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Optimum inspection planning for minimizing fatigue damage detection delay of ship hull structures

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ABSTRACT

Fatigue is one of the main factors which can produce cracks, and lead to failure of ships. For these structures, damage occurrence and propagation due to fatigue are affected by the action of sea water waves and the sea environment as well as operation, fabrication, and modeling of ship structures under uncertainties. In order to efficiently maintain the safety of ship structures, an optimum inspection plan should be made by considering these uncertainties using a probabilistic approach. In this paper, such an approach is presented and applied to ship hull structures subjected to fatigue. The resulting inspection plan is the solution of an optimization problem based on the minimization of expected fatigue damage detection delay. Damage detection delay will produce the maintenance delay which, in turn, is likely to endanger the serviceability and even the survival of the structure. The formulation of the expected damage detection delay includes uncertainties associated with damage occurrence, propagation, and detection. The effects of the quality and number of inspections on the optimum inspection planning are investigated. A well-balanced inspection planning is considered as a solution of an optimization problem with two conflicting criteria. This well-balanced inspection planning provides optimum inspection types and times. Furthermore, the cost-effective inspection plans are designed to provide the optimum strategy either by considering a single type or multiple types of inspections.

1. Introduction

The deterioration of a ship structure over its service life can be the result of fatigue induced by various loadings. The fatigue can develop into crack, and lead to unexpected failure or out-of-service of the ship structure. This problem is one of the major threats to the structural integrity of deteriorating ship structures [1]. Due to both aleatory and epistemic uncertainties associated with the action of sea water waves and the sea environment as well as operation, fabrication, and modeling of ship structures, a probabilistic approach has to be applied to assess and predict their fatigue performance [18,19,27,28,3]. Such an approach can provide cost-effective inspection maintenance strategies for structure managers to maintain or extend the service life of ship structures. Approaches for reliability-based optimum inspection and maintenance planning of ship structures were proposed by Madsen and Sørensen [18], Madsen et al. [19], and Garbatov and Soares [12], among others.

Maintenance actions generally depend on the inspection quality [23,10,11,21]. Ship inspections can lead to effective and timely maintenance actions. If the inspection reveals that cracking due to fatigue is present, an appropriate repair should be applied [9]. However, if damage is not detected, repair will not be applied on time. Damage detection delay will produce maintenance delay which, in turn, is likely to endanger the serviceability and even the survival of the structure. The damage detection delay is caused by the uncertainties related to an inspection method and time of damage occurrence. Therefore, a probabilistic approach considering these uncertainties in a rational way should be used to establish a cost-effective inspection planning associated with minimum damage detection delay. Probabilistic inspection and monitoring planning for reinforced concrete structures based on corrosion damage detection delay was studied in Kim and Frangopol [16].

In this study, a probabilistic approach to establish the cost-effective inspection planning is presented and applied to ship hull structures subjected to fatigue. The optimum inspection plan is based on the minimization of expected fatigue damage detection delay. The formulation of the expected fatigue damage detection delay includes uncertainties associated with damage occurrence time and probability of damage detection. The probability of detection is expressed by the damage intensity in terms of time-dependent crack size under uncertainty. The effects of probability of detection and number of inspections on expected damage

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detection delay are investigated. Increasing the number of inspections and/or probability of detection require additional cost, while the expected damage detection delay is reduced. A well-balanced inspection planning is considered as a solution of a bi-objective optimization problem with two conflicting criteria associated with the minimization of both expected damage detection delay and total inspection cost. The inspection cost is estimated considering quality of an inspection method. This well-balanced inspection planning provides optimum inspection types and times. Furthermore, the cost-effective inspection plans are provided considering same type or different types of inspections.

2. Prediction of crack length

Fatigue is the process of initiation and growth of cracks under repetitive loads; the crack may be pre-existing from fabrication, and be initiated by fatigue and/or corrosion [9]. The crack growth can be affected by the location and length of initial crack, stress range near the initial crack, number of cycles associated with the stress range, material and geometric properties of a structure with crack damage [9]. All these factors have complex relation to each other. Due to this complexity of the fatigue fracture process, it is difficult to predict crack length accurately. So far several empirical and phenomenological-based crack propagation models have been proposed to predict fatigue life [8,26,22]. In order to predict crack length, Paris' equation based on linear elastic fracture mechanics has been generally used. The ratio of the crack length increment to stress cycle increment is described by the following equation [25]

$$\frac{da}{dN} = C(\Delta K)^m \quad \text{for } \Delta K > \Delta K_{thr} \tag{1}$$

where a is the crack length; N is the number of cycles; ΔK is the stress intensity factor; and ΔK_{thr} is the threshold of stress intensity factor. C and m are material parameters. The stress intensity factor ΔK is [15]

$$\Delta K = S \cdot Y(a)\sqrt{\pi a} \tag{2}$$

where S is the stress range, and $Y(a)$ is the geometry function. If the geometry function is constant (*i.e.*, $Y(a) = Y$) and the stress intensity factor ΔK is larger than ΔK_{thr}, the crack length after N cycles $a(N)$ can be obtained by integrating Eq. (1) [17]

$$a(N) = \left[a_o^{(2-m)/2} + \left(\frac{2-m}{2}\right) \cdot C \cdot S^m \cdot Y^m \cdot \pi^{m/2} \cdot N\right]^{\left(\frac{2}{2-m}\right)} \quad \text{for } m \neq 2 \tag{3a}$$

$$a(N) = a_o \cdot \exp[C \cdot S^m \cdot Y^m \cdot \pi \cdot N] \quad \text{for } m = 2 \tag{3b}$$

where a_0 is the initial crack length when $N = 0$. When the annual number of cycles N_{an} is constant over time t (years), the total number of cycles N after t years is $t \times N_{an}$. The time t to crack propagation from the initial crack length a_0 to the crack length a_t can be obtained as [27,28]

$$t = \frac{a_t^{(2-m)/2} - a_o^{(2-m)/2}}{\left(\frac{2-m}{2}\right) \cdot C \cdot S^m \cdot Y^m \cdot \pi^{m/2} \cdot N_{an}} \quad \text{for } m \neq 2 \tag{4a}$$

$$t = \frac{\ln(a_t) - \ln(a_o)}{C \cdot S^m \cdot Y^m \cdot \pi \cdot N_{an}} \quad \text{for } m = 2 \tag{4b}$$

3. Probability of damage detection

Inspection methods to detect and measure cracks in steel member include ultrasonic inspection, magnetic particle inspection, penetrant inspection, radiographic inspection, acoustic emission inspection, and visual inspection [9,5]. Results from these inspection methods include significant uncertainties [23,10] related to damage occurrence and the imperfection of an inspection method, among others. In order to detect damage on time, the uncertainties associated with both prediction of damage occurrence/propagation and quality of inspection should be treated in a rational way.

The inspection quality is related to the probability that a given degree of damage is detected [19]. The probability of damage detection depends on the degree of damage intensity (*i.e.*, crack length or defect size) and quality of inspection. Packman et al. [24], Berens and Hovey [4], Madsen et al. [19], Mori and Ellingwood [23], and Chung et al. [5] investigated the relation between probability of detection and crack length or defect size. The representative forms of this relation include a shifted exponential form, logistic curve form, and normal cumulative distribution function (CDF) form. In this study, the normal CDF form based on damage intensity is used. The value of damage intensity ranges from zero (*i.e.*, no damage) to one (*i.e.*, full damage) [10]. The damage intensity function $\delta(t)$ at time t in terms of crack length a_t can be expressed as

$$\delta(t) = 0 \quad \text{for } a_t < a_{\min} \tag{5a}$$

$$\delta(t) = \frac{a_t - a_{\min}}{a_{\max} - a_{\min}} \quad \text{for } a_{\min} \leqslant a_t < a_{\max} \tag{5b}$$

$$\delta(t) = 1 \quad \text{for } a_{\max} \leqslant a_t \tag{5c}$$

where a_t is the crack length at time t. $a_{\min}$ and $a_{\max}$ are the minimum and maximum crack length for damage intensity $\delta(t)$, respectively. When the crack length a_t is less than $a_{\min}$, the damage intensity $\delta(t)$ is zero. Conversely, if the crack length a_t is equal to or larger than $a_{\max}$, the damage intensity is one; in this case the cracked component will lose its structural capacity.

The probability of detection P_d for given damage intensity $\delta(t)$ is estimated as [10]

$$P_d = \Phi\left(\frac{\delta(t) - \delta_{0.5}}{\sigma_\delta}\right) \tag{6}$$

where $\Phi(\cdot)$ is the standard normal CDF; $\delta_{0.5}$ is the damage intensity at which the inspection method has a probability of detection of 0.5; and σ_δ is the standard deviation of the damage intensity. In this study, σ_δ is assumed $0.1\delta_{0.5}$. In Eq. (6), the quality of inspection is characterized by $\delta_{0.5}$. An inspection method with a larger value of $\delta_{0.5}$ has a lower

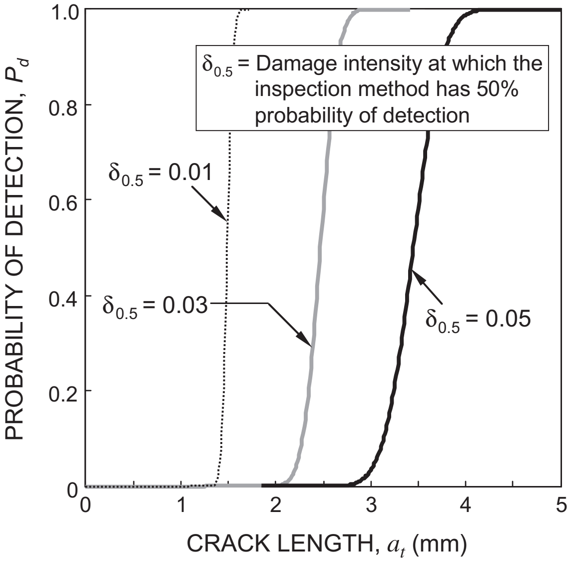

Fig. 1. Relation between probability of detection and crack length for $\delta_{0.5} = 0.01$, $\delta_{0.5} = 0.03$, and $\delta_{0.5} = 0.05$.