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Distribution of weld toe stress concentration factors on the central brace in two-planar CHS DKT-connections of steel offshore structures

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ABSTRACT

Two major issues can be noted regarding the research efforts expended so far on the calculation of stress concentration factors (SCFs) in tubular joints: (1) majority of these research works focused on the values of the SCF at certain positions such as the saddle and the crown, and they have ignored the hot-spot stress at other locations along the weld toe; (2) significant effort has been devoted to the study of SCFs in various uni-planar tubular joints. Nevertheless, for multi-planar joints, which cover the majority of practical applications, very few investigations have been reported due to the complexity and high cost involved. In this paper, the effects of geometrical parameters on the SCF distribution along the weld toe of two-planar tubular DKT-joints under the axial loads are investigated. In order to study the multi-planar effect, SCF distribution in multi-planar joints is compared with the distribution in a uni-planar joint with the same geometrical properties. Based on the multi-planar DKT-joint FE models, which are verified against experimental results and the predictions of Lloyd's Register (LR) equations, a complete set of SCF database is constructed. The FE models cover a wide range of geometrical parameters. Through nonlinear regression analysis, a new set of SCF parametric equations is established for the accurate and reliable fatigue design of multi-planar DKT-joints under axial loads. An assessment study of these equations is conducted against the experimental data and the acceptance criteria recommended by the UK DoE.

1. Introduction

Steel offshore structures commonly used for exploration and production of oil and gas (such as jackets and jack-ups) generally employ circular hollow sections (CHSs) as the primary structural components. In such structures, the hollow section members (tubulars) are joined together forming a tubular joint by welding the profiled ends of the secondary members, the braces, onto the circumference of the main member, the chord. Tubular joints are constantly exposed to cyclic environmental loading caused by the seawater waves, which induces fatigue damage in the form of fatigue crack growth affecting the structural integrity. These welded connections are susceptible to localized fatigue failure as a result of the high stress concentration at the brace-to-chord intersection regions, owing to the complex geometry of the joint. UK HSE data have shown that fatigue damage is the most frequent single cause of repairs, representing 25% of all repairs to steel platforms in the North Sea [1]. Thus, fatigue of tubular welded joints is a main concern in the design as well as during the operational life of offshore platforms.

The hot-spot stress method has evolved as the most suitable means for practical fatigue design purposes. In this method, the nominal stress range on the joint members is multiplied by an appropriate stress concentration factor (SCF) to provide geometric stress at a certain location. The SCF is the ratio of the local surface stress to the nominal direct stress in the brace. Geometric stresses are calculated at various locations around the welds and the maximum geometric stress is the hot-spot stress (HSS) S. The fatigue life of the joint is estimated through an appropriate S–N fatigue curve, N being the number of load cycles. Hence, hot-spot stress method relies on the accurate prediction of SCFs for tubular joints. The SCF value depends on joint geometry, loading type, weld size and type, and the location around the weld under consideration.

Two major issues can be noted regarding the research efforts accomplished so far on the SCF calculation in tubular joints:

(a) many parametric design equations (formulae) in terms of the joint geometrical parameters have been proposed, providing SCF values at certain locations adjacent to the weld for several loading conditions. However, majority of these research works focused on the values of the SCF at certain positions such as the

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saddle and the crown, and they have ignored the SCFs at other positions along the weld toe and (b) significant effort has been devoted to the study of SCFs in various uni-planar tubular joints (i.e. joints where the axes of the chord and the braces lay in the same plane). Nevertheless, for multi-planar joints, which cover the majority of practical applications, very few investigations have been reported due to the complexity and the high cost involved.

In service, it is impractical to inspect all underwater members due to the high cost of inspections by divers. Thus inspections can only be carried out on some selected critical joints [2]. Whether the joint is more susceptible to fatigue damage is determined by the value of its HSS range. Therefore, it is crucial to accurately predict the HSS. It is possible through determining the SCF distribution along the intersection region. Offshore structures are subjected to multiple-axis loading, i.e. combined axial force, in-plane bending (IPB) and out-of-plane bending (OPB) loading moments. The HSS may be located at any point along the intersection under these loads. The conventional method adopted by the API code [3] to determine the HSS is to sum up the products of the nominal stresses due to each load type and the corresponding maximum SCFs. Obviously, this approach does not take the location of the HSS into account and normally leads to excessively conservative estimates of fatigue lives. More accurate HSS can be obtained by the superposition of stress distributions from each of the uni-axis load modes. Stress distribution information is also needed for predicting fatigue crack growth and the remaining life for in-service cracked joints, using advanced fracture mechanics models such as J-integral, AVS, and TPM [2]. Thus it is very important to have accurate stress distributions along the intersection under each uni-axis loading.

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 parametric stress formulae of simple uni-planar tubular joints are not applicable in SCF prediction.

In order to easily relate the behavior of a tubular joint to its geometrical characteristics, a set of non-dimensional geometrical parameters has been defined. Fig. 1 shows a right-angle two-planar tubular DKT-joint with the two commonly named locations along the intersection of the chord with the central brace: saddle and crown. Geometrical parameters (β, γ, τ, ζ, α and α_B) respective to chord and brace diameters D and d, and the corresponding wall thicknesses T and t are defined in Fig. 1. This type of the tubular joint is frequently used in the construction of offshore jacket structures and is one of the most important joint types since it is commonly used to connect the brace members to the main legs of the jacket template.

In the present paper, the results of analyzing the 81 steel multi-planar tubular DKT-joints are used to present general remarks on the effect of geometrical parameters including τ (brace-to-chord thickness ratio), γ (chord wall slenderness ratio), β (brace-to-chord diameter ratio) and θ (outer brace-to-chord inclination angle) on the SCF distribution along the weld toe under axial loads. The studied loading condition is shown in Fig. 1. This specific axial load case has been selected because the initial analyses of the authors showed that it highlights the multi-planar effect more significantly compared to the other axial load combinations. This conclusion was also drawn during the experimental study conducted by the Lloyd's Register of Shipping whose results have been published in the HSE OTH 353 report [4]. Since the SCFs in the central braces are generally much bigger than the corresponding SCFs in the outer braces, the present study focuses only on the central braces. In order to study the multi-planar effect, SCF distribution in multi-planar joints is compared with the distribution in a uni-planar joint with the same geometrical properties. Based on the multi-planar DKT-joint FE models, which are verified against experimental results and the predictions of Lloyd's Register (LR) equations, a complete set of SCF database is constructed. The FE models cover a wide range of geometrical parameters. Through nonlinear regression analysis, a new set of SCF parametric equations is established for the fatigue design of multi-planar DKT-joints under axial loads. An assessment study of these equations is conducted against the experimental data and the acceptance criteria recommended by UK DoE [5].

2. Literature review

Over the past three decades, significant effort has been devoted to the study of SCFs in various uni-planar tubular joints. As a result, many parametric design formulae in terms of the joint geometrical parameters have been proposed, providing SCF values at certain locations adjacent to the weld for several loading conditions.

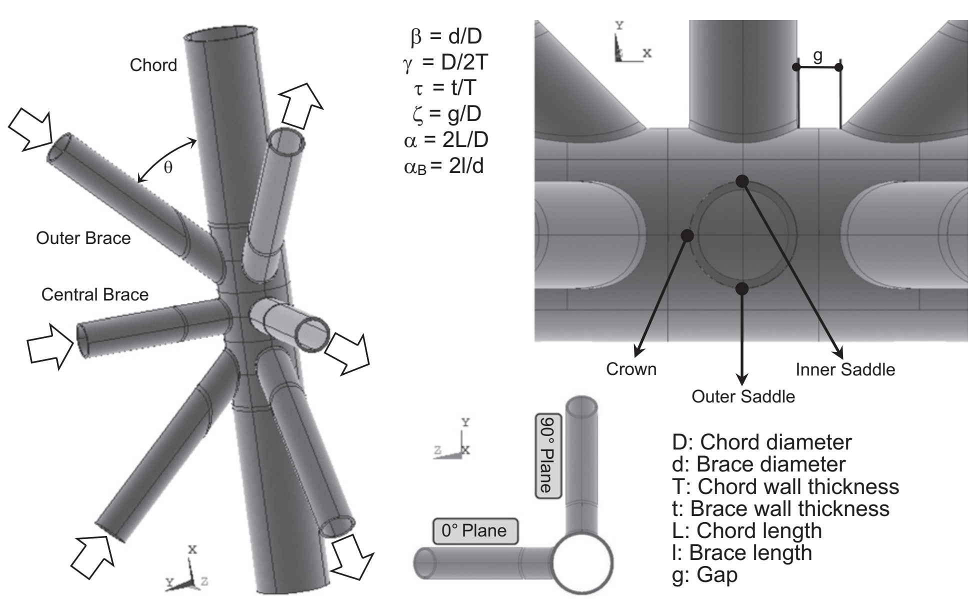

Fig. 1. Geometrical notation for a two-planar tubular DKT-joint and the studied loading condition.