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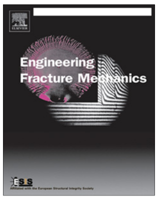

A stress intensity factor estimation method for kinked crack

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ABSTRACT

A method for estimating the stress intensity factors (SIFs) of kinked crack with finite kink length is presented. This method is based on an estimation expression which is derived by He et al. according to the work of Cotterell and Rice from the stress field series of the original (unkinked) crack tip to the second order by using weight function (WF). In order to increase the estimation accuracy for the kinked crack with finite kink length, the third order coefficients of the stress field series of the original crack tip are introduced into this expression and these parameters can be obtained by a fitting procedure. Application of this modified expression to the cases of singly-kinked, edge kinked and doubly-kinked cracks reveals a good approximation with the finite element (FE) results of SIFs and showed that the accuracy is increased.

1. Introduction

In general, crack direction changes during the fatigue crack growth process. Cracks with direction change are defined as kinked cracks and the number of kinks is the number of direction changes. As the simplified and elementary problem of the real fatigue crack with complex 3D geometry, the study of the 2D kinked crack has received special attention.

The evaluation of stress intensity factor (SIF) is the main subject in the study of kinked cracks. Kitagawa et al. [1,2] studied the problem of singly-kinked crack based on the Muskhelishvili's theory of complex potentials [3] combined with conformal mapping and obtained the SIFs numerically. For the more general case, Cotterell and Rice [4] kept the first order terms (relate to mode I and mode II SIFs) in the crack-tip stress field series [5] and derived an estimation expression that expresses the SIFs of the kinked crack with an infinitesimal kink length as a linear combination of the SIFs of the original (unkinked) crack. And this expression will be denoted as CR in the following. Considering the influence of T-stress, Karihaloo et al. [6] estimated SIFs for kinked crack and studied the stability of crack growth. Furthermore, He et al. [7] added the corresponding terms related to kink length and T-stress into CR. This expression will be denoted as CRT in the following. Leblond [8] established an expansion that expresses the SIFs of an arbitrary kinked or curved crack in powers of the kink length. Then Amestoy and Leblond [9] calculated the parameters in the expression for the case of a crack composed of two straight branches. Melin [10] modified this method and obtained a more accurate estimation expression with the coefficients expressed as tabular form.

The Weight Function (WF) method [11] was also used to calculate the SIFs of kinked crack. Fett et al. [12,13] derived a modified CR expression with increased accuracy by using WF and finite element method (FEM). Beghini et al. [14,15] developed a numerical method for estimating SIFs of the inclined kinked edge crack in semi-plane by using WF combined with

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Nomenclature

a_0	initial crack length
a_1	first kink length of doubly-kinked crack
CR	stress intensity factor estimation expression according to Cotterell and Rice [4]
CRT	stress intensity factor estimation expression including T-stress terms according to He et al. [7] based on Cotterell and Rice [4]
C_3	first coefficient of the third order terms in crack-tip stress field series
D_3	second coefficient of the third order terms in crack-tip stress field series
FE/FEM	finite element/finite element method
K_{I}	mode I stress intensity factor of original crack
K_{II}	mode II stress intensity factor of original crack
k_1	mode I stress intensity factor of kinked crack
k_2	mode II stress intensity factor of kinked crack
l	kink length
RMSE	root mean squared error
SIF	stress intensity factor
T	T-stress
WF	weight function
α	incline angle of the original crack
β	kink angle of the first kink segment of doubly-kinked crack
θ	kink angle

FEM. Later, Benedetti [16] improved the previous method in accuracy and generality and compared their calculations to the results in [6,9].

The method of dislocation distribution based on superposition and dislocation theory was developed by Burton and Phoenix [17] to analyze the stress field of multiple crack arrays. Then, Yavuz et al. [18] studied the SIFs of multiple interacting cracks including kinked and branched crack using integral equations expressed in terms of dislocation distribution. Hallbäck and Tofique [19] used a distributed dislocation dipole technique to analyze the SIFs of multiple kinked and branched crack and obtained the SIF results. Chen et al. [20] calculated the SIFs of kinked crack by numerical technique of solving a singular integral equation for branch crack problem which depends on dislocation distribution. They found that the asymptotic solution derived from the condition of infinitesimal kink length can only give sufficiently accurate results in a narrow range of kink length and kink angle.

The use of the results for kinked crack lies in several aspects. Wang et al. [21] analyzed the kinked cracks in cup specimens with various kinked length by axisymmetric and three-dimensional finite element models, the values of the results are much higher than the values estimated by closed form solutions including CR. Bechtle et al. [22] studied the mixed-mode SIFs of kinked crack with finite kink length from the results of infinitely small kinks and slant cracks. They applied the results in determining the fracture resistance curves of enamel and dentin with single edge notched bending specimens. Pippan [23] studied the crack driving force based on the maximum strain energy release rate by using the asymptotic expression of doubly-kinked crack SIFs derived by Suresh [24]. Spagnoli et al. [25] studied the fatigue behavior of crack based on a theoretical model of a periodically multi-kinked crack and interpreted experimental findings about fatigue threshold, short crack growth and growth in Paris regime.

In the regime of authors' knowledge, the general form expressions for estimating mixed-mode SIFs of kinked crack are CR and CRT. They are based on the analysis of infinitesimal kinks, the later works aimed at increasing accuracy of these expressions by modifying the coefficients through numerical procedure. Other analytical based methods including WF and dislocation distribution can be used to analyze kinked cracks with different shapes but a general formula is still not available. The derivation of CR and CRT comes from the stress field near the crack tip up to second order terms about SIF and T-stress, but the influence of the third terms in estimating kinked crack SIFs has not received as much attention as the SIF and T-stress. In fact, Karihaloo and Zhao [26,27] and their later researches [28,29] used a hybrid crack element to obtain the approximate analytical expressions for the higher order terms in the crack tip stress field for several typical specimens. Yuan and Yang [30] noticed the third order terms for kinked crack in anisotropic bodies and calculated the coefficients in the estimation expressions for SIFs and T-stress by integral equations based on dislocation distribution. But the coefficients in their expressions were expressed as tabular form. From these researches, the third order coefficients revealed its potential in estimating SIFs for kinked crack.

The aim of this paper is to modify CR and CRT by considering the influence of the third order terms in crack tip stress field in order to increase the accuracy for estimating SIFs of kinked crack with finite kink length. The problem of evaluating the added third order coefficients is discussed. The benefit of this method is that once the parameters of original crack have been obtained, the SIFs of kinked crack with different kink angle and kink length can be estimated without performing FE computations which need to rebuild the FE model. The comparison of SIFs estimated by the modified expression with the results

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