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Semi-empirical equation for determination of stress concentration factors (SCF) in tubular joints of fixed offshore platforms subjected to axial forces

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Abstract. Considering the importance of studying fatigue failure in offshore structures, the stress concentration factor (SCF) is one of the most relevant parameters for its evaluation, obtained through equations that vary according to the geometry of the tubular joint; the type of joint in question; and the load to which it is subjected. Even though numerical research on KT-type tubular joints is widely discussed in the literature, this article applies the symbolic regression method in order to evaluate and discuss existing equations. Through a parametric study in finite elements, using the ANSYS software, with a variation of KT joints subjected to an axial load, it is possible to obtain the SCFs, using a specific point for analysis. Thus, through the use of dimensionless geometric parameters, the parametric equations for the SCFs are obtained, using the symbolic regression method. Based on these equations, it will be possible to make a comparison with existing equations and verify the possibility of improving the values of SCFs.

Keywords: stress concentration factors, tubular KT-joint, parametric equation.

1 Introduction

Fixed platforms, also called jackets, are one of the first structures that have been used in the offshore industry and still are to this day. As part of the support system in the area of oil extraction and production, its application is restricted to depths less than 400 meters, being a good solution when used in a viable way. Considering its exposure to several factors and the long-life span of this type of structure, it is necessary to evaluate its structural integrity.

Jackets are nothing more than interconnections composed of tubular steel elements, forming an excessively hyperstatic structure, known as tubular joints, being one of the points to be analyzed in the structure due to its fragility. As a form of simplification, tubular joints are often considered to have an absolutely rigid behavior in structural analyses, however, this simplification does not represent what actually happens in practice, since tubular joints present local flexibilities, and when mathematical models are used in the analysis, it is possible to verify the actual behavior of the structure considering the loads foreseen in the project. Therefore, numerical models are developed in order to assist in the representation of existing behavior in practice. Based on the geometric characteristics of the joints, it is possible to classify them, among several different types. For the present article, the joint to be analyzed will be of the KT type.

Knowing that the structure may fail due to fatigue and that this usually occurs at the joint nodes, due to the nominal stresses of the analyses ending up not corresponding to the true stresses that occur, a Stress Concentration Factor (SCF) must be considered in stress analysis. Values for this factor depend on the tubular joint rating, joint geometry, and type of loading applied.

1.1 Literature review

The definition of the Stress Concentration Factor (SCF), is then the relationship between the hot spot stress and the nominal stress present in the cross section, as shown in eq. (1).

$$SCF = \frac{\sigma_{hotspot}}{\sigma_{nominal}}. \tag{1}$$

The hot spot stress is defined by the greatest value of the extrapolation of the maximum principal stress distribution immediately outside the region affected by the weld's geometry.

The approach to calculate SCF using parametric equation formulas is most often used for tubular joints, where parametric equations have been developed by several authors over the years, based on finite element analysis, where there are different equations for each of the classifications of the joints.

The first SCF parametric equations for simple tubular joints were developed by Toprac, et al. [1], using a very limited database with steel joints. Reber [2], Visser [3], Kuang, et al.[4] and Kuang, et al. [5] developed steel models for finite element analysis based on analytical cylinder models.

Subsequent equations of Wordsworth, et al. [6] and Wordsworth [7] using model testing on tubular joints and by Efthymiou, et al. [8] and Efthymiou [9] employing 3D shell finite element analysis, have made considerable advances in the accuracy of parametric equations. Over this period, differences emerged between the experimental procedures used to determine stress concentration factors in simple tubular joints. These differences have led to inconsistencies both in the measured SCFs themselves, as well as in the parametric formulas of the SCFs based on these values of the measured SCFs.

Lloyd's Register [10] published equations developed from data that was acquired using small-size acrylic models and full-size steel models, and presents equations where exposed SCFs correspond only to specific points in the joint.

2 Finite Element modeling

To study the behavior of a tubular joint and clearly relate this behavior to the geometric characteristics of the joint, dimensionless geometric parameters were defined for modeling and analysis in finite elements, as shown in Fig. 1.

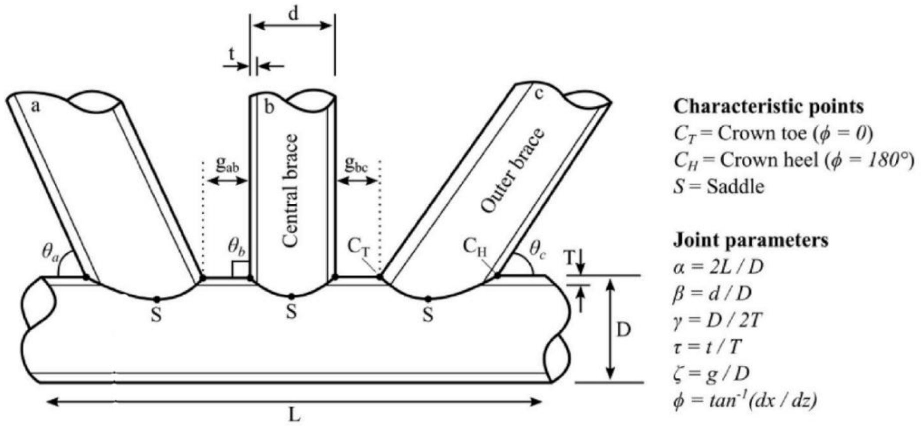

Figure 1. Dimensionless geometric parameters for a KT joint (Zavvar [11]).

The ANSYS software was used for the development of the numerical model through a linear elastic analysis, applying a solid element SOLID95, to model the KT joint and the weld profiles. By using this type of element, it was possible to model the weld profile as an acute notch, and thus, to obtain a more precise and detailed stress distribution in the weld region.

In the model, both ends of the chord were assumed to be fixed, with the corresponding nodes constrained. As the weld profile has a significant influence on the calculation of SCFs in welded steel tubular joints, it is important to carry out its modeling, which in this case used the AWS [12] recommendations. In order to obtain the stress values in the hot spot, a linear extrapolation method was used, provided in the IIW-XV-E [13] guidelines, as shown in Fig. 2.

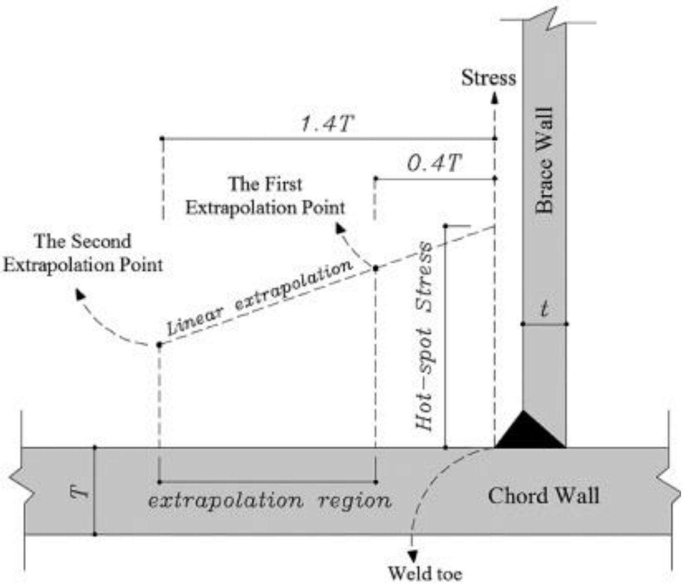

Figure 2. Linear extrapolation method recommended by IIW-XV-E [13].

A convergence analysis was performed to define the finite element mesh to be used, to ensure that the results are not affected by inadequate quality or by the size of the generated mesh, using different densities, with the objective of obtaining a high convergence with a smaller computational cost. Figure. 3 shows (a) the model developed in finite elements and (b) the mesh generated from the model. After the convergence test, 81 different models were generated for analysis, and it is possible to observe in Fig. 4 the mesh density used in different regions of the model.

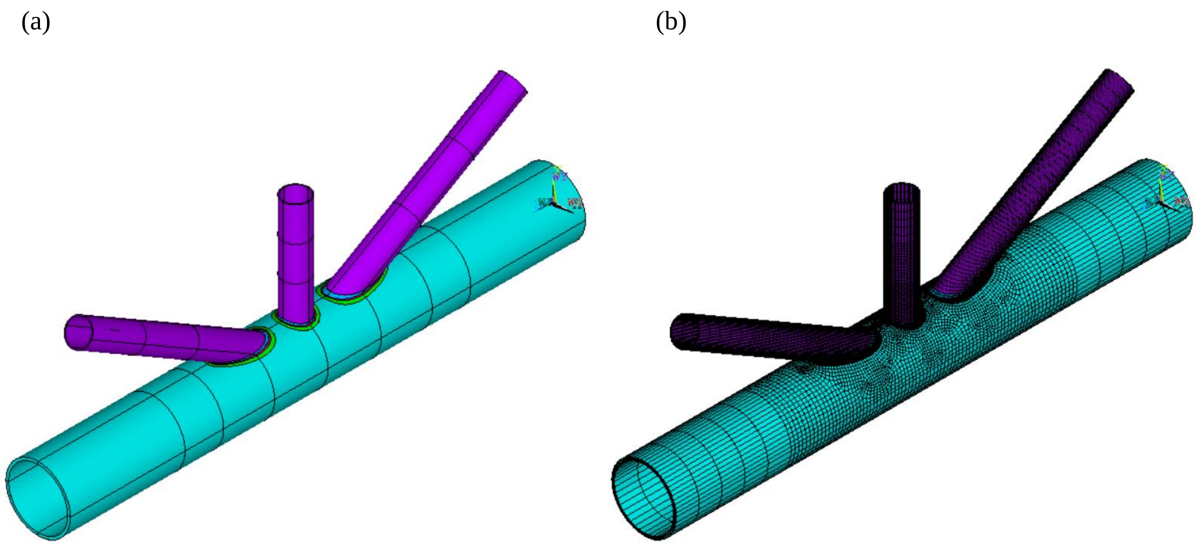

Figure 3. (a) FE model; (b) the model mesh.

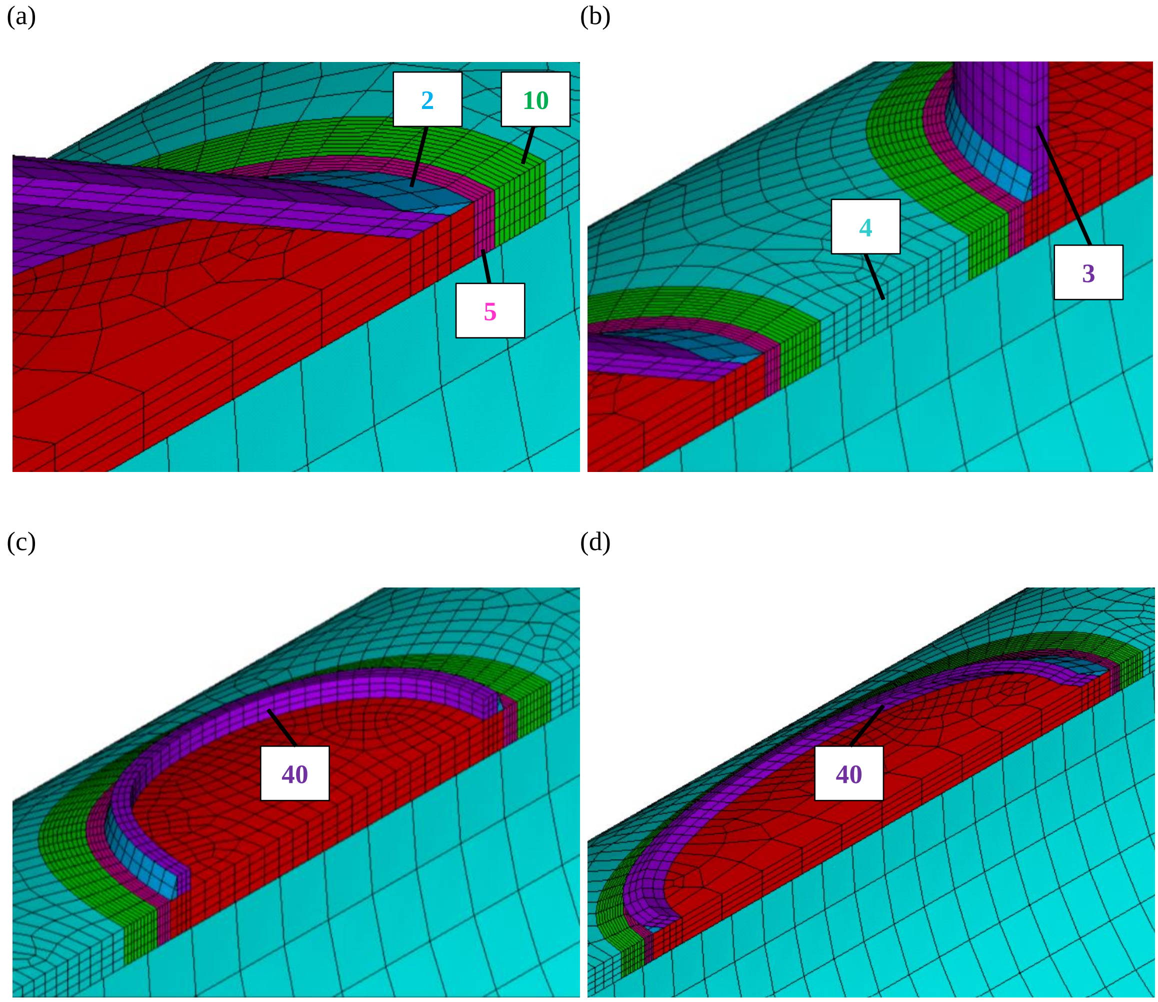

Figure 4. The mesh density of: (a) extrapolation region and weld profile; (b) chord and brace members; (c) brace-to-chord intersection in brace 1; (d) brace-to-chord intersection in brace 2.

3 Parametric equations

Knowing the most critical points of the structure, a certain critical point was chosen in the finite element model to perform the analysis and obtain the parametric equation, considering a specific loading condition. Fig. 5 (a) shows the type of axial loading used and Fig. 5 (b) shows the point chosen to perform the analysis, called crown. As it is a symmetrical load, the equation can be applied to the two points of the crown adjacent to the central arm. Considering that linear elastic materials are assigned to FE models, and that the SCF value is calculated from the stress ratio as shown in eq. (1), it can be said that the magnitude of the applied load is arbitrary. For this study, the value of the applied axial load is 100 kN.

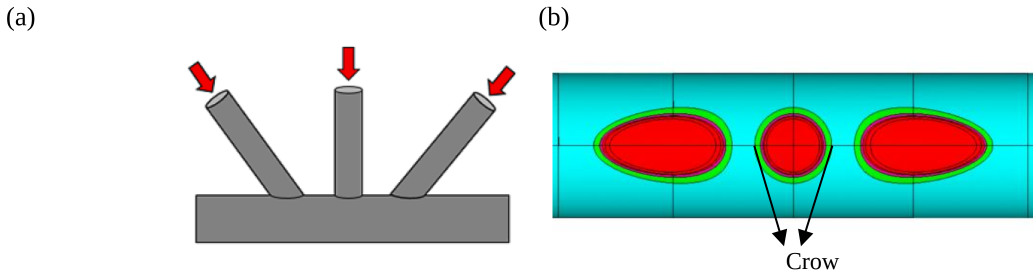

Figure 5. (a) Axial load applied to the model; (b) Analysis point and obtaining the equation for the SCF.

Starting from the dimensionless parameters shown in Tab. 1 applied to the model described in this article, the TuringBot software was used to generate the parametric equation. TuringBot uses Symbolic Regression to find mathematical formulas from data values based on Simulated Annealing, which is a probabilistic technique for approximating the global optimum of a given function. Specifically, it is a metaheuristic to approximate global optimization in a large search space for an optimization problem.

Table 1. Values assigned to dimensionless parameter

Parameter	Definition	Value(s)
α	2L/D	16
β	d/D	0.4, 0.5, 0.6
γ	D/2T	12, 18, 24
τ	t/T	0.4, 0.7, 1.0
θ	-	30°, 45°, 60°
ξ	g/D	0.3

Equation (2) shows the parametric equation obtained by TuringBot.

$$SCF_{TuringBot} = 5.554\ \ \tau + tan\ \ \tau\ \ \cdot\ \ 0.137 - \ \ -0.007 \cdot\ \ \theta + 4.528 \cdot cos\ \ \ 2.406 \cdot\ \ -6.592 + \gamma\ \ + \theta\ \ \cdot \gamma$$
$$+ \left(\theta \cdot \left(0.009 \cdot \left(\gamma - \left(12.127 - \left(\frac{0.060 \cdot\ \ \theta - 22.086}{-0.179 + \beta} \right)^{\tau} \right) \right) \right) \cdot\ \ \beta - 0.543\ \ \right). \quad (2)$$

3.1 Comparison

In a recent work, Hosseini et al [14] proposed some equations to calculate the SCFs for unreinforced and reinforced KT joints using multiple nonlinear regression analyses. For this analysis, they organized a matrix composed by the dependent variable (SCF) and the independent variables, which are the dimensionless geometric parameters (α, β, γ, τ, θ e ξ). The values assigned to each dimensionless parameter are shown in Tab. 1. The expressions chosen by them were those that had the greatest consistency with data behavior. Figure 6 (a) shows the comparison between the values obtained by Hosseini et al [14], comparing the SCF extracted by the FE model and by the proposed equation, as shown in eq. (3), and for central arm crown. Fig.6 (b) shows the comparison between the SCF values obtained by the finite element model and the values obtained by the symbolic regression method.

$$SCF_{Hosseini} = (1.449\tau^{0.827}\gamma^{0.040}\beta^{0.400}\theta^{-1.141})(2.675\beta\theta - 2.096\beta + 3.667\tau\theta + 4.214\theta - 0.569\tau). \quad (3)$$

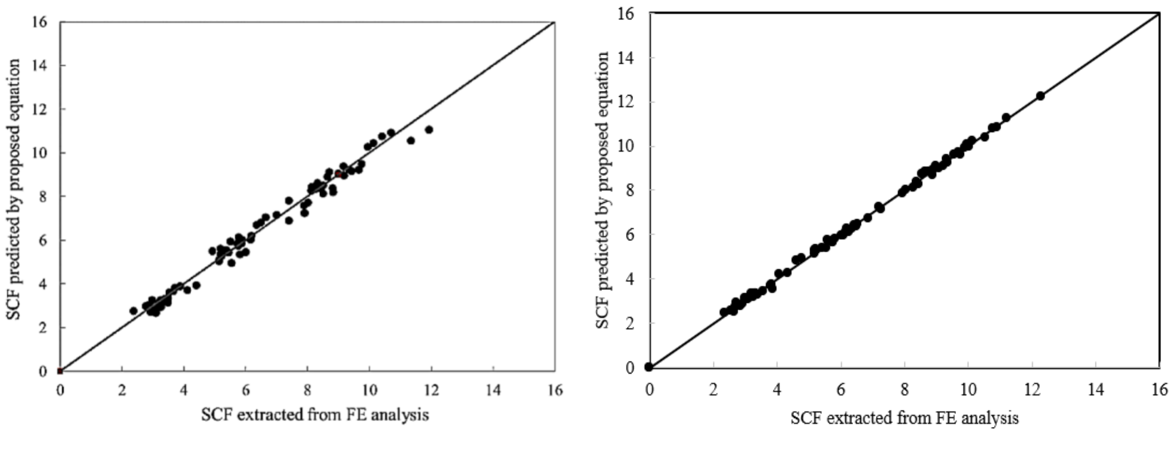

Figure 6. Modeled data versus formula predictions for the joints: (a) Hosseini et al. [14]; (b) symbolic regression.

4 Conclusions

Due to the analysis of Fig.6, one can observe that by using the symbolic regression method, the equations return SCF values closer to those obtained through the finite element model, when compared to the equations obtained by multiple nonlinear regression methods.

Considering this, it is possible to apply it to other critical points of the KT tubular joint and obtain the equations by the symbolic regression method. It is also possible to redo the analysis with other axial loads combinations in order to obtain the parametric equations for the SCFs.

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