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Regular Article

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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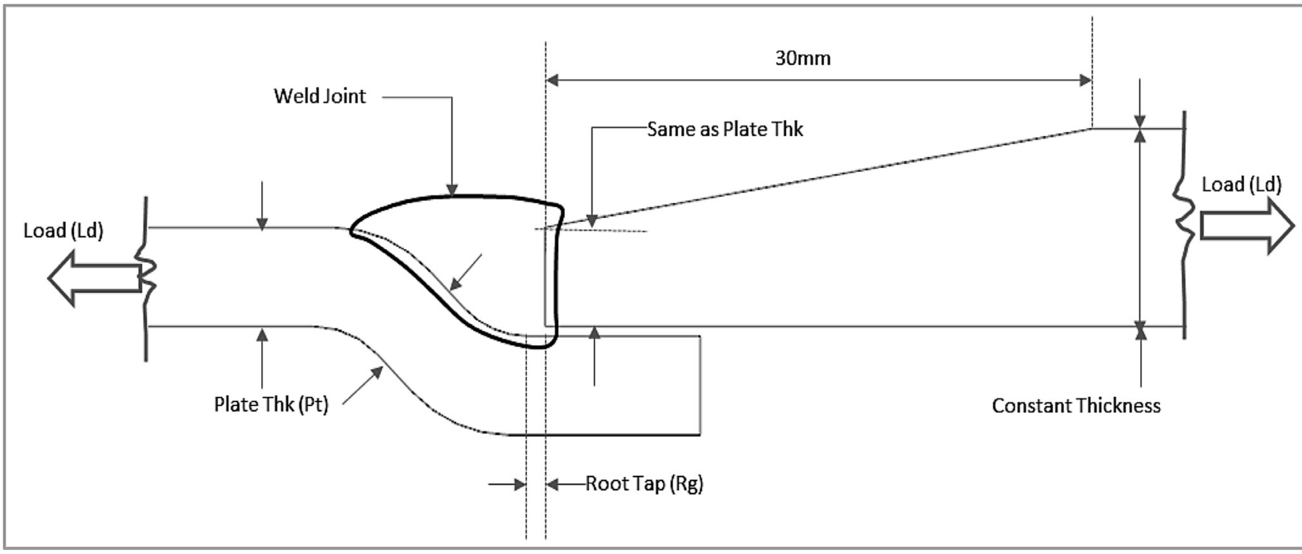

Fig. 1. Joggle weld joint with parameters definitions.

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.

$$X_i = \frac{\text{Chosen parametric values} - \text{Central rank of parameters}}{\text{Interval of variation}}, \tag{1}$$

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

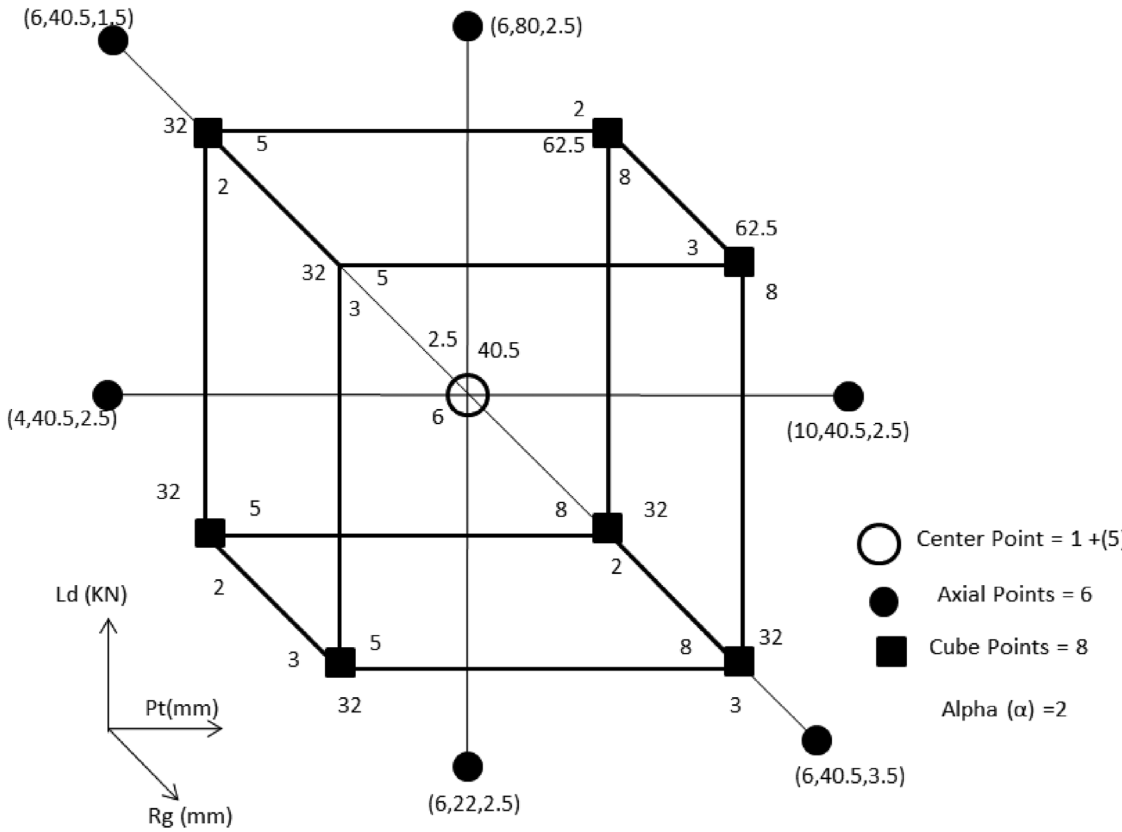

Fig. 2. Central composite design with $\alpha = 2$.

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

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

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

Table 2. DOE table.

Std order	Run order	Plate thickness (Pt) (mm)		Load (Ld) (kN)		Root gap (Rg) (mm)	
		Coded − X1	Actual	Coded − X2	Actual	Coded − X3	Actual
18	1	0	6	0	40.5	0	2.5
7	2	−1	5	1	62.5	1	3.0
20	3	0	6	0	40.5	0	2.5
10	4	2	10	0	40.5	0	2.5
12	5	0	6	2	80	0	2.5
9	6	−2	4	0	40.5	0	2.5
5	7	−1	5	−1	32	1	3.0
11	8	0	6	−2	22	0	2.5
2	9	1	8	−1	32	−1	2.0
6	10	1	8	−1	32	1	3.0
8	11	1	8	1	62.5	1	3.0
19	12	0	6	0	40.5	0	2.5
4	13	1	8	1	62.5	−1	2.0
1	14	−1	5	−1	32	−1	2.0
17	15	0	6	0	40.5	0	2.5
16	16	0	6	0	40.5	0	2.5
14	17	0	6	0	40.5	2	3.5
13	18	0	6	0	40.5	−2	1.5
3	19	−1	5	1	62.5	−1	2.0
15	20	0	6	0	40.5	0	2.5

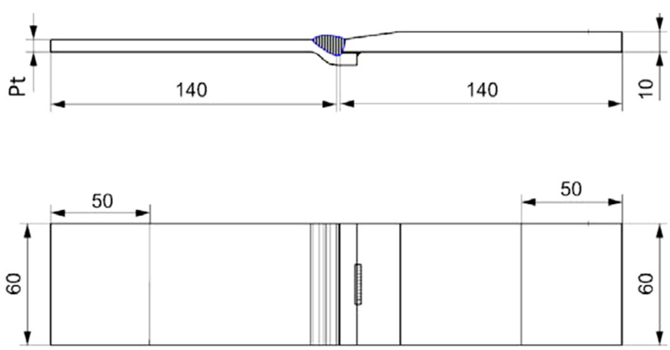

Fig. 3. Sample preparation drawing.

principal stress. The uniaxial stress–strain equations given in equations (2) and (3) are applied and the results are as shown in Table 3.

$$\in_x = \frac{\sigma_x}{E}, \tag{2}$$

$$\sigma_x = E \in_x. \tag{3}$$

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.

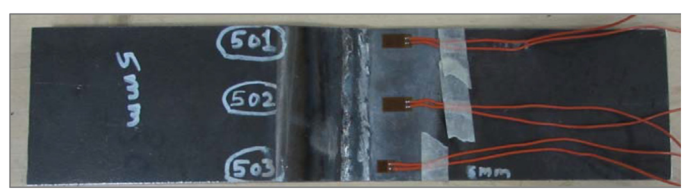

Fig. 4. Strain gauge sample with gauge pasted.

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.

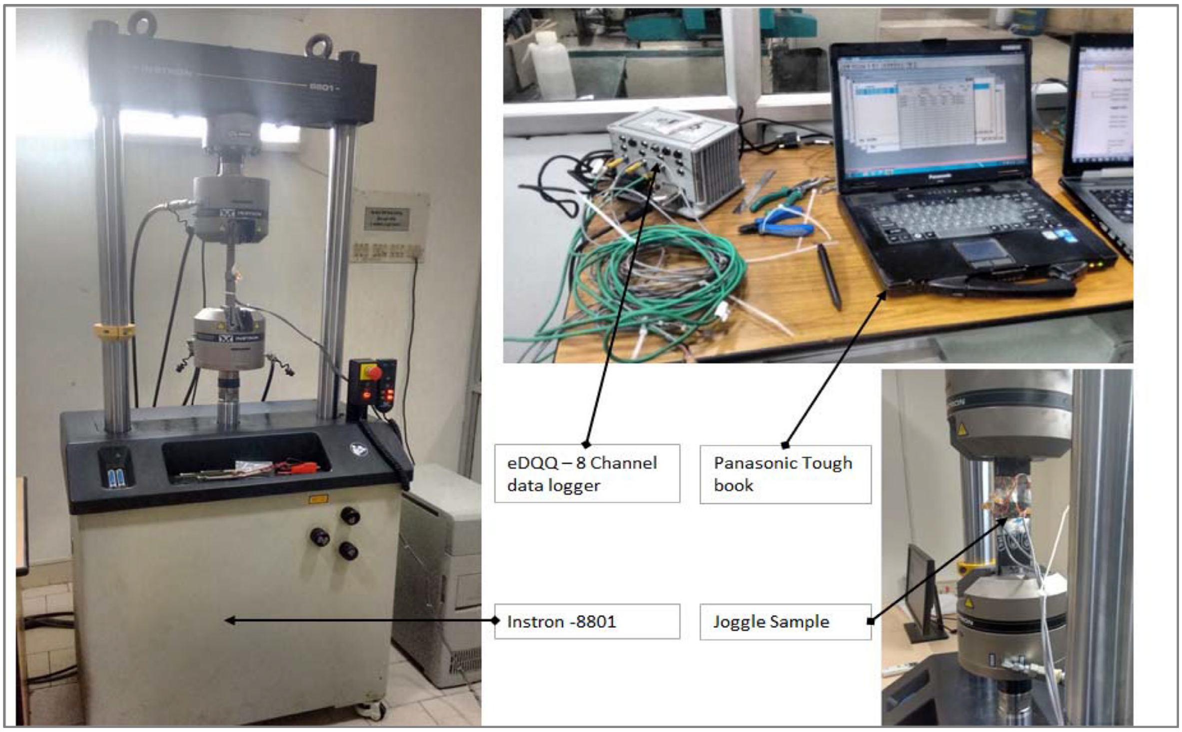

Fig. 5. Fatigue testing setup.

Fig. 6. Fatigue testing setup.

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

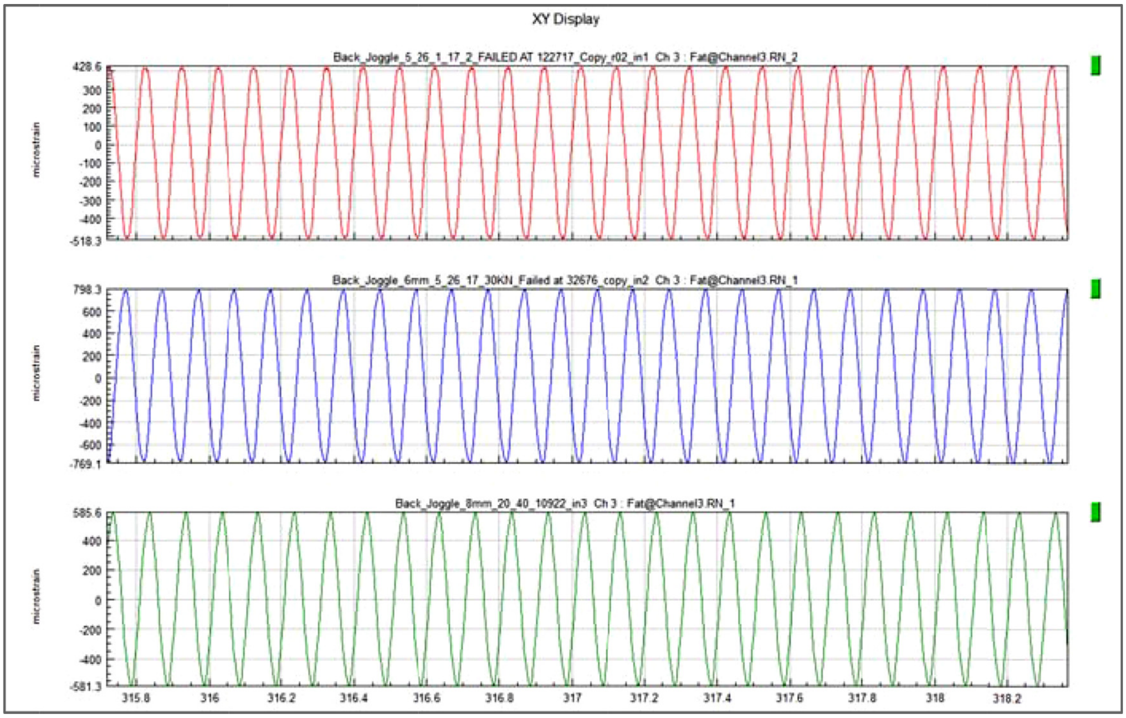

Fig. 7. Strain signals for run order 2, 4 and 5 for the middle gauge.

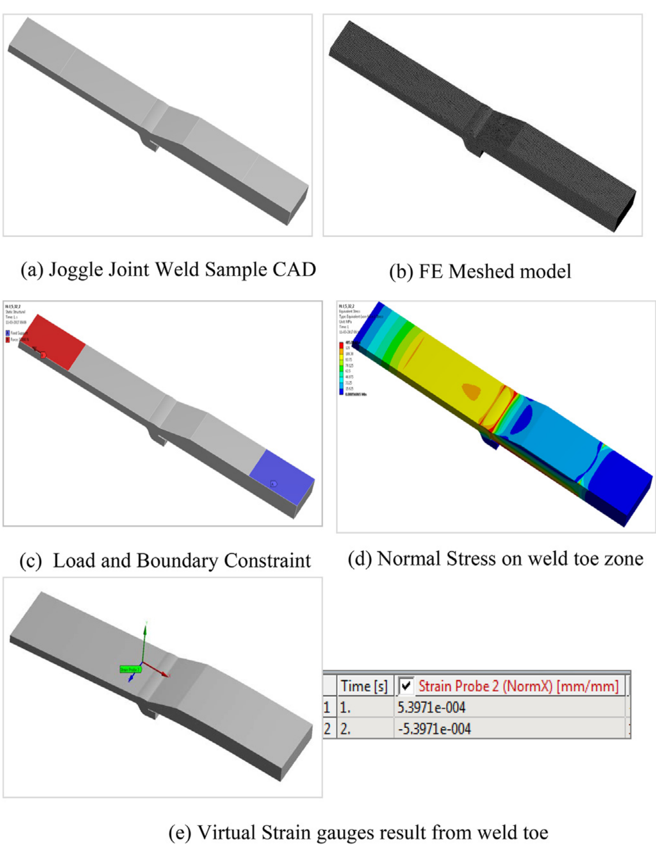

Fig. 8. FEA results for run order 4.

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

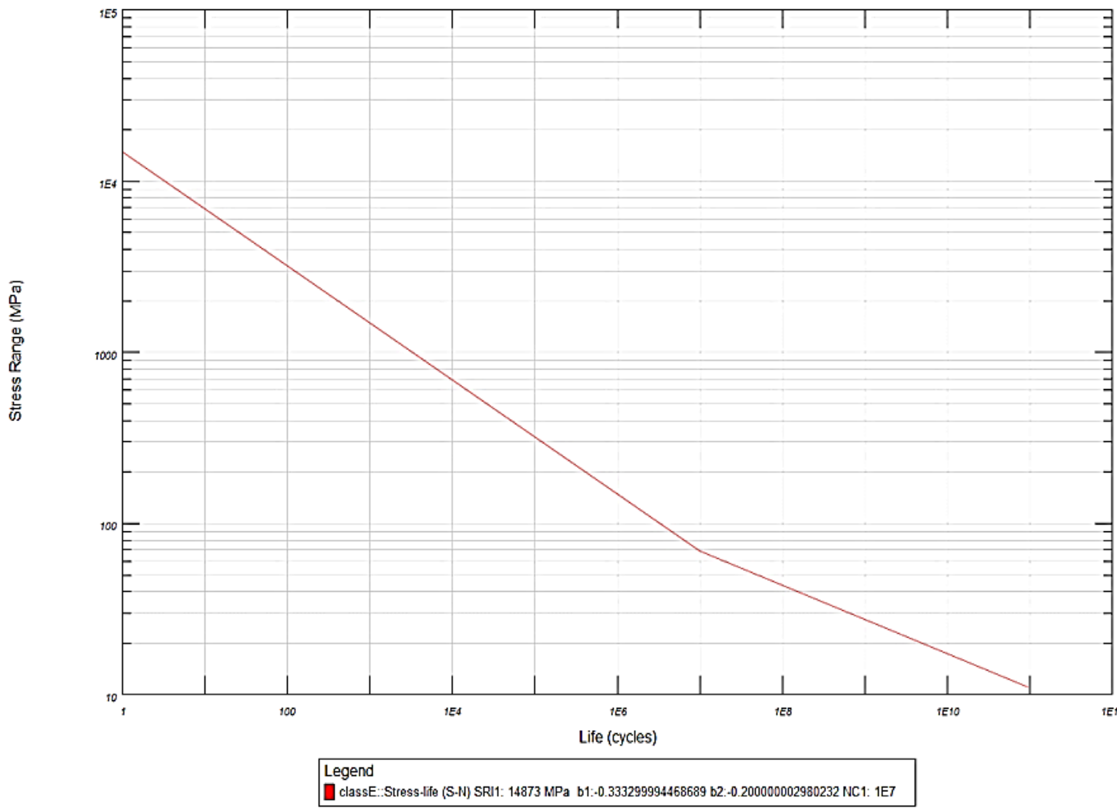

Fig. 9. "E" class weld S–N curve [BS7608].

Table 3. Fatigue results FEA versus experimentations.

Std order	Run order	Plate thickness	Root gap	Load	FEA results			Fatigue testing results			
		Actual	Actual	Actual	Strain	Stress (MPa)	Life (Mean-2SD) cycles	Strain	Stress (MPa)	Life prediction (Mean-2SD) cycles	Actual sample life
4	3	8	2	62.5	1313	249	51441	1166	221	30356	10922
1	14	5	2	32	1079	205	92952	946	1791	137701	122717
20	3	6	2.5	40.5	1138	216	78790	1567	297	73573	32676

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 (Lf)

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.

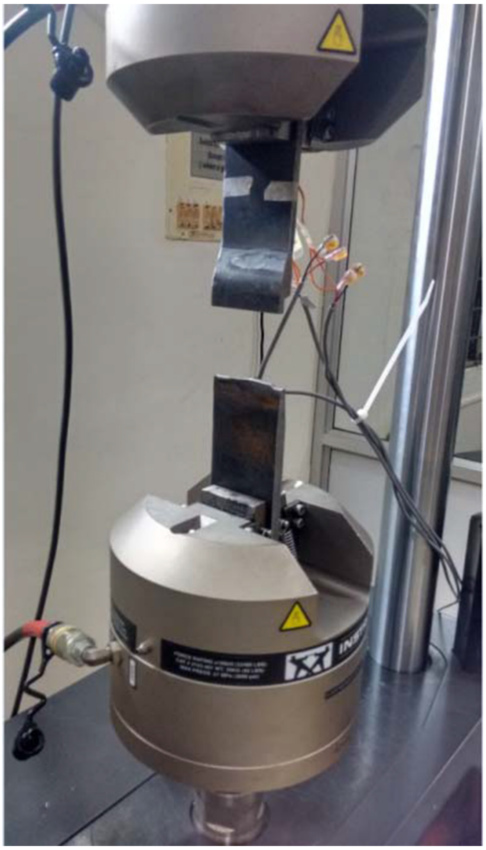

Fig. 10. Broken specimen during fatigue testing.

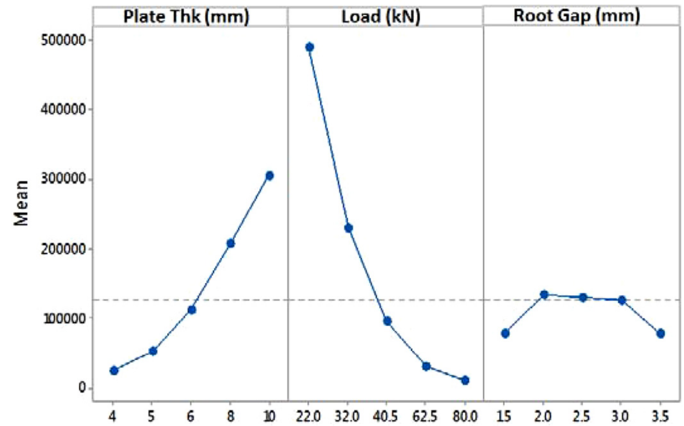

Fig. 11. Main effect plot of fatigue life.

Equation (4) presents the second order polynomial regression equation for fatigue life.

$$\begin{aligned}\text{Fatigue life (cycles)} = {} & 224402 + (126291 \times \text{Plate thickness}) \\ & - (24031 \times \text{Load}) + (40093 \\ & \times \text{Root gap}) + (1596 \\ & \times \text{Plate thickness} \times \text{Plate thickness}) \\ & + (279.5 \times \text{Load} \times \text{Load}) - (3672 \\ & \times \text{Root gap} \times \text{Root gap}) \\ & - (1824 \times \text{Plate thickness} \times \text{Load}) \\ & - (6810 \times \text{Plate thickness} \times \text{Root gap}) \\ & + (371 \times \text{Load} \times \text{Root gap}). \qquad (4)\end{aligned}$$

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) Mean-2SD
		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

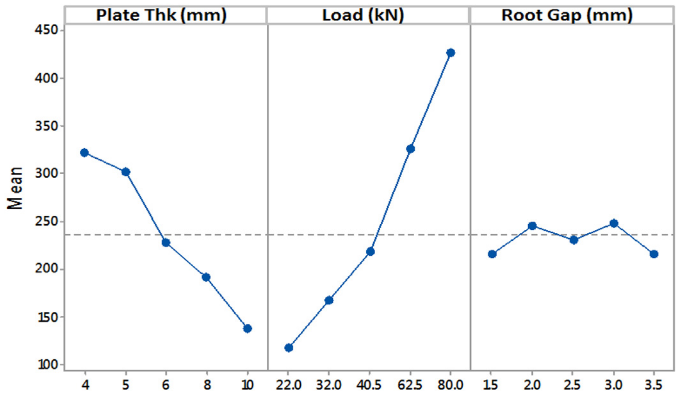

Fig. 12. Main effect plot of normal stress.

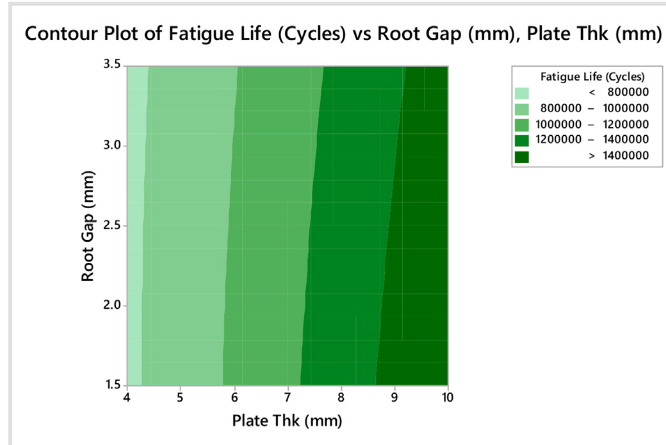

Fig. 15. Influence of plate thickness and root gap on fatigue life.

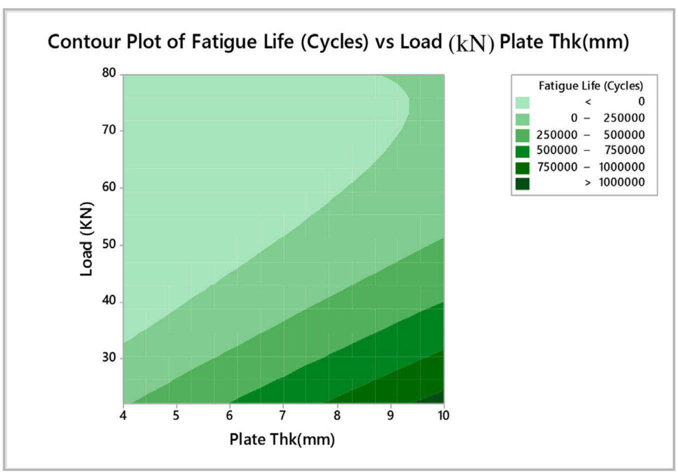

Fig. 13. Influence of load and plate thickness on fatigue life.

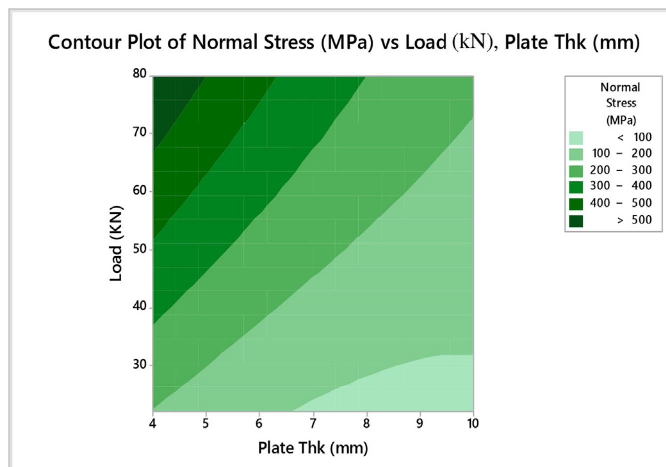

Fig. 16. Influence of plate thickness and root gap on normal stress.

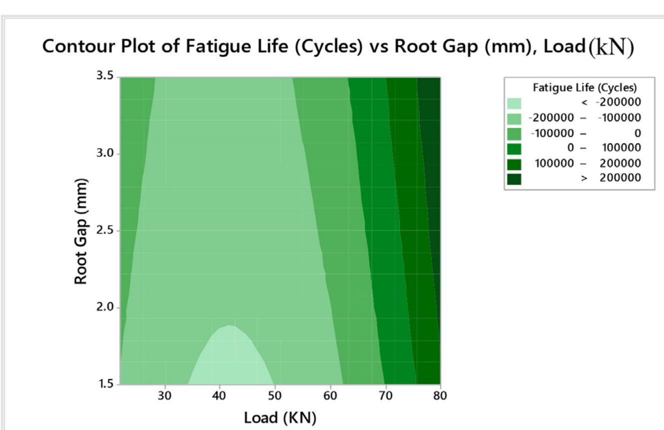

Fig. 14. Influence of root gap and load on fatigue life.

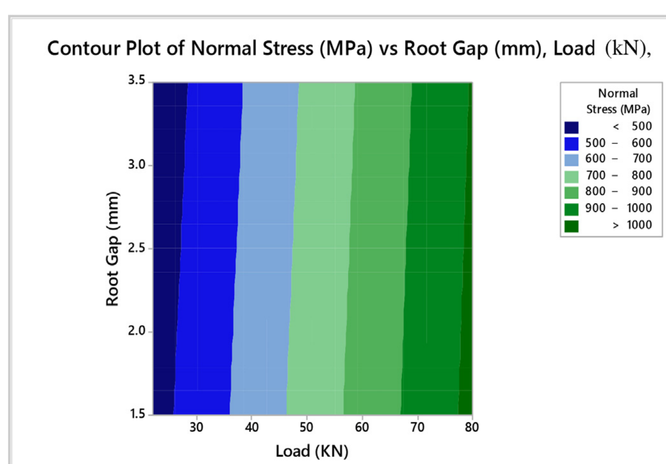

Fig. 17. Influence of root gap and load on normal stress.

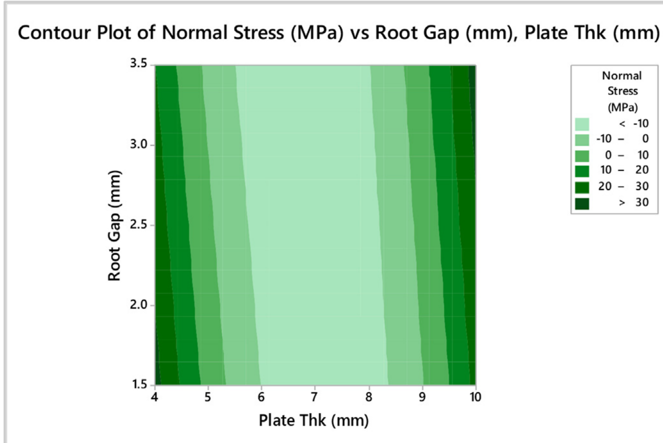

Fig. 18. Influence of root gap and load on normal stress.

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	76104503562	25368167854	8.64	0.004
Plate thickness × plate thickness	1	285081187	285081187	0.10	0.762
Root gap × root gap	1	70596493340	70596493340	24.04	0.001
Load × load	1	21036882	21036882	0.01	0.934
2-way interaction	3	15953385510	5317795170	1.81	0.209
Plate thickness × root gap	1	15679810111	15679810111	5.34	0.043
Plate thickness × load	1	219255313	219255313	0.07	0.790
Root gap × load	1	70016073	70016073	0.02	0.880
Error	10	29360653988	2936065399		
Lock of fit	5	29360653988	5872130798		
Pure error	5	0	0		
Total	19	3.63932E + 11			

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.

$$\begin{aligned}\text{Normal stress (MPa)} = {} & 266.0 - (75.48 \times \text{Plate thickness}) \\ & + (9.932 \times \text{load}) \\ & - (15.7 \times \text{Root gap}) + (5.038 \\ & \times \text{Plate thickness} \\ & \times \text{Plate thickness}) - (0.00353 \\ & \times \text{Load} \times \text{Load}) + (0.16 \\ & \times \text{Root gap} \times \text{Root gap}) \\ & - (0.7132 \times \text{Plate thickness} \\ & \times \text{Load}) + (2.07 \times \text{Plate thickness} \\ & \times \text{Root gap}) + (0.074 \times \text{Load} \\ & \times \text{Root gap})\end{aligned} \tag{5}$$

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.

– Normal stress (MPa) = 266 – (75.48 × 8) + (9.932 × 32)– (15.7 × 3) + (5.03 × 8 × 8) – (0.00353 × 32 × 32) + (0.16 ×

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	0	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	6	40.5	2.5	216	78790	217	94263
7	2	5	62.5	3	400	12439	397	−29740
20	3	6	40.5	2.5	216	78790	217	94263
10	4	10	40.5	2.5	138	305948	143	337983
12	5	6	80	2.5	427	10220	431	79737
9	6	4	40.5	2.5	321	24177	315	−8445
5	7	5	32	3	204	92725	207	141830
11	8	6	22	2.5	117	491648	114	400970
2	9	8	32	2	127	383334	123	367428
6	10	8	32	3	131	350672	127	346553
8	11	8	62.5	3	256	48330	252	8087
19	12	6	40.5	2.5	216	78790	217	94263
4	13	8	62.5	2	249	51441	246	17646
1	14	5	32	2	205	92952	209	142275
17	15	6	40.5	2.5	216	78790	217	94263
16	16	6	40.5	2.5	216	78790	217.	94263
14	17	6	40.5	3.5	216	78790	218	86489
13	18	6	40.5	1.5	216	78760	217	94692
3	19	5	62.5	2	400	12474	397	−40611
15	20	6	40.5	2.5	216	78790	217	94263

$3 \times 3) - (0.7132 \times 8 \times 32) + (2.07 \times 8 \times 3) + (0.074 \times 32 \times 3) = 127.35$ MPa, whereas FEA results = 131.58 MPa.
– Fatigue life $= 224402 + (126291 \times 8) - (24031 \times 32) + (40093 \times 3) + (1596 \times 8 \times 8) + (279.5 \times 32 \times 32) - (3672 \times 3 \times 3) - (1824 \times 8 \times 32) - (6810 \times 8 \times 3) + (371 \times 32 \times 3) =$ 3,46,553 cycles, whereas FEA results = 3,50,672 cycles.

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.

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