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Simulation of Ti-6Al-4V cruciform welded joints subjected to fatigue load using XFEM

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ABSTRACT

The stress distribution of cruciform shape welded joints is to be analyze by finite element codes ABAQUS. Welded joints with various weld shapes and sizes are to be investigated to estimate the fatigue life of joints. The fatigue behavior is to be evaluated under constant amplitude load ratio (R=0.1). The main aim of present work is to estimate the fatigue behavior of fillet weld cruciform joint for different weld bead shape geometry under various stress. The weld geometry is considered as concave, convex and flat weld shape of different weld sizes. The stress intensity factor (SIF) of a Ti-6Al-4V is calculated based on extended finite element method in ABAQUS software. Simulations of fatigue life for different weld shapes at different stresses are analyzed and crack initiations are identified. The number of severe fatigue life cycles which are obtained are very close to the theoretical values. In the present work the XFEM method is used to predict the crack growth rate and Stress intensity factor for convex specimen which is subjected to maximum fatigue stress.

Keywords: Extended finite element method; fatigue crack growth; cruciform shape welded joint; stress intensity factor; initial crack.

INTRODUCTION

Welding is one of the effective and economic methods to join metals. It is used widely in industrial applications, ship industry and aerospace, the welded joints which are subjected to fatigue load may fail due to many reasons e.g. stress concentration, residual stress, and weld flaws, which lead to fatigue damage. Many tests are done by investing huge money, but some large welding structures are not able analyze by experiment test. Therefore, stress intensity factor is significant parameter for assessing the fatigue failure of the specimens by simulation procedure. The stress intensity factor (SIF) is executed using numerical techniques like extended finite element method (XFEM), J-integral technique and theoretical values. Finite element method (FEM) was implemented for welding simulation, stress field analysis, fatigue life etc. It can make up the deficiency of test methods. However, FE method was affected by element type [1] the way of mesh generation, the mesh size and spacing [2] weld width, weld height, flank angle and so on, so FEA method only gaining a proximate result and the choose of FE model must be agreed with real engineering. In the present work, the stress state of the cruciform welded joints was simulated by FEA codes ABAQUS. The solid element was utilized in order to express the real structured. The model contains three weld bead shapes, and two different thicknesses. The XFEM [3-5] estimated the displacement field which is discontinuous nearby the cracks and not depend on FE mesh, Interpolation functions, are able to explain the displacement field at the various cracks in the structure. Then, modeling of cracks is done when various stress applied on the model specimens and concept of fracture mechanics is executed in simple way by XFEM than by predictable FEM. The numerical presentations were executed by Sukumar et al. [6]. A 2-dimensional mathematical model is developed based on static crack propagation and micro structural effects in brittle type materials under XFEM is simulated by Sukumar et al. [7]. Cracks were modeled with several branches, many cracks and holes which are originating from holes is represented [8]. From the point of observation of material behavior both FEM and XFEM simulation requires basic tensile properties, elastic and elasto-plastic, as well as parameters rate of the crack growth [9] In this study a 2D axisymmetric method is developed for simulation of the fillet welds of stiffened cylindrical shell using finite element method [10] Based on the computation theory of stress intensity factor of welded joints with 45^0 inclined angle, under former corrosion and complex stress fields are simulated with help of FRANC3D software [11]. Finite element numerical analysis of dynamic test on a T- shape weld joint which shows strong influence on the material properties leads to plastic strain localization and as a result on the fracture mode occurs [12]. The analysis of the results has shown that the obtained solutions can be used for the prediction of SIFs of analyzed and acceptable accuracy; well defined mesh, and well-set boundary conditions, 3D simulation of a typical 2D problem by using the XFEM gives very good results [13]. The application of various numerical methods is discretized for 2D and 3D structure models, by considering fracture mechanics laws and enables solving the problems in comfortable manner [14] Crack propagation in un stiffened part of the structure among two Friction stir welded joints are analyzed in this Numerical method XEFM method has been used [15].

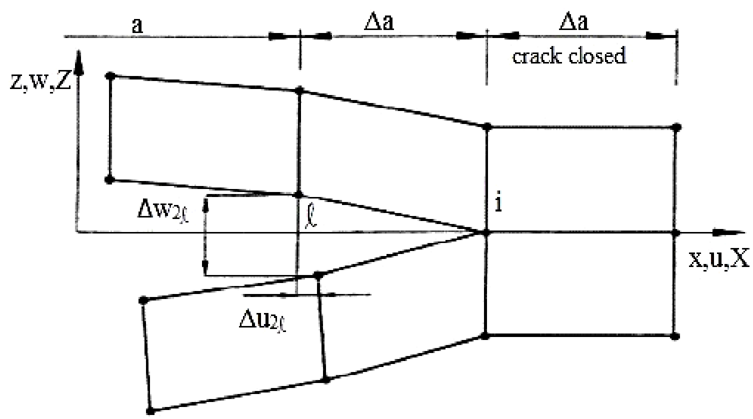
By observing all previous studies of simulation using XFEM method, no observations are found for simulation of cruciform welded joints, to predict the rate of crack growth and number of cycles. There is necessity of predicting the crack growth, fatigue life simulations of a different weld bead shapes, and stress intensity factor values are to be consider to predict the fatigue life and crack growth rate simulations, using the XFEM.

METHODOLOGY

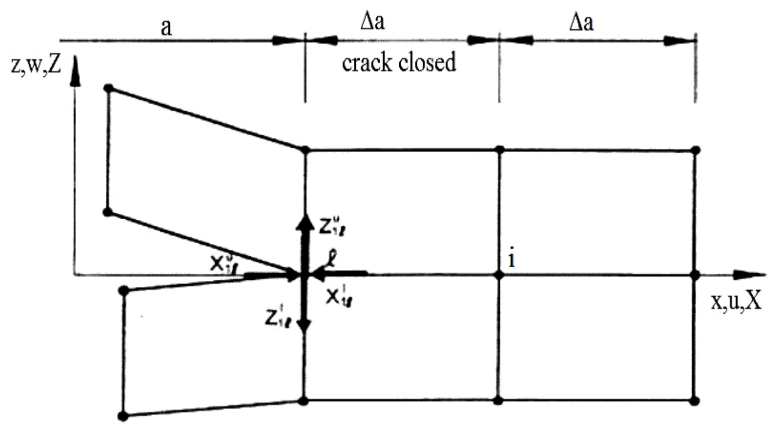
Crack Closure Technique

Crack closure is one of technique which is known for a fracture i.e. of crack length ‘a’ and the fracture of a modeled specimen can be predicted by estimating stress position at the fracture tip, and attainment of dislocations are shown in Figure 1. Fracture is observed from a to $a+\Delta a$.

Crack closure technique is well-known for a minute opening of fracture. Moreover, it is expected that a change of crack from $a+\Delta a$ at i node to $a+2\Delta a$ at k node will considerably not able to change the condition at the crack tip as shown in Figure 3. Hence, if the tip of crack is situated at k node, the obtained displacements after the crack tip at node point i are almost same to the displacements at the rear the crack tip at l node.



(a) Extended crack



(b) Closed crack

Figure 1. Method of crack closure (a) extended crack and (b) closed crack [16].

Stress Intensity Factor

Stress Intensity Factor (SIF) is defined as magnitude of the elastic stress field for an elastic body is well defined as the stress intensity factor and it is mathematical representation of force which is applied, geometry of specimen and crack length. The cracks in welded parts are concerned; there are the two approaches for the estimating the SIF based on the method of weight function and FEM. The K is a related to both strain and stress circumstances of crack tip of noticeably sharp crack in elastic type material. Size of crack, applied stress and mode of loading will elucidate on the structure of the specimen. The form of applying load will influence the various stress positions at tip of crack as revealed in Figure 2. Opening Mode (K_I) is found serious condition of failure when compared to other three failures.

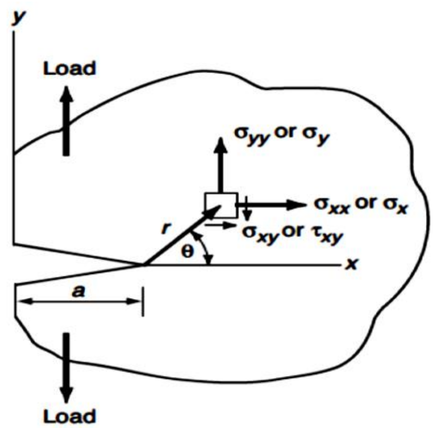


Figure 2. Stresses observed in co-ordinate system to the front of the crack [16].

$$\sigma_{XX} = \frac{\sigma\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right. \quad (1)$$

$$\sigma_{YY} = \frac{\sigma\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right) + \cdots r \ll a\right. \quad (2)$$

$$\tau_{YY} = \frac{\sigma\sqrt{\pi a}}{\sqrt{2\pi r}}\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right) \quad (3)$$

$$\sigma_{ZZ} = \vartheta(\sigma_{XX} - \sigma_{YY}) \ldots \ldots \quad (4)$$

where, θ and r represent the coordinate points on the crack tip, σ_{XX}, σ_{YY}, σ_{ZZ} denote the direct stresses and τ_{XY} is the shear stress.

$$K_I = \sigma Y\sqrt{\pi a} \quad (5)$$

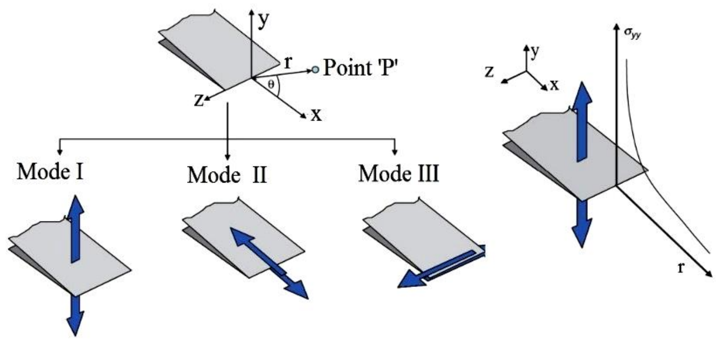


Figure 3. Modes of failure [16].

The magnitude value of SIF depends on geometry of model, the size, position of the crack and applied stress on the components or modeled specimens.

SIMULATION OF THE WELDED JOINT

The model contains a main plate with 100mm×24mm×6mm and an attached plate with 100mm×24mm×6 mm. Figure 5. represents boundary condition and load acting on the model. The under face of the main board was constrained such that Y direction movement and X axis, Z axis rotation, and the left face of the attach board was constrained such that X direction movement and Y axis, Z axis rotation. At the same time, a tensile stress with 230 MPa was applied to the main board. Eight nodal solid elements with linear reduced integration (C3D8R) are used.

The mathematical expression to calculate the strain is given by:

$$F = ku \tag{6}$$

where, F is the force applied, k is the global stiffness matrix. Software will primarily evaluate the stiffness matrix for each element (local). This will be consolidated to form global matrix) u = displacement/strain of the system due to the load applied. The expression to calculate stress.

$$\sigma = E\varepsilon \tag{7}$$

where, σ is the stress, E is the Young’s modulus of the material and ϵ is the strain of the system due to the load applied. The C3D8 element is a generally used as linear form of brick element, and with 2 x 2 x 2 method of integration. The integration points are represented based on numbering according to Figure 4. While the structure of element is clearcut, it must not be used in the following circumstances, because of the integration, the element type will perform poorly for isochoric of material due to plastic behaviour or high values of Poisson's coefficient.

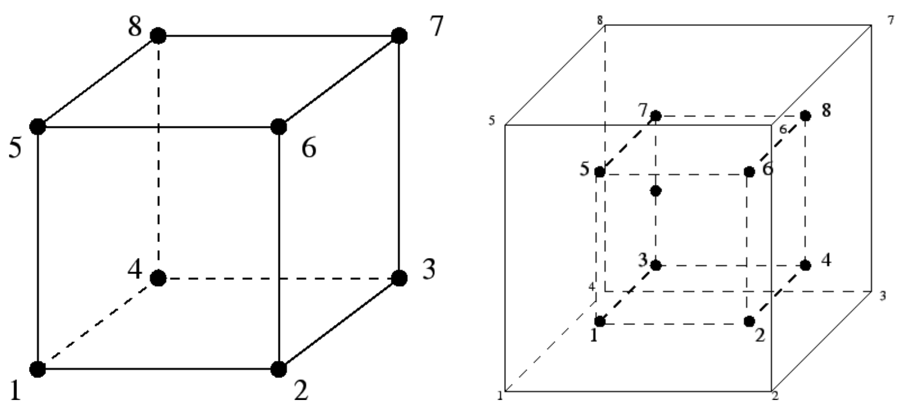


Figure 4. Noded Brick element with Reduced Integration (C3D8R).

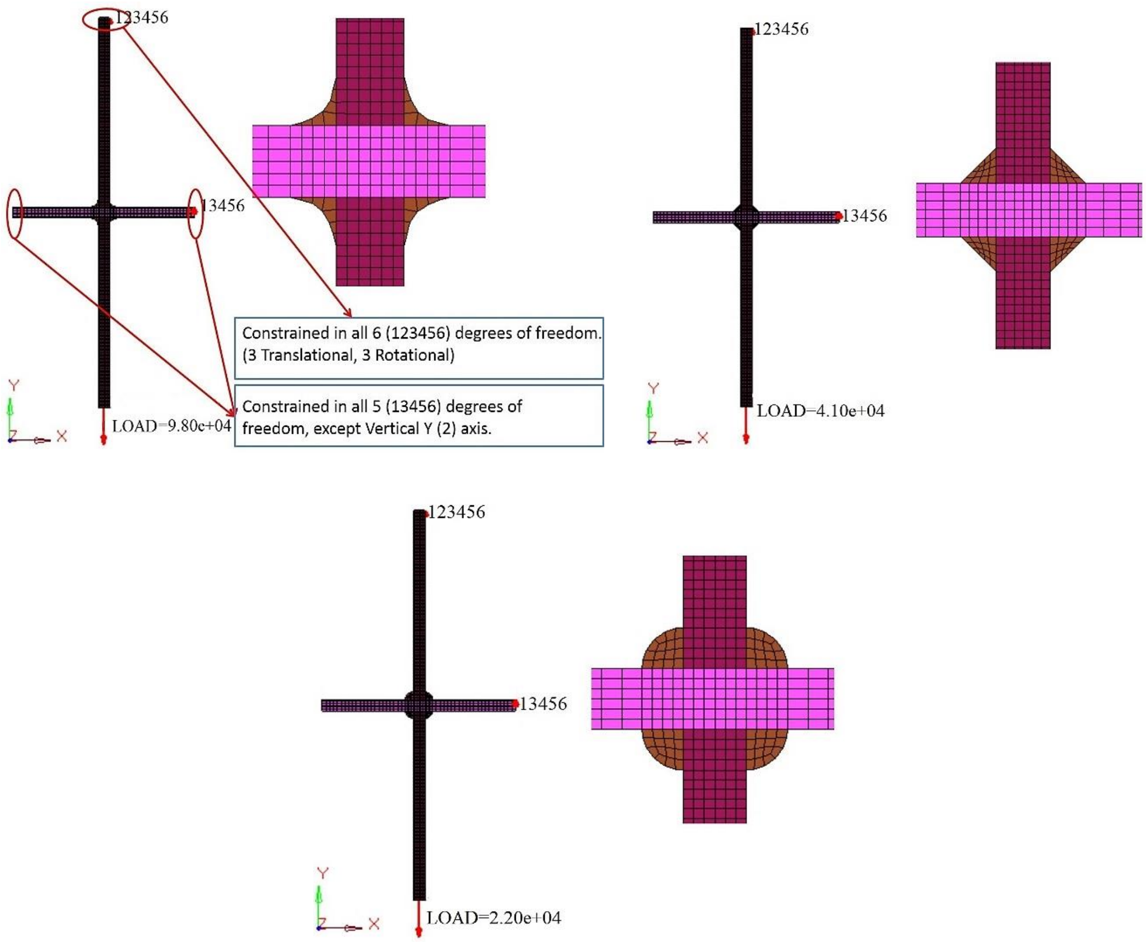
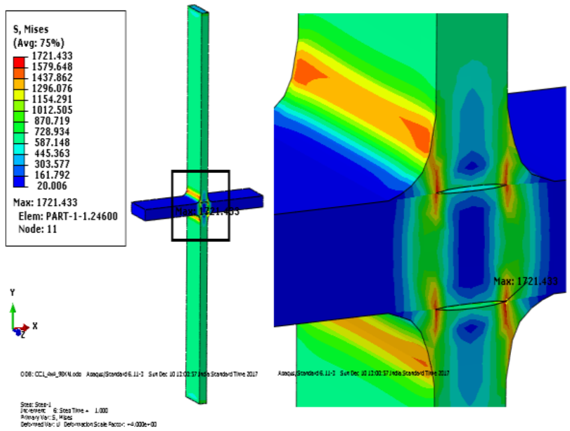
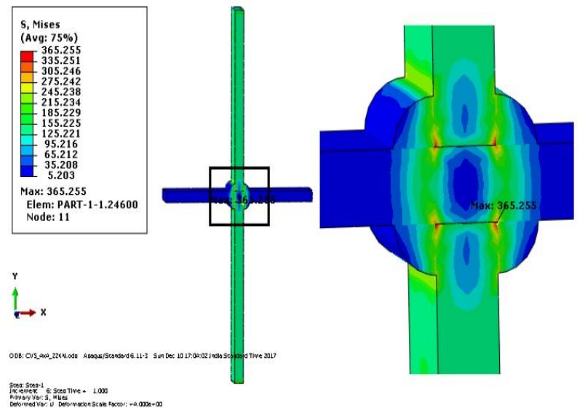


Figure 5. Boundary conditions for concave, flat and convex shape specimen.

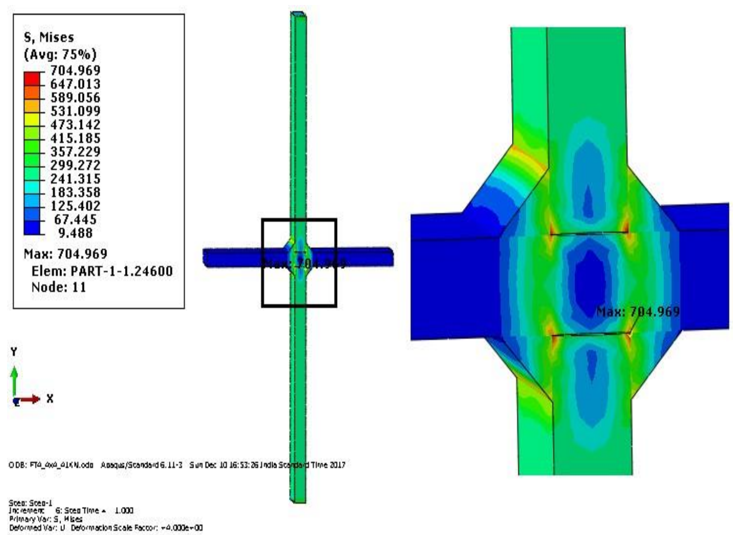
Boundary conditions for three different models is shown in figure where tensile load is acted on down side cross plate and upper grip cross plate and main plate are constrained in all directions except vertical (Y) axis respectively. Maximum static stress is observed at upper weld toe and at root corner of weld for the concave specimen where more chances of stress concentration takes place maximum amount of stress is induced for concave specimen and minimum amount of stress is observed for convex specimen.



(a)



(b)

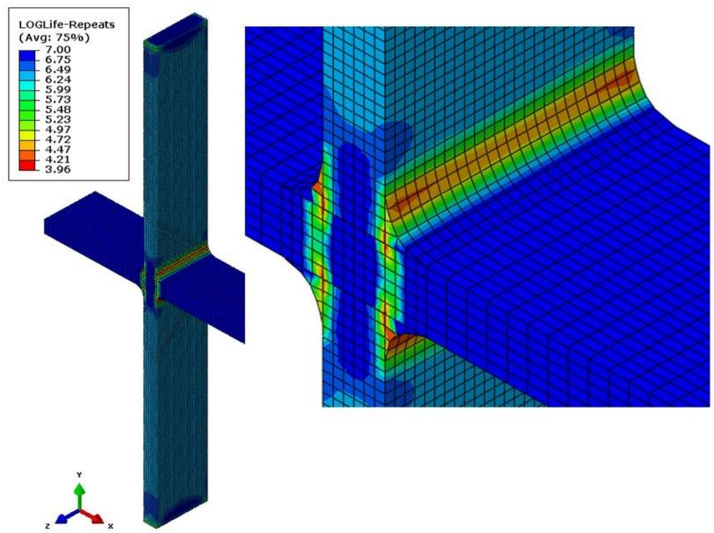


(c)

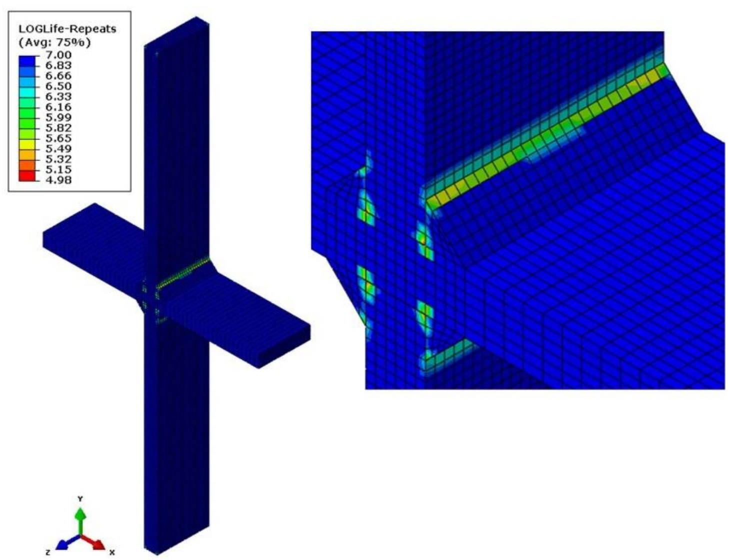
Figure 6. Static analysis of cruciform weld joints of different weld bead shapes
(a) Concave specimen, (b) Convex shape specimen and (c) flat weld shape.

FATIGUE ANALYSIS

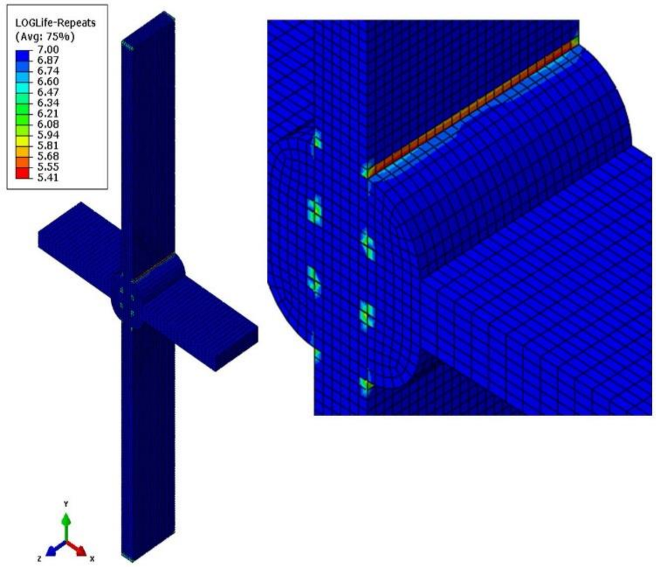
The fatigue life and performance of load carrying cruciform shape weld joint for different weld bead shapes with different L/T_p ratio is investigated at various fatigue stress. The cruciform joint is modeled in hyper mesh and simulation is done in Abaqus software.



(a) Worst fatigue life is log of 3.96 (number of cycles is 9120)



(b) Worst fatigue life is log of 4.98 (Number of cycles is 95499)



(c) Worst fatigue life is log of 5.41 (Number of cycles is 257039)

Figure 7. Fatigue life (a) concave specimen when subjected to 58 kN (397MPa), (b) flat specimen when subjected to 22 kN (152 MPa) and (c) convex specimen when subjected to 41 kN (281MPa).

Crack is initiated at upper weld toe line and maximum fatigue load is obtained for minimum load, a Crack is initiated at weld root and more chances of failure region is at upper weld toe line, crack is propagated along the upper weld toe line whereas at lower weld toe maximum life is obtained. The failure region is at the intersection of cross and main plate because of this reason, minimum numbers of cycles are observed i.e 1.2 x10^4 cycles. All the welded regions of joint are shown in blue which indicated that joint is having maximum fatigue life i.e. 2.57 x10^5 cycles.

RESULTS AND DISCUSSIONS

For maximum stress severe fatigue life is observed and for minimum stress maximum number of cycles is obtained and concave specimens static stress is maximum and number of cycles obtained is minimum for L/T_p ratio is 0.6. From above table it is observed that severe fatigue life is observed at 3211 cycles for convex specimen at 671MPa for L/T_p =1. In present theme of our work severe fatigue life is observed at weld toe region when specimen is subjected to high stress and the reason for crack initiation is concentration of more stress at the weld toe region.

Table 1. Fatigue life of various load carrying cruciform joints at weld root and weld toe regions.

No.	Specimen ID	Applied Load	L/T_p ratio	Static analysis (Max stress in MPa)	Stress range (MPa)	Number of cycles to failure		
						Crack at weld root	Crack at weld upper toe	Severe Fatigue life
1	Concave	98KN	0.6	1721	671	1905	870	870
2	Concave	58KN	0.6	1018	397	52480	16218	9120
3	Concave	41KN	1	682	281	83176	275422	83176
4	Concave	22KN	1	366	152	398107	360780	1,20,226
5	Flat	41KN	0.6	704	281	67608	234221	67,608
6	Flat	22KN	0.6	378	152	446683	309029	95,499
7	Flat	78KN	1	1079	397	39810	10,350	7079
8	Flat	58KN	1	803	541	50118	33113	33113
9	Convex	58KN	0.6	962	397	12589	66069	12,589
10	Convex	22KN	0.6	365	152	158489	501187	1,23,026
11	Convex	98KN	1	1275	671	12589	181970	3311
12	Convex	41KN	1	533	281	257039	870963	2,57,039

Table 2. Fatigue test results of load carrying cruciform weld joints with severe fatigue life.

No.	Specimen shape	Applied load	L/T_p ratio	Static analysis	Number of elements	Number of Nodes	Applied stress (MPa)	Severe Fatigue life	Crack Initiation region or line
1	Concave	98KN	0.6	1721	41201	50103	671	870	weld toe
2	Concave	58KN	0.6	1018	41201	50103	397	9120	weld toe
3	Concave	41KN	1	682	42001	50883	281	83176	weld root
4	Concave	22KN	1	366	42001	50883	152	1,20,226	weld root
5	Flat	41KN	0.6	704	42001	51039	281	67,608	weld toe
6	Flat	22KN	0.6	378	42001	51039	152	95,499	weld root
7	Flat	78KN	1	1079	44001	53067	397	7079	weld toe
8	Flat	58KN	1	803	44001	53067	541	33113	weld root
9	Convex	58KN	0.6	962	42001	51039	397	12,589	weld toe
10	Convex	22KN	0.6	365	42001	51039	152	1,23,026	weld toe
11	Convex	98KN	1	1275	44001	53067	671	3311	weld toe
12	Convex	41KN	1	533	44001	53067	281	2,57,039	weld toe

For low stress values maximum number of cycles are obtained for all weld bead shapes, where concave weld shape enduring more number of cycles with L/T_p ratio =1. From above table it is observed that maximum failure or crack initiation taken place at weld toe and whereas for concave and flat shape specimen for low stresses value crack initiation takes place at weld root and maximum number of cycles are endured. Least number of cycles i.e. 870 is observed for convex specimen when it is subjected to 98KN load.

SIF Evaluation and Crack Growth Rate for the Cruciform Weld Joint

Theoretical fatigue life is calculated based on Paris power law by identifying the SIF range value which is obtained from (Frank and Fisher) Cycles are calculated as follows for the 1 mm crack growth the necessary cycles obtained are:

$$1\text{mm} / N = C\,(\Delta K)^{m} \quad \text{or } N = C\,(\Delta K)^{-m}$$
$$N = 4.2 \times 10^{-11}\,(\Delta K)^{-4.6} \text{ for } L/T_p \text{ ratio} = 0.6$$
$$N = 1.4\times 10^{-9}\,(\Delta K)^{-3.4} \quad \text{for } L/T_p \text{ ratio} = 1$$

The examination is based on the Paris power law and based on fracture mechanics approach:

$$\frac{da}{dN} = C\,(\Delta K)^{m} \tag{8}$$

da/dN is known as rate of crack growth, ΔK -SIF range, m and C are constants.

Table 3. Comparison of Simulation fatigue life values with theoretical & AWS D1.9.2007.

Stress range	Concave shape weld		Convex shape weld		Flat shape weld		AWS D1.9.2007 Titanium welded joints	Theoretical calculation based on Paris law	
	0.6	1	0.6	1	0.6	1		0.6	1
750MPa	355	645	525	1640	365	975	500	350	635
671MPa	875	1650	1750	3311	1590	2670	6500	591	1870
541MPa	4140	6750	6150	9120	5350	7079	13700	2147	8511
397MPa	9120	26930	12589	76700	11065	33113	25000	8835	19967
281MPa	42750	83176	64750	257039	67608	81540	38000	40040	50355
152MPa	83250	120226	123026	317550	95499	153500	105000	184000	162500
75 MPa	135915	185350	225700	389500	115035	295700	315000	255950	284500

The ratio of length of weld leg (L) and thickness of plate (T_p),will decide the ultimate size of weld for the cruciform shape weld joints and fatigue life depends upon the result of L/T_p ratio for different values of fillet angle and LOP size, and it became obvious that greater the L/T_p ratio and better fatigue strength can be estimated.The reason can be definitely understand from the SIF range expression and for a cruciform welded joint at the tip of a root that is Lack of penetration defect.

$$\Delta K = \frac{\Delta\sigma}{1+2(\frac{L}{Tp})}[A_1 + A_2\, a^*][\pi a.\sec(\pi a^*/2)]^{1/2} \qquad (9)$$

where, A_1 & A_2 are the constants of size of weld (L/Tp), and

$$A_1 = 0.526 + 3.28(L/T_p) - 4.360(L/T_p)^2 + 3.66(L/T_p)^3 - 1.88(L/T_p)^4 + 0.414(L/T_p)^5 \text{ and}$$
$$A_2 = 0.217 + 2.77(L/T_p) - 10.16(L/T_p)^2 + 13.123(L/T_p)^3 - 7.774(L/T_p)^4 + 1.786(L/T_p)^5$$

From above expression $\Delta\sigma$ is known as stress 'a' is the half crack length; where a*=a/W is the defined as normalized length of crack; A_1 and A_2 are coefficients which will depend up on the weld size, it is clearly observed from the expression that SIF range is not dependent on the L/T_p ratio and is inversely proportional. From theoretical calculations L/T_p ratio is high the Stress Intensity factor range will be less and therefore initiation of the crack in the specimens takes place therefore propagation of crack and final failure is postponed. The da/dN crack growth rate, and propagation stage is estimated for steady state of growth regime, at various intervals and increment of length of crack against the related to Number of cycles to propagate. The correlation between SIF and the equivalent crack growth rate (da/dN) for L/T_p ratio 0.6 and 1 is shown in following Figure 8 and 9.

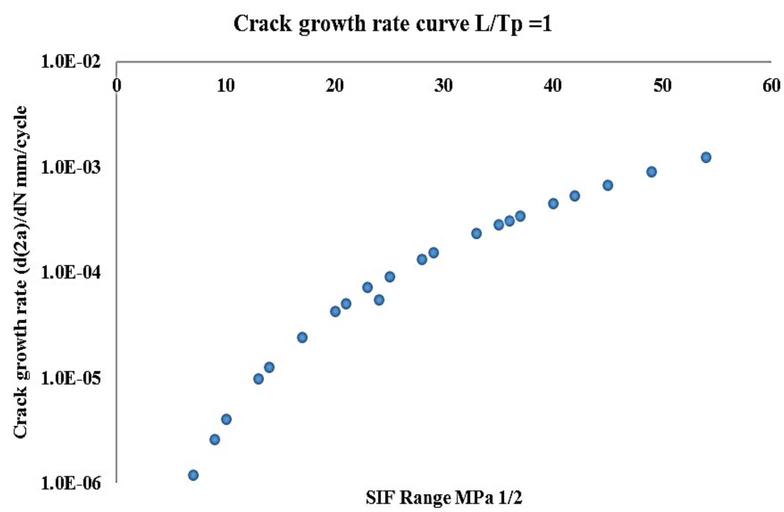


Figure 8. Comparison of SIF and rate of crack growth (L/T_p=1).

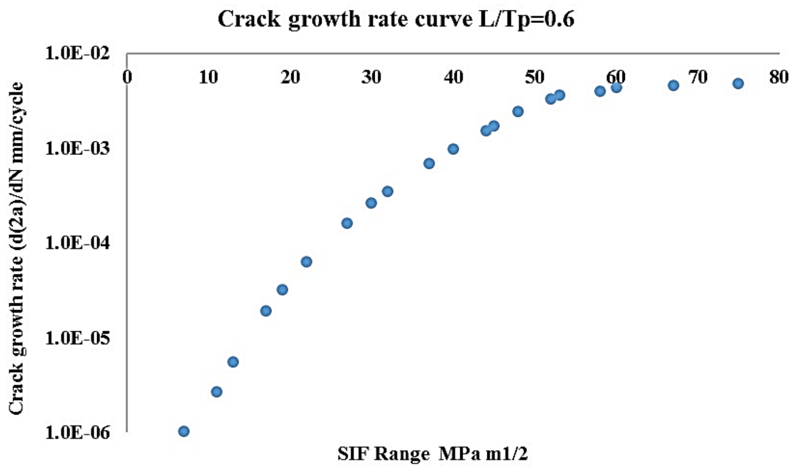


Figure 9. Comparison of SIF and rate of crack growth (L/T_p=0.6).

Crack Propagation in Cruciform Welded Joint using XFEM Software

The crack growth related to Linear elastic fracture mechanics technique such as the SIF makes it is likely to estimate the rate of crack growth, when subjected to cyclic stress. Hence the model specimen life time and SIF are obtained for a crack to be grown after its early crack length to critical length beginning severe failure will be estimated. The boundary conditions and mesh generation is hexahedra form as shown in Figure 5. to find exact results, a sort of awareness is essential in the field of FEM and there is a need to understand the elements types which will apply to create the final mesh. However, if the model is, the hexahedral mesh is the most acceptable.

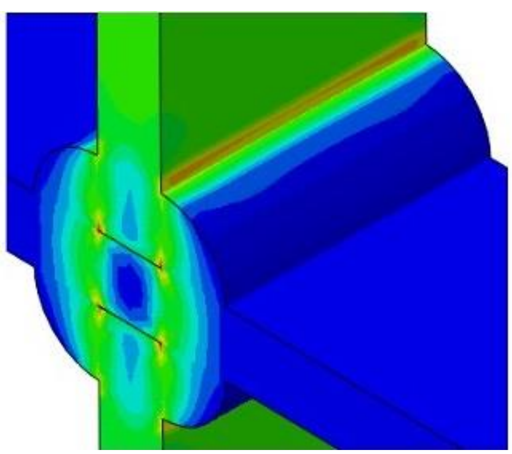


Figure 10. 3D model of cruciform weld shape (convex).

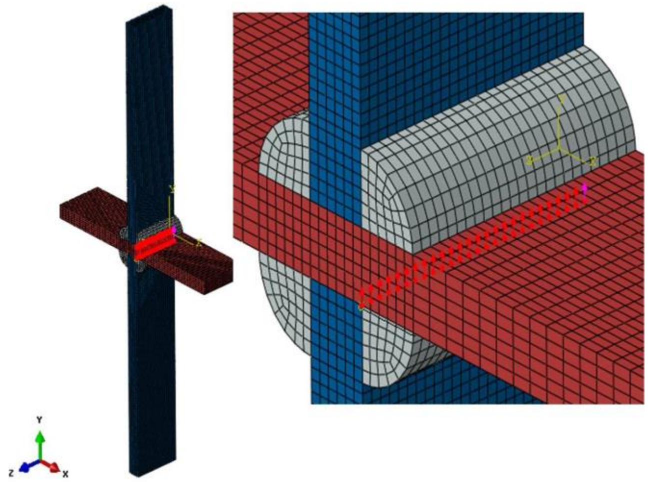


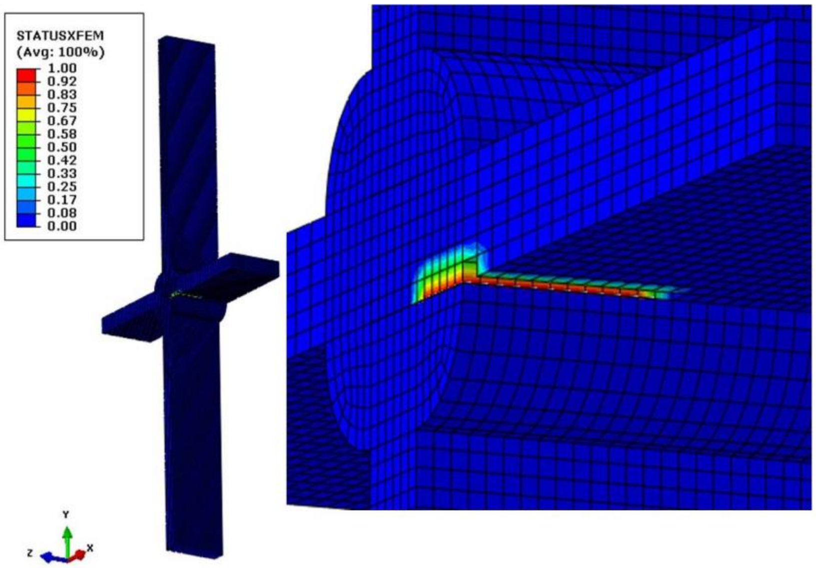
Figure 11. Meshing of convex shape weld joint.

To investigate the performance of the cruciform weld plate under action of 670 MPa stress, to study the crack length variation and corresponding number of cycles. Red color arrow mark in the Figure 11 indicates that, the stress intensity factor of convex shape along the weld toe. The crack is propagated in various directions and rate of propagation of crack is majorly depends on the initial crack, and the concentration of the mesh generated in the region of cracked area. It is clearly observed that growth of crack is along the transverse direction of weld. Variation of SIF with crack growth rate of convex specimen subjected to maximum stress and shear stresses with in structure which leads to two other modes of fracture and its stress intensity factor are represented with K_{II}, K_{III}. The distribution of stress intensity factor for the propagation of crack and steps for various modes are represented in Table 4.

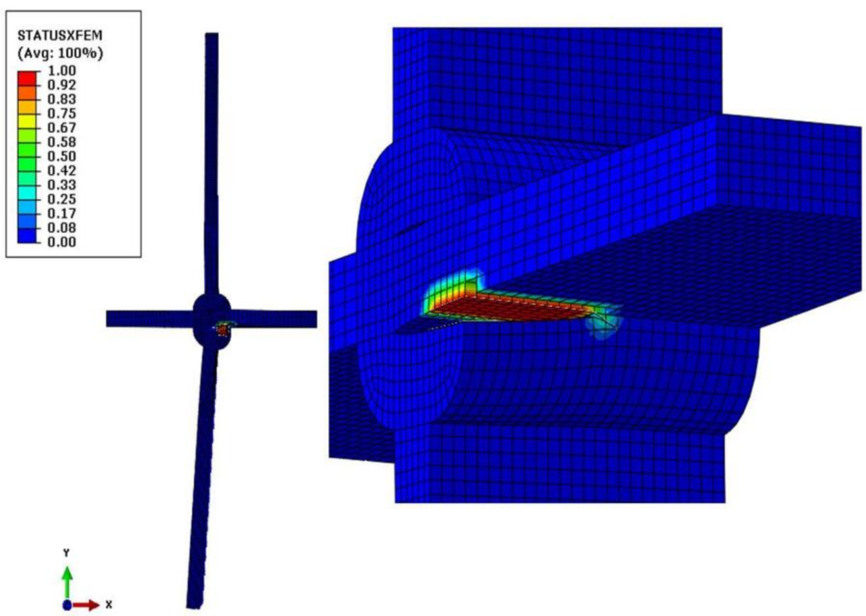
Table 4. Stress Intensity factor at (K_I,K_{II},K_{III}) for convex welded specimen.

	K_I (MPa mm$^{1/2}$)	K_{II} (MPa mm$^{1/2}$)	K_{III} (MPa mm$^{1/2}$)
step 1	89.59	-477.2	-71.83
step 3	136	-460	-34.27
step 6	148	-440	-33.83
step 9	139	-425	-22.32
step 11	133	-416	-12.33
step 13	128	-410	-5.18
step 16	126	-407	-.072

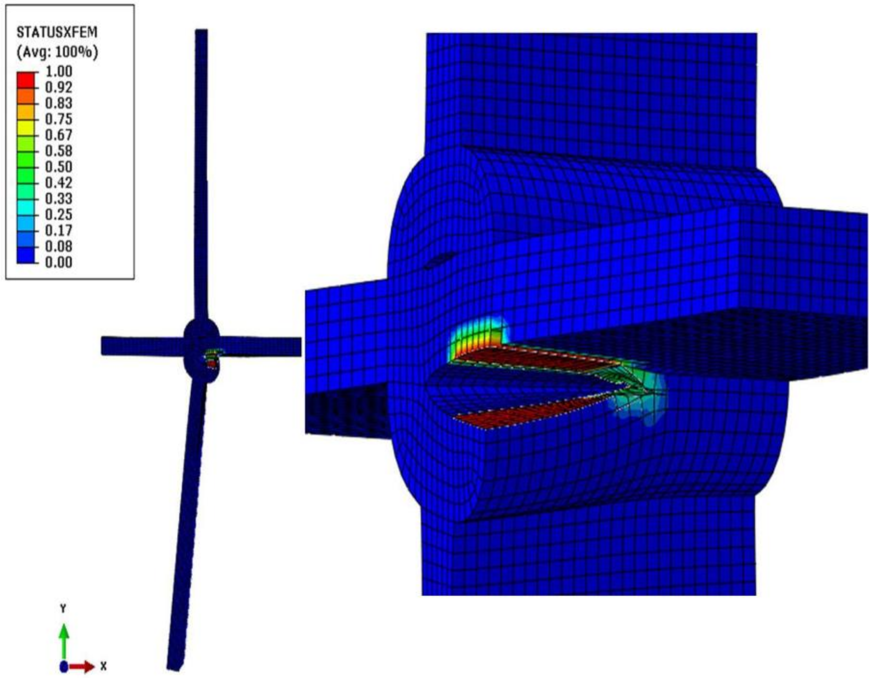
In the further analysis, the effect of high cycle load is observed, for a tensile load value of σ = 670 MPa. By applying higher values of tensile load, the structure can be subjected to a minimum number of load cycles; *N* where an unstable crack growth occurs that would lead to fracture. Initially un deformed model with an initial crack is considered and next undeformed model with a crack at a given moment (step) and at last a deformed model with a crack in a given moment (step) with von Mises stress distribution.



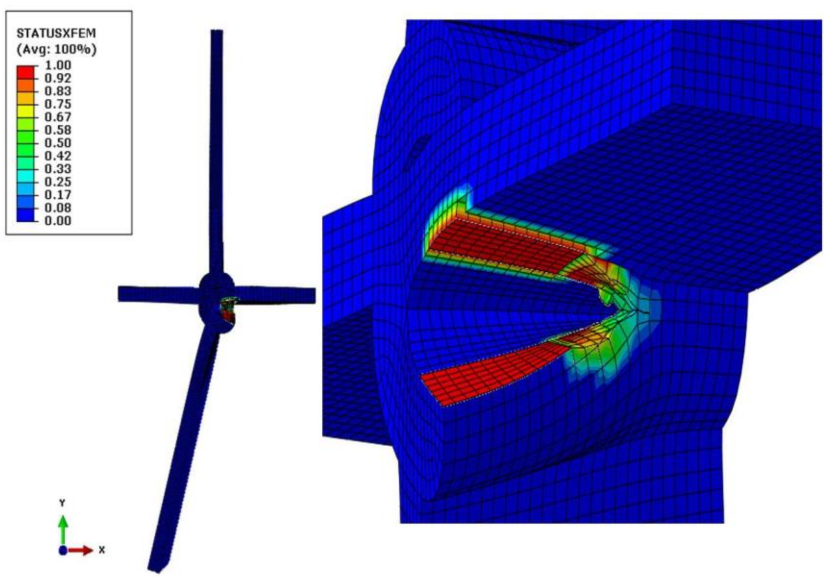
(a) Crack propagation at step 3



(b) Crack propagation at step 6



(c) Crack propagation at step 11



(d) Crack propagation at step 16

Figure 12. Crack opening at different steps (3, 6, 11, and 16) for convex specimen subjected to 670 MPa stress.

Table 5. Variation of SIF and rate of crack growth corresponding to crack length.

Number of Steps	crack length	K_I	da /d N mm/cycles	Number of cycles using XEFM method
Step1	2 mm	89	0.0059	337
Step2	4 mm	136	0.0251	160
Step3	6 mm	148	0.0334	200
Step4	8 mm	139	0.0270	148
Step5	12 mm	133	0.0232	434
Step6	14 mm	128	0.0210	600
Step7	16 mm	126	0.020	736

Sudden increase in crack length at a very low number of load cycles can be noticed, as a result of applying a high value of tensile load, σ = 671 MPa. Welded specimens are loaded with tensile load with steady amplitude. Early crack and crack at final are obtained at 2mm and 16 mm respectively. The crack length at final fracture is assumed for the limit of rate crack growth. In crack propagation which is observed from convex specimen shape weld joint using XFEM technique, the fatigue failure is occurred at 2 mm, 4 mm, 6mm and 8 mm cracks are 337,160, 200 and 148 cycles respectively and Figure 12 shows the crack propagation in step wise based on crack length.

CONCLUSIONS

In the present study stress intensity factor numerical results obtained from XFEM procedure are inferior to theoretical values therefore good conformity obtained between SIFs and XFEM method and results which are estimated confirms the strength and exactness of the formulation based on method. The path of propagation of crack is simulated by method of XFEM, in Abaqus software and results which are achieved, and displays good when compare with the theoretical and 2-D FEM represents the accuracy of the method. Simulation of crack propagation identified that for convex specimen using XEFM in abaqus and exhibits good result when compare with theoretical values. For crack growth analysis .SIF calculation is necessary and the singularity stress is fixed at tip of crack in XEFM.

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