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Numerical analysis on the HSS and SIF of multi-planar DX-joint welds for offshore platforms

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A R T I C L E I N F O

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A B S T R A C T

Among offshore platform structures, multi-planar tubular joints are usually in the most dangerous positions and generate fatigue cracks the earliest. In this study, DX-joints were regarded as the research object, and finite element method was adopted to conduct systematic research on the fatigue properties of multi-planar tubular joint welds. Axial, in-plane bending moment, and out-of-plane bending moment loads were applied to explore the stress distribution along the weld path and the hotspot location under different load conditions. Results indicated that the hotspot stress (HSS) location of DX-joints changed with the variation in the combined stress ratio. Through HSS analysis, cracks were prefabricated at the hotspot location of DX-joints to analyze the change rule of the stress intensity factor (SIF). The influence of different loads, crack lengths, and crack depths on SIF was studied to estimate the growth trend of the weld crack and its dominance. The findings can provide theoretical guidance for fatigue damage and safety assessment of offshore platforms.

1. Introduction

During the utilization of offshore platforms, their structures suffer from various damages under long-term multiple environmental loads of sea wind, wave, and current (Gholizad et al., 2012). Offshore jacket platforms are usually welded with numerous circular tube structures. Among them, the weld points that connect the welding portions of the circular tube play an important role in the platform (Tang et al., 2015). The residual stress or defects of tubular joint welds may lead to stress concentration (Chen et al., 2015; Habibi et al., 2012). The location of maximum stress concentration is called the hotspot, and the corresponding local stress is referred to as hotspot stress (HSS). The HSS range can be determined from a parameter called the stress concentration factor (SCF). The SCF is the ratio of the local surface stress to the nominal direct stress in the brace. When tiny fatigue cracks are generated near the HSS locations, the surface cracks grow continuously under the constant circulation of fatigue loads (Qu et al., 2014). This condition causes certain damages that may trigger the structural damage of the entire platform.

In recent studies, scholars mainly adopted numerical and experimental methods to analyze the tubular joint fatigue of offshore structures (Du et al., 2015). Romeijn et al. (1993) selected the 3D solid element to model tubular joints, including the weld. They adopted the interpolation method to calculate the stress of the weld toe near tubular joint welds and proposed the SCF equations. Chiew et al. (2000) presented a set of parametric equations to determine the SCFs for multi-planar tubular XX-joints under axial (AX), in-plane bending moment (IPB), and out-of-plane bending moment (OPB) loads. Gho and Gao (2004), Gao (2006), and Gao et al. (2007) proposed parametric SCF formulae for completely overlapped tubular K(N)-joints under lap brace AX, OPB, and IPB loads, respectively. Shao et al. (2009) presented a set of parametric equations to predict the HSS distribution for tubular K-joints under basic loading. Lotfollahi-Yaghin and Ahmadi (2010) studied the effect of normalized geometrical parameters and brace-to-chord inclination angle on SCF distribution along the weld toe of tubular KT-joints under balanced AX loads. Subsequently, Ahmadi et al. (2012) conducted a series of parametric stress analyses of two-planar tubular DKT-joints under different AX loading conditions. A new set of SCF parametric equations was established for fatigue design purposes based on results of the finite element analysis (FEA). Ahmadi (2016) proposed a probability distribution model for SCFs in tubular KT-joints reinforced with internal ring stiffeners and subjected to OPB loads.

Generally, stress intensity factor (SIF) is a measurement of crack growth trend. Newman and Raju (1981) proposed the hypothesis that crack growth maintains a semi-elliptical shape by conducting numerous surface crack growth tests on a flat plate structure. They also calculated SIFs at points in the depth and freedom directions of cracks

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and established many empirical fitting formulas. Chiew et al. (2001) adopted the FE method to calculate the SIFs of surface cracks at the Y-joint under different loads, and 1/4 singular element was used in the crack front. The precision of Types I, II, and III SIFs verified the reliability of this method. Lee and Bowness (2002) proposed an engineering methodology for estimating SIF solutions for semi-elliptical weld-toe cracks in tubular joints. Lie et al. (2005) evaluated the SIF values along the crack front of a tubular K-joint by FE methods. Then, numerical analysis of SIF for cracked tubular K-joints was conducted in the recent study of Shao (2006). A full-scale K-joint was tested under balanced AX load, and SIFs at the deepest point of different crack shapes were calculated. Shen and Choo (2012) determined the SIFs of an as-welded tubular T-joint with grouted chord by numerical and empirical methods. The SIF results were found to be consistent and in agreement of the fatigue test results. Qian et al. (2013) investigated the effects of the crack propagation angle in CHS X-joints, the crack-front profile and the interaction between adjacent fatigue cracks on the fatigue driving force, measured by SIFs.

Representative studies in different years indicate that the FE method for numerical analysis on the fatigue properties of tubular joints demonstrates high feasibility, precision, and efficiency (e.g. Hellier et al. (1990), Morgan and Lee (1998), Chang and Dover (1999), Shao (2007), Shao et al. (2009), Lotfollahi-Yaghin and Ahmadi (2010), Ahmadi et al. (2011), and Ahmadi (2016) for SCFs; and Bowness and Lee (1998), Lee et al. (2005), Shao and Lie (2005), Shao (2006), and Shen and Choo (2012) for SIFs). However, most analyses on the fatigue properties of tubular joint welds focused on uniplanar and two-planar tubular joints, and the effects of load and crack shape parameters on SIF were ignored. In the current study, DX-joints were selected as the research object for a systematic HSS and SIF analysis to investigate fatigue properties of multi-planar tubular joint welds.

The rest of this paper is organized as follows. The FE model of multi-planar DX-joints is built, meshed, and verified in Section 2. In Section 3, the stress distribution along the weld path and the hotspot location of the DX-joints are explored under different load conditions. In Section 4, cracks are prefabricated in the hotspot locations of the DX-joints. The effects of different loads, crack lengths, and crack depths on SIF are also analyzed to estimate the growth trend of the weld crack and its dominance. The results are summarized and conclusions are presented in Section 5.

2. FE modeling of multi-planar DX-joints

The offshore platform structure bears complex marine environment loads during its service period. Regions near multi-planar tubular joint welds generate a large amount of stress, so fatigue failure usually occurs easily in these locations. Therefore, the FE model of DX-joints is built, meshed, and verified in this section to conduct the HSS analysis.

2.1. Modeling of DX-joints

DX-joints were selected as the research object to study the fatigue properties of multi-planar tubular joint welds. The model of tubular joints was built based on the FE method and the material selected high-strength steel D36. A 3D solid element type of ANSYS, SOLID186, was used to model the chord, brace, and overall welds of the DX-joints. SOLID186 possesses 20 nodes, with each node having three degrees of freedom. It is suitable for generating an irregular grid model without reducing accuracy (Ahmadi et al., 2012). These elements have compatible displacements and are suitable for modeling tubular joints. The geometric parameters of multi-planar DX-joints are shown in Table 1. The geometrical model in ANSYS is shown in Fig. 1.

Considering the comprehensive factors of geometric discontinuity around DX-joint welds and the difference in regional stress gradient under loads, the method of using different regional grids was used to divide a high-quality mesh, as shown in Fig. 2. The meshing around the DX-joint welds should satisfy linear interpolation regional regulations to facilitate the most effective value of regional node stress.

The modeling precision of tubular joint welds is the most influential factor of stress distribution around welds. In this study, weld modeling at the intersection line of tubular joints followed the welding specification proposed by the American Welding Society (US American Welding Society, 2007), as shown in Fig. 3.

Local stress is mainly caused by the discontinuity of the geometrical shape near tubular joint welds and manufacturing defects. At present, no effective method can be used to calculate this stress. In numerical analysis of the static force of tubular joints, directly measuring the point stress around welds cannot estimate the stress distribution accurately. To obtain accurate geometrical stress, scholars (N'Diaye et al., 2007; Tong et al., 2006) defined the region close to welds as the stress interpolation region, which is about 0.4–1.4 times the chord thickness far from the weld toe. In the past, the linear interpolation method was utilized to solve HSS at the weld toe of tubular joints, as shown in Fig. 4.

2.2. Verification of the FE model

The FE method can be utilized to calculate the stress distribution near tubular joint welds efficiently and conveniently. However, the accuracy of FEA predictions should be verified against experimental test results. To our knowledge, no experimental database of fatigue properties for steel multi-planar DX-joints is available in literature. To validate the FE model, several related geometries, including T-, Y-, and K-joints, are modeled, and the FE results are validated against the test results published in the HSE OTH 354 Report (UK Health and Safety Executive, 1997). The method of modeling the chord, brace, and weld profile as well as the mesh generation procedure (including selection of the element type) and the analysis method are identical for model validation and the considered multi-planar DX-joints. Hence, the conclusion of the verification of T-, Y-, and K-joints with the experimental test results can be used to validate the generated multi-planar DX-joint models (Lotfollahi-Yaghin and Ahmadi, 2010).

The verification results, which are separately presented at saddle and crown positions, are summarized in Table 2. In this table, M denotes the percentage of the relative difference between the results of the FE model and experimental results. The value of M is greater than 20% only when at the saddle position of Y-joint; thus, these two results have good consistency. Comparison of the FE results and experimental data shows that the FE model can produce valid results.

3. HSS results of DX-joint welds

In the stress analysis of multi-planar DX-joints, three forms of loads, including AX, IPB, and OPB loads, were applied on the brace. For calculation and processing convenience, the nominal stress of AX and bending-moment loads applied at the end of the brace was 1 MPa. Fixed constraints were applied at both ends of the chord and the end of a pair of braces. Five different types of combined loads of AX and plane bending moment were applied at the end of the other pair of braces at a ratio of 0.2, 0.5, 1.0, 2.0, and 5.0. In other words, the other loads under different conditions are 1, 2, and 5 MPa when the basic load of 1 MPa remains unchanged.

The stress distribution at each point near the weld of the chord and brace was obtained under different loading conditions. The curve

Table 1
Geometric parameters of multi-planar DX-joints.

D [mm]	d [mm]	T [mm]	t [mm]	β	γ	τ	α	α_β
400	120	10	4	0.3	20	0.4	12	8