International Journal of Fatigue 46 (2013) 58–66

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

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

Stress intensity factor analysis of through thickness effects

J. Garcia-Manrique, D. Camas, P. Lopez-Crespo *, A. Gonzalez-Herrera

Departamento de Ingeniería Civil, de Materiales y Fabricación, Universidad de Málaga, Escuela de Ingenierías, C/Doctor Ortiz Ramos, s/n Campus de Teatinos, E-29071 Málaga, Spain

ARTICLE INFO

Article history:
Received 27 July 2011
Received in revised form 30 November 2011
Accepted 9 December 2011
Available online 21 December 2011

Keywords:
Finite element analysis
Fracture mechanic
Crack growth
Fatigue crack closure
Stress intensity factor (SIF)

ABSTRACT

The study of crack tip fields in mode I is often conducted assuming a homogeneous behaviour through the thickness. Depending on the specimen thickness, a state of plane stress or plane strain is normally presumed. However, recent studies have shown a more complex behaviour along the thickness. On the one hand, plasticity-induced crack closure effects affect mainly to a small region close to the specimen surface. On the other hand, the plastic zone evolution along the thickness is not as simple as the classic dog-bone shape normally described in Fracture Mechanics textbooks. Unlike what is normally expected, the size of the plastic zone decreases in a very small region close to the surface, as we move from the interior to the surface of the specimen. These two effects can be detected if the mesh used in the finite element model is sufficiently fine. Both effects are probably related to an uneven distribution of the load along the thickness. One of the consequences of these effects on the fatigue crack growth is the curvature of the crack front which can be explained by two mechanisms. The first one is related to the crack closure effect near the surface, it would imply a smaller effective ΔK close to the surface, and therefore a slower crack growth rate. The second one (plastic zone size decrease in a small region close to surface) is probably due to ΔK being smaller near the surface than in the interior. The current work attempts to evaluate numerically both effects in order to separate their individual influence and their magnitude. This is done by evaluating the K distribution along the thickness at different planes on an Al 2024-T35 compact tension specimen under mode I nominal loading. The plastic wake effect is removed from the model in order to distinguish between both effects.

1. Introduction

The fatigue crack growth is closely related to the stress distribution around the crack tip. The fatigue problem was initially studied considering only two dimensions and neglecting or oversimplifying mechanisms taking place through the thickness. However, it has been shown that thickness effects influence considerably the crack tip behaviour. Accordingly, it seems logical to investigate the problem from a 3D viewpoint.

A number of authors have investigated the crack front in fatigue from a 3D perspective through different parameters. Analytical solutions of crack tip stress fields are limited. Sternberg and Sadowsky [1] found an approximate solution for the 3D stress distribution near a circular hole. Hartranft and Sih [2] used an approximate theory of plates and concluded that stress state results are noticeably different from equations of generalised plane stress. Kotousov and Wang [3] presented an analytical solution describing 3D stress distribution around typical stress concentrators in isotropic plates of arbitrary thickness. Finite element (FE) method has also been used to investigate the problem in 3D. For example, Nakamura and Parks [4] obtained the size of the plastic zone at the mid-plane through the thickness and at the surface. Pook [5] calculated SIF with a crack model as a narrow parallel-side notch with a semicircular tip with good accuracy for modes I, II and III. Subramany et al. [6] developed numerical models of 3D elastic–plastic stress field near the crack front in ductile material. Wang et al. [7] studied the out-of-plane stress and strain fields around the crack. Guo [8,9] proposed a factor (Tz) widely accepted to simulate 3D effects in 2D analysis. Berto et al. [10] presented FE results of linear elastic distributions of stress and strain energy density ahead of V-shaped notches in plates.

The evolution of the crack front shape as well as fatigue life predictions are studied very often via numerical models. These are based typically in determining K at different points along the front. Newman and Raju [11] have studied the crack growth assuming that the crack front shape remains constant during the propagation. Lin and Smith [12–15] considered several points along the thickness, thus allowing variation of the crack shape during the process. They discussed the evaluation of SIF and its sensitivity to crack shape in circular and semi-elliptical crack FE models.

Others authors studied crack shape evolution based in SIF results. They used FE calculations to obtain ΔK_{eff} at different position

* Corresponding author. Tel.: +34 951952440.
E-mail addresses: josegmo@uma.es (J. Garcia-Manrique), dcp@uma.es (D. Camas), plopezcrespo@uma.es (P. Lopez-Crespo), agh@uma.es (A. Gonzalez-Herrera).

0142-1123/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2011.12.012

Nomenclature

a	crack length	P	load applied
b	specimen's thickness	R	stress ratio
COD	crack opening displacement	r_{pD}	dugdale's plastic zone size
CT	compact tension specimen	s	distance along the path
E	Young's modulus	t_x,t_y	traction vectors along x, y axis
FE	finite element analysis	u_y	open crack displacement
K,SIF	stress intensity factor	W	specimen's width
K_{COD}	stress intensity factor due to COD method	W_e	strain energy per unit volume
K_J	stress intensity factor due to J-integral method	γ	path surrounding a crack tip
K_{max}	maximum stress intensity factor	ΔK_{eff}	effective range of stress intensity factor
K_{min}	minimum stress intensity factor	ν	Poisson's ratio
K_{nom}	nominal stress intensity factor		

along the thickness. They applied these values to evaluate the crack growth rate at this position. Couroneau and Royer [16,17] present an analytical propagation model based in an approximated SIF factor solution for fatigue growth in round bars under mode I. Smith and Cooper [18] present a general FE model to calculate SIF along the front of an irregular planar crack and used it to study its shape development. Nykänen [19] simulated fatigue crack growth at the surface of a plate, and from the toe of a transverse non-load-bearing fillet weld in a T-joint. Lee and Lee [20] investigated fatigue crack growth in single side repairs aluminium plate. Branco et al. [21] used these techniques to evaluate the curvature of the crack front. They found that and stable crack curvature was achieved independently from the starting shape. A limitation in the through-thickness meshing and the technique employed to evaluate K limited the extension of their conclusions. An interesting methodology for 3D evolutions of the crack front in mixed-mode II + III has been recently developed by Doquet et al. [22].

Authors concluded crack always attempts to propagate towards and iso-K configuration, where SIF distribution is uniform along the crack front [21,23,24]. Lee and Lee [20] suggest that the actual crack front shape should be considered in fatigue analyses because of its large influence on the SIF variation.

An important aspect of this K distribution is the 3D corner singularity at the intersection of the crack front and the free surface presented by Benthem [25]. Bazant and Estenssoro [26] used and FE method to propose that this singularity produce the deviation of the crack front from the orthogonal direction in the vicinity of the surface. The size of the influence of corner point singularity is in general not known. Pook [27] suggest that is a function of load and concluded that crack front intersects a free surface at a critical angle, which is function of the loading type and the Poisson's ratio. Kotousov et al. [28,29] applied the first-order plate theory to deal the corner and the out-of-plane singularities.

Hutar et al. [30,31] presented a very interesting methodology based on generalised SIF to describe crack behaviour close to the free surface. They studied the evolution of the crack shape due to the free surface influence and his relevance with the structure thickness.

All the above mentioned works, as well as other ones dealing with fatigue and fracture, are based on analytical solutions relating K and other variables such as crack growth rate or crack tip stress field. Therefore an accurate determination of K is essential and becomes a crucial parameter of existing predictive methods. Most common method is the extrapolation of the displacement in the vicinity of the crack using LEFM analytical expressions [16–19]. On the other hand we have energetic methods as the strain energy density (SED) [30–32] or J-integral [20,24].

In previous works [34–37] fundamental parameters such as minimum element size, plastic wake, plastic zone size or crack closure stress have been evaluated by FE analysis. Nevertheless, due to its influence, we need to improve them introducing a more realistic K characterisation through the thickness. The present paper focuses on developing a new methodology to calculate accurately and analyze the SIF in mode I for a CT specimen. Small scale yielding, long crack ($a = 0.4$ W) and plastic behaviour material have been considered.

2. Background

The study of crack tip fields is often conducted assuming a relatively simple behaviour through the thickness. Depending on the specimen thickness, a state of plane stress or plane strain is normally presumed. In the more general case, a small linear transition is normally presumed [33]. However, recent studies have shown a more complex behaviour along the thickness. Recently, Camas et al. [34] have studied numerically the evolution of the plastic zone across the thickness.

Fig. 1 shows the crack displacement field obtained by means of FE calculations in an 3D crack. These results correspond to the simulation of the fatigue crack growth in a CT specimen. Straight crack front is assumed and plastic crack wake is developed by cycle by cycle crack advance. Further details of the methodology herein used can be found in [35]. The load case correspond to $R = 0.3$, $b = 3$ mm and $K_{max} = 25$ MPa m$^{1/2}$. Vertical displacement of the crack flanks near the crack is shown at minimum load, K_{min}, (Fig. 1a) and maximum load, K_{max} (Fig. 1b). The mid plane of the specimen is that of the top right corner, and the free surface of the specimen is on the bottom left corner in Fig. 1. The contact points between crack flanks are also shown in Fig. 1. This contact is caused by plasticity-induced crack closure [35]. Different qualitative issues can be observed. It can be seen that plasticity-induced crack closure affects mainly to a small region close to the specimen surface. Only one line of nodes is in contact in the interior zone while all the area where the plastic wake has been simulated is in contact at minimum load in a region very close to the exterior. In addition, if we observe the crack opening displacement (COD) at K_{max} (Fig. 1b) it is higher at the interior than the exterior.

Fig. 2 depicts the evolution of the plastic zone along the thickness. It can be seen that it is not as simple as the classic dog-bone shape normally described in Fracture Mechanics textbooks [33]. A number of different cases with varying values of R, K_{max} and b were simulated and same trends were observed for all cases. Similar qualitative behaviour has recently been observed with a slightly different model but analogous methodology [34]. Therefore Fig. 2 is representative of the general behaviour. Unlike what is normally expected, the size of the plastic zone decreases in a very small region close to the surface, as we move from the interior of the