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Stochastic nonlinear fatigue crack growth predictions for simple specimens subject to representative ship structural loading sequences

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ABSTRACT

Recent work by the authors investigated an extension of the finite element analysis of plasticity-induced crack closure to non-stationary, ship structural loading sequences by taking advantage of their inherent time-dependent nature in which the larger loading cycles tend to be clustered together. In doing so, first-order load interactions are presumed to arise from the random occurrence and severity of physical storms encountered by ships and offshore structures throughout their service lives. This material hysteresis is captured through a time-dependent crack “opening” level (K_{op}) which is based on the evolution of a rate-independent, incremental plasticity model simulating combined nonlinear kinematic and isotropic hardening. The result is a mechanistic rather than phenomenological numerical model requiring only experimentally measured fatigue crack growth rates under constant amplitude, cyclic loading (e.g., ASTM E647-13) and a full material constitutive model defined through experimental push–pull tests for the same material. This approach permits a consideration of material behaviors which are physically relevant to structural steels, yet necessarily omitted in the similar application of a strip-yield model.

The present paper generalizes the model originally proposed by the authors to now consider arbitrary storm model loading sequences taken from high-fidelity, time-domain seakeeping codes. To predict the fatigue fracture induced by variable amplitude stress records with upwards of 5×10^6 time-dependent cycles, a consistent modeling reduction is applied based on the Ordered Overall Range (OOR) or racetrack counting method. The resultant crack growth behavior is demonstrated to converge remarkably well for sufficiently small refined mesh sizes. Using this model, and by considering different arrangements of the same stress record, the importance of nonlinearities (i.e., those associated with ship response as well as material hysteresis) are emphasized.

1. Introduction

Despite an underlying safe-life design approach, detectable fatigue cracks are routinely observed in ship structures during scheduled maintenance periods and inspections. While these cracks are not considered to be an immediate threat to the structural integrity of the ship, their behavior is nevertheless not well-understood from the standpoint of a damage tolerant design. This owes partially to the fact that applicable physical experiments are largely impractical considering the sheer size of the structures involved, variabilities in fabrication, and the roughly 10^8 time-dependent cycles which comprise a nominal service life. But more so, it stems from the uniqueness of the non-stationary, stochastic loading typical of the marine environment through which known load interactions are introduced. The present paper aims to elucidate the macroscopic fatigue crack growth behavior associated with representative ship structural loading sequences through the consideration of cycle-by-cycle material hysteresis based on a time-dependent crack “opening” level. In doing so, a novel modeling approach is presented which extends the finite element analysis of plasticity-induced crack closure to variable-amplitude, high-cycle fatigue predictions.

1.1. The time-dependent, nonlinear nature of ship structural loading

The non-stationary, stochastic nature of the marine environment is most commonly represented in a time-independent fashion through a wave-scatter diagram, e.g., [1]. While this is a convenient approximation ideally suited to a linear damage hypothesis, it is a poor reflection of reality. Nevertheless, to the best of the authors’ knowledge, only two time-dependent alternatives exist (i.e., aside from real-time measurements). The first approach relies on hindcast weather data. Specifically, a vessel is

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Nomenclature

a	crack length – see Fig. 1	N	cycle number within a time-dependent load sequence
Δa	refined mesh size/extent of incremental crack advance	R	stress ratio, $R = S_{min}/S_{max}$
C, m	Paris law coefficient/exponent	$2\ r_f$	monotonic forward plastic zone size (Irwin's approximation) $2\ r_f = 1/(\alpha\ \pi)\ (K_{max}/\sigma_o)^2$
da/dN	crack growth rate per loading cycle	S	applied remote stress (associated with a specific K)
H_s	significant wave height	S_{max}	maximum applied remote stress
i	subscript denoting the current increment of discrete crack growth in the underlying elastic–plastic finite element analysis	S_{min}	minimum applied remote stress
K	(Mode-I) stress intensity factor	T_z	zero-crossing period
K_{max}	(Mode-I) maximum stress intensity factor	U_o	vessel steady forward speed
K_{min}	(Mode-I) minimum stress intensity factor	α	plastic constraint factor, $\alpha = 1$ (plane-stress) and $\alpha = 3$ (plane-strain)
K_{op}	(Mode-I) crack "opening" stress intensity factor	β	wave heading angle (head seas = 180°)
ΔK	(Mode-I) stress intensity factor range $\Delta K = (K_{max} - K_{min})\ \forall R \geqslant 0$; $\Delta K = K_{max}\ \forall R < 0$	σ_o	flow stress (stress at which plastic flow initiates)
ΔK_{eff}	(Mode-I) effective stress intensity factor range $\Delta K = (K_{max} - K_{op})\vert K_{op} \in [K_{min},\ K_{max}]$	σ_y	yield stress (0.2% offset)
n	number of significant reversal pairs explicitly simulated between each increment of crack advance (Δa)	σ_u	ultimate tensile strength

piloted over a notional route (in the past) for which localized sea conditions are known (based on past physical measurements) as a function of time. The second approach relies on the storm model loading originally proposed by Tomita et al. [2] in which a storm condition (comprising physical storms of varying severity) and a non-storm condition are taken as mutually exclusive events which alternate, in random order. The non-storm condition is modeled as a time-independent process and is defined according to a maximum or threshold significant wave height. The storm condition, on the other hand, applies to periods of time during which the significant wave height exceeds this threshold. During a storm, the significant wave height (i.e., that which characterizes the underlying spectrum) increases with time, reaches a maximum, and then decreases to its previous non-storm condition value.

In a typical spectral-based fatigue analysis, stress transfer functions or response amplitude operators (RAOs) are used to determine ship motions and responses within the context of linear seakeeping theory, e.g., [3,4]. While this can be an accurate engineering approximation in many applications, it fails to capture two important nonlinearities which are especially relevant to physical storms. First, as wave height increases, the accuracy of a wall-sided hullform approximation lessens causing the hogging and sagging vertical bending moments to be distributed differently. The result can be viewed as adding skewness to an otherwise assumed Gaussian process. Second, these storms can cause bow emergence which, upon subsequent re-entry above a certain threshold relative velocity, produces an impact load (slam event), inducing a 2-node vibration of the primary ship hull girder (whipping response). The resultant structural vibrations occur at a much higher frequency than the wave-induced bending response and tend to enlarge the sagging moment, but decay (i.e., for typical values of structural damping) before having a similar effect on the subsequent hogging moment. Unlike wave-induced vertical bending, the nonlinearities associated with a whipping response tend to be highly correlated in time. This results in an additional non-stationary process, albeit at a shorter timescale than discussed in the preceding paragraph. Recent work by Matsuda and Gotoh [5], considering superimposed loading sequences at two different

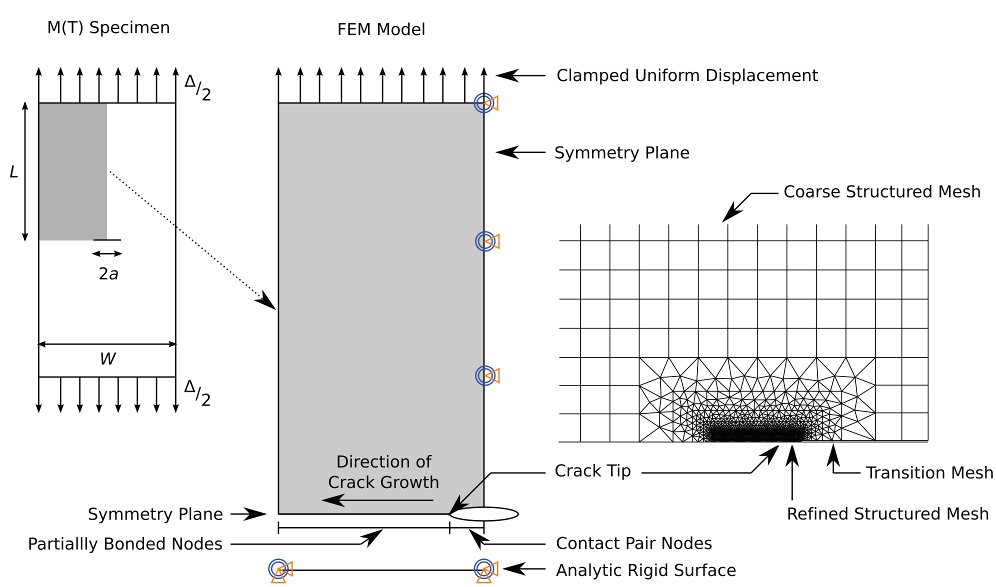

Fig. 1. Finite element model of M(T) specimen in Abaqus™ – see Section 2.3.1.