Ocean Engineering 101 (2015) 161–171

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Risk-informed life-cycle optimum inspection and maintenance of ship structures considering corrosion and fatigue

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ARTICLE INFO

Article history:
Received 4 December 2014
Accepted 4 April 2015
Available online 28 April 2015

Keywords:
Risk assessment
Optimization
Inspection planning
Corrosion and fatigue crack
Uncertainty
Life-cycle maintenance

ABSTRACT

During its life-cycle, a ship structure may suffer from structural deterioration associated with corrosion and/or fatigue. A prolonged exposure to these hazards results in a reduction of structural resistance which can lead to failure. Optimum inspection and maintenance planning of ship structures is a challenging process needed to ensure ship safety during the life-cycle. This paper presents a probabilistic approach to provide optimum inspection and repair plans for ship structures considering corrosion and fatigue. Uncertainties in the damage assessment associated with corrosion and fatigue are taken into account. Risk is assessed by considering the direct losses associated with flexural failure. A multi-objective optimization problem, which accounts for structural deterioration scenarios and various uncertainties, is formulated to find the optimum inspection and repair planning of ship structures. The life-cycle risk associated with flexural failure and expected total inspection and maintenance costs are considered as conflicting criteria. The proposed probabilistic optimization approach is illustrated on the VLCC ship structure. Genetic algorithms are used to solve the optimization problem.

1. Introduction

Aging ships may suffer from structural deterioration associated with corrosion and/or fatigue, resulting in a reduction of their resistance. This reduction can lead to structural failure. Moreover, load effects on ship structures contain high levels of uncertainty and may exceed the associated design loads. Inspection and maintenance of aging ship structures are needed to ensure satisfactory structural performance during their life-cycle (Kim and Frangopol, 2012; Kwon et al., 2013; Zhu and Frangopol, 2013a; Zhu and Frangopol, 2013b). In general, the most significant strength deterioration mechanisms associated with ship structures are corrosion and fatigue (Guedes Soares and Garbatov, 1999; Kwon and Frangopol, 2012). Therefore, it is essential to mitigate the adverse consequences associated with structural failure under corrosion and fatigue. Furthermore, there are significant uncertainties associated with corrosion and fatigue models. The corrosion of a ship structure is affected by many factors such as corrosion protection, temperature and humidity. Fatigue crack propagation is also affected by many parameters such as initial crack size, history of local nominal stresses, and load sequence. Consequently, uncertainties must be incorporated within the structural performance deterioration process. This paper aims to provide a probabilistic methodology for optimum inspection and maintenance planning of ship structures to mitigate risk under corrosion and fatigue.

Crack growth at a critical structural detail can be predicted using fracture mechanics. The most commonly used mechanistic model is based on the Paris-Erdogan formula (Paris and Erdogan, 1963). Overall, fatigue cracks can propagate under repetitive loadings and affect structural integrity associated with ship hulls, while corrosion can also affect the ultimate strength of ship structures. Therefore, it is of vital importance to control the relevant fatigue cracks and corrosion level to meet the design and operational tolerance levels for ship structures. The fatigue model that predicts cracking damage considered in this paper is incorporated within a corrosion model to investigate the ship performance level associated with ultimate flexural failure. In general, structural damage associated with corrosion and fatigue can reduce the ship load-carrying capacity. Moreover, such damage may lead to partial failure or total loss of marine vessels. In order to minimize the economic loss and fatalities associated with structural failure, it is of vital importance to investigate ship performance under corrosion and fatigue. In this paper, the separate and combined effects of corrosion and fatigue on ship structural ultimate flexural failure are considered.

During the past few decades, the field of ship structural reliability assessment has been developed considerably (Paik and Frieze, 2001; Okasha et al., 2011; Frangopol and Soliman, 2014).

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http://dx.doi.org/10.1016/j.oceaneng.2015.04.020
0029-8018/

In its most broad terms, structural reliability is a measure of the probability of a system's survival under a given limit state. Ship performance associated with ultimate flexural failure of the hull's mid-ship section is considered as one of the most critical criteria regarding ship safety assessment (Decò et al., 2011, 2012). The probability of failure and reliability index of ships have been previously investigated by Ayyub et al. (2000), Paik and Frieze (2001) and Okasha et al. (2011). Reliability-based structural performance indicators reflect the uncertainty in load, resistance, and modeling. However, these indicators do not account for the outcome of a failure event in terms of economic losses. A risk-based performance indicator provides means of combining the probability of component or system failure with consequences of this event. Nowadays, risk is an essential structural performance indicator (IACS, 2006; Decò and Frangopol, 2013, 2015; Dong and Frangopol 2015). Although there have been significant efforts to investigate reliability of ship structures, 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 is emphasized in this paper. The flowchart for risk assessment of ship structures considering corrosion and fatigue is shown in Fig. 1. Since failures associated with ship structures have significant impacts on surrounding economic, social, and environmental networks, risk-based methodologies are more appropriate for life-cycle management of ships. Accordingly, risk-based methodologies can be used to determine the optimal intervention strategies. However, to the best of authors' knowledge, there have been no studies to establish a framework for risk-based optimum inspection and maintenance planning of ship structures considering corrosion and fatigue.

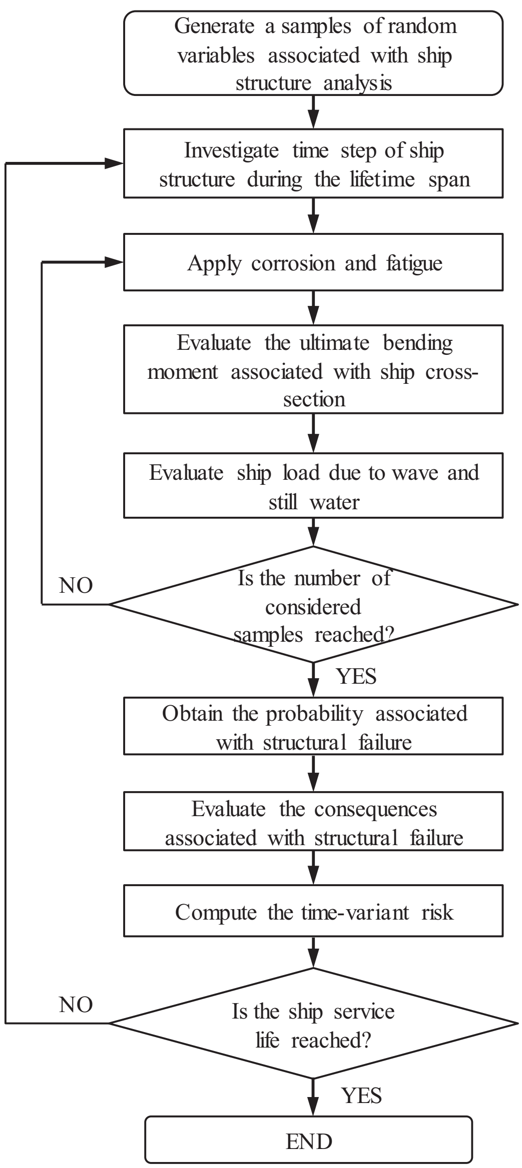

Fig. 1. Flowchart for the life-cycle risk assessment of ship structures considering corrosion and fatigue.

Overall, inspection and maintenance planning focuses on estimating the timing and types of these actions to ensure structural safety and serviceability under corrosion and fatigue. Multi-objective optimization concepts and sensitivity analysis methods play an important role in allocating limited resources in an efficient way to balance both cost and performance (Frangopol, 1985; Bucher and Frangopol, 2006; Frangopol, 2011; Frangopol and Soliman, 2015). Within the adopted bi-objective framework, the risk is aimed to be minimized during an investigated time horizon. Recent efforts have performed optimization procedures that minimize the life-cycle cost of a structure under given constraints on performance (Okasha and Frangopol, 2009; Kim and Frangopol, 2011; Kim et al., 2013). Although extensive research has been conducted on the optimization of intervention strategies based on life-cycle costs, there is very limited research regarding risk-informed life-cycle optimization of ship structures. The best inspection and maintenance plans can be obtained through an optimization process that considers risk and cost of keeping structural performance above prescribed thresholds during the life-cycle of marine vessels.

In this paper, a probabilistic framework for risk-informed life-cycle optimum maintenance of ship structures is presented. The effects of corrosion and fatigue on the ultimate strength of ships are considered in the framework; additionally, uncertainties associated with these two deteriorating mechanisms are incorporated within the risk assessment process. The effects of inspection and repair on the ultimate bending moment are assessed. The methodology proposed in this paper can quantify risk-based structural performance of ships during their life-cycles. A bi-objective optimization problem accounting for common deterioration mechanisms and their associated uncertainties is formulated to find the best lifetime inspection and repair plan for ship structures. The maximum annual risk associated with ship structural failure during the investigated time interval, in addition to expected total inspection and repair costs are considered as conflicting criteria. The proposed probabilistic approach uses optimization techniques based on genetic algorithms (GAs) in order to determine optimum inspection planning that reduces the extent of adverse consequence associated with ship failure while simultaneously minimizing the expected total maintenance cost. Decision makers can use the results of the proposed approach to make optimal risk-informed decisions regarding life-cycle inspection and repair of ships. The capabilities of the approach are demonstrated through its application to a real vessel, the Very Large Crude Carrier (VLCC) ship structure. GAs are used to solve the bi-objective optimization problem.

2. Risk assessment

Risk-based performance measures combine the probability of system failure with the consequences associated with this particular event. In general, since failures associated with structural systems result in significant economic and social impacts, risk-based methodologies are most appropriate for structural system management. The aim of risk-based management is to develop a management plan that can prevent failures and, consequently, reduce the impact of adverse consequences. The importance of