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A probabilistic approach for optimizing inspection, monitoring, and maintenance actions against fatigue of critical ship details

Mohamed Soliman [a], Dan M. Frangopol [b,*], Alysson Mondoro [b]

[a] *School of Civil and Environmental Engineering, College of Engineering, Architecture and Technology, Oklahoma State University, 207 Engineering South, Stillwater, OK 74078-5033, United States*

[b] *Department of Civil and Environmental Engineering, ATLSS Engineering Research Center, Lehigh University, 117 ATLSS Dr., Bethlehem, PA 18015-4729, United States*

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ABSTRACT

Fatigue is one of the main deteriorating mechanisms that affect the safety and reliability of ship structures. Fatigue cracks can appear at various locations along the ship structure and may occur at early stages in the service life of a ship. Inspection, monitoring and/or repair actions are applied to prevent sudden failures of damaged structural components and their associated consequences. However, these actions increase the operational cost of the ship and should be optimally planned during its service life. Due to the presence of significant uncertainties associated with crack initiation and propagation, the planning of such actions should be performed probabilistically. In this paper, a probabilistic approach for inspection, monitoring, and maintenance optimization for ship details under fatigue effects is proposed. Based on the stress profile and the crack geometry at the damaged location, intervention times and types are determined by solving an optimization problem which simultaneously minimizes the life-cycle cost, maximizes the expected service life, and minimizes the expected maintenance delay over the life-cycle. The life-cycle cost includes the cost of inspection, monitoring, and maintenance actions, as well as the cost of failure of the detail. The proposed approach is applied to a side shell detail of a steel ship.

1. Introduction

Ship structures are subjected to various environmental and mechanical stressors through their service life. These stressors may induce several types of structural deterioration including fatigue damage [1]. Fatigue is defined as the process of damage accumulation resulting from repeated load fluctuations. The damage may occur around regions of high stress concentrations where there are existing flaws in the material due to welding and/or fabrication. Over a certain number of stress fluctuations, the initiation and propagation of cracks may occur, and, eventually, cause fracture in the component [2]. Inspection and monitoring actions are performed to assist in fatigue damage diagnosis and prognosis [3]. Additionally, maintenance and repairs can be performed to improve the structural performance and extend the service life [4].

However, these actions significantly impact the total life-cycle cost of a structure, especially if their application requires setting the structure out of service for a certain period of time. Moreover, since fatigue damage may lead to catastrophic failures [5], delayed maintenance can endanger the serviceability and survival of a structure. Therefore, minimizing the maintenance delay, defined in general as the time lag between the damage occurrence and the application of the maintenance, may require additional inspections and maintenance actions to be performed yielding a higher life-cycle cost. Thus, interventions must be rationally planned along the service life of a structure to maintain an optimal balance between the service life, life-cycle cost, and maintenance delay. This task represents a major challenge for infrastructure managers due to the presence of various uncertainties associated with the performance prediction, damage initiation and propagation, inspection and monitoring outcomes, and the effect of maintenance on the structural performance. Therefore, the optimization of these interventions must be performed within a probabilistic framework.

Several approaches have been proposed for the probabilistic inspection and/or maintenance planning for fatigue critical structures [6–9]. In these studies, probabilistic performance indicators such as the probabilistic damage level (e.g., crack size) or reliability index have been used. The main outcomes of such studies include the optimum non-destructive inspection (NDI) times and types, as

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[*] Corresponding author.

E-mail addresses: mohamed.soliman@okstate.edu (M. Soliman), dan.frangopol@lehigh.edu (D.M. Frangopol), alm312@lehigh.edu (A. Mondoro).

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well as, the ideal maintenance times. In addition to these outcomes, Kim et al. [10] and Kwon and Frangopol [11] provide the optimum maintenance types for fatigue critical structures under uncertainty.

The use of monitoring systems with automated ability to detect fatigue crack growth has emerged as an alternative to traditional NDI methods. These systems rely on installing sensors that continuously monitor and record the structural response or emissions and attempt to identify and localize the damage based on the recorded data. Thus, they can detect the damage with minimal disturbance to the operational schedule of the ship. An example of such systems is the acoustic emission (AE) monitoring for steel and aluminum structures [12–14]. However, the use of long-term monitoring may impose a high life-cycle cost associated with the continuous need to transfer and process acquired data, in addition to the maintenance of the monitoring system itself.

As a result, several studies focused on optimizing the inspection and monitoring activities along the service life of a structure. Kim and Frangopol [8] proposed an approach for the inspection and monitoring optimization of structures under fatigue effects. The approach was focused on minimizing the expected damage detection delay and the inspection and monitoring cost. Orcesi and Frangopol [15] proposed another approach in which the optimization problem was formulated to find the best monitoring plan to minimize the error in the collected data that arises from interrupting the monitoring activities throughout the service life. Minimizing the monitoring cost was also included as an objective. Although these studies performed the scheduling for inspection and monitoring actions, maintenance and repair planning was not included; this limits their applicability and precludes them from being integrated into a method to extend service life.

This paper proposes a comprehensive probabilistic framework for optimizing the inspection, monitoring, and maintenance activities during the service life of fatigue critical structures with emphasis on ship details. A multi-objective optimization problem is formulated and solved to simultaneously minimize the total life-cycle cost, maximize the expected service life, and minimize the expected maintenance delay. The life-cycle cost includes the costs associated with inspection, monitoring, and maintenance activities, as well as the expected failure cost. This last cost is computed by combining the monetary loss resulting from structural failure and the time-based probability of failure defined in terms of the required service life and the probability density function (PDF) of the service life extended through the application of maintenance actions.

The proposed approach contributes to the life-cycle management problem by: (a) being able to simultaneously schedule inspection, monitoring, and maintenance activities, (b) integrating the probability of failure and the failure cost into the life-cycle cost formulation, and (c) providing the ability to minimize the delay associated with the application of maintenance actions along the service life. The results of this approach are the optimum inspection times, monitoring times and durations, and critical crack size for applying maintenance. This approach provides the ability to use the damage level measured during inspection and monitoring actions to identify the need for maintenance. Accordingly, the resulting management plans allow for an effective and reliable decision making process. The proposed approach is illustrated on a ship detail subjected to fatigue.

2. Time-based performance and probability of failure

Fatigue cracking represents a major threat to the safety and reliability of ship structures. Fatigue problems manifest themselves in ships due to the nature of fluctuating sea loads and the large number of welded connections where stress concentrations may arise. Despite the existence of several design codes and regulations to assist in the fatigue design and assessment, fatigue cracking occurs in various types of ships [16]. Fatigue cracking is a highly uncertain phenomenon; this justifies the use of probabilistic methodologies to assess the fatigue reliability and service life [17].

Traditionally, the fatigue behavior of ship structures is assessed through either the S–N (i.e., stress-life) approach or the methodologies based on fracture mechanics. The S–N approach is widely used by the codes and regulations for fatigue design and assessment [18–20]. However, it cannot be used to study the crack condition at a damaged detail. For ship details, linear elastic fracture mechanics can be used for studying the crack growth [2]. In this paper, the fatigue performance is measured in terms of the probabilistic damage level which is considered herein as the time-dependent crack size obtained by employing Paris' equation. This equation relates the crack growth rate to the range of the stress intensity factor and is given by [21]:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{1}$$

where a is the crack size, N is the number of cycles, ΔK represents the range of the stress intensity factor, while C and m are material parameters. The range of the stress intensity factor can be expressed as:

$$\Delta K = K(a) \cdot S_{re} \cdot \sqrt{\pi a} \tag{2}$$

where S_{re} is the equivalent constant-amplitude stress range and $K(a)$ is the generalized stress intensity factor which depends on the crack orientation and shape. This factor takes into account the effects of the elliptical crack shape, free surface, finite width (or thickness), and non-uniform stress acting on the crack. Detailed empirical and exact solutions for $K(a)$ can be found in [5,22].

Based on Eqs. (1) and (2), the cumulative number of cycles required for the crack to grow from an initial size of a_o to a size of a_t is

$$N = \frac{1}{C \cdot S_{re}^m} \cdot \int_{a_o}^{a_t} \frac{1}{\left(K(a) \cdot \sqrt{\pi a}\right)^m} da \tag{3}$$

Considering the annual average number of cycles N_{avg}, the number of years t associated with a crack growth from a_o to a size of a_t is

$$t = \frac{1}{N_{avg} \cdot C \cdot S_{re}^m} \cdot \int_{a_o}^{a_t} \frac{1}{\left(K(a) \cdot \sqrt{\pi a}\right)^m} da \tag{4}$$

By considering a_t to be equal to the critical crack size a_f, the time to failure T (i.e., service life) of the detail can be obtained. Since the initial crack size a_0, crack growth parameter C, exponent m, stress range S_{re}, and the average annual number of cycles N_{avg} are random, Monte Carlo simulation is used to draw samples from the time to failure T.

The PDF of $T, f_T(t)$, can be then obtained through an appropriate distribution fitting process such as the maximum likelihood method [23]. For small time interval Δt and a given time t, this PDF provides the probability that the failure will occur between the time t and $(t + \Delta t)$. Therefore, it has the following probabilistic interpretation [24]:

$$f_T(t) = \frac{P(t \leqslant T \leqslant (t + \Delta t))}{\Delta t} \tag{5}$$

where $P(\cdot)$ represents the probability of occurrence of the event between parentheses. Based on the simulated PDF, $f_T(t)$, the cumulative probability of failure (CDF), $F_T(t)$, representing the probability that the time to failure T (i.e., service life) of a component is less than t, is calculated as: