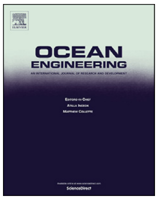
Ocean Engineering 160 (2018) 389–396

Contents lists available at ScienceDirect

Ocean Engineering

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



A simple method to determine crack opening stress for the center cracked plate under cyclic tensile loads

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ARTICLE INFO

Keywords:
Crack opening stress
Maximum crack opening displacement
Center cracked tension specimen
Finite element analysis
Crack growth

ABSTRACT

A new approach is proposed to determine crack opening stress (COS) on the basis of the variable quantity of maximum crack opening displacement (VMCOD). Based on elastic–plastic finite element analysis of center cracked finite plate, and accounting for the effects of crack geometry size, stress *R*-ratio, Young's modulus, yield stress and strain hardening, the explicit expression of relationship between COS and VMCOD is presented. This method avoids adopting parameters around crack tip and also is applicable to large-scale yielding state. Further studies show this relationship could be applied to predict crack growth rates, which correlate well with experimental results.

1. Introduction

Crack propagation usually occupies a significant part of the fatigue life in marine structures that suffer cyclic loading in service. Elber (1970) found the plasticity-induced crack closure phenomenon, and pointed out that the effective driving force for crack growth might be characterized by the effective stress intensity factor range. A crack is fully open for only a part of the load cycle, even when the loading cycle is fully in tension. The crack opening stress (COS), corresponding to the load at which the contact between the crack surfaces is broken, is intimately related with fatigue crack propagation rate. Therefore, COS should be considered in safety assessment involved in crack components.

Until now, many researchers have made attempts to the determination of COS in pioneering works. Budiansky and Hutchinson (1978) presented a theoretical model to determine COS of infinite plates under small-scale yielding. Correia et al. (2016a), and Blasón et al. (2016) proposed a theoretical model to estimate the COS intensity factor. Later, based on crack closure and crack growth experiments, Schijve (1981), de Koning (1981), Kumar and Garg (1989), Lang (2000), ,Correia et al. (2016b) Lesiuk et al. (2017) proposed empirical models to determine COS of specimens. These empirical models obtained from experiments are usually available to the experimental range of material types or load ratios.

As an alternative, finite element method is frequently used in COS assessments. Previously, a great amount of significant studies (Antunes et al., 2015; de Matos and Nowell, 2007; Solanki et al. 2004a; Solanki et al., 2003; González-Herrera and Zapatero, 2005; Antunes and Rodrigues, 2008; Singh et al., 2008; Newman, 1976) focused mainly on the optimization of numerical parameters such as mesh refinement, crack advancement schemes, COS assessment methods and crack opening assessment location. The accuracy of the finite element method therefore is heavily dependent on these factors. Besides, these calculations are very time-consuming. To avoid these problems, Aguilar et al. (2016) utilized mesh optimization and a restart analysis to determine COS of long cracks. And other researchers further proposed alternative empirical models based on numerical results to calculate COS. These models include various controlling parameters. For example, Newman (1984) presented equations including stress ratios for COS under uniaxial loading. Solanki et al., 2004b calculated COS based on the crack surface nodal force distribution. Tong and Wu (2014) discussed the effect of crack tip element on determining COS. Antunes et al. (2014) proposed empirical models for COS based on maximum stress intensity factor and stress intensity factor range. Besides, an empirical model (Antunes et al., 2016) based on the integration of vertical plastic deformation perpendicularly to crack flank has also been proposed to quantify COS and Shi et al. (2016) developed a model based on the effective cyclic plastic zone to determine COS. Most of the above studies are limited to small-scale yielding ranges. To solve the issue, Wang et al. (2003) used crack tip opening displacement to calculate COS under large-scale yielding.

Despite the existence of different procedure to quantify COS, issues remain associated with the practical implementation to accurately

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https://doi.org/10.1016/j.oceaneng.2018.04.069
Received 12 July 2017; Received in revised form 23 February 2018; Accepted 18 April 2018

Nomenclature

a	initial half crack length
C	Paris constant
E	Young's modulus
$K_{\max}$	maximum stress intensity factor
$K_{\min}$	minimum stress intensity factor
K_{op}	crack opening stress intensity factor
L	half-length of plate
m	Paris constant
n	strain-hardening exponent of material
R	stress ratio, $R = \sigma_{\min}/\sigma_{\max}$
W	half-width of plate
r_p	crack-tip forward plastic zone size
r_y	crack-tip plastic zone size
$u_{\max}$	maximum crack opening displacement corresponding to $\sigma_{\max}$
$u_{\min}$	minimum crack opening displacement corresponding to $\sigma_{\min}$
Δu	the variable quantity of maximum crack opening displacement (VMCOD)
ΔK_{eff}	effective stress intensity factor range
ΔK	stress intensity factor range
σ	applied load
σ_{op}	crack opening stress (COS)
σ_0	yield stress of material
$\sigma_{\max}$	maximum stress in the cyclic tensile load
$\sigma_{\min}$	minimum stress in the cyclic tensile load
ν	Poisson's ratio

determine COS. One of the significant issues is that most numerical approaches above to determine COS are associated with the calculations of crack-tip stress-field and displacement-field, but relevant fracture parameters in crack tip field could not be conveniently obtained in practice. Besides, most analyses are confined to small-scale yielding state. Therefore, more convenient fracture parameters that quantify the damage processes occurring at the crack-tip are in desperate needed to accurately determine COS in engineering practices.

In this work, a new method is introduced to determine COS based on the variable quantity of maximum crack opening displacement (VMCOD). Aimed at the center cracked tension (CCT) specimen, the relationship between normalized COS and normalized VMCOD is established. It is demonstrated that the presented relation here is not affected by crack geometry size, yield stress, Young's modulus, stress ratio as well as strain hardening. And the correlation is applicable under small-scale and large-scale yielding. Besides, taking into account of the crack closure effect, the relationship between COS and VMCOD is applied to predict crack growth rates. The predicted results are in good agreement with the experimental crack growth data.

2. Theoretical considerations

Elber (1970) has indicated that the permanent tensile plastic deformation left in the wake of the propagating crack results in the crack closure phenomenon. The plasticity-induced crack closure (PICC) is linked closely with the monotonic and reversed plastic deformation occurring at the crack tip, therefore, COS has a certain relationship with crack-tip plastic zone that is simply expressed as:

$$\sigma_{op} = f(ry) \tag{1}$$

where σ_{op} is crack opening stress, r_y is crack-tip plastic zone.

In our previous work (Jingjie et al., 2014; Yi et al., 2010a,), we proposed the estimation method of monotonic plastic zone size ahead of crack determined by maximum crack opening displacement(MCOD) during loading, and the reverse plastic zone size determined by VMCOD during unloading. Hence, the crack-tip plastic zone is linked to VMCOD, the relationship can be simply and distinctly expressed as

$$r_y = f(\Delta u) \tag{2}$$

where Δu is the variable quantity of maximum crack opening displacement (VMCOD).

According to Eq. (1) and Eq. (2), it is clear that COS is related to VMCOD during the crack propagation. The relationship between COS and VMCOD could be simply and markedly written as

$$\sigma_{op} = f(\Delta u) \tag{3}$$

where Δu denotes VMCOD and can be expressed as.

$$\Delta u = u_{\max} - u_{\min} \tag{4}$$

In Eq. (4), $u_{\max}$ and $u_{\min}$ represent the resulting MCOD perpendicular to crack surfaces corresponding to the maximum stress $\sigma_{\max}$ and minimum stress $\sigma_{\min}$ in the cyclic tensile load respectively which is shown in Fig. 2.

Once the expression of the relationship between COS and VMCOD is given, the COS could be obtained more conveniently by VMCOD.

3. Finite element analysis

3.1. Establishment of the FE model

Eight-node quadrilateral elements, target elements and contact elements are used for performing the two-dimensional finite element analysis of the specimen based on the ANSYS15.0. Plane stress condition is assumed.

The geometric dimensions of the model are shown in Fig. 1. $W = 40$ mm, $L = 40$ mm, and the specimen has an initial crack length of

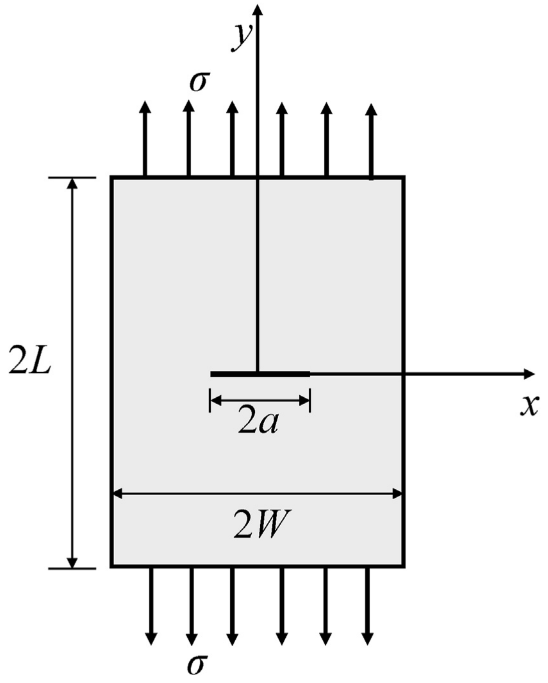

Fig. 1. A center cracked tension specimen.