FATIGUE LIFE ESTIMATION OF VARIOUS WELD BED SHAPES FOR TITANIUM ALLOY USING FEM

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Abstract : Fatigue failure of welded structures are major cause of failure due to which there is a loss of material and life especially in the field of marine and aerospace structures. Such catastrophic behavior of welded structures usually occurs under cyclic loading, where the stresses are within working limits. In the present project a fem based approach has been followed to estimate the fatigue life of welded titanium Grade 5 alloy for various weld bed shapes (flat, concave and convex), under different loading conditions. An S-N based fatigue approach which predicts complete life, starting from crack initiation, propagation and final failure of the structure is implemented to obtain the fatigue life of the welded structure. The purpose of this thesis is to provide the designer with better understanding of different fatigue calculation methods used in the industry in the present day and aim at decreasing the probability of failure with a higher control of a fatigue failure site.

IndexTerms **– Titanium Grade5, Structure Analysis, Fatigue Life.**

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1. INTRODUCTION

1.1 Introduction and Motivation of work

In this day and age the marine structures functioning at sea are available in large quantities and contain quite a lot of structural components. Many of these marine structures are inclined to some form of failure. In order to avoid major concerns of failure in marine structures all patrons should attempt at reduction of possibility of failure to a minimum. The tolerating ability of floating structures will improve by reduction of probability of failure, thereby improving the safety of workforces and properties. Fatigue is the main cause of failure of structural and welded components. By increasing the fatigue calculation accuracy we can improve the functioning lifetime of structures, henceforth the quantity of material used is reduced. The main objective of this thesis is to help the designer to reduce the likelihood of catastrophe with a higher control of the fatigue failure site in the fillet weld and to improve accuracy in fatigue strength calculations. The structures should be designed with sufficient fatigue strength based on the rules, where fatigue strength is assessed using stress-based approaches (the high-cycle fatigue analysis).

1.2 Methodology

In order to evaluate the fatigue life, fillet weld joints are subjected to loads and boundary conditions in analysis. Based on these load cases, using stress life approach method, the alternating stress and fatigue life is estimated from the analysis and compared with theoretical values.

1.3 Limitations

The fillet welds were demonstrated as ideal welds with the same material properties as the base material. It was assumed that the stresses are below the yield strength of the material, leading to a stress based linear finite element (FE), analysis. The material affected by the heat produced by the welding process was also excluded from the analysis.

2. LITERATURE REVIEW

Studies on fatigue of metals is being done for nearly 200 years. August Wohler is one of the many renowned initial fatigue researchers. Between the periods of 1850 to 1875 many experiments were conducted to institute a safe alternating stress that would not allow failure to happen. To institute the endurance limit conception for design many full scale axles along with small workshop samples were engaged. Over hundred years of research was done to practically institute the effects of the many variables that could impact the longer life of fatigue strength of metals.

Coffin and Manson began their work during the 1950's and instituted quantifiable relation between plastic strain and fatigue life. The problems of fatigue in metals at high temperatures where inelastic strain cannot be ignored was the main inspiration to their work.

During the 1960's, Irwin and others started developing fracture mechanics as a practical engineering tool. Paris quantified the relation for fatigue crack propagation. Paris commented his original work in "Twenty Years of Reflection on ·Questions Involving Fatigue Crack Growth." The paper was rejected by the reviewers of three leading journals, with an assumption that it is impossible that an elastic parameter such as K can account for the ·self-evident plasticity effects in correlating fatigue crack growth rates.

Fatigue analysis became a recognized engineering tool in many industrial applications during 1970’s. Even after all this research, unintended fatigue failures continued to happen. This is now at a stage where research will not solve most of these problems but education will. Many of the failures are a result of fatigue technology being in the hands of the "experts" rather than the people who design and build structures and components.

Balasubramanian and Guha: [13]Established the criteria for root and toe cracking of load carrying cruciform joints of pressure vessel grade steel. A series of cruciform load-carrying fillet welds and suggested that a definition of stress intensity factor at weld root and weld toe should be used for failure mode determination.

Maddox,2008: [14] Fatigue performance of fillet welds, proposed a relationship of optimum fillet weld size and plate thickness by equating the fatigue life of weld toe failure and weld root failure. The results indicate that the optimum weld size increases as plate thickness decreases.

Iwata and Matsuoka,2013: Fatigue tests for weldments made of commercial pure titanium i.e. Grade 2 including transverse butt-welded plate and cruciform fillet-welded. The resulting test data were represented in the form of nominal stress range versus cycle to failure.

Al-Mukhtar et al, 2010: Compared the stress intensity factor of load-carrying cruciform welded joints with different geometries

Katia Casavola,2009: Focused on the study of static and fatigue behavior of butt welded joints in titanium grade 2 and grade 5, all obtained by laser welding technique. The results say titanium grade 5 has greater strength and can be preferred for components hardly stressed, but it is more difficult to weld and to work with titanium grade 2.

Shabnam Hosseini,2012: Titanium alloys have a high strength to weight ratio with a density approximately 60% that of steel. Presence of notch in Ti-6Al-4V alloy, doesn't affect the fatigue crack growth behavior, under the condition of HCF and LCF. Therefore, this alloy with high strength is the most suitable for parts that are used in HCF conditions.

3. FINITE ELEMENT ANALASYS AND NUMERICAL CALCULATIONS

3.1 Joint Preparation

A cruciform joint is prepared amongst three specimens, with two specimens located approximately at right angle to the third specimen in the form of a sign +. In the present work titanium (grade5) 2 attached plates of (96 mm × 24 mm × 6 mm) and one base plate of (130× 24× 6) with welding size (3.5×3.5,4.5×4.5,5.5×5.5) are considered. The cruciform joint was prepared for different weld geometry is as shown in figure.

In order to create fillet welding in the model, three specimens will not connect to each other. The connected area will be the welded material only. In this model base plate and welded metal will be different parts. To disconnect the surface, in the connection tab, from model tree we can find contact region and suppress plate connection. After applying load there is no connection between plates except welding.

3.1.1 Flat Weld Bed Shape:

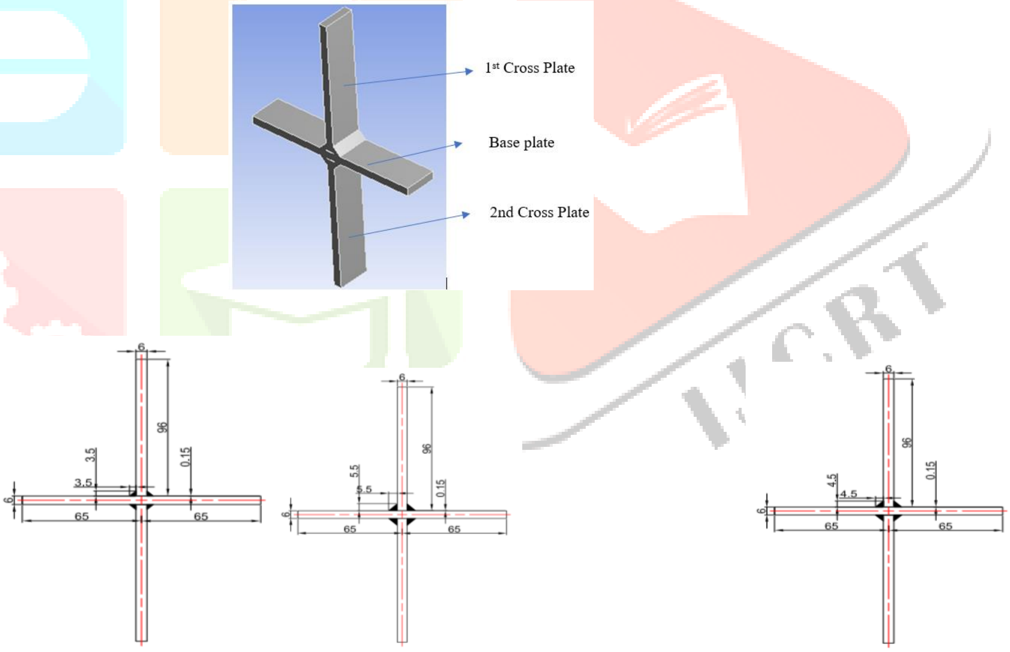


Figure 3.1: Cruciform Weld Joint: Flat welded joint geometry for a. 3.5x3.5, b. 4.5×4.5 and c. 5.5×5.5 with considered dimensions.

3.1.2 Convex Weld Bed Shape:

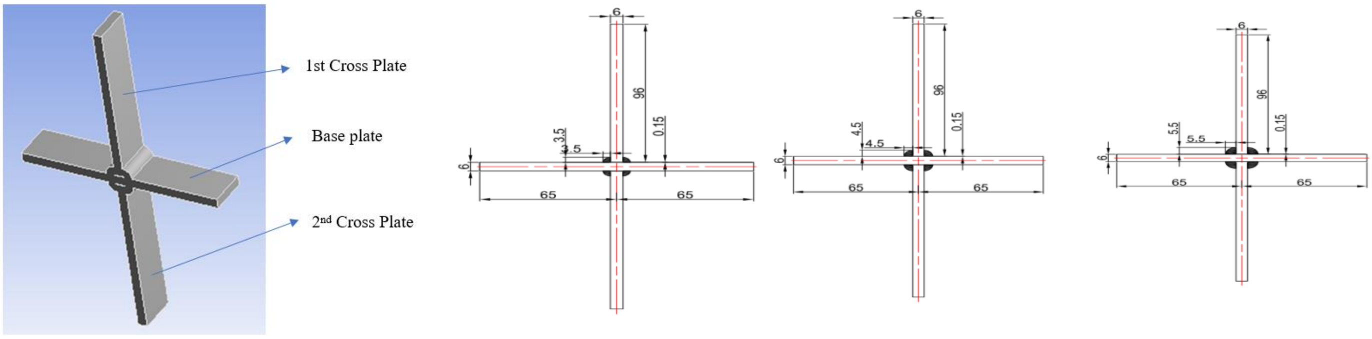


Figure 3.2: convex welded joint geometry with for 3.5x3.5, 4.5×4.5 and 5.5×5.5 with considered dimensions.

3.1.3 Concave Weld Bed Shape:

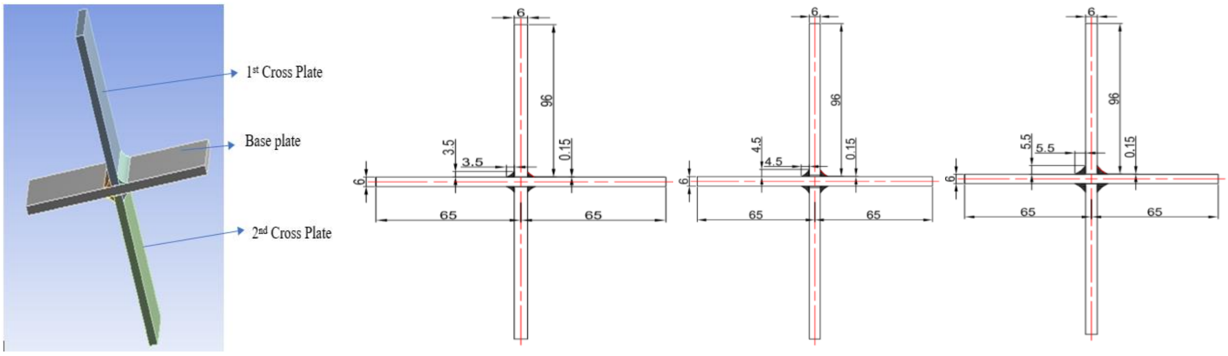


Figure 3.3: concave welded joint geometry for 3.5x3.5, 4.5×4.5 and 5.5×5.5 with considered dimensions.

3.2 Fatigue Behavior of Cruciform Joint:

The fatigue behavior of load carrying cruciform welded joint for different weld geometry was investigated by considering the presence of residual stress. The cruciform joint was modeled in finite element program and simulation was done for different weld geometry.

3.2.1 Finite element Method:

Finite element method is one of the accurate engineering technique is used in research work and in industry for analysis of actual problems. In this work welding simulation was done by using commercially available finite element program i.e. ANSYS15.

3.2.2 Structural Analysis:

Structural analysis is a higher order 3-D node solid element that exhibits quadratic displacement behavior. The element is defined by nodes having three degrees of freedom per node and translations in the nodal x, y, and z directions. The element supports various capabilities such as plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain.

The boundary condition was applied at the cross plate and Load applied at the end of cross plate to calculate the Equivalent stress for different loading conditions. This Equivalent stress further used in fatigue analysis to evaluate the fatigue life of load carrying fillet welded cruciform joint.

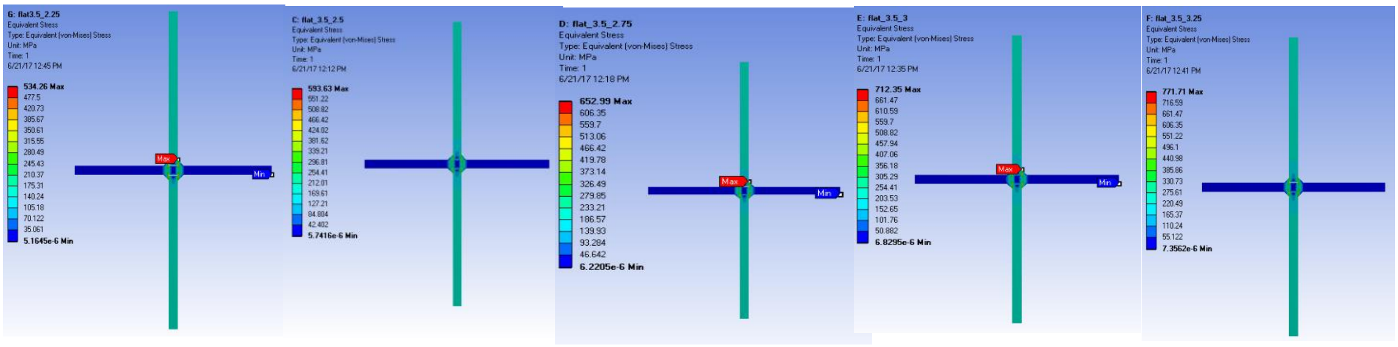
3.2.3 Fatigue Analysis:

Fatigue behavior of engineering component can calculate with the help of three basic approaches which are Stress-life Approach, Strain-Life approach, Linear elastic fracture mechanics approach. Fatigue failures are typically characterized as either low-cycle (<1000 cycle) or high cycle (>1000 cycles). In the present work SN approach is used. In S-N approach ‘S’ stands for the cyclic stress range while ‘N’ represents the number of cycles to failure. With the help of S-N approach total life of model including the crack initiation to crack propagation is calculated. The stress range applied was constant amplitude nature (R=0). Equivalent stress range component is considered on the basis of von-mises failure theory. In the present work Goodman mean stress correction theory is considered to calculate the fatigue life of welded structure. Fatigue data of material is considered on the basis of relation between the ultimate strength and endurance limit of the material.

3.3 Stress and Fatigue Life analysis of Fillet Weld Model:

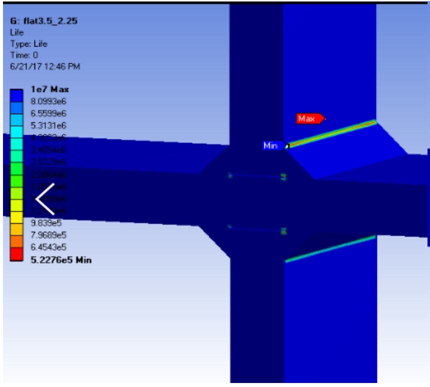
3.3.1 Stress analysis for Flat Welded Structure (3.5*3.5):

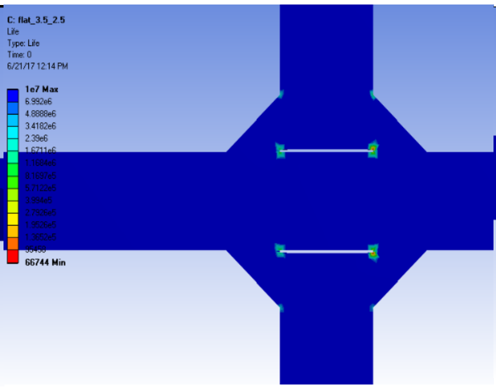
The applied load is 22.5,25,27.5,30 and 32.5kN load and alternating maximum stress found was 534.26, 593.63, 653, 712.35, 771.71 MPa at the concentrated area as shown in below ANSYS images.

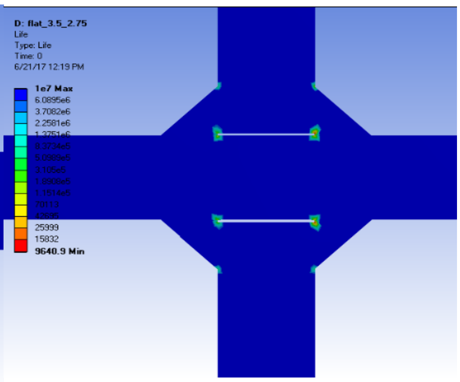


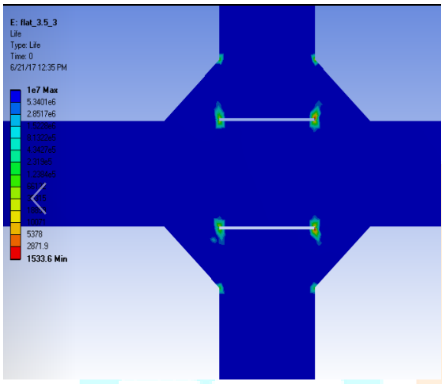
3.3.2 Fatigue life analysis for Flat Welded Structure (3.5*3.5):

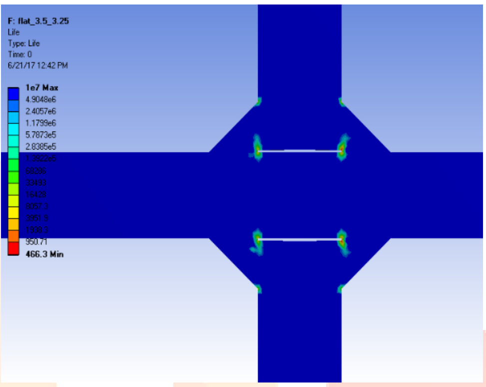
In order to predict fatigue life of the structure, select fatigue tool in this analysis from solution tab and select life. The loading type used is repeated constant amplitude and stress life with Goodman mean stress theory. Following figure shows the fatigue life in terms of cycle.









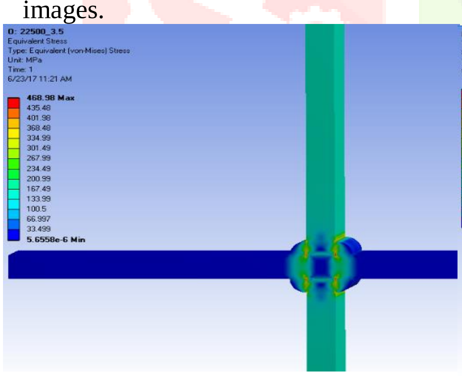


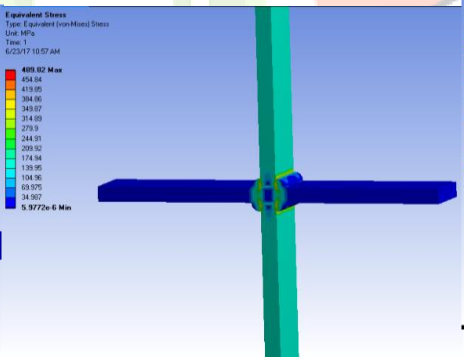
Above Figure shows the calculated fatigue life. The red spotted line shows the minimum cycles of alternating load that can be applied. The alternating stress and minimum number of cycles are listed in results.

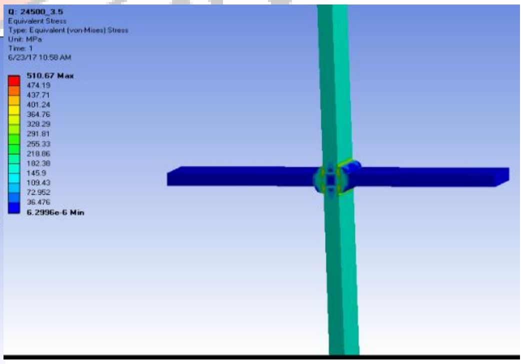
NOTE: Similarly stress and fatigue analysis for Flat Welded Structures of sizes 4.5*4.5 and 5.5*5.5 was done and results were noted.

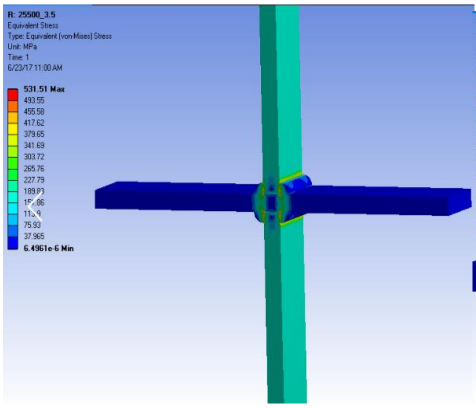
3.3.3 Stress analysis for Convex Welded Structure (3.5*5.5):

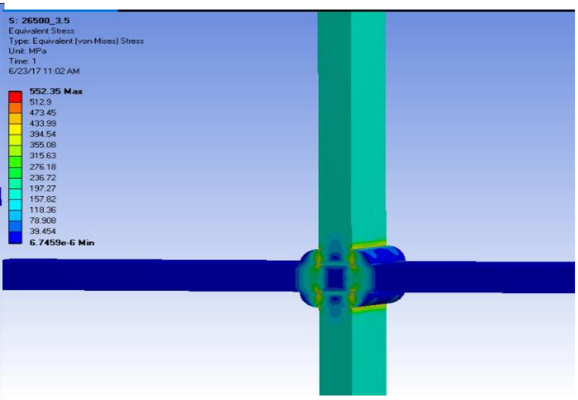
The applied load is 22.5,23.5,24.5,25.5 and 26.5 KN load and alternating maximum stress found is 468.56, 489.23, 510.62, 531.64 and 552.67 MPa at the concentrated area as shown in below ANSYS images.





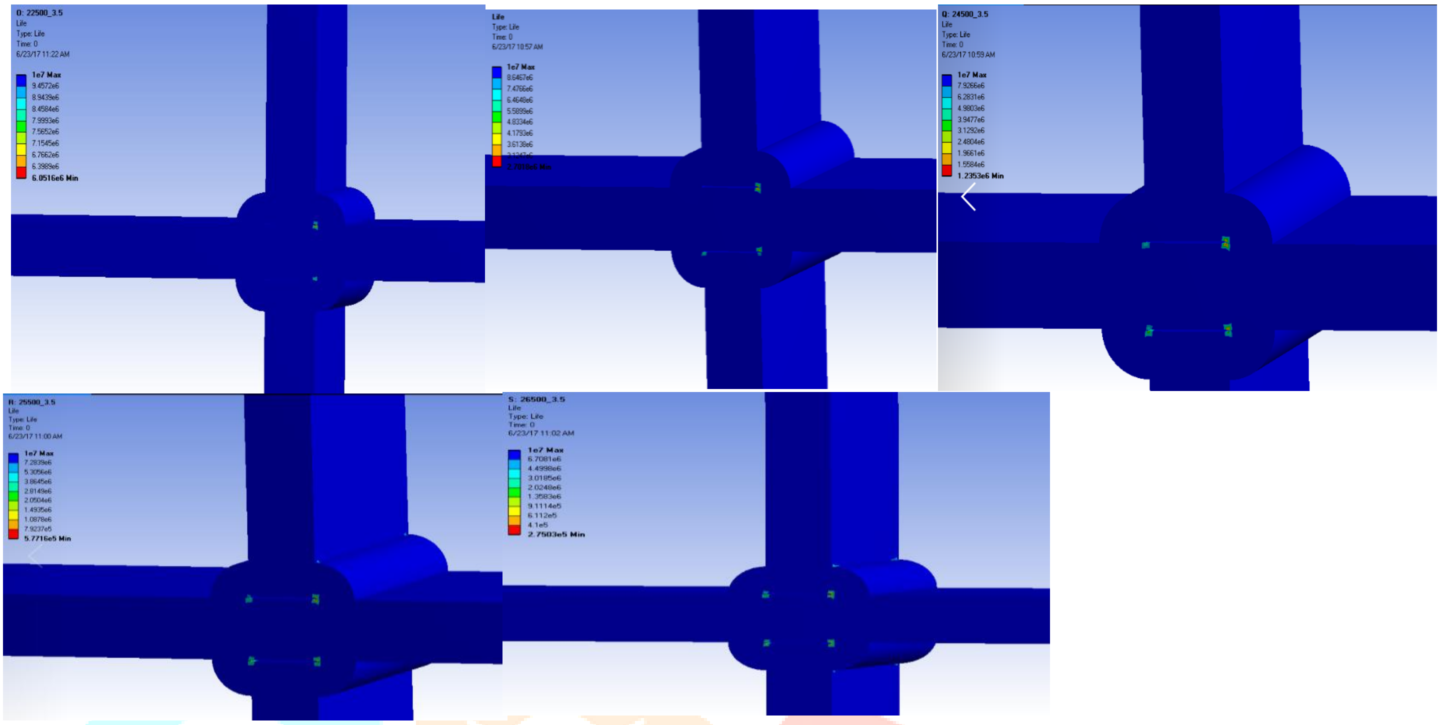






3.3.4 Fatigue life analysis for Convex Welded Structure (3.5*3.5):

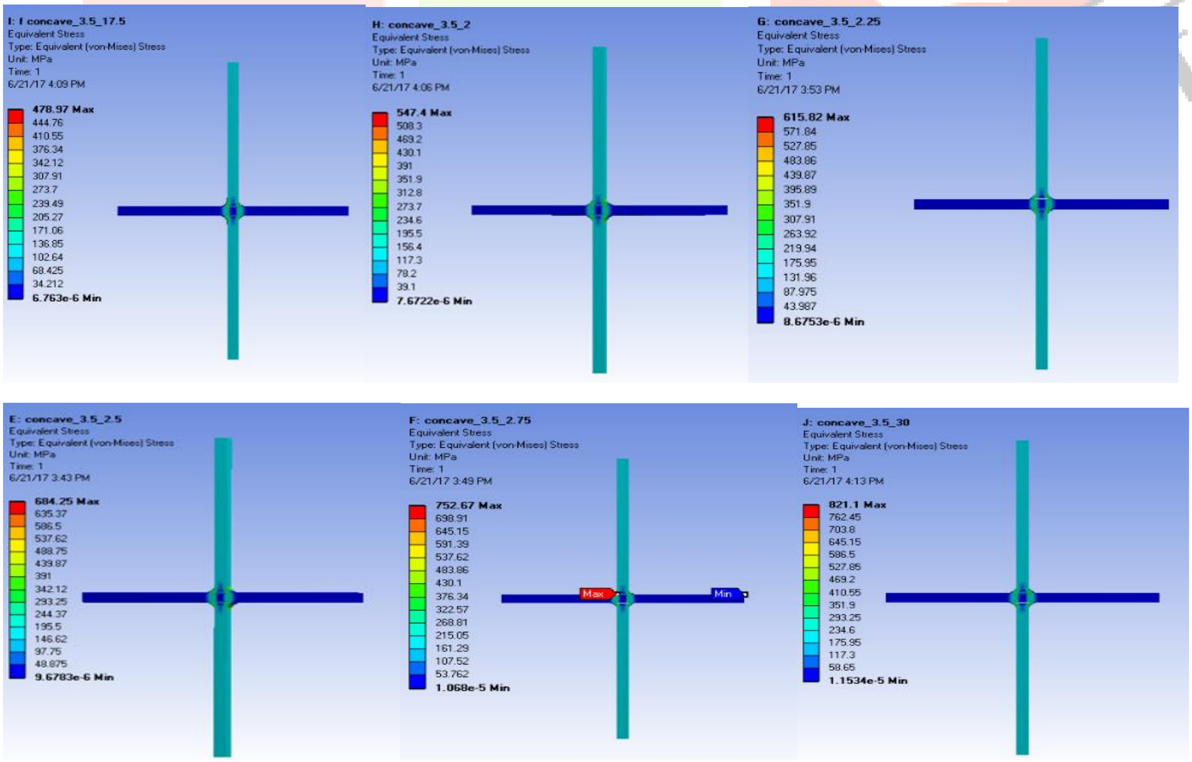
Below Figure shows the calculated fatigue life. The red spotted line shows the minimum cycles of alternating load that can be applied. The alternating stress and minimum number of cycles are listed in results.



NOTE: Similarly stress and fatigue analysis for Convex Welded Structures of sizes 4.5*4.5 and 5.5*5.5 was done and results were noted.

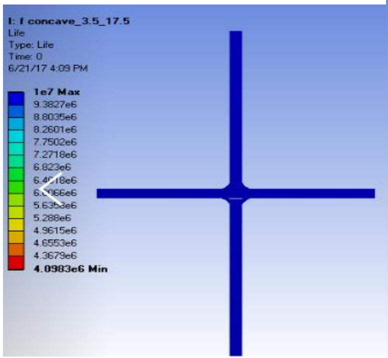
3.3.5 Stress analysis for Concave Welded Structure (3.5*3.5):

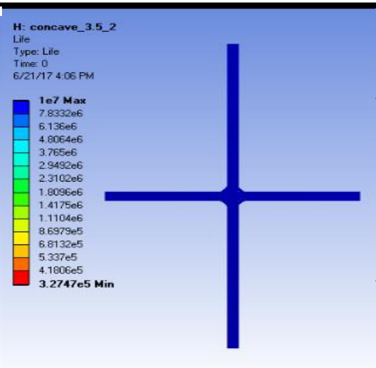
The applied load is 17.5,20,22.5,25,27.5 and 30 KN load and alternating maximum stress found is 478.97, 547.4, 615.82, 684.25,752.67 and 821.1 MPa at the concentrated area as shown in below ANSYS images

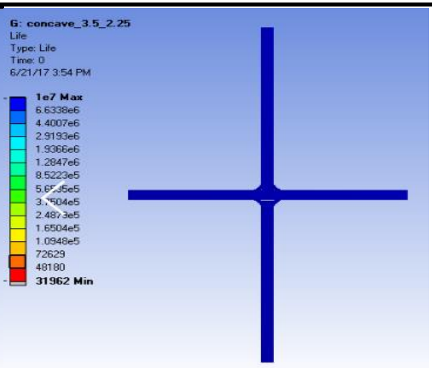


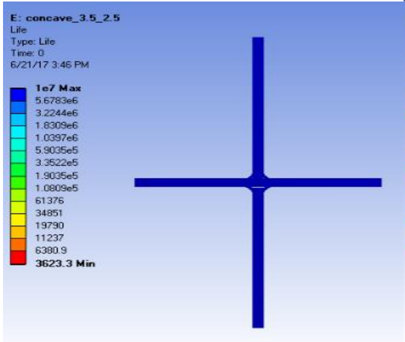
3.3.6 Fatigue life analysis for Concave Welded Structure (3.5*3.5):

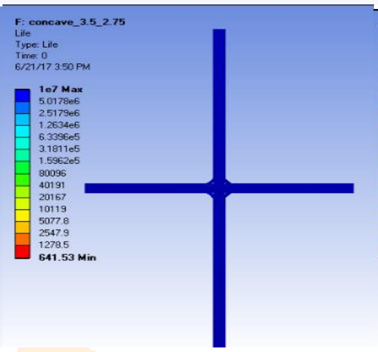
Below Figure shows the calculated fatigue life. The red spotted line shows the minimum cycles of alternating load that can be applied. The alternating stress and minimum number of cycles are listed in results.

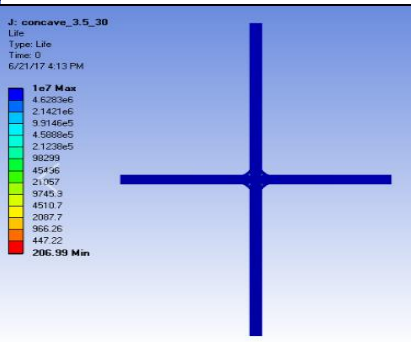












<u>NOTE:</u> Similarly stress and fatigue analysis for Concave Welded Structures of sizes 4.5*4.5 and 5.5*5.5 was done and results were noted.

3.4 Numerical Calculations:

There are four different mean stress theories can used to evaluate the fatigue behavior of components as shown in figure3.8. In the present work Goodman mean stress correction theory is considered to calculate the fatigue life. Fatigue data of material is considered on the basis of relation between the ultimate strength and endurance limit of the material (5).

3.4.1 Goodman Method:

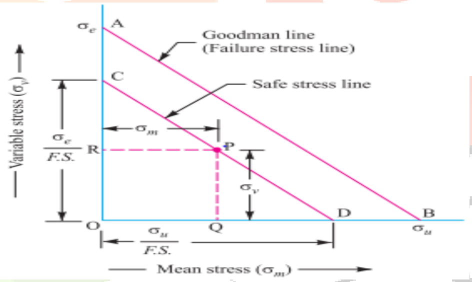


Figure 3.4: Goodman method

The Goodman suggestion follows the line AB shown in the figure below, this line connects the endurance limit (σe) and the ultimate strength(σu). In figure 5.8 line AB connects σe and σu is called Goodman's failure stress line. A safe stress line CD can be drawn parallelly to the line AB if an appropriate factor of safety(FS) is applied. Assume a point P on the CD line.

From similar triangles COD and PQD,

$$PQ/CO = QD/OD = OD - OQ/OD = 1 - OQ/OD$$

$$\sigma v/\sigma e/FS = 1 - \sigma m/\sigma u/FS$$

$$\sigma v = \sigma e/FS[1 - \sigma m/\sigma u/FS] = \sigma e[1/FS - \sigma m/\sigma u]$$

or

$$1/FS = \sigma m/\sigma u + \sigma v/\sigma e$$

Where, $\sigma m = Mean\ Stress,$

$\sigma u = Ultimate\ stress,$

$\sigma v = Variable\ stress,$

$\sigma e = Edurance\ limit, and$

$FS = Factor\ of\ safety$

3.4.2 Flat(3.5x3.5) Weldment Under Tensile Load

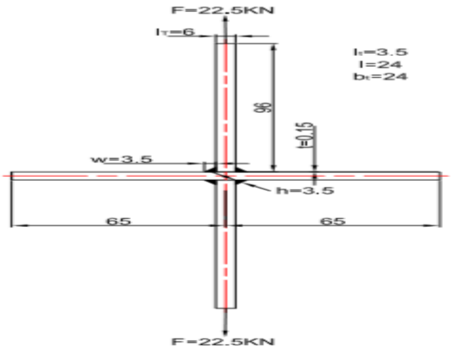


Figure 3.5: Flat weld size 3.5x3.5 of T-Joint with 0.15mm gap

The above Figure represents the T joint fillet weld sections with dimensions (96x25x6mm) with fillet angle 45º. Here 22.5 KN tensile load acting upward on the top of the section.

T-joint fillet welds the dimensions are specified are as follows:

F-Tensile load on vertical plate =22.5KN, w-Leg length of weld=3.5mm, h-Throat of fillet weld =w * cos 45º, l- Length of weld =24mm, l_T – Length of top load section=6mm, b_T- Breath of top load section=24mm, l_t-Throat length =3.5mm, t- Gap maintained between vertical plate and base plate=0.15mm, A- Area of weld section

Area of weld section (A)=$2A_f+A_l-A_t$

Where

A_f – Area of fillet section = $cos\theta * w * l$

A_l – Area of load section = $lT * bT$

A_t - Throat area = $t * lt$

Under 22.5KN load Ɵ=45^0 and 0.15mm gap,

Breaking stress (mean stress) $\sigma m = F/A * K$

Where,

$$A = 2Af + Al - At$$
$$= 2(cos\ 450 * 3.5 * 24) + (6 * 24) - (0.15 * 3.5)$$
$$= 262.251\ mm2$$
$$\sigma m = 22500/262.251 * 1$$
$$= 85.79 \text{ Mpa}$$

As per Goodman Method,

$$1/FS = \sigma m/\sigma u + \ \sigma v/\sigma e$$

From the above equation,

$$\sigma v = \ \sigma e[1/FS - \sigma m/\sigma u]$$

For flat weld 3.5*3.5, at 22500 N

Alternating stress, $\sigma v = \ \sigma e[1/FS - \sigma m/\sigma u]$

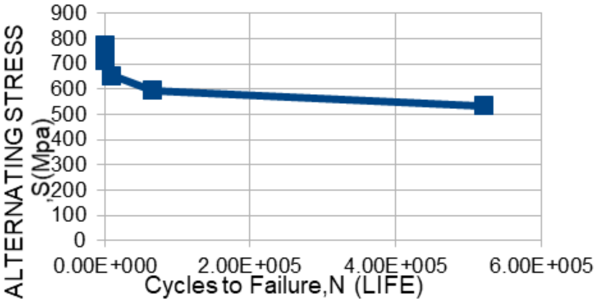
$= \ 0.5 * 950\,[1/0.84768 - (85.79/950\,)]$

$= 517.45\ Mpa$

4. RESULTS

4.1 Results of Alternating Stress and Minimum Number of Cycles are listed and S-N Curve is Plotted:

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
22500	534.26	517.45	5.22E+005
25000	593.63	574.95	66744
27500	653	632.55	9640.9
30000	712.35	690.01	1533.6
32500	771.71	747.51	466.3



4.1.1 Flat Welded Structure (3.5*3.5):

Table 4.1: Alternating Stress, Minimum Number of Cycles and S-N curve for flat welded structure 3.5*3.5

4.1.2 Flat Welded Structure (4.5*4.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
25000	487.11	509.46	2.99E+006
27500	535.82	560.27	4.94E+005
30000	584.53	611.17	90684
32500	633.24	662.09	18132
35000	681.95	713.12	3889.7
37500	730.67	764.05	931.89

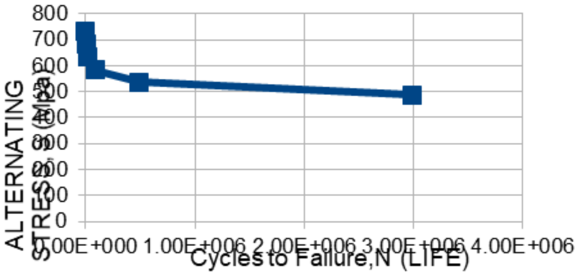


Table 4.2: Alternating Stress, Minimum Number of Cycles and S-N curve for flat welded structure 4.5*4.5

4.1.3 Flat Welded Structure (5.5*5.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
25000	458.91	457.15	9.01E+006
27500	504.8	493.74	1.54E+006
30000	550.7	584.57	2.92E+005
32500	596.59	594.27	60443
35000	642.48	639.97	13476
37500	688.37	685.69	3190.5
40000	734.26	731.42	876.45

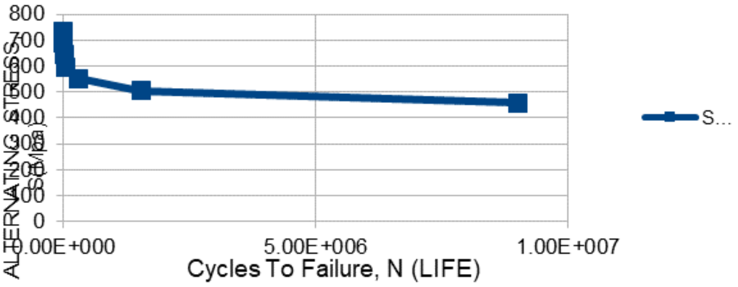


Table 4.3: Alternating Stress and Minimum Number of Cycles for flat welded structure 5.5*5.5

4.1.4 Convex Welded Structure (3.5*3.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
22500	468.56	435.72	6.05E+006
23500	489.23	455.06	2.70E+006
24500	510.62	474.40	1.23E+006
25500	531.64	493.79	5.70E+005
26500	552.67	513.14	2.70E+005

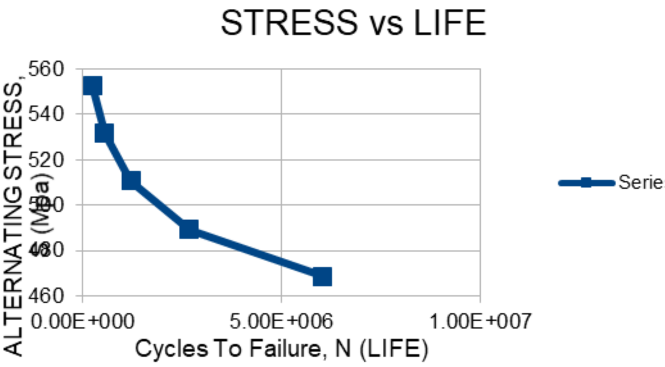


Table 4.4: Alternating Stress, Minimum Number of Cycles and S-N curve for Convex welded structure 3.5*3.5

4.1.5 Convex Welded Structure (4.5*4.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
25000	421.76	419.67	1.00E+007
27500	463.93	461.62	7.38E+006
30000	506.11	503.60	1.46E+006
32500	548.28	545.57	3.17E+005
35000	590.46	587.51	74236

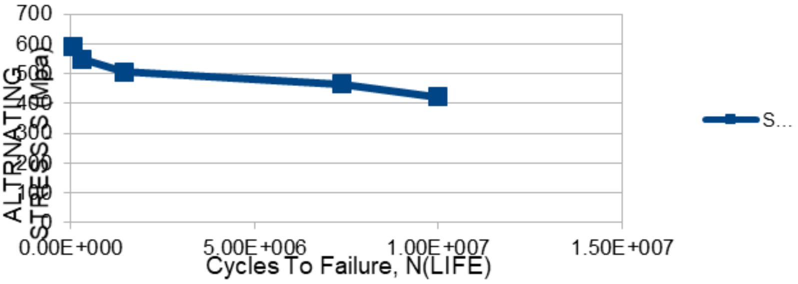


Table 4.5: Alternating Stress, Minimum Number of Cycles and S-N curve for Convex welded structure 4.5*4.5

4.1.6 Convex Welded Structure (5.5*5.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
25000	373.45	370.34	1.00E+007
30000	485.48	444.41	3.18E+006
35000	522.83	518.44	7.90E+005
37500	560.17	555.52	2.09E+005
40000	597.51	592.51	58596

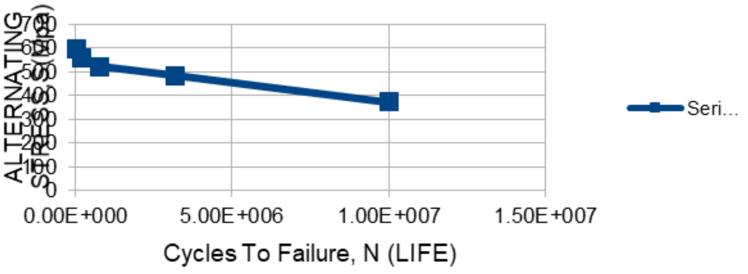


Table 4.6: Alternating Stress and Minimum Number of Cycles for Convex welded Structure 5.5*5.5

4.1.7 Concave Welded Structure (3.5*3.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
17500	478.97	434.72	4.09E+006
20000	547.4	496.75	3.24E+005
22500	615.82	558.84	31962
25000	684.25	620.94	3623.3
27500	752.67	683.13	641.53
30000	821.1	745.22	206.99

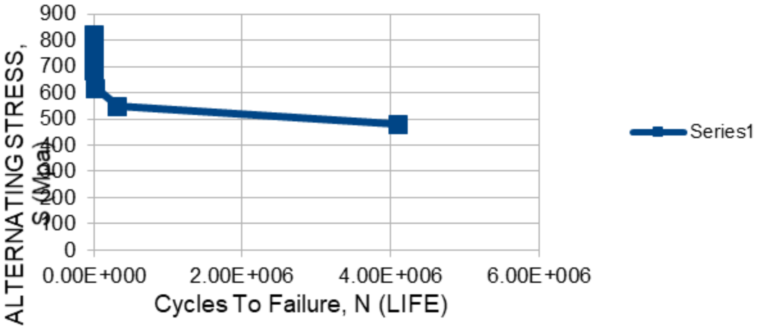


Table 4.7: Alternating Stress, Minimum Number of Cycles and S-N curve for Concave welded structure 3.5*3.5

4.1.8 Concave Welded Structure (4.5*4.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
20000	494.58	444.3237	2.25E+006
22500	556.41	499.87	2.38E+005
25000	734.1	555.45	878.82
27500	807.51	611.00	258.29

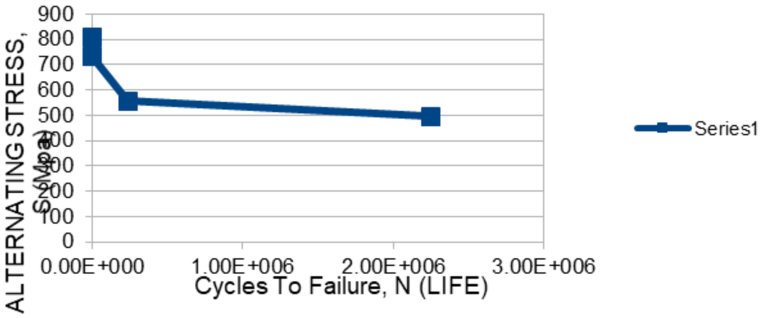


Table 4.8: Alternating Stress,Minimum Number of Cycles and S-N curve for Concave welded structure 4.5*4.5

4.1.9 Concave Welded Structure (5.5*5.5):

Applied Load(N)	Alternating stress max (Mpa)		Life (cycles)
	Analysis values	Theoretical values	
20000	424.31	402.56	1.00E+007
25000	530.38	503.19	6.01E+005
27500	583.42	553.55	94158
30000	636.46	603.85	16346
32500	689.5	654.144	3081.3
35000	742.54	704.52	761.39
37500	795.58	754.80	314.13

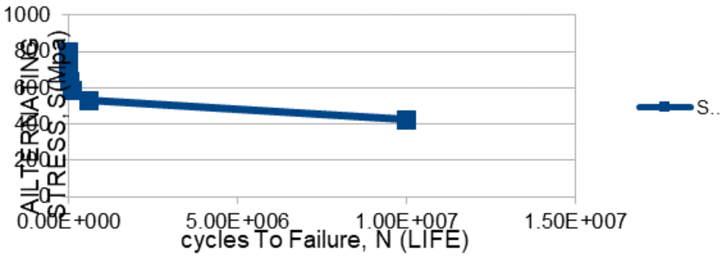


Table 4.9: Alternating Stress, Minimum Number of Cycles and S-N curve for Concave welded structure 5.5*5.5

5. CONCLUSION

In the present study the fatigue life estimation of cruciform weld joint has be analyzed using FEA, with respect to the results obtained from FEA the following conclusions are drawn for the respective case. The crack propagation in all the weld shapes are concluded with respect to the stress concentration regions and also the stress life approach defines the complete failure from crack initiation propagation and final failure.

Case I (FLAT): In the case of flat triangular weld with various sizing under 3.5,4.5,5.5 the possible knee occurs at 500-600 Mpa alternating stresses. The average life in this alternating state of stress is about 3.8e4,5.4e4, 1.5e5 cycles. The initial crack from a flat weld shape has high chances of failure from the weld toe region, where there is high stress concentration along the weld line. The generated crack will grow in orthogonal direction with respect to the load application along the base metal.

Case II (CONCAVE): The concave weld shape which has a fillet shaped profile is also modelled using different weld sizing as in the case of FLAT weld bed. The infinite life occurs at an alternating stress range of 480, 500,520Mpa the alternating stresses are well below the yielding strength of the material. The average infinite life occurs at about e5 cycles as in the case of general ductile materials. In the present case the failure of the concave weld starts from the weld root region and propagates through the weld along the throat.

Case III (CONVEX): The convex weld shape in general has high fatigue strength because of the amount of material used along the weld bed. The average alternating stress range under which the knee occurs is about 500-600Mpa. The failure of the convex weld starts from the root and propagates towards the weld toe because of the brittle nature of the weld and also there is high stress concentration over the weld toe and root region which can shear of the weld from the base metal.

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