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Fatigue crack propagation prediction for marine structures based on a spectral method

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A R T I C L E   I N F O

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A B S T R A C T

A method based on spectrum analysis is proposed for predicting fatigue crack propagation (FCP) of a crack in marine structures. The stress intensity factors (SIF) for a crack can be different under different load cases, such as loading conditions, heading angles and wave frequencies, even at the same level of nominal or hotspot stress. Therefore, the load spectrum obtained from the stress transfer function and wave spectrum may be failing to calculate the FCP accurately. In current study, SIF transfer functions were evaluated through detailed structural analysis for different crack sizes, and the short term SIF distribution obtained from the SIF transfer function. FCP life could then be calculated from numerous short term SIF distribution and the improved Paris formula. A sub-model technique was integrated, facilitating SIF re-analysis due to crack growth, and an Improved Euler method was adopted to reduce the computational steps. FCP of a semi elliptical surface crack at the weld toe between hatch coaming and forward bulkhead of a container ship superstructure was used to demonstrate the application of the proposed spectral method. This paper offers a way of combining the spectral analysis and fracture mechanics in fatigue crack growth calculation for marine structures.

1. Introduction

Ships and marine structures are subjected to fluctuating loading at sea, which could lead to inducing fatigue crack growth. Generally, ships are designed with a fatigue life of 25 years using conventional high cycle fatigue principles, i.e., the S-N method (Det Norsk Veritas, 2010). However, large uncertainties are often disregarded in ship structural fatigue analysis, such as real wave environments, corrosion, weld defects, etc. (Cui, 2003; Fricke et al., 2002). These factors contribute to fatigue cracks being initiated much earlier than expected in many vessels, which challenge ship safety and reliability.

The high expenses of repairs and lost time mean that it is not practical or possible to repair every minor to moderate crack at once (Mao, 2014). Hence, forecasting fatigue crack growth and identifying specific cracks that are critical to structural integrity are important issues (Okawa et al., 2007). Therefore, tools and methods based on fracture mechanics are required to predict fatigue crack propagation (FCP) lifetime and crack growing path rationally and accurately.

Among S-N methods, spectral based fatigue analysis provides a more accurate method to consider some factors, with a clear and reasonable calculation process (American Bureau Of Shipping, 2016). However, FCP using spectral based methods for marine structures is rarely applied. Some scholars (Jang et al., 2010; Mao, 2014; Yan et al., 2016a; 2016b) have derived the load spectrum, consisting of stress ranges, from the stress transfer function and wave spectrum, with the stress intensity factor (SIF) then calculated by empirical formula or a finite element model (FEM) to simulate the FCP. This is referred to as the stress spectral method.

Unfortunately, there are two drawbacks when using load spectra obtained from stress transfer functions in FCP.

(1) It is not easy to find the relationship between the SIF and the stress when the crack in the complex stress field. One needs to choose the appropriate stress (normally the maximum stress on the top surfaces), and then calculates the SIFs by empirical formula or FEA. However, many critical spots of marine structure are in complex stress states and may subject to tension, bending, shear, and non-uniform distributed boundary stresses synchronously. Thus, it can be difficult to determine how SIF can be calculated accurately from stress for the actual structure.
(2) The boundary conditions of actual structures are very complicated, and a single stress value cannot represent the true loading conditions. That is, the SIF for a crack can be different under different load cases, such as loading conditions and heading angles etc., even for the same value of nominal or hotspot stress. Thus, it may be difficult to determine a harmonious relationship between stress and

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Nomenclature

ω	Angular frequency (rad/s)
θ	Heading angles
U	Ship forward speed used in seakeeping analysis and spectral analysis, equal to 2/3 times design speed
H_s	Significant wave height
T_z	Wave period
$H_{sif}(\omega\|\theta)$	SIF transfer function
$S(\omega\|H_s, T_z)$	Wave energy spectrum
$S_{sif}(\omega\|\theta, H_s, T_z)$	SIF energy spectrum
λ_n	N-th order SIF energy spectral moment
K	SIF amplitude induced by waves
ΔK	SIF range induced by waves
ΔK_n	Nominal SIF range induced by waves
K_{static}	SIF induced by still water bending moment
ΔK_{eff}	Effective SIF range
K_{eq}	Equivalent SIF of mixed fracture modes
K_{max}, K_{min}	Maximum and minimum SIF value
K_{res}	SIF induced by residual stress
$\varsigma(K)$	Probability density function of SIF amplitude induced by waves
$\varsigma_{\Delta K}(\Delta K_n)$	Probability density function of nominal SIF range induced by waves
σ_x	Rayleigh distribution scale parameter
f	Average zero-up crossing frequency
$\lambda_0\lambda_2$	Zeroth, second order SIF energy spectral moment
da/dN	Fatigue crack propagation rate
C, m	Coefficient and exponent in crack growth relationship
β, β_1	Exponential parameters in Huang's model
R	Stress ratio
M_R	Correction factor for the effect of stress ratio
ΔK_{th}	Threshold of SIF range corresponding to stress ratio R = 0
$\Delta K'_{th}$	Value of ΔK when $M_R \Delta K \geq \Delta K_{th}$
da_i	Crack increment in a sea state i
$E(\cdot)$	Expected value
ΔN_i	The number of load cycles in sea state i
a, c	Depth and half length of the semi-elliptical crack
a_0, c_0	The initial crack size
Δa_{tol}	Accuracy controlling parameter
a_f	Critical crack depth

Subscripts

i	Sea state i
I, II, III	Opening, sliding and tearing fracture mode
a, c	Deepest point, surface ends point of a semi-elliptical crack

SIF for a crack in complex structural detail.

This study proposes an approach to predict fatigue crack propagation incorporating spectral analysis. Section 2 presents a method to generate short term SIF distributions for real structural details. Combining the short-term SIF distributions and improved Paris formula to calculate FCP directly is described in section 3. Validation for the proposed spectral methods are demonstrated using a semi-elliptical surface crack in a rectangular plate and a semi elliptical surface crack at the weld joint toe of a detail between hatch coaming and superstructure of a container ship in section 4 and section 5.

2. Spectral analysis for marine structures

Linear elastic fracture mechanics (LEFM) is often used to predict FCP (Stephens et al., 2000). The empirical Paris Law has become a

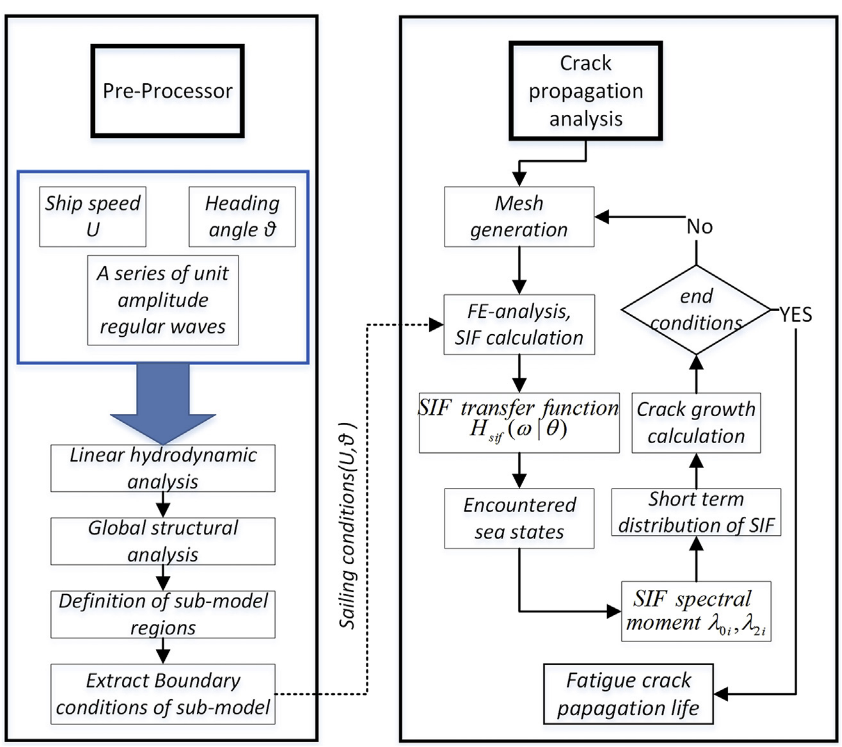

Fig. 1. Proposed spectral analysis procedure for fatigue crack propagation in marine structures.