中國機械工程學刊第四十三卷第二期第 127~141 頁(民國一百一十一年)
Journal of the Chinese Society of Mechanical Engineers, Vol.43, No.2, pp127~141 (2022)

Fatigue Life Prediction Using Virtual Strain Gauge for Backing Strip Full Penetration Weld Joint

Gopalan Venkatachalam*, Atul R Deshmukh**, A. Raja Annamalai***, Vignesh Pragasam****, Gokula Krishnan Balasubramanian*****, Vijay Venkataraman****** and Chun-Ping Jen*******,********

Keywords: Backing Strip Weld Joint, Strain life, Fatigue life, Response Surface Methodology, Finite Element Analysis

ABSTRACT

This paper focuses on the fatigue life estimation of backing strip full penetration weld joint by means of the virtual strain gauge and its validations via fatigue experiment. Currently, many commercial software packages are supporting stress-strain analysis using the finite element method but it is significant to validate the obtained results with experiment and established methodology. The finite element analysis is employed to predict the fatigue life by considering three input parameters such as the applied load (Ld), root gap (Rg) and thickness of the plate (Pt). Effect of input effect plot which is based on Response Surface parameters on response parameter i.e. fatigue life is analyzed through main Methodology, a Design of Experiments approach, with 20 set of experimentation and results are experiments. validated by performing the actual fatigue Based on virtual and actual experiments, it is observed that plate thickness is directly proportional to the fatigue life whereas load is inversely proportional. But root gap from 2mm to 3 mm is showing the negligible effect but after 3mm it is showing inverse effect on fatigue life. The use of design of experiments approach for the fatigue life estimation without performing the experimental validation will be extremely useful in upcoming future works and it also minimizes the time and cost.

Paper Received January, 2021. Revised January, 2021, Accepted February, 2021, Author for Correspondence: Chun-Ping Jen

**Professor, School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India.*

***Head, Centre of Expertise, JCB India Limited, Pune, India.*

****Associate Professor, Centre for Innovative Manufacturing Research, VIT, Vellore, India*

*****PhD scholar, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, India.*

******PG Student, School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India.*

*******Design Engineer, Byford equipment Pvt Ltd, Derrimut, Victoria, Australia.*

********Professor, School of Dentistry, College of Dental Medicine, Kaohsiung Medical University, Kaohsiung 80708, Taiwan, R.O.C.*

*********Professor, Department of Mechanical Engineering and Advanced Institute of Manufacturing for High-Tech Innovations, National Chung Cheng University, Chia-Yi, Taiwan, R.O.C.*

INTRODUCTION

Weld fatigue is a very complex process to understand. Many researchers are trying to develop simple algorithm/ method to understand it in a simple way. Over the years, literature is available on simple weld like Fillet and Butt weld joints and it has been achieved the good confidence on fatigue calculation but still lot of other weld joints are unaddressed like full penetration backing strip weld joint in off-highway vehicle. Understanding such typical weld joint used in heavy industry is essential because majority of off-highway vehicle welded components are subjected to cyclic load during field application.

Fatigue Failure at weld joint is a major reason for breakdown of fabricated structures in construction and mining equipments leading to substantial warranty costs. Most of the main structures and components in off-highway vehicles are fabricated welded steel structures from different steel grades. Each structural component is complex in terms of geometry, loading conditions and types of weld joint configurations.

Four different kinds of methods are used for weld fatigue life estimation in off-highway vehicles and those are classified under global and local methods. It is observed that the nominal stress method is widely used as a global method and the local method is based on the hot spot stress theory. Among the four methods reported, numerical methods like FEM based on S-N classification for weld classes are the first three methods to calculate the fatigue life of welded joints, whereas fracture mechanics theory is used as the fourth method.

Nominal Stress Approach

The application of nominal stress concept uses standard S-N Curve based on the weld joint classes found in BS7608. This approach is helpful to evaluate the fatigue life of welded joints and also for the non-welded parts. Only in case of welded joints, some of the variables are introduced differently. The S-N Curve is defined based on the weld class, notch factor, plate thickness effect and the weld quality of fabricated parts. However, in case of non-welded parts, it depends upon the material, geometry and surface parameters.

The weld joints are classified based on their shape, type of weld (Full penetration or partial penetration), type of loading and quality of manufacture. In case of complex weld joint configurations commonly used in off-highway vehicle structures, the nominal stress approach is not applicable due to weld joint configuration and the local joint stiffness. Over recent years, the consideration of several influence factors like plate thickness has significant effect on mean stress in the fatigue analysis. In case of nominal stress approach, bi-axial stress requires special focus, especially when the stress components are not in the same plane.

Hot Spot or Structural Stress Method

This method is called as the “geometric stress” approach because it is applicable to complex geometry along with the loading complexities and it is developed for the geometries where it is very difficult to calculate the nominal stress. The use of structural stress approach is increased rapidly in recent years for complex weld joints due to the development of finite element analysis and computational hardware development. Various international standards/codes are available for load assumptions, suitable S-N curve and stress concentration factors (SCFs) based on parametric hot-spot stress formula. But still these are not defining the complex weld joints.

This method addresses failures which start from the weld toe only. This methodology is suitable for fatigue failure initiated from weld toe and hot spot stress can be read directly from the finite element analysis results. It has been witnessed that the nodal averaging is substantial when coarse mesh is used during finite element modeling.

Effective Notch Stress Method

In this method, fatigue stress prediction is based on elastic notch at the critical points and this method was proposed by Radaj et al. (2006). The procedure followed here is same as nominal stress approach except that the effective local stress is considered in place of global nominal stress. During the application of effective notch stress approach in finite element analysis of weld joint, adequate mesh density is necessary around the toe of weld where stress concentration is higher. Such region should be modeled with fine mesh having sufficient accuracy which can be achieved with the help of 3D solid element. Accurate notch stresses near to the weld toe line can be computed through the sub-modeling technique that can help to take a closer look at details without refining the entire model. This is most common techniques in off-highway vehicles because of the size of components and most of the failure occurs from the weld toe and the root. In case of sub-modeling, displacement is used as boundary condition that is derived from full model.

Linear Elastic Fracture Mechanics (LEFM)

One of the first techniques established and briefed in BS7910 standard. Detailed engineering procedure for detection of flaws and deficiencies seen in the fusion-welded joints are mentioned in the British standard BS7910. This method works based on the assumption of an existence of an initial crack(s).

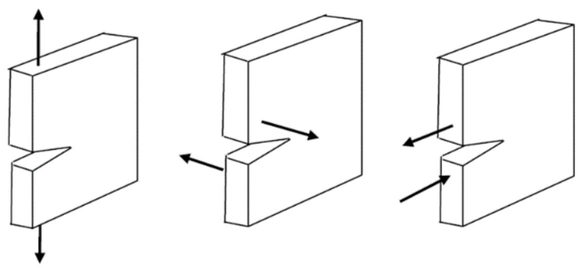


Fig. 1. Various loading modes, Mode 1: Normal to crack plane loading, Mode II: Shear loading, Mode III: Tearing loading

In case of mode I, shown in Fig. 1, stresses are perpendicular to plane of crack, so that crack surfaces are directly moving away from each other. Mode II is shear mode and it experiences when component is under shear loading and mode III is tearing mode that is due to out of shear plane.

Mode I is most important for welded joints and the stress intensity factors (SIF) in respective mode define the singular stresses near the crack tip. SIF controls the whole stress field prior to the crack front.

The concept of SIF is of a general nature and will be extended to a spread of geometries and loading modes.

The Application of Finite Element Analysis is very well integrated step of design process to get the valuable and reliable results and it is possible due to high power in computations and efficient technology in system software. Solid elements are much accepted in off-highway vehicles due to complex weld geometry and element itself can represent geometry in reality due to the fact that they are all 3-dimensional element. Weld joint is always observed with different thickness and during welding, material properties are strongly affected (Fricke, 2003) as the result of heating and cooling cycles during the weld process. Hence strain gauge position is strong challenge in front of test engineer and it is more critical when component having multiple welds and complex geometry loading and plate thickness are higher (Radaj et al., 2006). Fatigue Analysis for the welded structures can be categorized in to local and global approaches (Radaj et al., 2006) and it is based on stress, strain, and stress intensity factor or notch stress. Since the S-N Curve includes the corresponding weld class details and the local geometric properties, the Normal stress method comes under the category of global approach.

Methods based on Structural Stress (B. Atzori et al., 2001) disregard the detail classes but the local geometric properties (Sonsino, 2009) of the weld, e.g., weld angle, toe radius etc., are still considered to be included in the corresponding S-N curve (P. Dong et al., 2002). These days, the structural stress analysis of most complex structural model with very fine mesh can be done using computational hardware. Haibach primarily proposed a challenging approach (Haibach, 1968) for experimental estimation of fatigue life of complex welded joints like joggle joint which have dissimilar weld configurations and complex geometry, based on measurements of strain near the weld toe by placing strain gauges.

By using miniature strain gauges close to the weld toe (Fricke, 2012), the distance can be few tenths of a millimetre based on weld joint. Few attempts were made already on simple fillet joint and validated by strain gauge testing using 2mm-3mm strain gauge location from weld toe. In this work, backing strip weld joint is considered to predict the fatigue life using strain gauge measurements and it is estimated at 10mm distance from weld toe. The measurements from strain gauge give us an opportunity to measure secondary bending effects that occur in actual joints based on geometry of the joint configuration and loading conditions. By using 1mm mesh criteria, the fatigue life can be predicted virtually by finite element method. The regression equations developed from response surface methodology virtually predicts the fatigue life and saves the time and cost of experiment.

METHODOLOGY

Nowadays, the Finite Element Analysis (FEA) is employed for prediction of fatigue life for some of the most complex loading and complex manufactured components as well. Challenge is to apply such methods for typical weld joint configuration like backing strip full penetration weld joint. The FEA gives an approximate solution and its accuracy depends on how FE model represents the physical experiment. In order to represent the physical experiment more accurately and reduce solving time, sub modeling techniques are used. When geometrically complex due to some welding with different weld joint configurations in one part, a mostly wide process used in industry for fatigue life calculation is based on strain measurement close to weld toe. Backing strip weld joint specimens are designed as shown in Fig. 2 to investigate the state of stress level near to weld joint toe.

FEA helps in predicting fatigue life numerically. Number of FEA simulations to be performed is decided by design of experiment approach. Results of FEA simulations are analyzed using analysis of variance (ANOVA). One of the outcomes of ANOVA is regression equation which helps to understand the level of influence of input parameters on fatigue life. Design of Experiments (DOE) is employed to get the effect of the input parameters on response parameter. In this paper, weld joint parameters such as Root Gap (Rg), Plate thickness (Pt) and Load (Ld) are considered as input parameters with the fatigue life (Lf), as response parameter. Five different levels for each input parameters are selected as -2, -1, 0, 1 and 2 in closed form to have a rotatable design. A central composite design (CCD) is used with 20 experimental runs as given in figure 3 to conduct the experiments and the values of different parameters used along with their levels are shown in Table 1.

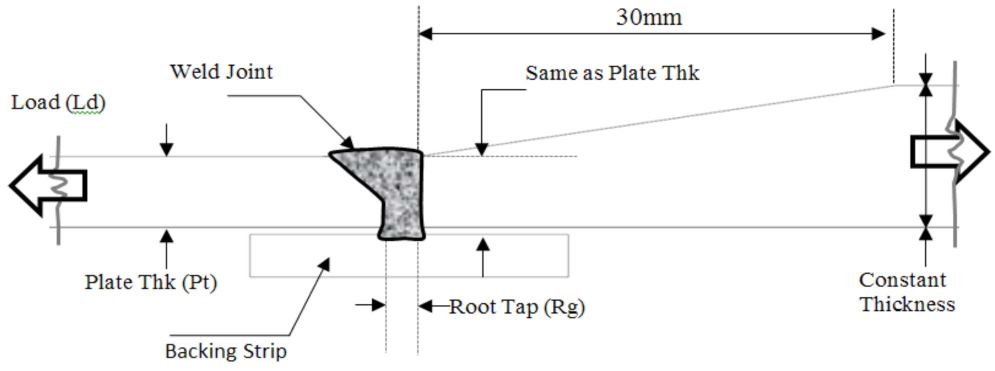


Fig. 2. Backing strip joint with parameters definitions.

Table 1. Welded joint parameters and their corresponding 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

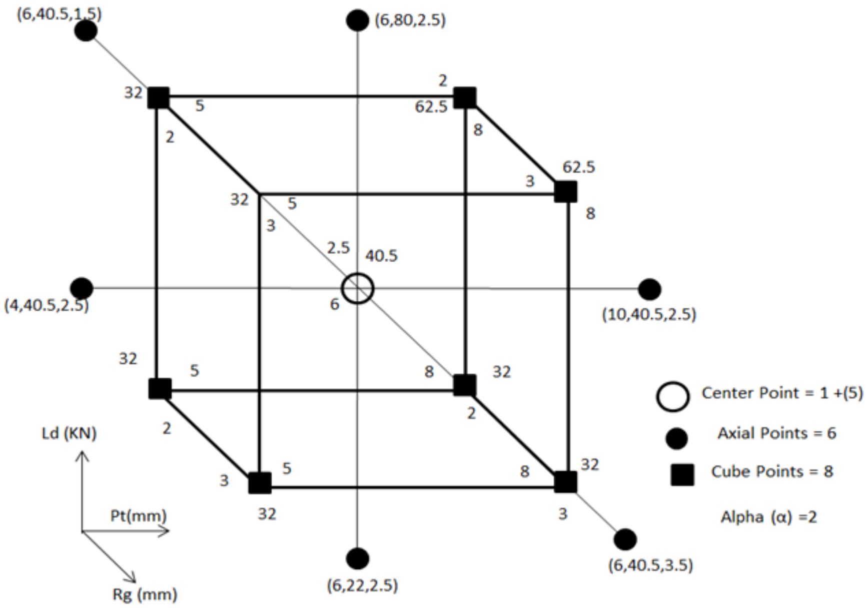


Fig. 3. Central composite design with α=2

$$Xi = \frac{\text{Chosen parametric values} - \text{Central rank of parameters}}{\text{Interval of variation}} \quad (1)$$

Where Xi is the coded values of the variables Pt, Rg and Ld, respectively. The values obtained from Eq.(1) are tabulated in Table 2 and it requires 20 experiments.

FATIGUE EXPERIMENT

To achieve the full penetration weld joint, backing strip weld joint configuration is commonly used in construction equipment industry. Weld specimens are designed and manufactured to reflect the weld joint that exist in actual application. IS2062 E350 Steel Alloy is used to make the steel specimens and its mechanical and chemical properties are shown in Table 3.

It is noted that for the comparison of behavior of a weld sample, the specimen is made with the same geometrical parameters using the same grade of material. When the geometry of the joint is complex in manufacturing and loading, the strain measurement at the weld toe is adopted widely for the actual experimentation. Three random samples from Table 2 are prepared by laying the Vishay micro measurement gauges CEA-XX-125UN-350 as shown in Figure 4. Strain gauge no 601 is pasted 2mm from plate edge, 10mm away from weld toe, Strain gauge 602 is pasted at middle of plate, 10mm away from weld toe and strain gauge 603 is 2mm from plate edge, 5mm away from weld toe.

It is further tested at the room temperature using INSTRON fatigue testing machine as shown in Figure 5 at the frequency of 10Hz and data was recorded using the eDAQ data logger in Panasonic Toughbook.

Table 2. DOE Table.

Grade Designation	Chemical Composition					Yield Stress	Tensile Strength
	C	Mn	S	P	Si	MPa	MPa
E350	0.20	1.55	0.040	0.040	0.45	350	490

Table 3. Material properties of plate

Standard 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
2	2	1	8	-1	32	-1	2
1	3	-1	5	-1	32	-1	2
16	4	0	6	0	40.5	0	2.5
13	5	0	6	0	40.5	-2	1.5
14	6	0	6	0	40.5	2	3.5
9	7	-2	4	0	40.5	0	2.5
11	8	0	6	-2	22	0	2.5
3	9	-1	5	1	62.5	-1	2
8	10	1	8	1	62.5	1	3
20	11	0	6	0	40.5	0	2.5
12	12	0	6	2	80	0	2.5
7	13	-1	5	1	62.5	1	3
15	14	0	6	0	40.5	0	2.5
19	15	0	6	0	40.5	0	2.5
4	16	1	8	1	62.5	-1	2
17	17	0	6	0	40.5	0	2.5
5	18	-1	5	-1	32	1	3
10	19	2	10	0	40.5	0	2.5
6	20	1	8	-1	32	1	3

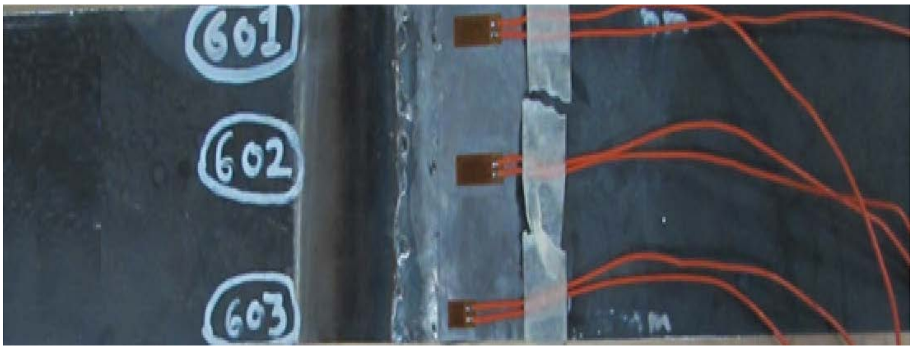


Fig. 4. Strain gauges sample of backing strip weld joint.

Fig. 5. Fatigue test of backing strip joint.

NUMERICAL MODELING OF THE BACKING STRIP WELDING JOINT

In order to understand the strain levels nearer to weld toe in backing strip weld joint configuration, a three-dimensional elastic plastic FEA is carried out using ANSYS 16.2 software as shown in Figure 6. The 20-node isoparametric Solid 186 finite element is used for each of the model and the size of element is 1mm as shown in Figure 7.

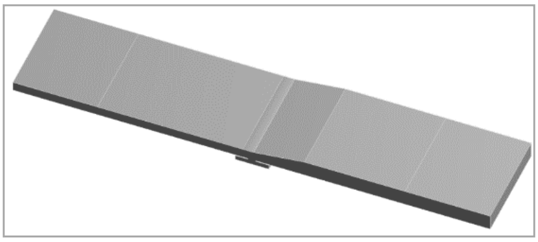


Fig. 6. Backing strip weld joint specimen.

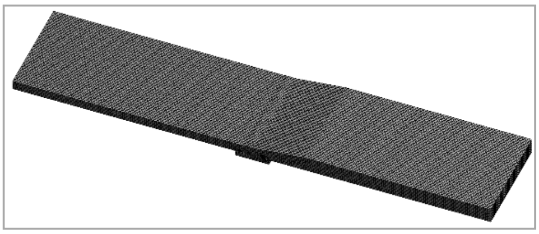


Fig. 7. Numerical model with mesh density of backing strip joint.

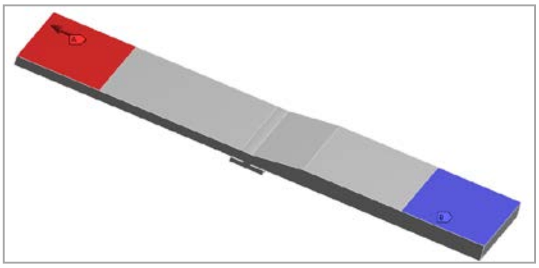


Fig. 8. Load and boundary condition.

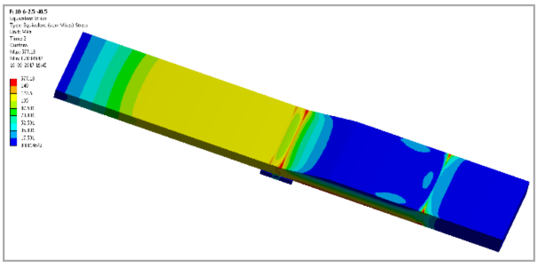
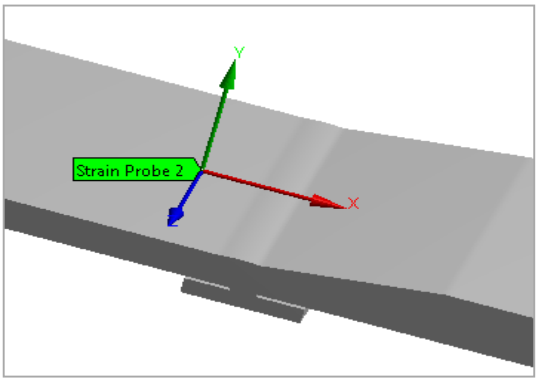


Fig. 9. Equivalent stress results for Run Order 18



Tabular Data

	Time [s]	☑ Strain Probe 3 (NormX) [mm/mm]
1	1.	5.6187e-004
2	2.	-5.6187e-004

Fig. 10. Virtual strain gauges result 10 mm weld toe.

The FEA is carried out by considering the isotropic elastic material for both base plates, weld metal and also the backing strip plates. For the complex weld joint, when the thickness of plate is different, there is a high stress concentration nearer to weld toe due to the stress component acting normal to the weld toe line which is predominantly responsible for the fatigue damage accumulation in this region. FE modeling and its results of run order 18 are shown in Figure 8 and Figure 9. Normal strain values 10mm away from weld toe are measured using the virtual strain gauge as shown in Figure 10.

RESULTS AND DISCUSSIONS

FEA Simulations and Practical Experimentation Comparative Analysis

Fatigue life estimation for complex weld joint through the experimental analysis is tedious, costly and time consuming because of geometry, the number of parameters involved and number of stress concentration points. Fatigue life of weld joint is evaluated by means of the normal stress methods and fall under the category of "E" Weld Class of the BS 7608 code with area ratio equal to one (Jonsson et al., 2012). "E" Class Stress life curve shown in Figure 11.

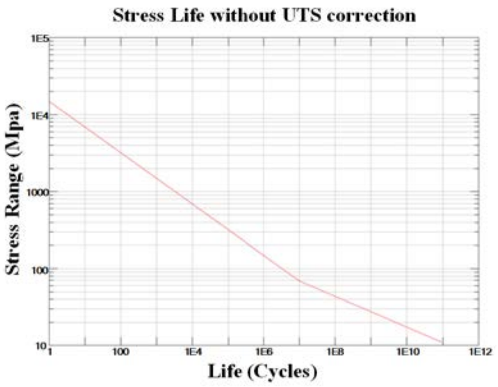


Fig. 11. "E" Class S-N curve as per BS7608 Standards

A uniaxial stress state exists where there is only one non-zero principal stress. The uniaxial stress-strain equations, given in equations (2) and (3) are applied and the results are as tabulated in Table 4.

$$\epsilon_x = \frac{\sigma_x}{E} \quad (2)$$

$$\sigma_x = E\epsilon_x \quad (3)$$

Table 3 compares the results of FEA and fatigue testing experiments. Less than 10% error between FEA and experiment shows the genuineness of the developed finite element model. Hence the further analysis is carried out using FEA. FEA is carried out for 20 different combinations suggested by Table 2. Fatigue life, predicted for 20 combinations, is tabulated in Table 5.

Main Effects Plot

Obtained from ANOVA, the Main effects plot helps to understand the level of influence of input variables on Fatigue life. The most influencing parameter, which influences the weld's fatigue life, is the plate's thickness. Figure 12 reveals that fatigue life increases with an increase in the thickness of the plate. The fatigue life up to 2 mm is affected by the root gap. Then it does not influence 3 mm. After 3 mm, the fatigue life is decreased. Figure 11 shows the inverse relationship between fatigue life and the load. The fatigue life is decreased when the load is increased.

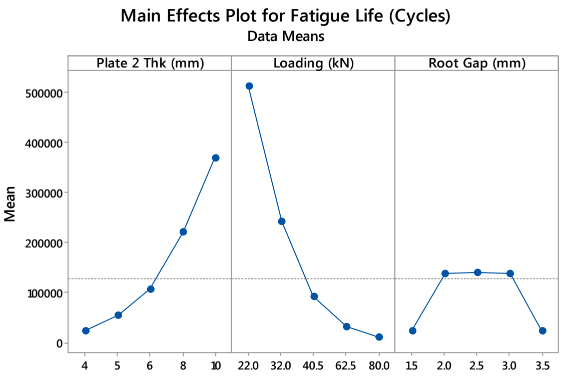


Fig. 12. Main effect plot

Contour Plot

For the various combinations of the influencing parameters, the corresponding contour plot is drawn. The variations in the magnitude of the shade in the plot correspond to the variations in the Fatigue performance i.e. Fatigue Life cycles. Figures 13 (a) – 13 (c) show the root gap's influences, the thickness of the plate, and Fatigue life load. As shown in Figure 13(a), the increased load with smaller thickness in plate results in lower fatigue life, which eventually confirms the basic of mechanism of fatigue life. Figure 13(b) shows the effect of the root gap and load on Fatigue life. The escalation in load and an increase in root gap display the mixed effect on fatigue life. The Root Gap of 1.5 mm is not appropriate for fatigue life as a lower root gap in manufacture creates a problem in attaining root fusion and a right sidewall. The fatigue life is significantly increased by increasing the root gap (Rg) and plate thickness (Pt). This can be seen in Figure 13(c).

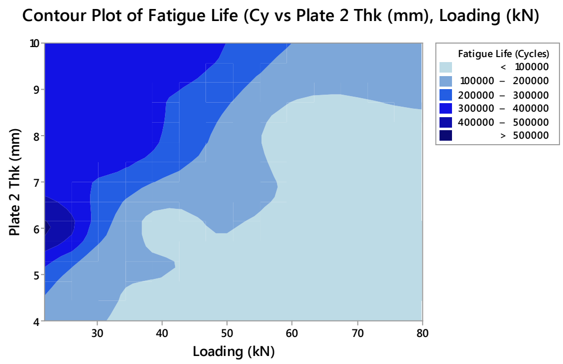


Fig. 13a. Effect of plate thickness and loading on life.

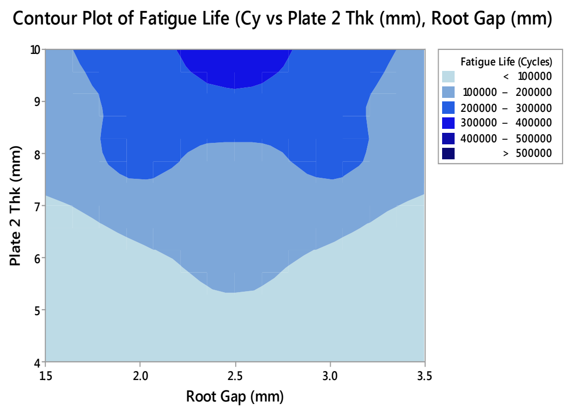


Fig. 13b. Effect of root gap and plate thickness on life.

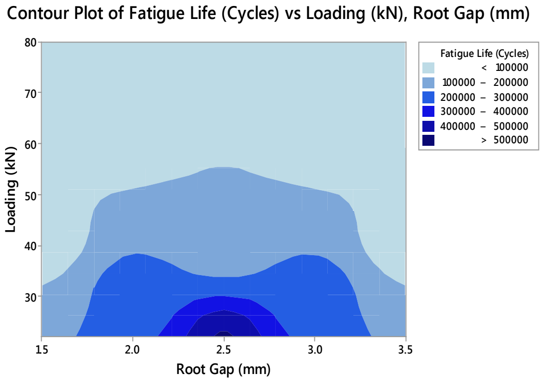


Fig. 13c. Effect of load and root gap on life.

Table 4. Fatigue results in FEA vs. Experiments

Standard Order	Plate thk (mm)	Load (L) kN	Root Gap (Rg)	FEA Results			Experimental Results			Error
				Strain Range	Stress (MPa)	Life (Mean - 2SD) Cycles	Strain Range	Stress (MPa)	Life (Mean - 2SD) Cycles	
18	6	40.5	2.5	1123.92	214	42342	1393.9	265	43162	2%
10	10	40.5	2.5	680.86	129	370441	700.6	133	339999	9%

Table 5. Fatigue life using FEA

Standard Order	Run Order	(Pt) Plate thickness mm		(Ld) Load kN		(Rg) Root Gap mm		Fatigue Life (Cycles) Mean -2SD
		Coded	Actual	Coded	Actual	Coded	Actual	
18	1	0	6	0	40.5	0	2.5	92342
2	2	1	8	-1	32	-1	2	390250
1	3	-1	5	-1	32	-1	2	127586
16	4	0	6	0	40.5	0	2.5	92342
13	5	0	6	0	40.5	-2	1.5	44901
14	6	0	6	0	40.5	2	3.5	44616
9	7	-2	4	0	40.5	0	2.5	24740
11	8	0	6	-2	22	0	2.5	413815
3	9	-1	5	1	62.5	-1	2	43094
8	10	1	8	1	62.5	1	3	62238
20	11	0	6	0	40.5	0	2.5	92342
12	12	0	6	2	80	0	2.5	90683
7	13	-1	5	1	62.5	1	3	43030
15	14	0	6	0	40.5	0	2.5	92342
19	15	0	6	0	40.5	0	2.5	92342
4	16	1	8	1	62.5	-1	2	12370
17	17	0	6	0	40.5	0	2.5	92342
5	18	-1	5	-1	32	1	3	127113
10	19	2	10	0	40.5	0	2.5	370441
6	20	1	8	-1	32	1	3	389272

Table 6 Response Surface (2^{nd} order) Quadratic Model (QM) of Fatigue Life using ANOVA

Sources	DF	Sum of Square	Mean Square	F Values	P-Values
Model	9	4.10599E+11	45622072461	14.22	0.00
Linear	3	29049101118	9683033706	3.00	0.081
Plate Thk	1	1954372989	1954372989	0.61	0.453
Root Gap	1	16528538194	16528538194	5.15	0.047
Load	1	3026367924	3026367924	0.94	0.354
Square	3	98271261456	32757087152	10.21	0.002
Plate Thk*Plate Thk	1	2325935420	2325935420	0.73	0.414
Root Gap * Root Gap	1	78956521552	78956521552	24.61	0.001
Load * Load	1	5210270032	5210270032	1.62	0.231
2-Way Interaction	3	19096745099	6365581700	1.98	0.035
Plate Thk * Root Gap	1	19096547270	19096547270	5.95	0.996
Plate Thk * Load	1	80160	80160	0.00	0.995
Root Gap * Load	1	130773	130773	0.00	
Error	10	32078722797	3207872280		
Lock of Fit	5	32078722797	6415744559		
Pure Error	5	0	0		
Total	19	4.42677E+11			

Regression Equation

Table 6 reveals the Analysis of Variance (ANOVA) of fatigue life. Variation analysis among the different parameters is carried with the help of F-test (ANOVA) at 95% confidence level. By correlating the F- Values with common values at the respective degree of freedom (DOF) and confidence level at 95%, significance and insignificance are obtained.

Fatigue Life

Fatigue life analysis, predicted using the quadratic model, is statistically noteworthy. Table 6 shows the ANOVA results and F-value, P-values & the sum of squares against fatigue life. Equation (4) represents the fatigue life regression equation which is 2^{nd} order polynomial equation. The influence of Weld joint factors on the principal response criteria, i.e., Fatigue life & Normal stress, are studied with the help of an interactive and high-order mathematical model developed using RSM through the various weld joint parameters as input variables. Equation 1.4 presents the regression model developed using ANOVA**.**

$$\text{Fatigue Life (Cycles)} = 35067 + 85190 \times \text{Plate Thk} - 23858 \times \text{Load} + 28879 \times \text{Root Gap} + 4558 \times \text{Plate Thk} \times \text{Plate Thk} + 295.6 \times \text{Load} \times \text{Load} - 57793 \times \text{Root Gap} \times \text{Root Gap} - 2013 \times \text{Plate Thk} \times \text{Load} - 13 \times \text{Plate Thk} \times \text{Root Gap} + 16 \times \text{Load} \times \text{Root Gap} \quad \textbf{(4)}$$

It also helps to understand the relationships among the model variables and allows more hypotheses to be tested. To understand the compatibility of the regression model, it is compared and tested with FEA Results. Order no 10 is randomly selected as an example for Normal stress and Fatigue Life calculations, and other run order samples calculated results are tabulated in Table 7.

For Run order 10, plate thickness (Pt) = 10 mm, Root gap (Rg) = 2.5 mm and the Load (Ld) = 40.5 kN,

$$\text{Fatigue Life (Cycles)} = 35067+(85190\times10)-(23858\times40.5)+(288799\times2.5)+(4558\times10\times10)+(295.6\times40.5\times40.5)-(57793\times2.5\times2.5)-(2013\times10\times40.5)-(130\times10\times2.5)+(16\times134\times2.5) = 405272 \text{ cycles.}$$

Table 7 RSM results vs. FEA results [Error % ≤ 3%]

Standard Order	Run Order	Plate thickness (Pt) -mm		Load (Ld) – kN		Root Gap (Rg) - mm		FEA Results	RSM Equations Results
		Coded-X1	Actual	Coded-X2	Actual	Coded-X3	Actual	Fatigue Life (Cycles) Mean -2SD	Fatigue Life (Cycles)
18	1	0	6	0	40.5	0	2.5	92342	100206
2	2	1	8	-1	32	-1	2	390250	377579
1	3	-1	5	-1	32	-1	2	127586	138275
16	4	0	6	0	40.5	0	2.5	92342	100206
13	5	0	6	0	40.5	-2	1.5	44901	42711
14	6	0	6	0	40.5	2	3.5	44616	42115
9	7	-2	4	0	40.5	0	2.5	24740	23690
11	8	0	6	-2	22	0	2.5	413815	422495
3	9	-1	5	1	62.5	-1	2	43094	-43407
8	10	1	8	1	62.5	1	3	52238	11502
20	11	0	6	0	40.5	0	2.5	92342	100206
12	12	0	6	2	80	0	2.5	90683	89296
7	13	-1	5	1	62.5	1	3	43030	-43223
15	14	0	6	0	40.5	0	2.5	92342	100206
19	15	0	6	0	40.5	0	2.5	92342	100206
4	16	1	8	1	62.5	-1	2	12370	11708
17	17	0	6	0	40.5	0	2.5	92342	100206
5	18	-1	5	-1	32	1	3	127113	137971
10	19	2	10	0	40.5	0	2.5	370441	405272
6	20	1	8	-1	32	1	3	389272	376885

Application of Backing Strip Weld Joint in Off-High Way Vehicle

The demand for a more sustainable structure with a lower weight and better fuel consumption leads to efficient and more accurate fatigue design methods applied in the early stage of the projects to cut the risk. Buttweld joint with the permanent backing strip is one of the most common weld joints used in off-highway vehicle structural parts. In the permanent backing strip at the root of the weld, stress concentrations are always challenged to have good fatigue loading performance due to the single-sided weld joint. One significant advantage of this weld joint is that fit-up tolerances can be relaxed as the strip acts as a locating feature and that's very important during the fabrication of the excavator boom. In root gap variation, the only real limitation is "wider the root gap, the greater the volume of weld metal and distortion"; hence, the optimum root gap is most important.

Boom is the most critical part of in excavator machine, and it always experiences compression & tension loadings during soil digging and dumping applications. It has many Butt weld joints with permanent backing strip [shown in Figure 14] that need fatigue life predication at the early stage of the design so that the position of weld joints and parameters of weld joint configuration can be optimized without doing the real testing.

In the excavator case, fatigue life prediction is tedious due to the various tasks performed and the number of weld joints in one component. To perform strain gauge testing in the field, parts need to be manufactured as per design that demands investment in fixtures and tooling. During the design stage, maximum force configuration at the hydraulic limit is used to predict the fatigue life and to decide the section size, thickness of the plate, position of weld joint [shown in Figure 15].

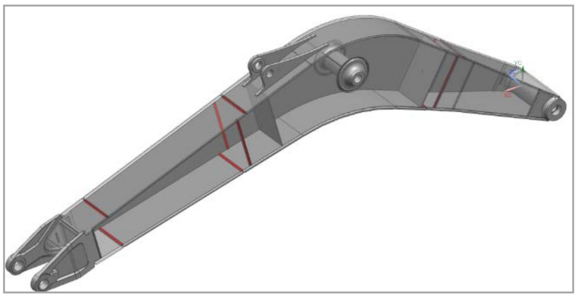


Fig. 14. Number of full penetration backing strip butt weld joint.

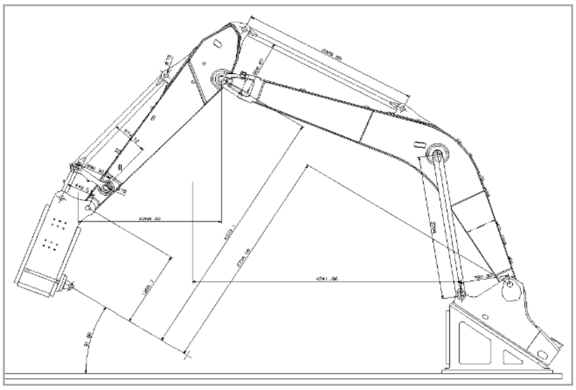


Fig. 15. Typical maximum force configurations.

In order to check the significance of the proposed methodology for fatigue life, one backing strip butt weld joint is selected for validation. A total of 20 strain gauges are mounted on the boom and two of them are shown in Figure 15. The loading condition in the boom consists of bending and axial forces, causes compression and tension on weld joint. Single grid strain gauges are aligned with the plate length of boom similar to weld fatigue experiment. The main strain gauges are used to validate the finite element model of boom and validate the virtual methodology. Gauges 100 and 200 are pasted on 12mm plate as shown in Figure 16. It is the butt weld joint with backing strip of two different plate thicknesses (12mm and 15mm) similar to weld configuration used in weld fatigue experiments.

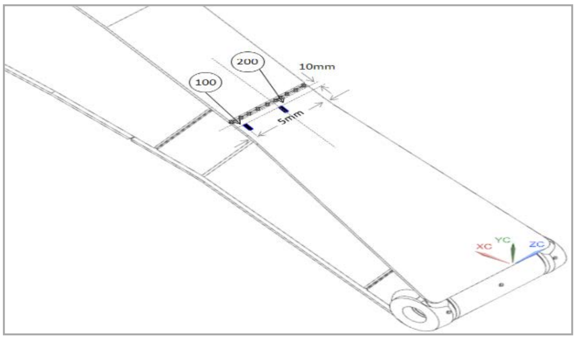


Fig. 16. Strain gauge location on boom.

A controlled field test is conducted as shown in Figure 17. During this test, a bucket is used through its full range of motion of digging cycles. The strain gauges are monitored using a high-speed data acquisition system and computer at a sampling rate of 1000 cycles per second. Other pressure and cylinder lengths are recorded. The test is repeated for 30 cycles to check the variation in strain level at each cycle and strain gauge data is recorded via eDAQ data logger.

Fig. 17. A controlled field test.

Raw data from strain range is collected during the controlled test as shown in Figure. 18 for gauge 100 and 200. In order to element the parasitic voltages (electronic noise) from the recorded data, the measured strain data are filtered using a low-pass filter.

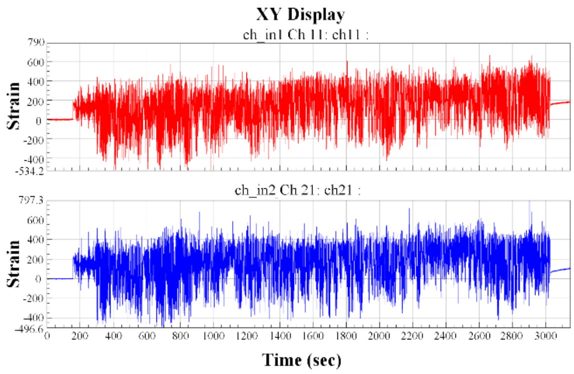


Fig. 18. Raw data from strain gauge 100 and 200.

Using the field event strain data, FEA is carried out in static load case as per the configuration shown in Figure 19, where maximum strain level is observed to predict the strain level in FEA to compare the field strain levels.

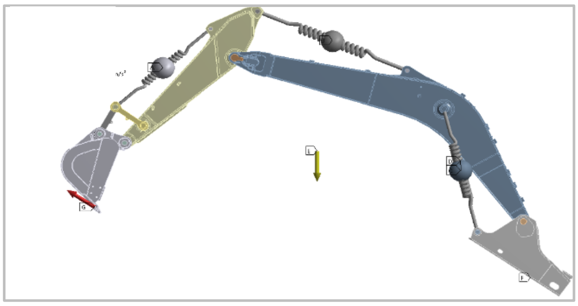


Fig. 19. Field event - Finite Element Analysis Configuration.

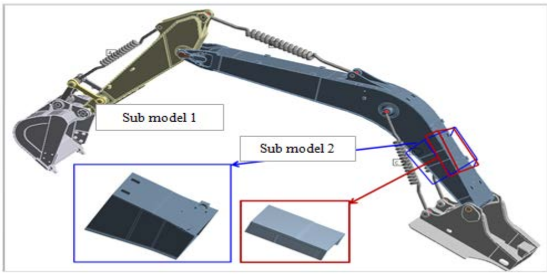


Fig. 20. Global model to the sub-model "cut boundaries" submodel 1 and sub-model 2.

To develop finite element mesh, local FE modelling is developed nearer to the butt weld joint using sub-modelling technique of ANSYS. Sub modelling uses two separate models. A full or global model representing the entire structure is used to transform global loads to local deformation as shown in Figure 20.

The sub-modeling algorithm interpolates the deformation from the global model to the sub model “cut boundaries” to convert the sub model 1 and sub model to 2 to have high level refine mesh and solves for the local stress state. The sub model includes the local geometric details with an appropriate mesh density as shown in Figure 21.

FEA results in Von Mises stresses using sub modelling are shown in Fig. 21, and strain levels from the virtual analysis using sub modelling techniques Vs. Global models are shown in Figure 22 and tabulated in Table 8.

The results presented in Table 8 are obtained using the sub modelling element technique. Strain level difference is 2.6% more in gauge 100 and 3.6 % more in gauge 200 as compared to global model. Gauge 200 is used to predict the fatigue life as per “E” Class weld BS 7608.The results of fatigue life using sub modelling techniques, field strain gauge data and from the RSM equation are tabulated in Table 9.

Evaluation of Fatigue Life on Excavator Boom Using Regression Equation

To understand the genuineness of regression equation, it is compared and tested with finite element results. Excavator Boom Butt weld with backing strip joint parameters are developed based on the RSM equation (Eqn. 5.1) which is used for fatigue life calculations by substituting the plate thickness (Pt) = 12 mm, the Load (Ld) = 134 kN, Root gap (Rg) = 2.5 mm.

$$\text{Fatigue Life (Cycles)} = 35067+(85190\times12)-(23858\times134)+(28879\times2.5)+(4558\times12\times12)+(295.6\times134\times134)-(57793\times2.5\times2.5)-(2013\times12\times134)-(130\times12\times2.5)+(16\times134\times2.5)=949838 \text{ Cycles}$$

The percentage of error in fatigue using the RSM equation Vs. FEA is 5% and % of error for FEA Vs. field is 6 %. Often, an "acceptable" margin of error used by survey researchers falls between 4% and 8% at the 95% confidence level.

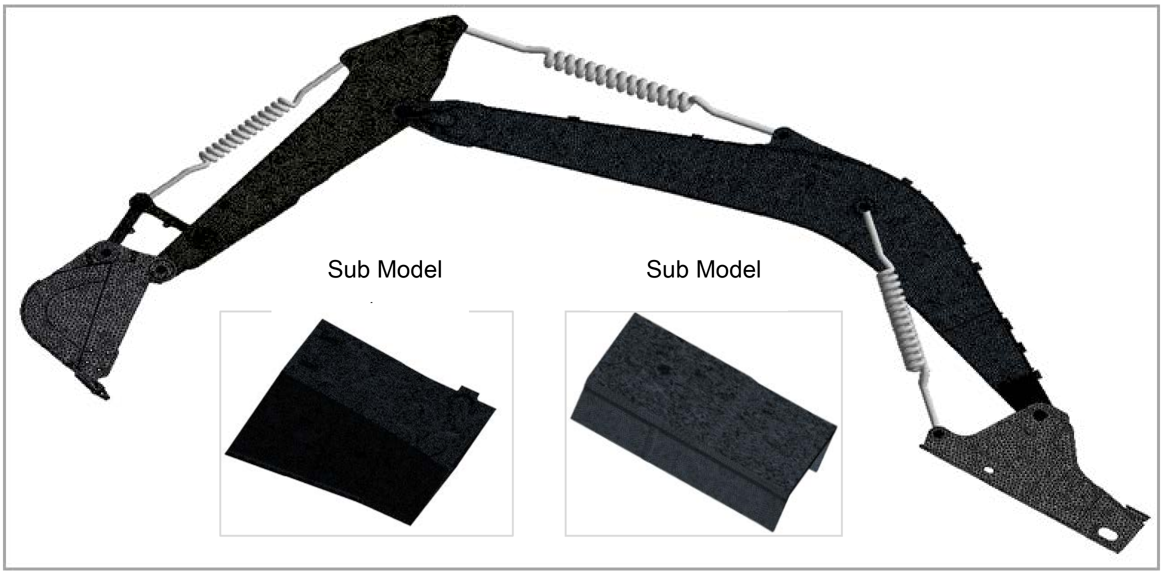


Fig. 21. Mesh model at Assembly level and sub-model level 1 and 2.

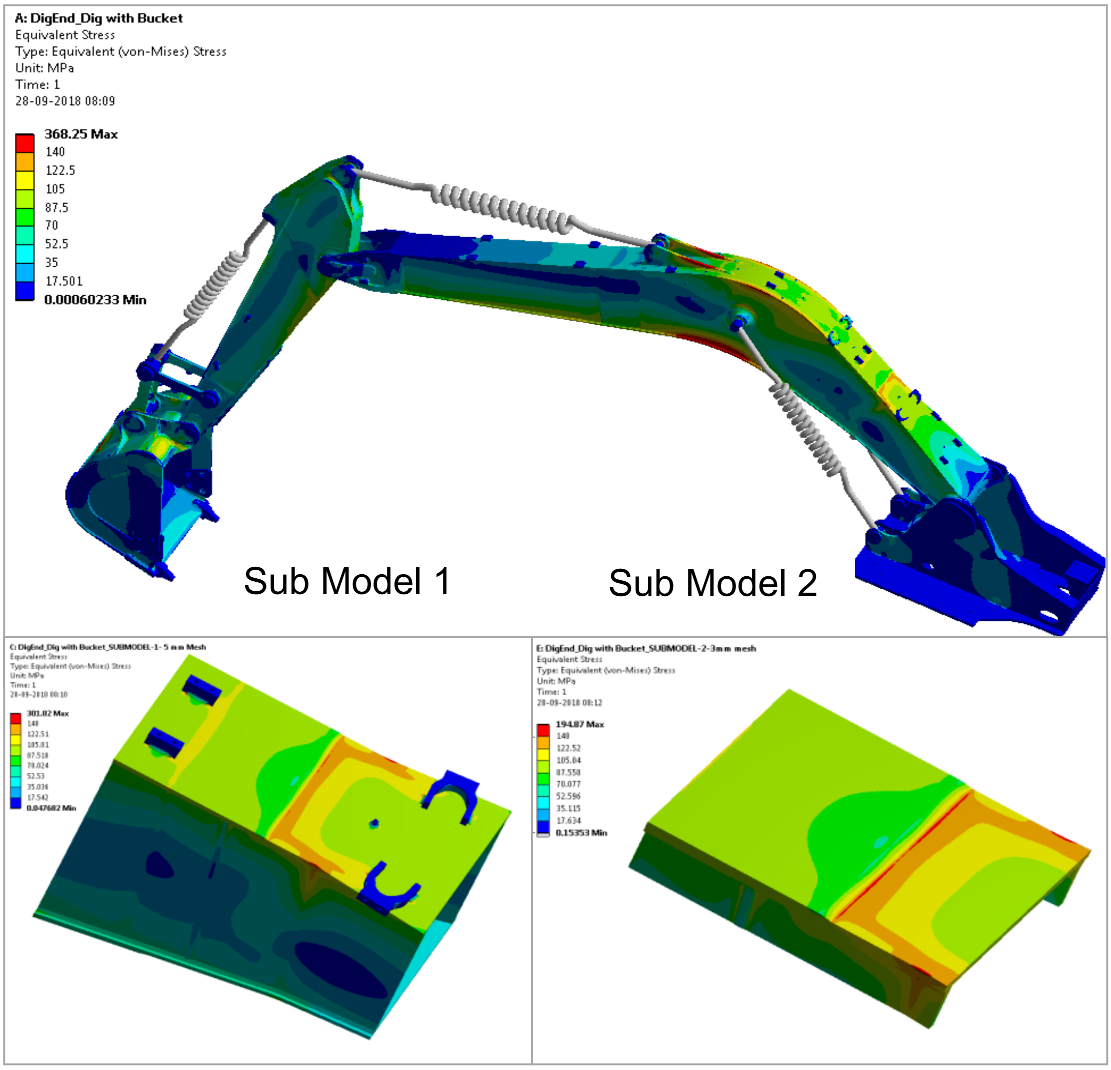


Fig. 22. Finite element Analysis results – full model and sub-model results

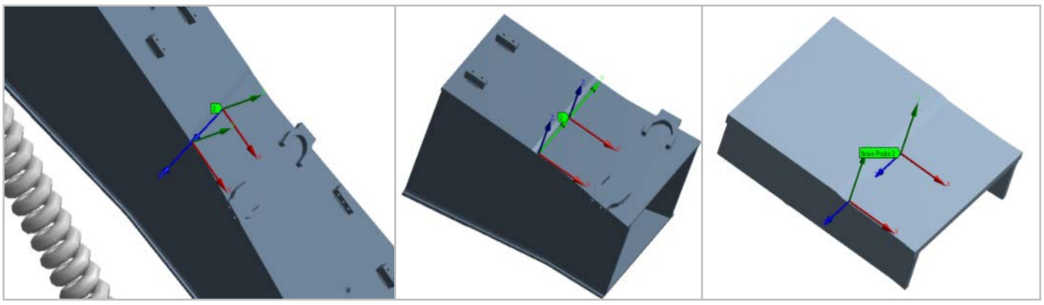


Fig. 23. Strain level from FEA - Global model vs. sub-model 1 and sub-model 2.

Table 8. Strain levels from FEA – Global vs. Submodel.

Strain level from FEA - Global and Submodel						
Gauge no	Full Model		Submodel-1		Submodel-2	
	Strain (Dig)	Strain (Dump)	Strain (Dig)	Strain (Dump)	Strain (Dig)	Strain (Dump)
100	478.8	-156.99	493.73	-171.15	491.33	-168
200	537.45	-219.35	553.98	-238.65	556.78	-243

Table 9. Field vs. FEA fatigue life comparison.

Gauge Number	Weld Class	Stress ratio	Field Strain	Fatigue Life Cycles	FEA Strain Submodel 2	Fatigue Life Cycles	Fatigue Life Cycle RMS equation
200	E	1	517 -202	845445	556 -243	899885	9,49,838

CONCLUSION

This Study associates the Stress Life equations with the Structural finite element analysis of Full penetration backing strip weld joint to obtain an effective and simple procedure for finding the fatigue life of welded joint and compare the obtained results with the actual experimental results successfully. In addition to that, the influence of weld geometry parameters such load, root gap and plate thickness on fatigue life of full penetration backing strip weld join is also investigated.

Based on the results, following conclusions are arrived.

- The regression equation and the Finite Element results shows very good agreement.
- Equally, local strain gauge measurements near to weld toe are used to validate the finite element model for the secondary bending effects due to manufacturing deficiencies which show that experimental and finite element analysis could give different signs also for the presence of a secondary bending.
- Results show that the root gap of 2.5mm is the optimum value for fatigue life and also it is good value to achieve the full penetration welding joint with good root and side wall fusion.
- The Estimation of fatigue life and the normal stress by using the regression equation without carrying out the actual experimentation on assumption of absence of secondary bending will be very useful for future work.
- The Strain gauge 200, on excavator boom application, shows very good agreement between FEA, Field testing and RSM results.
- Results comparison between FEA and field testing indicates that the developed FEA methodology is very useful to predict the fatigue life at the early stage of the design which is beneficial to save the significant cost and time instead of performing iterative strain gauge testing.

Declarations of Interest: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

Al-Mukhtar, A. M., Henkel, S., Biermann, H., & Hübner, P. (2009). “A finite element calculation of stress intensity factors of cruciform and butt welded joints for some geometrical parameters.”*Jordan Journal of Mechanical and Industrial Engineering*, *3*(4), 236-245.

Atzori, B., & Meneghetti, G. (2001). “Fatigue strength of fillet welded structural steels: finite elements, strain gauges and reality.”*International Journal of Fatigue*, *23*(8), 713-721.

Baik, B., Yamada, K., & Ishikawa, T. (2008). “Fatigue strength of fillet welded joint subjected to plate bending.”*International Journal of Steel Structures*, *8*(3), 163-169.

Confiant, R. (1993). *BS7608: Code of practice for fatigue design and assessment of steel structures*. BSI.

Dong, P., Hong, J. K., Osage, D. A., & Prager, M. (2002). “Master SN curve method for fatigue evaluation of welded components.”*Welding Research Council Bulletin*, (474).

Fricke, W. (2003). “Fatigue analysis of welded joints: state of development.”*Marine structures*, *16*(3), 185-200.

Fricke, W. (2012). *IIW recommendations for the fatigue assessment of welded structures by notch stress analysis: IIW-2006-09*. Woodhead Publishing.

Goes, K. C., Camarão, A. F., & Batalha, G. F. (2009). “Multiaxial fatigue of welded joints: a method for fatigue life prediction.” In *Proceedings of 20th International Congress of Mechanical Engineering, COBEM* (pp. 15-20).

Haibach, E. (1968). *Die Schwingfestigkeit von Schweißverbindungen aus der Sicht einer örtlichen Beanspruchungsmessung*. Fraunhofer-Ges. z. Förderung d. Angewandten Forschung eV.

Jonsson, B., Barsoum, Z., & Sperle, J. O. (2012). “Weight optimization and fatigue design of a welded bogie beam structure in a construction equipment.”*Engineering Failure Analysis*, *19*, 63-76.

Kalaimathi, M., Venkatachalam, G., Makhijani, N. P., Agrawal, A., & Sivakumar, M. (2014). “Investigations on machining of monel 400 alloys using electrochemical machining with sodium nitrate as electrolyte.” In *Applied Mechanics and Materials* (Vol. 592, pp. 467-472). Trans Tech Publications Ltd.

Kang, H. T., & Lee, Y. L. (2011). "Fatigue life prediction methods of seam-welded joints."*Metal Fatigue Analysis Handbook: Practical Problem-solving Techniques for Computer-aided Engineering*, 383-427.

Krejsa, M., Brozovsky, J., Mikolasek, D., Parenica, P., Koubova, L., & Materna, A. (2017). "Numerical modeling of fillet and butt welds in steel structural elements with verification using experiment."*Procedia Engineering*, *190*, 318-325.

Li, X. Y., Partanen, T., Nykänen, T., & Björk, T. (2001). "Finite element analysis of the effect of weld geometry and load condition on fatigue strength of lap joint." *International journal of pressure vessels and piping*, *78*(9), 591-597.

Melaku, A. F., & Jung, K. S. (2017). "Evaluation of welded joints of vertical stiffener to web under fatigue load by hotspot stress method." *International journal of steel structures*, *17*(1), 257-264.

Radaj, D., Sonsino, C. M., & Fricke, W. (2006). *Fatigue assessment of welded joints by local approaches*. Woodhead publishing.

Sonsino, C. M. (2009). "Effect of residual stresses on the fatigue behaviour of welded joints depending on loading conditions and weld geometry." *International Journal of Fatigue*, *31*(1), 88-101.

Teng, T. L., & Chang, P. H. (2004). "Effect of residual stresses on fatigue crack initiation life for butt-welded joints."*Journal of Materials Processing Technology*, *145*(3), 325-335.

Teng, T. L., Fung, C. P., & Chang, P. H. (2002). "Effect of weld geometry and residual stresses on fatigue in butt-welded joints." *International journal of pressure vessels and piping*, *79*(7), 467-482.

Zienkiewicz, O. C., Gago, J. D. S., & Kelly, D. W. (1983). "The hierarchical concept in finite element analysis."*Computers & Structures*, *16*(1-4), 53-65.

以虛擬應變計進行襯條全熔透焊縫之疲勞壽命預測

Gopalan Venkatachalam
School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India.

Atul R Deshmukh
Centre of Expertise, JCB India Limited, Pune, India.

A. Raja Annamalai
Centre for Innovative Manufacturing Research, VIT, Vellore, India.

Vignesh Pragasam
School of Mechanical Engineering, Vellore Institute of Technology, Vellore, India.

Gokula Krishnan Balasubramanian
School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India.

Vijay Venkataraman
Byford equipment Pvt Ltd, Derrimut, Victoria, Australia.

任春平
[7]School of Dentistry, College of Dental Medicine, Kaohsiung Medical University, Kaohsiung 80708, Taiwan, R.O.C.
Department of Mechanical Engineering and Advanced Institute of Manufacturing for High-Tech Innovations, National Chung Cheng University, Chia-Yi, Taiwan, R.O.C.

摘 要

本文著重於以虛擬應變計的量測評估襯條全熔透焊縫之疲勞壽命，並透過疲勞實驗進行驗證。目前，許多商用軟體都支援使用有限元素法的應力應變分析，然而，將其結果與實驗驗證並建構其分析模式更具有重大意義。有限元素法可由考慮施加負載、根隙以及板厚等三項參數以預測疲勞壽命。以主要方法論分析基於與響應參數（即疲勞壽命）有關的響應面參數之輸入效果圖的結果，設計出可得到 20 組實驗結果的實驗方法，並通過實際疲勞實驗進行驗證。基於虛擬與實際實驗，可以看出，板厚與疲勞壽命成正比，而與負載成反比。從 2 mm 到 3 mm 之根隙對疲勞壽命的影響可以忽略不計，而在 3 mm 之後的影響則相反。在不進行實驗驗證的情況下使用實驗設計方法進行疲勞壽命評估在未來的研究中會起到極大的作用，並且可以最大限度地減少時間和成本。