Computation of stress concentration factor of tubular joints for the fatigue analysis of steel structures

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Abstract. The offshore structures are welded tubular structures which are continuously subjected to cyclic environmental loads like waves, winds, currents, earthquakes etc. These cyclic environmental loads (predominantly wave loads) will induce time varying cyclic stresses on the offshore structures causing fatigue damages even at very low nominal stress levels. Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking under repeated alternating or cyclic stresses of intensity considerably below the normal strength. Fatigue is very critical at the welded joints, because the stresses at the welded regions are several times higher than the nominal stress. Stress Concentration Factors (SCFs) converts the nominal stress into higher stresses known as hot spot stresses. These SCFs are very sensitive in the computation of fatigue life of steel structures. A small difference in SCFs can cause a huge difference in fatigue life of steel structures. Different empirical methods give different values of SCFs for the same element, hence different fatigue life. This study aims to investigate the stress concentration factor of different configurations of tubular joints numerically using Finite Element Analysis (ANSYS) under certain boundary conditions and compare the result with the SCF obtained from empirical method (using parametric equations).

1. Introduction

The Tubular joint structures are widely used in every steel construction varying from stadiums, bridges and airports to commercial purposes like setup of offices, showrooms, malls and service camps. Offshore structures are also welded tubular structures, constantly subjected to environmental loads like the waves; winds may fracture even at very low nominal stress levels. The environmental loads (predominantly wave loads) are cyclic and therefore is the reason for the failure of the structure. Majority of the failures that occur in these structures are caused due to the action of fatigue. It is reported that the fatigue was the major contributor to failure of the offshore structure in the North Sea (Staney and Sharp, 2007) [1]. The failure of Alexander L. Kielland platform in the North Sea was also due to fatigue. This fatal accident took place in March of 1980. Critical investigation studies into the cause of failure suggested that the accident was due to failure of brace due to fatigue cracking followed by unstable fracture. The failure of this brace led to a chain effect causing the other supporting braces of the same column to fail as well. This accident took 123 human lives out of 212 men on board. Fatigue is very critical at the welded joints, because the stresses at the welded regions, known as ‘Hot spot stress’, are several times higher than the nominal stress.

Stress Concentration Factor (SCF) is defined as the ratio of hot spot stress to normal stress. Hot spot stress is the stress at the joints or points of discontinuity. Stress Concentration Factors (SCFs) converts the nominal stress into higher stresses known as hot spot stresses. Hot spot stress or structural
stress method is a method which uses this concept and evaluates the stresses around the circumference of intersection between the brace and the chord. These stresses are used for the fatigue life estimation of the structure.

Stress Concentration Factor can be computed using empirical formulas, finite element analysis such as ANSYS, etc. However, the stress concentration factor (SCF) calculated using these methods shows variation in value, and this in turn results in different values of fatigue life for the same element. Parametric equations are widely used for the determination of stress concentration factors. These equations are either based on experimental testing employing steel or sometimes acrylic models or are based on the Finite Element Analysis (FEA). The parametric equation in either of the cases is derived using regression analysis. These methods provide sufficiently accurate results in the majority of cases, but are also reported to deviate in some cases.

As of now, the fatigue life of structures is determined using different empirical methods which vary from the true value. A small difference in SCF can cause a huge difference in fatigue life of steel structures. This study aims to investigate the stress concentration factor of different configuration of tubular joints numerically using industry standard finite element software ANSYS under certain boundary conditions and compare the result with empirical method.

2. Methodology

Due to the difference in relative stiffness of the brace and the chord, the local stress near the welded connection between the chord and the brace is several times the nominal stress. Here, the stress concentration factor (SCF) is determined using the empirical equations and finite element modelling of local joint geometry (tetrahedral meshing is used). The empirical equation used depend upon the non-dimensional geometric parameters ($\alpha=2L/D$, $\beta=d/D$, $\gamma=D/2T$, $\tau=t/T$). This study focuses on two empirical equations; Efthymiou equations [2] and Hellier’s equations [3]. The stress concentration factor for selected models were determined for three loading cases; axial loading, in-plane bending and out-of-plane bending.

2.1. Validation Process.

For validation, the study conducted in [4] has been emulated in ANSYS and the results obtained are compared. The structure and corresponding dimensions (see Table 1), the properties of the ordinary steel composing the T-joint (see Table 2) and all notations are the same as those presented in [4]: the purpose herein is to draw comparisons between our results and those derived by the other authors, and verify the validity of these results. The result of axial loading shows a difference of 0.07, 0.09 in case of in-plane bending and 1.3 in case of out-of-plane bending.

| Table 1. Dimensions of the tubular T-joint[4] |
|-----------------------------------------------|
| $L=4130\text{mm}$ | $T=12.7\text{mm}$ |
| $D=406\text{mm}$  | $D=508\text{mm}$  |
| $T=9.5\text{mm}$  | Base and height of the fillet weld = 5 mm |
| $d/D=0.8$         | $R/T=20$           |
| $t/T=0.75$        | $L/D=16.25$        |

| Table 2. Properties of the ordinary steel used for the T-joint |
|---------------------------------------------------------------|
| $E = 207 \text{ GPa}$ | Young’s modulus   |
| $m = 0.3$            | Poisson’s ratio   |
| $q = 7.8 \times 10^{-6} \text{ kg/mm}^3$ | Specific mass    |
| $\sigma_e = 248 \text{ MPa}$ | Yield stress     |
2.2. Modelling and Analysis.
Models of different configurations (see Table 3) were modelled in Solid Works and exported to ANSYS, where the analysis was carried out. Welds of appropriate sizes for each model were also modelled in SolidWorks using fillet bead tool [5]. The models were designed such that its geometric parameters fell within the validity range and then the meshing was provided. Tetrahedral solid mesh was used for analysis of the models. Element size of 2.5e-003 m was adopted within the sphere of influence of 0.2 m around the joint (Fig. 1 and Fig. 2). Then, different loading conditions were applied such as axial loading (Fig. 4), In-plane loading (Fig. 5) and Out-of-plane loading (Fig. 6), and determined the stress at the joints. And the results from these two were compared.

### Table 3. Dimensions of the 16 tubular T-joints

| Sample No | Brace Diameter d (mm) | Chord Diameter D (mm) | Brace Thickness t (mm) | Chord Thickness T (mm) | Chord Length L (mm) |
|-----------|------------------------|-----------------------|------------------------|------------------------|---------------------|
| 1         | 88.9                   | 114.3                 | 3.2                    | 3.6                    | 1140                |
| 2         | 76.1                   | 114.3                 | 3.2                    | 3.6                    | 1140                |
| 3         | 60.3                   | 114.3                 | 2.9                    | 3.6                    | 1140                |
| 4         | 88.9                   | 114.3                 | 3.2                    | 4.5                    | 1140                |
| 5         | 88.9                   | 114.3                 | 4.0                    | 4.5                    | 1140                |
| 6         | 76.1                   | 114.3                 | 3.2                    | 4.5                    | 1140                |
| 7         | 76.1                   | 114.3                 | 3.6                    | 4.5                    | 1140                |
| 8         | 60.3                   | 114.3                 | 2.9                    | 4.5                    | 1140                |
| 9         | 60.3                   | 114.3                 | 3.6                    | 4.5                    | 1140                |
| 10        | 60.3                   | 88.9                  | 2.9                    | 3.2                    | 1140                |
| 11        | 76.1                   | 88.9                  | 3.2                    | 4.0                    | 1140                |
| 12        | 76.1                   | 88.9                  | 3.6                    | 4.0                    | 1140                |
| 13        | 60.3                   | 88.9                  | 2.9                    | 4.0                    | 1140                |
| 14        | 60.3                   | 88.9                  | 3.6                    | 4.0                    | 1140                |
| 15        | 60.3                   | 76.1                  | 2.9                    | 3.2                    | 1140                |
| 16        | 60.3                   | 76.1                  | 2.9                    | 3.6                    | 1140                |

![Figure 1. Meshed T-Joint](image1.png) ![Figure 2. Sphere of influence](image2.png)
3. Results
The results obtained from the use of parametric equations (Efthymiou equations and Hellier’s equations) are compared with the results obtained from finite element analysis.

The following observations are made from the comparison.

- Under axial loading, the SCF values obtained from the Hellier’s parametric equations shows larger deviation with respect to the values obtained from FEA when compared to that of Efthymiou equations.
- Under in-plane bending, SCF values obtained from Hellier’s parametric equations and Efthymiou equations are very close to the SCF values obtained from FEA except for a few cases on the chord side.
- Under out-of-plane bending, SCF values obtained from FEA (Brace) are larger than that of SCF values obtained from Efthymiou equations (Brace). SCF values obtained from Hellier’s parametric equations are nearly the same except in some cases on the brace side.
### Table 4. Comparing the SCF Values Obtained from FEA and Parametric equations in Axial loading

| Sample No | Efthymiou SCF | FEA SCF | Diff   | Efthymiou SCF | FEA SCF | Diff   | Hellier’s SCF | FEA SCF | Diff   | Hellier’s SCF | FEA SCF | Diff   |
|-----------|---------------|---------|--------|---------------|---------|--------|--------------|---------|--------|--------------|---------|--------|
| 1         | 12.700        | 11.59   | 1.106  | 8.546         | 10.381  | 1.835  | 13.901       | 11.59   | 2.307  | 11.402       | 10.381  | 1.021  |
| 2         | 14.591        | 14.15   | 0.440  | 9.802         | 10.936  | 1.134  | 17.542       | 14.15   | 3.391  | 13.215       | 10.936  | 2.279  |
| 3         | 13.889        | 13.75   | 0.144  | 9.998         | 10.744  | 0.746  | 16.79        | 13.75   | 3.045  | 13.564       | 10.744  | 2.82   |
| 4         | 7.949         | 7.23    | 0.722  | 6.462         | 7.3414  | 0.8794 | 7.892        | 7.23    | 0.665  | 8.256        | 7.3414  | 0.9146 |
| 5         | 10.16         | 9.94    | 0.225  | 7.097         | 8.7983  | 1.7013 | 11.635       | 9.94    | 1.700  | 9.929        | 8.7983  | 1.1307 |
| 6         | 9.132         | 9.25    | 0.115  | 7.356         | 8.6812  | 1.3252 | 10.159       | 9.25    | 0.912  | 9.618        | 8.6812  | 0.9368 |
| 7         | 10.395        | 8.83    | 1.564  | 7.739         | 8.0106  | 0.2716 | 12.298       | 8.83    | 3.467  | 10.583       | 8.0106  | 2.5724 |
| 8         | 8.693         | 9.05    | 0.362  | 7.496         | 8.5183  | 1.0223 | 10.054       | 9.05    | 0.999  | 9.922        | 8.5183  | 1.4037 |
| 9         | 11.027        | 11.71   | 0.685  | 8.233         | 10.275  | 2.042  | 13.904       | 11.71   | 2.192  | 11.749       | 10.275  | 1.474  |
| 10        | 12.889        | 13.48   | 0.588  | 8.908         | 10.359  | 1.451  | 16.233       | 13.48   | 2.756  | 12.297       | 10.359  | 1.938  |
| 11        | 6.705         | 6.08    | 0.624  | 5.359         | 5.6796  | 0.3206 | 6.531        | 6.08    | 0.450  | 7.27         | 5.6796  | 1.5904 |
| 12        | 8.774         | 7.64    | 1.133  | 5.615         | 6.2486  | 0.6336 | 8.118        | 7.64    | 0.477  | 8.017        | 6.2486  | 1.7684 |
| 13        | 8.073         | 7.51    | 0.564  | 6.72          | 7.5388  | 0.8188 | 9.123        | 7.51    | 1.614  | 8.865        | 7.5388  | 1.3262 |
| 14        | 10.241        | 9.40    | 0.844  | 7.365         | 8.875   | 1.51   | 13.088       | 9.40    | 3.691  | 10.549       | 8.875   | 1.674  |
| 15        | 9.467         | 10.4    | 0.933  | 6.843         | 8.0004  | 1.1574 | 11.041       | 10.4    | 0.641  | 9.536        | 8.0004  | 1.5356 |
| 16        | 8.33          | 9.40    | 1.067  | 5.934         | 7.0564  | 1.1224 | 7.934        | 9.40    | 1.463  | 7.976        | 7.0564  | 0.9196 |

### Table 5. Comparing the SCF Values Obtained from FEA and Parametric equations in In-plane bending

| Sample No | In-plane bending (Chord) | In-plane bending (Brace) | In-plane bending (Chord) | In-plane bending (Brace) |
|-----------|--------------------------|--------------------------|--------------------------|--------------------------|
|           | Efthymiou SCF | FEA SCF | Diff   | Efthymiou SCF | FEA SCF | Diff   | Hellier’s SCF | FEA SCF | Diff   | Hellier’s SCF | FEA SCF | Diff   |
| 1         | 3.753         | 2.962  | 0.791  | 2.875         | 2.454   | 0.421  | 4.660        | 2.962   | 1.698  | 2.920        | 2.454   | 0.467  |
| 2         | 3.966         | 4.203  | 0.237  | 3.037         | 3.111   | 0.074  | 4.649        | 4.203   | 0.446  | 3.270        | 3.111   | 0.159  |
| 3         | 3.748         | 3.168  | 0.580  | 3.083         | 2.518   | 0.564  | 4.215        | 3.168   | 1.047  | 3.424        | 2.518   | 0.906  |
| Sample No | Out-of-plane bending (Chord) | Out-of-plane bending (Brace) | Out-of-plane bending (Chord) | Out-of-plane bending (Brace) |
|-----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|           | Efthymiou SCF | FEA SCF | Diff | Efthymiou SCF | FEA SCF | Diff | Efthymiou SCF | FEA SCF | Diff | Efthymiou SCF | FEA SCF | Diff |
| 1         | 13.24          | 11.99  | 1.249 | 8.030          | 9.593  | 1.562 | 12.56          | 11.99  | 0.568 | 11.804          | 9.593  | 2.212 |
| 2         | 13.06          | 12.84  | 0.216 | 8.397          | 8.784  | 0.387 | 12.51          | 12.84  | 0.330 | 11.280          | 8.784  | 2.495 |
| 3         | 10.43          | 10.65  | 0.221 | 7.638          | 7.724  | 0.086 | 11.22          | 10.65  | 0.569 | 9.371           | 7.724  | 1.648 |
| 4         | 8.47           | 7.98   | 0.496 | 5.863          | 7.061  | 1.198 | 7.89           | 7.98   | 0.085 | 7.796           | 7.061  | 0.735 |
| 5         | 10.59          | 11.10  | 0.510 | 6.496          | 8.754  | 2.258 | 9.86           | 11.10  | 1.237 | 9.652           | 8.754  | 0.898 |
| 6         | 8.36           | 8.84   | 0.481 | 6.131          | 7.213  | 1.082 | 7.86           | 8.84   | 0.975 | 7.450           | 7.213  | 0.237 |
| 7         | 9.40           | 8.30   | 1.108 | 6.472          | 6.455  | 0.017 | 8.85           | 8.30   | 0.552 | 8.339           | 6.455  | 1.884 |
| 8         | 6.67           | 7.28   | 0.605 | 5.576          | 6.071  | 0.495 | 7.05           | 7.28   | 0.230 | 6.189           | 6.071  | 0.118 |
| 9         | 8.29           | 9.19   | 0.905 | 6.159          | 7.287  | 1.128 | 8.75           | 9.19   | 0.440 | 7.612           | 7.287  | 0.325 |
| 10        | 11.72          | 10.64  | 1.077 | 7.455          | 7.874  | 0.419 | 11.20          | 10.64  | 0.558 | 10.485          | 7.874  | 2.611 |
| 11        | 7.92           | 7.01   | 0.919 | 4.998          | 6.686  | 1.687 | 7.80           | 7.01   | 0.791 | 8.099           | 6.686  | 1.413 |
| 12        | 8.92           | 6.88   | 2.036 | 5.276          | 6.379  | 1.103 | 8.77           | 6.88   | 1.892 | 9.065           | 6.379  | 2.686 |
| 13        | 7.50           | 7.47   | 0.034 | 5.443          | 5.931  | 0.489 | 7.04           | 7.47   | 0.428 | 6.925           | 5.931  | 0.994 |
| 14        | 9.31           | 9.22   | 0.086 | 6.012          | 7.197  | 1.185 | 8.74           | 9.22   | 0.487 | 8.517           | 7.197  | 1.320 |
| 15        | 10.06          | 9.04   | 1.017 | 6.082          | 7.493  | 1.411 | 9.57           | 9.04   | 0.536 | 9.661           | 7.493  | 2.168 |
| 16        | 7.94           | 7.71   | 0.236 | 5.151          | 6.416  | 1.265 | 7.49           | 7.71   | 0.217 | 7.761           | 6.416  | 1.344 |

Table 6. Comparing the SCF Values Obtained from FEA and Parametric equations in Out-of-plane bending
4. Conclusion
The SCFs obtained from the Efthymiou’s parametric equations were found to be generally higher than that estimated with FEA. The variations in the SCFs determined may be due to the fact that the FEA analysis used in this study is an advanced form of finite element analysis with solid elements used for modelling of joints.

The variations can also be due to the fact that the joints considered in this study have β value (β = d/D) nearer to the extreme validity range of Efthymiou equations. Under In-plane bending Efthymiou’s equation gives good results for SCF. The SCFs obtained from the Hellier’s parametric equations were found to be generally higher than that estimated with FEA.

The SCFs on the chord side were larger than the SCFs on the brace side, for most of the considered joints when determined from empirical equations. Also, SCFs on the chord side were larger than SCFs on the brace side when estimated using FEA. This is due to the fact that for joints with β value near to 0.9, the empirical equations are not able to predict the behaviour accurately.

From the study, it is recommended that greater care should be made while selecting the method for SCF determination, as small variations in SCFs can lead to large variations in the fatigue life estimates. The FEA is preferable in case of joints having β value near to 0.9 (close to boundary of validity range), as the parametric equations are not able to predict the behaviour correctly because the validity range of β value is 0.2 to 1.0. As the FE analysis is very costly and time consuming, suitable modifications in parametric equations shall be made so that it can predict the behaviour of the joints having β value near to 0.9.

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