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Fatigue reliability of a web frame subjected to random non-uniform corrosion wastage

W. Huang, Y. Garbatov, C. Guedes Soares *

Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

An approach for reliability assessment of a welded structure subjected to corrosion degradation and fatigue is developed. The objective of this work is to evaluate the fatigue reliability of a complicated ship welded structure subjected to random non-uniform corrosion and fatigue loading simultaneously. A three-dimensional finite element model accounting for randomly distributed non-uniform corrosion wastage based on non-linear time-dependent model is generated. Randomly corroded surface geometries are simulated by the use of the Monte Carlo simulation technique for different service times of corrosion wastage and linear elastic finite element analysis are performed. Hotspot stresses around welded details on a web frame joint are determined. Based on nonlinear regression analysis, the time-dependent functions for the hot-spot stresses affected by corrosion deterioration are fitted. The relationship between the structural fatigue damage and corrosion deterioration caused by corrosion thickness wastage at different times is quantified employing S–N approach. The statistical properties of fatigue damage and service life of critical hot-spots in the web frame welded joint are estimated taking into account random non-uniform time-dependent corrosion wastage. The fatigue reliability of the web frame welded joint during its service life is modelled as a series system of correlated components using the Ditlevsen bounds method.

1. Introduction

Corrosion and fatigue have been recognised as significant and major damage mechanisms for marine structures. Fatigue strength is modelled as a time-variant process that decreases as a function of corrosion wastage. These two phenomena have a common characteristic that they are a monotonic time variant function. With the extension of the service life, the problem of fatigue damage becomes to be even more important and has received a special attention recently. These problems are of a major importance to the structural safety of ageing marine structures, many of which continue to operate beyond their design service life.

Stiffener welded frame structures, analysed here, are common structural components in ship hull structure and they have a major role in providing strength to the overall hull girder. The fatigue damage assessment accounting for the effect of corrosion is particularly important because the failure is generally in an unstable mode, which has harmful consequences from the point of view of safety. Statistics for ship hulls show that around 90% of ship structural failures are attributed to corrosion, including corrosion fatigue [1].

Two main corrosion mechanisms are generally present in marine structures. One is a general corrosion wastage that reflects in a generalised decrease of plate thickness, which in turn decreases the actual area of the structural cross section and thus induces higher stress concentration levels for the same applied loadings. Another mechanism is pitting, which consists of much localised corrosion with very deep holes appearing is the structural surface.

There are many studies about the considered models of general corrosion wastage during the last decades. Shi [2] has studied the effect of general corrosion in decreasing the thickness of the plating linearly with time. However, Southwell et al. [3] have observed that the wastage thickness increases non-linearly in a period initial exposure, but afterwards it becomes relatively constant, and Guedes Soares and Garbatov [4] proposed a model that describes that type of growth of corrosion wastage by a non-linear function of time in three phases. Guedes Soares et al. [5] proposed a new corrosion wastage model based on a reference non-linear time-dependent corrosion model that is modified by the effect of different environmental factors contained in the marine atmosphere. The reference to these aforementioned works shows that

* Corresponding author.
E-mail address: guedess@mar.ist.utl.pt (C. Guedes Soares).

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the non-linear time dependence of corrosion rate has been already demonstrated to be more appropriate.

Much effort has been spent to develop methodologies for predicting the fatigue strength or life of welded joints in structures. The main steps in fatigue analysis are based on direct calculations that involve the description of the wave induced loading [6], the stress distribution [7], fatigue life estimation [8] and the probabilistic evaluation of the different steps to arrive at a reliability index or time dependent reliability [9].

The hot-spot stress approach, using the structural stress range at the weld, considers additionally the effect of the structural discontinuity. The hot-spot stress approach accounts for the stress increases due to the structural configuration or in other words, the macro-geometry. The hot-spot stress approach [10,11] defines the reference points for the stress evaluation and extrapolation at certain distances away from the weld, which depend on the plate or shell thickness. Fricke and Kahl [12] applied three different structural stress approaches to fatigue strength assessment of three welded structural details. Fatigue lives were predicted using the design S–N curves recommended within the different approaches and compared with the results of fatigue tests evaluated for a corresponding probability of survival.

Many earlier studies have been carried out to predict the behaviour of structures affected by fatigue damage and corrosion degradation in a deterministic way. But fatigue life is affected by the randomness of loads, structural geometry, quality of welds and welding defects as well as material properties, the structural fatigue damage can be modelled as a stochastic process [13]. The damage mechanism caused by corrosion is more complicated, and there is a large amount of uncertainties in the corrosion fatigue failure process. The occurrence of corrosion, their spatial distribution on a structure, and the time-dependent growth and interactions in-service are random phenomena, therefore probabilistic approaches have been already recommended to better analyse the effect of those aforementioned uncertainties and random variables on fatigue life.

Due to the casualties of ageing ships during the last two decades, several studies on the reliability assessment of ship structures subjected to corrosion and fatigue were performed. The time variant formulation of ship reliability results from modelling the problem with stochastic processes that represent the random nature of the load and strength parameters. Normally both fatigue and corrosion are present and their combined effect needs to be considered in that the decreased net section due to corrosion will increase the stress levels, which in turn increase the rate of crack growth [14]. This effect has been considered in [15], which showed that depending on the repair policy adopted one of the two phenomena, would be the dominating one.

The model proposed by Caiza and Ummenhofera [16] is one alternative to describe the statistical fatigue behaviour, based on fatigue test results, which are described by the three-parameter Weibull distribution. Pagnacco et al. [17] established a probabilistic distribution model of stochastic fatigue damage, where the stochastic stress process is interpreted by the random distribution of stress amplitude and cycles at a given amplitude, and randomness of fatigue resistance of material is described by introducing a random variable of single cycle fatigue damage.

Classical theory of system maintenance describes the failure of components by probabilistic models, often of the Weibull family, which represent failure rates in operational phases and in the ageing phases of the life of components as described in various textbooks [18–20].

Probabilistic approaches can provide tools to better assess the impact of uncertainties and random variables on the component service life and probability of failure. Probabilistic tools applied to risk-based condition assessment and life prediction help managers to make better risk-informed decisions regarding ship structures. In addition to assessing structural reliability, probabilistic methods also provide information for performing an analysis of the cost of continuing operation based on risks and their financial consequence.

Fatigue reliability considering corrosion and fatigue has received increasing attention recently. Guedes Soares and Garbatov [21] have dealt with this problem in terms of its impact on the global hull girder of ships, as a result of the distribution of global loads. The next step is to move to the important components of the structure, such as stiffened panels and stiffeners and to use a more detailed modeling based on finite element results, to predict more accurately the local fatigue damage [22,23].

However the present study is different from the one presented in [22,23] and investigates the effect of non-linear randomly distributed non-uniform corrosion wastage on the structural reliability of a complex web frame structure subjected to fatigue loading. A three-dimensional finite element model of the web frame structure with welded details accounting for randomly distributed corrosion wastage is generated by the use of the commercial finite element code ANSYS, applying 20-node solid elements. Corrosion wastage growth rate varies with the time non-linearly and is modelled as a random variable. Monte Carlo simulation is employed for computing the local stochastic hot-spot stresses (mean stress and stress range). Time-dependent hot-spot stresses of welded details increase because of corrosion degradation in time. The probabilistic characteristics of structural stresses and cumulative fatigue damage of all the hot-spots in the welded structure analysed here are estimated at different service time. The Ditlevsen bounds [24] are used to calculate the fatigue reliability of the web frame during its service life, which is modelled as a series system of correlated components.

2. Corrosion model

The conventional models of corrosion assume a constant corrosion rate, leading to a linear relationship between the material lost and time. Experimental evidence of corrosion reported by various authors show that a non-linear model is more appropriate. A non-linear model of time that developed in [4] describes the growth of corrosion in three different phases is adopted here. In the initial phase, $t \in [0, A]$ as can be seen in Fig. 1, it is assumed that there is no corrosion because the corrosion protection system of metal structure surface is effective. In the second phase, failure of the protection system will occur at a random point of time, and then the corrosion wastage will initiate, which decreases the thickness of the plate as a function of time, $t \in [A, B]$. In the third phase, the

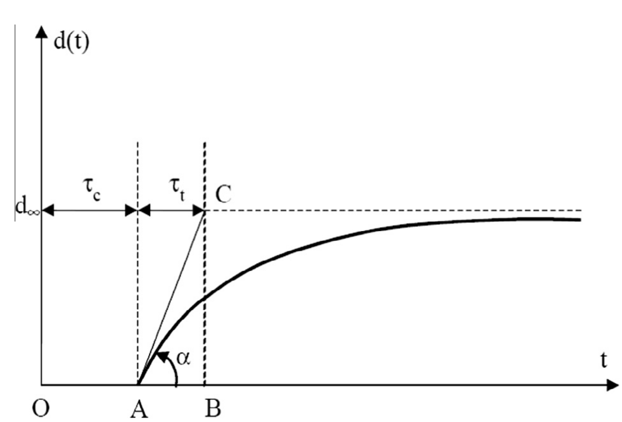

Fig. 1. Thickness of corrosion wastage as a function of time [4].