



A novel framework for deriving the unified SCF in multi-planar overlapped tubular joints

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ABSTRACT

For the past few decades, a significant number of research efforts have been devoted to the studies of SCF values and parametric design formulae at certain positions in various uniplanar and multi-planar tubular joints. However, very few investigations on the multi-planar overlapped tubular joints have been reported. The main reason may lie in the complexity of combining effects between multi-planarity and overlapping. In this paper, a novel framework for deriving the unified SCFs is proposed by reducing joint modeling from multi-planar out-of-plane overlapping to equivalent uniplanar non-overlapping. By integrating the equivalent beam model with solid finite element modeling for the overlapped tubular KK-joint in offshore jack-ups, the procedures for computing the unified SCF values in the equivalent beam stick model are successfully developed. Verification of the proposed framework is obtained by comparing the unified SCFs based on basic load cases with those based on actual wave loading typically experienced by the jack-up.

1. Introduction

Circular hollow section (CHS) members are widely used as the primary components in offshore tubular lattice structures such as jack-ups [1]. The circular hollow sections are joined together to form a tubular joint where the profiled ends of secondary members (the braces) are welded onto the circumference of the main member (the chord). Due to the complex geometry of such joints, cyclic wave loading on offshore structures may induce localized fatigue damage and failure as a result of high stress concentration at the vicinity of brace-to-chord intersections. For the purpose of fatigue design, the hot spot stress method [2] has been quite efficient and widely used to predict the fatigue life of offshore tubular joints. In this method, the nominal stress range at the joint members is multiplied by an appropriate stress concentration factor (SCF) to provide the geometric stress at a certain location. The SCF is the ratio of the local surface stress at the brace-to-chord intersection to the nominal stress in the brace [3]. Geometric stresses are calculated at various locations around the welded region and the maximum geometric stress is the hot spot stress (HSS). The fatigue life of the joint is estimated through an appropriate *S-N* fatigue curve [2], *N* being the number of load cycles. Therefore, the hot spot stress method depends on the accurate prediction of SCFs for tubular joints.

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A significant number of research programs have been carried out over the past thirty years on the study of parametric design formulae and SCF values at certain positions in various uniplanar tubular joints, in which the axes of the chord member and brace members reside in the same plane [4–12]. If the axes of the brace members, as well as the chord member, are in different planes, they are considered as multi-planar joints. Multi-planar joints dominate the practical applications for offshore tubular structures, which are generally three-dimensional truss structures. Multi-planarity effects play an important role in the stress distribution at the vicinity of joint intersection. Thus, the parametric formulae of uniplanar tubular joints for SCF prediction may not be suitable for such multi-planar connections. In the context of research effort on multi-planar joints, much fewer investigations have been reported due to the complexity and high cost involved. Karamanos et al. [13] and Chiew et al. [14] developed parametric equations to determine the SCFs for multi-planar tubular XX-joints. Karamanos et al. [15,16] proposed SCF equations in multi-planar tubular DT-joints including axial and bending effects. Van Wingerde et al. [17] presented simplified SCF formulae and graphs for multi-planar KK-connections, while Woghiren and Brennan [18] proposed a set of parametric SCF equations for multi-planar stiffened tubular KK-joints. Lotfollahi-Yaghin and Ahmadi [19] and Ahmadi and Zavvar [20] performed parametric SCF studies for multi-planar KT-joints under axial, in-plane and out-of-plane bending loads.

Due to the ease of fabrication and the availability of many assessment methods for ultimate strength and fatigue performance, non-overlapped joints [4,6,10,17–20] are widely used for the construction of many tubular structures. However, when the brace-to-chord diameter ratio is higher than 0.7, non-overlapped *K*-joints may not be easily designed due to the limited validity range of design code [21]. Instead, an overlapped joint may be needed, which can be in-plane (the chord axis rests in the same plane with the axes of overlapped braces) or out-of-plane (the chord axis rest in a different plane from the axes of overlapped braces). By partially overlapping the brace, the chord eccentricity and unbalanced moment due to the gap between the braces could be eliminated [22]. In general, an overlapped CHS *K*-joint has a higher fabrication cost than a non-overlapped *K*-joint due to the more complex intersection profile and construction procedure. However, an overlapped CHS *K*-joint outperforms its non-overlapped counterpart in terms of ultimate strength capacity [23], cost effectiveness [24] and fatigue strength [25]. Efthymiou and Durkin [4] developed the SCF and HSS equations for partially overlapped joints based on a small scale finite element study involving 100 joint configurations and loading cases. Their equations were verified experimentally by Dharmavasan and Seneviratne [26] using scaled down acrylic models and it was found that overlapping helps reduce the chord SCFs. Lee et al. [22] carried out full scale tests on overlapped CHS *K*-joints and found that the formulae of Efthymiou and Durkin [4] are conservative only when the joints were subjected to in-plane bending loading, but not for the case of axial loading. Lee et al. [27] conducted a parametric numerical study to compare the fatigue performances of non-overlapped and partially overlapped CHS *K*-joint under different loading conditions. They concluded that, as during actual truss design most of the members will be assumed to be axially loading only, a partially overlapped CHS *K*-joint could be regarded as a favorite when comparing with its non-overlapped counterpart in terms of fatigue performance. Research on fatigue behavior of overlapped tubular *K*-joints with an overlapping ratio, the overlapped length to the diameter of the brace, larger than 50% can be found in the works of Gao et al. [8], Gho et al. [28] and Pang et al. [29].

The research efforts expanded so far on the overlapped tubular joints are mainly for uniplanar *K*-joint with in-plane overlapping. However, very few investigations on the multi-planar overlapped tubular joints, which indicate that the axis of the chord member resides in a different plane from the axes of overlapped brace members, have been reported. One of the main challenges is possibly that multi-planar overlapped joint normally involves out-of-plane overlapping. Another challenge may lie in the complexity of combining effects between multi-planarity and brace overlapping.

To address the above challenges, a general framework for deriving the unified SCFs in multi-planar overlapped tubular joints is proposed in this paper. Taking the multi-planar overlapped tubular *KK*-joint in offshore jack-ups as an example, an equivalent beam stick model is firstly proposed to simplify modeling procedure for the joint. Then, a calculation procedure for the unified SCFs is devised based on basic loading cases using the solid joint model and its equivalent beam model. The calculation procedure is further developed for the SCFs based on actual wave load cases experienced by the jack-up. Verification of the proposed framework is subsequently obtained by comparing the unified SCFs based on basic load cases with those obtained by actual wave loading. Lastly, conclusions from the present study are given.

2. Multi-planar overlapped joint modeling

2.1. Background

Jack-up is a mobile self-elevating drilling unit used for offshore oil and gas exploration in shallow water. It typically comprises a buoyant, approximately triangular hull supported by three lattice legs, each resting on a large inverted conical footing (spudcan). The multi-planar overlapped *KK*-joint under investigation is an integral part of the lattice legs, as shown in Fig. 1. The schematic diagram of a multi-planar overlapped *KK*-joint is plotted in Fig. 2. It can be observed that the axes of the chord and the overlapping braces are in different planes.

For fatigue design of non-overlapped tubular joints, the hot spot stress is calculated as the nominal stress in a brace multiplied by appropriate SCFs [3]. Carry-over effect is defined as the stress concentration at a certain location near the weld toe due to a load (axial or bending) on another brace. Refer to the joint of Fig. 2, the local stress at a weld location of brace (a) or brace (b) due to a load on brace (c) is a “carry-over effect”. In such a case, braces (a) and (b) are called the “reference brace”, while brace (c) is the “carry-over brace”. According to the studies by Karamanos et al. [15,16] for multi-planar non-overlapped tubular joints, stress concentrations due to carry-over effects can be neglected at crown locations of the reference brace for both axial and bending cases. However, due to overlapping effects, stress concentrations should be considered at crown locations of the overlapping (reference)

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