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Fatigue reliability assessment of a complex welded structure subjected to multiple cracks

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ABSTRACT

A probabilistic approach for fatigue reliability assessment of a complicated ship welded structure subjected to a correlated growth of multiple site cracks is developed here. It is assumed that five through thickness cracks will initiate and propagate at the critical hotspots in the web frame structure. Stress intensity factors at the tips of cracks, considering all possible combinations of all cracks of different lengths, are calculated by finite element analysis. The geometry correction functions of the five cracks, as a function of a crack size are determined by using nonlinear regression analysis estimating the statistical descriptors of the five geometry correction functions. The Paris–Erdogan law is used to predict the fatigue crack propagation life. Fatigue reliability of the web-frame welded structure is evaluated while accounting for the correlation between any two-fatigue failure modes caused by multiple site fatigue cracks propagating in the welded structure.

1. Introduction

With the service life extension requirements, structural fatigue damage becomes an even more important problem. This problem is of major importance to the structural safety of marine structures, many of which continue to operate beyond their design service life. Fatigue assessment has been gaining attention during the last decades and much effort has been spent to develop methodologies for predicting their life, namely the ones based on crack growth approaches.

Web-frame welded structures, analysed here, are common structure in ship hull and they have a major role in providing strength to the overall hull girder. The fatigue damage assessment is particularly important because when the failure is in an unstable mode, it has harmful consequences from the point of view of safety. Statistics for ship hulls show that ship structural failures are predominantly attributed to fatigue and corrosion as has been reported in [1,2].

Fatigue cracks are prone to initiate at the welded joints due to the existence of initial defects caused by welding, fatigue loads and high stress concentrations at dangerous fatigue details. These fatigue cracks may propagate and reach the critical sizes, leading to unstable crack growth.

The main steps in fatigue analysis, which is based on direct calculations, involve the description of the wave induced loading [3], the stress distribution [4], fatigue life estimation [5] and reliability index or time dependent reliability assessment [6].

Fricke [7] reviewed different methods of fatigue analysis of welded structures. The fatigue life of a welded detail may be estimated based on S–N approaches (nominal stress, structural stress and notch stress) and in a presence of a crack by fracture mechanics approach. Moreover, Fricke et al. [8] performed the fatigue strength assessment based on different classification societies for a hatch cover bearing pad in a comparative study. The S–N method is the simpler one. The major shortcoming of this method is that it cannot mathematically predict the change in crack size during the fatigue life and hence may not incorporate the results of any in-service inspection of a structure. Fricke and Kahl [9] applied three different structural stress approaches to fatigue strength assessment of three welded structural details. Fatigue life was predicted using the design S–N curves recommended within the different approaches and compared with the results of fatigue tests.

Fracture mechanics approach, which assumes the existence of an initial crack is suitable for quantifying the process of fatigue crack propagation and evaluates the integrity of a structure. The approach can be used for the assessment of a crack propagation life from an initial crack size to a final size defined as a critical crack size. The crack propagation assessment in a welded joint, as performed by the fracture mechanics approach [10], is based on the Paris–Erdogan crack propagation law [11], which is a function of the stress intensity factor range, ΔK, which describes the crack growth per cycle.

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Much attention has been paid to the fatigue crack propagation in welded joints of marine structures. Several analyses are summarized together with different assumptions for material parameters in the IIW recommendations [12]. Petershagen et al. [13] conducted several fatigue crack growth experiments on stiffened panels and reported that the stiffeners with cutouts such as drain holes were ineffective. A series of experiments were conducted in [14,15] to study the growth of large fatigue cracks in welded stiffened panels. These experiments confirmed that the crack propagates in a stable manner in redundant stiffened panels and showed the effects of welding residual stress, transverse butt welds and stiffener details on the growth rate of these cracks. Deeper analyses of crack propagations for welding stiffened panels has been performed in [15,16] and the Green function was used to calculate the stress intensity factor accounting for residual stresses and confirmed by finite element analysis of linear-elastic fracture mechanics. Yuen et al. [17] studied the propagation of fatigue cracks in stiffened plates under constant amplitude cyclic loading. Fatigue testing indicated that the fatigue crack growth rates of the stiffened plates were lower than that of a un-stiffened plate.

Many earlier models and studies have been carried out to predict the behaviour of structures affected by fatigue damage in a deterministic way. However, there are considerable uncertainties in the factors governing the fatigue performance of welded structures. Due to the uncertainties in material properties, geometries, quality of welds and welding defects, loads, boundary conditions and environmental factors, have to be modelled as random quantities, therefore the structural fatigue damage can be modelled as a stochastic process. The study of structural reliability is concerned with defining a limit state function at any stage of a structural life. A probabilistic approach can be used as a tool for providing a better assessment of the effect of uncertainties and random variables on the fatigue life and to the risk of the unacceptable consequences at the design stage.

The fatigue reliability assessment of a welded structure has attracted considerable attention to the development of probabilistic methods. These methods [18,19] rationally take into account the uncertainties in loading, response and structural strength, representing all of them as random variables. By combining loads and structural strength distribution, the probability of structural failure is calculated by using an appropriate procedure.

The time variant formulation of ship structural reliability results from modelling the problem by stochastic processes that represent the inherent random nature of the load and strength parameters. The initial formulations of the time variant approach to ship structural reliability were developed in connection with the fatigue problem, in particular to be able to deal with the time degradation of reliability as presented in [20] and with the improvements made by maintenance actions [21]. The probabilistic tools applied to risk-based assessment and life prediction help maintenance managers to make better risk-informed decisions regarding ship structures. In addition to assessing structural reliability, the probabilistic methods also provided information for performing an analysis of the cost of continuing operation based on risks and their financial consequence. Risk-based methods for inspection and maintenance can reduce life cycle cost of planning an inspection and repair intervals. Guedes Soares and Garbatov [22] studied the reliability of a corrosion-protected plate subjected to compressive loads and maintenance actions. In that work, the reliability of the collapse strength against compressive loading is predicted by a time-variant formulation and the effects of repair actions in the reliability assessment are shown.

Some recent studies have been focused on the stochastic formulations of fatigue damage growth. Guedes Soares and Garbatov [23–25] developed a method to assess the reliability of the ship hull subjected to potential cracks initiated at the welded joints between stiffeners and plating. The crack propagation is governed by the effect of the longitudinal stresses associated with the overall bending of the hull. The effect of a random number of cracks was accounted for by considering the decrease in the net sectional area that is available to resist the vertical bending of the hull. Feng et al. [26,27] developed a probabilistic model for the growth of correlated cracks in a stiffened panel. The model provides information about how the crack growth in the plate and stiffener as a function of time accounting for the correlation between them.

The objective of the present work is to develop a probabilistic approach for the fatigue reliability analysis of a complicated welded structure allowing for the existence of multiple site fatigue cracks in the web-frame welded joints and accounting for the correlations of the growth of these fatigue cracks. A finite element model of the web-frame welded structure with multiple crack details in welded joints is generated by the use of the commercial finite element code ANSYS [28]. It is assumed that five through thickness cracks will be simulated and analysed by the finite element method. The propagation of every crack is divided into five steps from the initial crack size to the final one. The simulations of fatigue crack propagation process, considering all possible variations of all correlated crack growths at different lengths, are performed and the stress intensity factors for all crack growth variations are calculated based on finite element analysis. The Paris–Erdogan law is employed to describe the fatigue crack propagation. The geometry correction function of each crack is fitted to a predefined function using nonlinear regression analysis based on all possible combinations. Simultaneously, the statistical properties of each geometry function are estimated respectively. The probabilistic crack growth models of these five fatigue cracks in the studied welded structure, subjected to fatigue loadings, are derived and the fatigue failure probability assessment of each fatigue crack growth is performed. The time-variant fatigue reliability of the web-frame welded structure with multiple site fatigue cracks is calculated based on the Ditlevsen [29] bounds, accounting for the correlations of multiple fatigue failure modes.

The principal objective here is to evaluate the fatigue reliability of the web-frame welded structure accounting for the correlation between any two-fatigue failure modes caused by multiple fatigue cracks propagating in a welded structure. A probabilistic approach for fatigue reliability assessment of a welded structure subjected to a correlated growth of multiple cracks is developed. It is assumed that five through thickness cracks will initiate and propagate at the critical hot-spots in the stiffener frame structure. Stress intensity factors at the tips of cracks, considering all possible combinations of all cracks of different lengths, are calculated by finite element analysis. The Paris–Erdogan law is used to predict the fatigue crack propagation life.

2. Finite element model

The web-frame welded structure analysed here is composed of a ship side shell plate, a longitudinal stiffener, five equally spaced transverse web-frames with stiffener and welded lugs as may be seen in Fig. 1. The structure is made of normal shipbuilding steel, 235 MPa of the yield stress.

The ship side shell plate is defined as 12,800 × 800 × 16 mm; five web-frames of 1300 × 800 × 12 mm, which are welded on the ship side shell longitudinal direction (see Fig. 2); the lugs are of 180 × 149 × 12 mm, which are attached to longitudinal stiffener and the web-frame. The longitudinal stiffener, which is made of HP 320 × 14 is 12,800 mm long. The stiffeners on the web-frames are made of HP 260 × 12. The FE model is defined in the way that