Stress Concentration Factor Estimation of a Multi-planar DKT Tubular Joint through Finite Element and Machine Learning Approaches

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Abstract. The Double KT (DKT) multi-planar tubular joint is frequently found in the jacket offshore structures. An important aspect in designing the multi-planar tubular joint is accuracy in predicting the Stress Concentration Factor (SCF). Despite its practicability with considerable accuracy on stress analysis and estimating the SCF, the Finite Element (FE) method needs high computational time and effort. Therefore, this study will develop alternative SCF equations for DKT tubular joint with regression analysis as one of the machine learning techniques to increase equation's accuracy while reducing computational time. The variation of the DKT tubular joint was determined based on the validity range of the geometric parameters of the tubular joint (β, τ , and γ) and the combination of axial, in-plane bending (IPB), and out-plane bending (OPB) moment loadings. Stress distribution and concentration factor of the DKT joints were analyzed based on FE model of the joint. Then, the SCF results from the FE analysis were used in the regression analysis to obtain new equations. Six SCF equations including for both brace-side and chord-side have been obtained while the reliability of the equation has been checked using Acceptance Criteria based on UK Department of Energy and showed good results.

Keywords: Multiplanar DKT tubular joint, Finite element method, Machine learning, Regression, Stress concentration factor.

1 Introduction

The jacket platform is an offshore structure widely used to exploit oil and gas. The jacket structure members are dominated by tubular joints, which intersect between chords and braces. A tubular joint is the most susceptible to stress concentration and has a major impact on the service life of a jacket structure.

Studies of the tubular joint so far have focused on the uni-planar joint. However, many jacket structures consist of multi-planar tubular joints. Uni-planar joints have a branching configuration between chords and braces in one plane.

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Meanwhile, multi-planar joints have two to three planes. Complexity and high computational cost are the primary constraints [1]. Various geometry configurations of tubular joints are Y, T, X, K, and KT. In the case of a double KT multi-planar tubular joint, for example, it can be concluded that the equation of stress concentration factor resulting from the study of a KT uni-planar tubular joint to calculate the stress concentration factor value in a double KT multi-planar tubular joint can lead to inaccurate prediction results (too low or too high) [2].

In order to improve the accuracy of the prediction of the SCF equation on multi-planar tubular joints, a regression analysis, one of the machine learning methods, was carried out on the data obtained from finite element modeling. For example, a study on stress concentration factor prediction for multi-planar DT tubular joint subjected to axial loads was performed using the regression analysis performed by Jiang et al. [3]. Other type of tubular joints are also studied by using finite element method analysis[4, 5]. Then, Ahmadi et al. [1] studied the prediction of SCF equations in the multi-planar DKT tubular joint using non-linear regression analysis. Next, the research conducted by Oshogbunu [6] regarding the prediction of stress concentration factors in multi-planar tubular DKK joint also uses GRG (Generalized Reduced Gradient) based regression analysis.

Considering the lack of studies, the high computational cost, and the crucial role of multi-planar tubular joints (especially double KT tubular joints) make this study able to contribute to the development of prediction equations for SCF multi-planar tubular joints DKT. Those equations can be utilized by designers of offshore platforms during the design optimization phase and achieve optimal structure for marginal field [6–8]. The variation of the multi-planar DKT tubular joint was determined based on the validity range of the geometric parameters of the tubular joint (β, τ, and γ) and the combination of axial, in-plane bending (IPB), and out-plane bending (OPB) moment loadings. First, the DKT multi-planar joints' stress distribution and concentration factor were analyzed numerically (finite element method). Then, the SCF results from the numerical analysis are modeled using the regression method as a part of machine learning. After that, the reliability of the SCF equation was checked using the Acceptance Criteria based on the UK DoE recommendation.

2 Method of Study

2.1 Data and Global Model

Data needed for this study, namely platform data, geometry data and material properties of the DKT tubular joints, are based on [9]. The platform and the DKT connection are shown in Fig. 1 and Fig. 2, with the geometry and material properties are presented in Table 1 and Table 2. The platform was globally modelled and analyzed and produced member forces data for the intended DKT joint as listed in

Table 3. Such the global analysis is beyond the scope of this paper. The DKT joint was then locally modeled using FE software including the weld geometry model as calculated by AWS-D1.1 [10]. The loads applied to the joint local model are axial force, IPB, and OPB based on member end forces data in Table 3.

Fig. 1. The minimum jacket platform with the analized multi-planar DKT tubular joint.

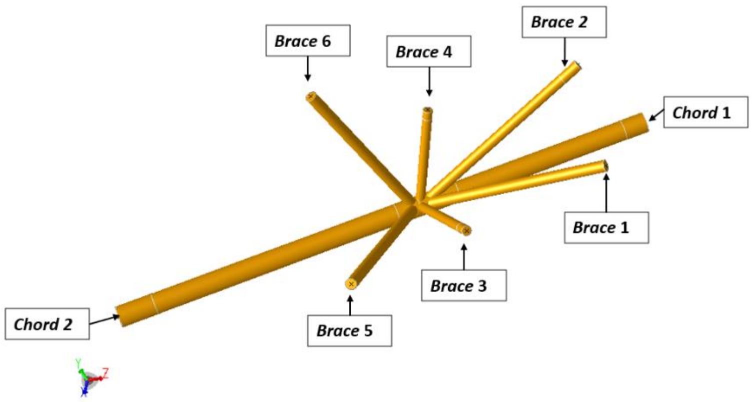


Fig. 2. Description of the multi-planar DKT tubular Joint.

Table 1. Geometry data of the analyzed DKT multi-planar joint.

Member	Wall Thickness (t) (in)	Outside Diameter (OD) (in)	Inside Diameter (ID) (in)	Length (L) (ft)
Chord 1	2.5	54	49	52
Chord 2	2.5	54	49	64
Brace 1	1.25	28	25	43
Brace 2	1.25	28	25	45
Brace 3	0.75	24	22.5	32.5
Brace 4	0.75	24	22.5	25
Brace 5	1.25	28	25	43
Brace 6	1.25	28	25	40

Table 2. Material properties of the DKT multi-planar joint.

Material Properties	Value
Density, ρ (lb/ft^3)	490
Yield Strength, σ_y (ksi)	36
Modulus Young, E (ksi)	29,000
Shear Modulus, G (ksi)	11,200
Poisson's ratio, v	0.3

Table 3. Member Forces data from the global analysis of the platform.

Member		*Axial Forces* (kips)	*Bending Moments* (in-kips)		
		fx	Mx	My	Mz
Brace 1	0016-0050	225.58	14.04	345.77	437.75
Brace 2	0050-0022	135.86	-34.08	502.83	35.08
Brace 3	0056-0050	-73.13	-61.41	-1,015.78	25.07
Brace 4	0050-0104	-49.52	53.86	-881.28	68.05
Brace 5	0068-0050	-48.40	143.02	931.57	645.36
Brace 6	0072-0050	24.39	-7.13	877.52	75.68

2.2 Geometric Parameters Variations

In local modeling of the joint the geometric parameters that has ben varied for this study consist of beta (β), tau (τ), and gamma (γ). β is the ratio between brace and chord diameters, τ is the ratio between the brace and chord wall thickness, and γ is the ratio between chord diameter and chord thickness. Those three parameters are shown in equations (1) – (3),

$$\beta = \frac{d}{D} \tag{1}$$

$$\tau = \frac{t}{T} \tag{2}$$

$$\gamma = \frac{D}{2T} \tag{3}$$

where d and D are brace and chord diameters, respectively. While t and T are wall thickness of the brace and chord, respectively. Variation values used for the three parameters by considering the range of validity which was adopted from Oshogbunu [6], namely 0.4 to 0.6 for β, 0.25 to 1.0 for τ, and γ that ranges from 12 until 24. Eleven variations were made based on that validity range are presented in Table 4.

2.3 Meshing Sensitivity Analysis

Generally, in FE modeling proces the meshing sensitivity analysis is mandatory. This analysis aims to check the sensitivity of the mesh of the DKT tubular joint model to stress output, especially in the discontinuity area (around the weld area) where in the stress is concentrated. This analysis produces proper number and size of elements created in the model. The proper meshing provides a good level of accuracy in describing stresses occurred in the model. The analysis is done by changing the size and number of element in the model with a specific range to get a mesh configuration that can produces relatively constant stress at the observed location of interest.

Table 4. Model variations of the DKT multi-planar joint.

Variation	D (in)	T (in)	d (in)	t (in)	β	τ	γ
Original	54.00	2.50	28.00	1.25	0.52	0.50	10.80
1	54.00	2.25	24.00	1.20	0.40	0.50	12.00
2	54.00	1.13	24.00	0.60	0.40	0.50	24.00
3	54.00	2.25	24.00	2.40	0.40	1.00	12.00
4	54.00	1.13	24.00	1.20	0.40	1.00	24.00
5	50.00	2.00	30.00	1.00	0.60	0.50	12.50
6	48.00	1.00	30.00	0.50	0.60	0.50	24.00
7	48.00	2.00	28.00	1.80	0.60	1.00	12.00
8	48.00	1.00	28.00	1.00	0.60	1.00	24.00
9	54.00	2.25	24.00	1.68	0.40	0.75	12.00
10	54.00	2.25	27.00	1.20	0.50	0.50	12.00
11	54.00	1.50	24.00	0.80	0.40	0.50	18.00

2.4 Hotspot Stress

Hotspot stress on the weld toe of the joint model is obtained by linear extrapolation technique based on two points data $(\sigma_{\perp En})$. In this study, the point used as a reference to perform linear extrapolation is located at a location where the maximum equivalent stress occurred. Then the hotspot stress $(\sigma_{\perp W})$ can be calculated using the following Equation 4 [11].

$$\sigma_{\perp W} = 1{,}4\sigma_{\perp E1} - 0{,}4\sigma_{\perp E2} \tag{4}$$

2.5 Stress Concentration Factor

The stress concentration factor is obtained by dividing the hotspot stress against the nominal stress as in Equation 5 [11]. Hotspot stress is obtained by previous outlined linear extrapolation, and nominal stress is obtained from the braces at locations where relatively uniform stresses occurred. The larger the SCF, the more concentrated stress occurs at the location under consideration.

$$SCF = \sigma_{\perp W}/\sigma_n \tag{5}$$

2.6 SCF_{ML} Equation Modeling Using Regression Method

The SCF_{ML} equation is modeled from the SCF obtained from variations of non-dimensional geometric parameters using regression analysis. This method is part of machine learning, training data on parameter variations and SCF that have been obtained to model new SCF_{ML} equations.

There are six SCF_{ML} equation models based on the location of the weld toe and the type of loading, namely SCF_{ML} axial brace-side weld toe, SCF_{ML} axial chord-side weld toe, SCF_{ML} IPB brace-side weld toe, SCF_{ML} IPB chord-side weld toe, SCF_{ML} OPB brace- side weld toe, and SCF_{ML} OPB chord-side weld toe. The SCF data used to create the equations match the modeled SCF_{ML} equations (for example, SCF axial brace-side weld toe data are collected and used to model the SCF_{ML} axial brace-side weld toe equations).

The SCF_{ML} equation is obtained by transforming the following Equation 6 [6]:

$$SCF = \mathrm{C}\beta^{x1}\tau^{x2}\gamma^{x3} \quad (6)$$

Then, here are the steps in getting the SCF_{ML} equation:

a. Transform Equation 6 by multiplying both sides by the natural logarithm with the result as in Equation 7 (C is a constant or intercept in the model):

$$lnSCF = \mathrm{lnC}\beta^{x1}\tau^{x2}\gamma^{x3} \quad (7)$$

b. By applying the natural logarithm, Equation 8 is obtained and simplified to Equation 9 below:

$$lnSCF = \mathrm{lnC} + ln\beta^{x1}ln\tau^{x2}ln\gamma^{x3} \quad (8)$$

$$lnSCF = \mathrm{lnC} + X_1 ln\beta + X_2 ln\tau + X_3 ln\gamma \quad (9)$$

c. Calculate the natural logarithm value of the geometric parameter variables and SCF in Equation 9.

d. The least square method can be done in Equation 9 using SPSS software. The values of lnC, lnβ, lnτ, and lnγ as predictors, and lnSCF is the dependent variable.

e. The values of x_1, x_2, and x_3 are obtained and used as known variables in Equation 9 and make lnC, lnβ, lnτ, and lnγ as unknown variables. In addition, lnSCF is also used as an unknown variable and converted to $lnSCF_{ML}$ to get a new SCF_{ML}.

f. Re-transform Equation 9 by raising the exponential on both sides to be like the following Equation 10:

$$e^{\ln SCF_{ML}} = e^{X_1 \ln\beta + X_2 \ln\tau + X_3 \ln\gamma + \ln C} \quad (10)$$

g. By applying the properties of exponents and exponentials, Equation 11 is obtained and simplified to the following Equation 12:

$$e^{\ln SCF_{ML}} = e^{X_1 \ln \beta}\, e^{X_2 \ln \tau}\, e^{X_3 \ln \gamma} e^{\ln C} \quad (11)$$

$$SCF_{ML} = \mathrm{C}\beta^{x1}\tau^{x2}\gamma^{x3} \quad (12)$$

2.7 Acceptance Criteria from UK DoE

The SCF_{ML} equation was checked for its reliability using recommendations from the UK DoE. If it meets the criteria, the equation can be declared reliable to use for the DKT tubular joint. The following criteria are based on the UK DoE summarized by Ahmadi et al. [1]:

- If [P/R<1] ≤ 25% and [P/R<0.8] ≤ 5%, the new equations can be accepted.
- In addition to the first criterion, the new equations can be considered conservative if [P/R>1.5] ≥50%.
- If 25% ≤ [P/R<1] ≤ 30% and/or 5% ≤ [P/R<0.8] ≤ 7,5%, the new equations can be considered as engineering judgements.
- If the P/R does not meet the criteria above, the new equations are rejected because they are too optimistic.

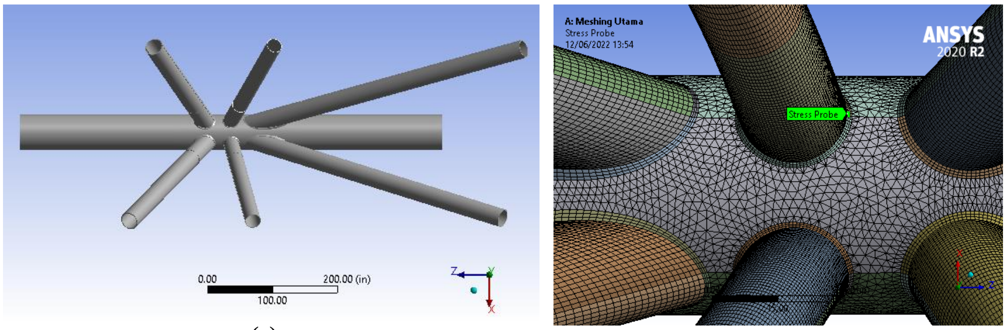
3. Result and Discussion

3.1 Local Modeling of the DKT Joint

The FE model of the tubular joint is made on the static structural design modeler in the ANSYS Workbench software. The geometry configuration used in this modeling is based on data of chord and brace diameters, chord and brace thicknesses, chord and brace lengths, and angles between braces and chords, which have been provided in Table 1. In this study, element type of a three dimensional (3D) solid element was used to model the entire tubular joint which are the chord, brace and weld profile. This type of element can be used to properly model the weld profile with a sharp notch. This model will produce more accurate and detailed stress distribution near the brace-chord intersection. By using the nowadays technology of digital computers the computing time needed to slove the 3D solid models can be significantly reduced.

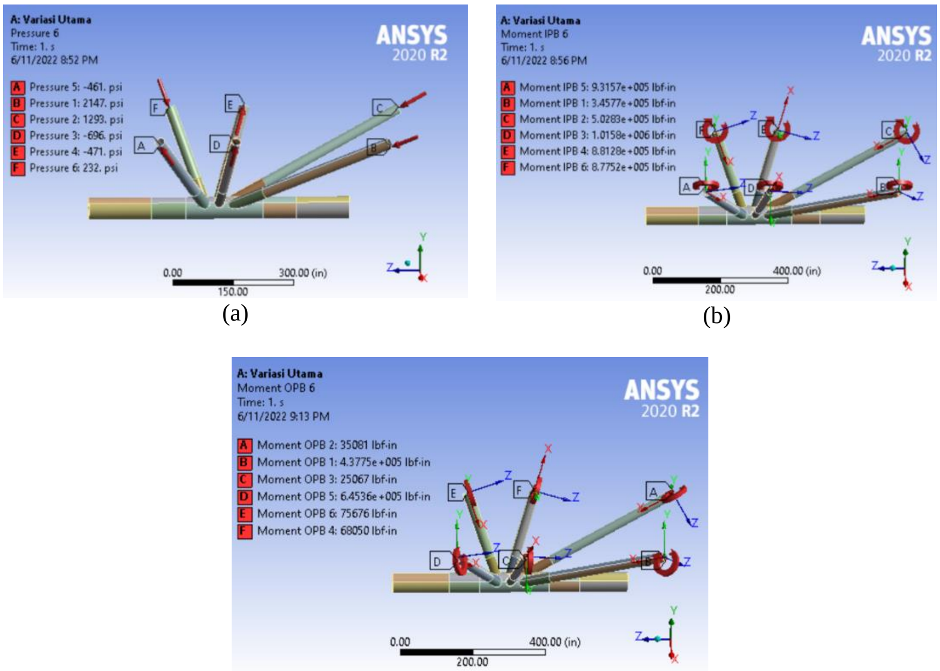
The geometry along the brace–chord intersection of the DKT joint is very complex, so that the mesh generation process for the FE analysis of the joint is a tedious work. To assure the mesh quality, the entire tubular model is divided into several different regions. Fine mesh to be applied in around the weld toes areas to consider the stress concentration. Meanwhile, the coarse meshes are gradually applied at those regions far away from the weld because the the coarse mesh in these regions has no significant effect on the stress distribution along the weld toe. Then by merging the meshes of all the regions, the entire mesh of the tubular model can be obtained. Using this mesh generation strategy can reduce the number of elements and in turn to save the computation time.

Chord length determination refers to Efthymiou [12], which is minimum of six times the chord diameter (6D). The following is the geometric model results of the DKT tubular joint as shown in Fig. 3. Imposing the loading on the model is based on the data from the global structural analysis (see Table 2), which are axial force, IPB, and OPB based on each member end forces as shown in
Fig. 4.



(a) (b)

Fig. 3. Finite element model of the DKT joint: (a) Geometry model (b) Meshing of the model.



(a) (b)

(c)

Fig. 4. Loading cases applied to the model: (a) Axial loading, (b) IPB loading, and (c) OPB loading.

3.2 Meshing Sensitivity Analysis

This analysis was conducted to determine the consistency and accuracy of the finite element software modeling output based on the number of elements used. Variations are made on the number of mesh elements, while the support and loading are fixed (not varied). The point (node) that is reviewed must be at the same point to determine the consistency of the output at various variations in the number of elements.

The consistency parameter of the meshing sensitivity analysis is an increase in the number and increase in mesh density which is increased slowly until a certain number and density of mesh produces constant stress. The loading conditions carried out in the sensitivity analysis of the meshing of DKT tubular joints have three types, axial load, IPB, and OPB.

The number of meshes created will then be varied up to a certain amount. In this meshing sensitivity analysis, 12 variations are conducted, with the number of elements ranging from about 340,000 to 1,000,000. The results of the meshing sensitivity are presented in Fig. 5 for the axial load, in-plane bending moment, and out-of-plane bending moment, respectively. Based on the graph of the meshing sensitivity results for the three loading types, a variation with constant stress was obtained to be used in the next analysis. The constant variation is the tenth model, with the number of meshes reaching around 800,000.

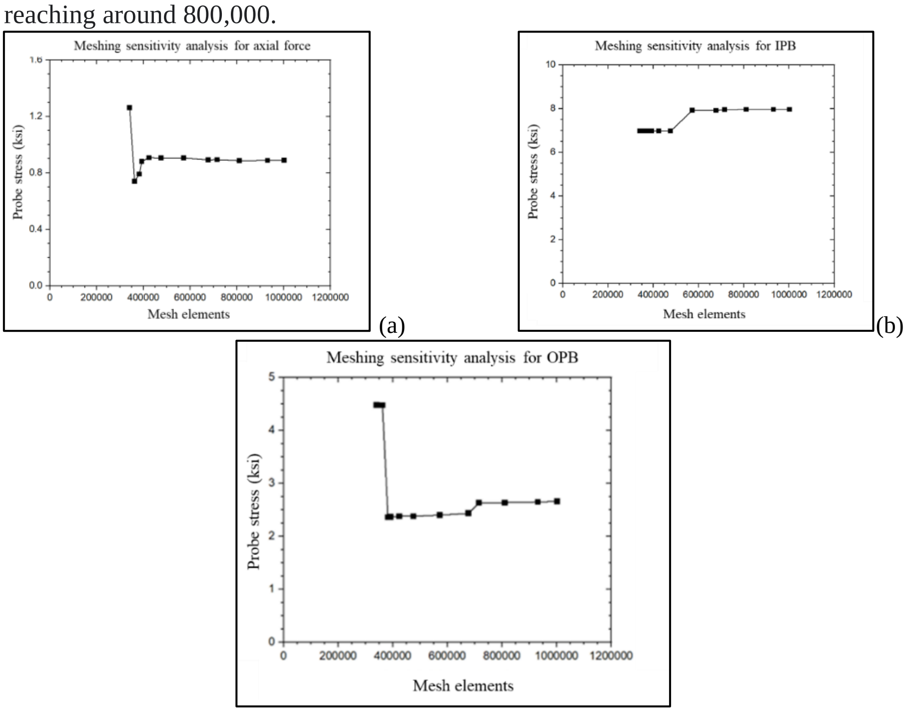


Fig. 5. Graph of the meshing sensitivity analysis results for each load case: (a) Axial load, (b) IPB load, and (c) OPB load.

3.2 Hotspot Stress

A linear extrapolation method is needed to obtain hotspot stress. This method is done by making two extrapolation points on the part of an area to be analyzed. The area that will be extrapolated in this study is the area of the weld toe (attached to the brace and chord) which experiences maximum equivalent stress.

The reference used to make linear extrapolation points is IIW-XV-E using the equation formulated by Nassiraei and Rezadoost [11]. The equation is available in Equation 4. The hotspot stress obtained is the hotspot stress due to axial, IPB, and OPB loadings.

The following are the hotspot stress results in the original model for the respective loadings on the brace side, as shown in Table 5, and the chord side, as shown in Table 6 (to summarize, the hotspot stress results for the other models are not included).

Table 5. Hotspot stress on the brace-side weld toe.

Description	*Node* (in)	*Stress (Axial Load)* (ksi)	*Stress (IPB Load)* (ksi)	*Stress (OPB Load)* (ksi)
Starting point	0 t	4.57	7.09	3.62
E1	0.4 t	3.55	5.06	2.49
E2	1.4 t	3.26	3.25	1.75
HSS		3.67	5.79	2.79

Table 6 Hotspot stress on the chord-side weld toe.

Description	*Node* (in)	*Stress (Axial Load)* (ksi)	*Stress (IPB Load)* (ksi)	*Stress (OPB Load)* (ksi)
Starting point	0 t	5.16	4.30	2.63
E1	0.4 t	3.65	2.15	2.15
E2	1.4 t	2.60	0.86	1.12
HSS		4.07	2.66	2.56

3.3 Stress Concentration Factor

Table 7. Maximum SCF results.

Loading Type	HSS *brace-side* (ksi)	HSS *chord-side* (ksi)	Nominal Stress (ksi)	$SCF_{brace\text{-}side}$	$SCF_{chord\text{-}side}$
Axial	8.85	11.18	2.62	3.37	4.26
IPB	5.79	8.97	1.51 (*brace*); 2.18 (*chord*)	3.83	4.12
OPB	10.70	13.57	1.38	7.74	9.81

The stress concentration factor is obtained by dividing the hotspot stress by the nominal stress, as in Equation 5. Table 7 below is the summary of maximum SCF results obtained for each axial load, IPB, and OPB from all models.

The maximum SCF is found in the fourth variation model with β, τ, and γ are 0.4, 1, and 24, respectively. Meanwhile, a different result is shown on the IPB loading condition on the brace-side, which is found in the original model variation. The maximum SCF due to axial load on the brace-side and chord-side weld toe is 3.37 and 4.26, respectively. Then, the maximum SCF due to IPB on the brace-side and chord-side weld toe are 3.83 and 4.12, respectively. Finally, the maximum SCF due to OPB on the brace-side and chord-side weld toe are 7.74 and 9.81, respectively.

3.4 Modeling the Equation of SCF with Machine Learning

The SCF_{ML} equation model is made based on the location and type of loading. Thus, there are six SCF_{ML} equation models made in this study. To make it easier to read the equations in the future, Table 8 below is a summary of the model and equation result for estimating the SCF_{ML}.

Table 8. Model and codes of SCF_{ML} equations.

No.	Equation Model	Equation Codes	Results of Equation's Modeling
1.	SCF_{ML} *Axial Brace-Side Weld Toe*	SCF_{ML1}	$SCF_{ML1} = 0{,}691\ \beta^{-0{,}159}\tau^{0{,}342}\gamma^{0{,}420}$
2.	SCF_{ML} *Axial Chord-Side Weld Toe*	SCF_{ML2}	$SCF_{ML2} = 0{,}471\ \beta^{-0{,}058}\tau^{0{,}469}\gamma^{0{,}638}$
3.	SCF_{ML} IPB *Brace-Side Weld Toe*	SCF_{ML3}	$SCF_{ML3} = 1{,}373\ \beta^{0{,}068}\tau^{-0{,}036}\gamma^{0{,}229}$
4.	SCF_{ML} IPB *Chord-Side Weld Toe*	SCF_{ML4}	$SCF_{ML4} = 0{,}232\ \beta^{-0{,}334}\tau^{0{,}586}\gamma^{0{,}814}$
5.	SCF_{ML} OPB *Brace-Side Weld Toe*	SCF_{ML5}	$SCF_{ML5} = 0{,}240\ \beta^{-0{,}039}\tau^{0{,}145}\gamma^{1{,}069}$
6.	SCF_{ML} OPB *Chord-Side Weld Toe*	SCF_{ML6}	$SCF_{ML6} = 0{,}112\ \beta^{-0{,}055}\tau^{0{,}493}\gamma^{1{,}420}$

The SCF_{ML} of the obtained equation must show a close relationship with the SCF obtained by the finite element method. The relationship is known through the adjusted coefficient of determination (R_a^2) for brace-side axial load, chord-side axial load, brace-side IPB, chord-side IPB, brace-side OPB, and chord-side OPB respectively is 0.93; 0.89; 0.03; 0.95; 0.99; and 0.92. Thus, all comparisons of SCF_{ML} with SCF_{FEM} for all locations and loadings showed a close relationship because they had results that ranged from 0.9, except for brace-side IPB, which had results of 0.03. Based on the results of the adjusted coefficient of determination for brace-side IPB, it can be concluded that the equation is rejected/cannot be used.

3.5 SCF_{ML} Equation Validation Using $SCF_{Efthymiou}$

The conventional equation used for comparison in this study is the SCF of Efthymiou [12, 13]. The results of the SCF_{ML} equation are used to obtain SCF_{ML} on chord and brace-side weld toe with axial, in-plane bending moment, and out-of-plane bending moment loadings. Conservative levels of SCF_{ML} need to be checked against

$SCF_{Efthymiou}$. Then, it can be determined whether the SCF_{ML} equation is more optimum than $SCF_{Efthymiou}$, or vice versa.

Comparisons between $SCF_{Efthymiou}$ and SCF_{ML} are given in percent (%) and are not absolute. So, if the comparison value is positive, SCF_{ML} is smaller (optimum) than $SCF_{Efthymiou}$ and vice versa. Table 9 below is the average result of the validation of the SCF_{ML} equation using $SCF_{Efthymiou}$ for all model variations.

Table 9. Average results of SCF_{ML} equation validation using $SCF_{Efthymiou}$.

Loading Type	*Brace-Side Weld Toe*			*Chord-Side Weld Toe*		
	$SCF_{Efthymiou}$	SCF_{ML}	Comparison (%)	$SCF_{Efthymiou}$	SCF_{ML}	Comparison (%)
Axial	2.75	2.16	20.84%	3.92	2.40	36.53%
IPB	-	-	-	3.30	2.29	29.56%
OPB	6.69	4.65	29.46%	8.48	5.31	35.14%

The results above indicate that the SCF_{ML} results are lower than $SCF_{Efthymiou}$ for both locations (brace and chord-side weld toe) and all loadings, except for the brace-side IPB, which cannot be used for further analysis based on the analysis. This statement is evidenced by a positive comparison of all variations in all locations and types of loading. Then, the optimization rate of the SCF_{ML} equation is expressed by the average result of the comparison between the two equations. The average value for all comparisons ranges from 13 – 36%, which means that SCF_{ML} is 13-36% more optimum than the $SCF_{Efthymiou}$ equation.

3.5 SCF_{ML} Check Using Acceptance Criteria from UK DoE

The results of the SCF_{ML} equation are used to obtain SCF_{ML} on the brace and chord-side weld toe with the axial, in-plane bending moment, and out-of-plane bending moment loadings. The SCF_{ML} equation model is checked based on the criteria to determine whether the SCF_{ML} equation is acceptable or not. SCF_{ML} data is used as predicted data, and SCF_{FEM} data as recorded data. Table 10 below is a summary of the results of the acceptance criteria.

Table 10. Summary of acceptance criteria results.

SCF_{ML} Equation	Condition			Status
	[%P/R<1]	[%P/R<0,8]	[%P/R>1,5]	
SCF_{ML1}	9% < 25% OK	0% < 5% OK	0% < 50% OK	Accepted
SCF_{ML2}	18% < 25% OK	0% < 5% OK	0% < 50% OK	Accepted
SCF_{ML3}	-	-	-	-
SCF_{ML4}	9% < 25% OK	0% < 5% OK	0% < 50% OK	Accepted
SCF_{ML5}	0% < 25% OK	0% < 5% OK	0% < 50% OK	Accepted
SCF_{ML6}	27% > 25% CEK	0% < 5% OK	0% < 50% OK	Re-Check

Based on Table 10, the status of all SCF_{ML} equation models (SCF_{ML1} to SCF_{ML6}) is concluded, except for IPB Brace-Side, which cannot be used. It is known that all equation models have met the criteria, except for SCF_{ML6}. The criteria that were not met by SCF_{ML6} were [%P/R<1], which reached 27%. A re-examination is carried out to determine whether the equation can still meet the Acceptance Criteria. Based on the third point of the Acceptance Criteria, if the equation has a value of 25% < [%P/R<1] < 30%, the equation can be considered an engineering judgment. Thus, SCF_{ML6} can still be considered an engineering judgment.

4. Conclusion

The following conclusions can be summarized from this research:

1. The stress concentration factor (SCF) in the double KT tubular joint can be obtained using the finite element method from variations in geometric parameters due to axial, in-plane bending moment, and out-of-plane bending moment loadings. The largest SCF due to all the loading cases on the brace-side weld toe occurred in the fourth variation, main data, and fourth variation, respectively. The SCF are 3.37, 3.83, and 7.74, respectively. Meanwhile, the largest SCF on the chord-side weld toe occurred entirely in the fourth variation, which are 4.26, 4.12, and 9.81, respectively.

2. SCFML equation modeling for the DKT tubular joints is obtained by performing regression analysis (one of the machine learning methods) using SCF_{FEM} data. There are 6 (six) SCF_{ML} equation models, namely SCF_{ML} Axial Brace-Side Weld Toe (SCF_{ML1}), SCF_{ML} Axial Chord-Side Weld Toe (SCF_{ML2}), SCF_{ML} IPB Brace-Side Weld Toe (SCF_{ML3}), SCF_{ML} IPB Chord-Side Weld Toe (SCF_{ML4}), SCF_{ML} OPB Brace-Side Weld Toe (SCF_{ML5}), and SCF_{ML} OPB Chord-Side Weld Toe (SCF_{ML6}). The equations SCF_{ML1}, SCF_{ML2}, SCF_{ML4}, SCF_{ML5}, and SCF_{ML6} can be accepted so that each can be used to obtain SCF Brace-Side Weld Toe due to axial load, SCF Chord-Side Weld Toe due to axial load, SCF Chord-Side Weld Toe due to IPB, SCF Brace-Side Weld Toe due to OPB, and SCF Chord-Side Weld Toe due to OPB. Meanwhile, SCF_{ML3} was rejected, so it could not be used to obtain SCF Brace-Side Weld Toe due to IPB.

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