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A quantitative study on the influence of compressive stress on crack-tip opening displacement

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ABSTRACT

To fill the research gap of estimating crack-tip opening displacement (CTOD) under compressive portion within a cyclic loading, a numerical study is conducted in this paper to quantify the influence of compressive stress on CTOD, and a calculation model of CTOD is established for center-cracked plates under tension-compression loading. The residual CTOD and the variable quantity of CTOD are introduced. Based on a series of finite element analyses, a simple relationship between the variable quantity of CTOD and compressive stress is obtained, which considers the influences of plate width, crack length, stress level (the maximum tensile and compressive stresses) and material property (yield stress, elastic modulus and material hardening). Finally, an example is given and the method in this paper is validated. The proposed calculation model of CTOD has a wide application range and is applicable for finite plates of different materials under tension-compression cyclic loading.

1. Introduction

Crack-tip opening displacement (CTOD), as one of the most viable parameters of elastic–plastic fracture mechanics to characterize crack growth in ductile materials (Hutchinson, 1983), has been widely used in integrity analysis of marine structures. Hence, it is quite significant to determine CTOD for engineering.

The importance of CTOD has motivated many researchers to conduct different studies for the determination of CTOD. Various calculation models are put forward, such as those based on stress intensity factor (Toribio and Kharin, 2009), the local strain (Hiroshi and Takehiro, 2007; Jayadevan et al., 2004), J-integral (Huang and Zhou, 2014) and the maximum crack opening displacement (Chen et al., 2011). However, these calculation models almost revolve around static or cyclic tensile load, without consideration of compressive stress in the loading scenario.

During the last several decades, it has been observed that CTOD is non-zero at zero applied stress during tensile unloading and the compressive portion (at negative stress ratio) of a cyclic loading has significant effects on fatigue crack growth rate for many materials (Halliday et al., 1997; Silva, 2005, 2004). In consideration of CTOD characterizing crack growth (Željko et al., 2011), compressive portions of cyclic loadings should be included in the calculation model of CTOD. The scarcity of studies in relation to CTOD under compressive stress has promoted several researchers to consider the influences of compressive stress on CTOD. Zhang et al. (2010, 2007) and Iranpour and Taheri (2014) elaborate the distributions of displacement and stress fields in the vicinity of crack tip under compressive stresses. However the aforementioned studies cannot apply to the determination of CTOD as they only give qualitative predictions, but not quantitative results.

To fill the research gap of CTOD estimation under compressive portions within cyclic loadings, this paper will conduct a quantitative study on the influence of compressive stress on CTOD. The main purpose is to develop a simple calculation model of CTOD under compressive stress. Firstly, the trend of CTOD is analyzed and two variables are introduced, the residual CTOD (symbolized by δ_0) and the variation of CTOD (symbolized by $\Delta'\delta$). A simple method to determine CTOD under compressive loading is proposed by subtracting $\Delta'\delta$ from δ_0. Subsequently, a series of simulation cases are performed to cover the effects of various parameters on $\Delta'\delta$, namely range of plate width, crack length, stress level (the maximum tensile and compressive stresses) and material property (yield stress, elastic modulus and material hardening). Finally, a function relationship between $\Delta'\delta$ and compressive stress is obtained, and the calculation model for CTOD is estabilished. It is noticed that the calculation model is applicable to center-cracked finite plates of various materials, filling the research gap of CTOD estimation under tension-compression load at stress ratio $R < 0$.

Abbreviations: CTOD, crack-tip opening displacement; MCOD, the maximum crack opening displacement; COD, crack opening displacement; VCTOD, the variation of CTOD

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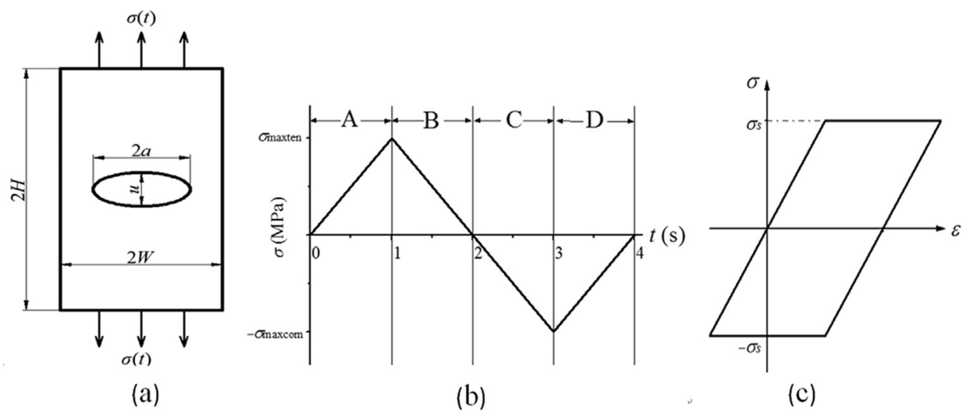

Fig. 1. A center-cracked plate under tension-compression load. (a) Plate model. (b) Loading history. (c) Cyclic stress-strain curve.

2. Finite element model

The specimen used in this work is a center-cracked plate subjected to uniaxial tension-compression loading. The crack is open under tension loading, as shown in Fig. 1(a). a = 10 mm, W = 13a, and H = 15a. Since the values of W/a and H/a are large enough, the end effect is considered negligible and the plate can be approximately taken as an infinite one. The material is assumed to be elastic-perfectly plastic and the cyclic stress-strain curve is described as Fig. 1(c). The properties of the material are as follows: Elastic modulus E = 210 GPa, the yield stress σ_s = 235 MPa and Poisson's ratio μ= 0.3. The uniaxial tension-compression load $\sigma(t)$ is applied perpendicularly toward the crack surface. The maximum tensile stress σ_{maxten} = 90 MPa and the absolute value of maximum compressive stress σ_{maxcom} = 200 MPa, as presented in Fig. 1(b).

The finite element software ANSYS (v14.5) is employed for the two-dimensional modeling and elastic-plastic analysis. The Von Mises criterion is used. Due to the symmetry, only half of the specimen is modeled with symmetrical constraint boundary conditions. The finite element mesh, which is composed of 17236 eight-node isoperimetric quadrilateral elements, is highly refined near the crack tip and enlarged gradually at relatively remote positions, as showed in Fig. 2. To simulate the contact behavior of crack surfaces under compression loadings, one pair of contact elements is used, the target element (targe169) and the contact element (conta173). CTOD is extracted from the opening displacement normal to the crack surface of the node behind the initial crack tip. The finite element model is developed based on that in our previous works, which has been sufficiently validated for the analysis of crack-tip opening displacement.

3. Relationship between CTOD and compressive stress

Elastic-plastic finite element analysis is performed with the model mentioned above and the results of CTOD varying with time are plotted in Fig. 3.

In Fig. 3, it is obvious that CTOD is none-zero at t = 2 s, indicating that the crack tip reminds open when the tension stress is unloaded from the peak to zero (B in Fig. 1). This phenomenon is also corroborated by other investigators with different materials (Iranpour and Taheri, 2014; Makabe et al., 2004; Zhang et al., 2010, 2007). The non-zero CTOD occurs due to the plastic deformation at the crack tip. CTOD at the peak tensile load consists of elastic and plastic CTOD, and the latter cannot return to zero even if the load has been removed. Therefore, the non-zero residual CTOD is left. The residual CTOD will result in stress concentration at the crack tip during the subsequent loading. Moreover, CTOD is inversely proportional to the compressive stress during compressive loading (C in Fig. 1). With the increase of compressive stress, CTOD decreases significantly at first, then relatively slowly and finally trends to zero. That is because the reduction of CTOD decreases the influence of CTOD as a stress raiser, which will in turn affect the changing rate of CTOD.

In order to facilitate the analysis of CTOD during compressive loading, two variables are introduced: the residual CTOD δ_0 and the variation of CTOD $\Delta'\delta$, which are defined as described in Fig. 3.
δ_0 is the value of CTOD at zero applied stress when unloading from peak tensile stress. In our previous work, simple approximate formulae (Eq.(1)) are proposed for the estimation of CTOD under the tensile portion (A and B in Fig. 1) based on the maximum crack opening displacement (MCOD) and the variation of MCOD. MCOD (symbolized as u) is the maximum value of crack opening displacement (COD) normal to the crack surface, which is also defined as COD at the midpoint of crack length under uniform tension, as described in Fig. 1(a). It is noticed that these formulae consider the influences of plate width, crack length, applied stress and material property. Hence, δ_0 can be obtained with these formulae by measuring MCOD.

$$\frac{\delta E}{\sigma_s a} = -0.0132\left(\frac{uE}{\sigma_s a}\right)^3 + 0.20604\left(\frac{uE}{\sigma_s a}\right)^2 - 0.01268\left(\frac{uE}{\sigma_s a}\right) + 0.00639 \quad \text{(tensile loading)}$$
$$\frac{\Delta\delta E}{\sigma_s a} = 0.00114\left(\frac{\Delta uE}{\sigma_s a}\right)^3 + 0.0745\left(\frac{\Delta uE}{\sigma_s a}\right)^2 + 0.03202\left(\frac{\Delta uE}{\sigma_s a}\right) + 0.00164 \quad \text{(tensile unloading)} \tag{1}$$

Where $\Delta\delta$ and Δu are the variations of CTOD and MCOD during tensile unloading, which can be calculated from $\Delta u = u_{\max} - u$ and $\Delta\delta = \delta_{\max} - \delta$.
$\Delta'\delta$, variation of CTOD (VCTOD), is the difference between δ_0 and instantaneous CTOD δ during compressive loading. It can be expressed as follows:

$$\Delta'\delta = \delta_0 - \delta \tag{2}$$

Hence, δ during compressive loading can be easily obtained as long as $\Delta'\delta$ is determined. Considering MCOD remains zero and CTOD is a function of compressive stress (Iranpour and Taheri, 2014) during compressive loading, the main objective of the present study is to develop a method to estimate $\Delta'\delta$ based on compressive stress σ_{com}.

Fig. 4 shows the relationship between $\Delta'\delta E/a$ and σ_{com} under the given conditions. According to these results, an exponential function expression can be fitted. However, it is worth noting that these results are derived on the basis of specific conditions. Before the function expression is fitted, the influences of some factors should be taken into further consideration in the subsequent section, namely crack length, plate width, stress level (the maximum tensile and compressive stresses) and material property (yield stress, elastic modulus and material hardening).