mixed Mode I/II loading, Erdogan and Sih [1] proposed that fracture was controlled by a maximum hoop stress criterion (MHSC) at the crack tip. The MHSC correlated well with the experimental crack initiation under mixed mode I/II loading [7,8]. A second (non-regular) term was included for calculating the stress distribution around the crack tip to obtain a better prediction for the angle of fracture when using the MHSC [2]. With the consideration of the material ductility, the material failed on the competition of the attainment of a tensile fracturing stress and a shear fracturing stress at a fixed