Stress Concentration Factors (SCFs) for Partial Joint Penetration Plus (PJP+) welds for tubular joints

L. Tang
MT 10.17
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1 Introduction

Steel circular hollow sections (tubulars) have a good resistance against bending, torsion and buckling. They also have a high strength-to-weight ratio. For these reasons tubular joints are widely used for jackets in offshore platforms, shown respectively in figure 1 and figure 2.

One of the main causes of damage to offshore structures is fatigue failure of the tubular joints. This is because the tubular joints are subjected to loadings caused by alternating wave forces. At high stress locations cracks will initiate, develop and continue to grow until fatigue failure occurs. The Stress Concentration Factor (SCF) approach can be used to determine the fatigue life of tubular joints. This relates the stress at the critical location to the nominal stress.

The objective of this report is to measure the SCFs of Partial Joint Penetration plus (PJP+) tubular X-joints and see if the results are in good agreement with the SCFs obtained by Finite Element analysis. Chapter 2 will cover background information about the geometry of the joints which are tested and an explanation of SCF will be given. In chapter 3 numerical modeling of the tubular joints will be described. The experimental test and the results compared to the numerical model will be presented and discussed in chapter 4. Finally, chapter 5 covers conclusions and recommendations for further research.
2 Background

Fatigue loadings arising from wave and wind loadings often cause damage to offshore structures. In many cases fatigue failure occurs at the joint between the tubular members where the local peak stresses appear. At these high stress positions cracks will develop and continue to grow with the load cycles until fatigue failure occurs. For this reason local peak stresses play an important role in the development of these cracks. The high peak stresses are dependent on the geometry of the joint and the loading it is subjected to. The fatigue life of a tubular joint can be estimated if the loading and the geometrical parameters of the joint are given.

2.1 Geometry of welded tubular joints

Welding is the process of joining metal pieces together by heating the metal to a fluid state. In offshore platform jackets large steel tubular joints are connected by welding the brace member onto the outer surface of the chord member. The joint type analyzed and tested in this project is the X-joint. The geometry of the joint is shown in the figure below and can be described by the following dimensions:

- \( d_c \) (outer diameter of the chord)
- \( d_b \) (outer diameter of the brace)
- \( t_c \) (thickness of the chord)
- \( t_b \) (thickness of the brace)
- \( l_c \) (length of the chord)

Usually some non-dimensional parameters are used to describe the geometry of joints. These parameters are listed below:

- \( \alpha \): chord length to half chord diameter ratio \( (\alpha = \frac{2l_c}{d_c}) \) (1a)
- \( \beta \): brace diameter to chord diameter ratio \( (\beta = \frac{d_b}{d_c}) \) (1b)
- \( \gamma \): radius to wall thickness ratio of chord member \( (\gamma = \frac{d_c}{2t_c}) \) (1c)
- \( \tau \): brace to chord wall thickness ratio \( (\tau = \frac{t_b}{t_c}) \) (1d)

The brace-to-chord intersection angle is given by \( \theta \). Details of the Partial Joint Penetration plus (PJP+) weld are shown in appendix A.
2.2 Fatigue life of tubular joints
The behavior of the welded tubular joints in offshore platform jackets is complex. Long-term exposure to alternating loading can lead to failure of the tubular joints to fatigue. Usually cracks will initiate and develop along the weld profile where high local peak stresses occurs. This is caused by imperfection in welding and other possible defects. One way to determine the fatigue life of tubular joints is the Stress Concentration Factor approach. The details and definitions of this approach will be described further in this chapter. First the stress categories used in fatigue analysis are explained.

2.2.1 Nominal stress
In this report the nominal stress is defined as the maximum stress in a cross section of the loaded brace member using the formula:

\[ \sigma_{\text{nom}} = \frac{My}{I} \]  

Where \( M \) is the bending moment, \( y \) is the distance from the centre of brace to the point considered and \( I \) is the moment of inertia of the cross section.

2.2.2 Hot spot stress
To refer to the critical point in a structure the term hot spot stress is used. Here fatigue cracking can be expected to occur due to a discontinuity and/or notch. Nominal stress and the effects of structural discontinuities are both included in the hot spot stress. Although the hot spot is located at a local notch, for example the weld toe, the hot spot stress does not include the nonlinear stress peak caused by the local notch as shown in figure 4.

The hot spot stress is determined by extrapolating the stresses in a defined distance to the weld toe. Reason for extrapolation is to exclude the effects caused by local notch. The extrapolation region is defined by a specified minimum and maximum distance from the weld toe of the joint. In section 2.3 the extrapolation method will be further explained.

2.2.3 Notch stress
The total stress located at the root of a notch, such as a weld toe, is called the local notch stress, as illustrated in the figure above. The main effect of a local notch is to produce nonlinearity in the stress distribution. Usually this happens in the thickness direction. In many cases the yield strength of the material will be exceeded by the notch stress. Therefore elastic-plastic behavior will be formed. Between different welds the geometry of the local notch at the weld toe varies significantly. A very tiny change of local notch will cause great difference to the notch stress. For this reason notch stress has a random value which is quite different from nominal stress or hot spot stress. So, in the fatigue design of a tubular joint, the notch stress must be excluded from the nominal stress or the hot spot stress.
2.3 Extrapolation method
At a particular location along the brace-chord intersection the hot spot stress is determined by extrapolation of the stresses in the extrapolation region to the weld toe position. The following criteria are recommended by the International Institute of Welding (IIW) design guide to determine the extrapolation region of tubular joints:

- chord member:
  \[ I_{r_{\text{min}}} = 0.4 \times t_c \]  
  \[ I_{r_{\text{max}}} = 1.4 \times t_c \]  

- brace member
  \[ I_{r_{\text{min}}} = 0.4 \times t_b \]  
  \[ I_{r_{\text{max}}} = 1.4 \times t_b \]

Where \( I_{r_{\text{min}}} \) and \( I_{r_{\text{max}}} \) refer to the minimum and maximum distance of the extrapolation region from the weld toe position and \( t_c \) and \( t_b \) are the thickness of chord and brace member respectively.

Different extrapolation method results in different hot spot stress values. Two different extrapolation methods are normally used:

1) Linear extrapolation: linear line fitting through data points in the extrapolation region considered and extrapolating the obtained linear line to the weld toe position
2) Quadratic extrapolation: parabolic curve fitting through data points in the extrapolation region and extrapolating the obtained curve to the weld toe position

Usually two types of stress are considered in determining the hot spot stress, the stress perpendicular to the weld (primary stresses) and the maximum principal stresses. Because the direction of crack growth is usually along the weld path and only stresses perpendicular to the weld are enlarged by the weld shape, the stresses perpendicular to the weld profile are used to derive the hot spot stress in this project. The details of using the extrapolation method to obtain the hot spot stress at the weld toe position will be explained in chapter 3.

2.4 Stress Concentration Factor (SCF)
The hot spot stress can be calculated by multiply a factor to the nominal stress. This factor is called the Stress Concentration Factor. This is a measurement used to quantify the peak stress in welded tubular joints for fatigue assessment and can be expressed by the following formula:

\[ SCF = \frac{\sigma_{hs}}{\sigma_{nom}} \]  

Where \( \sigma_{hs} \) is the hot spot stress and \( \sigma_{nom} \) is the nominal stress. Various researches have been carried out in the last few decades to investigate the SCFs of tubular joints and various sets of SCF equations were recommended by different design standards or guides. Research was based on experimental or numerical tests results such as Finite Element Method (FEM).

The following paragraphs provide relevant studies on the SCFs of tubular joints. Two sets of existing parametric equations for SCFs in X-joints are reviewed and discussed, namely Efthymiou equations and Lloyd’s Register equations.
2.4.1 Efthymiou equations
Efthymiou used Finite Element Method to study the stress concentration factor in tubular joints. The hot spot stress was obtained by linear extrapolation of the maximum principal stresses to the weld toe. As a result he published a comprehensive set of equations covering the tubular X-joint configuration. These equations are presented for the maximum outer surface SCF on the chord and the brace. The disadvantage of this study is that the SCFs are only given at certain positions around the weld, such as saddle and crown (see figure 3) of the chord and brace. Further information on the SCF distribution around the intersection is not given. However, these equations are widely accepted and used in the offshore industry. The relevant Efthymiou equations for SCF in tubular X-joints for in-plane bending are listed below.

- chord crown:
  \[ SCF = 1.45\beta r^{0.85}\gamma^{1-0.68\beta}sin^{0.7}\theta \]  
  (6a)

- brace crown:
  \[ SCF = 1 + 0.65\beta r^{0.4}\gamma^{1.09-0.77\beta}sin^{0.06\gamma-1.16\theta} \]  
  (6b)

Stress Concentration Factors for chord saddle and brace saddle negligible. The equations are valid if each parameter is between the following regions:

\[ 4 \leq \alpha \leq 40 \]
\[ 0.2 \leq \beta \leq 1.0 \]
\[ 8 \leq \gamma \leq 32 \]
\[ 0.2 \leq \tau \leq 1.0 \]
\[ 20^\circ \leq \theta \leq 90^\circ \]

2.4.2 Lloyd’s Register equations
The Lloyd’s Register equations are based on experimental results. From a SCF database of steel and acrylic test results the equations were developed. The relevant Lloyd’s Register equations for SCF are as following:

- chord crown:
  \[ SCF = 1.23\gamma^{(0.5\beta-0.5)}r^{0.8}\beta(1-0.32\beta^5)sin^{0.5}\theta \]  
  (7a)

- brace crown:
  \[ SCF = 1.12 + 1.12\gamma^{0.8}\beta(0.32-0.25\beta)sin^{1.5}\theta \]  
  (7b)

Just like for the Efthymiou equations the SCF for chord saddle and brace saddle are negligible. The range of the parameters is:

\[ 4 \leq \alpha \leq 40 \]
\[ 0.13 \leq \beta \leq 1.0 \]
\[ 10 \leq \gamma \leq 35 \]
\[ 0.25 \leq \tau \leq 1.0 \]
\[ 30^\circ \leq \theta \leq 90^\circ \]
3 Numerical modeling of tubular X-joints

Stress Concentration Factors of tubular joints can be obtained by experimental test or by numerical methods, like Finite Element Method. Most research projects are based on FEM because of the high costs of conducting experimental tests. Along the brace-chord intersection the geometry of a tubular joint is very complex. Therefore the most difficult task in the Finite Element analysis is usually the mesh generation process. Since the stress distributions near the intersection of the tubular joints are influenced by the shape of the weld, the weld profile must be modeled accurately. In this chapter the finite element model and all the aspects of the X-joints in this project will be explained.

3.1 Tubular X-joint
In this project two different steel tubular X-joints are modeled and tested, J1 and J2. The geometry of both joints is shown in the figure 5 and figure 6 respectively.

Figure 5: Tubular joint J1
The dimensions of joint J1 and joint J2 are listed in the table below.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Joint J1</th>
<th>Joint J2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_c$, outer diameter of the chord</td>
<td>750 mm</td>
<td>750 mm</td>
</tr>
<tr>
<td>$d_b$, outer diameter of the brace</td>
<td>406.4 mm</td>
<td>406.4 mm</td>
</tr>
<tr>
<td>$t_c$, thickness of the chord</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>$t_b$, thickness of the brace</td>
<td>12.5 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>$l_c$, length of the chord</td>
<td>1750 mm</td>
<td>1750 mm</td>
</tr>
</tbody>
</table>

It can be seen that the only difference between the two joints is the thickness of the brace.

In chapter 2 the definitions of the non-dimensional parameters are already mentioned. These parameters can be calculated (formula (1a)-(1d)) for the tubular X-joints in this project and the values are given in table 2.

<table>
<thead>
<tr>
<th>Non-dimensional parameters</th>
<th>Joint J1</th>
<th>Joint J2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$: chord length to half chord diameter ratio</td>
<td>4.67</td>
<td>4.67</td>
</tr>
<tr>
<td>$\beta$: brace diameter to chord diameter ratio</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>$\gamma$: radius to wall thickness ratio of chord member</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$\tau$: brace to chord wall thickness ratio</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>brace-to-chord intersection angle $\theta$</td>
<td>60°</td>
<td>60°</td>
</tr>
</tbody>
</table>
3.2 Finite Element modeling

In this project, the numerical analysis was carried out in ABAQUS/CAE Version 6.8-2. This is a finite element software package designed to simulate large scale, complex linear and nonlinear problems. First the meshes of the tubular X-joints were built using MSC. Patran (2007) and an input file for ABAQUS is generated with this program. The input file consists of the information about the nodes and elements of the mesh. The element type, boundary conditions, material properties and applied load are modeled in ABAQUS. The analyses were carried out on a Hewlett Packard workstation. After the simulations, the finite element results were output into a data file including the nodal stresses and the coordinates of each node in the extrapolation region. The stresses and the coordinates of these nodes are used to calculate the stresses perpendicular to the weld and the Stress Concentration Factors of the joints. More details of the model will be described in the following paragraphs.

3.2.1 Element type

As said before the geometry of tubular joints, especially the weld profile is complex. In order to find out the best element type for modeling tubular joints, Romeijn has carried out a research. Four different types of FE models are compared in his research:

1) Joint modeled with 4-node shell elements, excluding the weld profile
2) Joint modeled with 8-node shell elements, excluding the weld profile
3) Joint modeled with 20-node solid elements, including the weld profile
4) Joint modeled with 8-node shell elements, including the weld profile modeled with 20-node solid elements. Between the shell and solid elements, 13-node transition elements are used.

Romeijn found that the results of FE models largely depends on the type of the elements, mesh refinement and the integration scheme. The use of elements having a midside node, like 8-node shell and 20-node solid, is recommended by Romeijn. The 20-node solid element is most suitable for modeling tubular joints because the weld profiles also influence the SCF results and 8-node shell elements are unable to model weld profiles. Romeijn also recommended that the reduced integration scheme should be used. Otherwise the joint stiffness will be overestimated and the results will be less accurate.

For these reasons 20-node solid elements with reduced integration scheme (ABAQUS element type C3D20R) were used for the modeling of the tubular X-joints in this project.

3.2.2 Mesh and boundary conditions

Only half of the whole tubular joint is modeled because of symmetry. The mesh of joint J1 is shown in the figures below. For joint J2 the mesh is built in the same way.

![Figure 7a: Finite element mesh for tubular joint J1 (3D view)](image)
![Figure 7b: Finite element mesh for tubular joint J1 (front view)](image)
A more refined mesh is needed around the brace-chord intersection of the joint because the stresses in this region are imported for the Stress Concentration Factor. This mesh of the weld region is shown in figure 8.

For all the nodes on the symmetry plane the displacement perpendicular to this plane is restrained. The corresponding plane is shown in the figure below.
Besides the boundary condition for symmetry there are also boundary conditions for the brace. At each end of the brace member the finite element model includes a rigid plate. The purpose of this plate is for the convenience of applying the boundary conditions. An overview of the boundary conditions is shown in the following figure.

The boundary condition applied for the left end of the brace is pin constraint. The horizontal and vertical displacement is restricted for the node at the center point of the rigid plate (see figure 11).
The right end of the brace experiences roller constraint. The node at the center point of the rigid plate is constrained vertically. This is shown in figure 12.

![Fig. 12: Roller supported brace end (right)](image)

### 3.2.3 Material properties

The numerical analysis computes the Stress Concentration Factors in the linear-elastic region. For that reason only linear-elastic material properties are needed for the model. The elastic isotropic material properties for steel used in the model are:

- Young’s modulus ($E$) of 205 GPa
- Poisson ratio ($\nu$) of 0.3

These material properties are used for brace and chord member. The elements of the rigid plates at the end of the brace member and the elements near the concentrated load on the chord surface have an assigned Young’s modulus 1000 times larger than the Young’s modulus of the elements of chord and brace member. This is done to facilitate the distribution of the concentrated load in the joint. In the figure below an overview of the stiff elements in the model are shown.

![Figure 13: Stiff elements](image)
3.2.4 Applied load

For the finite element model a concentrated load on the chord surface acting through the intersection of the longitudinal axes of the brace and chord member is used. In order to make the numerical calculation of the Stress Concentration Factor easier, the load in the model is applied in a certain value to produce a nominal stress equal to 1 MPa. Using this approach, the value of the hot spot stress derived from the finite element analysis is then equal to the SCF. In the following part the calculation of the value of the applied load to make the nominal stress equal to 1 MPa will be explained.

![Figure 14: Load in tubular X-joint](image)

As mentioned in paragraph 2.2.1 the nominal stress for the joint subjected to a bending load is given by:

\[ \sigma_{nom} = \frac{M_y}{I} \]  

(2)

With \( M \) the moment as shown in figure 14, given by:

\[ M = \frac{P l}{2} \]  

(8)

With \( P \) the applied load and \( l \) the distance defined as in figure 14. The distance from centre of the brace to mid-thickness of the brace is calculated with:

\[ y = \frac{d_b}{2} - \frac{t_b}{2} \]  

(9)

With \( d_b \) the diameter of the brace and \( t_b \) the thickness of the brace. The brace member can be seen as a hollow cylindrical cross section and the moment of inertia is given by:

\[ I = \frac{\pi}{64} (d_o^4 - d_i^4) \]  

(10)

With \( d_o \) the outer diameter of the brace member and \( d_i \) the inner diameter of the brace member.

After rearrangement of the formulas above and setting the nominal stress equal to 1MPa, it will follow that the applied load for the model should be \( P = 1850.13 \) N and \( P = 3480.53 \) N for tubular joint J1 and joint J2 respectively.
3.3 Calculation of SCF
The value of the hot spot stress derived from the finite element analysis will be equal to the Stress Concentration Factor because the load is applied to make the nominal stress equal to 1 MPa. The hot spot stress at a particular location along the brace-chord intersection is determined by extrapolation of the stresses in the extrapolation region to the weld toe position as mentioned in chapter 2.

According to design guidelines of the International Institute of Welding, the minimum distance from the extrapolation region to the weld toe is $0.4 \times t_c$ for chord member and $0.4 \times t_b$ for brace member. The maximum distance is $1.4 \times t_c$ for chord and $1.4 \times t_b$ for brace. The extrapolation can be carried out by using linear or parabolic curve fitting. In order to derive the hot spot stress and corresponding SCFs, the mesh around the weld profile along the brace-chord intersection are refined. From the weld toe to the maximum distance of the extrapolation region there are seven rows of elements. The determination of the stress perpendicular to the weld, the primary stress, using the finite element model will be explained in the following part.

A path perpendicular to the weld goes through seven solid elements so there are eight nodes on the path, excluding the mid-side nodes. Since the extrapolation region is from $0.4 \times t$ to $1.4 \times t$, there are six nodes in the extrapolation region. An example is shown below.

![Figure 15: Nodes in extrapolation region](image)

First the normal vector to the weld profile has to be calculated. The nodal coordinates can be determined from the finite element model. In the extrapolation region the first node is given as $n_1(x_1, y_1, z_1)$ and the last node as $n_6(x_6, y_6, z_6)$. The unit vector normal to the weld can be calculated with the following formula:

$$
\vec{n} = \begin{bmatrix}
  a \\
  b \\
  c
\end{bmatrix} = a\vec{i} + b\vec{j} + c\vec{k} = \frac{x_6 - x_1}{L}\vec{i} + \frac{y_6 - y_1}{L}\vec{j} + \frac{z_6 - z_1}{L}\vec{k}
$$

(11)

Where $L$ is the length between the nodes $n_1$ and $n_6$, given by:

$$
L = \sqrt{(x_6 - x_1)^2 + (y_6 - y_1)^2 + (z_6 - z_1)^2}
$$

(12)
The calculation of the primary stresses of the nodes in the extrapolation region can be done by using dot product between stress tensor and normal vector, as shown in the formula below.

\[ \sigma_p = \vec{n}^T \sigma \vec{n} \]  

With \( \sigma \) the stress tensor which is written in the form:

\[
\sigma = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\]  

The stress tensors for each node in the extrapolation region can be obtained from finite element results. Using formula (13) the primary stresses for all the nodes in the extrapolation region can be calculated. Quadratic or linear extrapolation of the primary stresses is done to determine the hot spot stress at the weld toe position which is equal to the Stress Concentration Factor as explained before. A detailed calculation of the SCF at a certain position along the weld is shown in appendix B.

The maximum SCF can be obtained by calculating the hot spot stresses for brace and chord member along the entire weld. This requires a lot of stress data, nodal coordinates and calculations. In this project the process of calculation of the hot spot stress can be done in MS Excel but this is time consuming and errors can easily occur. Therefore a post processing program for SCF calculation is developed by Yuth Petchdemaneengam. This post processing tool is more flexible and only taking a few minutes to compute. The SCF results are exactly similar to what can be done with MS Excel. The numerical SCF results will be discussed in the next paragraph.
3.4 Numerical results
For both tubular X-joints (J1 and J2) numerical simulations are done to determine the maximum Stress Concentration Factor. The numerical analysis for joint J1 and J2 is done in the same way. First the analysis of tubular joint J1 is explained and the results of the SCF are shown. Then the results for tubular joint J2 will follow.

3.4.1 Joint J1
In the figures below the result of the von Mises stress of the deformed tubular joint J1 is shown.

A nominal stress of 1 MPa is produced as explained earlier in the report. Therefore the limits of the legend for the von Mises stress are set from 0 - 1 MPa. From the FE results the high stress locations on the tubular joint are now easily determined. The grey areas on the joint are the places with stresses above 1 MPa. For tubular joints cracks usually initiates on the weld profile. Therefore the value of the Stress Concentration Factor along the weld is important.
The post processing tool calculates automatically the SCF from the finite element results along the entire weld for brace and chord member. In appendix C an example of the results following from the post processing tool is shown. The result file shows the SCF for both linear and quadratic extrapolation. The angle theta in the file is the angle from brace crown, which is shown in the figure below.

As mentioned before quadratic extrapolation of the hot spot stress is recommended so the results of the quadratic SCF method are used. In figure 18 an overview of the SCF of J1 for brace and chord member is plotted. The figure easily shows that the highest SCFs are located at the left brace. The maximum SCF for J1 is 2.69 on the left brace at 117° from brace crown (appendix C).

To lower the maximum Stress Concentration Factor, the chord can be filled with grouted mortar. In the next paragraph the analysis of SCF of grouted tubular joint J1 will be explained.
3.4.2 Joint J1 grouted

In Abaqus a block grouted mortar is modeled (see figure 19) to determine the Stress Concentration Factor of grouted joint J1. The modulus of elasticity ($E_c$) of concrete (normal weight, normal density) can be calculated with the following formula:

$$E_c = 4700\sqrt{f'_c} \text{ MPa} \quad (15)$$

With $f'_c$ the compressive strength of concrete.

In the numerical model a Young’s modulus of 25000 MPa and a Poisson ratio of 0.17 for the block mortar is used. The SCF of grouted J1 is simply analyzed by tying the inner chord wall with the mortar block. This is shown in the figures below.

Stresses on the grouted joint J1 are in general lower, especially along the weld profile. This can be seen in the following figures.
The result file for grouted J1 gives a maximum SCF of 2.58 on the left brace at 180° from brace crown. Compared to ungrouted J1 the value of the maximum SCF is a bit lower. The location is still on the left brace but at a different angle from brace crown.

As can be seen in the following figures, the mesh size of the block mortar is large compared to the chord. Therefore the block mortar is not tied smoothly to the inner wall of the chord. Figure 22b shows that there are some gaps present between the surface of the block mortar and the surface of the inner wall of the chord.

Simulations with different mesh sizes of the block mortar are done to see if this result in a lower maximum SCF. These different mesh sizes are listed in the table below:

<table>
<thead>
<tr>
<th>Name</th>
<th>Mesh size block mortar (elements along width-length-curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh 1</td>
<td>10-10-10</td>
</tr>
<tr>
<td>Mesh 2</td>
<td>16-15-20</td>
</tr>
<tr>
<td>Mesh 3</td>
<td>20-20-40</td>
</tr>
<tr>
<td>Mesh 4</td>
<td>30-40-40</td>
</tr>
</tbody>
</table>
The gaps between the mortar and the chord become smaller with increasing number of elements along the curve of the block mortar. In the following figures this is shown for the different mesh sizes.

Figure 23a: Block mortar (mesh 2)  
Figure 23b: Zoomed in on block mortar tied to inner chord wall

Figure 24a: Block mortar (mesh 3)  
Figure 24b: Zoomed in on block mortar tied to inner chord wall

Figure 25a: Block mortar (mesh 4)  
Figure 25b: Zoomed in on block mortar tied to inner chord wall
For forty elements along the curve of the block mortar (mesh 3 and mesh 4) the mortar is tied smoothly to the inner wall of the chord and there are no gaps anymore between the block mortar and the chord.

The chord is entirely filled with the block mortar, because the length of the block mortar is exactly the same as the length of the chord. Stresses along the weld profile are important because usually cracks will initiate from the weld. Therefore a shorter block mortar is modeled so that the chord is only filled with mortar around the weld profile. This is shown in the figures below. Along the length, width and curve of the block mortar twenty elements are taken.

An overview of the maximum SCF for joint J1, ungrouted and grouted, is shown in table 4.

<table>
<thead>
<tr>
<th>Model name</th>
<th>SCF</th>
<th>Location</th>
<th>CPU time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2.69</td>
<td>Brace left - 117° from brace crown</td>
<td>63.820</td>
</tr>
<tr>
<td>J1G (mesh 1)</td>
<td>2.58</td>
<td>Brace left - 180° from brace crown</td>
<td>76.410</td>
</tr>
<tr>
<td>J1G2 (mesh 2)</td>
<td>2.36</td>
<td>Brace left - 180° from brace crown</td>
<td>104.10</td>
</tr>
<tr>
<td>J1G3 (mesh 3)</td>
<td>2.23</td>
<td>Brace left - 180° from brace crown</td>
<td>206.43</td>
</tr>
<tr>
<td>J1G4 (mesh 4)</td>
<td>2.28</td>
<td>Brace left - 180° from brace crown</td>
<td>504.37</td>
</tr>
<tr>
<td>J1G_short</td>
<td>2.05</td>
<td>Brace left - 180° from brace crown</td>
<td>122.21</td>
</tr>
</tbody>
</table>

For grouted J1 the results are a little bit better because the value of the maximum SCF is lower. Another difference is the location of the maximum SCF. It is still located on the left brace but at a different angle from brace crown. The best result of the maximum SCF is obtained by grouted joint J1 with a short block mortar. In the following figures the SCF of model J1G_short is compared to J1 ungrouted for brace and chord member.
Figure 28a: Stress Concentration Factor brace left

Figure 28b: Stress Concentration Factor chord left

Figure 28c: Stress Concentration Factor brace right
3.4.3 Joint J2

The Stress Concentration Factor of tubular joint J2 is determined in the same way as for tubular joint J1. First the SCF is calculated for ungrouted J2 and then for grouted J2 in the same way as explained in the previous paragraphs. The result of the von Mises stress of the deformed joint J2 is shown in the figures below.

![Figure 28d: Stress Concentration Factor chord right](image)

**Figure 28d: Stress Concentration Factor chord right**

**Figure 29a: 3D view of deformed joint J2**

**Figure 29b: Front view of deformed joint J2**

**Figure 29c: Back view of deformed joint J2**
There are many grey areas which mean that there are many high stresses locations present after deformation of joint J2. With the post processing tool the Stress Concentration Factor is calculated automatically. The result of the SCF of J2 for brace and chord member is plotted in figure 30.

The maximum Stress Concentration Factor for J2 is located at chord left and the value is 5.15 at 126° from brace crown. For joint J2 the chord also can be filled with grouted mortar to lower the maximum SCF. The result of this is shown in the next paragraph.

**3.4.4 Joint J2 grouted**

In the numerical model for grouted joint J2 the block grouted mortar is modeled as described in paragraph 3.4.2. The block mortar has the same material properties as chosen for the block mortar in grouted joint J1. The figures below show that the stresses for grouted joint J2 are lower than for ungrouted J2, especially along the weld profile.

*Figure 30: Stress Concentration Factor of J2*

The maximum Stress Concentration Factor for J2 is located at chord left and the value is 5.15 at 126° from brace crown. For joint J2 the chord also can be filled with grouted mortar to lower the maximum SCF. The result of this is shown in the next paragraph.

**3.4.4 Joint J2 grouted**

In the numerical model for grouted joint J2 the block grouted mortar is modeled as described in paragraph 3.4.2. The block mortar has the same material properties as chosen for the block mortar in grouted joint J1. The figures below show that the stresses for grouted joint J2 are lower than for ungrouted J2, especially along the weld profile.

*Figure 31a: Weld profile left (ung grouted)  Figure 31b: Weld profile left (grouted)*
To determine the maximum Stress Concentration Factor the analysis is done for the different meshes of the mortar block and the short block mortar.

An overview of the results for the maximum SCF is given in the table below.

Table 5: Maximum SCF for joint J2

<table>
<thead>
<tr>
<th>Model name</th>
<th>SCF</th>
<th>Location</th>
<th>CPU time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2</td>
<td>5.15</td>
<td>Chord left - 126° from brace crown</td>
<td>58.760</td>
</tr>
<tr>
<td>J2G (mesh 1)</td>
<td>2.84</td>
<td>Brace left - 180° from brace crown</td>
<td>69.010</td>
</tr>
<tr>
<td>J2G2 (mesh 2)</td>
<td>2.84</td>
<td>Brace left - 180° from brace crown</td>
<td>98.170</td>
</tr>
<tr>
<td>J2G3 (mesh 3)</td>
<td>2.76</td>
<td>Brace left - 180° from brace crown</td>
<td>198.43</td>
</tr>
<tr>
<td>J2G4 (mesh 4)</td>
<td>2.76</td>
<td>Brace left - 180° from brace crown</td>
<td>525.98</td>
</tr>
<tr>
<td>J2G_short</td>
<td>2.52</td>
<td>Brace left - 180° from brace crown</td>
<td>117.01</td>
</tr>
</tbody>
</table>

It can be easily seen that the location of the maximum SCF changes from chord member for ungrouted joint J2 to brace member for grouted joint J2. For grouted joint J2 the maximum SCF is quite lower than ungrouted J2. The model J2G_short gives the best result. The comparison of the SCF of J2G_short and J2 ungrouted is shown in the following figures.

Figure 31c: Weld profile right (ungrouted)  
Figure 31d: Weld profile right (grouted)

Figure 32a: Stress Concentration factor brace left
Figure 32b: Stress Concentration factor chord left

Figure 32c: Stress Concentration factor brace right

Figure 32d: Stress Concentration factor chord right
4 Experimental testing

Besides numerical methods, the Stress Concentration Factors can also be obtained by experimental tests. In this chapter the experimental test to measure the SCF will be described and explained. The test is done for the modeled tubular X-joint J1 as described in the previous chapter. After explanation of the experimental testing, the determination of the SCF will be explained and the results are shown and compared to the Finite Element results.

4.1 Test set-up
The ungrouted tubular joint J1 is arranged in a 200 ton test rig as shown in the figure below.

![Joint J1 in 200 ton rig](image)

At the left end of the specimen there is a pin support and at the right end a roller support, so the boundary conditions are the same as in the numerical analysis. To obtain the Stress Concentration Factor of joint J1, the strain needs to be measured during loading. Strain gauges are installed along the weld profile on ten different positions on brace and chord member. Grid lines are drawn to determine the exact angle from brace crown. An overview of these positions is given below and a schematic drawing is shown in figure 34.

- Brace and chord left: 135°, 165° and 180° from brace crown
- Brace and chord right: 135° and 180° from brace crown
Strip gauges with five elements of strain gauges are used and they have to be installed perpendicular to the weld toe. The spacing between the five elements is 2 mm. As explained in section 3.3 the extrapolation region of the stresses to the weld toe position is from \(0.4 \times t\) to \(1.4 \times t\), with \(t\) the thickness of the chord and brace member. The first element of the strip gauge is therefore placed at a distance of 10 mm and 5 mm from the weld toe for chord and brace respectively. In the figure below the strip gauge which is used for the testing is shown.

![Figure 34: Schematic diagram of positions of the strain gauges](image)

To ensure that the applied load from the testing rig is correct, four single strain gauges are installed on both sides of the brace. They are placed approximately at a distance of 600 mm from the pin and roller support. The angle from brace crown is 0°, 90°, 180° and 270°. In figure 34 the green strips are the positions of the single strain gauges. Before the loading is applied to measure the Stress Concentration Factor, several displacement transducers are placed on chord and brace member. This is done to check if the specimen will not move out of plane during loading. In the next section the loading procedure for measuring the SCF will be explained.
4.2 Loading procedure
First the tubular joint J1 is pre-loaded to ensure that the test set-up is stable. During this pre-loading the joint is loaded to 50 kN and unloaded to 10 kN approximately. Then the joint is again loaded to 100 kN and unloaded to 10 kN. Finite element results showed that the plastic deformation (hot spot stress is greater than yield strength) starts to occur when the load is about 250 kN. In order to measure the Stress Concentration Factor accurately, two sets of load level are applied. The loads are estimated such that the maximum stress occurs in the tubular joint are still elastic. A static loading will be used to measure the Stress Concentration Factor and the loading procedure is given below.

- Load the joint to 110 kN and unload to 10 kN for three cycles
- At the end of the third cycle, hold the load of 10 kN for 30 minutes
- Load the joint to 235 kN and unload to 25 kN for three cycles
- At the end of the third cycle, hold the load of 25 kN for 30 minutes

During the entire loading procedure the strains from the strain gauges are monitored. After testing the strain data and loading history is collected. This data is used to determine the Stress Concentration Factor. The results will follow in section 4.3.

4.3 SCF test results of joint J1
The strain measured by the strip gauges during the loading procedure for the Stress Concentration Factor gives strange values. For every position of the strip gauges the first element should measure the highest strain because this element is placed nearest to the weld toe. Further from the weld toe the strain should be decreasing so the strain will decrease from element one to element five of the strip gauge. The collected strain data shows fluctuating strains for the strip gauges. The cause of this fluctuation is unknown but the values are not reliable. Therefore the data will not be used for calculating the SCF. The data of the pre-loading is used to determine the SCF. In the figure below the loading history during pre-loading is shown.

![Loading history](image)

To check if the applied load from the testing rig is correct, the actual stress is compared to the calculated stress. At every step the applied load is known and the stress can be calculated analytical with formula (16).

\[
\sigma = \frac{P \gamma}{I} \text{ [MPa]}
\]  

(16)

With \( P \) [N] the applied load, \( l \) [mm] the distance of single strain gauge to support, \( y \) [mm] the centre of the brace to bottom fiber and \( I \) [mm^4] the moment of inertia.
This calculated stress can be compared to the measured stress which is simply derived from the measured strain in the single strain gauge at bottom fiber by:

$$\sigma = E \cdot \varepsilon \text{ [MPa]} \quad (17)$$

With $\varepsilon [-]$ the measured strain and $E \text{ [MPa]}$ the Young's modulus.

An overview of the calculated and measured stresses for every step is given in the table below.

<table>
<thead>
<tr>
<th>Step</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>26.90</td>
<td>52.26</td>
<td>29.08</td>
<td>4.76</td>
<td>52.02</td>
<td>99.92</td>
<td>54.20</td>
<td>10.32</td>
</tr>
</tbody>
</table>

| Stress in left gauge [MPa] | 5.66 | 10.93 | 6.25 | 1.17 | 10.93 | 18.74 | 9.96 | 0.98 |
| Calculated stress [MPa]   | 5.46 | 10.61 | 5.90 | 0.97 | 10.56 | 20.28 | 11.00 | 2.09 |
| Difference [%]             | 3.56 | 2.97  | 5.52 | 17.52 | 3.42 | 7.59  | 9.50 | 53.40 |

| Stress in right gauge [MPa] | 5.27 | 9.96  | 5.66 | 1.17 | 10.35 | 18.74 | 10.15 | 2.15 |
| Calculated stress [MPa]    | 5.37 | 10.43 | 5.80 | 0.95 | 10.38 | 19.94 | 10.82 | 2.06 |
| Difference [%]              | 1.83 | 4.55  | 2.46 | 18.89 | 0.35 | 6.03  | 6.16 | 4.08 |

It seems that the difference between the actual stress and the calculated stress is not very large for most of the steps so it can be assumed that the applied load on the specimen is correct.

To determine the Stress Concentration Factor the strain data from the ten strip gauges on brace and chord are used. Every strip gauge exists of five elements and the first element is placed at a distance of 5 mm and 10 mm from the weld toe for brace and chord respectively as mentioned in section 4.1. The strain in all the five elements is monitored during the pre-loading. With the known strains and the distances from the weld toe (spacing between elements is 2 mm) the strain can be extrapolated quadratic to the weld toe. The stress at weld toe can be easily calculated with formula (18), which is known as the hot spot stress.

$$\sigma_{\text{weld toe}} = \sigma_{hs} = 1.15(E \cdot \varepsilon_{\text{weld toe}}) \text{ [MPa]} \quad (18)$$

The nominal stress is calculated with the formula shown below as explained in section 2.2.1.

$$\sigma_{\text{nom}} = \frac{My}{I} \quad (2)$$

Finally the Stress Concentration Factor can be calculated at every position of the strip gauges for different loading steps, see formula (5).

$$SCF = \frac{\sigma_{hs}}{\sigma_{\text{nom}}} \quad (5)$$
An overview of the test results of the SCF for brace and chord member during pre-loading is given in the table below.

<table>
<thead>
<tr>
<th>Step</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied load [kN]</td>
<td>26.90</td>
<td>52.26</td>
<td>29.08</td>
<td>4.76</td>
<td>52.02</td>
<td>99.92</td>
<td>54.34</td>
<td>10.32</td>
<td></td>
</tr>
<tr>
<td>BL135</td>
<td>2.54</td>
<td>2.57</td>
<td>2.66</td>
<td>2.55</td>
<td>2.59</td>
<td>2.27</td>
<td>2.03</td>
<td>2.37</td>
<td>2.35</td>
</tr>
<tr>
<td>CL135</td>
<td>2.35</td>
<td>2.14</td>
<td>2.33</td>
<td>2.17</td>
<td>2.17</td>
<td>2.18</td>
<td>2.13</td>
<td>1.60</td>
<td>2.18</td>
</tr>
<tr>
<td>BL165</td>
<td>2.25</td>
<td>2.26</td>
<td>2.07</td>
<td>2.14</td>
<td>2.02</td>
<td>1.88</td>
<td>1.93</td>
<td>1.78</td>
<td>1.89</td>
</tr>
<tr>
<td>CL165</td>
<td>1.7</td>
<td>1.7</td>
<td>1.36</td>
<td>1.54</td>
<td>1.12</td>
<td>1.09</td>
<td>1.4</td>
<td>1.24</td>
<td>1.44</td>
</tr>
<tr>
<td>BL180</td>
<td>1.56</td>
<td>1.54</td>
<td>1.53</td>
<td>1.67</td>
<td>1.58</td>
<td>1.63</td>
<td>1.66</td>
<td>1.53</td>
<td>1.93</td>
</tr>
<tr>
<td>CL180</td>
<td>1.1</td>
<td>1.19</td>
<td>1.68</td>
<td>2.12</td>
<td>1.18</td>
<td>1.22</td>
<td>1.38</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>BR135</td>
<td>1.36</td>
<td>1.36</td>
<td>1.28</td>
<td>1.72</td>
<td>1.36</td>
<td>1.38</td>
<td>1.58</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>CR135</td>
<td>1.61</td>
<td>1.51</td>
<td>1.51</td>
<td>2.42</td>
<td>1.57</td>
<td>1.55</td>
<td>1.62</td>
<td>1.58</td>
<td>2.01</td>
</tr>
<tr>
<td>BR180</td>
<td>1.41</td>
<td>1.33</td>
<td>1.36</td>
<td>1.92</td>
<td>1.32</td>
<td>1.31</td>
<td>1.36</td>
<td>1.74</td>
<td>1.98</td>
</tr>
<tr>
<td>CR180</td>
<td>1.36</td>
<td>1.45</td>
<td>1.37</td>
<td>1.22</td>
<td>1.32</td>
<td>1.58</td>
<td>1.61</td>
<td>1.50</td>
<td>1.93</td>
</tr>
</tbody>
</table>

In the next section the experimental SCF results will be compared to SCF results based on the numerical analysis.

4.4. Comparison SCF test results with numerical SCF results

To see if the numerical model of the tubular X-joint can be used to predict the Stress Concentration Factor distribution along the weld profile the SCF test results have to be compared to the SCF results based on the Finite Element Model. In the following figures the SCF results of the experimental test are plotted against the SCF results obtained from the Finite Element analysis. This is done for brace and chord member for the various loading steps.

Figure 37a: SCF results brace left
Figure 37b: SCF results brace right

Figure 37c: SCF results chord left

Figure 37d: SCF results chord right
The results of the various loading steps plotted against the numerical SCF distribution are also shown individual in appendix D. The figures show that the experimental results of the SCF are close to the numerical SCF results. In the table below the difference between the SCF obtained from Finite Element analysis and the SCF test results is shown.

<table>
<thead>
<tr>
<th>Step</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEA</td>
<td>Test</td>
<td>FEA</td>
<td>Test</td>
<td>FEA</td>
<td>Test</td>
<td>FEA</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL135</td>
<td>0.92</td>
<td>0.92</td>
<td>0.88</td>
<td>0.92</td>
<td>0.91</td>
<td>1.03</td>
<td>1.16</td>
<td>0.99</td>
</tr>
<tr>
<td>CL135</td>
<td>0.93</td>
<td>1.02</td>
<td>0.94</td>
<td>1.01</td>
<td>1.00</td>
<td>1.00</td>
<td>1.02</td>
<td>1.36</td>
</tr>
<tr>
<td>BL165</td>
<td>0.84</td>
<td>0.84</td>
<td>0.91</td>
<td>0.88</td>
<td>0.93</td>
<td>1.00</td>
<td>0.98</td>
<td>1.06</td>
</tr>
<tr>
<td>CL165</td>
<td>1.24</td>
<td>0.85</td>
<td>1.06</td>
<td>0.93</td>
<td>1.29</td>
<td>1.32</td>
<td>1.26</td>
<td>1.16</td>
</tr>
<tr>
<td>BL180</td>
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<td>1.25</td>
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<td>1.16</td>
<td>1.27</td>
</tr>
<tr>
<td>CL180</td>
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<td>1.30</td>
<td>0.92</td>
<td>0.73</td>
<td>1.31</td>
<td>1.27</td>
<td>1.13</td>
<td>1.00</td>
</tr>
<tr>
<td>BR135</td>
<td>1.48</td>
<td>1.47</td>
<td>1.56</td>
<td>1.17</td>
<td>1.47</td>
<td>1.47</td>
<td>1.45</td>
<td>1.26</td>
</tr>
<tr>
<td>CR135</td>
<td>1.24</td>
<td>1.33</td>
<td>1.33</td>
<td>0.83</td>
<td>1.28</td>
<td>1.29</td>
<td>1.24</td>
<td>1.27</td>
</tr>
<tr>
<td>BR180</td>
<td>1.40</td>
<td>1.48</td>
<td>1.45</td>
<td>1.03</td>
<td>1.49</td>
<td>1.51</td>
<td>1.46</td>
<td>1.14</td>
</tr>
<tr>
<td>CR180</td>
<td>1.42</td>
<td>1.33</td>
<td>1.40</td>
<td>1.58</td>
<td>1.46</td>
<td>1.22</td>
<td>1.20</td>
<td>1.28</td>
</tr>
</tbody>
</table>

The maximum SCF for J1 determined from the Finite Element model is 2.69 on the left brace at 117° from brace crown. From the table it can be observed that near this location the SCFs obtained from FE analysis are in good agreement with those from the experimental test. The maximum difference of SCFs for brace left at 135° (BL135) is 16%. Looking at the peak values of the loading history, step 1 and step 3, it can be observed that the results of the SCFs from FE analysis are quite accurate. Only at brace right (BR135 and BR180) the SCFs of the testing are around 50% different then from the numerical result. For the other locations the maximum difference of SCFs is around 30%.
5 Conclusion and recommendations

The objective of this report is to measure the Stress Concentration Factor (SCF) of Partial Joint Penetration plus (PJP+) tubular X-joints and see if the results are in good agreement with the SCFs obtained by Finite Element analysis. SCF is used as a reference to quantify the peak stress in welded tubular joints for fatigue assessment. Complex equations are available for calculating SCFs but only at certain positions around the weld and not along the entire weld profile. An alternative approach to predict the SCF distribution along the weld brace-chord intersection is Finite Element Method (FEM). In this project two different steel tubular X-joints (J1 and J2) are analyzed and a numerical model of the joints is made. The difference between the joints is the thickness of the brace. The SCFs along the weld profile are calculated with the Finite Element model. From the numerical analysis it can be concluded that joint J1 has a lower maximum SCF value than joint J2. Also the locations of the maximum SCF are different for both joints. To lower the maximum SCF, the chord member can be filled with grouted mortar. This is done by modeling a block grouted mortar and tying it to the inner chord wall. Following from the numerical model the best result of the maximum SCF is achieved by a short block of mortar around the weld profile. Especially for joint J2 the short block of mortar gives a large decrease in maximum SCF. In this case the locations of the maximum SCF are for both joints the same.

The results of the SCFs of the numerical analysis are compared to the SCFs of experimental testing of the tubular joints. Unfortunately due to lack of time only one experimental test is done. Based on the comparison between the Stress Concentration Factor obtained from Finite Element analysis and the SCF results of the experimental test, it can be concluded that the numerical model predicts the SCF distribution along the weld profile with an acceptable accuracy. More experimental tests should be done to confirm this conclusion.

Finally some recommendations for future research of the Stress Concentration Factor of welded tubular joints are given below.

- The shape of the weld profile will influence the hot spot stress. In the Finite Element model the weld profile should be modeled more accurately to see if this leads to a better prediction of the experimental SCF results.
- Use linear extrapolation to see if this gives better agreement between SCFs obtained from Finite Element analysis and experimental SCFs
- In this project tubular X-joints are analyzed and tested. Research of other tubular joints can be done such as Y-joints or K-joints.
- For the experimental test it is recommended to use more strip gauges along the weld profile to obtain the SCF at more locations, especially around the maximum SCF location predicted by Finite Element analysis.
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DEFINITION OF NEW TUBULAR PJP+DETAILS

Root face 3 mm for \( t > 18 \) mm
Root face \( t/6 \) for \( 6 \) mm \( \leq t \leq 18 \) mm
Use fillet welds for \( t < 6 \) mm

Appendix A - Details of the PJP+ welds
Appendix B – Detailed calculation of SCF for joint J1 using FEM results

Calculation of SCF is in this appendix is done for 117° at brace left. In the table below the coordinates of the nodes in the extrapolation region are listed.

Table B1: Nodal coordinates of nodes in extrapolation region

<table>
<thead>
<tr>
<th>Node</th>
<th>x</th>
<th>y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-83.4794</td>
<td>185.325</td>
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<td>-82.2114</td>
<td>185.899</td>
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<td>-80.9435</td>
<td>186.473</td>
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<tr>
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<td>-79.6756</td>
<td>187.048</td>
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<td>-78.4075</td>
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<tr>
<td>6</td>
<td>-461.465</td>
<td>-77.1395</td>
<td>188.196</td>
</tr>
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</table>

The length \( l \) between the nodes \( n_1 \) and \( n_6 \) can be calculated with formula (12):

\[
L = \sqrt{(x_6 - x_1)^2 + (y_6 - y_1)^2 + (z_6 - z_1)^2} \quad (12)
\]

\[
L = \sqrt{(-10.321)^2 + (6.3399)^2 + (2.871)^2}
\]

\[
L = \sqrt{106.5230 + 40.1943 + 8.2426} = \sqrt{154.9599} = 12.4483
\]

Since the length \( l \) is known, the unit vector normal to the weld can easily be determined with the formula below:

\[
\mathbf{n} = \begin{bmatrix}
\frac{x_6 - x_1}{l} \\
\frac{y_6 - y_1}{l} \\
\frac{z_6 - z_1}{l}
\end{bmatrix}
\]

\[
\mathbf{n} = \begin{bmatrix}
-10.321 \\
6.3399 \\
2.871
\end{bmatrix}
\]

\[
\mathbf{n} = \begin{bmatrix}
-0.8291 \\
0.5093 \\
0.2306
\end{bmatrix}
\]

From the Finite Element Model the nodal stresses can be obtained and these stresses are listed in the following table:

Table B2: Nodal stresses of nodes in extrapolation region

<table>
<thead>
<tr>
<th>Node</th>
<th>S11</th>
<th>S22</th>
<th>S33</th>
<th>S12</th>
<th>S13</th>
<th>S23</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>0.22551</td>
<td>-0.496871</td>
<td>-0.171639</td>
<td>0.528852</td>
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<td>1.93272</td>
<td>1.13643</td>
<td>0.222666</td>
<td>-0.432337</td>
<td>-0.17493</td>
<td>0.501367</td>
</tr>
<tr>
<td>3</td>
<td>1.8205</td>
<td>1.07201</td>
<td>0.198287</td>
<td>-0.393284</td>
<td>-0.15745</td>
<td>0.470212</td>
</tr>
<tr>
<td>4</td>
<td>1.71296</td>
<td>1.01041</td>
<td>0.186482</td>
<td>-0.35448</td>
<td>-0.142544</td>
<td>0.43632</td>
</tr>
<tr>
<td>5</td>
<td>1.60344</td>
<td>0.94453</td>
<td>0.167451</td>
<td>-0.318536</td>
<td>-0.128087</td>
<td>0.404415</td>
</tr>
<tr>
<td>6</td>
<td>1.49171</td>
<td>0.881438</td>
<td>0.146171</td>
<td>-0.285986</td>
<td>-0.105161</td>
<td>0.3672</td>
</tr>
</tbody>
</table>

The stress tensor \( \mathbf{\sigma} \) for each node can be determined as shown below:

\[
\mathbf{\sigma} = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\]

\[
(14)
\]

With formula (13) the primary stresses of the nodes in the extrapolation region can be calculated.

\[
\sigma_p = \mathbf{n}^T \mathbf{\sigma} \mathbf{n}
\]

(13)
In the table below the results of the primary stresses are listed.

**Table B3: Primary stresses of nodes in extrapolation region**

<table>
<thead>
<tr>
<th>Node</th>
<th>Distance from weld toe</th>
<th>Primary stress</th>
</tr>
</thead>
<tbody>
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<td>2.3605</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>2.1850</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2.0428</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>1.9059</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>1.7691</td>
</tr>
<tr>
<td>6</td>
<td>17.5</td>
<td>1.6298</td>
</tr>
</tbody>
</table>

The Stress Concentration Factor is obtained by extrapolation of the primary stresses in the extrapolation region to the weld toe position. In this case the equations of the fitting curve for quadratic and linear extrapolation are as following:

\[
y = 0.0006x^2 - 0.0706x + 2.6926 \\
y = -0.0576x + 2.6299
\]  
(B1)  
(B2)

Making \(x = 0\) the values for SCF can be calculated. The SCF is 2.69 and 2.63 for quadratic and linear extrapolation respectively. In the figures below the nodal stresses and the fitting curve of the stresses within the extrapolation region are shown. The SCFs at other locations along the weld profile can be obtained in the same way.

*Fig B1: Linear extrapolation of nodal stresses*

*Fig B2: Quadratic extrapolation of nodal stresses*
Appendix C – SCF results resulting from post processing tool for joint J1

The results of the SCF for 117 degrees at brace left are the same as calculated in appendix B which confirms that the post processing tool gives exactly the same results.

**************************************************
*  Automatic determination of SCF for X-joints   *
*     Programmed by Yuthdanai Petchdemaneengam   *
*        Last Updated: Sep 26, 2009, at NUS.     *
**************************************************

---

sten

<table>
<thead>
<tr>
<th>THETA (DEG)</th>
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<th>SCF(QUADRATIC) R2</th>
</tr>
</thead>
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<td>0</td>
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<td>-1.99 0.9996</td>
</tr>
<tr>
<td>9</td>
<td>-1.87 0.9953</td>
<td>-1.97 0.9995</td>
</tr>
<tr>
<td>18</td>
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<td>-2.00 0.9995</td>
</tr>
<tr>
<td>27</td>
<td>-1.99 0.9958</td>
<td>-2.08 0.9994</td>
</tr>
<tr>
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<td>-2.13 0.9994</td>
</tr>
<tr>
<td>45</td>
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</tr>
<tr>
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<td>-1.38 0.9993</td>
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<tr>
<td>72</td>
<td>-0.68 0.9851</td>
<td>-0.71 0.9977</td>
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<tr>
<td>81</td>
<td>0.10 0.9994</td>
<td>0.09 1.0000</td>
</tr>
<tr>
<td>90</td>
<td>0.92 0.9997</td>
<td>0.93 0.9998</td>
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<tr>
<td>99</td>
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<td>1.71 0.9997</td>
</tr>
<tr>
<td>108</td>
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<td>2.33 0.9994</td>
</tr>
<tr>
<td>117</td>
<td>2.63 0.9980</td>
<td>2.69 0.9994</td>
</tr>
<tr>
<td>126</td>
<td>2.57 0.9968</td>
<td>2.64 0.9992</td>
</tr>
<tr>
<td>135</td>
<td>2.29 0.9962</td>
<td>2.35 0.9990</td>
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<tr>
<td>153</td>
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<tr>
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<td>171</td>
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<tr>
<td>180</td>
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<td>1.93 0.9995</td>
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</table>

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CHORD LEFT

<table>
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<td>180</td>
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</tr>
</tbody>
</table>

POSTPROCESSING COMPLETED
Appendix D - SCF results of the various loading steps

Step 0.5

Figure D1a: SCF results brace left

Figure D1b: SCF results chord left

Figure D1c: SCF results brace right

Figure D1d: SCF results chord right
Step 1

Figure D2a: SCF results brace left

Figure D2b: SCF results chord left

Figure D2c: SCF results brace right

Figure D2d: SCF results chord right
Step 1.5

Figure D3a: SCF results brace left

Figure D3b: SCF results chord left

Figure D3c: SCF results brace right

Figure D3d: SCF results chord right
Step 2

Figure D4a: SCF results brace left

Figure D4b: SCF results chord left

Figure D4c: SCF results brace right

Figure D4d: SCF results chord right
Step 2.5

Figure D5a: SCF results brace left

Figure D5b: SCF results chord left

Figure D5c: SCF results brace right

Figure D5d: SCF results chord right
Step 3

Figure D6a: SCF results brace left

Figure D6b: SCF results chord left

Figure D6c: SCF results brace right

Figure D6d: SCF results chord right
Step 3.5

Figure D7a: SCF results brace left

Figure D7b: SCF results chord left

Figure D7c: SCF results brace right

Figure D7d: SCF results chord right
Step 4

Figure D8a: SCF results brace left

Figure D8b: SCF results chord left

Figure D8c: SCF results brace right

Figure D8d: SCF results chord right