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Effect of stress concentration factors on the structural integrity assessment of multi-planar offshore tubular DKT-joints based on the fracture mechanics fatigue reliability approach

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ABSTRACT

A reasonably accurate estimate of fatigue reliability is considered to be essential for offshore structures due to their high construction cost and failure consequences. In the present paper, firstly, a fracture mechanics based fatigue limit-state function is derived and effects of assigning different values to deterministic variables involved in this limit-state function on the results of reliability analysis are investigated. These deterministic variables are the material parameter, number of stress cycles, and the mean value of critical crack size. Afterwards, effects of stress concentration factors (SCFs) on the reliability of the tubular joint are studied. The SCF is one of the most important parameters in the fatigue reliability analysis, which exhibits considerable scatter. Results showed that change of the mean value of SCF, from the value typically assumed in the previous research works (=2.5) to a realistic value obtained in the present research for a widely used multi-planar joint (~15), leads to considerable decrease in the reliability index and consequently significant increase in the probability of failure. However, change of the coefficient of variation (CoV) of SCFs, from the typically assumed value (=0.15) to a realistic value obtained in the present research (~1.048), does not considerably affect the results.

1. Introduction

Fixed offshore steel structures are usually fabricated using tubular members, which are interconnected through welded joints. Fatigue cracks are expected to occur at the welded joints due to the presence of small initial defects caused by welding, high stress concentrations at the intersection, and the oscillatory stresses due to environmental loads. These fatigue cracks may grow and reach unacceptable sizes, e.g. economic repair sizes, through thickness cracks, and unstable fracture. Failure of a joint does not necessarily lead to failure of the structure due to the redundancy, which is typically present. However, each member is put there for a purpose and its absence would degrade the structural performance. Currently, there are two methods available for analysis of a component subjected to fatigue: *S–N* curves and fracture mechanics (FM). The *S–N* method, which is the simpler one is usually used during the design stage. Design standards such as API RP-2A (2000) provide guidelines for deterministic fatigue analysis of offshore structures using the *S–N* based method. The drawback of this method is that it cannot mathematically predict the change in crack size during fatigue life and hence may not incorporate the results of any in-service inspection of strucutre. Fracture mechanics (FM), on the other hand, relate the increase of crack size to the number of fatigue stress cycles and may be used to quantify the fatigue crack growth process. FM-based techniques are currently finding increasing use in the design of novel structures and in the validation of critical connections whose acceptability may be difficult to demonstrate using conventional methods.

Some of the key parameters of the problem in a fatigue analysis can exhibit considerable scatter and, therefore, have to be modeled as random quantities. Methods of structural fatigue reliability are used to manage uncertainties. The study of structural reliability is concerned with the calculation and prediction of the probability of limit-state violations at any stage during a structure's life. In a structural design problem involving uncertainties, a structure designed using a deterministic approach may have a greater probability of failure than a structure of the same cost designed using a probabilistic approach that accounts for uncertainties. This is because the design requirements are precisely satisfied in the deterministic approach, and any variation of the parameters could potentially violate the system constraints (Choi et al., 2007). Probabilistic methods are convenient tools to

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describe or model physical phenomena that are too complex to treat with the present level of scientific knowledge. Due to the inherent random nature of various inputs affecting the response of offshore structures subjected to fatigue, reliability analysis assumes great importance in the design of these structures. Computation of fatigue reliability is also useful for planning in-service inspection and for checking the design and certification. In carrying out a reliability analysis, the various input parameters to the analysis are categorized as either deterministic or random variables. For the random variables, the form or the variability is reflected by selection of probability distributions. The fundamentals of reliability assessment, if properly applied, can provide immense insight into the performance of the structural system.

Result of the sensitivity analysis performed by Pillai and Prasad (2000) calls for greater emphasis in accurately computing the stress concentration factor (SCF) during the prediction of the fatigue life of offshore structures. The SCF is the ratio of the local surface stress to the nominal direct stress in the brace. A review of the previous research works on the determination of SCFs is presented in Section 4.1. Two major shortcomings can be noted regarding the research efforts expended so far on the calculation of SCFs in tubular joints: (a) multi-planar joints are an intrinsic feature of offshore tubular structures. The multi-planar effect plays an important role in the stress distribution at the brace-to-chord intersection areas of the spatial tubular joints. For such multi-planar connections, the SCFs of simple uni-planar tubular joints are not applicable. However, despite the significant effort devoted to the study of SCFs in various uni-planar connections, very few investigations have been reported for multi-planar joints, which cover the majority of practical applications. The main reasons are the complexity and high cost involved; and (b) majority of these research works focused on the study of SCFs at certain positions such as the saddle and crown, and they have ignored the hot-spot stress (HSS) at other positions along the weld toe. Stress distribution information is needed for predicting fatigue crack growth and the remaining life for in-service cracked joints, using advanced fracture mechanics models such as O-integral, AVS, and TPM (Chang and Dover, 1999). Thus it is very important to have accurate stress *distributions* along the intersection under each uni-axis loading.

Published research papers on the fatigue reliability analysis of offshore structures, particularly jacket-type platforms, are briefly discussed subsequently. Wirsching (1984) summarized the results of a four-year project, sponsored by the American Petroleum Institute, to investigate the fatigue design process in the welded joints of steel offshore structures based on reliability analysis. Kirkemo (1988) reviewed the applications of probabilistic fracture mechanics to offshore structures. The presented model accounts for uncertainties in loading, initial and critical defect sizes, material parameters, and the uncertainty related to computation of the stress intensity factor. Failure probabilities were computed by first-order reliability methods and sensitivity factors were determined. Model updating based on in-service inspection results has been formulated. Uncertainties with respect to detecting a crack and to correctly sizing a crack were included. Pittaluga et al. (1991) reviewed the uncertainties in the fatigue design of offshore structures. Jiao and Moan (1992) presented reliability-based fatigue and fracture design criteria for welded offshore structures. Design formats were presented using a usage factor or partial safety coefficients associated with the basic random variables. Target safety levels were determined according to consequences of failure, inspection strategy and system effect. Probabilistic calibration was performed using uncertainty measures for some typical offshore components. Kam and Birkinshaw (1994) presented a reliability-based fatigue and fracture mechanics assessment methodology for offshore structural components. Mosayyebi and Aghakuchak (2000) used the Response Surface Method (RSM) for the fatigue reliability analysis of offshore structures. Aghakouchak and Stiemer (2001) applied the FM-based fatigue reliability analysis to the assessment of existing offshore structures. Pillai and Prasad (2000) performed a fatigue reliability analysis in time domain for inspection strategy of fixed offshore structures. Advanced Second Moment method was used to find the reliability index. The total life of the structure was divided into a set of stationary sea-states, occurring during storms and described by directional power spectrum. The method has been illustrated through application to a typical jacket platform. Usefulness of the methodology for planning in-service inspections has been highlighted. A reliability analysis was carried out by Rajasankar et al. (2003) using Monte Carlo Simulation technique and First-Order Reliability Method (FORM). The crack in addition to the geometry, material, and loading of the tubular joint were modeled as random variables to compute the reliability of the joint. Degradation in the reliability of the tubular member due to crack propagation was estimated.

In the present paper, after formulating the FM-based fatigue limit-state function, effects of choosing different values for the deterministic variables on the FM-based fatigue reliability results, i.e. the probability of failure and the safety index (reliability index), are investigated. The SCF is one of the most important parameters in the fatigue reliability analysis, which exhibit considerable scatter depending on the joint geometry, loading type, weld size and type, and the location around the weld under consideration. This calls for greater emphasis in accurately computing the parameters of probability density function (PDF) assigned to the SCF in the fatigue reliability analysis of steel offshore structures. After investigating the effects of deterministic parameters, effects of parameters selected for the probability distribution of SCFs on the reliability of the tubular joint are studied. The process of studying the SCF effect involves the construction of an SCF sample database using the results of FE analyses carried out on the right-angle two-planar tubular DKT-joints. This particular type of tubular joint is selected because it is frequently adapted in the construction of offshore jacket-type structures and is one of the most important joint types since it is commonly used to connect the brace members to the main leg of the jacket template (Fig. 1). The importance of

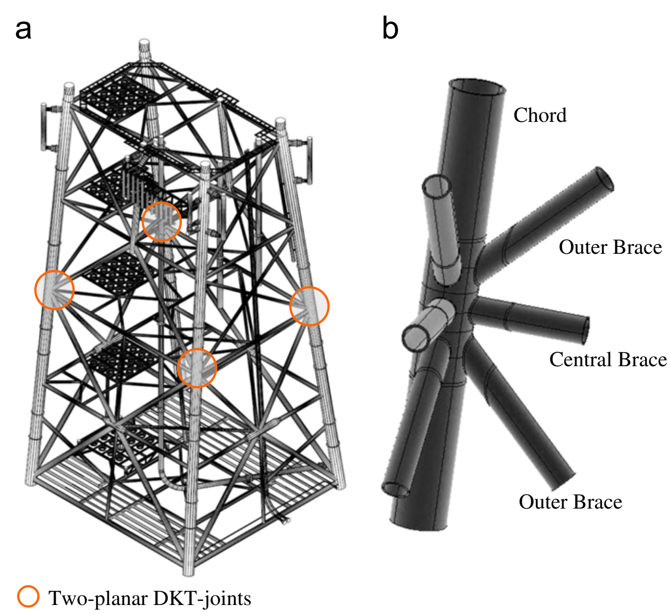

Fig. 1. (a) Two-planar DKT-joints in a typical jacket-type offshore structure and (b) Geometrical configuration of a right-angle two-planar DKT-joint.