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Two simplified methods for fatigue crack growth prediction under compression-compression cyclic loading

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ABSTRACT

Submersibles and submarines are subject to cyclic compressive sea loading during their service life, which is quite different from the ships and platforms under tensile and bending loading. It is important to study the fatigue crack propagation under cyclic compression in order to assess the fatigue life of the submersible and submarine. An extended McEvily model is proposed for the fatigue crack growth prediction under cyclic compression-compression loading. First, Finite Element Method (FEM) simulation and a simplified stress estimation method are proposed for efficient fatigue crack growth analysis. In the Finite Element Method simulation, the crack opening loads of different crack lengths are calculated individually instead of plastic wake calculation behind crack tip with node releasing technique, which will save a lot of calculating time. Afterwards the fatigue life under cyclic compression is predicted based on new fatigue crack growth rate curve model for cyclic compression. Meanwhile the analytical method is an engineering estimation for fatigue crack growth under constant amplitude compression. In this method, the crack opening load is estimated based on the symmetry of compression and tension. Then the fatigue life under cyclic compression is also predicted based on a new model for cyclic compression. Finally, fatigue life prediction of a double edged specimen under cyclic compressive loading is taken for example to illustrate the analysis procedure of two simplified methods. By comparing the predicted results with the test data, it is found that the *a-N* curve and final crack length by two methods are in good agreement with the test data, so the Finite Element Method and analytical method are reasonable and feasible for fatigue crack growth prediction of deepwater structure under cyclic compression.

1. Introduction

Deepwater structures such as deep diving submersibles and submarines are subject to cyclic compressive sea loading during their service life, which is quite different from the ships and platforms under tensile and bending loading. Cyclic compressive sea loading will cause low cycle fatigue damage of submersibles and submarines. Weld defects in the pressure hull of the submersible are inevitable during the fabrication procedure. Stress concentration will occur at weld defects under compression loading similar with stress concentration at the notch, which may cause the crack initiation and propagation. So it is important to study the fatigue crack propagation under cyclic compression in order to assess the fatigue life of the submersible. According to ASTM E647, it is assumed only the effective part of tension stress intensity factor range will lead to fatigue crack growth based on the Paris law, while the compression stress range will not lead to crack growth at all. However, Paris law is not valid in cyclic compression-compression

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Nomenclature

N	Load cycles
a	Crack length
$\mathrm{d}a/\mathrm{d}N$	Crack growth rate
$K_{\max}$	Maximum stress intensity factor
$K_{\min}$	Minimum stress intensity factor
ΔK	Stress intensity factor range
K_C	Fracture toughness
K_{op}	The stress intensity factor at the crack opening level
ΔK_{eff}	The effective stress intensity factor range
ΔK_{effth}	The threshold of the effective stress intensity factor range
f_{op}	A crack opening function defined as the ratio $K_{op}/K_{\max}$
R	The stress ratio defined by $\sigma_{\min}/\sigma_{\max}$
A	A material constant in the crack growth rate model
m	A constant representing the slope of the corresponding fatigue crack growth rate curve in crack growth rate model
n	The index indicating the unstable fracture in the crack growth rate model
$\sigma_{\max}$	The maximum stress level
$\sigma_{\min}$	The minimum stress level
σ_{op}	The crack opening stress level
σ_Y	The yield stress of the material
σ_u	The ultimate strength of the material
σ_V	The "virtual strength" of the material representing the material strength at limit of "perfect" condition ($r_e = 0$)
r_e	An empirical material constant of the inherent flaw length of the order of 1 μm
$Y(a)$	A geometrical factor to calculate the stress intensity factors under crack length a
E	Elastic modulus of the material

fatigue loadings. It was observed that cracks initiated and grew at the notch roots despite the fact that loading was fully compressive in tests [1–3]. The residual tensile stress induced by the compressive loads was the driving force for crack growth and the crack growth rate decreased during the crack propagation. In recent years, many studies were performed to investigate the fatigue crack growth behavior under cyclic compression loading and most of them are based on the crack closure theory. Huang et al. [4] analyzed the residual stress along the crack surface by Finite Element Method (FEM) and predicted the crack growth under compressive fluctuating loading based on a unique crack growth rate curve model. Cui et al. [5] proposed a unified fatigue life prediction method (extended McEvily model) for marine structures and illustrated this method can be applied to crack growth prediction under compressive loading, but the details was not mentioned. Li et al. [6]proposed a plasticity-corrected stress intensity factor (PC-SIF) range and demonstrated that the PC-SIF was an effective single mechanical parameter for crack growth under cyclic compressive loading. Vasudevan and Sadananda [7] proposed a unified method in which the two parameters of stress intensity factor range ΔK and maximum intensity factor $K_{\max}$ are both the crack growth driving forces. This method is extended for fatigue life prediction from cyclic tension fatigue analysis to cyclic compression fatigue analysis without the assumption of crack closure [8]. Luo et al. [9] calculated the residual stress distribution along the crack grows by multi-step analysis and node releasing technology using FEM and the crack growth life was predicted based on the unified (extended McEvily) model. The major drawback is that the calculation of residual stress distribution with the crack growth is very time consuming.

In the present study, the authors attend to calculate the fatigue crack growth under cyclic loading without explicitly releasing the node, which will be computationally very efficient. First, an extended McEvily model is proposed for the fatigue crack growth prediction under cyclic compression-compression loading. Following this, a Finite Element Method (FEM) and a simplified stress estimation method for cyclic compression is proposed to improve the calculation efficiency, which are more convenient and less time consuming. Finally, the double edged specimen under constant amplitude compression is used to illustrate the analysis procedure of two simplified methods and validate the feasibility of these two methods.

2. Life prediction methodology

The stress intensity factor calculation and fatigue crack growth rate model are two important factors in fatigue life prediction under cyclic compression. If these two factors are achieved, the fatigue life under cyclic compression can be calculated with cycle by cycle integration from initial crack length to the final crack length.

2.1. New crack growth rate model for cyclic compression

There are many equations or models for describing the crack growth rate curve ${}^{da}/_{dN} \sim \Delta K$. The most popular one is the Paris model [10], which is expressed as Eq. (1).

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m \tag{1}$$

where C and m are material parameter constants.$\mathrm{d}a/\mathrm{d}N$ is crack growth rate.ΔK is stress intensity factor range.

The Paris model is widely used in crack growth prediction and has been coded in some commercial software because of its simplicity. Elber [11]proposed an effective stress intensity factor model based on the crack closure concept to collapse the crack growth rate curves under different R ratios into one curve of ${}^{da}/_{dN} \sim \Delta K_{eff}$.