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THERMAL STRESSES AND FATIGUE CRACK PROPAGATION ANALYSIS OF BOILER STEAM DRUM

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ABSTRACT

The Boiler steam drum operates at 350 ℃ to 380 ℃ temperature and 110 kg/cm^2 pressure. Since there is a continuous generation of steam from the boiler at higher temperature and pressure. There is repetitive thermal load acting on steam drum which results in thermal expansion of the steam drum material where this leads to formation of thermal stresses and finally results in cracks on the surface of the material. Thermal stresses are driven by strains created in the structure by a temperature load. One of the complexities of this loading is that stresses develop if the structure undergoes expansion. With this volumetric enlargement, the elements of a solid undergo greater levels of stress. Thermal stresses can have significant effect on a structure's strength and stability, potentially causing cracks or breaks within certain components. Such failures compromise the overall design of the structure, which can lead to possible weakening and deformation. Due to repetitive thermal load acting on the material could lead to fatigue, the cracks are formed at the critical welded joint locations due to fatigue. So it is necessary to perform fatigue assessment of welded joints and crack propagation analysis through stress intensity factor and to obtain fracture toughness of the material.

To find a solution for this problem it is necessary to study the thermal behavior by designing a 3D CAD model of a boiler steam drum component and to perform a finite element thermal stress analysis using MSC Nastran.

Keywords: MSC NASTRAN, Thermal stress analysis, Fatigue welded joints, crack propagation etc.

I. INTRODUTION

The welded joints are the most critical locations of steel structures due to high stress concentration and due to possible cracking originated from welding process. Large number of cracks were detected of varying length on the welded areas of boiler steam drum. In the present work fatigue assessment of welded joints are carried out for the critical locations which were identified from the static and thermal stress analysis. Fatigue in the steam drum is primarily caused by the combined action of pressure and temperature loading. The Boiler steam drum operates at 110 kg/cm^2 and at 350º C to 380 º C temperature. Due to this Thermal loads a significant amount of stresses are induced at welded locations where in particular the crack initiates at the weld toe region. These regions are analysed for structural hot spot stresses. The structural hot spot stress can be determined using reference points by extrapolation to the weld toe under consideration from stresses at reference points. The SN

IJARSE
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ISSN (P) 2319 - 8346

Curves of steel are used for verification in such cases depend largely on the geometric and dimensional parameters. The Fatigue life of critical welded locations are identified and calculated accordingly. Fatigue assessment of welded joints for boiler steam drum are carried out as per International Institute of welding process and applications. Weld crack growth analysis are performed at those critical locations and propagation stresses are determined and calculated.The Designing of CAD model is done through CATIA V5 R18 Software and Finite element modelling is performed in Hypermesh V12, The Final FEM model is analysed through MSC Nastran 2008 R1 and at last post processing of results are carried out in MSC Patran 2010 version.

The obtained von mises and max principal stresses are compared with the material allowable limit and justified as the design is safe. Based on these results Fatigue life calculations of welded joints are performed and compared with the SN curve of the steel material and justified as our fatigue life obtained is safe as per welded design process and methodologies.The Fracture toughness of the material is identified for the carbon steel material i.e is SA 299 Gr.A. The crackpropagation life are calculated through stress intensity factors for the typical welded joint critical location and based on the results obtained it is recommended and concluded to operate the boiler steam drum at designed limit as it is observed during my Internship work at (BMM ISPAT LTD), that most of the time plant is exceeding the allowable limit of the boiler steam drum in intention of producing maximum amount of electricity at particular shift.

1.1 Physical Model

Fig. 1130 TPH CFBC Boiler Steam drum (Company: - BMM ISPAT LTD)

The Function of steam drum is to separate the water from the steam generated in the furnace walls and to reduce the resultant solid contents of the steam to below the prescribed limit of 1 ppm. The drum is located on the upper front of the boiler.The arc plates are mounted along whole straight section of drum, forming a casing space at two sides of drum. Water mixture introduced from furnace rises enters the casing, and then goes into horizontal separator for primary separation, while the water from horizontal separator enters water area through outfall and steel wire net. The steel wire net will reduce the kinetic energy and help the steam get out. Water in

IJARSE
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ISSN (P) 2319 - 8346

water area enters down comer through cyclone arrester to participate in the next circle. While steam flows up through the centre of the drum into top steam space and flow into dryness box. When steam enters the dryness box, the velocity of the steam is low, while the way changes for several times, which makes the drip in steam adhere to the surface of under board well. So the dip will fall into the water area by gravity, achieve a second separation between steam and water. Then the steam enters steam container, fetched out by connecting pipe from the head of the drum.

1.2 Design of CAD Model

The designing of CAD model is done through CATIA V5 serves the basic design tasks by providing innovative technologies, for maximum productivity and creativity from the concept to the final product. CATIA V5 reduces the learning curve for the user, as it allows the flexibility of using feature based and parametric designs.

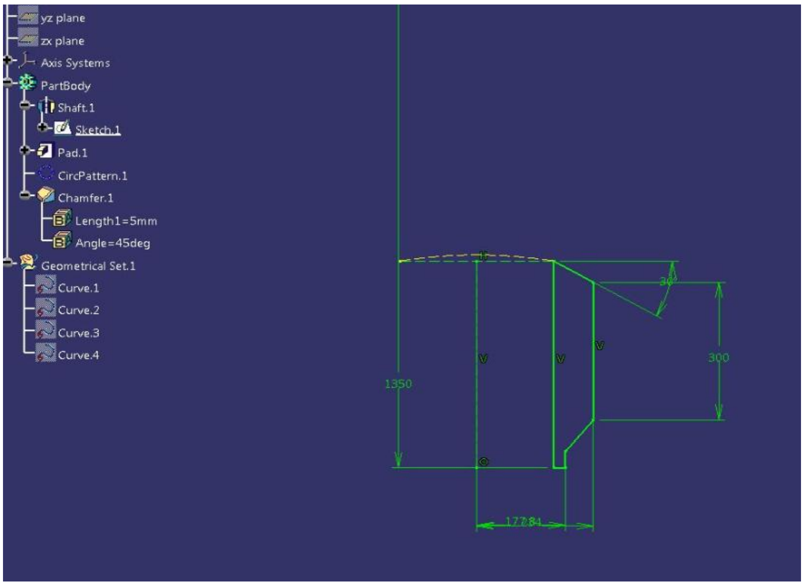

Fig. 2CATIA V5 - 2D Sketcher Environment

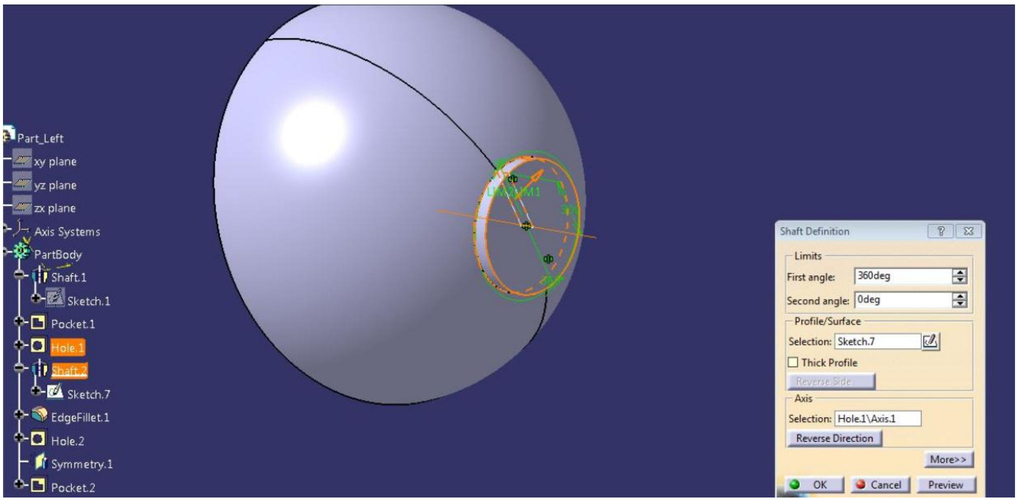

Fig. 3CAD modelling drum side

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

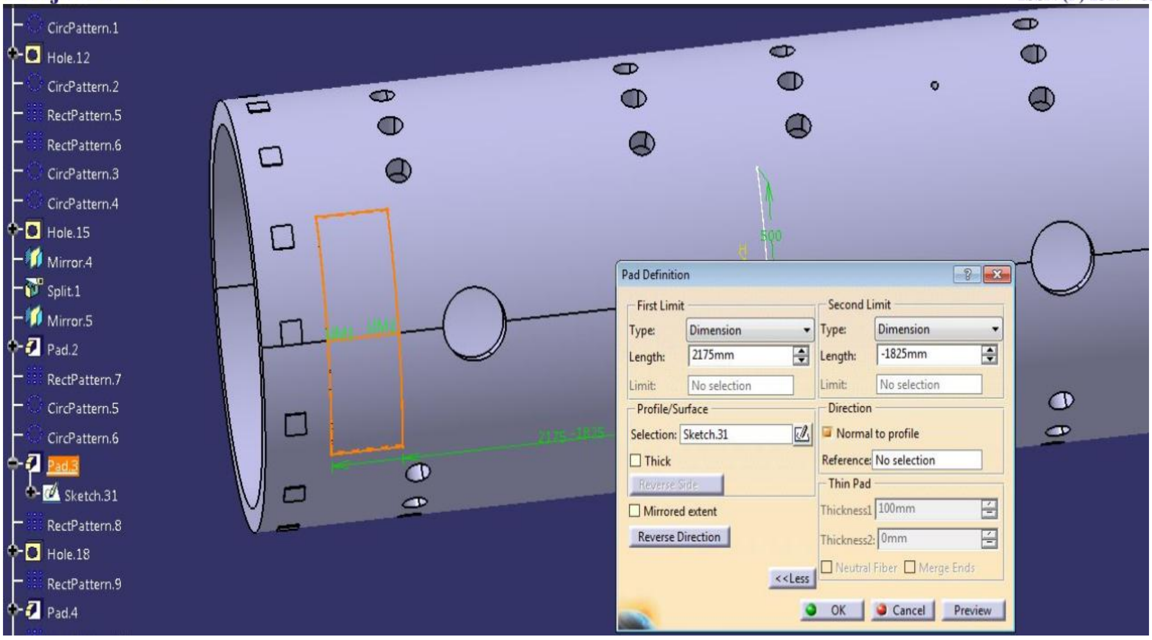

Fig. 4Creation of holes in drum shell

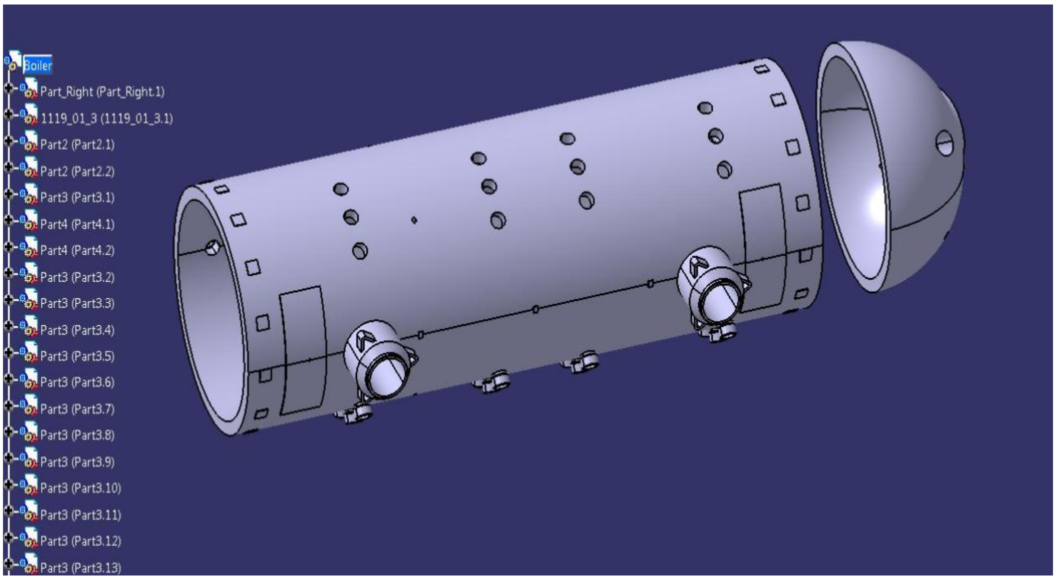

Fig. 5Assembly of Individual Components-1

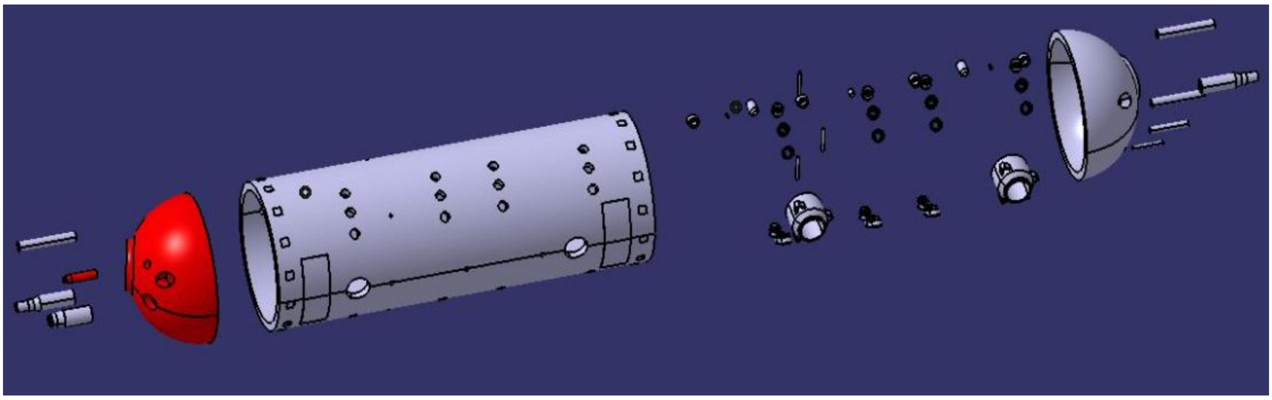

Fig. 6 Assembly of Components- 2

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

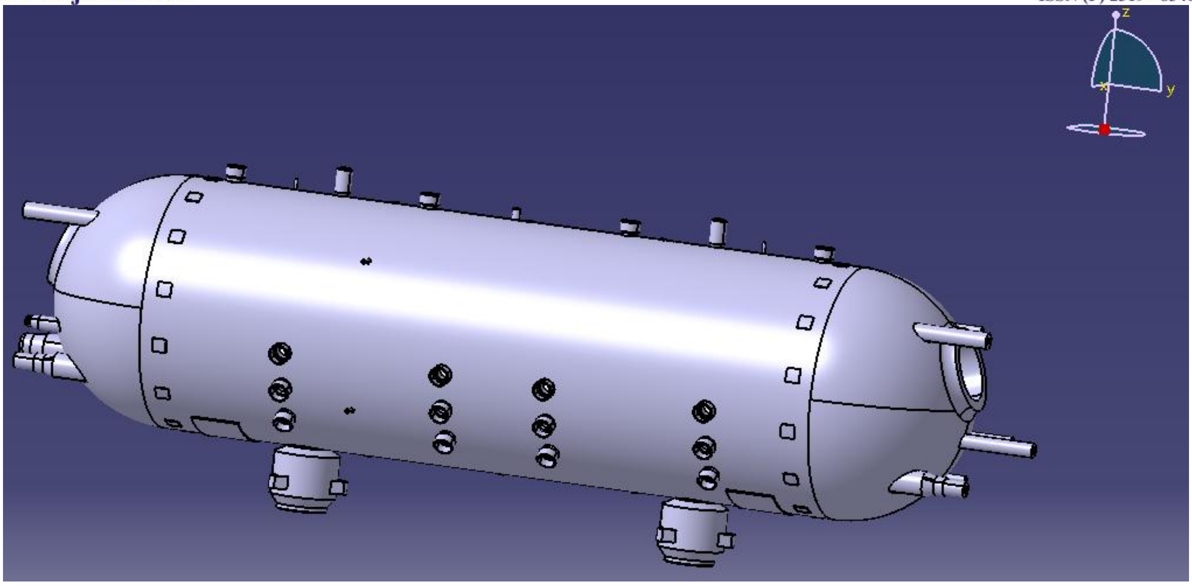

Fig. 7Final Assembled boiler steam drum CAD model

1.3 Finite Element Modeling of CAD Model

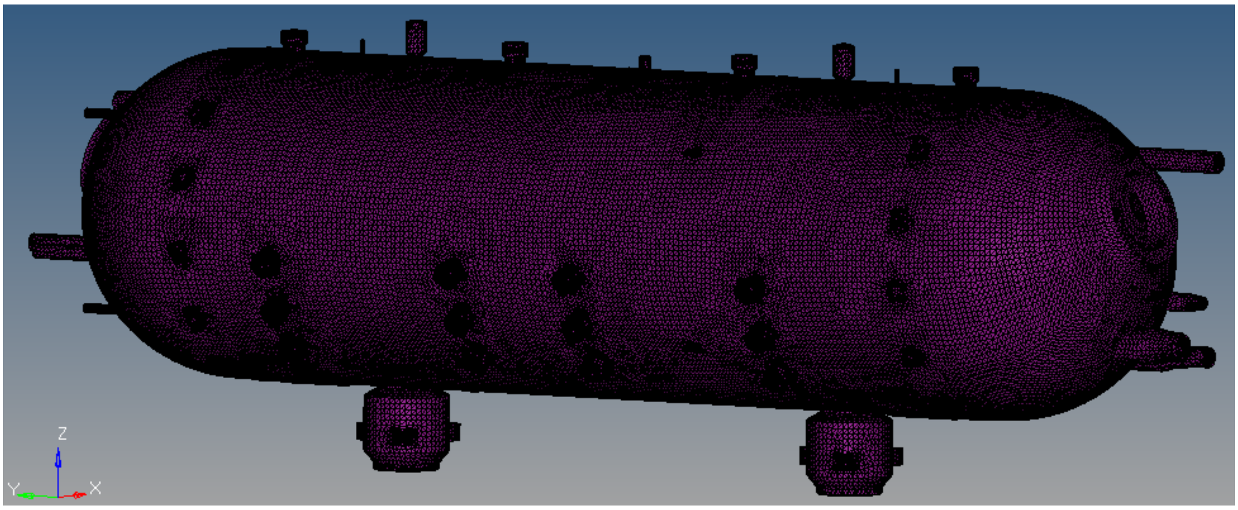

Fig. 8FE Model of Boiler steam drum using TETRA Element

FE Model building is very important step in FE Analysis, irrespective of what kind of analysis to be performed. Selection of appropriate element for certain application is very important. The FEA is provided with part surface data, which is required to be meshed with elements to get the component mesh. When all the parts in the assembly are meshed, they are all connected together using appropriate fastening element.Second order Tetra elements are used for building the Boiler steam drum component. It is recommended to mesh the complex portion of a part first then proceed towards the simple or plane areas to ensure good quality mesh in the FE model. If load transfer is supposed to take place from one surface in a structure to the other, a contact set should be defined between them.

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1.4 Load Applications

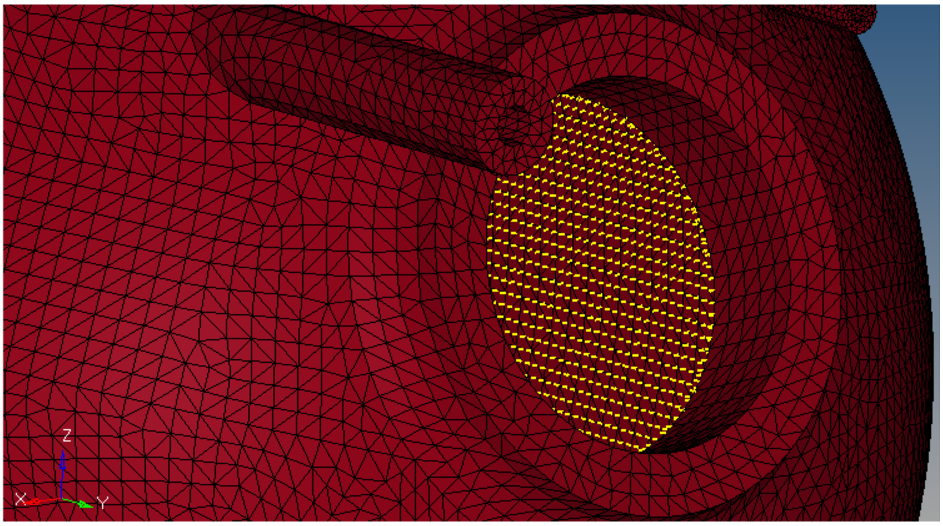

Fig. 9Pressure load Applied

The Boiler steam drum operates at 350°C to 380°C temperature and 110 kg/cm^2 of Pressure.The pressure load is applied to the drum inner surface area and temperature load is applied to the whole Drum FE structure to perform thermal stress analysis.

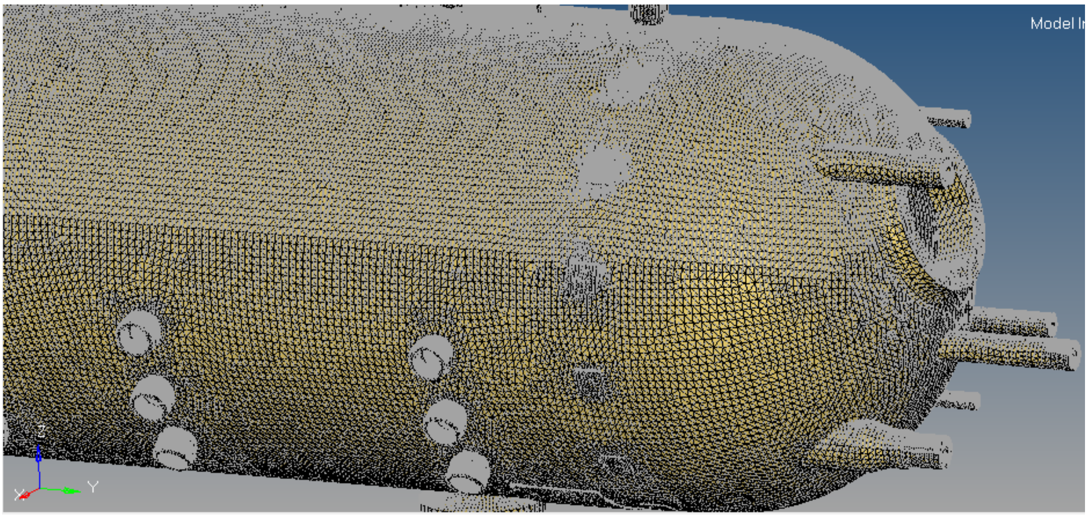

Fig. 10Temperature Load Applied to the Boiler Steam Drum FE Model

Since the Boiler steam drum operates at350°C to 380°C temperature. So the maximum temperature load has been applied to the entire drum structure by creating a subcase TEMP_380. This subcase gives a clear idea how temp load is acting uniformly to the structure and how thermal stresses are caused.

IJARSE
ISSN (O) 2319 - 8354
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1.5 Boundary Conditions

Three Translational and Three Rotational Degrees of freedom are fixed at the down comers, steam vent locations.

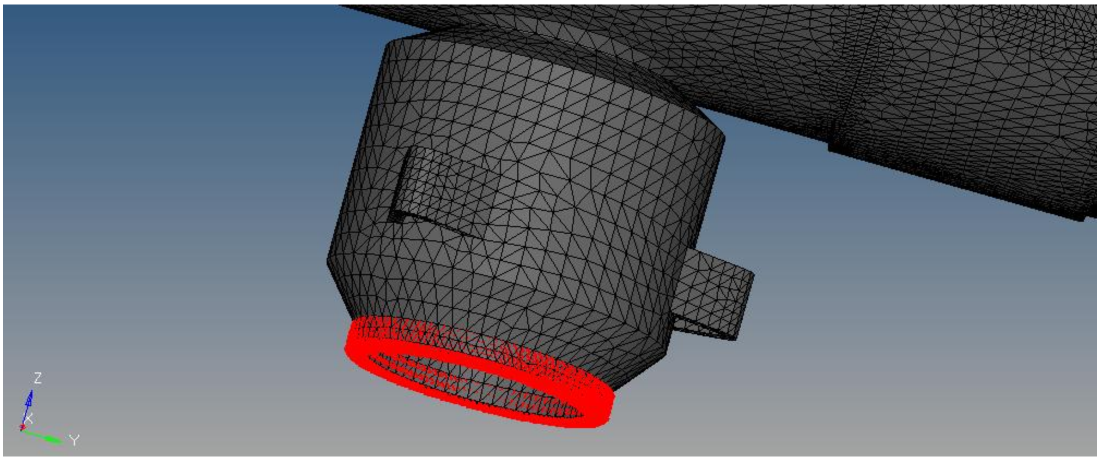

Fig. 11Constrained at down comer location

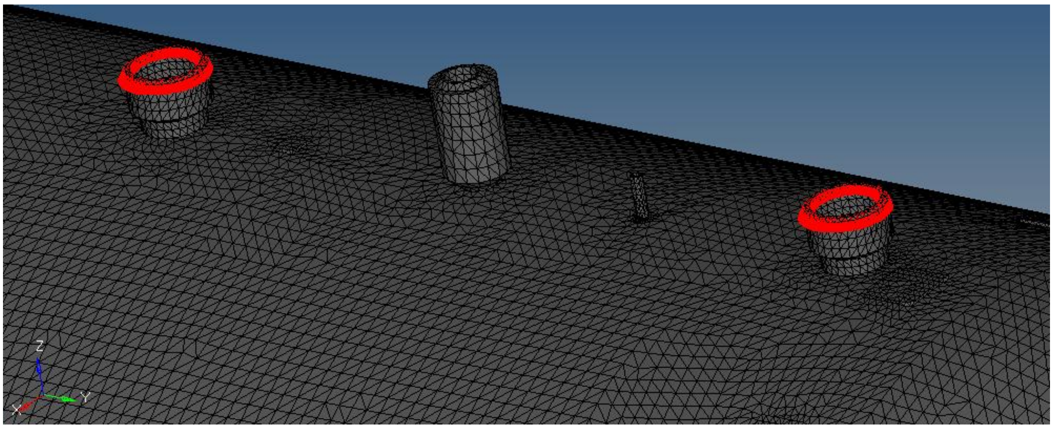

Fig. 12Constrained at steam vent location

1.6 Fatigue Analysis of welded joints in boiler steam drum

International Institute of welding – (A Recommendations for fatigue design of welded joints and components).

The aim of these recommendations is to provide a basis for the design and analysis of welded components loaded by fluctuating forces, to avoid failure by fatigue. In Addition they may assist other bodies who are establishing fatigue design codes. It is assumed that the user has a working knowledge of the basics of fatigue and fracture mechanics.The Purpose of designing a structure against the limit state due to fatigue damage is to ensure. With an adequate survival probability, is obtained by the use of appropriate partial safety factors.

The Fatigue action where structural Hot Spot stress at weld toe location is selected for the assessment of Fatigue for the boiler steam drum structure.

Structural Hot spot stresses

The structural or geometric stress $\boldsymbol{\sigma_{hs}}$ at the hot spot includes all stress raising effects of a structural detail excluding that due to the local weld profile itself. So, the non-linear peak stress $\boldsymbol{\sigma_{nlp}}$ caused by the local notch i.e the weld toe, is excluded from the structural stress. The Structural stress is dependent on the global dimensional

IJARSE
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ISSN (P) 2319 - 8346

and loading parameters of the component in the vicinity of the joint. It is determined on the surface at the hot spot of the component which is to be assessed. Structural hot spot stresses σ_{hs} are generally defined for plate.

The Structural hot- spot stress can be determined using reference points by extrapolation to the weld toe under consideration from stresses at reference points. Strictly speaking, the method as defined here is limited to the assessment of the weld toe , however approach may be extended to the assessment of other potential fatigue crack initiation sites including the weld root, by using the structural hot spot stress on the surface as an indication of that in the region of interest. The SN Curve or the stress concentration used for verification in such cases depend largely on the geometric and dimensional parameters and are only valid in the range of these parameters.

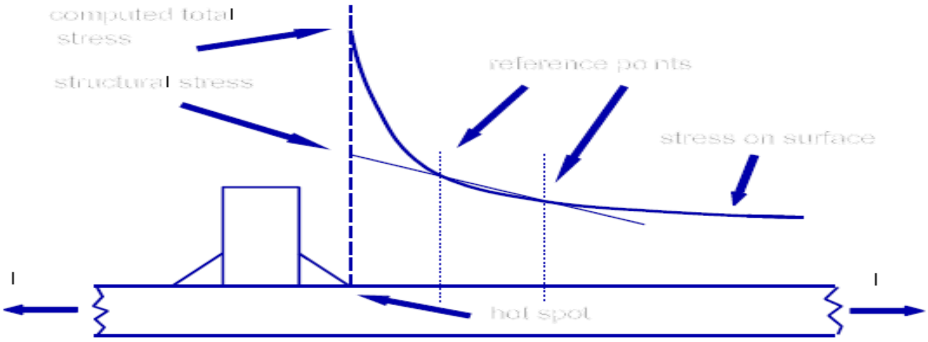

Fig. 13Definition of structural hot- spot stress

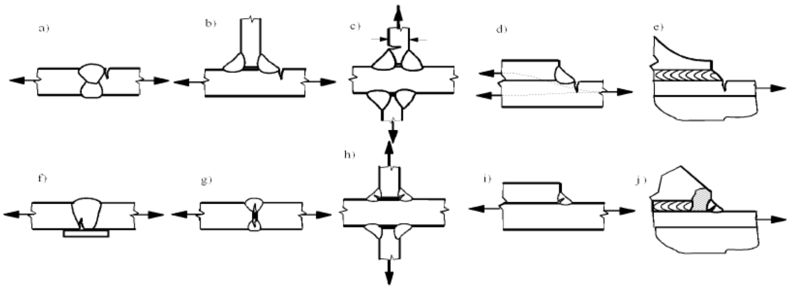

Fig. 14.various locations of crack propagation in welded joints

Calculation of structural hot spot stress

The structural hot spot stress is calculated on the basis of an idealized, perfectly aligned welded joint. Consequently, any possible misalignment has to be taken explicitly into consideration in the FEA model or by applying an appropriate stress magnification factor k_m, this applies particularly to butt welds, cruciform joints and one sided transverse fillet welded attachments on one side of a unsupported plate.

The extent of the finite element model has to be chosen such that constraining boundary effects of the structural detail analyzed are comparable to the actual structure.

The Solid Elements like Hexa or Tetra Elements have a displacement function allowing steep stress gradients as well as plate bending with linear stress distribution in the plate thickness direction may be used. The mid side nodes at the edges, which allow only one element to be arranged in plate thickness direction due to the quadratic displacement function and the linear stress distribution. By reduced integration, the linear part of the stresses can be directly evaluated at the shell surface and extrapolated to the weld toe. Modelling of welds is generally

IJARSE
ISSN (O) 2319 - 8354
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recommended in the alternative with a multi- layer arrangement of solid elements allows to linearize the stresses over the plate thickness at the weld toe.

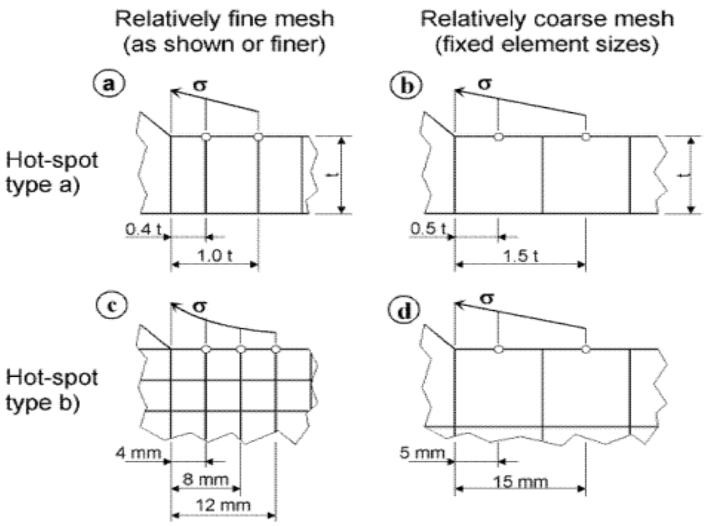


Fig. 15Reference points at different types of meshing

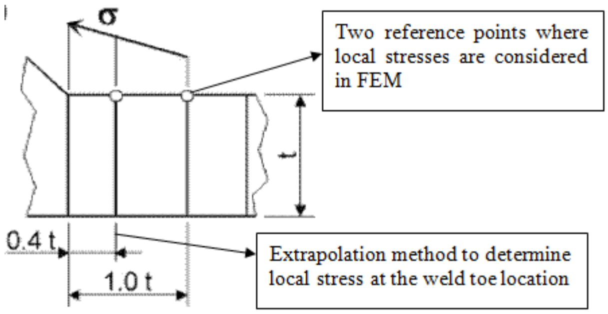


Fig. 16Type "a" Hot spot stress representation

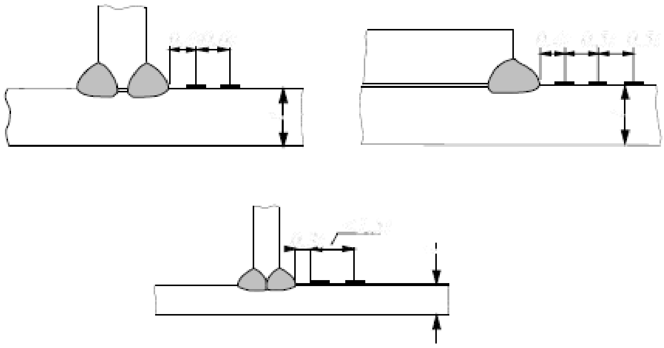


Fig. 17Measurement of structural hot spot stresses

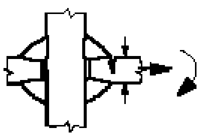
Structural detail	Description	Requirements	FAT Steel
	Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90

Fig. 18Representation of Fillet welded joints and its FAT class.

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

II GOVERNING EQUATIONS

The structural hot spot stress σ_{hs} isdetermined using the reference points and extrapolation equations.

Fine mesh with element length not more than 0.4t at the hot spot, Evaluation of nodal stresses at two reference points 0.4t and 1.0 t and linear extrapolation.

1.2.1 Structural hot spot stress equation

= 1.67. – 0.67. (1)

1.2.2 Mean stress for Soderberg curve

= (2)

1.2.3 Fatigue Failure of SN Curve

N= (3)

1.2.4 Mean Stress

= (4)

1.2.5 Amplitude stress

= (5)

1.2.6Stress Intensity Factor

(6)

III. RESULTS AND DISCUSSION

The results shows that the boiler steam drum design and structure is safe, hence it is less than the yield strength of the material (290 MPa) and for Fatigue crack initiation and propagation- max principal stresses are considered because they have direction, whereas von mises stress doesn't have direction, Hence the structural design is safe because the obtained stress value is less than the yield strength of the material.

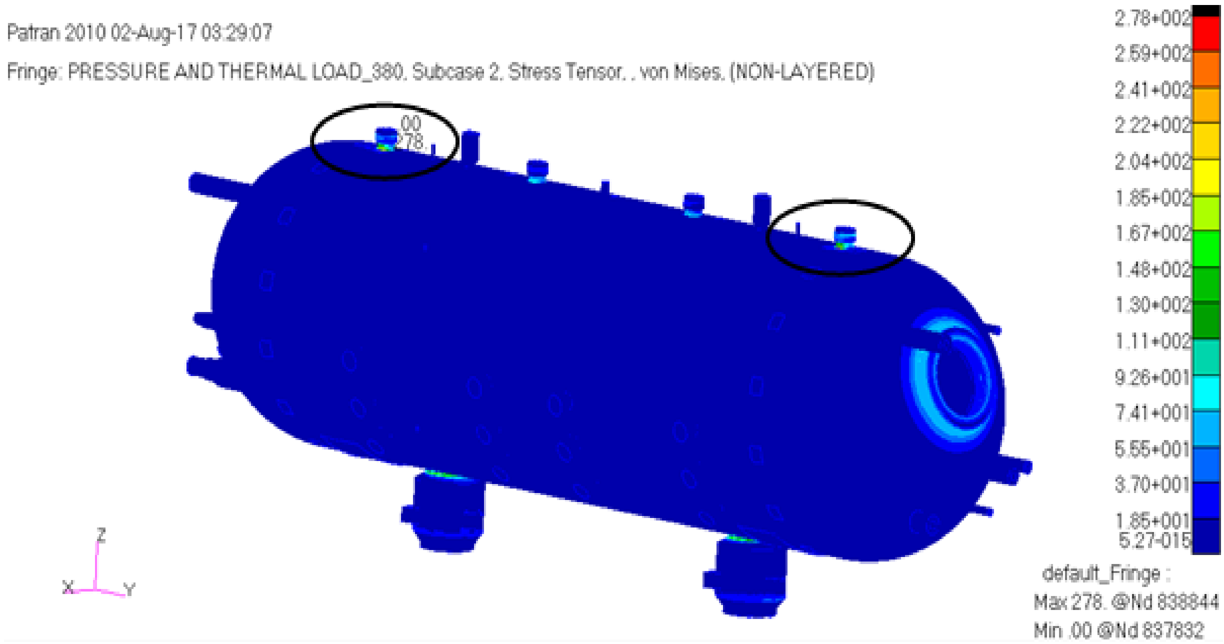


Fig.19 Von mises stress = 278 MPa

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

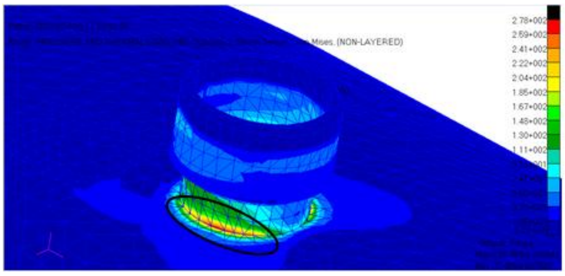


Fig.20.Enlarged View, Von Mises Stress = 278 MPa

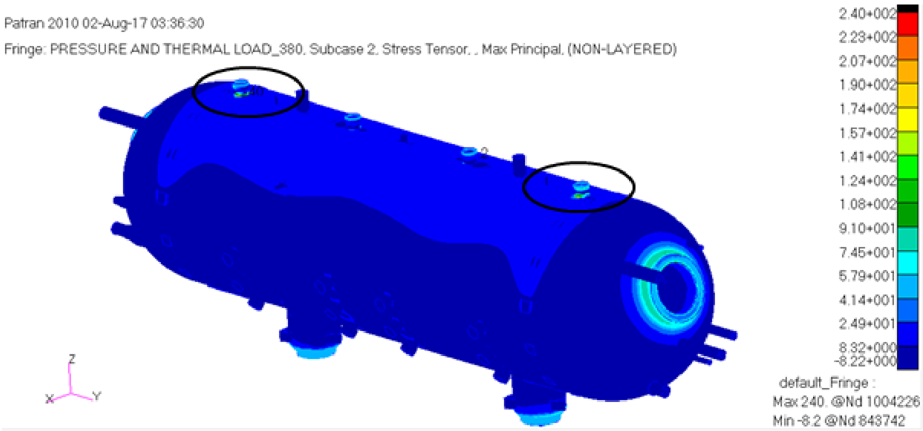


Fig.21Max Principal Stress =240 MPa

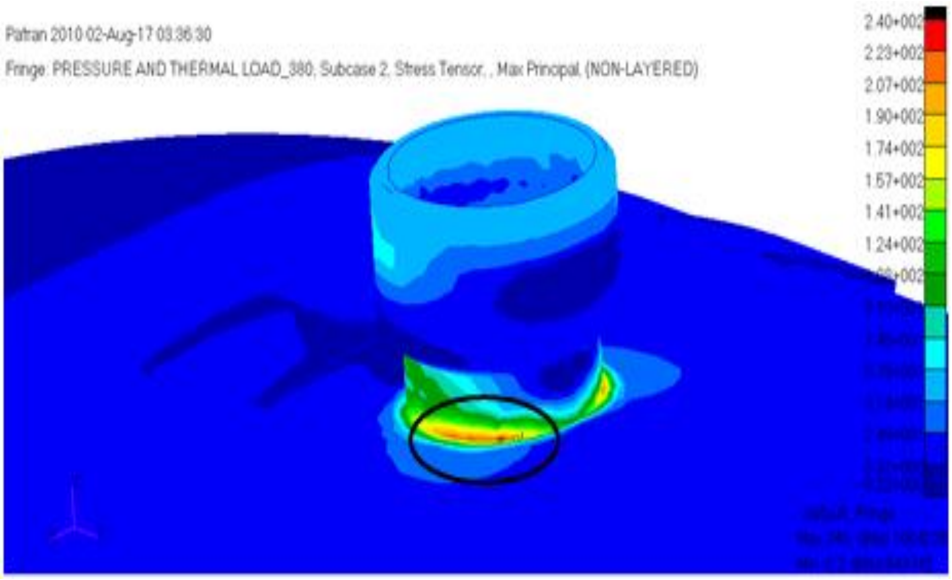


Fig.22. Enlarged View, Max Principal Stress = 240 MPa

The Critical locations are identified at the welded locations of the boiler steam drum where fatigue welded joint and crack propagation analysis are performed.

Critical location are identified at

1) Steam Vent :- welded joints

2) Downcomer :- welded joints

IJARSE
ISSN (O) 2319 - 8354
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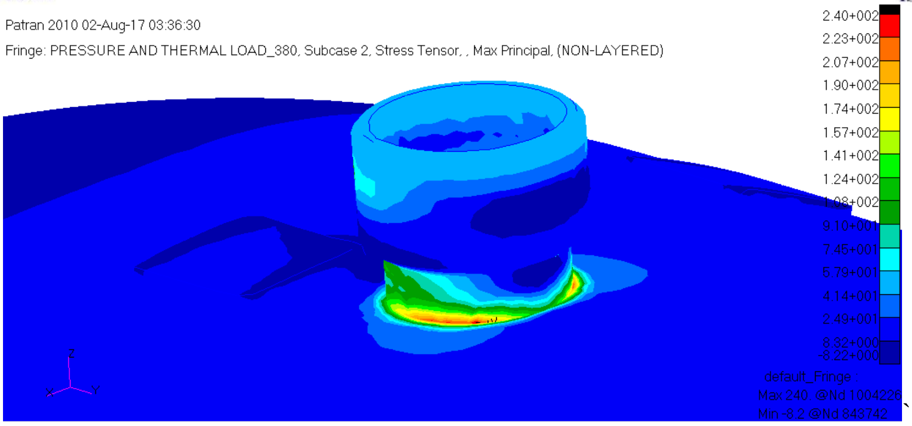

Fig.23 Critical location welded joint at steam vent(1) location

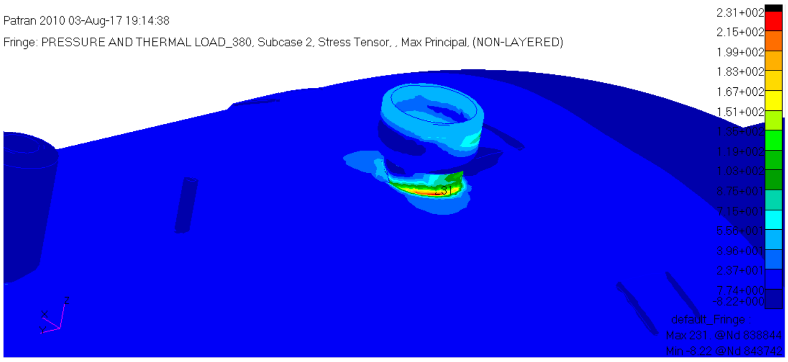

Fig.24 Critical location welded joint at steam vent (2) location

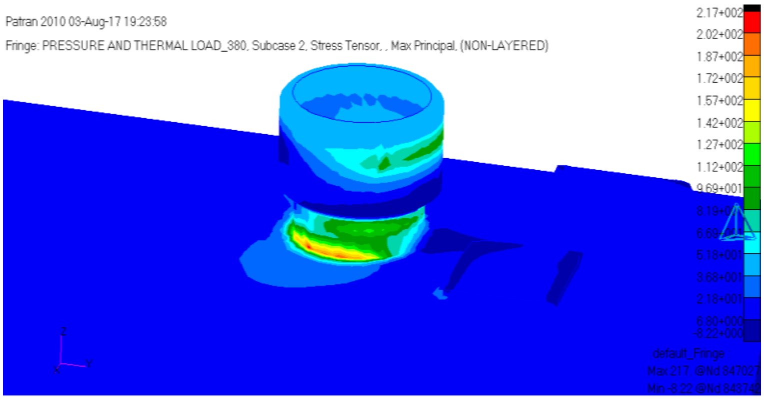

Fig.25Critical location welded joint at steam vent (3) location

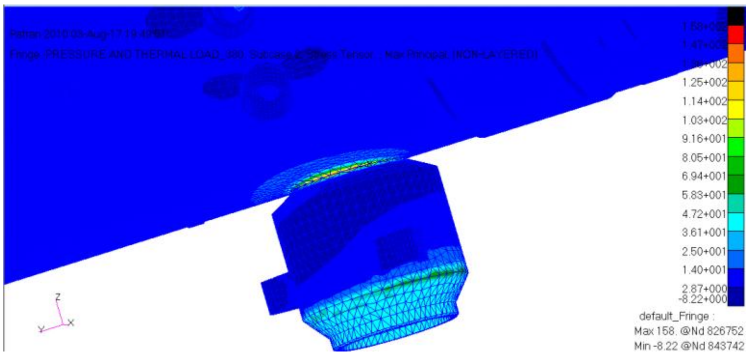

Fig.26Critical location welded joint at down comer location.

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Table 1 Max Principal Stress Values of Critical Locations

Critical Location	Max Principal Stress value
1st Location	240 MPa
2nd Location	231 MPa
3rd Location	217 MPa
4th Location	158 MPa

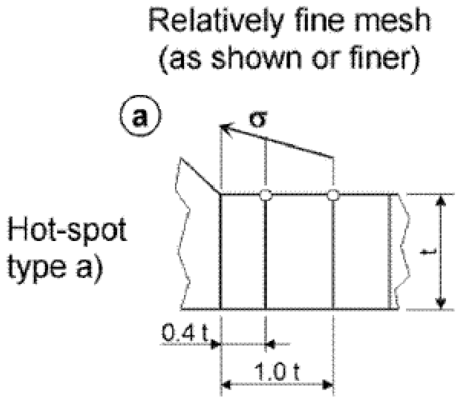

Fig.27Type "a" Hot spot stress representation.

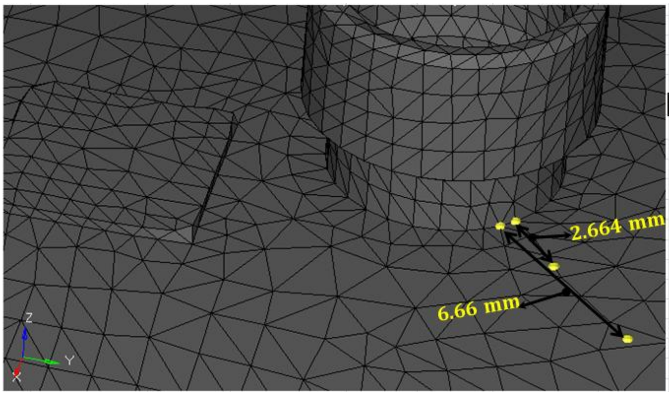

Fig.28Measurement of reference points in FE Model.

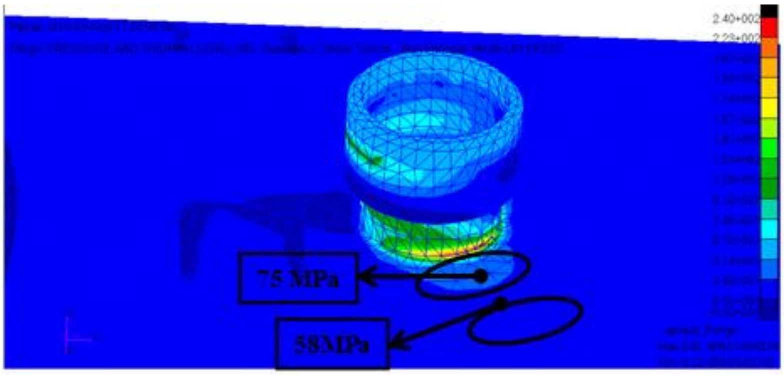

Fig.29Critical welded location for measurement of reference points.

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Table 2 Distance to Measure Stress at A Point

Reference points	Thickness "t"	Hot spot type "a"	Distance to measure Stress at the point
0.4×t	1st Reference point	0.4×6.66	2.664 mm
1.0×t	2nd Reference point	1.0×6.66	6.66 mm

The stress at 0.4×t is 75 MPa and the stress at 1.0×t is 58 MPa

Scaled thickness of drum shell t = 6.66 mm.

Calculation of Hot spot stress:-

= 1.67. – 0.67.

= 1.67×75 – 0.67×58

σ_{hs} = 86.39 MPa (Hot spot structural stress at weld toe location).

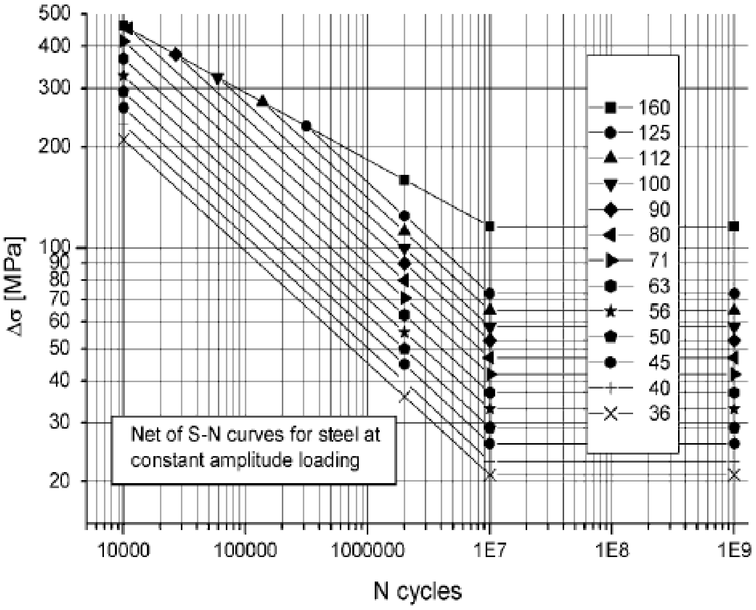

Fig.3. Fatigue Resistance S-N Curve for Steel

Constant Amplitude knee point is assumed at N= 10^7 Cycles,

Let us assume the hot spot structural stress σ_{hs} = 86.39 MPa is the σ_{max}

$\sigma_{hs=}$ $\sigma_{max\,=}$ 86.39 MPa

σ_{min} = 0 MPa (from FE Model)

=

= σ_{mean}= 43.19 MPa

=

=

$\sigma_{amplitude\,=}$ 43.19 MPa

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

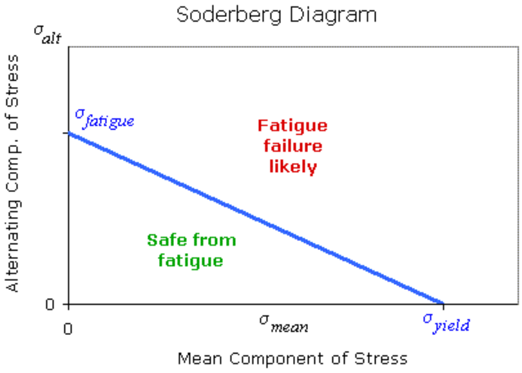

Fig.31Soderberg curve for fatigue welded

=

=

$\sigma_{a} =$ 50.74 MPa (Amplitude stress for mean stress = 0)

So the obtained $\sigma_{a} =$ 50.74 MPa is our $\Delta\sigma$ value.

Fatigue life formula for welded joints

N=

N: - No of Fatigue life

C& m: - are fatigue constants

$\Delta\sigma$: - stress at FEM

Stress ranges		Values of constant C: $N=C/\Delta\sigma^m$ or $N=C/\Delta\tau^m$		
FAT class [MPa]	Stress at knee point $\Delta\sigma_{i,R,k}$ [MPa]	For stress ranges above knee point	For stress ranges below knee point Constant C: $N=C/\Delta\sigma^m$	
Δσ at 2E+6 cycles	**Δσ at 1E+7 cycles**	**m=3**	constant amplitude **m=22**	variable amplitude **m=5**
125	73.1	3.906E+12	1.014E+48	2.091e+16
112	65.5	2.810E+12	9.064E+46	1.207E+16
100	58.5	2.000E+12	7.541E+45	6.851E+15
90	52.7	1.458E+12	7.583E+44	4.046E+15
80	46.8	1.024E+12	5.564E+43	2.245E+15
71	41.5	7.158E+11	3.954E+42	1.236E+15
63	36.9	5.001E+11	2.983E+41	6.800E+14
56	32.8	3.512E+11	2.235E+40	3.773E+14
50	29.3	2.500E+11	1.867E+39	2.141E+14
45	26.3	1.823E+11	1.734E+38	1.264E+14

Fig.32FAT data, stress at knee point of SN Curve

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Fatigue Life Calculation of critical location near the welded joint.

m= 22 (obtained from the above figure)

$\Delta\sigma$ = 50.74 MPa (obtained from the FEM, which is less than the stress knee point)

C = 7.583×10^44

N=

N= 23.02× 10^6 cycles < 10^7 cycles

Crack Propagation analysis of Boiler steam drum using e-fatigue Tool

The crack growth analysis can provide an estimate of the remaining safe life a structure that contains a crack. Fracture mechanics is based on the concept of stress intensity, K that describes the magnitude of both stress and strain fields around a crack.

1) Loading: - Loads can be entered as either the maximum and minimum values or as the stress range and R ratio. Stresses entered are assumed to be elastic. Fracture mechanics is based on the nominal stress in the uncracked structure.

Loading units :- (MPa)

Maximum Stress: - σ_{max} = 42 MPa **(Far field stresses obtained for FE Model).**

Minimum Stress: - $\sigma_{min} =$ 0 MPa.

2) Material:-

Name: - Carbon steel

Type: - Steel

Crack growth Intercept: - [C] = 4.24E-13 m/cycle

Crack Growth Exponent: - [m] = 3.8

Elastic Modulus: - E = 2×10^5 MPa

3) Stress Intensity Factor:-

Stress intensity factors, K, describes the stresses and strain fields around a crack, stress intensity factors continuously change as the crack grows in the structure.

The general form of the stress intensity is given by:-

4**) Stress intensity factor finder**

Crack Type: - Single Fillet weld with a surface crack.

Crack Size:-

Initial = 2 mm

Final = 6.6 mm

IJARSE
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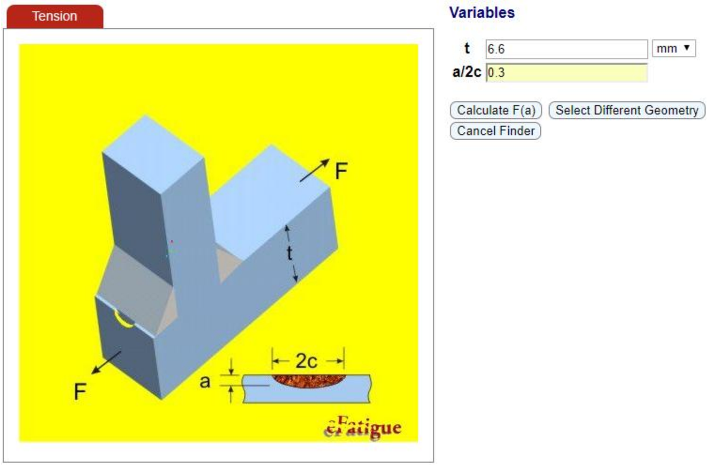

Fig.33Single fillet weld with a surface crack.

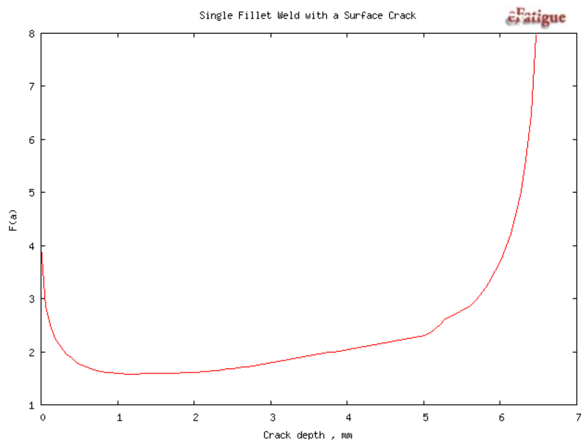

Fig.34Stress Intensity Factor Plot F(a) v/s Crack depth mm.

a, meters	F(a)
0	3.9889
6.60E-05	2.8409
1.32E-04	2.4429
1.98E-04	2.2236
2.64E-04	2.0772
3.30E-04	1.9661
3.96E-04	1.8806
4.62E-04	1.8056
5.28E-04	1.7497
5.94E-04	1.7083
6.60E-04	1.6773
7.26E-04	1.6517
7.92E-04	1.6316
8.58E-04	1.6169
9.24E-04	1.6008
9.90E-04	1.5904
0.001056	1.587
0.001122	1.5832
0.001188	1.5832
0.001254	1.5833
0.00132	1.5835
0.001386	1.5842
0.001452	1.5855
0.001518	1.5879
0.001584	1.589
0.00165	1.5909
0.001716	1.5935
0.001782	1.5969
0.001848	1.601
0.001914	1.6063
0.00198	1.6112
0.002046	1.6145
0.002112	1.6183
0.002178	1.6254
0.002244	1.6357
0.00231	1.6461
0.002376	1.6591
0.002442	1.6716
0.002508	1.6827
0.002574	1.6959
0.00264	1.7091
0.002706	1.7226
0.002772	1.7362
0.002838	1.7504
0.002904	1.7672
0.00297	1.7842
0.003036	1.8014
0.003102	1.8178
0.003168	1.8339
0.003234	1.8509
0.0033	1.8673
0.003366	1.884
0.003432	1.9007
0.003498	1.9173
0.003564	1.934
0.00363	1.9507
0.003696	1.9674
0.003762	1.9841
0.003828	2.0008
0.003894	2.0175
0.00396	2.0341
0.004026	2.0508
0.004092	2.0675
0.004158	2.0842
0.004224	2.1009
0.00429	2.1176
0.004356	2.1343
0.004422	2.151
0.004488	2.1676
0.004554	2.1843
0.00462	2.201
0.004686	2.2177
0.004752	2.2344
0.004818	2.2511
0.004884	2.2678
0.00495	2.2845
0.005016	2.3055
0.005082	2.3654
0.005148	2.4343
0.005214	2.5151
0.00528	2.6126
0.005346	2.6573
0.005412	2.7048
0.005478	2.7553
0.005544	2.8095
0.00561	2.8678
0.005676	2.9636
0.005742	3.0793
0.005808	3.209
0.005874	3.3559
0.00594	3.5241
0.006006	3.7193
0.006072	3.9498
0.006138	4.2278
0.006204	4.5722
0.00627	5.0148
0.006336	5.6137
0.006402	6.4902
0.006468	7.9586
0.006534	11.269

Fig.35Stress Intensity factor calculated values

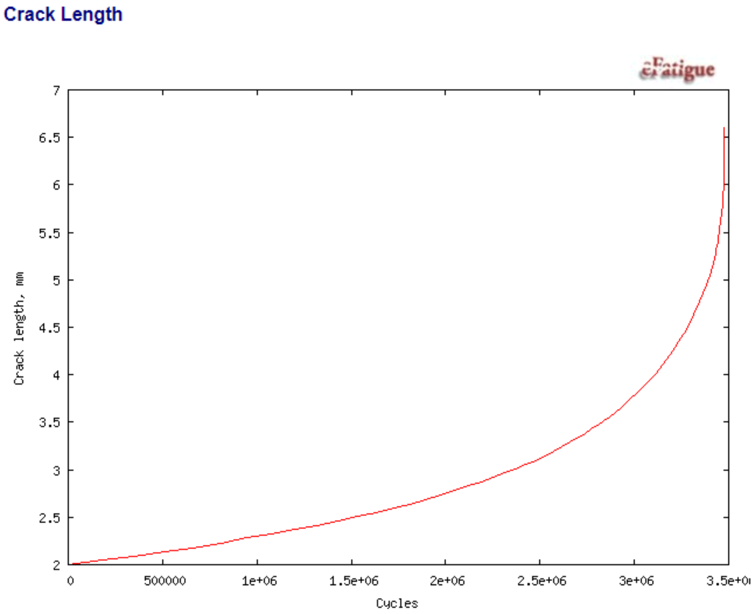

Fig.36Crack growth curve (crack length v/s cycles)

Results obtained from e-fatigue tool for Crack propagation analysis

Specified input data:-

σ_{max} = 42 MPa

σ_{min} = 0 MPa

Material type = steel

Material Name = Carbon steel

C = 4.24×10^{-13} m/cycle

m =3.8

E = 2×10^{5}

Crack Type = Single Fillet weld with a Surface crack

a_i (Initial Crack size) = 2 mm

a_f (Final Crack size) = 6.6 mm

Default Values

Crack growth R ratio [R_{mat}] = 0.1

Threshold stress intensity ΔK_{TH} = 5.0

a_i = 0.00200 m

a_f = 0.00660 m

Calculated Values

ΔS = 42 MPa

R= 0.00

ΔS (Stress range) = 42 MPa

N_f (No of Crack propagation cycles) = **3477424**

Crack propagation life of the critical welded location = **3.4×10^{6} cycles**

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IV.CONCLUSION

This work aimed to address all factors that could affect the fatigue life of the steam drum significantly, the major high risk locations directed are at welded locations such as downcomer welds, steam vent welds and safety valve welds, major loadings considered in the fatigue analysis were pressure load, temperature load caused by the thermal expansion of the steam drum. Static and Thermal stress analysis were performed to identify the critical stress concentration areas to obtain von mises stress and max principal stress. Critical locations identified are found to be particularly at weld toe locations, The Fatigue life of weld toe locations are calculated as per International Institute of welding approach and Methodologies, finallycrack propagation stresses were calculated at the critical weld toe locations through stress intensity factors, Fracture toughness of the carbon steel material (SA 299 Gr.A) were calculated, Finally it is concluded that Boiler steam drum can operate at 23.02×10^{6} cycles(Fatigue life cycles)and Crack propagation life of the critical welded location is 3.4×10^{6} cycles. It is also recommended that to operate the boiler steam drum at designed limit as it is observed during my Internship work at (BMM ISPAT LTD), that most of the time plant is exceeding the allowable limit of the boiler steam drum in intention of producing maximum amount of electricity at particular shift.Future applications are as follows; - Weld improvement techniques may increase the fatigue resistance, generally as a result of an improvement in the weld profile. Some of the improvement techniques would be: Method for improvement of weld profile i) Machining of but weld cap flush to the surface, machining of weld transition at the toe.ii) Methods for improvement of environmental conditions such as Painting and Resin coating. iii) Method for improvement of residual stress conditions: - Peening, Overstressing and stress relief.

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