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Stress Concentration Factors at Saddle and Crown Positions on the Central Brace of Two-Planar Welded CHS DKT-connections

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Abstract: A set of parametric stress analyses was carried out for two-planar tubular DKT-joints under different axial loading conditions. The analysis results were used to present general remarks on the effects of the geometrical parameters on stress concentration factors (SCFs) at the inner saddle, outer saddle, and crown positions on the central brace. Based on results of finite element (FE) analysis and through nonlinear regression analysis, a new set of SCF parametric equations was established for fatigue design purposes. An assessment study of equations was conducted against the experimental data and original SCF database. The satisfaction of acceptance criteria proposed by the UK Department of Energy (UK DoE) was also checked. Results of parametric study showed that highly remarkable differences exist between the SCF values in a multi-planar DKT-joint and the corresponding SCFs in an equivalent uni-planar KT-joint having the same geometrical properties. It can be clearly concluded from this observation that using the equations proposed for uni-planar KT-connections to compute the SCFs in multi-planar DKT-joints will lead to either considerably under-predicting or over-predicting results. Hence, it is necessary to develop SCF formulae specially designed for multi-planar DKT-joints. Good results of equation assessment according to UK DoE acceptance criteria, high values of correlation coefficients, and the satisfactory agreement between the predictions of the proposed equations and the experimental data guarantee the accuracy of the equations. Therefore, the developed equations can be reliably used for fatigue design of offshore structures.
Keywords: offshore jacket structure; multi-planar tubular DKT-joint; fatigue; hot-spot stress method; stress concentration factor (SCF)
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1 Introduction

Offshore jacket structures are mainly fabricated from steel circular hollow section (CHS) members because of their excellent structural and mechanical properties, such as a high strength-to-weight ratio, non-directional buckling and bending strength, and low wave resistance. Fatigue failure has long been an important issue for ships and offshore structures (Liu *et al.*, 2006). In a tubular joint, circular hollow members (tubulars) are connected by welding the prepared end of the brace members onto the surface of the chord member. The fatigue design of such joints constitutes a critical factor towards safeguarding the integrity of tubular structures. The complex joint geometry causes significant stress concentrations in the vicinity of the welds. Under repeated loadings they result in the formation of cracks, which can grow to a size sufficient to cause joint failure. The location of maximum stress concentration is called a "hot-spot" and the corresponding local stress is referred to as "hot-spot stress" (HSS). For fatigue design purposes, the hot-spot stress method has been quite efficient and popular. According to this method, the nominal stress range $\Delta\sigma_{\text{nom}}$ at the joint members is multiplied by an appropriate stress concentration factor (SCF) to provide the so-called "geometric stress" S' at a certain location. Hence, this design method relies on the accurate prediction of SCFs for tubular joints. When the members of a joint are subjected to a combination of axial and bending loads on all members, the geometric stress at a specific location around the weld is calculated by superimposing the contributions of the nominal stresses from each loading type (k) considering the corresponding SCF values:

$$S' = \sum_k (\text{SCF})_k \, \Delta\sigma_{\text{nom}}^k \tag{1}$$

The SCF is the ratio of the local surface stress to the nominal direct stress in the brace. The SCF value depends on joint geometry, loading type, weld size and type, and the location around the weld under consideration. Geometric stresses S' are calculated at various locations around the welds, and the maximum geometric stress is the hot-spot stress S. The fatigue life of the joint is estimated through an appropriate S–N fatigue curve, N being the number of load cycles.

Over the past three decades, 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). As a result, many parametric design equations (formulae) in terms of the joint geometrical

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parameters have been proposed, providing SCF values at certain locations adjacent to the weld for several loading conditions. The reader is referred for example to Kuang *et al.* (1975), Wordsworth and Smedley (1978), Wordsworth (1981), Efthymiou and Durkin (1985), Efthymiou (1988), Hellier *et al.* (1990), Smedley and Fisher (1991), HSE OTH 354 (1997), and Karamanos *et al.* (2000) (for SCF calculation at the saddle and crown positions of simple uni-planar T-, Y-, X-, K- and KT-joints); HSE OTH 91 353 (1992), Gho and Gao (2004), Gao (2006), and Gao *et al.* (2007) (for SCF determination in uni-planar overlapped tubular joints); Morgan and Lee (1998a and b), Chang and Dover (1999), Shao (2004), Ahmadi and Lotfollahi-Yaghin (2008), Lotfollahi-Yaghin and Ahmadi (2009, 2010), Shao *et al*. (2009), and Ahmadi *et al*. (2011) (for the study of SCF distribution along the weld toe of various uni-planar joints); and Lee (1999), Chiew *et al*. (2001), Lie *et al.* (2001, 2005), and N'Diaye *et al*. (2007, 2009) (for other aspects of the SCF determination process such as weld and crack modeling).

Multi-planar joints are an intrinsic feature of offshore tubular structures. As can be seen in Fig. 1, right-angle two-planar DKT- and DT-joints connecting the braces to the main legs are some of the most critical tubular joints in a typical jacket structure. 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. 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. The following paragraph reviews the research currently available.

Karamanos *et al*. (1999) proposed a set of parametric equations to determine the SCFs for multi-planar welded CHS XX-connections. In this study, the weld profile was modeled using 20-node solid elements while 8-node shell elements were used to model the chord and braces. This research covered the various loading modes including reference and carry-over loadings. Chiew *et al.* (1999) studied the stress concentrations in DX-joints due to axial loads. Chiew *et al.* (2000) developed a set of design formulae to determine the SCFs for multi-planar tubular XX-joints under axial (AX), in-plane bending (IPB), and out-of-plane bending (OPB) loadings. Van Wingerde *et al.* (2001) presented the equations and graphs to predict the SCFs for multi-planar KK-joints. The aim of this study was to simplify the equations for design purposes. Karamanos *et al.* (2002) proposed SCF equations in multi-planar welded tubular DT-joints including bending effects. Woghiren and Brennan (2009) developed a set of parametric formulae to predict the values of SCF in multi-planar rack-stiffened tubular KK-joints. An experimental database of SCFs for acrylic specimens of multi-planar K- and KT-joints was presented in the HSE OTH 91 353 (1992) prepared by Lloyd's Register. This report covers only the value of SCF at the chord saddle position. It can be seen that in the case of multi-planar joints, the studied connection types and load cases are very limited. Despite the frequent use of multi-planar CHS DKT-joints in the design of offshore jacket structures (see Fig.1), no parametric equation is available to predict the SCF values in such tubular joints.

Under any specific loading condition, the value of SCF along the weld toe of a tubular joint is mainly determined by the joint geometry. In order to study the behavior of tubular joints and to easily relate this behavior to the geometrical properties of the joint, a set of dimensionless geometrical parameters has been defined. Fig.2 shows a right-angle two-planar tubular DKT-joint with the two commonly named locations along the brace-chord intersection of the central brace: saddle and crown, and the geometrical parameters (β, γ, τ, ζ, α, and α_B) for chord and brace diameters D and d, as well as the corresponding wall thicknesses T and t.

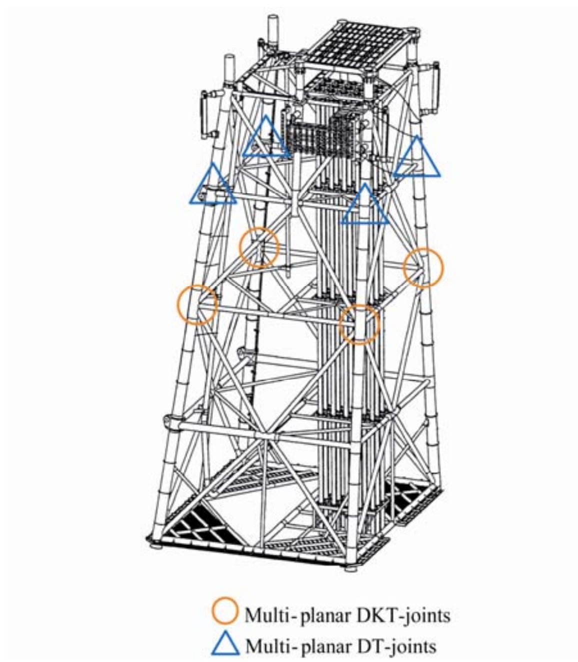


Fig.1 Two-planar DKT- and DT-joints in a typical jacket structure

In this paper, parametric stress analysis has been carried out for 81 steel multi-planar (right-angle two-planar) tubular DKT-joints under two different axial loading conditions. The analysis results 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 values at the inner saddle, outer saddle, and crown positions on the central brace. Since the SCFs in the central braces are generally much larger than the corresponding SCFs in the outer braces, the present study focuses only on the central braces. To study the multi-planar effect and to investigate the effect of loading conditions, SCFs in multi-planar joints under two axial load cases are compared with the SCFs in a uni-planar KT-joint having the same geometrical properties. Based on the multi-planar DKT-joint finite element (FE) models which are verified against both experimental results published in HSE OTH 354 (1997) and the predictions of Lloyd's Register (LR) equations, a complete SCF database is constructed for the two considered axial load cases at three typical hot-spot weld toe locations, i.e. the inner saddle, outer saddle, and crown. The FE models cover a wide range of geometrical parameters. Through nonlinear regression analysis, a new set of SCF design 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 original FEM SCF database and the experimental data is provided in HSE OTH 91 353 (1992). The satisfaction of the acceptance criteria proposed by the UK department of energy (UK DoE, 1983) is also checked.

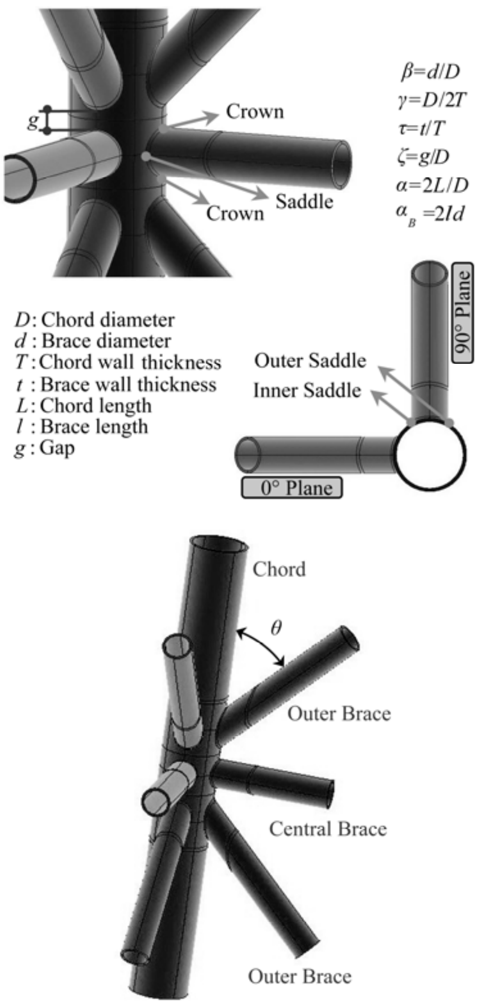


Fig.2 Geometrical notation for a right-angle two-planar tubular DKT-joint

2 Finite element modeling of multi-planar DKT-joints

It is difficult to calculate SCFs theoretically. The results from a strain gauged acrylic model test are not always reliable, as it can not simulate the weldment. The most accurate and reliable method for determining the SCFs is by testing strain gauged large scale or practical size steel joint specimens. However, due to high cost and testing facility limitations, such a method is difficult to use to comprehensively study the joints with various geometrical parameters and load conditions. The finite element method, which has been used successfully to analyze the joints with various geometrical sizes and different load conditions, is adopted in this study.

2.1 Geometrical parameter validation range

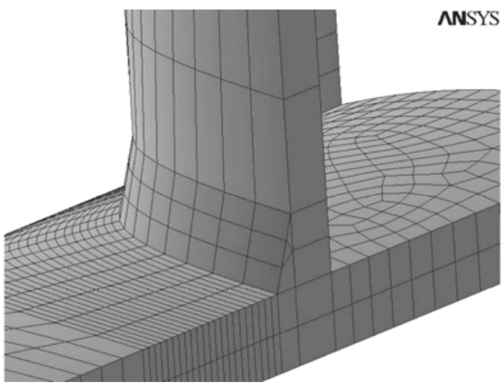
In order to investigate the stress concentration in multi-planar tubular DKT-joints, 81 models are generated and analyzed using the multi-purpose FEM based software package ANSYS. The aim is to study the effect of non-dimensional geometrical parameters on the SCF values at the inner saddle, outer saddle, and crown positions on the chord side of the central brace intersection. Different values assigned to each dimensionless parameter are as follows: β = 0.3, 0.4, 0.5; γ = 12, 18, 24; τ = 0.3, 0.6, 0.9; θ = 30°, 45°, 60°. These values cover the practical range of the normalized parameters typically found in multi-planar tubular joints of offshore structures. Geometrical characteristics of all braces are identical in each specific model. According to the values of γ, τ, and β in each joint, the values of diameter and the wall thickness of the braces are changed from one model to another. According to Lotfollahi-Yaghin and Ahmadi (2009, 2010), the relative gap (ζ=g/D) has no considerable effect on SCF values. The validity range for this conclusion is $0.2 \le \zeta \le 0.6$. Hence, a typical value of $\zeta = 0.2$ is assigned for all joints. The values of α and α_B which are fixed in all joints are 16 and 8, respectively. The reasons for choosing these specific values are given in sub-section 2.3. The 81 generated models span the following ranges of the geometric parameters:

$$\begin{aligned} &0.3 \le \beta \le 0.5 \\ &12 \le \gamma \le 24 \\ &0.3 \le \tau \le 0.9 \\ &30° \le \theta \le 60° \end{aligned} \tag{1}$$

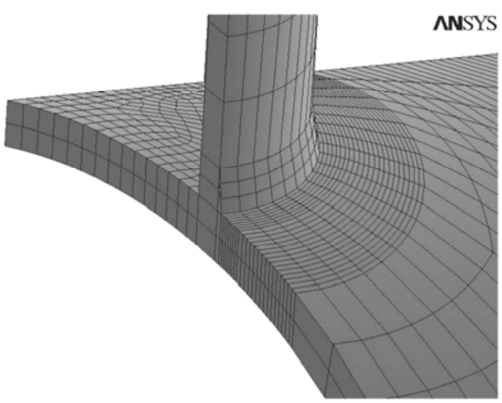
2.2 Mesh generation procedure

There must be a compromise between the accuracy of representation and the computer time taken to analyze a particular model. The entire tubular joint can be modeled by 3-D brick elements. Using these types of elements, the weld profile can be modeled as a sharp notch. This method will produce more accurate and detailed stress distribution near the intersection in comparison with a simple shell analysis. In the present study, an ANSYS element type, SOLID95, is used to model the chord, brace, and weld profiles. These elements have compatible displacements and are well suited to curved model boundaries. The element is defined by 20 nodes having three degrees of freedom per node. The element may have any spatial orientation.

In order to guarantee the mesh quality, a sub-zone mesh generation method is used during the FE modeling. In this method, the entire structure is divided into several different zones according to the computational requirements. The mesh of each zone is generated separately and then the mesh of the entire structure is obtained by merging the meshes of all the sub-zones. This method can easily control the mesh quantity and quality and avoid badly distorted elements. The mesh generated by this method for a multi-planar right-angle tubular DKT-joint is shown in Figs.3 and 4. It should be noted that in this study, the welding size along the brace-chord intersection satisfies the AWS D 1.1 specifications. Modeling of the weld profile according to AWS D 1.1 is extensively discussed in Lotfollahi-Yaghin and Ahmadi (2010). The models are meshed in such a way that leads to a compromise between the accuracy of results and the computer analyzing time as well as the software generated file volume. To verify the convergence of FE analysis, a convergence test is done, and meshes with different densities are used in this test. This test took place before generating the 81 models.



(a) Crown position



(b) Saddle position

Fig.3 The mesh generated by the sub-zone method in the regions adjacent to the central brace intersection

2.3 Boundary conditions and member length considerations

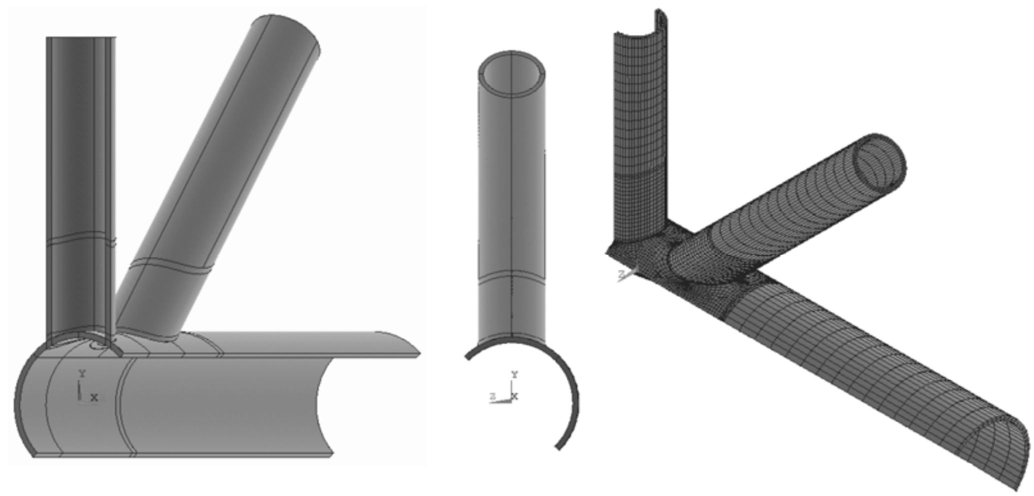
As shown in Fig.4, due to the symmetry in geometry of the connection and either symmetry or antisymmetry in loading conditions, only one fourth of the entire multi-planar right-angle DKT-joint and equivalent uni-planar KT-connection are modeled. The studied loading conditions are shown in Fig.5. The chord end fixity conditions of tubular joints in offshore structures may range from “almost fixed” to “almost pinned” with a tendency of being closer to “almost fixed” (Efthymiou, 1988). In practice, the value of α in over 60% of tubular joints is in excess of 20 and is larger than 40 in 35% of the joints (Smedley and Fisher, 1991). According to Morgan and Lee (1998a), changing the end restraint from fixed to pinned results in a maximum increase of 15% in the SCF at the crown for $\alpha = 6$ joints, and this increase is reduced to only 8% for $\alpha = 8$. In view of the fact that the effect of the chord end restraints is only significant for joints with $\alpha < 8$ for high β and γ values, which do not commonly occur in practice, both chord ends are assumed to be fixed, with the corresponding nodes restrained. Efthymiou (1988) showed that a sufficiently long chord greater than six chord diameters (i.e. $\alpha \geq 12$) must be used to ensure that the stresses at the brace-chord intersection are not affected by the end condition. Hence in this study, a realistic value of $\alpha = 16$ was assigned for all the models. The effect of brace length on the SCF has been studied by Chang and Dover (1999). It was concluded that there is no effect when the ratio α_B is greater than the critical value. In the present study, in order to avoid the effect of short brace length, a realistic value of $\alpha_B = 8$ is selected for all joints.

2.4 Load cases, analysis and SCF extraction

As shown in Fig.5, two different axial loading conditions are considered in the present research to study the SCFs in multi-planar DKT-joints. In the 1^{st} loading condition, all three braces located on the 0° plane are subjected to compressive loads while the ones on the 90° plane are under tensile loading. In the 2^{nd} loading condition, tensile loads are applied to all six braces. Equivalent uni-planar KT-joints are subjected to tensile axial loads exerted on the central and outer braces.

According to N’Diaye *et al.* (2007, 2009), static numerical calculations of the linear elastic type are appropriate to determine the SCFs in tubular joints. This type of analysis is used in the present study. The Young’s modulus and Poisson’s ratio are taken to be 207 GPa and 0.3, respectively.

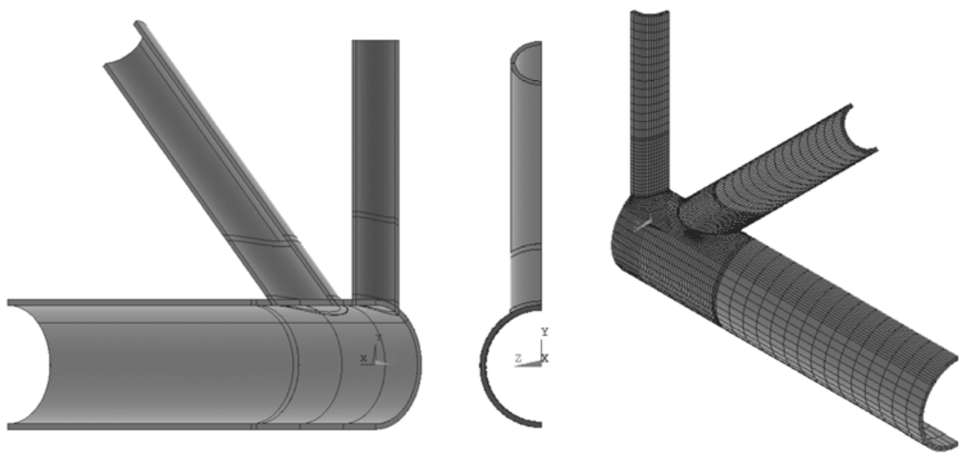
The widely accepted conventional approach for fatigue strength assessment of tubular joints is to use the geometric stresses at the weld toe. According to IIW-XV-E (1999), the peak stress is calculated from extrapolating the geometrical stresses at the two points linearly to the weld toe position. The minimum and maximum distances from the extrapolation region to the weld toe for the chord members are $0.4T$ and $1.4T$, respectively, where T is the thickness of the chord member (Fig.6). CIDECT (Zhao *et al.*, 2000) also recommends the linear extrapolation. However, the recommended minimum and maximum distances from the extrapolation region to the weld toe are $0.4T$ and $1.0T$, respectively.



(a) Two-planar DKT-joint: cuts trough symmetry and antisymmetry planes

(b) Two-planar DKT-joint: view along the chord's longitudinal axis

(c) Two-planar DKT-joint: generated mesh



(d) Uni-planar KT-joint: cuts trough symmetry and antisymmetry planes

(e) Uni-planar KT-joint: view along the chord's longitudinal axis

(f) Uni-planar KT-joint: generated mesh

Fig.4 One fourth of the entire two-planar right-angle DKT-joint and equivalent uni-planar KT-connection which were modeled owing to the existing symmetries and antisymmetries

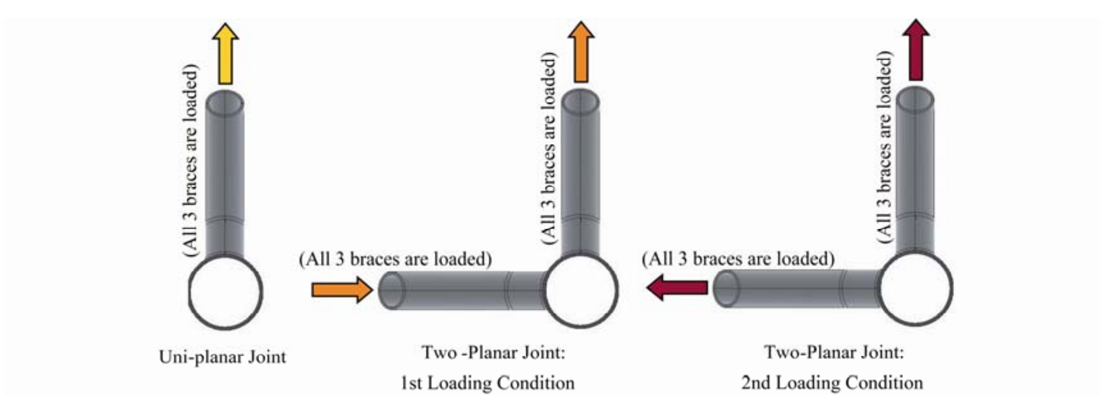


Fig.5 Studied loading conditions

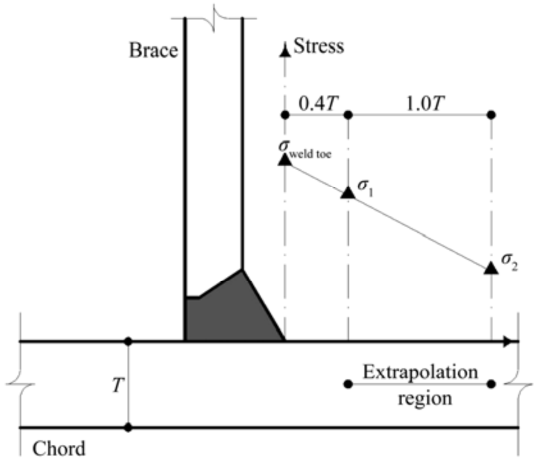


Fig.6 Extrapolation procedure recommended by IIW-XV-E (1999)

2.5 Verification of the FE model

The accuracy of the FEA predictions should be verified against the experimental test results. As far as the authors are aware, there is no experimental database of SCFs for *steel* uni-planar and multi-planar tubular KT-joints currently available in research literature. In order to validate the finite element model, several related geometries including T-, Y-, and K-joints are modeled and the FE results are validated against the LR Equations and test results which were published in HSE OTH 354 report (1997). The method of modeling the chord, the vertical brace, the inclined brace, and the weld profile as well as the mesh generation procedure (including the selection of the element type) and the analysis method are identical for the validating models and the considered uni-planar and multi-planar KT-joints. Hence, the conclusion of the verification of the T-, Y-, and K-joints with the experimental test results can be used to validate the generated uni-planar and multi-planar KT-joint models (Lotfollahi-Yaghin and Ahmadi, 2010).

Verification results which are separately presented at saddle and crown positions are summarized in Table 1. In this table, e_1 denotes the percentage of relative difference between the predictions of the LR equations and test results, and e_2 denotes the percentage of relative difference between the results of the FE model and experimental results. Hence, $|e_1|-|e_2|$ indicates the difference between the accuracy of LR equations and the FE model. A positive sign for value of $|e_1|-|e_2|$ means that the FE model presented in this study is more accurate for prediction of SCFs in comparison with LR equations. It can be concluded from the comparison of the FE results with experimental data and the values predicted by LR equations that the finite element model is considered to be adequate to produce valid results.

Table 1 Verification of the FEA results using the experimental data and predictions of LR equations

Joint type*	D/mm	θ	α	τ	γ	β	Position	Test	LR Eqs.	FEA	e_1*** /%	e_2*** /%	$\|e_1\|-\|e_2\|$/%
T	508	90	6.2	0.99	20.3	0.8	Saddle	11.4	10.54	11.26	8	1	+7
							Crown	5.4	3.92	4.6	27	15	+12
Y	508	45	6.2	1.05	20.3	0.8	Saddle	8.3	5.48	5.46	32	34	−2
							Crown	4.7	3.5	4.7	25	0	+25
K**	508	45	12.6	1.0	20.3	0.5	Saddle	6.8	4.8	6.76	29.5	0.5	+29
							Crown	4.6	4.56	4.8	1	−4	−3

*Project reference: JISSP; **ζ = 0.15; *** e_1= (Test−LR Eqs.)/Test, e_2= (Test−FE)/Test

3 Results of numerical parametric study

This section presents the results of numerical parametric studies carried out to investigate the effect of dimensionless geometrical parameters including β, γ, τ, and θ on the stress concentrations at the inner saddle, outer saddle, and crown positions on the chord side of the central brace intersection in two-planar right-angle DKT-joints.

3.1 Effect of β on the SCF values

The parameter β is the ratio of the brace diameter to chord diameter. Hence, increasing β in the models having constant value of chord diameter leads to an increase in brace diameter. This sub-section presents the results of investigating the effect of β on the SCFs. In this study, the influence of the parameters τ and γ over the effect of β on stress concentration is also investigated. For example, six diagrams are presented in Fig.7 showing the change of SCFs due to the change in the value of β and the interaction of this parameter with γ. Corresponding geometrical parameters, the position for the extraction of SCF, and the considered loading condition are given in the legend of each diagram. A total of 54 comparative diagrams were used to study the effect of β and only 6 of them are presented here for the sake of brevity.

Through investigating the effect of β on the SCFs, it can be concluded that:

1) Under the 1st loading condition, increasing β from 0.3 to 0.5 leads to an increase of SCFs at both inner and outer saddle positions. The magnitude of the change in the SCFs due to the increase of β is minimal for small values of γ (for example, γ = 12). Under this load case, maximum increase

in the SCF values at the inner and outer saddle positions due to increase of β are 13% and 18%, respectively.

2) Under the 1st loading condition, the change of the SCFs at the crown position due to the increase of β does not follow a regular pattern for different geometrical parameters. For example, increase of β results in a decrease of the SCF value at the crown position in the joints having small or intermediate values of γ and τ (for example, γ = 12, 18 and τ= 0.3, 0.6). However, for all values of τ and θ, the SCF is increased at the crown position due to the increase of β in the joints having larger values of γ (γ = 24). Also for the bigger values of τ (τ = 0.9), the change in the SCFs at the crown position follows an increasing pattern for all values of γ. Magnitude of the change in the SCFs at the crown position due to the change of β depends on the joint's geometrical parameters; its maximum value is 25%.

3) Under the 2nd loading condition, increase of β leads to a decrease in SCFs at inner and outer saddle positions but an increase of SCF value at the crown.

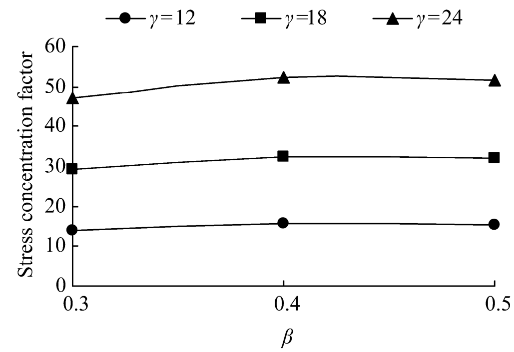
4) Under the 2nd loading condition, the magnitude of the decrease in the SCFs follows an increasing pattern as the values of γ and τ become larger. This reduction is more severe at the inner saddle compared with the outer saddle position. For example, in a joint having the following geometrical parameters, γ = 24, τ = 0.9, θ = 60°, the $SCF_{\beta=0.5}$/ $SCF_{\beta=0.3}$ ratio is 118% and 28% for inner and outer saddle positions, respectively.

5) In contrast to the 1st loading condition, the SCF value at the crown position becomes larger under the 2nd loading condition as β increases. The magnitude of the increase in the SCF value follows an increasing pattern as γ and τ become bigger. For example, the increase of the SCF at the crown position due to the change of β from 0.3 to 0.5 is 73% in a joint having the following geometrical parameters: γ = 24, τ = 0.9, θ = 60°.

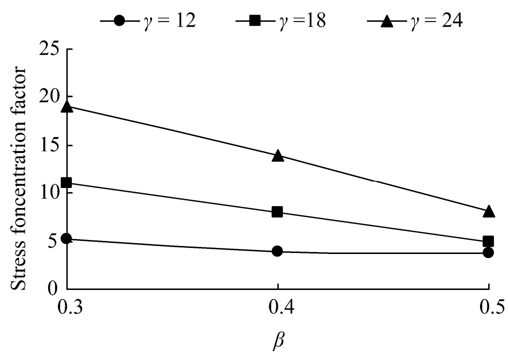
3.2 Effect of γ on the SCF values

The parameter γ is the ratio of radius to thickness of the chord. Hence, an increase of γ in the models having a constant value of chord diameter leads to a decrease in chord thickness. This sub-section presents the results of investigating the effect of γ on the SCFs. In this study, the influence of the parameters β and τ over the effect of β on stress concentration is also investigated. A total of 54 comparative diagrams were used to study the effect of γ, and only 3 of them are presented in Fig.8 for the sake of brevity. This figure shows the change of SCFs due to the change in the value of γ and the interaction of this parameter with τ. All three diagrams are results of the joints under the 1st loading condition.

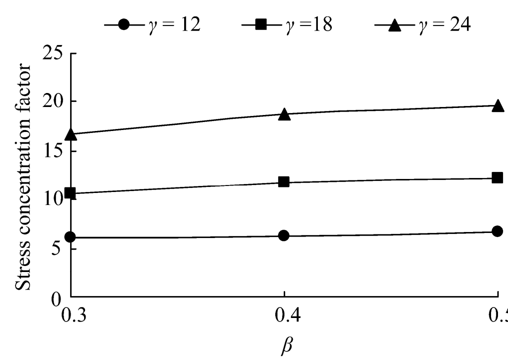
The general remarks which are concluded through investigating the effect of γ on the stress concentration can be summarized as follows:



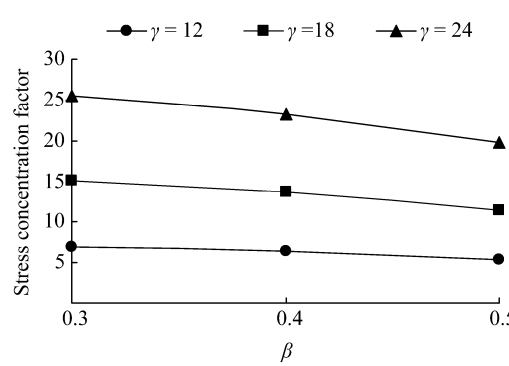
(a) τ = 0.6 , θ = 60°, inner saddle; 1st loading condition



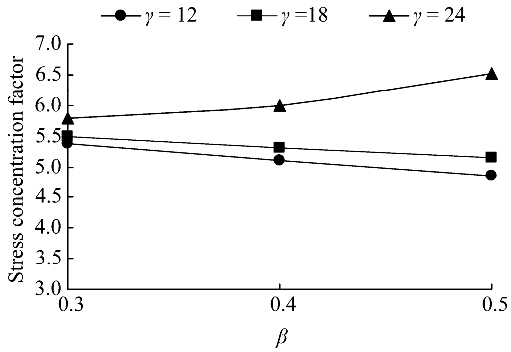
(b) τ = 0.6 , θ = 60°, inner saddle; 2nd loading condition



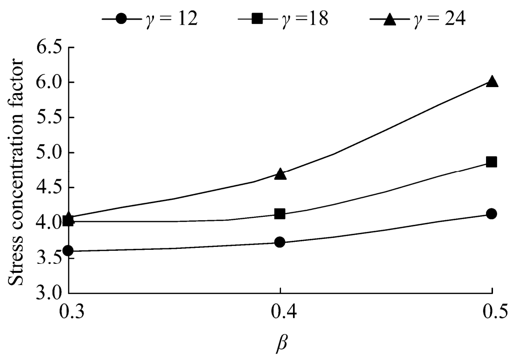
(c) τ = 0.6 , θ = 60°, outer saddle; 1st loading condition



(d) τ = 0.6 , θ = 60°, outer saddle; 2nd loading condition



(e) $\tau = 0.6$, $\theta = 60^\circ$, crown; 1st loading condition

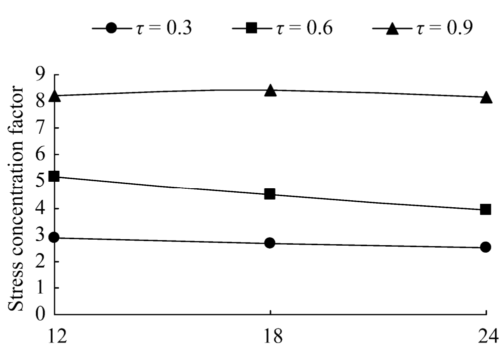


(f) $\tau = 0.6$, $\theta = 60^\circ$, crown; 2nd loading condition

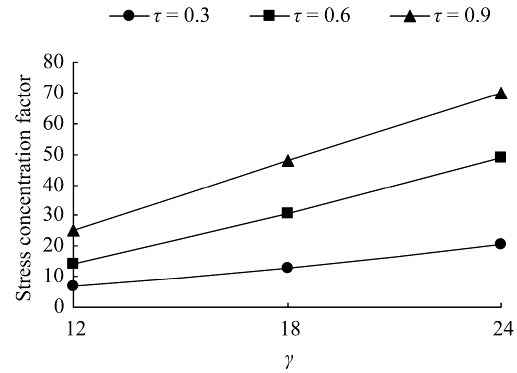
Fig.7 Effect of β on the SCFs at the inner saddle, outer saddle, and crown positions on the central brace

1) Under both loading conditions, an increase of γ results in an increase of SCF values at the inner and outer saddle positions. The magnitude of the increase in these SCFs becomes larger as τ increases. For example, in a joint having the following geometrical parameters $\beta = 0.5$, $\tau = 0.9$, $\theta = 45°$, the increase of the SCF at the outer saddle position due to the change of γ from 12 to 24 is 180%. In the other words, the SCF has increased by a factor of 2.8.

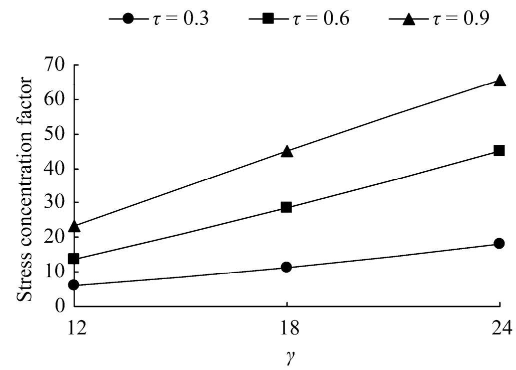
2) Under the 1^{st} loading condition, the SCF value at the crown position is reduced as γ becomes larger. On the contrary, an increase of γ results in an increase in the crown SCFs under the 2^{nd} loading condition. Under both loading conditions, the magnitude of the SCF change at the crown position is less than the corresponding values at the inner and outer saddle positions. For example, the maximum change is 45% ($\beta = 0.5$, $\tau = 0.9$, $\theta = 45°$).



(a) $\beta = 0.3$, $\theta = 45^\circ$, crown



(b) $\beta = 0.5$, $\theta = 45^\circ$, inner saddle



(c) $\beta = 0.5$, $\theta = 45^\circ$, outer saddle

Fig.8 Effect of γ on the SCFs at the inner saddle, outer saddle, and crown positions on the central brace

3.3 Effect of τ on the SCF values

The parameter τ is the ratio of brace thickness to chord thickness, and γ is the ratio of radius to thickness of the chord. Hence, an increase of τ in the models having a constant value of γ leads to increase of brace thickness. This sub-section presents the results of investigating the effect of τ on the SCFs. In this study, the influence of the parameters β and γ over the effect of τ on stress concentration is also investigated. For example, three diagrams are presented in Fig.9 showing the change of SCFs due to the change in the value of τ and the interaction of this parameter with β. All three diagrams are results of the joints under the 1^{st} loading condition. A total of 54 comparative diagrams were used to study the effect of τ and only 3 of them are presented here for the sake of brevity.

The main conclusions of investigating the effect of τ on the SCF values are summarized as follows:

1) Under both loading conditions, an increase of τ results in increase of SCF values at all three considered positions: inner saddle, outer saddle, and crown.

2) At the inner and outer saddle positions, under the 1^{st} loading condition, the magnitude of changing the SCF values due the increase of τ follows an increasing pattern as β takes bigger values. This behavior is in contrast to the 2^{nd} loading condition under which the increase of β leads to reduction in the magnitude of SCF change due to the

increase of τ.

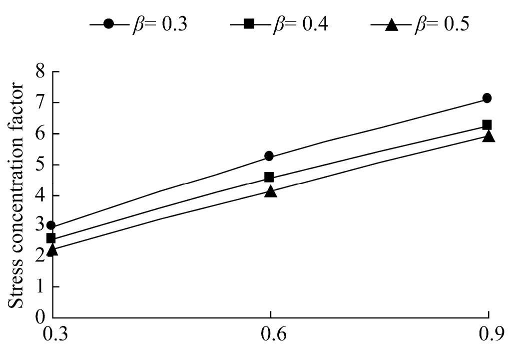
3) At the crown position, under the 1st and 2nd loading conditions, increase of β leads respectively to the decrease and increase in the magnitude of SCF growth due to the increase of τ.

4) At the saddle positions, magnitude of SCF growth due to the increase of τ is larger under the 1st loading condition compared with the 2nd one. On the contrary, this magnitude at the crown position is larger under the 2nd loading condition.

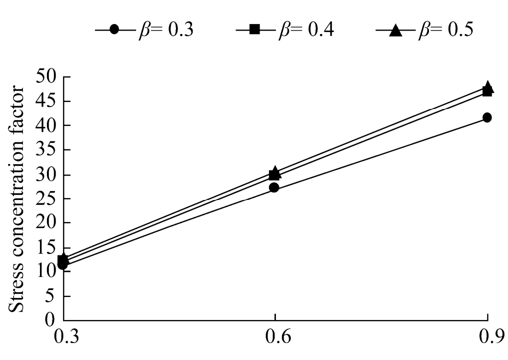
5) The magnitude of increase in the SCF values due to the increase of τ is highly remarkable in comparison with the other geometrical parameters. For example, as can be seen in Fig. 9, due to the change of τ from 0.3 to 0.9, the SCFs have increased by a factor of 2.39, 3.73, and 3.78 at the crown, inner saddle, and outer saddle positions, respectively.

3.4 Effect of θ on the SCF values

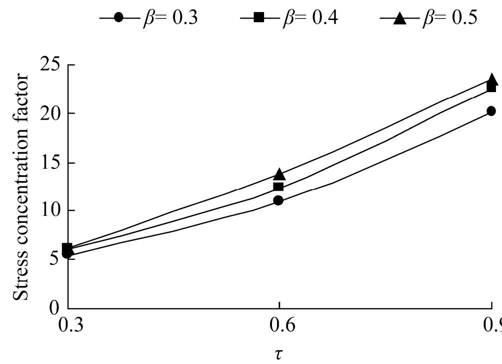
This sub-section presents the results of studying the effect of the outer brace inclination angle θ on the SCFs at different positions on the central brace and its interaction with the other dimensionless geometrical parameters. A total of 54 comparative diagrams were used to study the effect of θ and only 4 of them are presented in Fig.10 showing the change of the SCFs due to the change in the value of θ and the interaction of this parameter with β. All four diagrams are results of the joints under the 1st loading condition.



(a) γ = 18 , θ = 30˚, crown



(b) γ = 18 , θ = 45˚, inner saddle



(c) γ = 12 , θ = 45˚, outer saddle

Fig.9 Effect of τ on the SCFs at the inner saddle, outer saddle, and crown positions on the central brace

Through investigating the effect of θ on the SCFs, it can be concluded that:

1) Increasing θ from 30° to 60° leads to an increase of SCF values at the inner saddle, outer saddle, and crown positions.

2) At the inner and outer saddle positions, under the 1st loading condition, the magnitude of changing the SCF values due the increase of θ follows an increasing pattern as β takes larger values. This behavior is in contrast to the 2nd loading condition under which an increase of β leads to a reduction in the magnitude of SCF change due to the increase of θ. At the crown position, under the 1st and 2nd loading conditions, an increase of β respectively leads to the decrease and increase in the magnitude of SCF growth due to the increase of θ.

3) As was expected, the parameter θ (outer brace inclination angle) has less effect on the SCF values on the central brace compared with the other three geometrical parameters β, γ, and τ.

3.5 Comparison of the SCFs at the crown, inner saddle and outer saddle

The maximum stress concentration under the 1st and 2nd loading conditions always occurs at inner and outer saddle positions, respectively. While under both loading conditions, the minimum stress concentrations always occur at the crown position. In the other words:

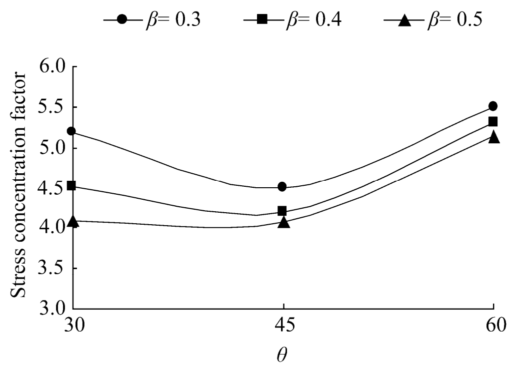
1st loading condition:

$$\mathrm{SCF}_{\text{inner saddle}} > \mathrm{SCF}_{\text{outer saddle}} > \mathrm{SCF}_{\text{crown}} \quad (3)$$

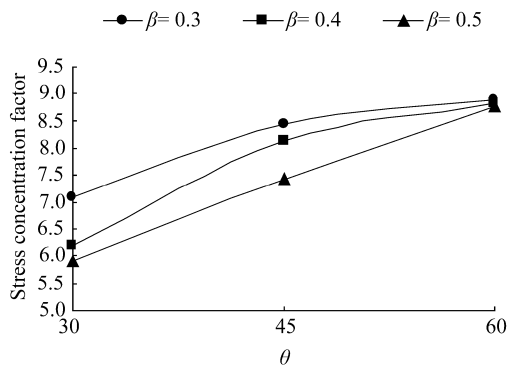
2nd loading condition:

$$\mathrm{SCF}_{\text{outer saddle}} > \mathrm{SCF}_{\text{inner saddle}} > \mathrm{SCF}_{\text{crown}} \quad (4)$$

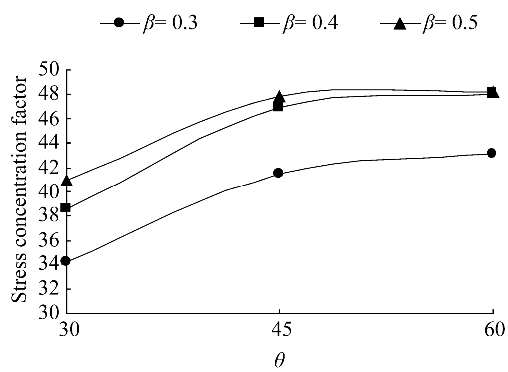
The above conclusion can clearly be observed in Fig.11, which is presented as an example. Fig.11 also shows that considerable difference exists between the saddle and crown SCFs. It can also be seen that under the 2nd loading condition, the difference between the $\mathrm{SCF}_{\text{inner saddle}}$ and $\mathrm{SCF}_{\text{outer saddle}}$ is much larger than this difference under the 1st loading condition. These two latest observations highlight the necessity of proposing six individual parametric equations for the calculation of SCFs at three studied positions on the central brace under two considered loading conditions.



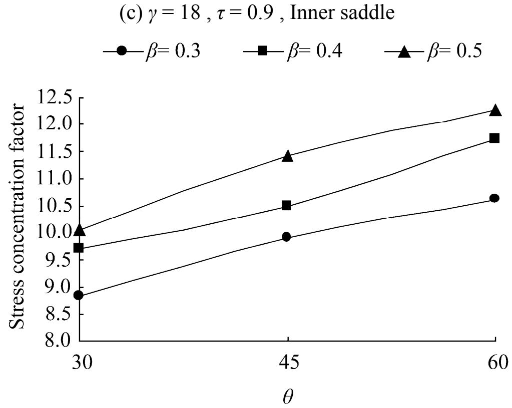
(a) $\gamma = 18$, $\tau = 0.6$, crown



(b) $\gamma = 18$, $\tau = 0.9$, crown

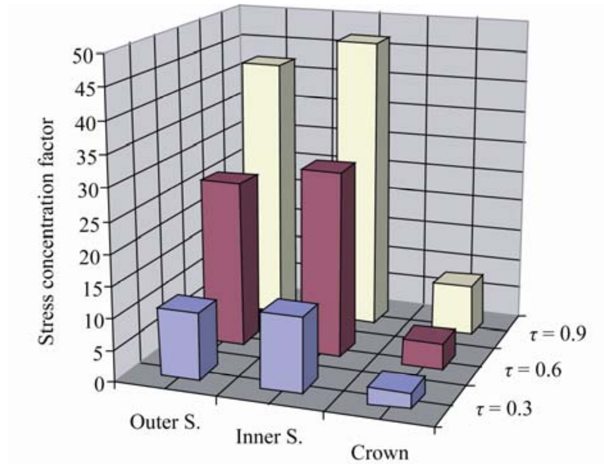


(c) $\gamma = 18$, $\tau = 0.9$, Inner saddle

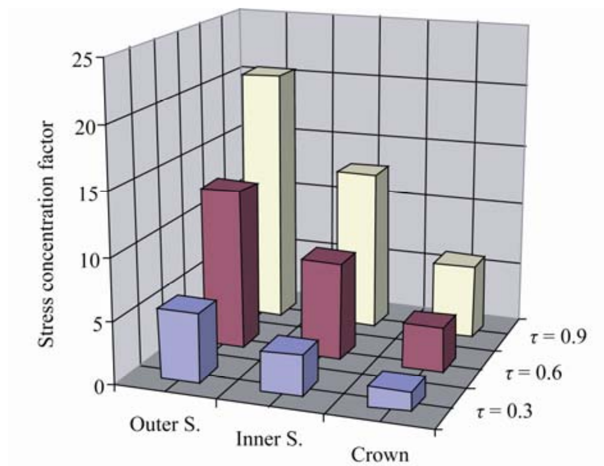


(d) $\gamma = 18$, $\tau = 0.3$, Outer saddle

Fig.10 Effect of θ on the SCFs at the inner saddle, outer saddle, and crown positions on the central brace



(a) $\theta = 45^{\circ}$, $\beta = 0.4$, $\gamma = 18$, 1st loading condition



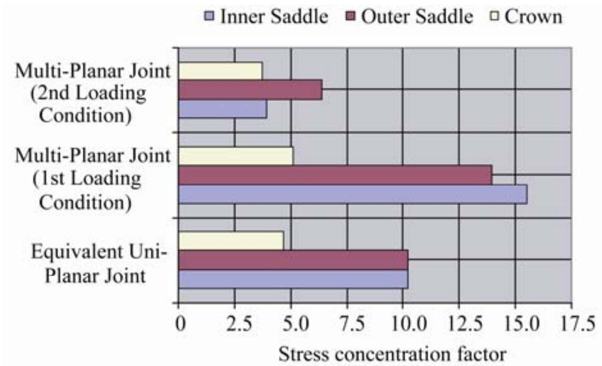
(b) $\theta = 45^{\circ}$, $\beta = 0.4$, $\gamma = 18$, 2nd loading condition

Fig.11 Comparison of the SCFs at the crown, inner saddle, and outer saddle

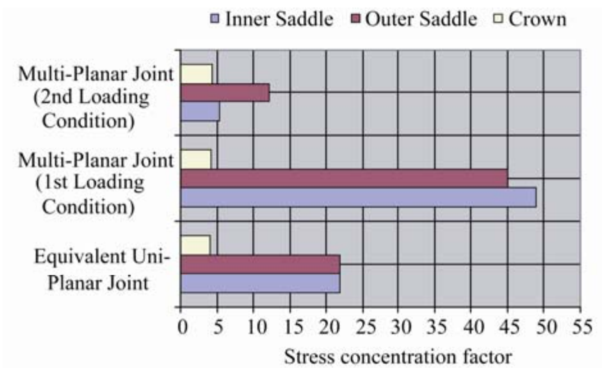
3.6 Comparison of the SCFs in uni- and multi-planar joints

As can be seen in Fig.12, highly remarkable differences exist between the SCF values in a multi-planar DKT-joint and the corresponding SCFs in an equivalent uni-planar KT-joint having the same geometrical properties. It can be clearly concluded from this observation that using the equations proposed for uni-planar KT-connections to compute the SCFs in multi-planar DKT-joints will lead to either considerably under-predicting or over-predicting results. Hence it is necessary to develop SCF formulae specially designed for multi-planar DKT-joints. As shown in Fig.12(b), the SCF value at the inner saddle position on the central brace of a multi-planar DKT-joint under the 1st loading condition can be 2.25 times bigger than the corresponding SCF value in the equivalent uni-planar KT-joint. However, this uni-planar SCF is 4 times larger than the corresponding SCF in the multi-planar joint under the 2nd loading condition. Such observations highlight the necessity of proposing individual parametric equations for each loading condition. It can also be concluded from Fig.12

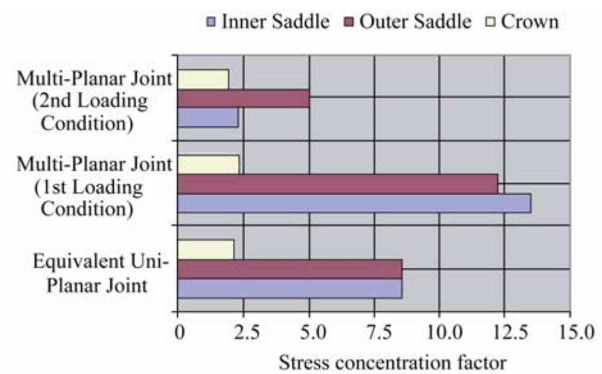
that under both loading conditions, the maximum difference between the SCFs in uni- and multi-planar joints always occurs at the inner saddle position while the minimum difference will always be at the crown position.



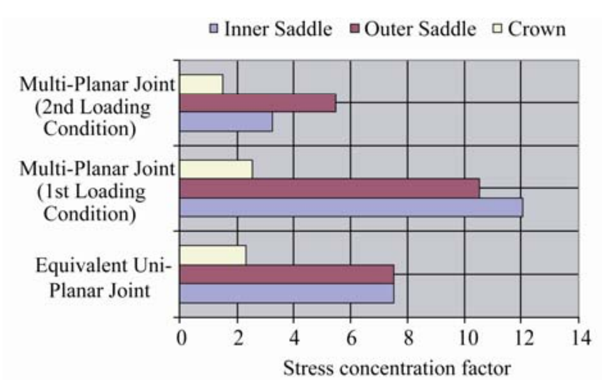
(a) $\theta = 60^{\circ}$, $\tau = 0.6$, $\gamma = 12$, $\beta = 0.4$



(b) $\theta = 45^{\circ}$, $\tau = 0.6$, $\gamma = 24$, $\beta = 0.5$



(c) $\theta = 60^{\circ}$, $\tau = 0.3$, $\gamma = 18$, $\beta = 0.5$



(d) $\theta = 45^{\circ}$, $\tau = 0.3$, $\gamma = 18$, $\beta = 0.4$

Fig.12 Comparison of the SCFs in uni- and multi-planar joints

4 SCF design formulae for central brace

Although the FEM has been successfully utilized to analyze the tubular joints, the extensive use of such a numerical method is not feasible in a normal day-to-day design office operation. Instead, parametric design equations expressed in the form of the non-dimensional geometrical parameters are useful and desirable for fatigue design. In the present study, six individual parametric equations are proposed for the calculation of the SCFs at the inner saddle, outer saddle, and crown positions on the central brace of a right-angle 2-planar DKT-joint under two considered axial loading conditions.

4.1 Nonlinear regression analysis

The parametric equations are derived based on multiple nonlinear regression analyses performed by the statistical software package SPSS. Values of the dependent variable (i.e. SCF) and independent variables (β, γ, τ, and θ) constitute the input data which is imported as a matrix. Each row of this matrix involves the information about the value of the SCF at a certain position in a multi-planar tubular DKT-joint having specific geometrical properties. The number of rows and columns of the input matrix for each equation is 81 (number of the joints) and 5 (number of variables), respectively. Hence, the whole FEM SCF database is arranged as six 81 × 5 input matrices.

When the dependent (i.e. SCF) and independent (i.e. β, γ, τ, and θ) variables are defined, a model expression must be built with defined parameters. The parameters of the model expression are unknown coefficients and exponents. The researcher must specify a starting value for each parameter, preferably as close as possible to the expected final solution. Poor starting values can result in failure to converge or in convergence on a solution that is local (rather than global) or physically impossible. Various model expressions must be built to derive a parametric equation having a high coefficient of correlation.

After performing nonlinear analysis, the following parametric equations are proposed for predicting the SCF values at the inner saddle, outer saddle, and crown positions on the chord side of the central brace intersection in a right-angle two-planar DKT-joint under two considered axial loading conditions:

1st loading condition:

$$\begin{aligned} &\text{SCF} = 0.619\beta^{0.247}\gamma^{1.615}\tau^{1.093}\theta^{0.293} \\ &(\text{Inner saddle}) \qquad R^2 = 0.994 \end{aligned} \tag{5}$$

$$\begin{aligned} &\text{SCF} = 0.631\beta^{0.325}\gamma^{1.604}\tau^{1.124}\theta^{0.286} \\ &(\text{Outer saddle}) \qquad R^2 = 0.995 \end{aligned} \tag{6}$$

$$\begin{aligned} &\text{SCF} = 7.397\beta^{-0.083}\gamma^{0.062}\tau^{1.073}\theta^{0.381} \\ &(\text{Crown}) \qquad R^2 = 0.952 \end{aligned} \tag{7}$$

2nd loading condition:

$$\begin{aligned}&\text{SCF} = 0.027\beta^{-1.318}\gamma^{1.732}\tau^{1.125}\theta^{0.102}\\&(\text{Inner saddle}) \quad R^2 = 0.979\end{aligned} \tag{8}$$

$$\begin{aligned}&\text{SCF} = 0.094\beta^{-0.466}\gamma^{1.747}\tau^{1.115}\theta^{0.227}\\&(\text{Outer saddle}) \quad R^2 = 0.988\end{aligned} \tag{9}$$

$$\begin{aligned}&\text{SCF} = 5.874\beta^{0.416}\gamma^{0.208}\tau^{1.077}\theta^{0.004}\\&(\text{Crown}) \quad R^2 = 0.955\end{aligned} \tag{10}$$

In the above equations, R^2 denotes the coefficient of correlation and θ should be inserted in radians.

4.2 Assessment according to UK DoE (1983) acceptance criteria

The UK Department of Energy (UK DoE, 1983) recommends the following assessment criteria regarding the applicability of the commonly used SCF parametric equations (P/R stands for the ratio of the *predicted* SCF from a given equation to the *recorded* SCF from test or analysis):

- For a given dataset, if % SCFs under-predicting ≤ 25%, i.e. [%P/R < 1.0] ≤ 25%, and if % SCFs considerably under-predicting ≤ 5%, i.e. [%P/R < 0.8] ≤ 5%, then the equation is accepted. If, in addition, the percentage SCFs considerably over-predicting ≤ 50%, i.e. [%P/R > 1.5] ≥ 50%, then the equation is regarded as generally conservative.

- If the acceptance criteria is nearly met, i.e. 25% < [%P/R < 1.0] ≤ 30%, and/or 5% < [%P/R < 0.8] ≤ 7.5%, then the equation is regarded as borderline and engineering judgment must be used to determine acceptance or rejection. Otherwise the equation is rejected as it is too optimistic.

In view of the fact that for a mean fit equation, there is always a large percentage of under-prediction, the requirement for joint under-prediction, i.e. P/R < 1.0, can be completely removed in the assessment of parametric equations. Assessment results according to the UK DoE (1983) criteria are tabulated in Table 2. As can be seen, the proposed equations satisfy the criteria and consequently are accepted according to the UK DoE.

4.3 Verification using the experimental data and original FE database

Table 3 presents the results of validating the proposed equations at the inner and outer saddle positions under the 1st loading condition using the data from a strain gauged acrylic model test. The source of the experimental data is the HSE OTH 91 353 report (1992) prepared by Lloyd's Register in which a comprehensive experimental database of SCFs for acrylic complex joints including multi-planar and overlapped K- and KT-joints has been presented. This report covers only the value of the SCF at the chord saddle position. As can be seen in Table 3, there is satisfactory agreement between the predictions of the proposed equations and the experimental measurements. It must be noted that since the weld profile is not included in an acrylic specimen, the SCFs obtained from the acrylic model tests are typically 5%–10% larger than the realistic values in the steel tubular joints.

In Fig.13, the SCF values predicted by the six proposed equations have been compared with the original SCFs from the FE analysis. Fig.13 shows that there is satisfactory agreement between the results of the equations and the numerically computed SCFs. This good agreement was expected considering the high coefficients of correlation.

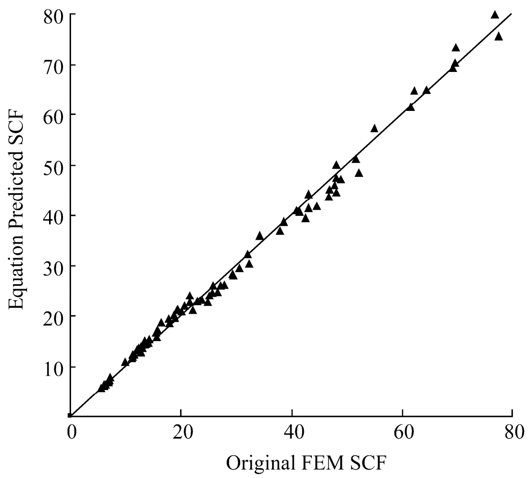
Table 2 Results of equation assessment according to UK DoE (1983) acceptance criteria

Load case	Equation	Respective position	Conditions		Overall status
			%P/R < 0.8	%P/R > 1.5	
1st loading condition	Eq.(5)	Inner saddle	0% < 5% OK.	0% < 50% OK.	accepted
	Eq.(6)	Outer saddle	0% < 5% OK.	0% < 50% OK.	accepted
	Eq.(7)	Crown	3.7% < 5% OK.	0% < 50% OK.	accepted
2nd loading condition	Eq.(8)	Inner saddle	4.9% < 5% OK.	1.2% < 50% OK.	accepted
	Eq.(9)	Outer saddle	0% < 5% OK.	0% < 50% OK.	accepted
	Eq.(10)	Crown	1.2% < 5% OK.	0% < 50% OK.	accepted

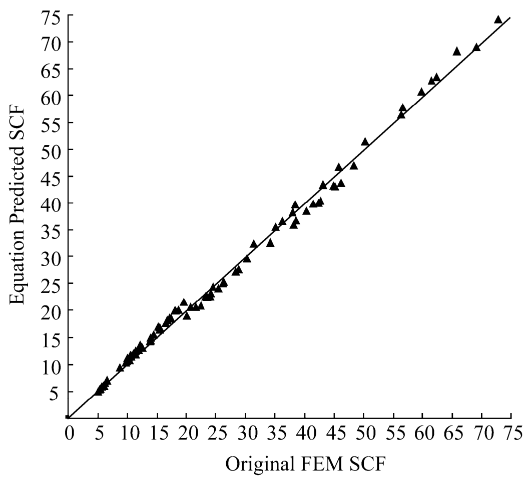
Table 3 Results of validating the proposed equations at the inner and outer saddle positions using the data from a strain gauged acrylic model test

Geometrical parameters	SCF value at the inner saddle			SCF value at the outer saddle		
	Experimental	Eq.(5)	Difference*	Experimental	Eq.(6)	Difference*
$D = 150$ mm , $\theta = 45$, $\tau = 0.6$, $\beta = 0.3$, $\gamma = 12$	14.02	13.55	3%	13.54	12.07	12%

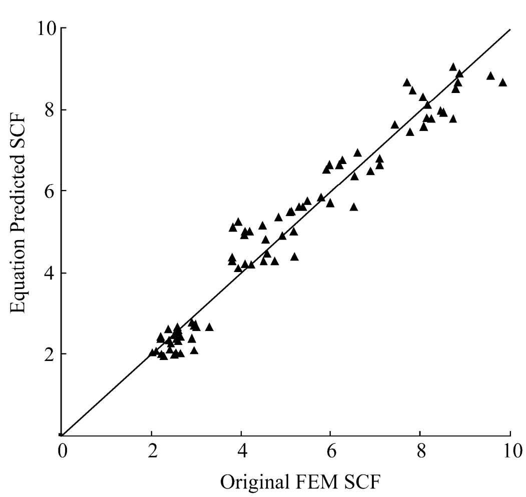
* Difference = (Experimental SCF/SCF predicted by proposed Eq.)–1.0



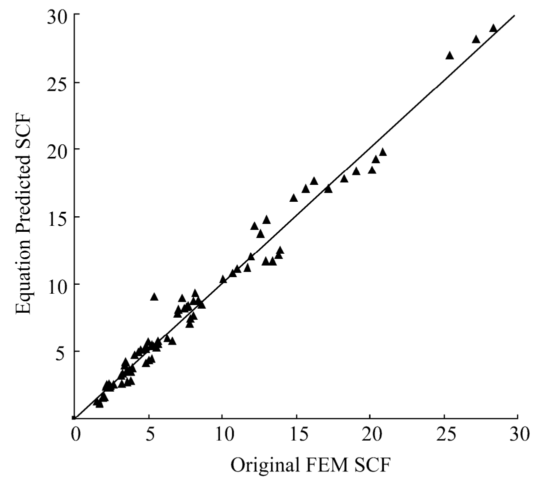
(a) 1st loading condition: inner saddle ($R^2 = 0.994$)



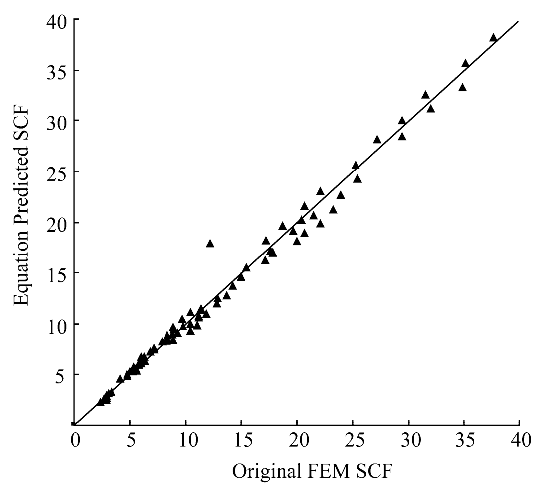
(b) 1st loading condition: outer saddle ($R^2 = 0.995$)



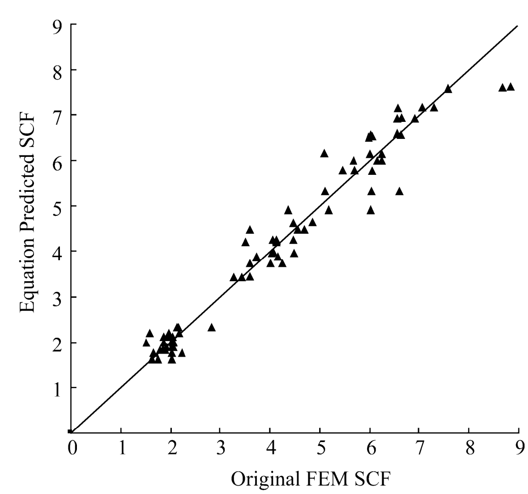
(c) 1st loading condition: crown ($R^2 = 0.952$)



(d) 2nd loading condition: inner saddle ($R^2 = 0.979$)



(e) 2nd loading condition: outer saddle ($R^2 = 0.988$)



(f) 2nd loading condition: crown ($R^2 = 0.955$)

Fig.13 Results of validating the proposed equations against the original FE database

5 Conclusions

In the present paper, parametric stress analysis was carried out for 81 steel right-angle 2-planar tubular DKT-joints under two different axial loading conditions. The analysis results were used to present general remarks on the effect of geometrical parameters including τ, γ, β, and θ on the SCF values at the inner saddle, outer saddle, and crown positions on the central brace. Based on the results of multi-planar DKT-joint finite element models which were verified against the experimental results, a complete SCF database was constructed for two considered axial load cases at three typical hot spot weld toe locations, the inner saddle, outer saddle, and crown. Through nonlinear regression analysis, a new set of SCF design equations was established for the fatigue design of multi-planar DKT-joints under axial loads. An assessment study of these equations was conducted against the original FEM SCF database and the experimental data. The satisfaction of the acceptance criteria proposed by the UK DoE was also checked.

The detailed and quantitative results of parametric study which were extensively discussed in the text are not repeated here for the sake of brevity, and only a summary of general remarks is presented:

- Under the 1st loading condition, increase of β leads to increase of the SCFs at both inner and outer saddle positions. However, the change of the SCFs at the crown position due to the increase of β does not follow a regular pattern for different geometrical parameters. Under the 2nd loading condition, an increase of β leads to a decrease of SCFs at inner and outer saddle positions but an increase of the SCF value at the crown.

- Under both loading conditions, an increase of γ results in an increase of SCF values at the inner and outer saddle positions. Magnitude of the increase in these SCFs becomes larger as τ increases. Under the 1st loading condition, the SCF value at the crown position is reduced as γ becomes bigger. On the contrary, an increase of γ results in an increase in the crown SCFs under the 2nd loading condition.

- Under both loading conditions, an increase of τ results in an increase of SCF values at all three considered positions: the inner saddle, outer saddle, and crown. The magnitude of the increase in the SCF values due to the increase of τ is highly remarkable in comparison with the other geometrical parameters.

- At the saddle positions, the magnitude of SCF growth due to the increase of τ is larger under the 1st loading condition compared to the 2nd condition. On the contrary, this magnitude at the crown position is larger under the 2nd loading condition.

- Increase of θ from 30° to 60° leads to an increase of SCF values at the inner saddle, outer saddle, and crown positions. As was expected, parameter θ (the outer brace inclination angle) has less effect on the SCF values on the central brace in comparison with the other three geometrical parameters β, γ, and τ.

- The maximum stress concentration under the 1st and 2nd loading conditions always occurs at the inner and outer saddle positions, respectively. While under both loading conditions, the minimum stress concentrations always occur at the crown position.

- Highly remarkable differences exist between the SCF values in a multi-planar DKT-joint and the corresponding SCFs in an equivalent uni-planar KT-joint having the same geometrical properties. It can be clearly concluded from this observation that using the equations proposed for uni-planar KT-connections to compute the SCFs in multi-planar DKT-joints will lead to either considerably under-predicting or over-predicting results. Hence, it is necessary to develop SCF formulae specially designed for multi-planar DKT-joints.

Good results of equation assessment according to UK DoE acceptance criteria, high values of correlation coefficients, and the satisfactory agreement between the predictions of the proposed equations and the experimental data guarantee the accuracy of the equations. Therefore, the developed equations can be reliably used for fatigue design of offshore structures.

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