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Prediction of stress concentration factor distribution for multi-planar tubular DT-joints under axial loads

Yongyi Jiang*, Kuilin Yuan**, Hongyu Cui

State Key Lab of Structural Analysis for Industrial Equipment, School of Naval Architecture Engineering, Dalian University of Technology, 116024, Dalian, PR China

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ABSTRACT

The stress concentration factor (SCF) plays an important role in the fatigue life assessment of tubular joints. Although various SCF parametric equations have been proposed for uni-planar tubular joints, only few are focused on multi-planar tubular joints. In the present study, the finite element (FE) method was employed to investigate the SCF distributions along the chord–brace intersection of multi-planar DT-joints. A method of sub-zone mesh generation was developed to ensure good quality and an appropriate number of FE meshes. The effects of the geometrical parameters on the SCF distributions were investigated. A set of equations was proposed based on the results of the FE analysis. Two types of error analysis were used to verify the reliability of developed equations.

1. Introduction

Circular hollow section (CHS) joints are widely used in offshore structures. Owing to the complex shapes of CHS joints, typically, a high-stress area is formed near the weld toe region. The fatigue strength of tubular joints is closely related to the hot spot stress ranges. In practice, S-N curves are commonly used to evaluate the fatigue life of offshore structures, for which the hot spot stress (HSS) is calculated as the product of the nominal stress and stress concentration factor (SCF). As is well known, a fatigue crack is prone to initiate from a stress concentration area [1]. Generally, high-SCF regions are considered to occur theoretically at the crown or saddle of tubular joints. However, the peak value of the SCF is typically not located at the position of the crown and saddle when the CHS tubular joint is subjected to a combination of axial loads and bending moments. The superposition method is recommended based on the API code [2] for the SCF calculation in the case of combined loads if the parametric expression of the SCF for each individual load is available.

In the past few decades, numerous efforts have attempted to investigate the stress distribution in various uni-planar tubular joints under different loading conditions. Consequently, various parametric formulas have been proposed in terms of the geometric parameters of joints for predicting the SCF values at certain positions adjacent to the weld or SCF distribution along the chord–brace intersection. Hellier et al. [3], Lloyd's Register [4], Karamanos et al. [5], and Shao [6] presented the parametric equations for the SCFs for the saddle and crown positions in uni-planar T-, Y-, X-, K-, and KT-joints under the basic loadings such as the axial (AX), in-plane bending (IPB), and out-of-plane bending (OPB) loadings. Gao et al. [7–9] and Yang et al. [10] proposed a series of equations for SCF determination in uni-planar completely overlapped tubular joints. Nwosu et al. [11], Hoon et al. [12]. Myers et al. [13], and Ahmadi et al. [14] numerically and experimentally investigated the effects of the geometrical parameters on the SCFs of T- and KT-

* Corresponding author.
** Corresponding author.
E-mail addresses: jyydlut@mail.dlut.edu.cn (Y. Jiang), yuan_kuilin@dlut.edu.cn (K. Yuan).

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reinforced tubular joints. With regard to the determination of the SCF distribution along the weld toe of the chord–brace intersection, Morgan and Lee [15–17] and Chang and Dover [1,18] separately presented the parametric equations for various uni-planar tubular joints under AX, IPB, and OPB loadings. Chiew et al. [19] and Sopha et al. [20] performed static and fatigue tests to investigate the SCF distributions along the chord–brace intersection of tubular joints under combined loads and identify the relationship between the peak HSS location and crack initiation position. Shao et al. [21,22] employed solid elements to model the weld region and numerically investigated the geometrical effects on the SCF distributions along the weld toe for tubular T- and K-joints subjected to AX, IPB, and OPB loadings. Ahmadi et al. [23–25] presented a complete set of parametric equations to determine the SCFs along the weld toe of uni-planar KT-, uni-planar DKT-, and internal ring-stiffened KT-joints under axial loads. Xu et al. [26] performed a series of tests for investigating the effects of the chord thickness and joint type on the HSS distribution along the chord–brace intersection of concrete-filled tubular T-, Y-, K-, and KT-joints under AX loading. Liu et al. [27] proposed the Zero Point Structural Stress (ZPSS) concept, instead of HSS, and developed the corresponding parametric formulas for the SCF distribution along the intersection of tubular T-joints.

Indeed, multi-planarity is an inherent feature of offshore tubular structures. The multi-planar effect plays an important role in the stress distribution along the chord–brace intersection of spatial tubular joints. For such multi-planar connections, the above-mentioned parametric formulas for simple uni-planar tubular joints may not be applicable for SCF prediction. However, very limited investigations on multi-planar joints have been reported owing to the complexity and high cost involved, and most of the studies were focused on critical locations. Chiew et al. [28] presented a set of parametric equations to determine the SCFs for the saddle points on both sides of the chord and brace of the multi-planar tubular XT-joints subjected to axial loads. Karamanos et al. [29] and Chiew et al. [30] studied the SCFs in multi-planar tubular XX-joints under AX, IPB, and OPB loadings. Karamanos et al. [31,32] proposed SCF equations for critical locations in multi-planar DT-joints. Wingerde et al. [33] presented a set of simplified design formulae and graphs to facilitate the determination of SCFs for KK-joints subjected to AX, IPB, and OPB loadings. Ahmadi et al. [34–37] established a series of SCF equations for different saddle positions of two- and three-planar tubular KT-joints. Woghiren and Brennan [38] developed a set of parametric formulae to predict the values of the SCF in multi-planar rack-stiffened tubular KK-joints. Few research studies have paid attention to the SCF distribution along the chord–brace intersection of multi-planar joints. Ahmadi et al. [39,40] investigated the SCF distribution along the weld toe on the chord side of the central brace and outer brace in case of multi-planar KT-joints under AX loadings. In addition, considering the different types and geometric dimensions of tubular joints, the SCF is supposed to be a random variable in the fatigue reliability assessment, in which the probability distribution significantly affects the accuracy of the assessment of the offshore structures. Ahmadi et al. [41–46] proposed probability distribution models for the SCFs of multi-planar tubular DKT-joints and internally ring-stiffened tubular KT-joints. Furthermore, the analysis of the effect of the SCFs in the structural integrity assessment of multi-planar offshore tubular DKT-joints was performed by the fracture mechanics-based fatigue reliability approach and S–N-based fatigue strength assessment.

It can be concluded from the preceding discussion that the investigations on the SCF distribution along the chord–brace intersection of multi-planar joints is very limited and no parametric equation is available for the frequently used multi-planar DT-joints. In this study, the SCFs for multi-planar tubular DT-joints are numerically investigated. Totally 352 FE models with different geometrical parameters were utilized. The variation in the SCF along the chord–brace intersection under AX loads with varying geometrical parameters is analysed. The accuracy of the FE analysis was verified against the experimental data published by Lloyd's Register [4] and the predicted results by using Efthymiou SCF equations recommended by API [2], CIDECT [47], and IIW [48]. Subsequently, with nonlinear regression analysis, a new set of parametric equations for the SCFs along the chord–brace intersection is established for the fatigue design of multi-planar DT-joints under two different axial load cases. An assessment study of these equations is conducted by two types of error analysis.

2. Finite element modelling of multi-planar CHS DT-joints

Owing to the complex geometry of CHS joints, it is impractical to calculate the SCFs along the chord–brace intersection by analytical methods. Finite element analysis and experimental methods have been widely used. The former is more efficient and convenient than the latter. Hence, the finite element method is used in this research.

2.1. Geometrical parameters of multi-planar DT-joints

A typical multi-planar DT-joint is illustrated in Fig. 1. In this research, two braces are assumed to be identical and perpendicular to the chord member. The axes of the two braces intersect at the mid-point of the chord axis. The SCFs along the chord–brace intersection of multi-planar DT-joint are related to parameters α (the ratio of the chord length to the chord outer radius, $2L/D$), β (ratio of the brace outer diameters to the chord outer diameter, d/D), γ (the ratio of the chord outer radius and chord thickness, $D/2T$), τ (the ratio of the brace thickness to the chord thickness, t/T), ϕ (polar angle), and ω (out-of-plane angle). Parameters of α, β, γ, and τ have been commonly employed in the existing parametric formulas to consider the geometric characteristics of tubular joints. Out-of-plane