Fatigue life investigation of non-load carrying fillet weld of structural offshore steel S460G2+M using experiment and FEM simulation

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Abstract. This research deals with the fatigue life investigation using experiment and FEM simulation on longitudinal fillet weld of structural offshore steel S460G2+M with a thickness of 10mm. The experimental fatigue test is conducted based on the nominal stress (NS) approach while the simulation uses the effective notch stress (ENS) approach for fatigue life assessment. The investigation begins with the preparation of the longitudinal fillet weld fatigue specimen using the Milling Machine based on the IIW fatigue specimen design recommendation and joined using the semi-automatic GMAW process following the AWS D1.1 procedure. Fatigue testing on non-load carrying fillet weld is conducted using the Instron Fatigue Machine with a stress ratio of 0.1 with constant amplitude loading and stress loading from 50%-75% of the yield strength of the base material. For the simulation approach, the 3D longitudinal fillet weld geometry is created using CAD based on the ENS design procedures of IIW where the sizes and dimensions are similar to the experimental fatigue specimen. The static elastic stress analysis of the model is conducted using MSC Marc/Mentat FEM software. Based on the IIW fatigue data evaluation, it is found that the natural mean curve of the longitudinal fillet weld obtained 146 MPa of FAT class which exceed approximately 106% from the IIW FAT class recommendation for a longitudinal fillet joint. However, the characteristic curve of 97.7% failure probability of the parts only attained 95 MPa of FAT class, but still exceed approximately 33% from the IIW FAT class. In the ENS fatigue assessment of the 3D longitudinal fillet weld, it is found that the model obtained 195MPa of FAT class which is inferior approximately 15 % from the FAT class recommendation of IIW. Also, it is found that both S-N curves of NS after conversion to ENS system have a good agreement with the S-N curve of ENS of 3D longitudinal fillet weld model and the IIW recommendation due to only 16 % and 34% lower as compared with the IIW FAT class recommendation for ENS.

1. Introduction
Weld fatigue failure is the establishment and dissemination of cracks due to a repetitive load that might significantly below the yield strength of the base material. It starts with the formation of microscopic crack followed by macroscopic crack propagation that finally damages the welded joint component. Welded joints with poor design geometry are defenseless to fatigue damage when subjected to repetitive
loadings. The welding heat, cooling process and the addition of filler material also give rise to fatigue failure. This phenomenon causes accidents and unbelievable economic harms since fatigue failure occurred without macroscopic plastic deformation [1]. Thus, it becomes the favorite issue among the scientists which motivates them to study this engineering problem using various fatigue assessment methods such as nominal stress (NS), hot spot stress (HSS), effective notch stress (ENS) and fracture mechanics (FM) for fatigue life assessment.

In this study, the non-load carrying longitudinal fillet weld of the structural offshore steel S460G2+M was assessed using NS and ENS approaches. The NS method is typically taken from the nominal stress amplitudes in the critical cross-section and matches them with the S–N curve of the acceptable nominal stress amplitudes [2]. It is practically an experimental test up to the final fracture. ENS approach is a fatigue life assessment that includes the stress raiser such as undercut and practically using the finite element method [3]. The ENS procedures were outlined in the IIW fatigue design recommendation [4].

Numerous research journals reporting the NS and ENS fatigue life assessment. Bertini et al. [5] studied the notch stress approach and the peak stress method for the fatigue life assessment of welded joints. They found that these local fatigue life assessment methods seemed to provide very similar outcomes in terms of scatter band and safety factors, with admiration for their corresponding reference design curve. Karakas et al. [6] investigated the fatigue performance of magnesium welded joints with the central objective to conclude the applicability of the critical distance method and compare the findings with Neuber's stress averaging method. They found that the scattered bands of the SN curve-lines of effective stresses resulting from the critical distance method are comparable with the scattered results from the Neuber's stress averaging method however expressively narrower than the scattered bands of SN-lines for notch stresses. Leitner et al. [7] studied the high-frequency mechanical impact (HFMI) treated joints using the master notch stress approach with over 230 experimental data tested using constant and variable amplitude. They found that the fatigue strength of the HFMI master notch stress approach, from constant amplitude loading, is fit for material strengths up to ultra-high-strength steels with a nominal yield limit of 1300 MPa. They also revealed that the notch stress-based service strength assessment of variable amplitude loaded HFMI-treated high-strength steel joints deliberating a specified damage sum of D=0.3 when using HFMI-treated joints. Nykänen et al. [8] studied the fatigue valuation of a welded joint with flexible amplitude loading using a novel notch stress approach. They found that the approach with modest residual stress guesses very similar linear damage sums with the damage sums from the nominal mean constant amplitude of S-N curves that derived experimentally from the specimens as used in variable amplitude tests. They also found that all data of constant amplitude notch stress range of failure were above the characteristic master S-N curve. Hyoung et al. [9] applied the effective notch stress approach on rib-to-deck joints and found a good correlation between the FEM results with the observed experimental results. Sonacci et al. [10] used the effective notch stress approach with a fictitious notch radius of 0.05 mm for thin-walled welded joints and 1 mm for thick-walled welded joints on the sandwich panels for ship decks, offshore K-nodes, an automobile door, and a trailing link. The FEM and experimental results were verified to check the consistency of the effective notch stress method to establish one single concept able to treat all possible weld geometry. Kaffenberger et al. [11] studied the effective notch radius of 0.2 mm on thin welded structures. They considered the radius from real scanned geometries and the effect of the radius and size effect. Malikoutsakis et al. [12] used the effective notch stress method in the 3D modeling and meshing of the weld toe and root on the motor truck with an effective notch radius of 0.2 mm for thin plates. They found that the ENS results have good agreement between the measured stresses of the strain gauge in the failure regions. In another investigation [13] they applied the effective notch stress approach on thick-walled rear axles and compared with numerical stress-strain results from experimental results under monotonic and cyclic loading to verify the accuracy of the modeling technique used. He obtained satisfactory results in complicated stress areas. Maljaars et al. [14] compared the nominal, structural and fictitious notch stresses for simple and complex welded joints with fillet welds. They found that three stresses difference is significant in complex cases and the fictitious notch stress approach showed good agreement with the experimental results. Park et al. [15] applied the effective notch stress approach on large-sized specimens of the diaphragm, cruciform, and out-of-plane gusset joints. They used a notch radius of 1 mm for the weld toes and weld roots to investigate the effects of the fixed effective notch radius on the weld size, plate thickness and width, and full
penetration. They found that the effective notch stress approach could determine cracks initiate either at the weld toe or the weld root. Pang et al. [16] used a simplified 2D finite element model with the effective notch stress approach on tubular booms of draglines under different loading cases. They found that the critical location occurs at the weld toe and the root of the 2D model. Hongchao et al. [17] studied the fatigue life of the base material, butt weld, and cross fillet weld of a high-strength steel bar of the Q460D and Q690D using the standard design curve of AISC360, EC3, and BS7608. They found that the base material of high-strength steel owns high fatigue resistance. They also found that the fatigue life of butt welds Q460D have an adequate safety margin, but only suitable for low-fatigue life estimation of the Q690D butt weld. The AISC360 design curve, not only found to be suitable for the fatigue life analysis of Q460D and Q690D but also has enough safety margins, while EC3 and BS7608 codes own a relatively low fatigue limit.

Lately, many researchers have given special attention to the high strength steel material due to brilliant mechanical properties, fracture toughness, and fatigue performances as compared with the conventional steel [18]-[20]. Those benefits manifest the material open for fatigue life investigation. Based on the literature review above it is understood that fatigue exploration is enormously essential for the safety assessment of welded steel structures. Thus, driven by these facts, this research aims to determine and match the fatigue life of longitudinal fillet weld S460G2+M as well as its FAT class using NS and ENS approaches.

2. Experimental Methodology

2.1. Material Selection

In this investigation, the main material is structural offshore steel S460G2+M with a 10 mm thickness which is also classified as high strength steel. It was designed for the harsh environment for the oil and gas and marine applications [21]. Table 1 shows the mechanical properties and chemical composition of the material.

| Table 1. Material properties of the S460G2+M [22]. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Thickness, t    | Yield strength (Ys) | Tensile Strength (UTS) | Ys/UTS | CVN (-40°C) | Elongation, % |
| t<16            | 460 MPa(min)      | 540-700 MPa      | Max.0.93 | >60J transverse | 17%            |

| Chemical composition |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C%          | Cu%          | Mn%         | V%          | Si%          | Al%        | Cr%         | Nb%         | Ni%         |
| 0.19        | 0.11         | 1.62        | 0.10        | 0.6          | 0.032      | 0.10        | 0.012       | 0.09        |

2.2 Fatigue Specimen

The fatigue specimen for the investigation is a longitudinal fillet weld. It was prepared using a milling machine. The size and geometry of the specimen were in accordance to the IIW fatigue specimen design recommendation as depicted in Figure 1 [23].

Figure 1. Fatigue specimen, a. Fatigue specimen recommendation by IIW, b. Size and dimension of longitudinal fillet joint, c. Longitudinal fillet weld fatigue specimen.
All the fatigue specimens were joined using gas metal arc welding (GMAW) by the non-certified welder but vast experiencing in joining metal using the suitable combination of welding parameter from [21]. However, its weld quality must comply with standard acceptance criteria of the AWS D1.1 [24]. Only one pass laid on the both sides of the fatigue specimen as shown in Figure 3c previously. The leg length of the welds is approximately 9-10mm. The current and voltage use is 200 Amp and 19 volts and joined in horizontal welding position using filler wire ER80S-N1 and mixed gases as shielding gas. The welding parameters for the GMAW process are summarized in Table 2.

| **Table 2. Welding parameters for GMAW** |
|------------------------------------------|
| **Variable**                             | **Value**                |
| Current                                  | 90-230 Amp               |
| Voltage                                  | 18-20 V                  |
| Travel speed                             | 20-25cm/min              |
| Filler wire (diameter)                   | ER80S-N1(1.0mm)          |
| Shielding gas                            | Mixed gases (80% Ar + 20% CO₂) |
| Welding position                         | Horizontal (2F)          |

2.3 Fatigue Loading
The stress loading for fatigue tests were calculated from variables of stress range (Δσ), mean stress (σmean), alternating stress (σa) and stress ratio (R) as presented in equation (1)-(4) [25]. The nominal stress ranges applied for fatigue test are 55%, 65% and 75% of the yield strength of the base material of S460G2+M. There were nine specimens tested for each nominal stress range.

\[
\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} \tag{1}
\]

\[
\sigma_{\text{mean}} = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \tag{2}
\]

\[
\sigma_{\text{a}} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \tag{3}
\]

\[
R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \tag{4}
\]

2.4 Effective Notch Stress (ENS) Modelling Procedure
The 3D longitudinal fillet weld geometry is modelled using the CATIA by assimilated the size and dimension of the experimental fatigue specimen based on the ENS procedures of IIW which includes the stress raisers of the fillet weld [4]. The stress raiser or notch is modelled with fictitious notch radius of 1mm since the thickness of the S460G2+M is 10mm. The fillet weld angle, \( \theta \) is 45° respectively. The 3D model longitudinal fillet weld for ENS fatigue life assessment is shown in Figure 2.

![Figure 2. IIW recommendation for effective notch stress (ENS) modelling](image-url)

The meshing procedure of the 3D longitudinal fillet weld is conducted using MSC. Marc/Mentat with 3D-solid quadratic tetrahedral element meshes. The mesh was applied to fictitious notch radius with
minimum size of 0.15 mm. The completed 3D mesh modelling at the weld toe of the part is shown in Figure 3.

![Figure 3. Mesh generation at the weld toe of longitudinal fillet weld.](image)

**2.5 Fatigue Life Evaluation of Experimental Data**

The experimental fatigue data were evaluated in accordance with IIW commission XIII as presented in equation (5) - (8) [4]. This evaluation procedure is important in order to develop the S-N curves and estimate the FAT class. The evaluation procedures are as follows:

a) Calculate $\log_{10}$ of all data: Stress range $\Delta \sigma$ and number of cycles $N$.

b) Calculate exponents’ $m$ and constant $\log C$ of the formulae using an equation (5).

$$\log N = \log C - m \cdot \log \Delta \sigma$$

(5)

c) Calculate mean $x_m$ and the standard deviation $\text{Stdv}$ of $\log C$ using $m$ obtained in b using equation (6) and (7).

$$x_m = \frac{\sum x_i}{n}$$

(6)

$$\text{Stdv} = \sqrt{\frac{\sum (x_m - x_i)^2}{n - 1}}$$

(7)

d) Calculate the characteristic values $x_k$ by the equation (8).

$$x_k = x_m - k \cdot \text{Stdv}$$

(8)

**2.6 Fatigue Life Assessment for Effective notch stress (ENS) Data.**

The fatigue life estimation of the longitudinal fillet welds of S460G2+M using ENS approach requiring the static elastic analysis to determine the stress concentration factor ($K_f$) in equation (9) as well as the maximum principal stress ($\sigma_r$) on the affected weld toe.

$$K_f = \frac{\sigma_{geom}}{\sigma_{Nom}}$$

(9)

The $\sigma_{geom}$ or $\sigma_r$ signifies as maximum principal stress and the $\sigma_{Nom}$ signifies as nominal stress applied on the longitudinal fillet weld. The nominal stresses applied to static elastic stress analyses were similar to the nominal stress for experimental fatigue tests. Due to uni-axial stress of fatigue assessment, the maximum principal stress represents the effective notch stress (ENS). The fatigue life estimation based on ENS approach is using an equation (10) [24].
The $\Delta \sigma_{rd}$ signifies the FAT class design recommendation which is FAT225 for 1mm radius by IIW. $N_t$ is the required life, which is 2 million cycles, $\sigma$ is the maximum principal stress form FEA and $m$ is the gradient of the S/N curve, which is 3 for welded structure.

2.7 Experimental Data Conversion Procedure for Effective Notch system

To compare the NS fatigue data with the ENS approach, $\Delta \sigma_K$, conversion procedure using the equation (11) should be conducted by multiplying the nominal stresses, $\Delta \sigma_n$, of the experimental fatigue tests with the stress concentration factor obtained from the FEM simulation.

$$\Delta \sigma_K = K_f \cdot \Delta \sigma_n$$

3. Results and Discussion

3.1 Fatigue Life of Longitudinal Fillet Weld

The fatigue lives of the longitudinal fillet welds of S460G2+M are presented in Table 3. It is shown that the fatigue life of the part influenced by the applied fatigue loads on the parts. Based on the Table 3, it is found that as the fatigue loads decreases the fatigue life of the parts also increases. On an average, there are approximately 56% of life increments when the fatigue loads decreased from 400 MPa to 374 MPa and 238% of life increments as the fatigue loads continue decrease to 294 MPa.

| Fatigue specimen       | No. specimen | Fatigue loads (MPa) | Fatigue life (N) |
|------------------------|--------------|---------------------|------------------|
| 1. Longitudinal fillet weld | 3           | 400                 | 38895            |
| 2. Longitudinal fillet weld | 3           | 347                 | 61043            |
| 3. Longitudinal fillet weld | 3           | 294                 | 131634           |

The fatigue life (N) in Table 3 is evaluated based on the IIW evaluation procedures for experimental data in order to establish the S-N curve and to determine the FAT class of the longitudinal fillet weld. The S-N curve of the parts is depicted in Figure 4.
Figure 4. The S-N curve of the longitudinal Fillet welds versus S-N curve of IIW recommendation for longitudinal fillet weld.

From the diagram above, it is found that the FAT class of longitudinal fillet weld is reached 146 MPa which equivalents to 106 % increment from the IIW FAT class recommendation for longitudinal fillet weld and is equivalent to 2.0 of bonus factor. This result shows that the weld quality of the parts is exceptional even though was joined by the non-certified welder. In addition, the welding parameters of the GMAW process are suitable to produce the longitudinal fillet welds.

3.2 Static Elastic Stress Analysis Results
The maximum principal stresses of the different nominal stresses applied on the 3D longitudinal fillet weld under static elastic stress analysis using FEM software MSc. Marc/Mentat is shown in Figure 5.

Figure 5. Maximum principal stress of the 3D longitudinal fillet weld.

Based on the Figure 5 above, it is found that the principal stresses in the model are perpendicular to the nominal stresses applied to the model due to its increase as the nominal stress increase. The weld toe region is found to have greater principal stresses as compared to the other regions of the model due to the location of the stress concentration. The principal stresses and intended stress concentration factors of the model are tabulated in Table 4.
Table 4. The maximum principal stresses and stress concentration factor of the 3D longitudinal fillet weld.

| Nominal stress, (MPa) | Maximum Principal stress, $\sigma_r$ (MPa) | Stress concentration factor, $K_f$ |
|-----------------------|------------------------------------------|-------------------------------|
| 400                   | 599                                      | 1.49                          |
| 347                   | 520                                      | 1.49                          |
| 294                   | 441                                      | 1.22                          |

Based on the Table 4 above, it is found that the stress concentration factor of the nominal stress 400MPa and 347MPa is 1.49 while the nominal stress of 239MPa is 1.22. These results show that the stress concentration factor does not relent to the nominal stress applied to the model but rely on the quality of the welds. The stress concentration basically represents the stress raiser of the weld such as undercut which commonly the location of the crack initiation when the structure exposed to cyclic loading. However, fatigue life estimation is puzzling due to differential geometry and stress loading will produce varies stress concentration factor. Therefore, it is important to reduce the amount of stress concentration by means of eliminating the notches where possible.

3.3 Fatigue Life of the 3D Longitudinal Fillet using Effective Notch Stress Approach

The fatigue life of the 3D longitudinal fillet welds that is subjected with varying stress loading are shown in Table 5. All the variables such as ENS FAT, safety factor and slope were taken from IIW standard.

Table 5. The fatigue life of the 3D longitudinal fillet welds using ENS approach

| IIW-ENS FAT (MPa) | Safety Factor, $\varphi Q$ | Slope, $m$ | Principal stress, $\sigma_r$ (MPa) | Fatigue life (N) |
|-------------------|-----------------------------|------------|-----------------------------------|------------------|
| 225               | 1.3                         | 3          | 599                               | 232877           |
| 225               | 1.3                         | 3          | 520                               | 355957           |
| 225               | 1.3                         | 3          | 441                               | 583568           |

Based on the Table 5 above, it is found that the fatigue life of the model influenced by the principal stresses on the component, where it increases as the principal stress decreased. There were 53% increment of fatigue life as the principal stress decreased to 520MPa and around 151% of increments when the principal stress decreases to 441MPa. The ENS approach includes the stress raisers from the local geometry, thus, according to IIW only one S-N-curve is required in respect to detail geometry. The S-N curve of the ENS of the longitudinal fillet weld is shown in Figure 6, which based on the characteristic mean curve of 95% survival probability. This curve is plotted with the FAT class of fatigue design strength of IIW for ENS approach.
Figure 6. The S-N curve of the fatigue life of the longitudinal fillet welds using ENS assessment approach.

Based on the S-N curve in Figure 6 above, it is found that the S-N curve agree quite well with the FAT class 225 MPa S-N curve recommended for ENS assessment by the IIW. However, the FAT class of the 3D longitudinal Fillet welds model is found to be 15% lower as compared with the FAT class of IIW for ENS assessment.

3.4 Comparison of Fatigue Life of the Nominal Stress and ENS Assessment system

The conversion of the NS fatigue data to ENS system is essential to ensure the experimental fatigue data agreed with the FAT 225 by IIW for ENS assessment. The S-N curve comparison between NS data converted to ENS system and ENS approach are shown in Figure 7.

Figure 7. S-N curve comparison between NS data converted to ENS system and ENS approach.
Based on the Figure 7 above, it is found that both S-N curves of NS after conversion to ENS system have a good agreement with the S-N curve of ENS of 3D longitudinal fillet weld model and the IIW recommendation for ENS. It is also found that both FAT classes of the converted NS and 3D longitudinal fillet weld model are lower around 16% and 34% as compared with the IIW FAT class recommendation for ENS. Even though, both FAT classes are below the FAT class of the IIW but it’s higher than the FAT class of NS experimental due to ENS fatigue assessment provides superior fatigue life estimation as compared with the NS approach.

4. Conclusion
The fatigue life of the longitudinal fillet welds was successfully investigated using nominal stress and effective notch stress approach. Based on this investigation there are some conclusions which are as follows:

- The fatigue life of the longitudinal fillet weld depends on the fatigue loads, weld quality and suitable combination of welding parameters of GMAW.
- The stress concentration factor of longitudinal fillet weld does not depend to the stress applied to the structure but depend on the quality of the welds.
- The principal stress from FEM simulation for the 3D longitudinal fillet weld depends on the applied stress to the parts, where it increases as the stress increases.
- The single design S-N curve FAT 225 of IIW for ENS approach has good agreement with the S-N curves of NS converted to ENS system and ENS approaches and relevant for fatigue life comparison between the NS and ENS approaches due to ENS provides a superior fatigue life estimation

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