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Research on CTOD for low-cycle fatigue analysis of central-through cracked plates considering accumulative plastic strain

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ABSTRACT

The plastic strain accumulation at the crack tips are used as controlling parameter to estimate cyclic CTOD for low-cycle failure analysis of the central-through cracked plate. The second order polynomial for the normalized CTOD defined as a function of the accumulative plastic strain, the ratio of mean stress to the yield stress, and the crack length is fitted by the least square method. The new accumulative plastic strain based on CTOD estimation presented in this paper provides a new way for low-cycle fatigue analysis, considering accumulative plastic damage for central-through cracked plates under high cyclic loadings.

1. Introduction

The fatigue strength of ship's structure has very important for the safety and survivability. With the increase in ship dimensions and the increased use of high-strength steel in recent years, ship structures are subjected to high stress and large deformation resulting in low-cycle-fatigue (LCF) damage to large-scale ships. This has become the key issue demanding prompt solution in the development of large-scale ships. For cracked plates of ship and marine structures, plastic strain would be generated near the crack tip when the local stress reaches the yield strength. When a ship is subjects to cyclic loads due to waves, plastic strain would accumulate in the local region of the crack tip, and this accumulative incremental plastic strain would speed up the fracture failure of the structure when it accumulates to a certain value with increase in the number of the cyclic loadings. Crack tip opening displacement (CTOD) and J integral are the major parameters to describe crack propagation of ductile structural materials [10]. However, J integral is rarely used to assess the structural fracture under cyclic loads because it cannot apply to unloading state. Therefore, studying and establishing assessment methods of CTOD based on accumulated plastic strain under cyclic loading are of great practical significance.

CTOD reflects the plastic deformation performance in the region near crack tip; its value reflects the resistance of material fracture toughness at crack tip. It is a measurement of plastic deformation at crack tip, so it is widely used as a criterion of the fracture failure. Previously, CTOD calculation models based on stress intensity factor K had been proposed for applying only to linear elastic state [7], Cottrell [4] and Yaowu [25]. Dugdale [7] model has been widely studied and used for establishing the corresponding relationship between external loads and crack parameters. Jiang [11] analyzed CTOD of ship stiffened plate based on Dugdale model and established the rules for predicting the influence of external load, stiffness ratio and other

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Nomenclature

δ	CTOD crack tip opening displacement
$\Delta\delta$	the variation of CTOD
$\Delta\varepsilon_p$	the accumulative increment plastic strain
σ_s	yield stress
σ	stress
σ_m	mean stress
σ_a	stress amplitude
K_I	stress intensity factor
a	crack length
$\bar{a}$	equivalent crack length
W	width of stiffened plate
$\Delta\sigma^p_{x(n+1)}, \Delta\sigma^p_{y(n+1)}$	plastic stresses and strains in $n+1$ cycle
$\Delta\varepsilon^p_{x(n+1)}, \Delta\varepsilon^p_{y(n+1)}$	plastic strains in $n+1$ cycle
b'	material cyclic hardening coefficient
K'	the cyclic strength coefficient

factors. Finite element method (Wu et al. [24]; Chen, 2010), [12] is one of the efficient ways in studying elastic–plastic fracture problems, and is widely used in various kinds of fracture assessments. It is used to study CTOD and other relative parameters through calculation of crack-tip stress-field and displacement-field. Wu et al. [24] proposed an effective method to estimate fracture toughness of the test specimen based on the numerical results of CTOD. In their study, elastic–plastic finite element method is used to calculate the CTOD, taking tensile specimen with axial notch as the research object. Chen [5], Chen and Huang [12] has carried out numerical analysis of CTOD based on the crack mouth opening displacement (CMOD), and simplified the finite element calculation model by eliminating the effects of external load, model dimensions, material properties, and crack length. Besides, some scholars have studied CTOD based on the local strain at the crack tip, and proposed the CTOD calculation model that can only be applied to low strain and static loading [22,15,13]. Shimanuki and Inoue [23] proposed a new method to assess local stress based on the relationship between local stress and linear elastic fracture mechanics. He discussed the corresponding relationship between local strain and CTOD, and realized the idea of determining CTOD based on local strain by two-dimensional finite element method. There are a lot of discussions about using these calculation models for cracked structures under complex load. At present, many scholars have studied CTOD under complex loads, after putting forward CTOD calculation models [3,26], Østby et al. [19] calculated large plastic strain of cracked pipeline structure, and proposed a simple CTOD evaluation method based on the plastic strain. Zhang et al. [27] discussed the CTOD evaluation model for marine pipeline structure under large plastic strain, considering the influence of crack size, material hardening exponent and external loads.

Among the above mentioned analyses, the studies on CTOD are either confined to linear elastic state or only about finite element analysis of plastic strain under static load. There are few fracture assessments of cracked plate under LCF load. Taking central-through cracked plate as the study object, this paper establishes a CTOD calculation model based on accumulative plastic strain at crack tip, under low cycle fatigue and high stress external load. The influence of mean stress and crack length is analyzed. The analysis provides a feasible way for fracture failure assessment for ship and marine structural component under actual cyclic loading.

2. Theoretical analysis

2.1. The relationship between CTOD and accumulative increment plastic strain at crack tip

Based on Dugdale model, Budiansky and Hutchinson [1] studied the effect of different stress ratio on plasticity induced crack closure (PICC) under the constant ΔK in crack propagation, and they put forward the relationship between crack tip opening displacement amplitude ΔCTOD and ΔK_{eff}:

$$\Delta \mathrm{CTOD} = 0.73\frac{(\Delta K_{\mathrm{eff}})^2}{E\sigma_Y} \tag{1}$$

where ΔK_{eff} is the effective stress intensity factor range, σ_Y is the yield strength of material and E is the elastic modulus.

In the determined plane state, the effective stress intensity factor range ΔK_{eff} is a function of stress amplitude $\Delta\sigma$, for infinite central-through cracked plate under cyclic loading, the corresponding function between CTOD and cyclic stress $\Delta\sigma$ of can be expressed as: