Theoretical and Applied Fracture Mechanics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Modeling of I + II mixed mode crack initiation and growth from the notch

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ARTICLE INFO

Article history:
Received 29 December 2015
Revised 27 March 2016
Accepted 27 March 2016
Available online xxxx

Keywords:
Notched component
I + II mixed mode
Fatigue crack initiation
Crack growth rate
Crack growth path

ABSTRACT

The fatigue crack initiation and growth from the notches under combined loading are modeled by the finite element method. The compact tension shear (CTS) specimens of Q345R steel are used to study the I + II mixed mode crack growth behavior. To consider the effect of the residual stress and loading history induced by fatigue crack growth, the dynamic crack propagation model is employed in the finite element simulation. A multiaxial fatigue damage criterion is employed and an Armstrong–Frederick type cyclic plasticity model was inputted as a UMAT to describe the material behavior. The fatigue crack initiation and growth from the notch root of the CTS specimen is determined by the stabilized stress–strain responses of the material points near the notch root and the fatigue damage of different material planes. The material point with maximum fatigue damage corresponds to the fatigue initiation position, and the crack growth orientation from the initiation position is identical to the material plane on which maximum fatigue damage arises. The fatigue crack propagates on the material plane with maximum crack growth rate. The results of prediction are in excellent agreement with the experimental observations in terms of crack initiation orientation, crack growth rate and crack growth path.

1. Introduction

Engineering structures may fail due to fatigue damage and fatigue crack growth when subjected to cyclic loading. Fatigue cracks may nucleate from a notch due to stress concentration induced by geometric discontinuity. Most research work on crack growth has been concentrated on fatigue life of smooth specimen and Mode I crack growth. Modeling of the crack initiation and growth from a notch under mixed mode loading is still a difficult task.

The I + II mixed mode fatigue crack growth behavior has been studied by a lot of crack growth experiments for various material [1–6]. Mageed and Pandey [1] have proposed that the crack growth direction had a tendency to be perpendicular to the loading direction based on experiments using 2024-T3 aluminum alloy. Sander and Richard [2] investigated the influence of the loading direction on the fatigue crack growth path by using the CTS specimen. Ding et al. [3] tested the compact specimens made of 1070 steel under multiple-step loading direction and found that the crack growth path was turning with the change of loading direction and the fatigue crack growth direction tended to follow pure Mode I cracking direction finally. Dahlin and Olsson [7] studied the influence of periodic Mode II loading on Mode I fatigue crack growth using a new type of loading device.

The prediction models of I + II mixed mode fatigue crack growth have been developed in last 20 years including the maximum strain energy release rate method [8–11], the minimum strain energy density factor method [12,13] the maximum tangential stress/strain model [12,14], the *J*-integral model [15,16], and the crack tip displacement method [17]. Among them, the model proposed by Jiang and co-workers is based on plastic strain energy density and has been used to predict the I + II mixed mode crack growth behavior. The Peak Stress Method has been proposed by Berto and his team [18] and has been used to estimate the strain energy density averaged in a structural volume which applied in the case of two-dimensional cracks subjected to I + II mixed mode loading. The averaged strain energy density approach also can been extended with the aim of studying three-dimensional effects arising at the notch tip considering plates of finite thickness subjected to in-plane shear fatigue loading [19].

When a crack initiates and grows near a notch, the complex stress–strain field due to the structure discontinuity and multiaxis loading do increase the difficulty of prediction. An attempt was made by Teh and Brennan [20] to determine the stress intensity factor considering the notch geometry. Bonora et al. [21] considered the notch effect in the valuation of the effective accumulated plastic strain with continuum damage mechanics

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http://dx.doi.org/10.1016/j.tafmec.2016.03.011

Nomenclature

R	stress ratio
$\Delta P/2$	load amplitude
P_i	external load
r_0	notch radius
β	loading angle
α_i	deflection angle
a_0	notch depth
a	crack length measured from the notch root along the crack wake
b	material constant in the fatigue criterion
D	fatigue damage
D_0	critical fatigue damage
m	material constant in the fatigue criterion
Y	plastic strain energy (density) on a material plane
σ	normal stress on a material plane
ε^p	plastic strain corresponding to σ
τ	shear stress on a material plane
γ^p	plastic strain corresponding to τ
σ_0	endurance limit of the material
σ_f	true fracture stress of the material
σ_{mr}	material memory parameter in the fatigue criterion
A	damaging area in the fatigue model
da/dN	crack growth rate
ΔD_1	pre-existing fatigue damage per loading cycle in residual damaging zone
r	polar coordinate in the radial direction starting from the crack tip or notch root
ε_{xx}	strain corresponding to the normal stress in the x direction
ε_{yy}	strain corresponding to the normal stress in the y direction
σ_{xx}	normal stress in the x direction
σ_{yy}	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

model. Li [22] suggested that the crack growth from a notch was dominated by the notch plastic zone and the plasticity induced crack closure (PICC). A special parameter was introduced to correlate the experimental results of fatigue growth in the near notch zone [23].

None of the approaches developed so far can properly predict the crack initiation and growth from the notch under I + II mixed mode loading. The current effort is to fulfill such a task. This paper simulates fatigue crack initiation from notches and growth behavior under I + II mixed mode loading in non-standard CTS specimens of Q345R steel. In order to obtain the accurate elastic–plastic stress–strain responses, the Armstrong–Frederick type cyclic plasticity model [24,25] was used. This theoretical model can describe the cyclic plasticity characterization of Q345R steel and was implemented into ABAQUS by the user subroutine UMAT. To consider the effect of the residual stress and loading history induced by fatigue crack growth, the dynamic crack propagation model is used in the finite element simulation. A multiaxial fatigue damage criterion [26] based on the critical material plane is adopted to calculate the accumulated fatigue damage. The material point with maximum fatigue damage corresponds to the fatigue initiation position, and the crack growth orientation from the initiation position is identical to the material plane on which maximum fatigue damage arises. Then, the position and orientation of fatigue crack initiation, the fatigue crack growth rate and fatigue crack growth path were predicted.

2. Fatigue crack initiation and growth experiments

The I + II mixed mode fatigue crack propagation experiments were conducted earlier by the co-workers [27]. The detailed process of specimen preparation, experimental operation and loading conditions can be found in Ref. [27]. The CTS specimens for the fatigue crack growth experiments were made from the 30 mm thickness hot-rolled Q345R steel plate. In order to facilitate reading the following sections of this paper, some main geometrical information and loading conditions of three CTS specimens are summarized in Table 1.

The structure and dimensions of the CTS specimens used in the current investigation are shown in Fig. 1. The notch radii of three CTS specimens, r_0, are 0.1 mm, 0.5 mm and 1.0 mm, respectively (refer to Fig. 1). These notches were made using a diamond saw cut. There are three loading holes of the same size in each specimen, which are numbered as shown in Fig. 1.

The experiments were conducted by a SHIMADZU fatigue machine with ±250 kN loading capacity. All the experiments were performed in air at room temperature. The load ratio (R-ratio) for all the specimens was 0.1. Each test was divided into three loading steps. The loading direction was changed by using different the loading holes in the specimen. P_i ($i = 1,2,3$) shown in Fig. 1 denotes the applied load at the ith step ($i = 1,2,3$) direction. Step 1 and Step 3 used the 1st and 2nd loading holes (same as the standard CT specimen), and Step 2 used the 1st and 3rd loading holes to simulate the I + II mixed model loading. The notch depth, a_0, is the distance between the line of action of the applied load P_1 and the notch root at the first loading step. The loading application angle as shown in Fig. 1, β, is plus at the count-clockwise direction on basis of the positive y axis; vice versa, it is minus. In Table 1, α_i ($i = 1,2,3$) denotes the deflection angle at each step. α_1 denotes the angle between the crack growth path of the first loading step and the positive x axis; α_2 is the acute angle between crack growth

Table 1
Loading conditions and results for the experiments.

Specimen	Loading step	β (°)	α_i (°)	$\Delta P/2$ (kN)	R-ratio	r_0 (mm)	a_0 (mm)	a_n (mm)
1	1	0	−16	2.25	0.1	0.5	10.859	3.026
	2	30	52	3.15	0.1	–		5.819
2	1	0	−6	1.8	0.1	1.0	14.848	4.013
	2	45	46	2.7	0.1	–		5.956
3	1	0	−6	1.5	0.1	0.1	14.822	5.793
	2	45	56	2.7	0.1	–		4.021