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Fatigue Life Prediction of Butt Weld Joints with Weld Defects at Multiple Locations

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A numerical model developed using finite element software is used to determine the fatigue life of an arc-welded butt joint with weld defects: lack of penetration, lack of fusion, and undercut, which occur predominantly in welded structures. High-strength, tempered, and quenched fine grain ASTM A517 grade F structural steel, widely used in welded structures, is selected as the base material. The finite element analysis approach adopted in the present work is validated using the experimental and analytical results by performing a benchmark study. The validated numerical approach is then used to generate datasets for developing an empirical model for predicting the fatigue life of a butt joint with defects, modelled as cracks at specific locations, subjected to bending and/or membrane stresses. An experimental investigation was undertaken to validate the empirical model. The influencing parameters are ranked based on their severity on the fatigue life of butt joint.
Keywords: butt joint, weld defects, fatigue loading, fatigue life

Highlights

- *The present paper takes into consideration the size and location of weld defect in addition to the type of loading and type of weld defect to predict the fatigue life of a butt welded joint.*
- *The analysis revealed that a lack of penetration and undercut lead to minimum fatigue life when the butt joint is subjected to pure membrane stress.*
- *The combined influence of multiple smaller defects at various locations as against a single bigger defect at a particular location in a butt-welded joint is investigated and reported.*
- *A regression model is used to rank the severity of weld defect on the fatigue life of butt weld joint, and an experimental investigation was carried out to validate the above model.*

0 INTRODUCTION

Butt welding is a commonly used joining technique for most of the components that require simpler and strong bonding. The ASTM A517 grade F structural steel is selected as the base material for the present study, since it is used widely in welded structures in all kinds of applications [1] to [3], such as pressure vessels, transport vehicles, bridges, hoisting, and earthmoving equipment.

Welding is a major factor in the fatigue life reduction of any large structure. In fillet welded joints, stress concentration occurs at the weld toe, weld root and between the base and weld metal [4] to [6]. The above zones with higher stress concentration are more likely to initiate cracks when subjected to dynamic loads. Even though the fatigue properties of the weld metal are good, failure can be caused by the existence of weld defects, such as lack of penetration, lack of fusion, undercut, and porosity. In a single-pass, butt-welded joint, a lack of penetration (LOP) occurs at the root of weldment, lack of fusion (LOF) occurs between the surfaces of weldment and base plate, and undercut (UC) occurs at the weld toe [7]. Porosity will be commonly found close to the upper surface of weld reinforcement. Under fatigue loading, a crack may be initiated from the weld defect and the propagation of such a crack in weldment is likely to result in the failure of the joint. In the presence of weld defects, the crack initiation period is shorter relative to the crack propagation period [8]. A weldment with a defect is considered to be a notched component, and the crack initiation life can be predicted using a local stress-strain approach. The crack propagation life depends on the growth rate of the crack from its initial size to the critical size; it can be predicted by means of stress intensity factor (SIF) at the crack tip [9]. Even though equations are provided in SIF data-books for obtaining solutions for simpler weld joints, it is challenging to obtain adequate solutions for structures with different weld configurations involving complex geometry and loading conditions [10] and [11].

The present study takes into consideration the presence of weld defects at different locations in addition to the type of loading, type of weld defect, and size of defect for analysis. The weld defects are modelled as semi-elliptical cracks based on the recommendations made by the IIW for the fatigue design of welded joints and components [11]. The stress intensity factor in the proximity of weld defect

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is evaluated with M-integral and the corresponding propagation life is calculated using the Paris law with the aid of fracture analysis (FRANC3D) software. The main objective of the work is to predict and rank the severity of weld defects on the fatigue life of a butt-welded joint shown in Fig. 1, considering defects at three locations (CL_1, CL_2, CL_3).

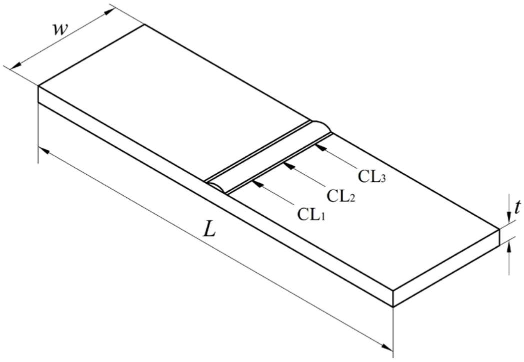


Fig. 1. *Crack locations in butt-welded joint*

1 BENCHMARK STUDY

Prior to performing the finite element analysis of a butt-welded joint with weld defect, a benchmark study considering a cruciform joint, with LOP defect, subjected to repeated tensile load (Fig. 2) is undertaken. The fatigue life corresponding to the failure of cruciform joint is determined using analytical and numerical methods and the same is compared with the experimental results presented by Balasubramanian and Guha [12].

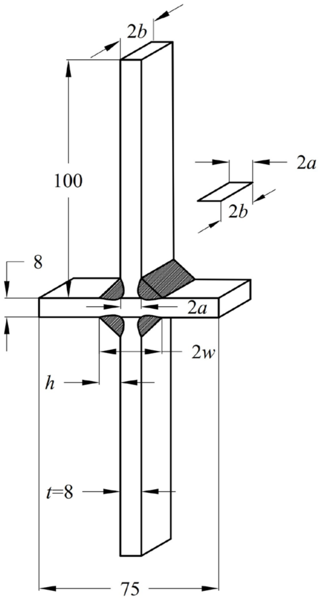


Fig. 2. *Cruciform joint with LOP defect*

The stress intensity at the crack tip is determined analytically by employing Eq. (1) proposed by Frank and Fisher [13] and numerically using FRANC3D software by modelling the LOP defect as a double-edge crack [11] and performing crack propagation analysis. The corresponding fatigue life is then calculated by using the Paris Erdogan law given by Eq. (2) [14] and [15].

$$K = \frac{\sigma\left(A_1 + A_2 \frac{a}{w}\right)\left(\pi a \sec\left(\pi \frac{a}{2w}\right)\right)}{1 + 2\frac{h}{t}}, \tag{1}$$

$$A_1 = 0.528 + 3.287\frac{h}{t} - 4.361\frac{h^2}{t} + 3.696\frac{h^3}{t} - 1.875\frac{h^4}{t} + 0.415\frac{h^5}{t},$$

$$A_2 = 0.218 + 2.717\frac{h}{t} - 10.171\frac{h^2}{t} + 13.122\frac{h^3}{t} - 7.755\frac{h^4}{t} + 1.783\frac{h^5}{t},$$

where σ is the normal stress range

$$w = h + \frac{t}{2}.$$

The above equation for stress intensity factor K is valid for the range of,

$$0.2 \le \frac{h}{t} \le 1.2 \quad \text{and} \quad 0.1 \le \frac{a}{w} \le 0.7.$$

$$\frac{da}{dN} = C(\Delta K)^m, \tag{2}$$

where C and m are Paris constants.

The experimental investigation [12] was carried out for both single-pass and double-pass welding considering various h/t ratios for the joint made of ASTM A517 grade F, at different stress levels. For the current benchmark study, a cruciform joint of $h/t=1$ with LOP of 7 mm and subjected to 120 MPa is considered. The corresponding fracture parameters [12] considered are as follows: fracture threshold ΔK_{th} of 126 MPa√mm, fracture toughness ΔK_{cr} of 1581 MPa√mm, and Paris constants ($C=1.29\text{e}^{-14}$, $m=3.4$).

Using an analytical approach, the initial SIF (ΔK_o) corresponding to the initial defect is determined as 256 MPa√mm. The size of defect is increased incrementally until the SIF reaches the fracture toughness of the material ($\Delta K_{cr}=1581$ MPa√mm), and the corresponding critical crack length is found to be 20.8 mm. Using Eq. (2), the corresponding fatigue life of the joint is calculated as 1.25×10^6 cycles.

As regards the numerical approach, a finite element model of the joint with defect is made using Brick 8 node 185 elements using Ansys software, as shown in Fig. 3a, and the fatigue life is determined using Franc3D software. The bottom end of the vertical plate of the cruciform joint is fully constrained and the load corresponding to a stress level of 120 MPa at weld zone is applied at the top end, and the principal stress distribution (Fig. 3b) is obtained.

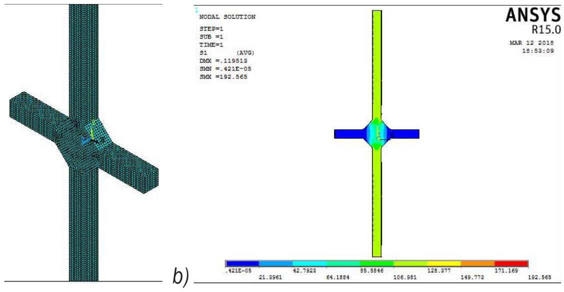


Fig. 3. *Cruciform joint; a) finite element model, and b) stress plot*

After performing stress analysis using Ansys software, the finite element model along with nodal displacements is imported into Franc3D software.

A double edge crack of length $2a$ = 7 mm and b = 8 mm is modelled and incorporated at LOP location in the weldment as shown in Fig. 4a. Franc3D uses an adaptive meshing technique, which allows fine mesh at the crack tip and coarse mesh at other geometric locations; therefore, mesh convergence is automatically taken care of. Static crack analysis predicts the initial SIF (ΔK_o) as 287 MPa√mm at the crack front of double edge crack. Furthermore, the crack was propagated at the rate of 0.3 mm until it reached the critical SIF value (1581 MPa√mm) as shown in Fig. 5. The finite element analysis (FEA) predicts the exact propagation path (Fig. 4b) in comparison to the experimentally determined path **[12]** and the fatigue life corresponding to the critical crack length is found to be 1.17 × 10^6 cycles.

Table 1. *Fatigue life of cruciform joint*

	Initial SIF ΔK_o [MPa√mm]	CI Life [×10^6 cycles]	CP Life [×10^6 cycles]	Total life [×10^6 cycles]
By analytical approach	282	-	1.25	-
By FEA	287	-	1.17	-
By expt. **[12]**	253	0.6	1.32	1.92

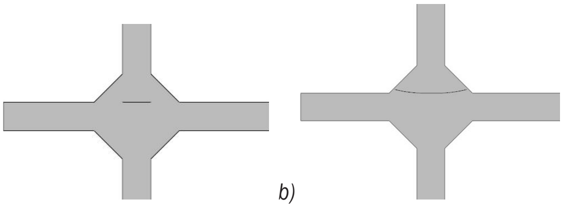


Fig. 4. *Crack propagation path; a) before propagation, and b) after propagation*

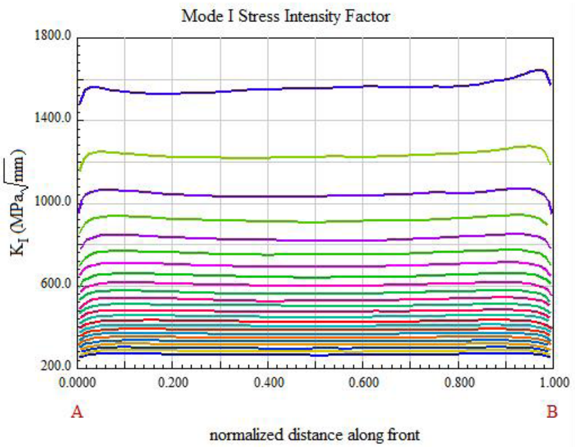


Fig. 5. *SIF along the crack front*

As shown in Fig. 6, the comparison plot shows good agreement between numerical and analytical solutions with a maximum deviation of 6.4 %. The numerical approach predicts the fatigue life with a deviation of 11 % compared to the experimental determination **[12]**.

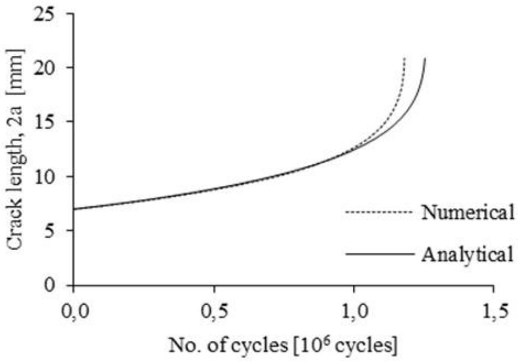


Fig. 6. *Comparison of crack propagation life of a cruciform joint*

Hence, the validated numerical approach is extended to predict the fatigue life of butt joint when the same is subjected to a combination of membrane and bending loads in the presence of weld defects at three locations.

2 FATIGUE LIFE PREDICTION OF A BUTT JOINT CONSIDERING WELD DEFECTS

The plate with the butt-welded joint is considered for the present study (Fig. 1). The material considered is ASTM A517 grade F steel for the plate as well as the weldment. In an in-depth approach, a hypothetical assumption is made to postulate defects with the assumption of severe violation of manufacturing standards.

The three major weld defects considered for the present investigation are lack of penetration [LOP], lack of fusion [LOF], and undercut as shown in Fig. 7. LOP happens when the metal groove is not entirely filled, with weld metal throughout joint thickness. LOP occurs because of improper edge preparation.

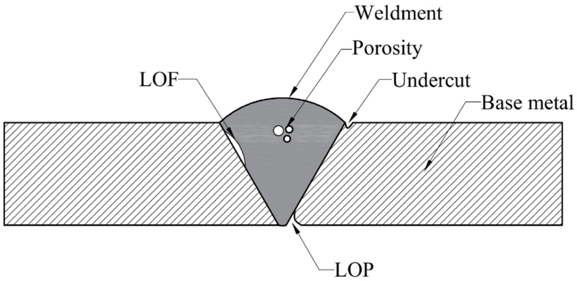


Fig. 7. *Types of weld defect*

LOF occur when there is an improper fusion between the metal and weld. This produces a gap inside the joint that is not filled with molten metal. A major cause of LOF is contamination of metal surface and use of low heat input. Undercut occurs at weld toe region because of an incorrect electrode angle and too high weld current. These defects will affect the fatigue strength of weld joint, which leads to joint failure. To rank the severity of these weld defects on the fatigue life of a butt-welded joint with respect to loading and position of defect, the following analysis is carried out.

The total length (*L*) of the two plates considered for analysis is 200 mm. The plate width (*w)* and plate thickness (*t)* are considered 60 mm and 8 mm, respectively. The initial dimensions of the weld defect LOP and LOF correspond to the length and depth are 15.2 mm and 1.6 mm, respectively. For undercut the values are 15.2 mm and 2 mm, respectively, as mentioned in Table 2. The initial weld defect dimensions are considered with respect to the maximum acceptable value mentioned as in the acceptance criteria for welds ASME B31.3 [16].

The above weld defects are modelled as equivalent cracks in the weld zones [11], and the crack growth behaviour is simulated using FRANC3D software. An initial non-cohesive semi-elliptical crack was placed in the finite element model depending upon the type of weld defect, as shown in Fig. 8. An adaptive mesh is auto-generated after incorporating the initial crack with appropriate dimensions and the fatigue life is estimated by performing crack propagation analysis. Fig. 9 shows the results of numerical simulation of crack propagation in a butt-welded joint.

Table 2. *Acceptance criteria - ASME B31.3 for weld defects*

Weld defect	Initial crack		Occurrence
	Length	Depth	
Lack of penetration	(38/150) w	0.20 t	Weld root
Lack of fusion	(38/150) w	0.20 t	Weld toe (Oriented to bead angle)
Undercut	(38/150) w	0.25 t	Weld toe

Fig. 8. *Finite element model of butt joint*

The simulation indicates the extent of crack propagation from top to bottom surface of the butt joint for lack of fusion and undercut and vice-versa for lack of penetration. The fatigue life corresponds to the number of cycles applied until the crack depth tends to approach plate thickness, where the crack becomes asymptotic.

Although LOF and undercut are modelled as cracks of the same dimensions, their position and orientation are different, as shown in Fig. 7. Therefore, LOF and undercut are likely to have a varying influence on fatigue life.

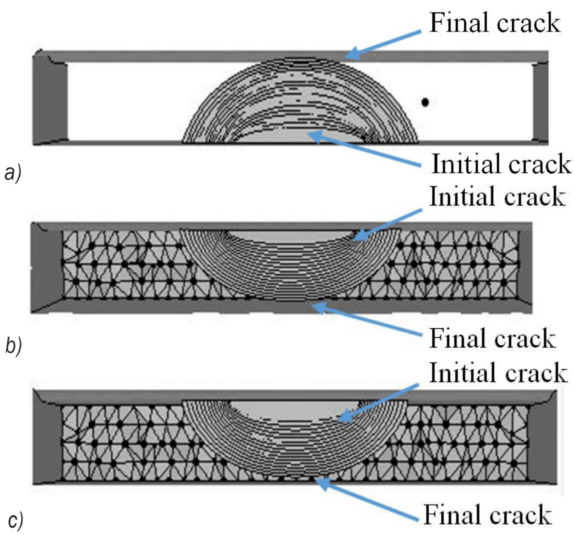


Fig. 9. *Numerical simulation of crack propagation in butt-weld joint; a) propagation of crack originating from LOP, b) propagation of crack originating from LOF, and c) propagation of crack originating from undercut*

3 TAGUCHI DESIGN FOR PREDICTION OF FATIGUE LIFE

Since the problem under consideration has a wide range of variables, a five-factor, three-level factorial design matrix was selected based on Taguchi design. The experimental design matrix contains the factors, viz., type of load (A), type of defect (B), Crack1(C), Crack2 (D) and Crack3 (E) at specific locations with their corresponding levels as shown in Table 3.

Table 3. *Control factors and their selected levels*

	Control factor	Level		
		1	2	3
A	Type of load	L1	L2	L3
B	Type of defect	LOP	LOF	UC
C	Location for Crack 1	CL1	CL2	CL3
D	Location for Crack 2	CL1	CL2	CL3
E	Location for Crack 3	CL1	CL2	CL3

Fig. 10 shows the stress distribution when the specimen is subjected to membrane load (P_m) and bending load (P_b) individually and as a combination of the above loads ($P_m + P_b$). On applying bending load in an upward direction, q lack of fusion will not have considerable influence on crack propagation in the top surface as it is subjected to compressive stress.

Similarly, for bending load in a downward direction, a lack of penetration will not have considerable influence on crack propagation. However, the high cyclic fatigue failure will occur at stress lesser than half the ultimate stress. Hence, the load applied on the plate corresponds to a normal stress of 120 MPa, which will aid in crack propagation analysis [17] and [18]; the same is considered while formulating the design matrix.

The specimen is fixed at one end, and a repeated load (zero to peak stress and back to zero) is applied with appropriate kinematic constraints for simulation to ensure that the plane section remains flat before and after application of load. Three types of repeated load (zero to peak stress and back to zero) considered for analysis are given below:

L1: Peak stress = 120 MPa (membrane),
L2: Peak stress = 60 MPa (membrane) + 60 MPa (tensile stress due to positive bending moment),
L3: Peak stress = 60 MPa (membrane) + 60 MPa (compressive stress due to negative bending moment).

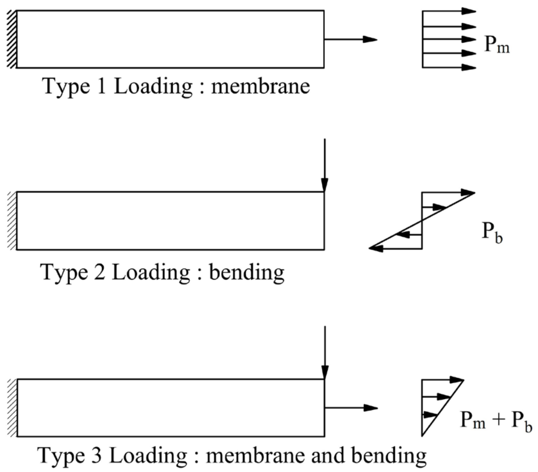


Fig. 10. *Types of loading on butt weld joint*

4 RANKING THE SEVERITY OF WELD DEFECTS ON FATIGUE LIFE

Based on the control factors and levels shown in Table 3, a design matrix is arrived with different datasets. The fatigue life of butt-joint is determined for each dataset in the design matrix by using simulation software (Franc3D) as shown in Table 4.

Considering the presence of three cracks (i.e., Crack1, Crack2 and Crack3) at the same location (CL1) as an example (Table 3), it implies that a bigger crack with thrice the dimensions of a single crack is incorporated in the finite element model for analysis. Since a higher fatigue life is desirable, the signal-to-noise ratio (S/N) is determined by using the criteria "larger is better", as shown in Table 5. To determine the fatigue life of butt-weld joint, a quadratic mathematical model of the second order is developed. The chosen empirical formula accounts for the influence of individual factors and their interactions. The empirical Eq. (3) obtained at 95 % confidence level using MINITAB statistical software is given ″in Eq. (3).

Table 4. *Design of experiments and results*

Type of load	Type of defect	Crack location			Fatigue life [cycles]
		Crack1	Crack2	Crack3	
L1	LOP	CL1	CL1	CL1	137511
L1	LOP	CL1	CL1	CL2	253440
L1	LOP	CL1	CL1	CL3	264217
L1	LOF	CL2	CL2	CL1	324471
L1	LOF	CL2	CL2	CL2	211396
L1	LOF	CL2	CL2	CL3	378649
L1	UC	CL3	CL3	CL1	218589
L1	UC	CL3	CL3	CL2	252548
L1	UC	CL3	CL3	CL3	127441
L2	LOP	CL2	CL3	CL1	907636
L2	LOP	CL2	CL3	CL2	572106
L2	LOP	CL2	CL3	CL3	557734
L2	LOF	CL3	CL1	CL1	378091
L2	LOF	CL3	CL1	CL2	484553
L2	LOF	CL3	CL1	CL3	381541
L2	UC	CL1	CL2	CL1	288604
L2	UC	CL1	CL2	CL2	334500
L2	UC	CL1	CL2	CL3	450367
L3	LOP	CL3	CL2	CL1	298335
L3	LOP	CL3	CL2	CL2	207791
L3	LOP	CL3	CL2	CL3	198583
L3	LOF	CL1	CL3	CL1	496818
L3	LOF	CL1	CL3	CL2	648794
L3	LOF	CL1	CL3	CL3	472327
L3	UC	CL2	CL1	CL1	364090
L3	UC	CL2	CL1	CL2	354164
L3	UC	CL2	CL1	CL3	532533

$$\begin{aligned} Fatigue\ life = & -861119 + 1060067\times A - 1158\times B \\ & + 830911\times C - 537257\times D - 83433\times E \\ & - 248806\times A\times A - 43478\times B\times B - 194710\times C\times C \\ & + 178706\times D\times D + 47164\times E\times E - 58972\times A\times E \\ & + 301728\times B\times E - 113427\times C\times E - 72243\times D\times E \\ & + 419643\times A\times A\times E - 55182\times A\times B\times E \\ & + 11372\times A\times C\times E - 6243\times A\times E\times E \\ & - 18200\times B\times B\times E - 16512\times B\times E\times E \\ & + 6368\times C\times E\times E - 3335\times D\times E\times E. \end{aligned} \tag{3}$$

The average S/N ratio and the average fatigue life for each factor at every level are obtained. Subsequently, delta values are computed, and the factors that influence the fatigue life are ranked as shown in Table 5. It is inferred from the table that the type of load has the largest effect on S/N ratio among the control factors considered. Furthermore, L_1 is found to have lower S/N ratio than the other two types of load, which implies that L_1 is more critical.

Table 5. *S/N ratio on fatigue life*

Level	Type of load	Type of defect	Crack location		
			Crack 1	Crack 2	Crack 3
1	107.2	110	110.6	110.3	110.5
2	113.2	112.1	112.7	109.2	110.6
3	111.4	109.6	108.4	112.2	110.6
Delta	6	2.5	4.3	3	0.2
Rank	1	4	2	3	5

Next, it is required to determine the effect of weld defect on fatigue life, considering the critical load type (L_1) by referring to Table 4. It is inferred from the table that two cases result in minimum fatigue life owing to the maximum severity of weld defect; lack of penetration leading to 137511 cycles and undercut leading to 127441 cycles, where either of the defects is concentrated at a single location.

The next level of severity pertaining to crack location is assessed by referring to Table 4, where the values of fatigue life are 198583 cycles and 288604 cycles. The fatigue life of 198583 cycles corresponds to lack of penetration, where the concentration of weld defect in terms of crack size at CL_3 is twice that of a single crack at CL_2. Similarly, the fatigue life of 288604 cycles corresponds to undercut, where the concentration of weld defect in terms of crack size at CL_1 is twice that of a single crack at CL_2. The lack of fusion is found to have a lesser influence towards reducing the fatigue life of butt welded joint.

In general, referring to Table 5, it is found that a bigger crack at a single location (rank 2) has more influence than relatively smaller cracks at multiple locations (rank 3 and rank 5).

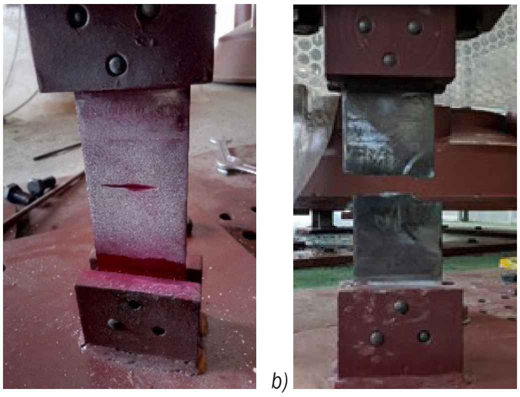
5 EXPERIMENTAL VALIDATION OF THE EMPIRICAL MODEL

By performing numerical analysis and subsequently adapting an empirical model for ranking the severity of weld defects on fatigue life of butt joint, it is found that undercut has more influence on fatigue life under tensile loading. To validate the empirical model, a typical dataset (L_1, UC, CL_2, CL_2, CL_2) is considered for experimental investigation. A BISS (Bangalore Integrated System Solutions) 50 kN hydraulic actuator with a maximum frequency of 20 Hz was used to propagate the crack in butt weld joint.

Two plates (130 mm × 60 mm × 12 mm) made of ASTM A517 grade F were welded together to form a butt joint, which was considered for numerical analysis; an additional length of 30 mm was provided at the ends to facilitate the clamping of specimen. The centre portion of the plate was reduced to a thickness of 8 mm by milling to obtain the desired stress level in the weld zone. An equivalent notch that represents undercut was made at the mid-location CL_2 by using a 0.5 mm metal cutting wheel. The specimen was held in a fixture using dowel pins and the fixture was connected between the actuator head and base plate by bolted connection as shown in Fig. 11. The butt-welded specimen with a notch of length 15 mm and depth 1.6 mm was preloaded by applying a force of 0.1 kN in the vertical direction to eliminate free play. To initiate crack at notch tip, the specimen was subjected to high cycle fatigue at a frequency of 5 Hz. A stress level of 80 MPa was maintained at the notch tip to avoid plastic deformation.

Fig. 11. *Butt joint under fatigue loading*

At the notch tip, dye penetrant testing as shown in Fig. 12a was carried out for every 10,000 cycles to monitor the crack growth behaviour. After a period of 1.1 × 10^5 cycles, a visible crack of 0.5 mm was identified at the notch tip. Furthermore, to propagate the crack, the specimen was subjected to low-cycle fatigue by increasing the stress level to 120 MPa. The loading frequency was maintained at 1 Hz to maintain the rate of propagation in a controlled manner. The propagation of crack was measured for every 10,000 cycles using a crack depth gauge; the corresponding crack length was plotted as shown in Fig. 13.



a) b)

Fig. 12. *Butt-welded joint; a) initial notch, and b) fractured specimen*

It is evident from the crack growth curve that the specimen fractured at 1.53×10^5 cycles. For the same dataset (L_1, UC, CL_2, CL_2, CL_2), the fatigue life of butt joint is estimated using the empirical model and the numerical technique. The corresponding fatigue lives are found to be 1.78×10^5 and 1.71×10^5 cycles, respectively.

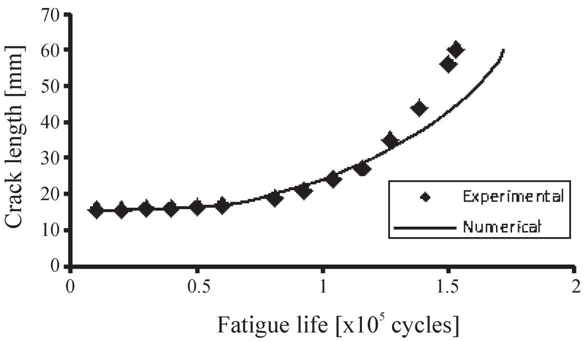


Fig. 13. *Crack growth curve*

The experimental determination shows 14 % deviation of fatigue life predicted by the empirical model, which accounts the deviation of 4 % between the prediction of numerical and empirical model. This gives more confidence on numerical procedure and the empirical model to determine the crack propagation life.

6 CONCLUSIONS

A systematic analysis of a butt weld joint using FEA was undertaken by incorporating weld defects as equivalent cracks and propagating them until they become through-wall cracks. The number of cycles taken for an initial crack to become a through-wall crack is estimated as the fatigue life of a butt-weld joint. The numerical model of cruciform joint with LOP defect was validated using an analytical equation and experimental results found in the literature.

A Taguchi experimental design was employed to determine the extent of severity of weld defects at multiple locations on the fatigue life of the butt-weld joint subjected to membrane and bending stresses. The lack of penetration and undercut were found to result in minimum fatigue life, when the joint is subjected to pure membrane stress rather than a combination of membrane and bending stresses.

In the presence of multiple defects in the butt-welded joint, the combined influence of three defects followed by two defects at either one-fourth or three-fourth locations along the length of weld is found to significantly reduce the fatigue life, more so than the presence of defect at mid-span of weldment. Also, compared to smaller multiple defects, a single defect of combined size of multiple cracks has more influence on the fatigue life of a butt weld joint. While ranking the weld defects based on severity, LOP has the highest influence on fatigue life, while undercut is marginally less severe. The least severe type of defect on fatigue life is found to be lack of fusion.

In the present work, stress is taken as the driving parameter and not the applied load. Furthermore, the defects are parametrically modelled and hence the size of defects is proportional to geometric dimensions of plate. Therefore, the results are geometry independent and are quite generic.

7 ACKNOWLEDGEMENTS

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