Effect of material grade on fatigue strength and residual stresses in high strength steel welds

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EFFECT OF MATERIAL GRADE ON FATIGUE STRENGTH AND RESIDUAL STRESSES IN HIGH STRENGTH STEEL WELDS

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Preface

This thesis work was performed at Volvo CE, Braås and division of lightweight structures, vehicle and aeronautical engineering department, KTH, Stockholm.

I am greatly thankful to my supervisors Dr. Zuheir Barsoum (KTH) and Bertil Jonsson (VCE) for their continuous support and guidance during the thesis work. Especially, I am highly indebted to Dr. Zuheir Barsoum for teaching me a lot and spending his precious time. I would also like to thank Ru Peng and Annethe Billenius from Linköping University for providing assistance in measurement of residual stresses.

Lastly, I want to thank my parents who have been a great source of moral support and encouragement to me during this work.

Stockholm, April 2012

Wasim Asghar,
Abstract.

This thesis work is concerned with effect of material grade on fatigue strength of welded joints. Fatigue strength evaluation of welded joints in as welded and post weld treated condition was carried out with effective notch method. Results of peak stress method have also been compared with those of effective notch method for as welded joints. In addition, using the results of effective notch method, the effect of important weld and global geometry factors on notch stress concentration factor has been studied with 2-level design of experiment and a mathematical relation among stress concentration factor and the geometric factors has been proposed. Overall, thickness of the base plate and toe radius is found to be the most important factors determining fatigue strength of the joint.

Welding induced residual stresses have also been predicted using 2D and 3D FEM analysis to see their effect on fatigue strength of the joints. Also, transversal residual stresses were measured using X-ray diffraction method to assess the accuracy of predicted results. Based on simulation results, effect of geometric factors on maximum value of transversal residual stress was also investigated.

Keywords. Fatigue Strength, Fillet Welded Joints, Effective Notch Method, Residual Stress Simulation.
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1 INTRODUCTION

1.1 Background

Volvo construction equipment is one of the largest manufacturers of construction equipment in the world. In Sweden, articulated haulers and wheel loaders are manufactured where welding is used primarily for joining steel structures. According to many regulations of fatigue in welded structures, high strength steels offer no advantage for fatigue loaded welded structures. This is because of crack like imperfections formed by welding processes which govern the fatigue life of the joint to a greater extent. It is however recently established by the researchers that a comparatively higher fatigue life can be obtained by using high strength steels for fatigue loaded welded structures provided that weld quality is controlled. The same is suggested by a typical Kitigawa diagram, see figure 1. Therefore it is required to formulate an acceptability criterion for defect size so that high strength steels can be used for achieving better fatigue life in as welded conditions.

![Figure 1 – Kitigawa diagram – An illustration of the effect of material grade on fatigue strength.](image)

1.2 Work Approach

The work is divided in two sections:

1. Fatigue assessment – Life prediction with FEM and parametric analysis.

Fatigue life assessment of fillet welded joints was carried out with effective notch stress method and peak stress method. A design of experiment was performed to identify the factors having major influence on fatigue strength. Consequently a mathematical model of stress concentration factor was proposed through regression analysis.

2. Residual Stresses – Measurement and FEM simulations

Transversal residual stresses induced by welding process were measured using X-ray diffraction method. Finite element modeling and sequentially coupled thermo-mechanical analysis of the welded joints was performed to predict the residual stress state. Furthermore a comparison of FEM results was made with experimental measurements and effect of different parameters on residual stresses was studied through finite element simulations.
2 LITERATURE REVIEW

2.1 Fatigue Assessment of Welded Joints

Apart from experimental investigation, a number of methods have been developed for fatigue evaluation of welded joints. Based on their approach, they are categorized as global method or local method. Global methods like nominal stress method and structural hot spot method do not take into account the stress concentration effects due to notches produced by welds and therefore are not good for critical evaluations. On the other hand, local methods e.g. effective notch stress method and linear elastic fracture mechanics (LEFM) address these issues very well and give comparatively accurate results. However working effort for these methods is relatively greater and is usually a trade-off between accuracy of the results and complexity of the structure, see figure 2. A detailed description of these can be found in [1].

![Figure 2 - Schematic illustration of the relation between accuracy, complexity and work effort required for fatigue analysis of welded structures](image)

Quite recently another method, called peak stress method, has been proposed for fatigue assessment of welded joints. This is an efficient method in terms of calculation time however it is restricted in applications. In this thesis work fatigue assessment of fillet welded joints was performed with effective notch stress method and peak stress method.

**Effective Notch Stress Method**

Effective notch stress method was introduced by International Institute of Welding (IIW) in 1996. According to Hobbacher [2], the stress at the root of the notch, obtained by assuming linear elastic material behavior represents effective notch stress. The statistical variation of weld shape and non-linear material behavior at the notch is accounted for by replacing the actual notch with an effective notch of $1\text{mm}$ radius as shown in figure 3.
Peak Stress Method
Peak stress method is based on notch stress intensity factor approach and can be utilized for fatigue assessment of welded joints by using the scatter bands proposed by Meneghetti [5 & 6]. The scatter bands have been validated on a number of different types of welded joints for steel and aluminium structures and are termed as unique based on their consistency to give sufficiently accurate results for different geometries and loading conditions. This method is much more efficient than other contemporary methods of fatigue assessment because it requires significantly less computational resources. However this efficiency has come with certain limitations on its applicability. It is currently valid for sharp notches restricted to an opening angle of $135^\circ$ degrees and therefore can't be used for fatigue assessment of post weld treated joints. Furthermore it has only been validated for fillet joints.

2.2 Residual Stresses
Due to rapid heating and cooling of welds, residual stresses are produced in the joints. Depending upon weld shape and boundary conditions these stresses may be tensile or compressive in the weld. While compressive residual stresses may be good for fatigue loaded structures, tensile stresses are detrimental and may significantly reduce the endurance limit of the structure. It has been demonstrated in several texts that residual stresses due to welding can be of the order of material yield strength.
3 METHODS

3.1 Model Description

Model consists of a fillet welded T-joint, see figure 4. The transversal dimension of the joint is taken long so that important residual stresses are present in the joint. It was however, limited by the envelope of the fatigue testing machine with a maximum load capacity of 250KN in dynamic loading.

![Figure 4 – Model of the fillet joint](image)

Two levels were chosen for base plate thickness, $t_1$ and stiffener plate thickness, $t_2$ with magnitudes 6 mm and 10 mm. Length of both plates (out of plane dimension) was selected to be 130 mm. Other parameters in the figure 4 and are defined below:

- Width of base plate = $w_1 = 300$ mm
- Width of stiffener plate = $w_2 = 50$ mm

Material properties of steel were used for fatigue life calculations i.e. Young’s modulus $E = 205$ GPa and Poisson ratio $\nu = 0.3$. For residual stress analysis, thermal and temperature dependent mechanical properties were also used for three different material grades corresponding to yield strength 350, 700 and 960 MPa. These properties are outlined in section 3.3 and appendix [1].

3.2 Fatigue Life Calculations

A 2D parametric analysis was performed with different weld geometry parameters for fatigue life calculation of the selected model using effective notch stress method and peak stress method. These parameters were selected for as welded and post weld treated joints and are outlined in section 4.2.

Effective Notch Method

Due to symmetry, half of the geometry was modeled with plain strain condition. Finite element mesh was generated with quadratic quadrilateral elements and sufficiently refined mesh at notches, see figure 5. A 10KN load was applied in four point bending arrangement with a load span of 100mm.

![Figure 5 – Modeling with effective notch method](image)
Fatigue lives were calculated using the following relation:

\[ N = \frac{C}{\Delta \sigma^m} \]

Here \( C \) and \( m \) are material parameters and \( \Delta \sigma \) represents stress range. \( C \) is calculated using recommended FAT value of 225 MPa at 2 million cycles [2].

**Peak Stress Method**

Only half of geometry was modelled due to symmetry with PLANE42 elements in ANSYS with free mesh having an element size of 1, as was done by Meneghetti [6]. With this element type and mesh generation code, \( K_{FE} = 1.38 \) was used [6] and notch stress intensity factor \( K_I \) was calculated using

\[ K_{FE}^* = \frac{K_I}{\sigma_{peak}d^{1-\lambda}} \approx 1.38 \]

Here \( K_i \) is the stress intensity factor; \( d \) is element size and \( \sigma_{peak} \) represents stress at weld toe determined through peak stress method. \( K_{FE} \) and \( \lambda \) are constants which depend on element type, mesh size and the software used. Fatigue life was estimated by using the lower scatter band as reference curve. Figure 6 shows mesh and loading condition.

![Figure 6 – Modelling with peak stress method](image)

**3.3 Residual Stresses – Prediction and Measurement**

It is well established from experiments that fatigue crack at weld toes usually propagate into base metal under tensile or bending loads. Therefore transversal residual stresses in the selected T-joint model become important. Residual stress analysis of the joint was performed with finite element based uncoupled thermal and mechanical analysis to study the stress state in the joint. Moreover, keeping in view the failure location suggested by fatigue calculations, transversal residual stresses were measured in the joints to see the actual stresses and verify the predicted results.

**Test Specimens**

T-joints were constructed from DOMEX steels with yield strength 355, 700 and 960 MPa. Geometry of the joints is described in section 3.1. The specimens were MAG welded, manually, in a single pass on each side with following welding conditions:

**Table 1 – Welding condition for T-joints.**

<table>
<thead>
<tr>
<th>Welding Process</th>
<th>Current ([A])</th>
<th>Voltage ([V])</th>
<th>Welding speed ([cm/min])</th>
<th>Filler wire diameter ([mm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAG</td>
<td>290</td>
<td>30.5</td>
<td>50</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Prediction of Residual Stresses

Welding simulations were performed in 2D and 3D by a sequentially uncoupled thermal and mechanical analysis. The temperature distribution predicted by transient thermal analysis was used as load for subsequent mechanical analysis to estimate stresses due to welding. Same mesh was used for mechanical analysis as was used in thermal analysis and is shown in the figure 7.

Boundary conditions shown in figure were used. Since base plate was tack welded on the bottom side before welding of stiffener plate, it was held fixed for first weld and stiffener plate was allowed to deform. For welding on the other side, boundary conditions on the base plate were removed and stiffener plate was constrained instead.

Figure 7 – FEM model for residual stress simulations. a) 2D Model with boundary conditions. b) boundary conditions for 3D model for first weld. c) boundary condition for weld on other side.

Heat source modeling described by Barsoum [10 & 11] was used for 2D simulations while a moving heat source with constant volume flux was implemented for 3D analysis. Moving heat source was implemented by dividing the weld volume into a finite number of volumes and then sequentially activating elements contained by each volume during welding. It was assumed that heat distribution due to welding arc was uniform and arc stayed on each volume for a specific time before moving on to next volume.

Figure 8 – Moving heat source for 3D analysis
Temperature dependent material properties were used for the simulations and are shown in figure 9 for DOMEX350. Material properties for other material grades were taken from JmatPro.

![Figure 9](image)

**Figure 9** – Temperature dependent material properties. **a)** conductivity and specific heat **b)** yield stress, tangent modulus and thermal expansion coefficient [10]

**Measurement of Transversal Residual Stresses**

Symmetrical distribution of transversal residual stress was assumed based on restraint conditions during welding and measurements were taken only on one side of the stiffener. X-ray diffraction method was used and measurements were taken on top surface of base plate. Measurements were also compared with results obtained through finite element simulations.
4 RESULTS AND DISCUSSION

4.1 Fatigue Strength Evaluation

Fatigue evaluation was carried out on the basis of first principle stress whose maximum value occurs at load carrying weld toe for all joints and marks the position of fatigue failure, see figure 10. 3D analysis also gives the same results and is shown in figure 10.

![Figure 10 – Distribution of first principal stress in the joint](image1)

Notch stress was evaluated along the longitudinal direction with 500mm joint length to figure out the possibility of a distinct failure location. It was observed that stress remains nearly constant in the middle except for the start and stop position where it declines sharply. Figure 11 shows the distribution of principle stress along longitudinal direction for a particular set of weld geometry.

![Figure 11 – First principal stress along longitudinal direction](image2)

The distribution shows no distinct location of fatigue failure and thus failure location is more governed by distribution of residual stress and welding defects.
It was further investigated whether this longitudinal distribution of maximum principal stress could be affected by different lengths of applied load and boundary condition, as shown in figure 12. Results show that longitudinal distribution of first principal notch stress remains nearly indifferent with different load lengths as modeled with parameter $L_d$, table 2.

![Figure 12 – Illustration of different load lengths](image)

<table>
<thead>
<tr>
<th>Table 2 – Distribution of first principal stress in longitudinal direction for different load lengths.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_d=10\text{mm}$</td>
</tr>
<tr>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>$L_d=50\text{mm}$</td>
</tr>
<tr>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>
Comparison between Effective Notch Method and Peak Stress Method

Fatigue strength data obtained through effective notch stress method has been mapped on scatter bands for steel, proposed by peak stress method [5 & 6]. The plot in figure 13 shows that peak stress method is more conservative than effective notch method for prediction of fatigue life for welded joints. This method is more efficient than other contemporary methods of fatigue assessment for welded joints because it requires significantly less computational resources. However this efficiency has come with certain limitations on its applicability. For instance, it is currently valid for sharp notches restricted to an opening angle of 135 degrees and therefore can’t be used for fatigue assessment of post weld treated joints.

Figure 13 – Fatigue lives of the joints mapped on peak stress scatter bands

4.2 Influence of Geometric Factors on Fatigue Strength

Non-load carrying cruciform and T-joints are critical to fatigue failure at weld toes when subjected to tensile and/or bending loads. Stress raising effects of the welded joint and thereby fatigue strength of the joint considerably depends on weld geometry. Therefore optimum weld geometry can be developed if a mathematical model correlating fatigue life and weld geometry parameters is known. To accomplish this, a 2-level full factorial design of experiment was performed to identify the weld and global geometry parameters affecting fatigue life of the joint. The fatigue lives and stress concentration factors were determined through effective notch stress method. Since fatigue failure at toe was suggested by FEM, the effect of weld penetration was not included in the study. Table 3 and 4 summarize the weld geometry parameters investigated.

Table 3 – Weld parameters for as welded joints.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe radius</td>
<td>( r )</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Throat thickness</td>
<td>( a )</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Flank Angle</td>
<td>( \alpha )</td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 4 – Weld parameters for post weld treated joints.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe radius*</td>
<td>( r )</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Throat thickness</td>
<td>( a )</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Flank Angle</td>
<td>( \alpha )</td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>

\(^*\)Toe radius here indicates effective notch radius.

As Welded Joints

Stress concentration factor \( K_t \) was calculated for different simulated cases and the effect of different geometric factor on stress concentration factor is shown in the plots below:

The plot shows that weld toe radius and base plate thickness are the most dominating factors affecting fatigue strength of the load carrying joint. While a higher toe radius tends to reduce the stress concentration factor significantly, thickness of the base plate does the opposite. Therefore a thinner fatigue loaded joint would be safer compared to a thicker one provided that nominal stress in the joint is same. This is because of thickness effect and has its explanation in sharp stress gradients associated with plate thickness [9].

Other factors and their interactions have a little impact on \( K_t \), as indicated by figure 14. Based on these observation, following mathematical model establishes a relationship among \( K_t \) and different geometric factors for as welded joints:

\[
K_t = 1.5075 + 0.0176r + 0.0515t_1 - 0.0233 \times rt_1 + 0.00274\alpha
\]

Post Weld Treated Joints

Design of experiment investigation for post weld treated joints show results similar to those of as welded joints. However, one notable thing is that the effect of weld geometry parameters, particularly weld toe radius becomes less pronounced. The relationship of \( K_t \) with geometric factors, for post weld treated joints is:
\[ K_t = 1.09352 - 0.01373r + 0.06927t_1 - 0.00654 \times rt_1 \]

**Figure 15** – Influence of main factors on stress concentration factor for post weld treated joints.

### 4.3 Welding Residual Stresses

**Simulation of Welding Residual Stress**

During thermal analysis, volume heat flux was adjusted with a body factor to obtain a reasonable size of molten weld pool [10] and is shown in figure 16. Temperature history of a point 15mm away from weld toe is also shown.

**Figure 16** – Temperature distribution in molten zone. a) HAZ zone b) Temperature history

Following diagrams show different stresses in 6mm thick joints. Results show that longitudinal stresses can be of the order of material yield strength or even more however transversal and axial stresses don’t.
Figure 17 - Stresses in 6mm joints. Sx-Transversal, Sy-Axial, Sz-Longitudinal.
Measurement of Transversal Residual Stress

Following figure show the measurements for transversal residual stress:

![Measurement of transversal residual stresses. a) 6mm joints b) 10mm joints](image)

The results show that transversal residual stresses have a peak value near weld toe and tend to relax sharply. Being tensile in nature, this can be detrimental for fatigue loaded joints. It can also been seen from the plots that irrespective of material yield strength and plate thickness, transversal residual stresses have a peak value at the same distance from toe and tend to relax at a same distance for all joints. This indicates that distribution of residual stresses is independent of mechanical properties and depends solely on thermal properties of the material.

Measurements on both sides of stiffener were also performed on another set of specimens and are shown in figure 18. They show nearly symmetrical distribution of transversal stress on both sides. For the second sample of 960MPa steel, plot shows a big variation which is possibly due to a different constraint condition during welding.
Figure 19 – Transversal residual stress
Comparison of FEM Results with Measurements

Figure 19 shows comparison of measurements with FEM results for 6mm joints. FEM results agree very well for 350MPa joint. They don’t agree well for other joints, however show similar distribution pattern.

![Comparison of measurements with FEM results]

Some Factors Influencing Peak value of Transversal Residual Stress

A design of experiment investigation was carried out to study different factors that may have an effect on peak value of transversal residual stresses. Factors studied include yield strength, plate thickness and throat thickness and are described in table 6.

Table 5 – Parameters for DoE investigation of Transversal Residual Stress

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Level</th>
<th>Intermediate level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength [MPa]</td>
<td>355</td>
<td>700</td>
<td>960</td>
</tr>
<tr>
<td>Plate thickness [mm]</td>
<td>6</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Throat Thickness [mm]</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Peak value of transversal stress for described boundary condition was, obtained through FEM simulations, was used as response. Following results were obtained:
Figure 21 – Factors affecting peak value of transversal residual stress. a) Main factors b) Interaction of parameters

Plots show that only yield strength of the material has a significant effect on peak value of transversal residual stress. With higher yield strength, peak value of residual stress increases, figure 18a, and the effect is more pronounced as thickness of the joint is increased, figure 18b. It should be noted, however, that these results are valid for a particular set of parameters and a specific boundary condition and does not represent fillet welded joints in general.
5 CONCLUSIONS

Based on above results, following conclusions can be made:

[1] Fatigue strength of fillet welded joints is considerably affected by plate thickness and toe radius. Other weld geometry parameters don’t play an important role for fatigue life enhancement.

[2] Notch stress, as calculated by effective notch method, remains almost constant along longitudinal direction of the joint and therefore no distinct failure point can be assumed.

[3] Longitudinal stresses due to welding can be of the order of material yield strength or even more however transversal and axial stresses remain much below yield limit.

[4] Transversal residual stresses tend to have peak value at same distance from toe location irrespective of material yield strength and plate thickness. They also tend to relax at same distance from toe.

[5] Material yield strength as well as constraint conditions during welding govern the peak value of transversal residual stresses in the joint.
REFERENCES


7 Appendix

7.1 Temperature dependent material properties

700MPa Steel:
G69 EN12534 S690QT Properties

Specific heat (J/mole K)

Temperature (°C)

COMPOSITION (W%)
Fe: 95.571
Cr: 0.34
Cu: 0.06
Mn: 1.57
Mo: 0.22
Ni: 1.46
Si: 0.59
V: 0.09
C: 0.09
P: 0.0080
S: 0.011

Grain size: 9.0 ASTM

G69 EN12534 S690QT Properties

Thermal conductivity (W/m°K)

Temperature (°C)

COMPOSITION (W%)
Fe: 95.571
Cr: 0.34
Cu: 0.06
Mn: 1.57
Mo: 0.22
Ni: 1.46
Si: 0.59
V: 0.09
C: 0.09
P: 0.0080
S: 0.011

Grain size: 9.0 ASTM
960MPa Steel:

G89 EN16834 S960QT Physical properties

G89 EN16834 S960QT Properties

Grain size: 9.0 ASTM

COMPOSITION (Wt%)
- Fe: 94.056
- C: 0.4
- Mn: 1.9
- Mo: 0.5
- Ni: 2.15
- Si: 0.8
- Ti: 0.1
- Cu: 0.09
- P: 0.0070
- S: 0.0070
G89 EN16834 S960QT Properties

- Specific heat (J/(mole K)) vs. Temperature (°C)
  - Grain size: 17.0 ASTM
  - Composition (wt%):
    - Fe: 94.056
    - Cr: 0.4
    - Mn: 1.9
    - Mo: 0.5
    - Ni: 2.15
    - Si: 0.8
    - Ti: 0.1
    - Cu: 0.09
    - P: 0.0070
    - S: 0.0070

G89 EN16834 S960QT Properties

- Thermal conductivity (W/(m·K)) vs. Temperature (°C)
  - Grain size: 17.0 ASTM
  - Composition (wt%):
    - Fe: 94.056
    - Cr: 0.4
    - Mn: 1.9
    - Mo: 0.5
    - Ni: 2.15
    - Si: 0.8
    - Ti: 0.1
    - Cu: 0.09
    - P: 0.0070
    - S: 0.0070