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Engineering criticality analysis on an offshore structure using the first- and second-order reliability method

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Abstract

Due to the uncertainties related to the flaw assessment parameters, such as flaw size, fracture toughness, loading spectrum and so on, the probability concept is preferred over deterministic one in flaw assessment. In this study, efforts have been made to develop the reliability based flaw assessment procedure which combines the flaw assessment procedure of BS7910 and first- and second-order reliability methods (FORM/SORM). Both crack length and depth of semi-elliptical surface crack at weld toe were handled as random variable whose probability distribution was defined as Gaussian with certain means and standard deviations. Then the limit state functions from static rupture and fatigue perspective were estimated using FORM and SORM in joint probability space of crack depth and length. The validity of predicted limit state functions were checked by comparing it with those obtained by Monte Carlo simulation. It was confirmed that the developed methodology worked perfectly in predicting the limit state functions without time-consuming Monte Carlo simulation.

Keywords: Engineering criticality analysis; BS7910; Fracture mechanics; Crack propagation; Limit state function; FORM; SORM

1. Introduction

Welded structures are inevitably susceptible to the cracks either at weld toe or within welds due to the variety of reasons, such as excessive residual stress, inclusion of impurities and unexpected lack of fusion and so on. These cracks pose a major threat to the integrity of entire structure during it service life under environmental loadings acting on it such as wind, wave and current loads. Engineering criticality analysis, which targets to assess the fitness for service of the structure during its lifetime, is defined as a fracture mechanics based numerical analysis aiming at the assessment of flaw susceptibility under the loadings that the structure is exposed to. A flaw may fracture, either in brittle or ductile way, due to excessive loading or may grow to the critical size which may lead to successive fracture or functional degradation such as leak. Flaw assessment is critical to both fabricator and operator point of view because a decision needs to be made whether the existing flaw should be repaired or not, which has a huge impact in terms of the CAPEX and OPEX.

Flaw assessment procedure is well documented in BS7910 (BSI, 2005) or other equivalent standards such as API (API, 2007). Even though the analysis procedure is fully mature, it lacks the consideration of the probabilistic natures of the analysis parameters such as crack length, depth, fracture toughness, crack growth constants and loading parameters etc. All these parameters are difficult to define in deterministic way due to the complexities involved in, hence the standards take this random effect into account by either relying on partial safety factor or using statistically conservative values, such as mean minus two standard deviation or something equivalent. On the other hand, the reliability concept has been utilized in many engineering field for years targeting the

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probability based assessment on the structural integrity. The probabilistic nature of analysis parameters may be handled by a Monte Carlo simulation (Metropolis and Ulam, 1949), but large number of sample and corresponding simulation require practically infeasible computational burden. The computation cost increase dramatically especially when the number of random variables exceed 3 or 4 eventually leading to several thousand calculations. To overcome this difficulty, so called first- and second-order reliability concept was developed and successfully applied in many engineering structural problems (Cornell, 1969; Hasofer et al., 1974; Rackwitz and Fiessler, 1978; Fiessler et al., 1979; Breitung, 1984; Hohenbichler et al., 1987; Tvedt, 1990). First- and second order reliability methods rely on Taylor series expansion in joint probability space to approximate the Limit State Function (LSF) with some truncation errors. First Order Reliability Method (FORM) approximate the limit state function as a hyper-plane in multidimensional space, based upon the limit state value and its gradients in all directions. FORM works fine provided that the LSF is linear or near-linear in the region of interest. When the LSF is not linear enough, the higher order terms need to be included in the Taylor expansion in order to achieve better approximation of LSF. In SORM, second order terms are taken into account so that curvature of LSF is captured providing far better representation of LSF.

Kim and Yang (1997) calculated the probability failure of simple one dimensional spring-mass system under the assumption that both the excitation and system parameters are randomly distributed stochastic variables. Lee and Kim (2007) applied first- and second-order reliability method to estimate the failure probability of a crack in single edge crack specimen. They applied FORM, SORM and Monte Carlo simulation combined with Paris–Walker crack propagation model to estimate the failure probability of specimen under fatigue loading and concluded that the slope of Paris equation had the main influence on the failure probability. Yu et al. (2012) proposed an improved probabilistic fracture mechanics assessment method and modified sensitivity analysis to calculate the failure probability of high pressure pipe containing an semi-elliptical surface crack. They claimed that both methods can give consistent sensitivities of input parameters but the interval sensitivity analysis is computationally more efficient. Feng et al. (2012) analyzed the fatigue reliability of a stiffened panel subjected to the growth of correlated cracks. They applied both Monte Carlo simulation and FORM to estimate the failure probability, where the residual strength of the plate and stiffener in the stiffened panel was measured using crack tip opening displacement. Jensen (2015) suggests the use of FORM to get a better estimation of the tail in the distribution of the estimated fatigue damage and thereby reducing the variance. He considered the stresses in a tendon of TLP holding a wind turbine and found that the scatter of fatigue damage was reduced by a factor of three.

This paper extends the authors' previous work (Kang et al., 2015), where the flaw assessment following BS7910 was performed for a crack of a mooring anchor pile in a deterministic way. A semi-elliptical surface flaw in a weld toe of a mooring anchor pile subjected to both extreme and repeated fatigue loadings was assessed using FORM and SORM, and the failure probability was calculated under probabilistic crack length and depth. The LSF which corresponds to both static yield and fracture was approximated in joint probability space using first- and second-order method. The obtained failure probability was also compared with Monte Carlo simulation results which were obtained by running the sensitivity analysis module of RESCEW (Kang et al., 2015). Same analysis has been done for the LSF of fatigue, where a given loading spectrum was used as functional loading. For the LSF of fatigue, crack propagation analysis by numerically integrating Paris equation was performed based upon the procedure defined in BS7910.

2. Theoretical background

2.1. Flaw assessment procedure of BS7910

Flaw assessment procedure may be categorized into three different kinds, and they are fracture/yield assessment, fatigue assessment and combined fatigue-fracture/yield assessment. Because actual crack shape and stresses acting on it, together with material behavior, are too much complicated, the idealization on the analysis parameters is inevitable. Among others, the simplification and clarification on stresses are of utmost importance. Stresses acting on the flaw are classified into two kinds depending on its mechanical characteristics, such as primary and secondary ones. Primary stresses are defined as the stresses which may lead to the gross yield of net section, whereas the secondary stresses as those are not related to the yield of cross section. Stress on the wall of pressure vessel induced by the internal pressure is typical example of primary stress and residual stresses across the plate thickness are that of the secondary stress. Secondary stresses are not considered as a fatigue loading, but considered as a fracture/yield loading. On the other hand, stresses acting on flaws distribute quite complicated especially when the flaws are near the structural discontinuity, which is usually the case. This complicated stress field is processed in such a way that both membrane and bending components are extracted based on the stress linearization procedure and used for the flaw assessment.

Fig. 1(a) illustrates the fracture/yield assessment procedure, where a status was checked from static fracture as well as yield point of view. Some static loadings acting on a given geometry was analyzed and compared with both fracture toughness and yield strength of the material of interest. Depending on the consideration of combined effect of fracture and yield, three different Failure Assessment Diagrams (FAD) are proposed. Higher level of FAD is less conservative but it requests far more detailed information on the material behavior.

Fig. 1(b) summarizes fatigue assessment procedure. Dynamic stress, which may be represented by a given stress spectrum, acts on a specified initial crack of a geometry and the growth of crack with respect to the number of stress cycles is calculated by numerically integrating Paris equation. As was