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Effect of Geometric Parameters and Combined Loading on Stress Distribution of Tubular T-Joints

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1. Introduction

Due to their good strength/weight ratio and better buckling resistance, welded tubular joints are widely used in industrial construction, piping, handling cranes, bridges, platforms and especially maritime structures built for the offshore oil industry [1].

These assemblies being formed by welding the extremities of one or more braces on the side of the chord, are constantly subjected to multi-axial loadings, i.e. combined axial force, in-plane bending (IPB) and out-of-plane bending (OPB) (dynamic forces of waves, wind, flow, and even seismic activity). Such loadings give rise to a large number of stress cycles causing damage by elastic fatigue [2, 3].

These welded elements consist in tubular junctions classified according to their shape: T, Y, X, DT, DY (Fig.1). Several studies have been devoted to the determination of stress distributions near the intersections lines of tubular elements and to the location of areas of high stress concentrations (hot zones) [2]. The loadings applied to these junctions were basic but also combined loads of the traction / rotary bending type intended to better reproduce the stresses encountered in service.

The stress distribution is generally given by the stress concentration factors SCF, calculated using the ratio of each maximum geometric stress for each of the elements divided by the maximum nominal stress measured on the braces [4]. For some joints, the concentration of efforts can result in a maximum stress at the intersection as high as 20 times the nominal force acting in the members [5].

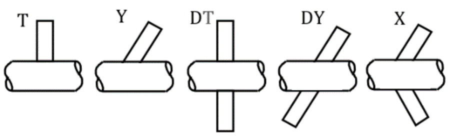


Fig. 1 Various types of tubular joints

2. Geometric parameters

Fig. 2 shows a tubular K-joint with the three commonly named locations along the brace–chord intersection: saddle, crown toe and crown heel, and the geometrical parameters for chord and brace diameters *D* and *d*, and the corresponding wall thicknesses *T* and *t*.

We use the following notations: *L* is chord length, *D* is chord diameter, *T* is chord wall thickness, *d* is brace diameter (in the case of several spacers, they are repeated by an index), *t* is brace wall thickness, *g* is theoretical spacing, *e* is joint eccentricity (positive or negative) and θ is the angle of brace/chord intersection.

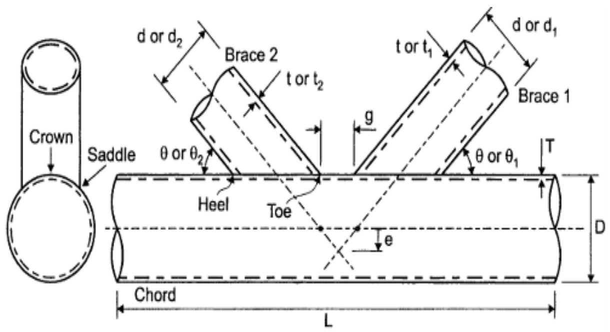


Fig. 2 Geometric notation for tubular joints [6]

The geometry of a tubular connection can be described using dimensionless parameters in addition to those cited above [7, 8].

Dimensionless parameters of joint

β: *d* /*D* ratio of the diameters, describing the surface topology; γ: *D/2T* parameter defining the "thickness" of frame wall; α: *2L/D* slenderness of the chord; τ: *t/T* thickness ratio; ζ: *g/D* relatives pacing.

Significant aspects of tubular junctions

The points of saddle and crown are remarkable geometric points in the junction zones of simple tubular assemblies of marine structures, where the usual loads reveal stress concentrations. The first is located at the angle 90 ° +/- 180 ° from the axis of the chord and the second is at the angle of 0 ° +/- 180 ° of the axis of the chord. Angle φ defines the position at the joint (origin at the crown toe point).

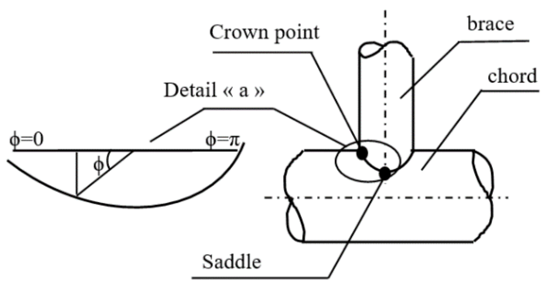


Fig. 3 Tapping a brace on a chord [7]

Table 1 gives the usual values of geometric parameters for oil works.

Table 1

Geometric joint parameters [8]

Parameter	Typical value	Min value	Max value
β=d/D	0.4-0.8	0.2	1.0
γ=D/2T	12-20	10	30
τ=t/T	0.3-0,7	0.2	1.0
θ	40-90°	20°	90°
ζ=g/D	<0 to 0.15	<0	1.0

3. Structural stress

The distribution of structural stress (σ_s) through plate thickness is usually the sum of membrane stress (σ_m) and shell bending stress (σ_b) derived from the mechanical equilibrium condition in front of the weld toe. These stress distribution at welded joints of the plate is actually non-linear. The stress components of this non-linear relationship can be separated into the membrane stress, shell-bending stress and non-linear peak stress (σ_{NLP}), as shown in Fig. 4.

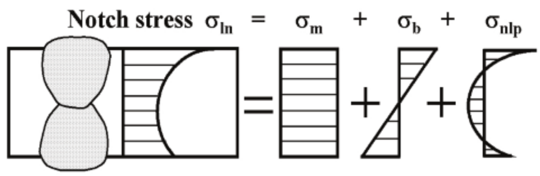


Fig. 4 Local notch stress distribution [9]

Once the nodal forces (*Fy*1, *Fy*2) in the y direction and moments with respect to the x axis are obtained as shown in Fig. 5, the corresponding line forces (*fy*1, *fy*2) can be calculated considering the mechanical equilibrium as derived in Eqs. (1-3). The derivation of line moments (*mx*1, *mx*2) is the same as that of the line forces with respect to the nodal moments (*Mx*1, *Mx*2) [10].

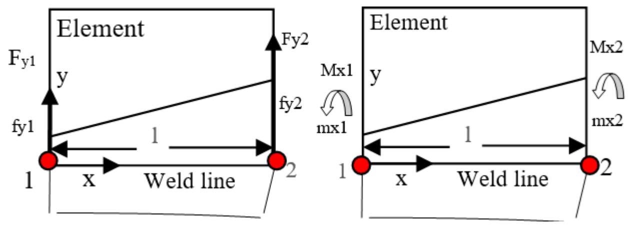


Fig. 5 Definition of structural stress method in single shell element

$$\sum F_{yi} + \int_0^l f_y(x)\,dx = 0, \tag{1}$$

$$\sum F_{yi}x_i + \int_0^l f_y(x)\,x\,dx = 0, \tag{2}$$

$$f_{y1} = \frac{2}{l}\left(2F_{y1} - F_{y2}\right),\ f_{y2} = \frac{2}{l}\left(2F_{y2} - F_{y1}\right), \tag{3}$$

$$m_{x1} = \frac{2}{l}\left(2M_{x1} - M_{x2}\right), m_{x2} = \frac{2}{l}\left(2M_{x2} - M_{x1}\right). \tag{4}$$

Where, l is the element size along the weld line as illustrated in Fig. 5.

Once the line force and the line moment are available, the structural stress at each node can be given by Eq. (5):

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_y}{t} + \frac{6m_x}{t^2}, \tag{5}$$

where: σ_s is the structural stress concentration effect due to joint geometry, and σ_m and σ_b the membrane and bending stresses respectively. From the above description, structural stress in multi elements can be calculated in a similar manner.

4. Numerical modeling

Due to the complex geometric nature of tubular joints, the analytical solutions determining the stress distributions are complex. For this reason, all the works related to tubular junctions mainly rely on two methods:

- the experimental method based on mechanical tests intended to determine the behavior of tubular junctions subjected to rather simple loads, and on the other hand to validate numerical simulations;
- finite element modeling, which advantages have been detailed above [11].

However, both shell and 3D elements are used in the FE analysis. The choice of elements type for the analysis depends on the geometry of the joint and the purpose for which the results of the analysis are to be used. A compromise must be found between accuracy and computation time on a particular model [1]. Theoretical shell analysis, thin shell and thick shell finite element analyses all reproduce the overall pattern of stress in the chord. However, in the vicinity of the weld, which is the region of interest for hot spot stress, thick shell modeling remains more realistic. The Gauss-Point Surface Stress (GPSS) is often considered as the most accurate stress within the element [12]. The chord end fixity conditions of tubular joints in offshore structures may range from almost fixed to almost pinned, while generally being closer to almost fixed. In practice, the value of parameter α in over 60% of tubular joints exceeds 20 and lies beyond 40 in 35% of the joints. In view of the fact that the effect of chord end restraints is only significant for joints with α<8 and high values of β and γ, which hardly ever occurs in practice, both chord ends were assumed to be fixed, with the corresponding nodes restrained [7].

3.1. Dimension and mesh of study joint

COMSOL MULTPHYSICS® software was selected to perform the computations. The accuracy of the results of tubular junction stress analysis by the finite element method depends on the types of elements used and the fineness of the mesh, especially in the vicinity of the zones of high stress concentrations.

To this end, we considered a zone of triangular elements ensuring the transition between the very fine mesh around the intersection (stress concentration zones), and quadrangular elements with a normal mesh for the rest of the structure. Indeed, this type of element is relatively simple to use and reduces CPU time. The stiffness of the element was determined based on four integration points [3].

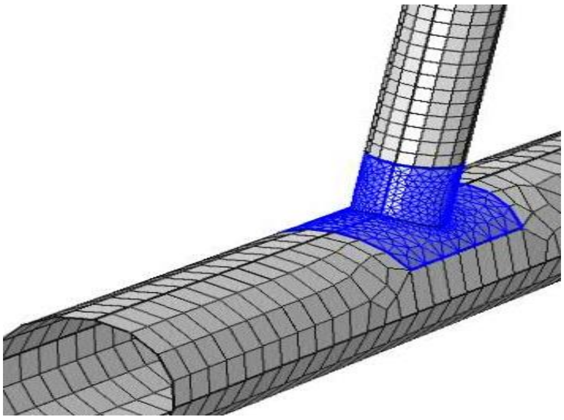


Fig. 6 Mesh used

The dimensions and properties of the model are presented in Table 2, according to [11].

Table 2

Dimensions of the tubular T-joint

D=2d, mm	100
L, mm	700
L, mm	300
τ	1

Table 3

Properties of the steel used for the T-joint

E = 210 GPa	Young's modulus
υ = 0.3	Poisson's ratio
σ_e=536 MPa	Yield stress

4.2. Loadings and boundary conditions of tubular joints

The loading sustained in service, lead to displacements of rotary translation of the platform surface [11]. The numerical simulations carried out in this study consider:

- three simple loadings: Traction (TRA), In-plane bending (IPB) and Out-of-plane bending (OPB) for the validation of the calculation method (see Fig. 5);
- combined loading composed of an axial loading (tension or compression) and a continuation of rotational bending obtained by rotating the force around the brace center in 36 steps. This load simulates more accurately the actual service conditions.

For this type of modeling, the boundary conditions consist in fixing both ends of the chord.

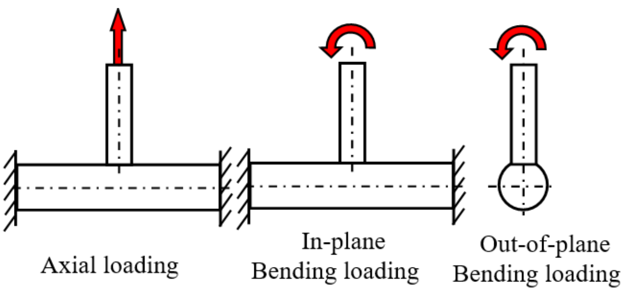


Fig. 7 Basic loads for tubular joints

5. Investigation of the geometric effect on the stress distribution along the chord-brace intersection

To study the effect of the joint geometry on the stress distribution in the hot spot stress region (Fig. 6), it is necessary to carry out a parametric study. In the parametric study, the effect of three commonly used normalized geometric parameters: $\gamma(D/2T)$, β (d/D) and α $(2L/D)$ is investigated. This study consists in analyzing 14 models subjected to three basic loadings Ax, IPB, OPB. The geometric parameters of tubular joints considered in the current study are summarized in Table 4.

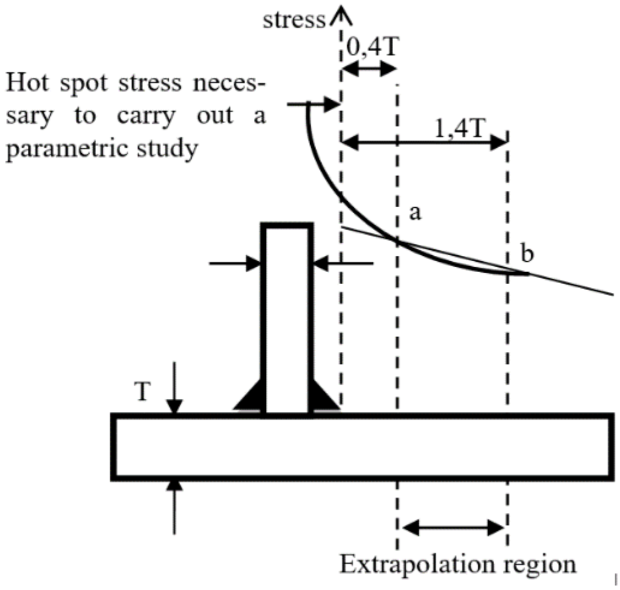


Fig. 8 Extrapolation region recommended by IIW-XVE [1]

Table 4

Geometric parameters of studied junction

Group 1: τ=1, β=0.5, α=14, D=100, d=50; L=700, l=300							
M	γ	T, t	Mod.	γ	T, t		
$M1$	10	5	M 4	25	2		
$M2$	15	3.3	M 5	30	1.67		
$M3$	20	2.5	M 6	35	1.4		
Group 2: τ=1,D=100, β=0.5, γ=25, d=50, T=t=2							
M	α	L	l	Mod.	α	L	l
$M7$	5	250	75	$M9$	25	1250	575
$M8$	10	500	200	$M10$	30	1500	700
Group 3: τ=1, D=100, γ=25, T=t=2, α=14, L=700, l=300							
M	β	d	M	β	d		
$M11$	0.15	15	$M13$	0.3	30		
$M12$	0.25	25	$M14$	0.75	75		

This study focuses on the variations of the following geometric parameters: $0.15 \le \beta \le 0.75$, $5 \le \alpha \le 30$ and $10 \le \gamma \le 35$

6. Results and discussion

6.1. Effect of loading type on stress distribution

Figs. 10 to 12 display the stress distributions at the chord/brace intersection of T-joints subjected to three simple loading cases as presented in Fig. 7. The distribution curves are plotted starting from the chord crown position according to angle φ. These distributions reveal the position of the hot spot stress. Fig. 11, a, b corresponding to axial loading and out-of-plane bending, indicate that the hot spot stress is located at the saddle point (90°+270°). For joints subjected to in-plane bending, the HSS is situated between the saddle and crown location (φ=45°+135°), (Fig. 1, c). These results are summarized in Fig. 9 and show good agreement with the works detailed in [2, 13].

In Table 5 we have shown only the maximum and minimum stresses for the three positions weld seam, brace and chord element according to the three loads in local coordinate system. It is clear that σ_{yy} stress component is the predominant one in weld line position.

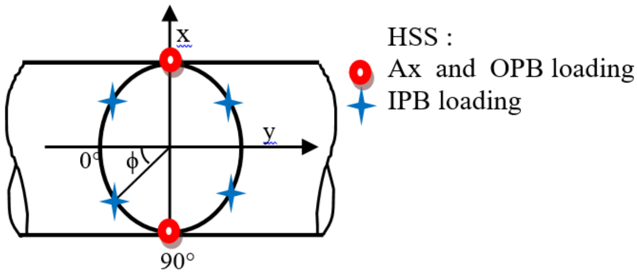
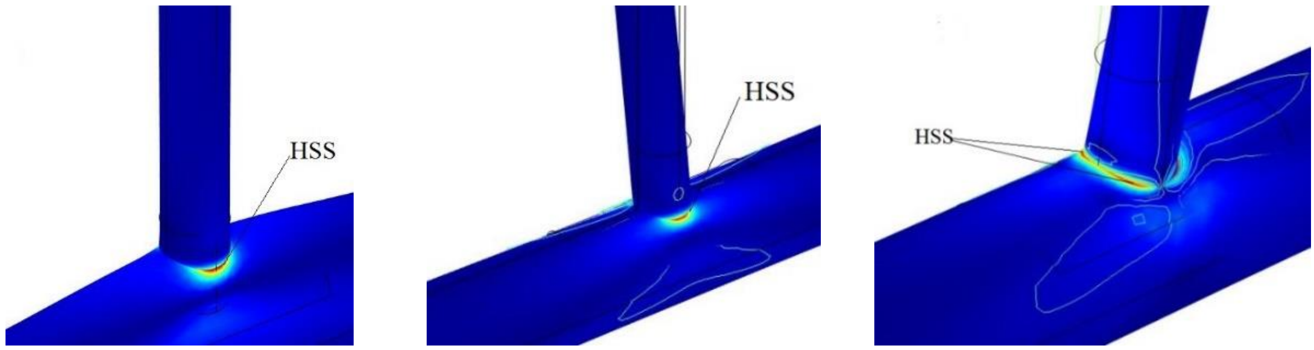


Fig. 9 Representation of hot spots stress according to φ

Table 5

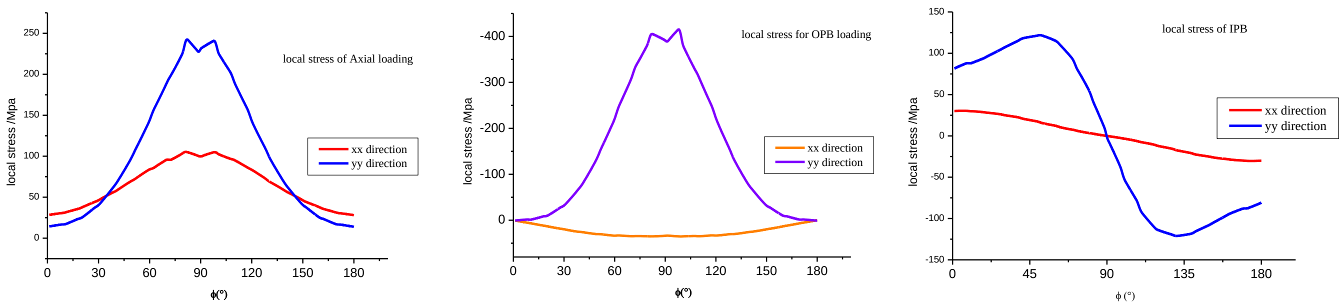
Representation of maximum stresses, MPa

	Stress, MPa	The maximum values of σ_{xx} (transversal)			The maximum value of σ_{yy} (longitudinal)		
		Weld line	chord	brace	Weld line	chord	brace
Axial loading	Max.	52,418	59,543	45,535	246,586	230,728	140,578
	Min.	13,955	22,499	3,526	14,312	17,668	3,294
IPB loading	Max.	53,419	59,327	24,670	121,872	114,581	72,365
	Min.	52,841	-59,2152	-24,323	-121,870	-114,705	-72,017
OPB loading	Max.	87,055	102,825	79,345	214,277	212,947	130,114
	Min.	-0,925	-0,546	-0,571	-0,771	-0,836	-1,042



a) b) c)

Fig. 10 Stress contour plot (a: AX loading, b: OPB loading, c: IPB loading)



a) Axial loading (AX) b) Out -plane bending (OPB) c) in-plane bending (IPB)

Fig. 11 Stress distribution for T-joint (φ measured starting from crown point)

Fig. 11 shows the local stress distribution along the chord/brace intersection subjected to a combined loading case; the distribution curves are plotted starting from the chord crown position. This figure indicates that the peak of hot spot stress occurs at the saddle (90° and 270°) and the minimal stress is reached at four positions (45°, 135°, 225° and 315°). Using these results (Max and Min stresses) allows determining the stress amplitude required to calculate the fatigue life.

5.2. Geometric effect on the stress distribution

The effect of parameter γ on the stress distribution for tubular T-joints is illustrated in Fig.12, a, b, c. As seen in this figure, the shapes of the local stress curves with different values of γ are quite similar, and the hot spot stress is always located at the saddle position for AX and OPB loadings, and around 45° for IPB loading. On the other hand, its influence is significant on the stress level, especially for AX and OPB loadings.

The effect of parameter α is illustrated in Fig.15, a, b, c. The value of α has no effect on the position of the peak stress and the stress distribution curves for the three simple load cases. For Axial loading case, it can be seen that an increase in α leads to an increase in stress values up to α=14. For higher values of α, the level of stress is stabilized, which is clearly visible in Fig. 15, a. For bending loading cases, the stress values get closer for higher values of α (α=25, 30).

Contrary to previous parameters α and γ, the effect of β on the stress distribution along the chord/brace intersection for tubular T-joints is very distinct. From Fig.16, a, b, c, it can be seen that increasing β leads to a small increase in the stress values for AX loading (Fig. 16, a), but has the opposite effect for bending loading (Fig. 16, b, c). Although the increase in β considerably affects the values of stress, it does not have considerable influence on the distribution pattern of Axial and OPB stress, the HSS indeed remains at the saddle position. However, smaller values of β gradually shift the location of HSS towards the crown position.

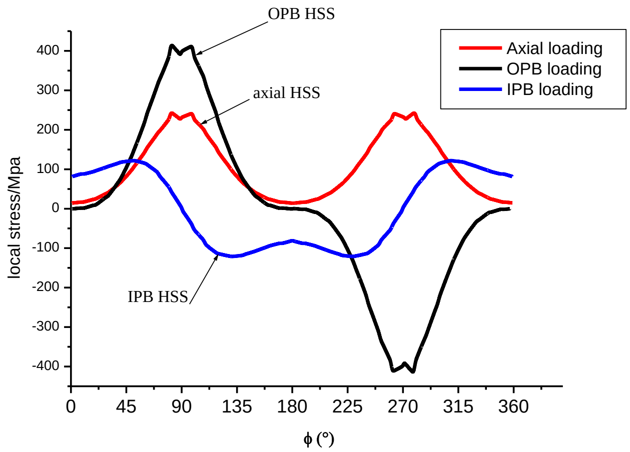


Fig. 12 Stress distribution for T joint in three types of basic loading

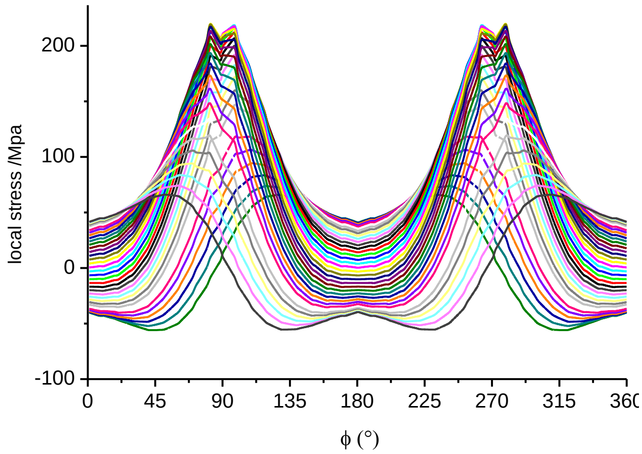
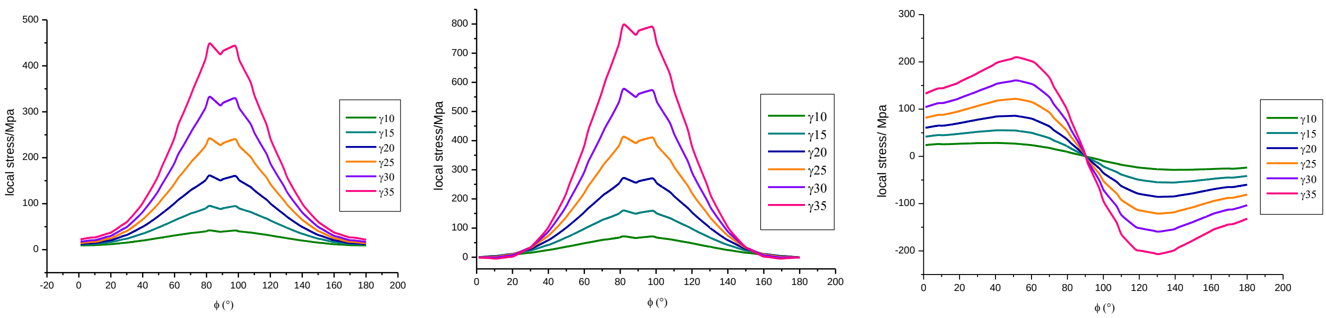


Fig. 13 Stress distributions in combined loading



a) b) c)

Fig. 14 Influence of parameter γ (Group1) on chord stress concentration around chord/brace intersection in AX loading (a), OPB loading (b), IPB (c) loading

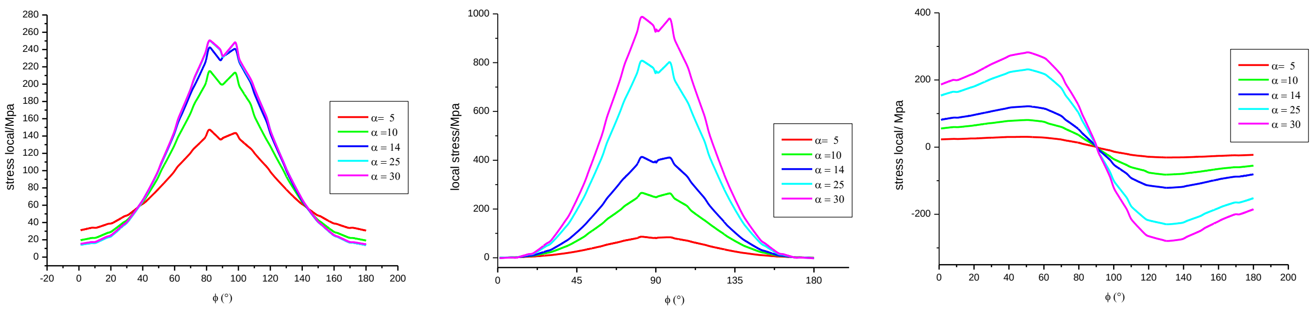


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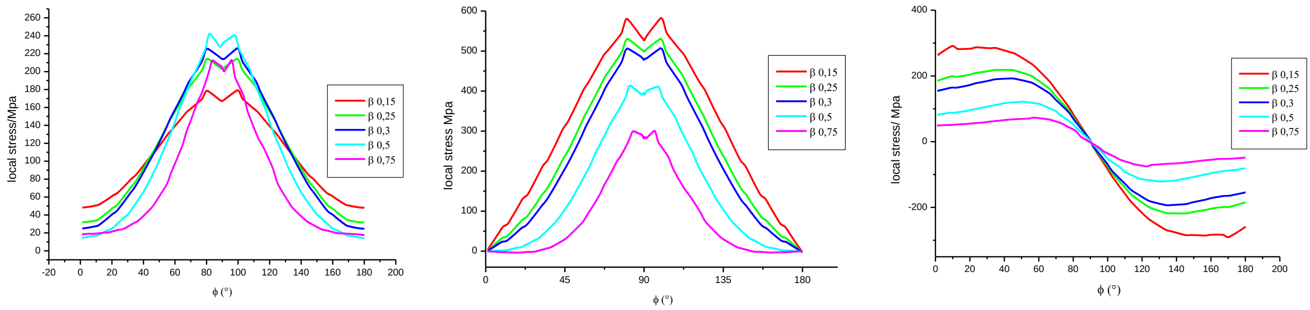
Fig. 15 Influence of parameter α (Group2) on chord stress concentration around chord/brace intersection in Ax loading (a), OPB loading (b), IPB (c) loading



c) b) c)

Fig. 16 Influence of parameter β (Group 3) on chord stress concentration around chord/brace intersection in Ax loading (a), OPB loading (b), IPB loading (c)

7. Conclusion

The objective of this work is to present a numerical model aimed at predicting stress concentrations around the weld bead zone of a T-type tubular junction. A numerical 2D modeling has been performed using the finite element method, and it is found to be reasonably accurate and reliable. Three basic loadings AX, IPB, OPB were considered to validate the model. The hot spots coincide with the saddle location ($\varphi = \pi/2+k\pi$) for loading AX and OPB. They lie between the saddle and crown locations for the FDP ($\pi/4+k\pi/2$). The case of combined loading simulating actual loading of tubular joints has been studied as well. We applied a rotational bending combined to an axial loading in 36 steps: the position of the hot spot is at the saddle point (φ=90°).

The model obtained is in good agreement with several other works. Based on the results obtained from the parametric study, it can be concluded that the geometric parameters have no influence on the HSS position, although they have a great effect on the stress levels for common loading cases, except for β where higher values have no influence on stress concentration values in AX loading. On the other hand, for FDP loading, smaller values of β gradually shift the location of HSS towards the crown position.

The results described herein allow optimizing the design of several types of welded joints according to their loading by highlighting the dangerous zones (hot spots). It is therefore possible to monitor those using sensors, which may increase the safety of offshore structures.

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EFFECT OF GEOMETRIC PARAMETERS AND COMBINED LOADING ON STRESS DISTRIBUTION OF TUBULAR T-JOINTS

Su m m a r y

Steel tubular structures are widely used in the construction of offshore platforms and T-type junctions are extensively used in this domain. The tubular members are welded, which generates significant stress concentrations at the edges. The stress levels reached in these critical places are used to assess lifetimes based on fatigue curves from tests conducted on standard samples. This study is devoted to the modeling and analysis of T-type welded tubular structures for the determination of hot spots stresses (HSS) at the chord/brace intersection, A numerical analysis was carried out to study the effect of a combined loading composed of an axial loading and a continuation of rational bending, that best assimilate real conditions, as well as the effect of normalized geometric parameters α, β, γ on the distribution of stress concentration (area and values) of T-joints. The mechanical behaviour has been modeled in 2D using quadrangular and triangular thin-shell elements by the finite element method (FEM). It is the most appropriate approach because it considers all geometric complexities and singularities of the structure, while the efforts as well as the computation time are considerably reduced compared to an experimental study or to complex FE models implementing solid elements. In this study, we use the COMSOL-MULTIPHYSICS® software.

Keywords: offshore platform, FEM, stress concentration, tubular modeling, bending stress, welded tubular joint, combined loadings.

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