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Incorporation of risk and updating in inspection of fatigue-sensitive details of ship structures

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ABSTRACT

Fatigue cracks, as a structural deterioration mechanism, may lead to unanticipated out of service of naval ships. Consequently, risk assessment and effective inspection planning of naval ships under fatigue damage are needed to achieve economic and sustainable performance of these structures. This paper presents a probabilistic framework for fatigue risk and updating assessment and updating through inspection events. The computation associated with fatigue damage is performed using fracture mechanics and uncertainties are considered within this process. Furthermore, a quantitative risk assessment model using rating functions is presented to identify inspection priority among multiple fatigue-sensitive details. Bayesian techniques are adopted for reliability and risk updating of both inspected and uninspected fatigue-sensitive details at component and system levels. Additionally, correlation of fatigue damage among different critical details is considered and incorporated within risk assessment and updating. A number of analyses are performed to investigate the fatigue risk ranking assessment and updating. Applications are presented on an existing tanker with multiple fatigue-sensitive details.

1. Introduction

Fatigue crack of ship critical details has always been a main concern associated with ship operation and is one of the deterioration mechanisms that can affect structural performance. Fatigue cracks may propagate and reach critical sizes; ultimately they can lead to unstable crack growth and/or unanticipated out of service. Generally, these cracks are prone to initiate at welded details due to the existence of initial defects, as qualitatively shown in Fig. 1(a), caused by several factors such as welding, fatigue loading, and/or environment [33,9]. Traditionally, non-destructive inspections (NDIs) are applied to ship structures periodically without considering the damage level associated with time. Inspection results can be used to update fatigue reliability and risk of investigated structural systems during their remaining service life using Bayes' techniques. Fatigue crack assessment should be performed during service life of ship structures in order to prevent loss of survivability and to achieve economic and reliable performance. This paper aims to develop a probabilistic framework incorporating risk and updating in the inspection of fatigue-sensitive details of ship structures.

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The fatigue deterioration process of structural systems is highly uncertain. Therefore, a probabilistic approach is necessary for considering this deterioration process. The assessment of fatigue crack size under uncertainty is qualitatively shown in Fig. 1(b). As indicated, the fatigue crack size increases significantly with time and uncertainties are incorporated within the process. The uncertainties are also associated with inspection events. The outcomes of an inspection event are affected by many factors, such as type of inspection method, human factors, and inspection quality. Consequently, uncertainties should be incorporated within the risk-informed decision making and updating. During the past few decades, the field of ship structural reliability assessment has been developed considerably [8,24,39,21,18,19,30]. In its most broad terms, structural reliability is a measure of the probability of a system's survival given a limit state. Reliability-based structural performance indicators reflect the uncertainty in load, resistance, and modeling. A risk-based performance indicator provides means of combining the probability of components or system failure with consequences of this event [12].

There has been a lack of research that focuses on risk-based performance assessment of ship structures. The importance of risk as a performance indicator for the inspection planning decision making is emphasized in this paper. The schematic flowchart of risk-informed inspection decision making process is shown in Fig. 2. The first step associated with the proposed methodology is to

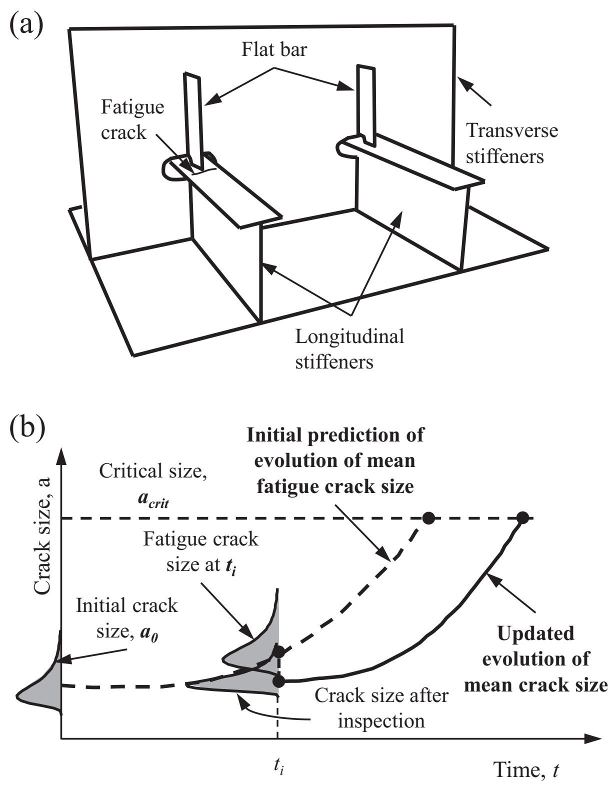

Fig. 1. (a) Typical fatigue crack of structural detail of a ship structure and (b) fatigue crack size evolution with and without inspection under uncertainty.

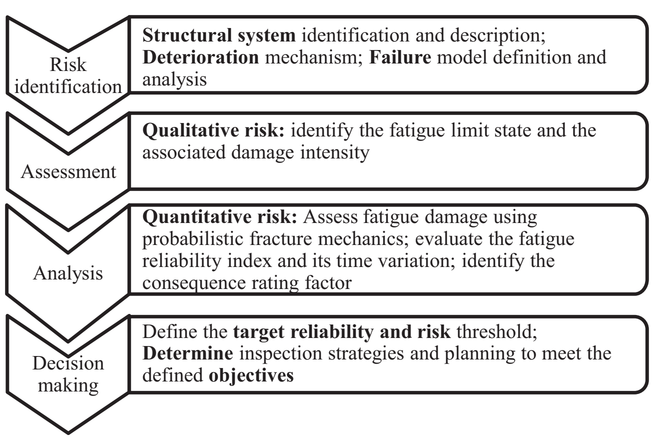

Fig. 2. Schematic flowchart of risk-informed decision making using a qualitative/quantitative model.

identify structural deterioration, possible hazard scenarios, and structural details that should be inspected. Subsequently, qualitative and quantitative risk assessments are conducted for the investigated details. Generally, qualitative risk assessment requires approximate estimates of failure likelihood and its consequences, while quantitative indicators of failure likelihood and consequences are needed for quantitative assessment associated with fatigue-sensitive details under high qualitative risk. To the best knowledge of the authors, there have been no studies focusing on the risk assessment and updating of multiple fatigue-sensitive details at system level using inspection information. This paper addresses this issue in detail. Finally, given the performance threshold associated with risk, the inspection decision can be made in a probabilistic life-cycle context [14].

The information on inspected details can be used to update deterioration models of a structural system to reduce epistemic uncertainty. The fatigue details associated with a given structural system are correlated due to common parameters associated with materials, design, fabrication, loading, and operational conditions. Based on these correlations, the inspection information of one particular detail can be used to update deterioration performance of others uninspected details. Probabilistic models have been used to evaluate and update the fatigue reliability using inspection information. These models can be used to determine the optimal number of inspected details to make the inspection strategies efficient and economic. Ayala-Uraga and Moan [4] and Moan and Song [25] investigated system fatigue reliability issues considering fatigue failure and updating based on inspection; Chen et al. [7] proposed a methodology for inspection planning on the basis of Palmgren–Miner's rule and fracture mechanics; Huang and Guedes Soares [16] computed the fatigue reliability index of a complex welded structure as a series model under multiple cracks; Maljaars and Vrouwenvelder [23] presented a reliability-based updating considering multiple critical locations in a bridge. While previous studies have emphasized on reliability-based decision making process using updating, there is limited research regarding transferring the information associated with a given inspection event to risk assessment of other details and/or system performance assessment considering numerous details. Another novelty of this paper derives from the risk assessment at system level under a specific system failure event. Based on the system risk, the inspection planning and repair priority among the investigated fatigue sensitive systems can be identified. In turn, the inspection results can be used to update risk and the timing for the following inspection.

This paper presents a probabilistic framework for fatigue reliability and risk assessment and updating through inspection events. The flowchart for risk-informed inspection planning for a structural system under fatigue damage considering updating under multiple fatigue-sensitive details is shown in Fig. 3. The computation associated with fatigue damage is performed using probabilistic fracture mechanics. Bayesian techniques [41,42] are adopted for reliability and risk updating of both inspected and uninspected fatigue-sensitive details. Additionally, correlation of fatigue damage among different critical details is considered and incorporated within risk assessment and updating. A number of analyses have been performed to investigate the fatigue risk assessment and updating. A methodology to quantify the risk using rating functions, which have the ability to take different consequences into account, is proposed in this paper. By using rating functions, the consequences with different units can all be transferred into the rating values. Additionally, the decision maker's preference can also be incorporated within the rating assessment process. The optimal inspection plan can be established on the basis of the comparison between the updated risk and target risk. Moreover, the inspection decision making process involves consideration of economic, environmental, and other factors. Applications are made on an existing tanker with multiple fatigue-sensitive details. Overall, this approach can aid in risk-informed decision making of ship structures under fatigue damage.

2. Fatigue reliability analysis: a review

Fatigue cracks generally initiate at structural discontinuities such as the welded detail of the intersection of longitudinal and transverse internal supporting members as shown in Fig. 1(a). One of the commonly used methods is Paris law which uses linear elastic fracture mechanics to predict the crack growth [29]. The fatigue crack reliability analysis is related to various factors such