SCF distribution along the weld toe in tubular X-joints reinforced with doubler plates subjected to axial loading: Study of geometrical effects and design formulation

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Abstract

Although tubular X-joints are quite common in offshore structural design and despite the crucial role of stress concentration factors (SCFs) in evaluating the fatigue performance of tubular joints, the SCF distribution in X-joints reinforced with doubler plates has not been investigated so far and no design equation is currently available to predict the distribution of chord-side SCFs along the weld toe of brace-to-chord intersection in this type of joint. In the present research, data extracted from the stress analysis of 81 finite element (FE) models, verified using available numerical results, was used to study the effects of geometrical parameters on the chord-side SCF distribution along the weld toe in doubler-plate reinforced tubular X-joints subjected to axial loading. Parametric FE study was followed by a set of nonlinear regression analyses to develop a new SCF parametric equation for the fatigue analysis and design of axially loaded tubular X-joints reinforced with doubler plates.

Keywords: Fatigue, Offshore jacket structure, Tubular X-joint, Doubler plate, Stress concentration factor (SCF), Parametric design equation

Nomenclature

API	American Petroleum Institute	OPB	Out-of-plane bending
AWS	American Welding Society	SCF	Stress concentration factor
d	External diameter of the brace	t	Brace thickness
D	External diameter of the chord	T	Chord thickness
DoE	Department of Energy	t_p	Doubler plate thickness
FE	Finite elements	α	Chord slenderness ration (= $2L/D$)
g	Gap	α_B	Brace slenderness ratio (= $2l/d$)
HSE	Health and Safety Executive	β	Brace-to-chord diameter ratio (= d/D)
HSS	Hot-spot stress	γ	Chord wall slenderness ratio (= $D/2T$)
IIW	International Institute of Welding	κ	Plate-to-chord thickness ratio (= t_p/T)
IPB	In-plane bending	θ	Brace inclination angle
l	Brace length	τ	Brace-to-chord thickness ratio (= t/T)
L	Chord length	φ	Polar angle measured around the intersection from crown heel
R^2	Coefficient of determination		

1. Introduction

The primary structural part of an offshore jacket-type platform, commonly used for the production of oil and gas from hydrocarbon reservoirs below the seabed (Fig. 1a), is fabricated from tubular members by welding one end of the branch member, i.e. brace, to the undisturbed surface of the main member, i.e. chord, resulting in what is known as a tubular joint (Fig. 1b). The static and fatigue strength of tubular joints are the governing factors in the design of jacket structures.

Tubular joints must be properly dimensioned during the design stage so that they perform satisfactorily in service and achieve a reasonable balance between the project cost and risk of failure. If the capacity of a joint is found to be inadequate during the design stage, it can be enhanced by welding a doubler plate onto the outer surface of the chord (Fig. 1c) as this is an efficient method to reduce the stress concentration, increase the load-carrying capacity and fatigue life of the joint, and avoid the attraction of additional wave forces. None of the major offshore design codes, such as API RP 2A [1] and HSE [2], provides any substantial quantitative recommendations on fatigue strength requirements for doubler-plate reinforced joints. This is due partly to the vast variety of possible plate arrangements and partly to the dearth of information available on such joints in research literature. There is, therefore, an urgent need for further research so that more detailed guidelines on fatigue strength estimation of doubler-plate reinforced tubular joints can be formulated, which is the incentive of the present work.

Significant stress concentrations at the vicinity of the welds are considerably detrimental to the fatigue performance of the joints. Hence, it is important to accurately determine the magnitude of stress concentration and to reduce it to a reasonable level. In the design practice, a parameter called the stress concentration factor (SCF) is used to evaluate the magnitude of the stress concentration. The SCF, defined as the ratio of the local surface stress at the brace-to-chord intersection to the nominal stress in the brace, exhibits considerable scatter depending on the joint geometry, loading type, weld size and type, and the considered position for the SCF calculation around the weld profile. Under any specific loading condition, the SCF value along the weld toe of a tubular joint is mainly determined by the joint geometry. To study the behavior of tubular joints and to easily relate this behavior to the geometrical characteristics of the joint, a set of dimensionless geometrical parameters has been defined. Fig. 1c depicts a doubler-plate reinforced tubular X-joint with the geometrical parameters τ, γ, β, κ, α, and α_B where D and d are the diameters of the chord and brace, respectively; L and l are the lengths of those members, respectively; and T, t, and t_p are the thickness of the chord, brace, and doubler plate, respectively. Critical positions along the weld toe of the brace-to-chord intersection for the calculation of SCFs in a tubular joint, i.e. saddle and crown, have been shown in Fig. 1b and c.

During the last 50 years, a large number of papers have been published on SCFs in tubular joints. However, the majority of these research works were focused on SCF determination at the saddle and crown positions; and they have ignored the SCFs at other locations along the weld toe. Although the results of such research efforts are quite useful, a number of solid reasons can be mentioned for the importance of studying the SCF distribution along the weld toe instead of the SCF determination only at certain locations such as crown and saddle:

- Through determining the SCF distribution along the brace-to-chord intersection, it is possible to accurately estimate the location of the hot-spot stress (HSS). It is known that fatigue-induced surface crack initiates from the position of the HSS. Therefore, identifying such position is very important for the prediction of crack propagation path and the fatigue life.

- Tubular members of offshore structures are subjected to multi-axis loading: i.e. combined axial force, in-plane bending (IPB) moment, and out-of-plane bending (OPB) moment. Under these loads, the HSS may be located at any position along the brace-to-chord intersection. The conventional method to determine the HSS, is to sum 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 it normally leads to an excessively conservative estimate of fatigue life [3]. More accurate HSS can be obtained by the superposition of stress distributions due to each of these three types of loading.
- The difference between the value of the peak stress concentration factor and the values of the SCF at saddle and crown positions might be considerable. Therefore, the use of the parametric equations which present the values of SCF only at saddle and crown positions leads to under-predicting estimates of HSS values. This is important because it is impractical in service 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 that have limited fatigue life [4]. Since the fatigue life of the joint is determined by the value of its HSS range, it is crucial to accurately predict the HSS.
- The information on the stress distribution is also needed for predicting fatigue crack growth and remaining life for in-service cracked joints when fracture mechanics models such as J-integral [5], AVS [6], and TPM [7] are used. Thus, it is very important to have an accurate stress distribution along the intersection.

In the present paper, results of a numerical investigation on the distribution of SCFs in tubular X-joints reinforced with doubler plates are presented and discussed. In this research program, a set of parametric finite element (FE) stress analyses was carried out on 81 doubler-plate reinforced tubular X-joint models subjected to axial loading (Fig. 1b). Analysis results were used to present general remarks on the effects of geometrical parameters including τ (brace-to-chord thickness ratio), γ (chord wall slenderness ratio), β (brace-to-chord diameter ratio), and κ (plate-to-chord thickness ratio) on the SCF distribution along the weld toe. Based on the results of X-joint FE models, verified using available numerical data, a SCF database was prepared. Then, a new SCF parametric equation was established, based on nonlinear regression analyses, for the fatigue analysis and design of doubler-plate reinforced X-joints subjected to axial loading. The reliability of proposed equation was evaluated according to the acceptance criteria recommended by the UK DoE [8].

Appropriate place for the insertion of Fig. 1

2. Literature review

2.1. Study of SCFs in unreinforced tubular joints

2.1.1. Determination of SCFs at saddle and crown positions

Over the past decades, significant effort has been devoted to the study of SCFs in various uniplanar tubular joints (i.e. joints where the axes of the chord and brace members lay in the same plane). As a result, many parametric design formulas in terms of the joint's geometrical parameters have been proposed providing SCF values at certain positions such as saddle and crown for several loading conditions. The reader is referred for example to Kuang et al. [9], Efthymiou [10], Hellier et al. [11], UK HSE OTH 354 [12], and Karamanos et al. [13] for the SCF calculation at the saddle and crown positions of simple uniplanar T-, Y-, X-, K-, and KT-joints; and Gho and Gao [14], Gao [15], Gao et al. [16], and Yang et al. [17] for the SCF determination in uniplanar overlapped tubular joints, among others.

Multi-planar joints are an intrinsic feature of offshore tubular structures. For multi-planar connections, the parametric formulas of simple uniplanar tubular joints may not be applicable for the SCF prediction, since such formulas may lead to highly over- or under-predicting results. For SCF studies in multi-planar joints, the reader is referred to Karamanos et al. [18] and Chiew et al. [19] for the SCF calculation in XX-joints; Wingerde et al. [20] for the SCF determination in KK-joints; Karamanos et al. [21] for the study of SCFs in DT-joints; Woghiren and Brennan [22] for the SCF calculation in stiffened KK-joints; Chiew et al. [23] for the study of SCFs in XT-joints; and Ahmadi et al. [24, 25], Ahmadi and Lotfollahi-Yaghin [26], and Ahmadi and Zavvar [27] for the investigation of SCFs in multi-planar KT-joints under axial loads, among others.

2.1.2. Determination of SCF distribution along the weld toe

For the study of SCF distribution along the weld toe in various tubular joints, the reader is referred to Morgan and Lee [28, 29] for K-joints; Chang and Dover [30, 31] for T-, Y-, X-, and DT-joints; Shao [32, 33] and Shao et al. [34] for T- and K-joints; Lotfollahi-Yaghin and Ahmadi [35], Ahmadi et al. [36], and Lotfollahi-Yaghin and Ahmadi [37] for KT- and DKT-joints; Xu et al. [38] for concrete-filled joints; and Liu et al. [39] for T-joints, among others.

2.2. Study of SCFs in reinforced tubular joints

2.2.1. Determination of SCFs at saddle and crown positions

For the SCF calculation in stiffened tubular joints, the reader is referred to Nwosu et al. [40] for ring-stiffened T-joints; Hoon et al. [41] for doubler-plate reinforced T-joints; Myers et al. [42] for rack-plate reinforced joints; Ahmadi and Lotfollahi-Yaghin [43] and Ahmadi and Zavvar [44] for ring-stiffened KT-joints subjected to IPB and OPB moment loadings; and Nassiraei and Rezadoost [45–50] for FRP-strengthened T/Y- and X-joints subjected to axial and bending loads.

2.2.2. Determination of SCF distribution along the weld toe

Ahmadi et al. [51, 52] investigated the SCF distribution along the weld toe of central and outer braces in tubular KT-joints reinforced with internal ring stiffeners and proposed a set of parametric equations to calculate the SCFs along the brace-to-chord intersection in internally ring-stiffened KT-joints subjected to axial loading.

2.3. Other SCF- and doubler plate-related studies in various tubular joints

For other SCF-related investigations such as probabilistic and reliability studies, the reader is referred for example to Ahmadi et al. [53], Gaspar et al. [54], Ahmadi and Lotfollahi-Yaghin [55, 56], Ahmadi et al. [57, 58], Ahmadi [59], and Ahmadi and Mousavi Nejad Benam [60].

Nassiraei [61] studied the effects of geometrical parameters on the LJF of tubular T/Y-joints reinforced with doubler plate. Nassiraei et al. [62–64] investigated the static strength of doubler plate reinforced tubular T/Y-joints subjected to axial and bending loads.

2.4. Concluding remarks

It can be clearly concluded from Sect. 2.1–2.3 that, over the past five decades, significant effort has been devoted to the study of SCFs at saddle and crown positions in various unstiffened tubular joints. However, the study of SCF distribution along the brace-to-chord intersection of unstiffened joints is rather limited. Moreover, it is evident that very few investigations have been reported for the SCF calculation at saddle and crown positions of stiffened tubular joints and it can also be seen that in the case of stiffened joints, the studies on the SCF distribution along the brace-to-chord intersection are very rare.

Despite the frequent use of tubular X-joints in the design of offshore jacket-type structures, the SCF distribution along the weld toe of doubler-plate reinforced X-joints has not been investigated and no design equation is currently available to determine the chord-side SCF distribution along the brace-to-chord intersection in this type of joint.

3. FE modeling

3.1. Simulation of the weld profile

Accurate modeling of the weld profile is one of the most critical factors affecting the accuracy of SCF results. Therefore, the weld sizes must be carefully included in the FE modeling. A number of research works has been carried out on the study of the weld effect. For example, the reader is referred to Lee and Wilmshurst [65], Cao et al. [66], and Lee [67], among others. It was found that the fatigue strength of the joint can be underestimated by 20% compared to the experimental data without considering the weld [68].

In the present study, the welding size along the brace-to-chord intersection satisfies the AWS D 1.1 [69] specifications. However, it should be noted that attempts to produce an improved as-welded profile often result in over-welding. Consequently, the actual weld size, typical of yard practice, is usually different from the nominal weld size recommended by AWS D 1.1 [69] specifications. For the correction of SCFs to consider the actual position of the weld toe, the reader is advised to follow the recommendations of Section C 5.3.2(a) of API RP 2A [1].

Considering the effect of possible weld defects, it should be noted that for fatigue design purposes, the HSS method has been quite efficient and popular. According to this method, the nominal stress at the joint members is multiplied by an appropriate SCF to provide the HSS at a certain location. HSSs are calculated at various positions around the weld and the maximum HSS range (S) is determined. Then, the fatigue life of the joint is estimated through an appropriate S–N fatigue curve, N being the number of load cycles. The HSS range concept places different structural geometries on a common basis, enabling them to be treated using a single S–N curve. The basis of this concept is to capture a stress (or strain) in the proximity of the weld toes, which characterizes the fatigue life of the joint, but excludes the very local microscopic effects like the sharp notch, undercut and crack-like defects at the weld toe. These local weld notch effects are included in the S–N curve.

The dihedral angle (ψ) which is an important parameter in determining the weld thickness is defined as the angle between the chord and brace surface along the intersection curve. The dihedral angle at the two typically important positions along the weld toe, i.e. saddle and crown, equals to $\pi - \cos^{-1}(\beta)$ and $\pi/2$, respectively. Details of weld profile modeling according to AWS D 1.1 [69] have been presented by Ahmadi et al. [25].

3.2. Boundary conditions

In offshore structures, the chord end fixity conditions of tubular joints may range from almost fixed to almost pinned with generally being closer to almost fixed [10]. In practice, the value of the parameter α in over 60% of tubular joints is in excess of 20 and is bigger than 40 in 35% of the joints [70]. Changing the end restraint from fixed to pinned results in a maximum increase of 15% in the SCF at the crown position for joints with $\alpha = 6$, and this increase reduces to only 8% for $\alpha = 8$ [29]. In the view of the fact that the effect of chord end restraints is only significant for joints with $\alpha < 8$ and high β and γ values, which do not commonly occur in practice, both chord ends were assumed to be fixed, with the corresponding nodes restrained.

Due to the symmetry in geometry and loading of the joint, only 1/8 of the entire doubler-plate reinforced X-joint is required to be modeled in order to reduce the computational time (Fig. 2). Appropriate symmetric boundary conditions were defined for the nodes located on the symmetry planes.

Appropriate place for the insertion of Fig. 2

3.3. Mesh generation

In the present study, ANSYS element SOLID95 was used to model the chord, braces, doubler plates, and weld profiles. This element has compatible displacements and is well-suited to model curved boundaries. It is defined by 20 nodes having three degrees of freedom per node and may have any spatial orientation. Using this type of 3-D brick 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 shell analysis.

To guarantee the mesh quality, a sub-zone mesh generation scheme was used during the FE modeling. The entire structure was divided to several zones according to computational requirements. The mesh of each zone was generated separately and then the mesh of the entire joint was produced by merging the meshes of all the sub-zones. This scheme can feasibly control the mesh quantity and quality and avoid badly distorted elements. The mesh generated by this procedure for a doubler-plate reinforced tubular X-joint is shown in Fig. 3.

As mentioned earlier, in order to determine the SCF, the stress at the weld toe should be divided by the nominal stress of the loaded brace. The stresses perpendicular to the weld toe at the extrapolation points are required to be calculated in order to determine the stress at the weld toe position. To extract and extrapolate the stresses perpendicular to the weld toe, as shown in Figs. 3 and 4b, the region between the weld toe and the second extrapolation point was meshed finely in such a way that each extrapolation point was placed between two nodes located in its immediate vicinity. These nodes are located on the element-generated paths which are perpendicular to the weld toe.

In order to verify the convergence of FE results, convergence test with different mesh densities was conducted before generating the 81 FE models for the parametric study.

Appropriate place for the insertion of Fig. 3

3.4. Analysis settings and SCF calculation

Static analysis of the linearly elastic type is suitable to determine the SCFs in tubular joints [71]. The Young's modulus and Poisson's ratio were taken to be 207 GPa and 0.3, respectively.

The weld-toe SCF is defined as:

$$\text{SCF} = \sigma_{\perp W} / \sigma_n \tag{1}$$

In Eq. (1), σ_n is the nominal stress of the axially loaded brace which is calculated as follows:

$$\sigma_n = \frac{4F_a}{\pi\left[d^2 - (d-2t)^2\right]} \tag{2}$$

where F_a is the applied axial force; and d and t are brace diameter and thickness, respectively.

To calculate the SCF, the stress at the weld toe position should be extracted from the stress field outside the region influenced by the local weld toe geometry. The location from which the stresses have to be extrapolated, *extrapolation region*, depends on the dimensions of the joint and on the position along the intersection. According to the linear extrapolation method recommended by IIW XV-E [72], the first extrapolation point must be at a distance of $0.4T$ from the weld toe, and the second point should lie at $1.0T$ further from the first point (Fig. 4a). In Eq. (1), $\sigma_{\perp W}$ is the extrapolated stress at the weld toe position which is perpendicular to the weld toe and is calculated by the following equation:

$$\sigma_{\perp W} = 1.4\sigma_{\perp E1} - 0.4\sigma_{\perp E2} \tag{3}$$

where $\sigma_{\perp E1}$ and $\sigma_{\perp E2}$ are the stresses at the first and second extrapolation points along the direction perpendicular to the weld toe, respectively.

The stress at an extrapolation point is obtained as follows:

$$\sigma_{\perp E} = \frac{\sigma_{\perp N1} - \sigma_{\perp N2}}{\delta_1 - \delta_2}\left(\Delta - \delta_2\right) + \sigma_{\perp N2} \tag{4}$$

where $\sigma_{\perp Ni}$ (i = 1 and 2) is the nodal stress at the immediate vicinity of the extrapolation point along the direction perpendicular to the weld toe at the saddle position (Eq. (5)); δ_i (i = 1 and 2) is the distance between the weld toe and the considered node inside the extrapolation region (Eq. (6)); and Δ equals to $0.4T$ and $1.4T$ for the first and second extrapolation points, respectively (Fig. 4b).

$$\sigma_{\perp N} = \sigma_x l_1^2 + \sigma_y m_1^2 + \sigma_z n_1^2 + 2\left(\tau_{xy} l_1 m_1 + \tau_{yz} m_1 n_1 + \tau_{zx} n_1 l_1\right) \tag{5}$$

$$\delta = \sqrt{\left(x_w - x_n\right)^2 + \left(y_w - y_n\right)^2 + \left(z_w - z_n\right)^2} \tag{6}$$

In Eq. (5), σ_a and τ_{ab} (a, b = x, y, z) are components of the stress tensor which can be extracted from ANSYS analysis results; and l_1, m_1, and n_1 are transformation components defined as:

$$l_1 = \cos\left(X_\perp, x\right);\; m_1 = \cos\left(X_\perp, y\right);\; n_1 = \cos\left(X_\perp, z\right) \tag{7}$$

where $X_\perp$ is the direction perpendicular to the weld toe; and x, y, and z are axes of the global coordinate system (Fig. 4b). These components can be calculated as below:

$$l_1 = \left(x_w - x_n\right)/\delta;\; m_1 = \left(y_w - y_n\right)/\delta;\; n_1 = \left(z_w - z_n\right)/\delta \tag{8}$$

where (x_n, y_n, z_n) and (x_w, y_w, z_w) are global coordinates of the considered node inside the extrapolation region and its corresponding node at the weld toe position, respectively.

At the saddle and crown positions, Eq. (5) is simplified as:

$$\sigma_{\perp N} = \sigma_y m_1^2 + \sigma_z n_1^2 + 2\tau_{yz} m_1 n_1 \text{ (Saddle)};\; \sigma_{\perp N} = \sigma_x \text{ (Crown)} \tag{9}$$

In order to facilitate the SCF calculation, above formulation was implemented in a *macro* developed by the ANSYS Parametric Design Language (APDL). The input data required to be provided by the user of the macro are the node number at the weld toe, the chord thickness, and the numbers of the nodes inside the extrapolation region. These nodes can be introduced using the Graphic user interface (GUI).

Appropriate place for the insertion of Fig. 4

3.5. FE model verification

Nazari et al. [73] conducted a numerical study on the SCFs in tubular X-joints with and without the doubler plates. Their study was limited to the extraction of SCFs at the saddle position and other locations along the brace-to-chord intersection were not covered by this investigation. They studied the effects of geometrical parameters on the SCF values and developed a set of parametric equations for the SCF calculation. In order to verify the FE models of present research, two tubular X-joints studied by Nazari et al. [73] were modeled by the authors and the FE results obtained from these validating models were compared with Nazari et al. [73] data

(Table 1). It can be seen that the maximum difference between the results of Nazari et al. [73] models and validating models of the present study in about 7%. Hence, it can be concluded that generated FE models can be considered to be accurate enough to provide valid results.

Appropriate place for the insertion of Table 1

4. Geometrical effects on the SCF distribution along the weld toe

4.1. Settings of parametric study

In order to study the SCFs along the weld toe in doubler-plate reinforced tubular X-joints subjected to axial loading (Fig. 1), 81 models were generated and analyzed using the FE software, ANSYS. The objective was to investigate the effects of non-dimensional geometrical parameters on the weld-toe SCF distribution along the brace-to-chord intersection. Different values assigned for parameters β, γ, τ, and κ have been presented in Table 2. These values cover the practical ranges of dimensionless parameters typically found in tubular joints of offshore jacket structures. If the chord is sufficiently long (i.e. $\alpha \geq 12$), the stresses at the brace-to-chord intersection are not affected by the chord ends fixity condition [10]. Hence, a realistic value of $\alpha = 16$ was designated in this study to all the models. The brace length has no effect on SCFs if the parameter α_B is greater than a critical value [31]. In the present study, in order to avoid the effect of short brace length, a realistic value of $\alpha_B = 8$ was assigned for all joints. The 81 generated models span the following ranges of the geometric parameters:

$$\begin{aligned} &0.4 \leq \beta \leq 0.6 \\ &12 \leq \gamma \leq 24 \\ &0.4 \leq \tau \leq 1.0 \\ &0.5 \leq \kappa \leq 1.0 \end{aligned} \tag{10}$$

Appropriate place for the insertion of Table 2

4.2. Effect of the γ on the SCF distribution along the weld toe

This section presents the results of investigating the effect of the γ on the SCF distribution along the weld toe. Since the parameter γ is the ratio of radius to thickness of the chord, the increase of the γ in a model having a fixed value of the chord diameter leads to the decrease of the chord thickness. In this study, the interaction of the γ with the other geometrical parameters was also investigated. Three charts are presented in Fig. 5, as an example, showing the distribution of SCFs along the weld toe in nine analyzed models. These charts illustrate the effect of the γ and its interaction with the β. Each chart in Fig. 5 shows the SCF distributions for three different values of the γ (12, 18, and 24). Values of the parameters β and τ are identical in three presented charts and the value of the β in Fig. 5a–c is 0.4, 0.5, and 0.6, respectively. A total of 27 comparative charts were used to study the effect of the γ and only three of them are presented here for the sake of brevity.

The general remarks concluded through investigating the effect of the parameter γ on the SCF distribution along the weld toe can be summarized as follows:

Regardless of the value of the β, the increase of the γ leads to an increase in SCFs at all positions along the weld toe. The minimum and maximum increases always occur at the crown and saddle positions, respectively; and the amount of this increment constantly increases along the weld toe from the crown toward the saddle. The peak SCF is always located at the saddle position regardless of the value of the γ.

Appropriate place for the insertion of Fig. 5

4.3. Effect of the τ on the SCF distribution along the weld toe

The parameter τ is the ratio of brace thickness to chord thickness and the γ is the ratio of radius to thickness of the chord. Hence, the increase of the τ in a model having fixed value of the γ leads to the increase of the brace thickness. This section presents the results of investigating the effect of the τ on the SCF distribution along the weld toe. In this study, the interaction of the τ with the other geometrical parameters was also investigated. A total of 27 comparative charts were used to study the effect of the τ and only three of them are presented in Fig. 6 for the sake of brevity. Fig. 6 shows the distribution of SCFs along the weld toe for nine analyzed models. These charts illustrate the effect of the τ and its interaction with the γ. Each chart in Fig. 6 shows the SCF distributions for three different values of the τ (0.4, 0.7, and 1.0). Values of the parameters β and κ are identical in three presented charts and the value of the γ in Fig. 6a–c is 12, 18, and 24, respectively.

Through investigating the effect of the τ on SCFs, it can be concluded that the increase of the τ, from 0.4 to 1.0, leads to an increase in SCFs at all positions along the weld toe. This result is independent from values of the other geometrical parameters. The magnitude of the increase in SCF values due to the increase of the τ is highly remarkable in comparison with the other geometrical parameters. Although the increase of the τ considerably affects the magnitude of SCFs, it does not have remarkable influence on the shape of the SCF distribution along the weld toe.

Appropriate place for the insertion of Fig. 6

4.4. Effect of the β on the SCF distribution along the weld toe

Since the parameter β is the ratio of the brace diameter to the chord diameter, the increase of the β in a model with fixed value of the chord diameter leads to an increase in the brace diameter. This section presents the results of investigating the effect of the β on the SCF distribution along the weld toe. In this study, the interaction of the β with the other geometrical parameters was also investigated. A total of 27 comparative charts were used to study the effect of the β and only three of them are presented in Fig. 7 for the sake of brevity. Fig. 7 shows the distribution of SCFs along the weld toe for nine analyzed models. These charts indicate the effect of the β and its interaction with the γ. Each chart in Fig. 7 shows the SCF distributions for three different values of the β (0.4, 0.5, and 0.6). Values of the parameters τ and κ are identical in three presented charts and the value of the γ in Fig. 7a–c is 12, 18, and 24, respectively.

Through investigating the effect of the β on the SCFs, it can be concluded that the increase of the β, from 0.4 to 0.6, does not have a considerable effect on the values and/or the distribution shape of the SCFs along the weld toe. This conclusion is independent from values of the other geometrical parameters.

Appropriate place for the insertion of Fig. 7

4.5. Effect of the κ on the SCF distribution along the weld toe

Results of investigating the effect of the κ on the SCF distribution along the weld toe are discussed in the present section. In this study, the interaction of the κ with the other geometrical parameters was also investigated. The parameter κ is the ratio of doubler plate thickness to chord thickness. Hence, providing that the value of the chord thickness remains unchanged, the increase of the κ leads to the increase of the doubler plate thickness. A chart is presented in Fig. 8a, as an example, showing the distribution of SCFs along the weld toe for three analyzed models having different values of the κ (0.5, 0.75, and 1.0). Fig. 8b compares the SCFs at the saddle position in models with different κ and γ values. Main conclusions of investigating the effect of the κ on the SCF values are summarized as follows:

The increase of the κ, from 0.5 to 1.0, leads to a decrease in SCFs at all positions along the weld toe. This result is independent from values of the other geometrical parameters. Although the increase of the κ affects the magnitude of SCFs, it usually does not have remarkable influence on the shape of the SCF distribution along the weld toe.

Appropriate place for the insertion of Fig. 8

5. Development of a parametric equation for the SCF calculation

The extensive use of the FE method for the SCF analysis of tubular joints is not feasible in a normal day-to-day design office operation. Instead, parametric design equations expressed in terms of dimensionless geometrical parameters are useful and desirable for fatigue design.

Fig. 9 shows that the presence of doubler plates in a sample X-joint has led to the decrease of the SCF at the saddle position from 5.01 to 2.52; i.e. the amount of SCF decrease due to the application of doubler plates can be even 100%. Hence, the use of equations already available for unreinforced tubular joints in order to calculate the SCFs in doubler-plate reinforced joints may lead to highly over-predicting outcomes. Thus, results of multiple nonlinear regression analyses performed by SPSS were used in the present research to develop a new parametric SCF equation for the design of doubler-plate reinforced X-joints. Values of dependent variable (i.e. SCF) and independent variables (i.e. β, γ, τ, κ, and φ) constitute the input data imported in the form of a matrix. Each row of this matrix involves the information about the SCF value at a specific position along the weld toe in an axially loaded doubler-plate reinforced X-joint having specific geometrical properties.

When the dependent and independent variables are defined, a model expression must be built with defined parameters. 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 is physically impossible. Various model expressions must be built to derive a parametric equation having a high coefficient of determination (R^2).

After performing a large number of nonlinear analyses, following parametric equation is proposed for predicting the SCF distribution along the weld toe in doubler-plate reinforced X-joints subjected to axial loading:

$$\mathrm{SCF} = \exp\,(0.0196\beta+0.053\gamma+1.54\tau-0.47\kappa+0.93\varphi-0.99) \quad ; \quad R^2 = 0.938 \qquad (11)$$

The parameter φ in Eq. (11) is the polar angle indicating the location for the calculation of SCF along the weld toe ($0^\circ \le \varphi \le 90^\circ$). Its value that should be inserted in radians is 0 and $\pi/2$ at crown and saddle positions, respectively. The value of R^2 is quite high indicating the accuracy of the fit. The validity ranges of dimensionless geometrical parameters for the developed equation have been given in Eq. (10).

In Fig. 10, the SCF values predicted by the proposed equation are compared with the SCFs extracted from FE analyses. It can be seen that there is a good agreement between the results of proposed equation and numerically computed values.

The UK Department of Energy [8] 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 $\leq$ 25%, i.e. [%P/R < 1.0] $\leq$ 25%, and if % SCFs considerably under-predicting $\leq$ 5%, i.e. [%P/R < 0.8] $\leq$ 5%, then accept the equation. If, in addition, the percentage SCFs considerably over-predicting $\leq$ 50%, i.e. [%P/R > 1.5] $\geq$50%, then the equation is regarded as generally conservative.
- If the acceptance criteria is nearly met i.e. 25% < [%P/R < 1.0] $\leq$ 30%, and/or 5% < [%P/R < 0.8] $\leq$ 7.5%, then the equation is regarded as borderline and engineering judgment must be used to determine acceptance or rejection.
- Otherwise reject the equation 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 [74]. Assessment results according to the UK Department of Energy [8] criteria are presented in Table 3. It can be seen that the proposed equation needs revision in order to satisfy the criteria recommended by the UK DoE. To revise this equation, the SCF values obtained from Eq. (11) were multiplied by a factor in such a way that resulted SCF values satisfy the UK DoE acceptance criteria. This idea of applying a design factor can be expressed as follows:

$$\text{Design factor} = SCF_{(Design)} / SCF_{(Eq.\ (11))} \tag{12}$$

where the values of $SCF_{(Eq.\ (11))}$ are calculated from the proposed equation and the values of $SCF_{(Design)}$ are expected to satisfy the UK DoE criteria.

Multiple comparative analyses were carried out to determine the optimum value of the design factor; and finally, the following equation is recommended for design purposes:

$$SCF_{(Design)} = 1.04\ SCF_{(Eq.\ (11))} \tag{13}$$

Appropriate place for the insertion of Figs. 9 & 10

Appropriate place for the insertion of Table 3

6. Conclusions

Results of a set of stress analyses performed on 81 FE models verified using available numerical data were used to investigate the effects of geometrical parameters on the distribution of weld-toe SCFs along the brace-to-chord intersection in tubular X-joints reinforced with doubler plates under the axial loading. A new SCF parametric equation was also developed for the fatigue design. Main conclusions are summarized as follows.

The increase of the parameters τ and/or γ leads to the increase of SCFs at all positions along the weld toe. The minimum and maximum increases always occur at the crown and saddle positions, respectively; and the amount of this increment constantly increases along the weld toe from the crown toward the saddle. The peak SCF is always located at the saddle position regardless of the value of dimensionless geometrical parameters. The increase of the β, from 0.4 to 0.6, does not have a considerable effect on the values and/or the distribution shape of SCFs along the weld toe. The increase of the κ leads to a decrease in SCFs at all positions along the weld toe. Although the increase of the κ affects the magnitude of SCFs, it usually does not have remarkable influence on the shape of the SCF distribution along the weld toe.

Since the presence of doubler plates significantly decreases the SCFs along the weld toe, the use of equations already available for unreinforced tubular joints in order to calculate the SCFs in doubler-plate reinforced joints may lead to highly over-predicting outcomes. Consequently, developing a specific parametric equation to determine the SCF distribution along the weld toe in doubler-plate reinforced X-joints has practical value. High coefficient of determination and the satisfaction of acceptance criteria recommended by the UK DoE guarantee the accuracy of parametric equation proposed in the present paper. Hence, the developed equation can reliably be used for the fatigue analysis and design of axially loaded tubular X-joints reinforced with doubler plates.

References

[1] American Petroleum Institute (API). Recommended practice for planning, designing and constructing fixed offshore platforms: Working stress design: RP 2A-WSD. 21st Edition, Errata and Supplement 3, Washington DC, US; 2007.

[2] UK Health and Safety Executive. Offshore installations: guidance on design, construction and certification, 3rd amendment to 4th edition. London, UK; 1995.

[3] Pang HLJ, Lee CW. The three dimensional finite element analysis of a tubular T-joint under combined axial and bending loading. Int J Fatigue 1995;17:313–20.

[4] E. Chang, W. D. Dover, Prediction of stress distributions along the intersection of tubular Y- and T-joints, Int. J. Fatigue 1999;21:361–81.

[5] Oore M, Burns DJ. Estimation of stress intensity factors for irregular cracks subjected to arbitrary normal stress field. Proceedings of the 4th International Conference on Pressure Vessel Technology, London, UK; 1980.

[6] Dover WD, Dharmavasan S. Fatigue fracture mechanics analysis of T and Y joints, Proceedings of the Offshore Technology Conference, Paper OTC 4404, Houston (TX), US; 1982.

[7] Kam JCP, Topp DA, Dover WD, Fracture mechanics modeling and structural integrity of welded tubular joints in fatigue, Proceedings of the 6th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Houston (TX), US; 1987.

[8] UK Department of Energy (DoE). Background notes to the fatigue guidance of offshore tubular joints. UK DoE, London, UK; 1983.

[9] Kuang JG, Potvin AB, Leick RD. Stress concentration in tubular joints. Proceedings of the Offshore Technology Conference, Paper OTC 2205, Houston (TX), US; 1975.

[10] Efthymiou M. Development of SCF formulae and generalized influence functions for use in fatigue analysis. OTJ 88, Surrey, UK; 1988.

[11] Hellier AK, Connolly M, Dover WD. Stress concentration factors for tubular Y and T-joints. Int J Fatigue 1990;12:13–23.

[12] UK Health and Safety Executive (HSE). OTH 354: Stress concentration factors for simple tubular joints − assessment of existing and development of new parametric formulae. UK HSE, London, UK; 1997.

[13] Karamanos SA, Romeijn A, Wardenier J. Stress concentrations in tubular gap K-joints: mechanics and fatigue design. Eng Struct 2000;22:4–14.

[14] Gho WM, Gao F. Parametric equations for stress concentration factors in completely overlapped tubular K(N)-joints. J Constr Steel Res 2004;60:1761–82.

[15] Gao F. Stress and strain concentrations of completely overlapped tubular joints under lap brace OPB load. Thin-Walled Struct 2006;44:861–71.

[16] Gao F, Shao YB, Gho WM. Stress and strain concentration factors of completely overlapped tubular joints under lap brace IPB load. J Constr Steel Res 2007;63: 305–16.

[17] Yang J, Chen Y, Hu K. Stress concentration factors of negative large eccentricity tubular N-joints under axial compressive loading in vertical brace. Thin-Walled Struct 2015;96:359−71.

[18] Karamanos SA, Romeijn A, Wardenier J. Stress concentrations in multi-planar welded CHS XX-connections. J Constr Steel Res 1999;50:259–82.

[19] Chiew SP, Soh CK, Wu NW. General SCF design equations for steel multiplanar tubular XX-joints. Int J Fatigue 2000;22:283–93.

[20] Wingerde AM, Packer JA, Wardenier J. Simplified SCF formulae and graphs for CHS and RHS K- and KK-connections. J Constr Steel Res 2001;57:221–52.

[21] Karamanos SA, Romeijn A, Wardenier J. SCF equations in multi-planar welded tubular DT-joints including bending effects. Mar Struct 2002;15:157–73.

[22] Woghiren CO, Brennan FP. Weld toe stress concentrations in multi planar stiffened tubular KK Joints. Int J Fatigue 2009;31:164–72.

[23] Chiew SP, Soh CK, Wu NW. Experimental and numerical stress analyses of tubular XT-joint. J Struct Eng 1999;125:1239–48.

[24] Ahmadi H, Lotfollahi-Yaghin MA, Aminfar MH. Distribution of weld toe stress concentration factors on the central brace in two-planar CHS DKT-connections of steel offshore structures. Thin-Walled Struct 2011;49:1225–36.

[25] Ahmadi H, Lotfollahi-Yaghin MA, Aminfar MH. The development of fatigue design formulas for the outer brace SCFs in offshore three-planar tubular KT-joints. Thin-Walled Struct 2012;58:67–78.

[26] Ahmadi H, Lotfollahi-Yaghin MA. Geometrically parametric study of central brace SCFs in offshore three-planar tubular KT-joints. J Constr Steel Res 2012;71:149–61.

[27] Ahmadi H, Zavvar E. The effect of multi-planarity on the SCFs in offshore tubular KT-joints subjected to in-plane and out-of-plane bending loads. Thin-Walled Struct 2016;106:148–65.

[28] Morgan MR, Lee MMK. Parametric equations for distributions of stress concentration factors in tubular K-joints under out-of-plane moment loading. Int J Fatigue 1998;20:449–61.

[29] Morgan MR, Lee MMK. Prediction of stress concentrations and degrees of bending in axially loaded tubular K-joints. J Constr Steel Res 1998;45(1):67–97.

[30] Chang E, Dover WD. Prediction of stress distributions along the intersection of tubular Y and T-joints. Int J Fatigue 1999;21: 361–81.

[31] Chang E, Dover WD. Parametric equations to predict stress distributions along the intersection of tubular X and DT-joints. Int J Fatigue 1999;21:619–35.

[32] Shao YB. Proposed equations of stress concentration factor (SCF) for gap tubular K-joints subjected to bending load. Int J Space Struct 2004;19:137–47.

[33] Shao YB. Geometrical effect on the stress distribution along weld toe for tubular T- and K-joints under axial loading. J Constr Steel Res 2007;63:1351–60.

[34] Shao YB, Du ZF, Lie ST. Prediction of hot spot stress distribution for tubular K-joints under basic loadings. J Constr Steel Res 2009;65:2011–26.

[35] Lotfollahi-Yaghin MA, Ahmadi H. Effect of geometrical parameters on SCF distribution along the weld toe of tubular KT-joints under balanced axial loads. Int J Fatigue 2010;32:703–19.

[36] Ahmadi H, Lotfollahi-Yaghin MA, Aminfar MH. Geometrical effect on SCF distribution in uni-planar tubular DKT-joints under axial loads. J Constr Steel Res 2011;67:1282–91.

[37] Lotfollahi-Yaghin MA, Ahmadi H. Geometric stress distribution along the weld toe of the outer brace in two-planar tubular DKT-joints: parametric study and deriving the SCF design equations. Mar Struct 2011;24:239–60.

[38] Xu F, Chen J, Jin W. Experimental investigation of SCF distribution for thin-walled concrete-filled CHS joints under axial tension loading. Thin-Walled Struct 2015;93:149−57.

[39] Liu G, Zhao X, Huang Y. Prediction of stress distribution along the intersection of tubular T-joints by a novel structural stress approach. Int J Fatigue 2015; 80:216−30.

[40] Nwosu DI, Swamidas ASJ, Munaswamy K. Numerical stress analysis of internal ring-stiffened tubular T-joints. J Offshore Mech Arct 1995;117: 113–25.

[41] Hoon KH, Wong LK, Soh AK. Experimental investigation of a doubler-plate reinforced tubular T-joint subjected to combined loadings. J Constr Steel Res 2001;57:1015–39.

[42] Myers PT, Brennan FP, Dover WD. The effect of rack/rib plate on the stress concentration factors in jack-up chords. Mar Struct 2001;14: 485–505.

[43] Ahmadi H, Lotfollahi-Yaghin MA. Stress concentration due to in-plane bending (IPB) loads in ring-stiffened tubular KT-joints of offshore structures: Parametric study and design formulation. Appl Ocean Res 2015;51:54–66.

[44] Ahmadi H, Zavvar E. Stress concentration factors induced by out-of-plane bending loads in ring-stiffened tubular KT-joints of jacket structures. Thin-Walled Struct 2015;91:82–95.

[45] Nassiraei H, Rezadoost P. SCFs in tubular X-connections retrofitted with FRP under in-plane bending load. Compos Struct 2021;274:114314.

[46] Nassiraei H, Rezadoost P. SCFs in tubular X-joints retrofitted with FRP under out-of-plane bending moment. Mar Struct 2021;79:103010.

[47] Nassiraei H, Rezadoost P. Stress concentration factors in tubular X-connections retrofitted with FRP under compressive load. Ocean Eng 2021;229:108562.

[48] Nassiraei H, Rezadoost P. Parametric study and formula for SCFs of FRP-strengthened CHS T/Y-joints under out-of-plane bending load. Ocean Eng 2021; 221:108313.

[49] Nassiraei H, Rezadoost P. Stress concentration factors in tubular T/Y-connections reinforced with FRP under in-plane bending load. Mar Struct 2021;76:102871.

[50] Nassiraei H, Rezadoost P. Stress concentration factors in tubular T/Y-joints strengthened with FRP subjected to compressive load in offshore structures. Int J Fatigue 2020;140:105719.

[51] Ahmadi H, Lotfollahi-Yaghin MA, Shao YB, Aminfar MH. Parametric study and formulation of outer-brace geometric stress concentration factors in internally ring-stiffened tubular KT-joints of offshore structures. Appl Ocean Res 2012;38:74−91.

[52] Ahmadi H, Lotfollahi-Yaghin MA, Shao YB. Chord-side SCF distribution of central brace in internally ring-stiffened tubular KT-joints: A geometrically parametric study. Thin-Walled Struct 2013;70:93−105.

[53] Ahmadi H, Lotfollahi-Yaghin MA, Aminfar MH. Effect of stress concentration factors on the structural integrity assessment of multi-planar offshore tubular DKT-joints based on the fracture mechanics fatigue reliability approach. Ocean Eng 2011;38:1883−93.

[54] Gaspar B, Garbatov Y, Guedes Soares C. Effect of weld shape imperfections on the structural hot-spot stress distribution. Ships Offshore Struct 2011;6(1-2):145–59.

[55] Ahmadi H, Lotfollahi-Yaghin MA. A probability distribution model for stress concentration factors in multi-planar tubular DKT-joints of steel offshore structures. Appl Ocean Res 2012;34:21−32.

[56] Ahmadi H, Lotfollahi-Yaghin MA. Effect of SCFs on S–N based fatigue reliability of multi-planar tubular DKT-joints of offshore jacket-type structures. Ships Offshore Struct 2013;8:55−72.

[57] Ahmadi H. Mohammadi AH, Yeganeh A. Probability density functions of SCFs in internally ring-stiffened tubular KT-joints of offshore structures subjected to axial load. Thin-Walled Struct 2015;94:485–99.

[58] Ahmadi H. Mohammadi AH, Yeganeh A, Zavvar E. Probabilistic analysis of stress concentration factors in tubular KT-joints reinforced with internal ring stiffeners under in-plane bending loads. Thin-Walled Struct 2016;99:58–75.

[59] Ahmadi H. A probability distribution model for SCFs in internally ring-stiffened tubular KT-joints of offshore structures subjected to out-of-plane bending loads. Ocean Eng 2016;116:184–99.

[60] Ahmadi H, Mousavi Nejad Benam MA. Probabilistic analysis of SCFs in unstiffened gap tubular KT-joints of jacket structures under the OPB moment loads. Adv Struct Eng 2017;20:595–615.

[61] Nassiraei H. Geometrical effects on the LJF of tubular T/Y-joints with doubler plate in offshore wind turbines. Ships Offshore Struct 2020; In Press.

[62] Nassiraei H, Lotfollahi-Yaghin MA, Ahmadi H. Static strength of doubler plate reinforced tubular T/Y-joints subjected to brace compressive loading: Study of geometrical effects and parametric formulation. Thin-Walled Struct 2016;107:231–47.

[63] Nassiraei H, Lotfollahi-Yaghin MA, Ahmadi H. Static performance of doubler plate reinforced tubular T/Y-joints subjected to brace tension. Thin-Walled Struct 2016;108:138–152.

[64] Nassiraei H, Lotfollahi-Yaghin MA, Ahmadi H, Zhu L. Static strength of doubler plate reinforced tubular T/Y-joints under in-plane bending load. J Constr Steel Res 2017;136:49–64.

[65] Lee MK, Wilmshurst SR. Numerical modeling of CHS joints with multiplanar double-K configuration. J Constr Steel Res 1995;32:281–301.

[66] Cao JJ, Yang GJ, Packer JA. FE mesh generation for circular tubular joints with or without cracks. Proceedings of the 7th International Offshore and Polar Engineering Conference, Honolulu (HI), US; 1997.

[67] Lee MMK. Strength, stress and fracture analyses of offshore tubular joints using finite elements. J Constr Steel Res 1999; 51:265–86.

[68] Shao YB. Fatigue behaviour of uni-planar CHS gap K-joints under axial and in-plane bending loads. PhD Thesis, School of Civil & Environmental Engineering, Nanyang Technological University, Singapore; 2004.

[69] American Welding Society (AWS). Structural welding code: AWS D 1.1. Miami (FL), US; 2002.

[70] Smedley P, Fisher P. Stress concentration factors for simple tubular joints. Proceedings of the International Offshore and Polar Engineering Conference (ISOPE), Edinburgh; 1991. p. 475–83.

[71] N'Diaye A, Hariri S, Pluvinage G, Azari Z. Stress concentration factor analysis for notched welded tubular T-joints. Int J Fatigue 2007;29:1554–70.

[72] IIW-XV-E. Recommended fatigue design procedure for welded hollow section joints, IIW Docs, XV-1035-99/XIII-1804-99. International Institute of Welding, France; 1999.

[73] Nazari A, Guan Z, Daniel WJT, Gurgenci H. Parametric study of hot spot stresses around tubular joints with doubler plates. Pract Period Struct Des Constr 2007;12(1):38–47.

[74] Bomel Consulting Engineers. Assessment of SCF equations using Shell/KSEPL finite element data. C5970R02.01 REV C; 1994.

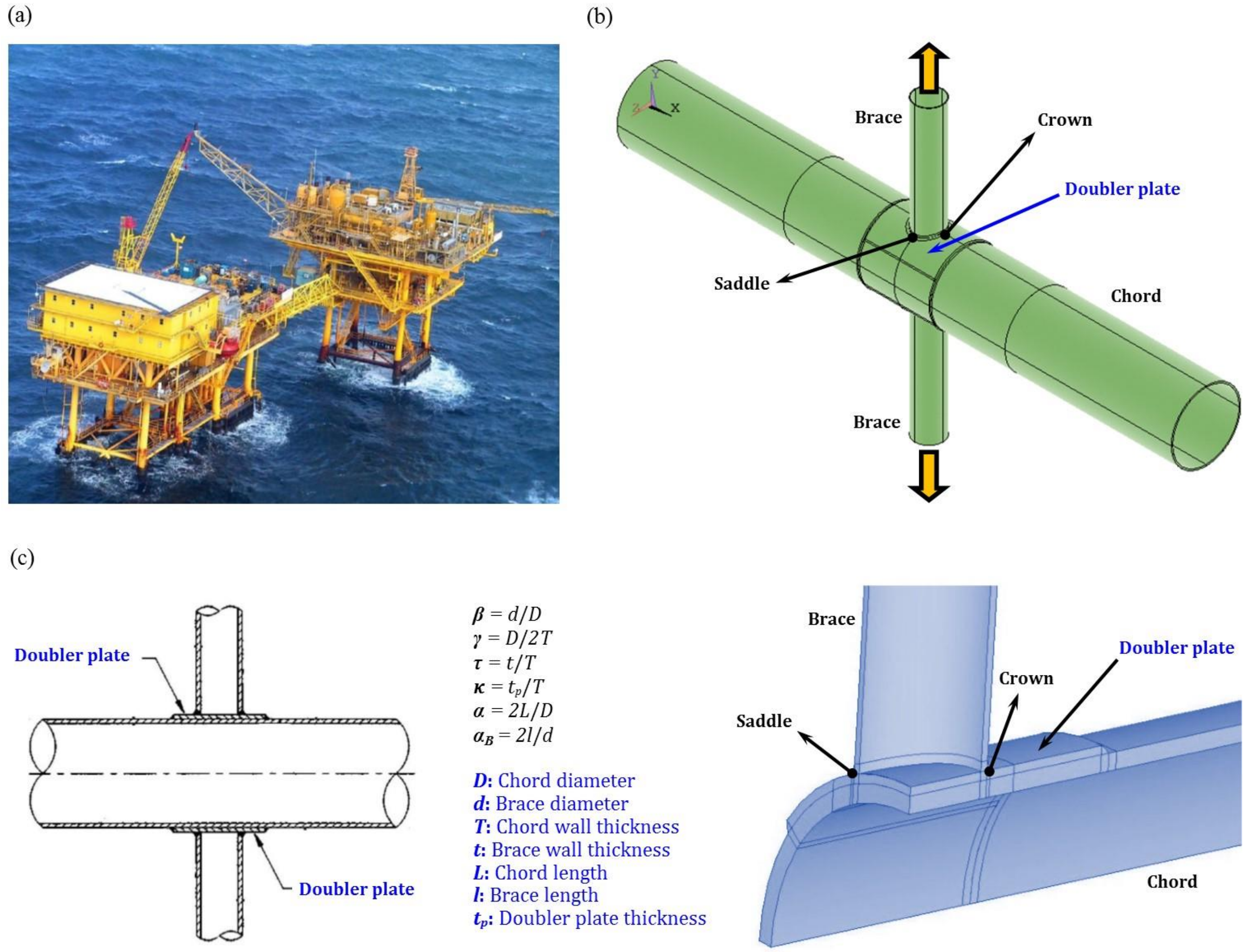

Fig. 1. (a) A jacket-type offshore platform, (b) An axially-loaded tubular X-joint reinforced with doubler plates, (c) Geometrical notation for a doubler-plate reinforced X-joint

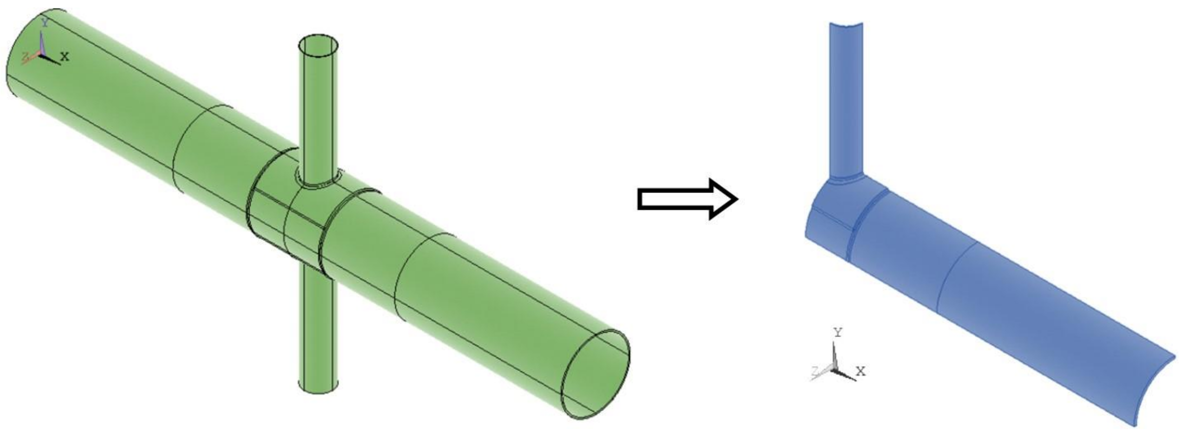

Fig. 2. 1/8 of the entire doubler-plate reinforced tubular X-joint that is required to be modeled under the axial loading

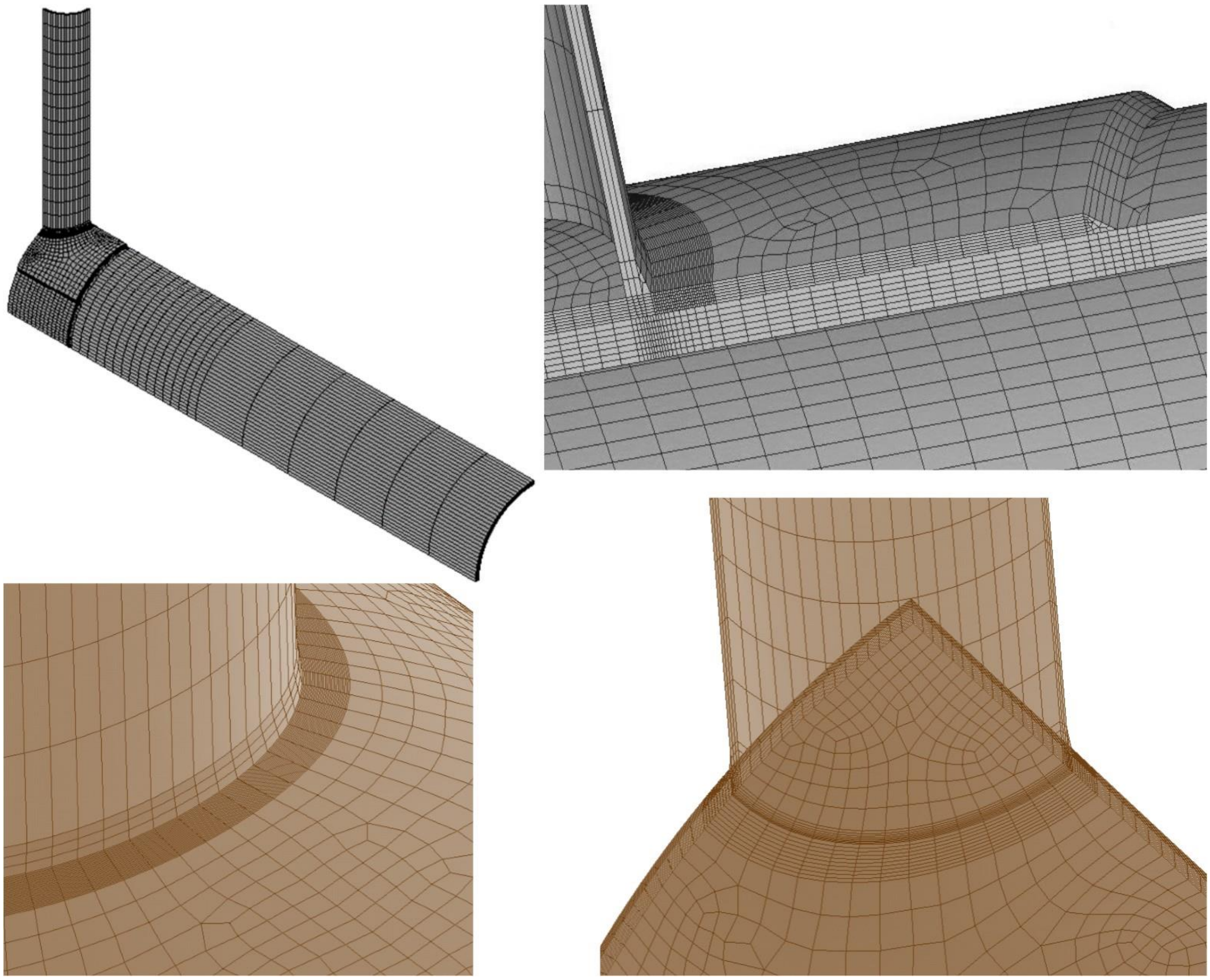

Fig. 3. Generated mesh by the sub-zone scheme for the 1/8 of a doubler-plate reinforced X-joint

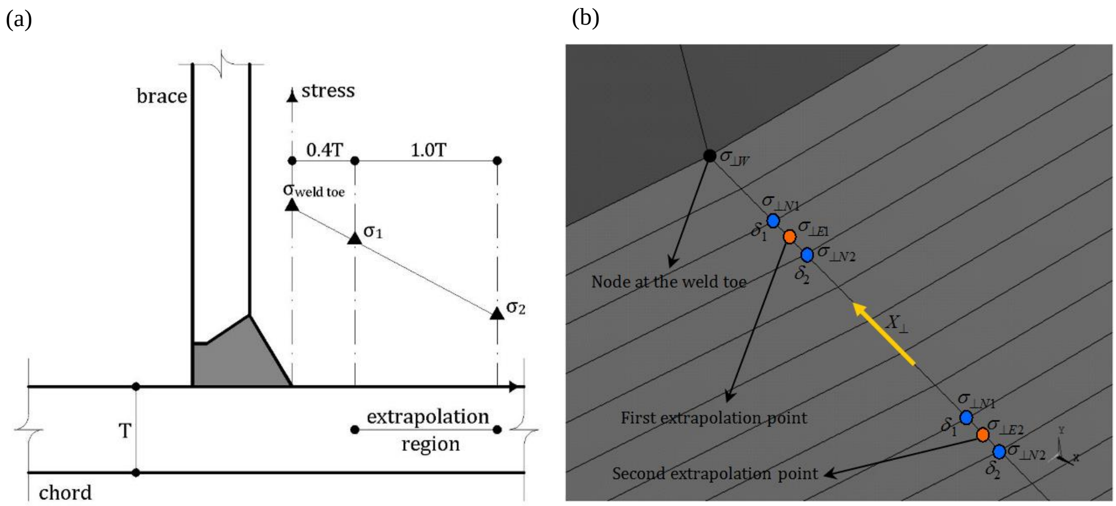

Fig. 4. (a) Extrapolation method according to IIW XV-E [72], (b) Required interpolations and extrapolations to extract the HSS value at the weld toe

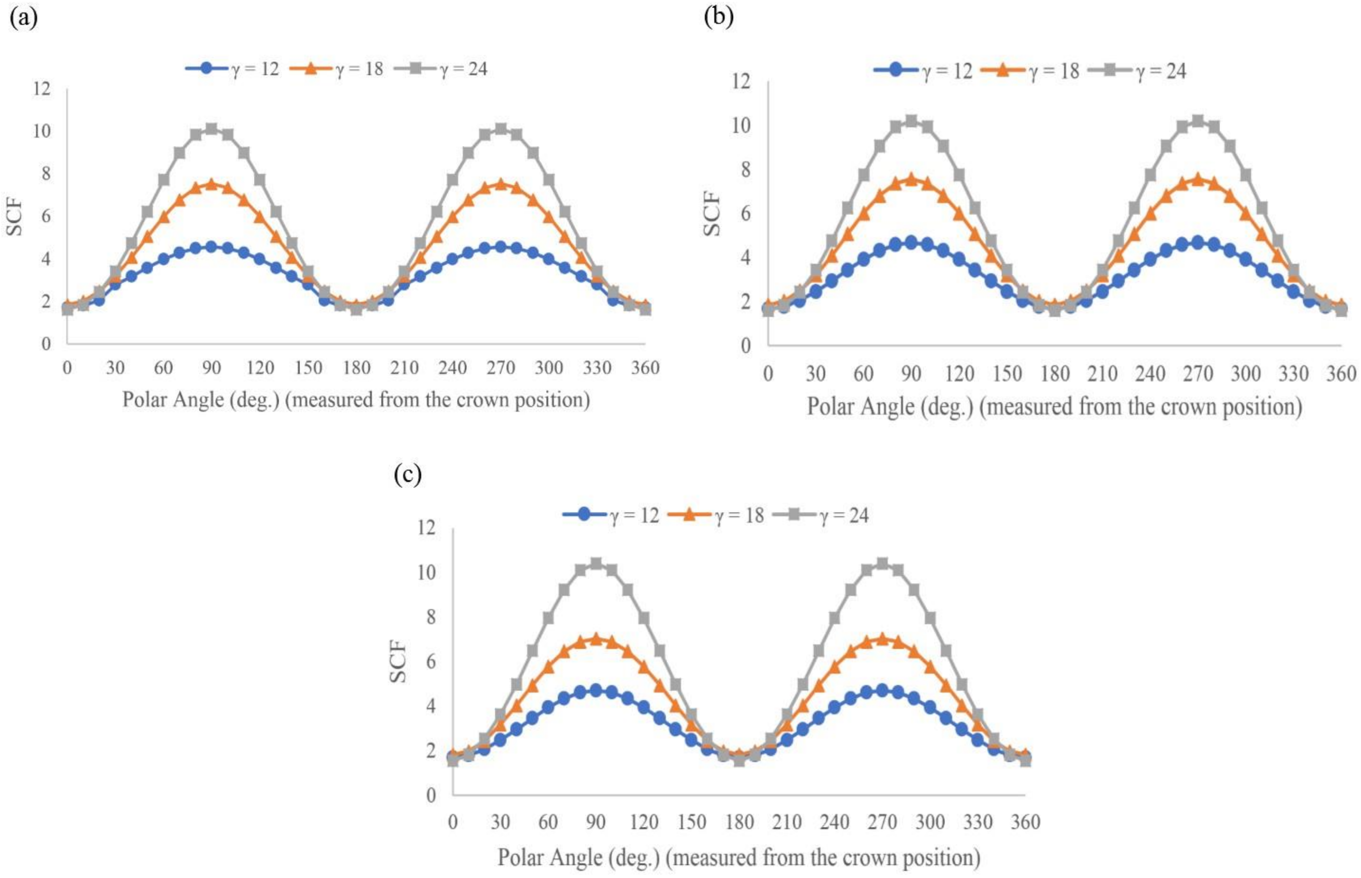

Fig. 5. The effect of the γ on the SCF distribution along the weld toe (τ = 0.7, κ = 1.0): (a) β = 0.4, (b) β = 0.5, (c) β = 0.6

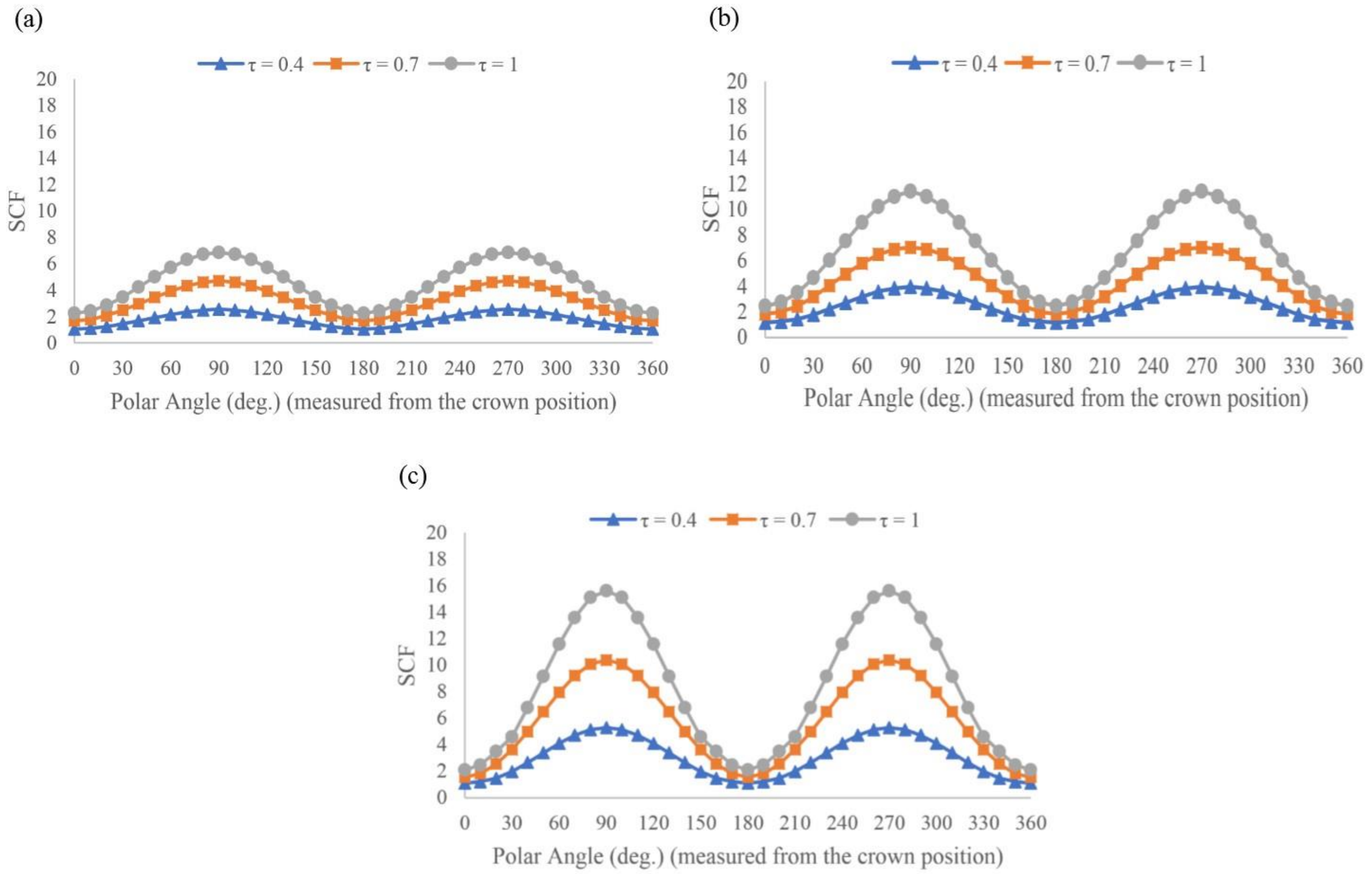

Fig. 6. The effect of the τ on the SCF distribution along the weld toe (β = 0.6, κ = 1.0): (a) γ = 12, (b) γ = 18, (c) γ = 24

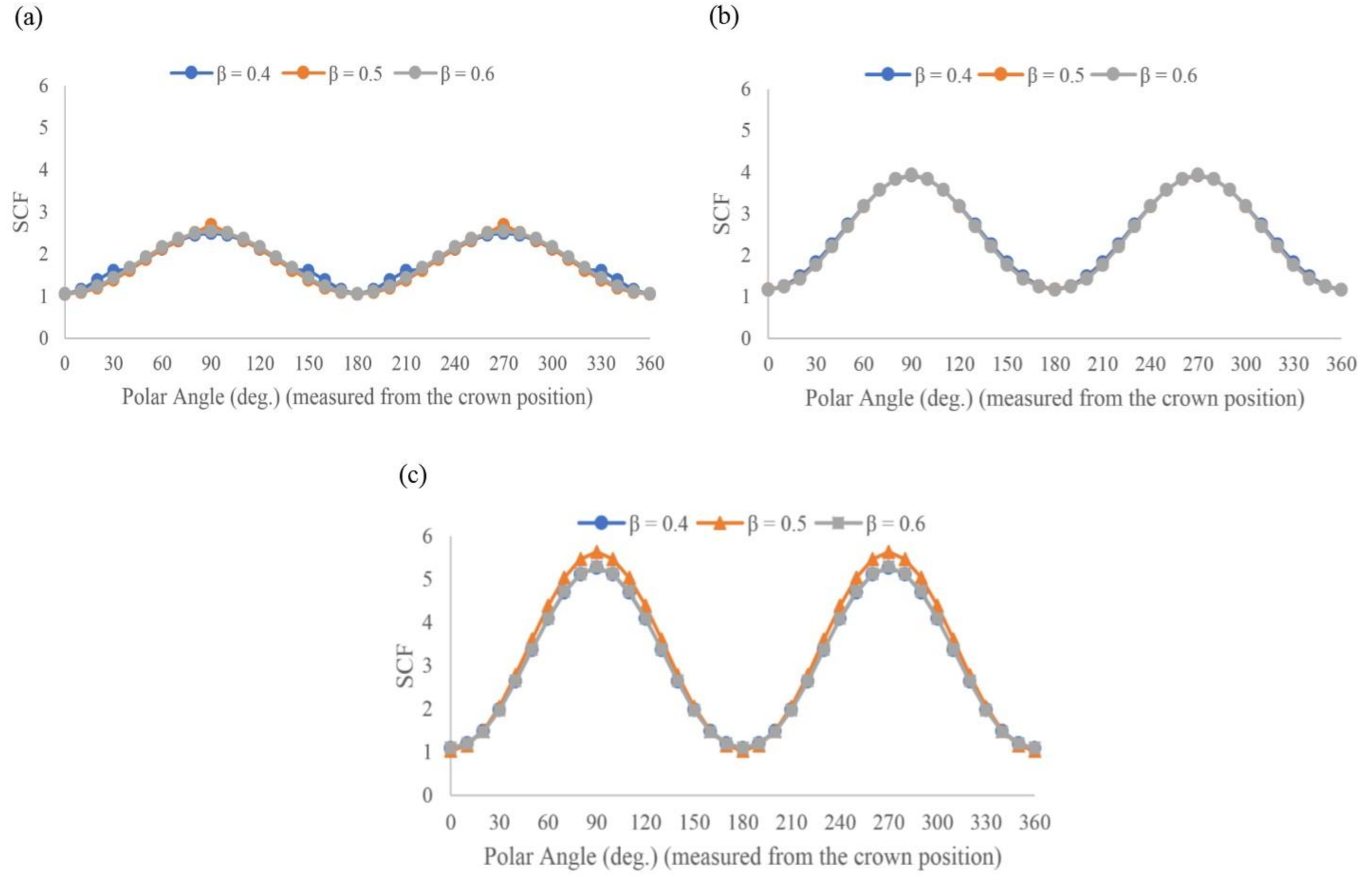

Fig. 7. The effect of the β on the SCF distribution along the weld toe (τ = 0.4, κ = 1.0): (a) γ = 12, (b) γ = 18, (c) γ = 24

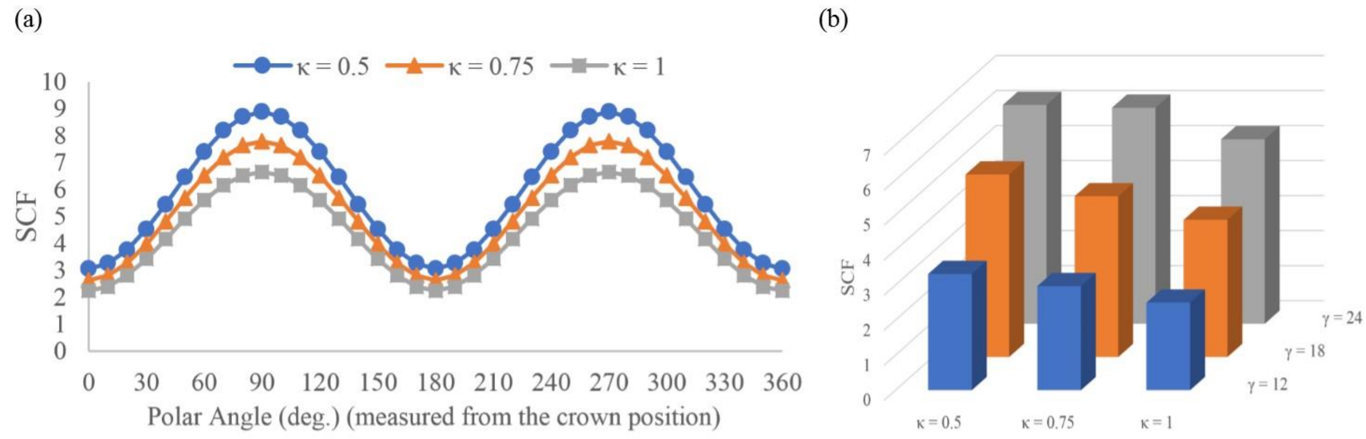

Fig. 8. (a) The effect of the κ on the SCF distribution along the weld toe (τ = 1.0, γ = 24), (b) The effect of the κ on the SCFs at the saddle position

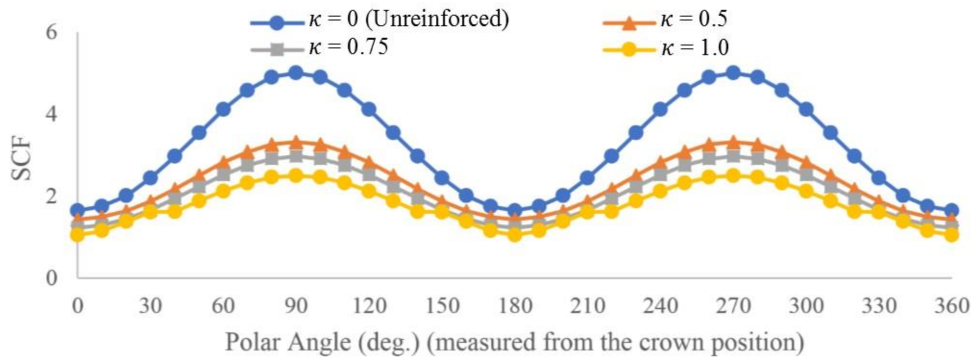

Fig. 9. Comparison of SCF distributions in unreinforced and doubler-plate reinforced tubular X-joints

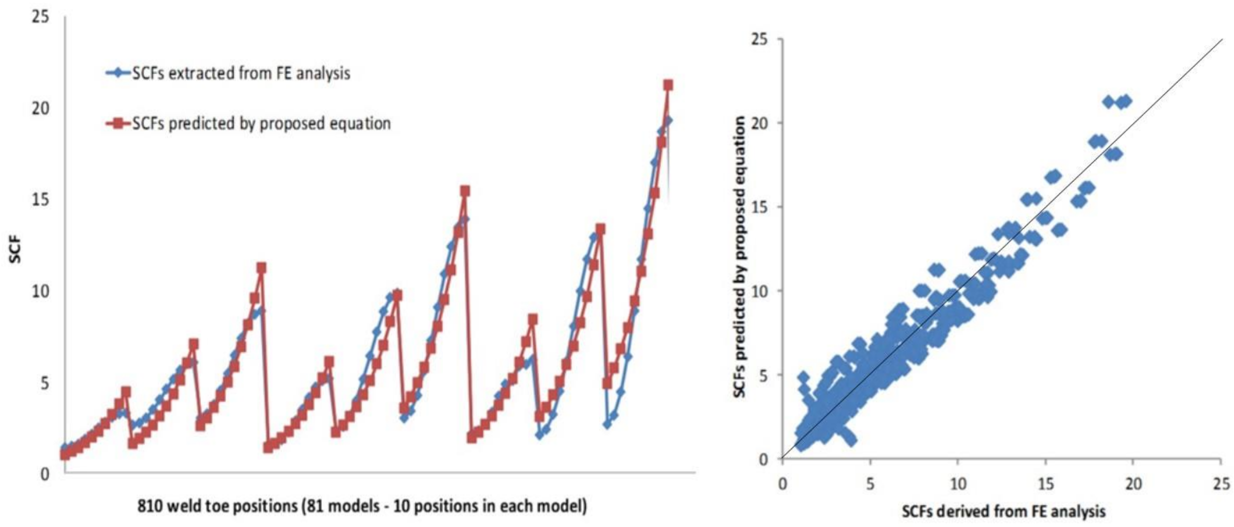

Fig. 10. Comparison of 810 SCF values predicted by the proposed equation with the 810 SCFs extracted from FE analyses

Table 1. Results of the FE model verification based on Nazari et al. [73] study

Position	Geometrical parameters				SCF		Difference
	τ	β	γ	κ	Present FE model	Nazari et al. [73] data	
Saddle	0.5	0.3	10.6	0	5.40	5.42	0.3%
Saddle	0.5	0.3	10.6	1.0	3.10	2.90	6.9%

Table 2. Values assigned to each dimensionless parameter

Parameter	Definition	Value(s)
β	d/D	0.4, 0.5, 0.6
γ	$D/2T$	12, 18, 24
τ	t/T	0.4, 0.7, 1.0
κ	t_p/T	0.5, 0.75, 1.0
α	$2L/D$	16
α_B	$2l/d$	8

Table 3. Results of equation assessment according to the UK DoE [8] acceptance criteria

Proposed equation	Conditions		Decision
	$\%P/R < 0.8$	$\%P/R > 1.5$	
Eq. (11)	7.03% > 5%	5.31% < 50% OK.	Eq. (11) needs revision
Eq. (13)	4.32% < 5% OK.	7.04% < 50% OK.	Eq. (13) is accepted