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Probabilistic flaw assessment of a surface crack in a mooring chain using the first- and second-order reliability method

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ABSTRACT

This study reports the results of a reliability-based flaw assessment for cracks in the mooring chain of a floating type offshore structure. The flaw assessment procedure of BS7910 was combined with the first- and second-order reliability method (FORM, SORM) so that the acceptance of a given flaw can be assessed considering the uncertainties of the parameters that play an important role in the flaw assessment. The failure probability was calculated using FORM and SORM considering the probabilistic nature of the crack size and the long-term distribution of stresses acting on the crack in the mooring chain. To check the validity of FORM and SORM, a Monte Carlo simulation was also carried out to derive the true limit state function and compared with the results of FORM and SORM.

1. Introduction

Floating offshore structures, such as FPSO and semi-submersible drilling rigs, generally maintain their position using mooring chains, which sometimes lead to enormous economic losses, such as the leakage of oil due to damage to the risers if the mooring chain is broken. For this reason, it is very important to guarantee the structural safety of the mooring chain during the entire or remaining operation time of the structure. In general, it is common for each link of the mooring chain to be connected by welding, and such weld connections are prone to initial defects caused by impurities, lack of fusion, etc. If there are initial defects in the weld zone, cracks can propagate due to the cyclic loading induced by the wave loads, which can lead to failure of the structure, as shown in Fig. 1. In addition, when a crack is detected through periodic inspections during the operation, it is necessary to make a quick decision regarding the maintenance of the defects, which can be judged based on the results of a safety evaluation on the detected crack. Therefore, a structural safety assessment of the potential flaws in the mooring chain during the entire or residual lifetime of the structure is a very important issue.

A flaw assessment is usually based on a deterministic evaluation method, which considers different variables, such as defect size, fatigue load distribution, fracture toughness, and yield strength of the chain as a single fixed value. The deterministic evaluation method is well established in standards, such as BS7910 [1] or API [2], and the safety factor or statistically conservative values for those uncertain analysis variables are recommended to avoid excessively optimistic predictions. On the other hand, the concept of reliability has been used in several engineering fields with the aim of a probability-based evaluation of the structural safety because the influence of uncertain factors can be considered stochastically. In the direct analysis method, such as Monte Carlo simulation [3], however, the number of analyses increases exponentially depending on the number of random variables to be considered. The FORM (First Order Reliability Method) and the SORM (Second Order Reliability Method) are methods designed to overcome this difficulty of

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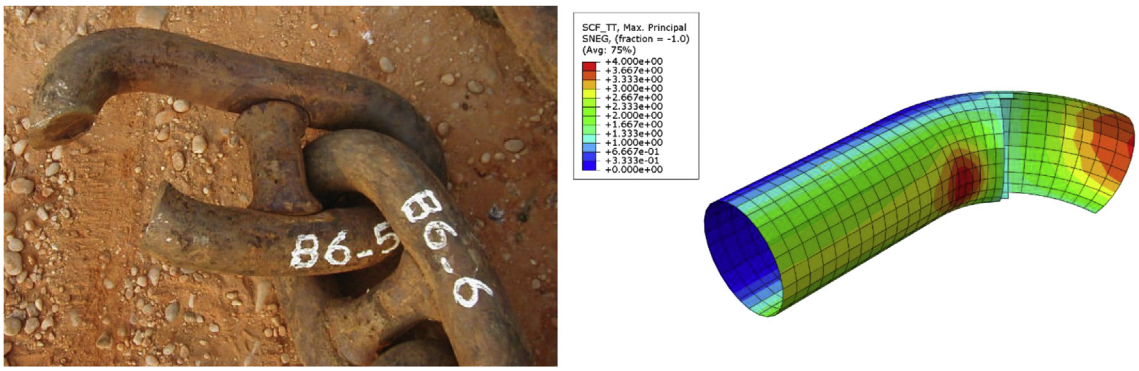

Fig. 1. Cracked mooring chain and stress distribution on the chain surface under tension.

probabilistic flaw assessments and provide numerical efficiency when calculating the failure probability of the structure.

FORM and SORM have been applied successfully in many engineering structural problems [4–10]. FORM and SORM rely on a Taylor series expansion in joint probability space to approximate the limit state function with some truncation errors. FORM approximates the limit state function as a hyper-plane in multidimensional space based on the limit state value and its gradients in all directions. FORM works well provided that the limit state function is linear or near-linear in the region of interest. When the limit state function is not linear enough, the higher order terms need to be included in the Taylor expansion to achieve a better approximation of the limit state function. In SORM, second order terms are taken into consideration so that the curvature of the limit state function is captured, providing a far better representation of the limit state function.

Previous research activities were dedicated to the flaw assessment combined with FORM and SORM. [11] calculated the probability failure of a simple one-dimensional spring-mass system under the assumption that both the excitation and system parameters are randomly distributed stochastic variables. [12] applied the first- and second-order reliability method to estimate the failure probability of a crack in a single edge crack specimen. They applied the FORM, SORM, and Monte Carlo simulation combined with Paris-Walker crack propagation model to estimate the failure probability of a specimen under a fatigue load and concluded that the slope of the Paris equation had the main influence on the failure probability. [13] proposed an improved probabilistic fracture mechanics assessment method and modified the sensitivity analysis to calculate the failure probability of a high pressure pipe containing a semi-elliptical surface crack. They claimed that both methods gave consistent sensitivities of the input parameters but interval sensitivity analysis was computationally more efficient. [14] analyzed the fatigue reliability of a stiffened panel subjected to the growth of correlated cracks. They applied both Monte Carlo simulations and FORM to estimate the failure probability, where the residual strengths of the plate and stiffener in the stiffened panel were measured using the crack tip opening displacement. [15] suggested the use of FORM to obtain a better estimation of the tail in the distribution of the estimated fatigue damage and thereby reducing the variance. He considered the stresses in the tendon of TLP holding a wind turbine and found that the scatter of fatigue damage was reduced by a factor of three. Recently, [16] calculated the failure probability of semi-elliptical surface cracks in the mooring anchor file by applying the FORM and SORM techniques combined with the flaw assessment procedure of BS7910.

This paper extends the authors' previous work [16], where the FORM and SORM-based flaw assessment procedures combined with BS7910 were applied to the crack of a mooring anchor pile, which was exposed to a repeated hammering load. In this paper, a probabilistic flaw assessment on a defect in the mooring chain was carried out using the flaw assessment program developed by [20] in accordance with the flaw assessment procedure of BS7910. The failure assessment diagram of BS7910 was used to define the limit state function, which was then approximated by FORM and SORM based on the reliability concept.

Assuming that the defect size and two parameters of a Weibull distribution characterizing the distribution of the long-term fatigue loading are random variables having a Gaussian distribution, the failure probability was targeted to be calculated. Defect size of 2.5 mm was assumed to be the one that has been identified during in-service inspection of chain link in the fairlead. Basic analysis data, such as the defect shape, material constants, stress concentration factor, static load, fracture toughness, and crack growth rate were assumed to be the deterministic values. Under this circumstances, fatigue crack propagation analysis was performed for a 20 years operation period and the failure probability was assessed. The failure probability was calculated by integrating the joint probability distribution in the failure region specified by the limit state function approximated by FORM and SORM. To verify the appropriateness of the calculated failure probability, a Monte Carlo simulation of 8000 random variable combinations was performed and the results were compared with the calculated failure probability.

2. Theoretical background

2.1. Combined fatigue-fracture/yield assessment

In this study, efforts have been made to evaluate the safety of defects in a mooring chain by both crack propagation analysis under a fatigue load and fracture/yield analysis under a static load. Crack propagation analysis was carried out with a given fatigue load and initial crack size, and the final crack size was then calculated when the fatigue load cycles were fully consumed. The calculated