Fatigue life prediction of joggle weld joint using virtual strain gauge and its validation through experiments

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Abstract. This paper highlights fatigue life prediction and interactions between weld design parameters and their effect on joggle weld joint using the virtual strain gauging and its validation through experimental testing. Based on the concept of linear elastic fracture mechanics, the effects of weld geometry, load conditions and the boundary constraints on the fatigue strength of joggle weld joint are investigated using the finite element analysis. Response surface methodology is used to evaluate the influences of three weld joint parameters: plate thickness (Pt), root gap (Rg) and load (Ld) on normal stress (St) and fatigue life (Lf). Main effect plot shows that the plate thickness and the load are important parameters affecting the normal strain and fatigue life, whereas root gap influences the fatigue life only up to 2 mm, but no influence on fatigue life is observed after 3 mm of root gap. Experimental results show that the presence of secondary bending affects the experimental values of fatigue life. Contour plot and regression equation are used to study the effects of weld joint parameters on normal stress and fatigue life.

Keywords: Response surface methodology (RSM) / strain life / fatigue life / finite element analysis

1 Introduction

Fatigue assessment is frequently the slowest and most critical link in the design process of fabricated structures. Several fatigue life prediction methods have been introduced by different researchers to assess durability of welded structures. Numerical methods are evolved as it is more sophisticated and also computers with increased speed and memory capacity are available. Fatigue assessment for welded structures can be based on strain, stress, notch stress or stress intensity factor, and methods can generally be classified as global and local approaches [1]. The normal stress method can be categorized as a global approach, because the local geometric properties of a weld are included in the corresponding detail weld class and corresponding S–N curve. Structural stress-based methods [2,3] omit the detail classes, but the local geometric properties [4] of the weld, such as toe radius, weld angle, etc., are still considered to be included in the appropriate S–N curve [5]. Unfortunately, weld profile data for most of the normal stress S–N curves have not been reported [6]. Fatigue of welds is even more complex. Welding strongly affects the material by the process of heating and subsequent cooling as well as by the fusion process with additional filler material, resulting in inhomogeneous and different materials [7], and hence strain gauge position is really challenging when one deals with higher thickness weld joint with main plate thicknesses ranging from 10 to 100 mm subjected to both axial and bending loads [1].

The application of the scatter band to local strain fields, evaluated by numerical analyses or measured by strain gauges, is also discussed and due to technology, it is now possible to conduct structural stress analysis of complicated structural detail model with very fine mesh. However, this method relies on structural analysis, which needs detail structural information in order to obtain precise stress value [8].

Experimental approach, based on the strain measurement near the weld toe, is widely adopted in industry particularly when geometrically complex welded components are concerned. This approach, initially proposed by Haibach [9], is always a challenge for the complex weld joint like joggle joint and strain gauge locations from weld toe. The main reasons behind this are the higher thickness and complex weld joint. By using miniature strain gauges close to the weld toe [10], the distance can be dropped to few tenths of a millimetre based on weld joint. Few attempts

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were made already on simple fillet joint and validated by strain gauge testing using 2–3 mm strain gauge location from weld toe.

In this paper, fatigue life for joggle weld joint is calculated at 10 mm distance from weld toe. Strain gauge measurements, which allow us to take into account the secondary bending effects that occur in actual joints, depend on joint geometry, loading conditions and welding procedure. Finite element method is also used to derive the fatigue life virtually using the 1 mm meshing criteria. Response surface methodology (RSM) is used to develop regression equations which predict the fatigue life virtually and it also saves the experimentation cost and time.

2 Methodology

Many time-consuming experiments can be replaced by computer simulations. The finite element fatigue analysis was made with the effective notch stress method using submodelling technique in order to reduce the computational time [11]. The FEM simulations are increasingly used for fatigue life prediction in the complex and typical weld joints of construction equipment industry. The FEM gives an approximate solution with an accuracy that depends mainly on the type of FE methodology (Fig. 1).

Design of experiments (DOE) is an efficient statistical technique that can be used to determine the effect of the various experimental parameters on responses. In this research, three weld joint parameters – plate thickness (Pt), root gap (Rg) and load (Ld) [12] as input – and two responses – normal stress (St) as direct response and fatigue life (Lf) as indirect response – are considered. Each of these process parameters are set at five different levels. The levels of each factor are chosen as –2, –1, 0, 1 and 2 in closed form to have a rotatable design. A central composite design (CCD) is used as an experimental plan with 20 experimental runs as given in Figure 2 and the values of different parameters used along with their levels are as shown in Table 1.

\[ X_i = \frac{\text{Chosen parametric values} - \text{Central rank of parameters}}{\text{Interval of variation}} \]

where \( X_i \) is the coded value of the variables Pt, Rg and Ld, respectively. The values obtained from equation (1) are tabulated in Table 2, and it requires 20 experiments for the three factors with five levels. An experimental approach based on the strain measurement near the weld toe is widely adopted, in particular when geometrically complex welded components are concerned.

Three random samples, from Table 2, are fabricated as per drawing shown in Figure 3 by laying the Vishay micro measurement gauges CEA-XX-125UN-350, which is shown in Figure 4. Root gap is maintained during sample preparation using the root weld spacing gauge with the help of laser sensing system installed in the robot.

Strain samples are further tested using INSTRON fatigue testing machine as shown in Figure 5a at a frequency of 10 Hz by holding both the ends of specimen with the help hydraulic jaws as shown in Figure 6.

Figure 7 shows the strain signals for run orders 2, 4 and 5 for the middle gauge using e-DAQ data logger. All strain values are measured at 10 mm from weld toe.

3 Results and discussions

3.1 Comparative analysis between FEA simulations and practical experimentations

Experimental estimation of the fatigue life of welded joints can be complex, costly and time-consuming, owing to the complex joint geometry, the number of stress

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**Fig. 1.** Joggle weld joint with parameters definitions.
concentration points and the heterogeneous material properties. Although the fatigue behaviour of welded joints has been thoroughly investigated by different researchers, no complete study has considered the combined effects of all the important parameters on the fatigue.

Normal strain values are recorded from weld toe using the virtual strain gauge using commercial finite element analysis package ANSYS and also measured in actual testing. The analysis is undertaken based on the assumption of an isotropic elastic material for both the base and its weld metal. For complex weld joint, the high stress concentration in weld toe is present due to the stress component normal to the weld toe line which is the largest in magnitude and it is predominantly responsible for the fatigue damage accumulation in this region. Usually, weldment contains flaws and crack-like defects. FEA setup and its results of run order 4 are shown in Figure 8a–e. This investigation extracted strain values from the top surface of the FE model at the same location as actual strain gauge in test sample to estimate strain levels and converts a load-time history of the weldments into a strain-time history using the finite element method.

The first step in the life prediction [13] is to obtain the normal strain using virtual strain gauging at three different positions from weld toe. Fatigue life of weld joint is assessed by means of the normal stress methods and falls within the category of “E” weld class of the BS 7608 code with area ratio equal to 1 [6]. Mean-2SD life is estimated using the “E” class weld S–N curve as per Figure 9.

Mean-2SD considers the 2.3% probability of failure that is getting applied on off-highway vehicle welded part. The uniaxial stress state exists where there is only one non-zero strain component. Table 1 shows the weld joint parameters and their values at different levels.

**Table 1.** Weld joint parameters and their values at different levels.

| Symbol | Weld joint parameters | Levels |
|--------|-----------------------|--------|
| X1     | Plate thickness (Pt) (mm) | -2 4 -1 5 0 6 1 8 2 10 |
| X2     | Root gap (Rg) (mm)       | -2 1.5 -1 2 0 2.5 1 3 2 3.5 |
| X3     | Load (Ld) (kN)           | -2 22 -1 32 0 40.5 1 62.5 2 80 |

**Fig. 2.** Central composite design with \( \alpha = 2 \).
principal stress. The uniaxial stress–strain equations given in equations (2) and (3) are applied and the results are as shown in Table 3.

\[ \varepsilon_x = \frac{\sigma_x}{E} \]  
\[ \sigma_x = E \varepsilon_x. \]  

Table 3 shows comparative study between FEA and experimental fatigue testing results. Data reveal the fact that run order 2, 4 and 5 show satisfactory normal stress, whereas fatigue life value of run order 4 correlate 75% with experimental fatigue life because of the absence of any type of plate bending. Run orders 2 and 5 show significant change in experimental fatigue life as compared to FEA life and mean-2SD predicted life due to the presence of secondary bending effect and hence different failure mode is observed [14]. Fatigue crack starts from root and propagates through plate thickness as shown in Figure 10.

Further analysis of samples is carried out using FEA in order to reduce cost, material and time consumption and results are tabulated in Table 4.

Analysis of variance (ANOVA) is mainly carried out to analyse the variation among the groups. ANOVA is performed for the model adequacy checking, which includes a test for the significance of the regression model, model coefficients and lack of fit.
3.2 Main effects plot

The main effects plot is used to graphically compare the level of a process output variable at various states of process “factors” and to gain an understanding of the main effect of a change in the factor on the output as shown in Figures 11 and 12.

Plate thickness is the most important parameter which affects the weld fatigue life. Figure 11 shows that increase in plate thickness increases the fatigue life. However, root gap affects the fatigue life up to 2 mm only. Horizontal line of graph up to 3 mm indicates no effect of root gap on fatigue life. But after 3 mm, increase in root gap decreases fatigue life. Figure 11 also indicates that load and fatigue life are inversely proportional to each other as load increases as the fatigue life decreases.

Graphs, shown in Figure 12, illustrate the effect of plate thickness, root gap and load on normal stress. Increase in plate thickness reduces stress, whereas in contrast as load increases, the normal stress increases. Root gap shows the fluctuating effect on normal stress.

3.3 Contour plot

Based on equations (2) and (3) obtained by the CCD of the response surface methodology, the effects of the various process parameters’ influence on the normal stress and fatigue life are analysed. The contour plots are drawn for various combinations of influencing parameters. The
changes in the intensity of the shade in the plot represent the change in the fatigue life cycles. Figures 13–15 represent the influence of plate thickness, load and root gap on fatigue life. Smaller plate thickness and increase in load, as shown in Figure 13, result in lower fatigue life. This confirms the fundamental of fatigue life mechanism. Figure 14 represents the effect of load and root gap on fatigue life. The increase in root gap along with increase in load shows the mixed influence on fatigue life. Root gap of 1.5 mm is not suitable for fatigue life as lower root gap in fabrication creates problem to achieve good side wall and root fusion. The increase in plate thickness (Pt) and root gap (Rg) enhances the fatigue life considerably. This can be seen in Figure 15.

Figures 16–18 illustrate the influences of plate thickness, root gap and load parameters on the normal stress (Ns). Figure 16 demonstrates the effect of plate thickness (Pt) and load (Ld) on the normal stress. Higher load with reduced plate thickness leads to a higher normal stress. Higher plate thickness and higher root gap do not show much influence on the normal stress. However, root gap of more than 3.5 mm is not advisable due to fusion defect at root gap and side wall (Fig. 17). Effects of root gap (Rg) and load (Ld) on normal stress are shown in Figure 18. Root gap is not showing much influence on normal stress compared to load.

### 3.4 Regression equation

Using RSM, a comprehensive mathematical model is developed to validate the interactive and higher-order
influences of various weld joint parameters on the dominant response criteria, i.e. the normal stress and the fatigue life. Table 5 shows the ANOVA for response surface quadratic model of fatigue life. ANOVA is mainly carried out to analyse the variation among the groups. This is done by F-test at 95% confidence level. Significance and insignificance are determined by comparing the F-values with standard tabulated values at the corresponding degrees of freedom and 95% confidence level.

The p-value for each term tests the null hypothesis that the coefficient is equal to zero (no effect). A low p-value (<0.05) indicates that you can reject the null hypothesis. In other words, a predictor that has a low p-value is likely to be a meaningful addition to the model because changes in the predictor’s value are related to changes in the response variable. Conversely, a larger (insignificant) p-value suggests that changes in the predictor are not associated with changes in the response.

### 3.4.1 Fatigue life (L_f)

The quadratic model is statistically significant for the analysis of fatigue life. The details of ANOVA for the response surface quadratic model along with the sum of squares on fatigue life are given in Table 5.
Equation (4) presents the second order polynomial regression equation for fatigue life.

\[
\text{Fatigue life (cycles)} = 224402 + \left(\frac{126291}{\text{Plate thickness}}\right) + \left(\frac{3672}{\text{Root gap}}\right) + \left(\frac{40093}{\text{Load}}\right) + \left(\frac{1596}{\text{Plate thickness}}\right) + \left(\frac{279}{\text{Load}}\right) + \left(\frac{24031}{\text{Plate thickness}}\right) + \left(\frac{1824}{\text{Root gap}}\right) + \left(\frac{371}{\text{Load}}\right) - \left(\frac{6810}{\text{Plate thickness}}\right).
\]

(4)

Table 4. RSM table with FEA values.

| Std order | Run order | Plate thickness (Pt) (mm) | Load (Lt) (kN) | Root gap (Rg) (mm) | FEA results – normal stress (MPa) | Fatigue life (cycles) |
|-----------|-----------|---------------------------|----------------|-------------------|----------------------------------|----------------------|
|           |           | Coded – X1 | Actual | Coded – X2 | MPa | Coded – X3 | Actual |                      |                      |                      |                      |
| 18        | 1         | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |
| 7         | 2         | -1          | 5      | 1         | 62.5 | 1         | 3.0    | 400                   | 12439               |
| 20        | 3         | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |
| 10        | 4         | 2           | 10     | 0         | 40.5 | 0         | 2.5    | 138                   | 305948              |
| 12        | 5         | 0           | 6      | 2         | 80   | 0         | 2.5    | 427                   | 10220               |
| 9         | 6         | -2          | 4      | 0         | 40.5 | 0         | 2.5    | 321                   | 24177               |
| 5         | 7         | -1          | 5      | -1        | 32   | 1         | 3.0    | 204                   | 92725               |
| 11        | 8         | 0           | 6      | -2        | 22   | 0         | 2.5    | 117                   | 491648              |
| 2         | 9         | 1           | 8      | -1        | 32   | -1        | 2.0    | 127                   | 383334              |
| 6         | 10        | 1           | 8      | -1        | 32   | 1         | 3.0    | 131                   | 350672              |
| 8         | 11        | 1           | 8      | 1         | 62.5 | 1         | 3.0    | 256                   | 48330               |
| 19        | 12        | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |
| 4         | 13        | 1           | 8      | 1         | 62.5 | -1        | 2.0    | 249                   | 51441               |
| 1         | 14        | -1          | 5      | -1        | 32   | -1        | 2.0    | 205                   | 92952               |
| 17        | 15        | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |
| 16        | 16        | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |
| 14        | 17        | 0           | 6      | 0         | 40.5 | 2         | 3.5    | 216                   | 78790               |
| 13        | 18        | 0           | 6      | 0         | 40.5 | -2        | 1.5    | 216                   | 78760               |
| 3         | 19        | -1          | 5      | 1         | 62.5 | -1        | 2.0    | 400                   | 12474               |
| 15        | 20        | 0           | 6      | 0         | 40.5 | 0         | 2.5    | 216                   | 78790               |

Fig. 10. Broken specimen during fatigue testing.

Fig. 11. Main effect plot of fatigue life.
Fig. 12. Main effect plot of normal stress.

Fig. 13. Influence of load and plate thickness on fatigue life.

Fig. 14. Influence of root gap and load on fatigue life.

Fig. 15. Influence of plate thickness and root gap on fatigue life.

Fig. 16. Influence of plate thickness and root gap on normal stress.

Fig. 17. Influence of root gap and load on normal stress.
3.4.2 Normal stress (Ns)

ANOVA technique is applied for determination of the normal stress and the results are shown in Table 6. Equation (5) gives the second-order polynomial equation for normal stress.

\[
\text{Normal stress (MPa)} = 266.0 - (75.48 \times \text{Plate thickness})
\]
\[
+ (9.932 \times \text{load})
\]
\[
- (15.7 \times \text{Root gap}) + (5.038 \times \text{Plate thickness} \times \text{Plate thickness})
\]
\[
- (0.00353 \times \text{Load} \times \text{Load}) + (0.16 \times \text{Root gap} \times \text{Root gap})
\]
\[
- (0.7132 \times \text{Plate thickness} \times \text{Load}) + (2.07 \times \text{Plate thickness} \times \text{Root gap})
\]
\[
+ (0.074 \times \text{Load} \times \text{Root gap})
\]

3.5 Evaluation of significance of the regression equation

Regression equations are obtained to describe the statistical relationship between one or more predictor variables and the response variable. It also helps to understand the relationships among the variables in the model and allows more hypotheses to be tested. Regression model is tested and compared with FEA results to understand its compatibility. Run order 10 is randomly selected as an example of normal stress and fatigue life calculations, and other run order samples calculated results are tabulated in Table 7. Run order 10, plate thickness (Pt) = 8 mm, Root gap (Rg) = 3 mm and the Load (Ld) = 32 kN.

![Contour Plot of Normal Stress (MPa) vs Root Gap (mm), Plate Thk (mm)](image)

**Fig. 18.** Influence of root gap and load on normal stress.

| Table 5. ANOVA for response surface quadratic model of fatigue life. |
| --- |
| Sources | DF | Sum of square | Mean square | F-values | p-values |
| Model | 9 | 3.34571E+11 | 37174582486 | 12.66 | 0.000 |
| Linear | 3 | 28591980233 | 9530660078 | 3.25 | 0.069 |
| Plate thickness | 1 | 4295147209 | 4295147209 | 1.46 | 0.254 |
| Root gap | 1 | 16768979873 | 16768979873 | 5.71 | 0.038 |
| Load | 1 | 58327991 | 58327991 | 0.02 | 0.891 |
| Square | 3 | 7610450362 | 25368167854 | 8.64 | 0.004 |
| Plate thickness \times plate thickness | 1 | 285081187 | 285081187 | 0.10 | 0.762 |
| Root gap \times root gap | 1 | 16768979873 | 16768979873 | 5.71 | 0.038 |
| Load \times load | 1 | 21036882 | 21036882 | 0.01 | 0.934 |
| 2-way interaction | 3 | 15953385510 | 5317795170 | 1.81 | 0.209 |
| Plate thickness \times root gap | 1 | 15679810111 | 15679810111 | 5.34 | 0.043 |
| Plate thickness \times load | 1 | 219255313 | 219255313 | 0.07 | 0.790 |
| Root gap \times load | 1 | 70016073 | 70016073 | 0.02 | 0.880 |
| Error | 10 | 29360653988 | | | |
| Lock of fit | 5 | 29360653988 | | | |
| Pure error | 5 | 0 | 0 | | |
| Total | 19 | 3.63932E + 11 | | | |
Table 6. ANOVA for response surface quadratic model — normal stress.

| Sources                                | DF | Sum of square | Mean square | F-values | p-values |
|----------------------------------------|----|---------------|-------------|----------|----------|
| Model                                  | 9  | 149518        | 16613.2     | 761.26   | 0.000    |
| Linear                                 | 3  | 6162          | 2054.0      | 94.12    | 0.000    |
| Plate thickness                        | 1  | 1534          | 1534.4      | 70.31    | 0.000    |
| Root gap                               | 1  | 2865          | 2864.5      | 131.26   | 0.000    |
| Load                                   | 1  | 9             | 8.9         | 0.41     | 0.537    |
| Square                                 | 3  | 3184          | 1061.3      | 48.63    | 0.000    |
| Plate thickness × plate thickness      | 1  | 2842          | 2842.5      | 130.25   | 0.000    |
| Root gap × root gap                    | 1  | 11            | 11          | 0.52     | 0.489    |
| Load × load                            | 1  | 1             | 0           | 0.00     | 0.967    |
| 2-way interaction                      | 3  | 2420          | 806.7       | 36.97    | 0.000    |
| Plate thickness × root gap             | 1  | 2396          | 2396.0      | 109.79   | 0.358    |
| Plate thickness × load                 | 1  | 20            | 20.2        | 0.93     | 0.728    |
| Root gap × load                        | 1  | 0             | 2.8         | 0.13     |          |
| Error                                  | 10 | 218           | 21.8        |          |          |
| Lock of fit                            | 5  | 218           | 43.6        |          |          |
| Pure error                             | 5  | 0             | 0           |          |          |
| Total                                  | 9  | 149737        |             |          |          |

Table 7. RSM results versus FEA results.

| Std. order | Run order | Plate thickness (Pt) | Load (Lt) | Root gap (Rg) | FEA results | RSM equations results |
|------------|-----------|----------------------|-----------|---------------|-------------|-----------------------|
|            |           | Actual               | Actual    | Actual        | Normal stress (MPa) | Fatigue life (cycles) mean-2SD | Normal stress (MPa) | Fatigue life (cycles) |
| 18         | 1         | 66.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
| 7          | 2         | 62.5                 | 3         | 400           | 12439       | 397                   | –29740                |
| 20         | 3         | 60.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
| 10         | 4         | 40.5                 | 2.5       | 138           | 305948      | 143                   | 337983                |
| 12         | 5         | 80                   | 2.5       | 427           | 10220       | 431                   | 79737                 |
| 9          | 6         | 40.5                 | 2.5       | 321           | 24177       | 315                   | –8445                 |
| 5          | 7         | 32                   | 3         | 204           | 92725       | 207                   | 141830                |
| 11         | 8         | 22                   | 2.5       | 117           | 491648      | 114                   | 400970                |
| 2          | 9         | 32                   | 2         | 127           | 383334      | 123                   | 367428                |
| 6          | 10        | 32                   | 3         | 131           | 350672      | 127                   | 346553                |
| 8          | 11        | 62.5                 | 3         | 256           | 48330       | 252                   | 8087                  |
| 19         | 12        | 40.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
| 4          | 13        | 62.5                 | 2         | 249           | 51441       | 246                   | 17646                 |
| 1          | 14        | 32                   | 2         | 205           | 92952       | 209                   | 142275                |
| 17         | 15        | 40.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
| 16         | 16        | 40.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
| 14         | 17        | 40.5                 | 3.5       | 216           | 78790       | 218                   | 86489                 |
| 13         | 18        | 40.5                 | 1.5       | 216           | 78760       | 217                   | 94692                 |
| 3          | 19        | 62.5                 | 2         | 400           | 12474       | 397                   | –40611                |
| 15         | 20        | 40.5                 | 2.5       | 216           | 78790       | 217                   | 94263                 |
4 Conclusion

This study combines finite element structural analysis with strain-life equations to develop a simple and effective procedure for forecasting the fatigue life of weldments and successfully compares the results obtained with experimental data.

Additionally, this work discusses the effects of weld geometry parameters such as plate thickness, root gap and load on fatigue life. Based on the results, it can be concluded that

- FEA results and regression equations values show the excellent compatibility except the run order 2, 4, 5 and 19 as in these samples, normal stress away from 10 mm weld toe are crossing the material yield stress limit that is due to the secondary bending effects because of manufacturing imperfections.
- In run orders 11 and 13, 8 mm plate thickness at 62.5 kN load does not show good compatibility in terms of fatigue life but normal stress results are satisfactory.
- The results show that the methodology developed for finite element mesh model shows the significant influence on the normal stress and fatigue life.
- Plate thickness and load show significant impact on normal stress and fatigue life as compared to root gap.
- Use of regression equation for the prediction of normal stress and fatigue life without performing the actual experimentation will be of great use in future work.

References

[1] D. Radaj, C.M. Sonsino, W. Fricke, Fatigue assessment of welded joints by local approaches, 2nd ed., Woodhead Publishing Ltd., Cambridge, 2006
[2] B. Atzori, G. Meneghetti, Fatigue strength of fillet welded structural steels: finite elements, strain gauges and reality, Int. J. Fatigue 23 (2001) 713–721
[3] X.Y. Li, T. Partanen, T. Nykanen, T. Bjork, Finite element analysis of the effect of weld geometry and load condition on the fatigue strength of lap joint, Int. J. Press. Vessel Piping 78 (2001) 591–597
[4] C.M. Sonsino, Effect of residual stresses on the fatigue behaviour of welded joints depending on loading conditions and weld geometry, Int. J. Fatigue 31 (2009) 88–101
[5] P. Dong, J.K. Hong, D. Osage, M. Prager, Master S–N curve approach for fatigue evaluation of welded components, WRC, Bulletin No. 474, Welding Research Council, New York, 2002
[6] BS7608: Code of Practice for Fatigue Design and Assessment of Steel Structures, British Standards Institution, London, 1993
[7] W. Fricke, Review fatigue analysis of welded joints: state of development, Marine Struct. 16 (2003) 185–200
[8] H. Yokota, K. Anami, Local stress approach for fatigue assessment of welded joint, Kochi University of Technology, 2007
[9] E. Haibach, Die Schwingfestigkeit von Schweissverbindungen aus der Sicht einer örtlichen Beanspruchungsassess, Laboratorium für Betriebsfestigkeit, Darmstadt, Bericht No. FB-77, 1968
[10] W. Fricke, IHW recommendations for the fatigue assessment of welded structures by notch stress analysis, Woodhead Publishing Ltd., Cambridge, 2012
[11] B. Jonsson, Z. Barsoum, J.-O. Sperle, Weight optimization and fatigue design of a welded bogie beam structure in a construction equipment, Eng. Failure Anal. 19 (2012) 63–76
[12] A.M. Al-Mukhtar, S. Henkel, H. Biermann, P. Hübner, A finite element calculation of stress intensity factors of cruciform and butt welded joints for some geometrical parameters, Jordan J. Mech. Ind. Eng. 3 (2009) 236-245
[13] K.C. Goes, A.F. Camarão, G.F. Batalha, Multiaxial fatigue of welded joints: a method for fatigue life prediction, in Proceedings of 20th International Congress of Mechanical Engineering, COBEM 2009, November 15–20, 2009, Gramado, RS, Brazil
[14] B. Baik, K. Yamada, T. Ishikawa, Fatigue strength of fillet welded joint subjected to plate bending, Steel Struct. 8 (2008) 163–169

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