

Finite Element Analysis of Skirt to Shell Junction in a Pressure Vessel

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Abstract

Objectives: The objective of this research work is to find the effect of providing hotbox at skirt to shell junction of a pressure vessel on the stresses induced at this junction. **Methods/Statistical Analysis:** In present work, since the vessel is to be supported at some elevation from ground, a conical skirt support is used. Two models of skirt to shell junction are made, in Unigraphics 10, one without hotbox while other with hotbox. A thermo-structural analysis of models is performed using ANSYS Workbench15. Stress linearization is done and stresses are limited to code allowable to ensure protection against plastic collapse and local failure. **Findings:** The result of finite element analysis for the case of model without hotbox shows that thermal stresses as high as 329 MPa are induced at the y-ring, which is much higher than the allowable stress at that temperature. When a hotbox is provided at this region, the stress is found to be reduced to 35.082 MPa, which is less than the allowable stress. So, the vessel will work safely if a hotbox of minimum 480 mm length is provided at the critical junction of skirt and shell. Stress is linearized at five stress classification lines. The linearized stresses and their combinations for four load cases are compared with the code allowable limit, and are found to be less than allowable stress. This ensures the protection of vessel against plastic collapse and local failure. **Application/Improvements:** Such analysis is needed to be performed for long vessels supported on skirt type of support, as the total vessel loads will be transferred to skirt from this junction only.

Keywords: Finite Element Analysis, Hotbox Analysis, Pressure Vessel, Skirt to Shell Junction, Stress Linearization

Nomenclature

FEA	Finite Element Analysis	σ_3	Linearized Minimum Principal Stress(MPa)
SST	Steady State Thermal	σ_{th}	Theoretical Circumferential Stress(MPa)
SS	Static Structural	R	Inside Radius of Shell(mm)
SCP	Stress Classification Plane	D	Inside Diameter of Shell(mm)
SCL	Stress Classification Line	t	Thickness of Shell(mm)
Pm	General Primary Membrane Stress(MPa)	S	Maximum Allowable Stress at Design Temperature (MPa)
PL	Local Primary Membrane Stress(MPa)	$S_{min.}$	Minimum of the Allowable Stresses for SA-240 and SA-516, at a temperature (MPa)
Pb	Primary Bending Stress(MPa)	P	Maximum Allowable Working Pressure(MPa)
Q	Secondary Membrane plus Bending Stress(MPa)	W	Dead Weight of Vessel(N)
σ_1	Linearized Maximum Principal Stress(MPa)	T	Design Temperature(°C)
σ_2	Linearized Middle Principal Stress(MPa)	E	SeismicLoad

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1. Introduction

A pressure vessel is one of the most vital components of a petrochemical refinery. These are used either to store solid, liquid or gaseous products, or to process a product to convert into another useful product. In case of the present work, a chemical process takes place in vessel, using a catalyst. Due to dissipation of heat during process, there will be mechanical load (pressure and temperature), acting at the inner wall of vessel. There will be other loads acting, like, self-weight and environmental loads (wind and seismic). High stresses will be produced due to these loads and their combinations, at critical region such as skirt to shell junction. In present case, the junction is a forged γ -ring, as shown in Figure 1. The vessel is designed as per procedures provided in ASME Section VIII Division 1. The wind and seismic load calculations are done as per NBCC2010.

¹ Authors have performed experiments on finite element analysis of pressure vessels with different type of head skipping the same cylindrical volume and thickness, for the cause of finding stress concentration zone for each head, under the same volume and pressure. The Maximum von-misses stresses were found to be minimum for Elliptical Head.

² Authors has performed finite element analysis to determine a Hot-box geometry which will minimize the thermal gradient stresses and improve fatigue life. Study demonstrates that modifying the dimensions of the hot box such as length, will affects the fatigue life of coke drum. The results indicate that by increasing the length of hot box, maximum Von Misses stress is reduced.

³ Authors have discussed the modeling, analysis, and monitoring of hot box designs. The importance of performing detailed sensitivity analyses is addressed if unknown thermal loading conditions exist. Additionally, this paper discusses the importance of making field measurements to enhance modeling assumptions.

⁴ Authors represents the guidelines in structural analysis for skirt to dished end junction. Analysis is carried out in compliance with ASME Section VIII Division 2. Finite elemental model of junction is prepared using UG-NX. It is then loaded in ANSYS 12.0 and results obtained are compared to code allowable.

⁵ Authors have performed stress analysis at skirt to dished end junction. They plotted a graph showing

stresses at various parts of vessel. By this they concluded that maximum stresses generated are at skirt to shell junction. The analysis is carried out in ASME section VIII, Div. 1. The model is made in Creo/Pro-E and then imported in ANSYSR15 and simulation is checked with ASME code.

⁶ Authors have performed elastic stress analysis of skirt to dished end joint, and concluded that by providing hot box at junction gives lower thermal gradient as compared to the case of junction without hot box case. Also, the center line matching method for the junction is found to be most suitable, as it can take more radiation heat transfer compared to the outer diameter matching method.

⁷ Authors have compared two methods, namely, stress classification method and direct route method, used for analysis of hydrogenation reactor skirt structure. The founding was, Stress classification method is an engineering approximation. The analysis is simple, mature, low computation cost. The direct route method avoids the problems caused by stress classification, the results are more reasonable. It is suitable for complex and important pressure equipment.

2. Geometric Model

A three dimensional 360° model of skirt to shell junction is prepared using UG NX 10. But, for clear visualization, results are shown on an 180° model.

2.1 Dimensions of Model

Table 1 show the dimensions of the geometric model and Figure 1 shows the geometric model of the skirt to shell junction, used for analysis

Table 1. Dimensions of Model

Specification	Dimension
Inside diameter of shell	2950mm
Thickness of shell	35mm
Outer diameter of skirt at base	2300mm
Thickness of skirt	35mm
Length of skirt	2721mm
Angle of inclination of skirt	15° to vertical
Length of Hotbox	480mm
Thickness of Insulation	240mm
Length of insulation on skirt	2193mm

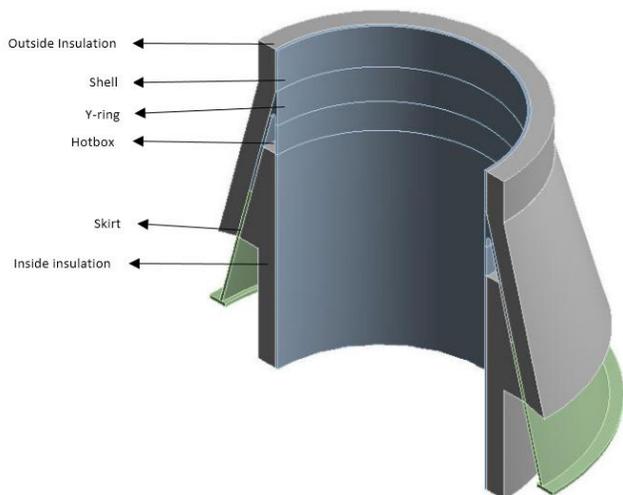


Figure 1. Geometric Model - 180° view

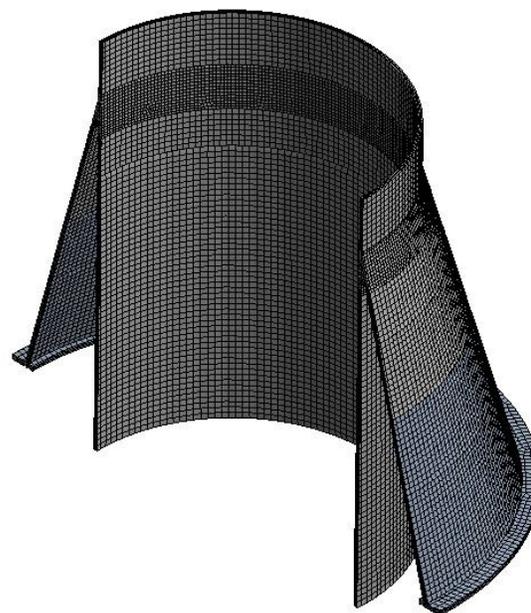


Figure 2 Full Model Mesh.

2.2 Material of Construction

Table 2 enlists the material of construction for shell, skirt, and, inside and outside insulation.

Table 2. Material of Construction

Sr. No.	Element	Material of Construction
1	Shell, Skirt top part, Y-ring	SA 240M Grade 304H
2	Skirt bottom part, Base ring	SA 516M Grade 485
3	Insulation	ASTM C1393 Type VI-B

3. Meshing of Model

Figure 2 shows complete meshed model and Figure 3 shows that fine meshing is done at y-ring, as it is the critical junction between skirt and shell, and therefore accurate results must be obtained here.

The element used for meshing is Hex 20.

Table 3 shows the details of mesh.

Table 3. Mesh Details

Sr. No.	Parameter	Value
1	No. of nodes	1755590
2	No. of elements	365707
3	Aspect ratio at y-ring	2.74
4	Aspect ratio at skirt	4.54

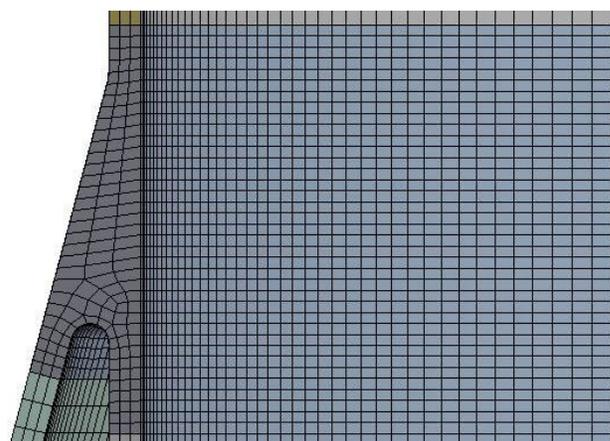


Figure 3. Fine Mesh at y-ring.

4. Boundary Conditions

For Steady State Thermal analysis, design temperature and for Static Structural analysis, maximum allowable working pressure is applied at the inner wall of vessel. The values of same are taken from the drawing.

4.1 Steady State Thermal Analysis

In the hotbox arrangement the primary mode of heat transfer inside hotbox is by radiation. Heat transfer between insulation/skirt and air, takes place through

convection. Emissivity values for steel and insulation are taken as 0.9 and 0.8 respectively and the convective heat transfer coefficients for pair of surfaces, namely, insulation-air and stainless steel-air, are taken to be $1 \times 10^{-5} \text{ W/mm}^2 \text{ } ^\circ\text{C}$ and $2.5 \times 10^{-5} \text{ W/mm}^2 \text{ } ^\circ\text{C}$ respectively.

Figure 4 shows the Steady State Thermal boundary condition for model with hotbox.

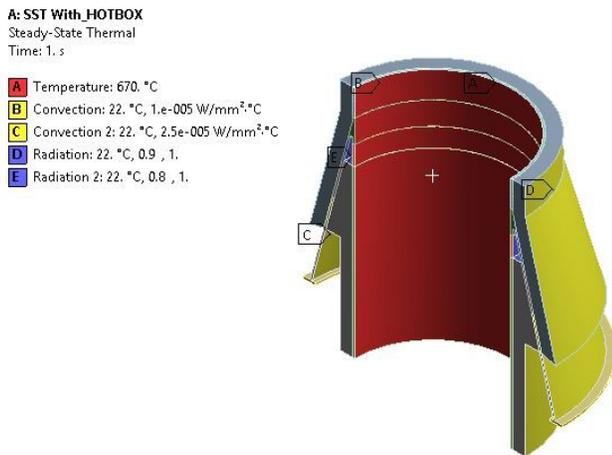


Figure 4. SST Boundary Conditions.

4.2 Static Structural Analysis

For static structural analysis, the base ring is constrained in all directions.

Internal pressure is applied at inside wall of vessel. An equivalent pressure thrust is applied at top and bottom faces of shell. Dead weights of upper and lower vessel are applied at respective center of gravities, and, seismic shear force and bending moment is applied at remote points taken individually for top and bottom vessel, which are connected to top and bottom faces of shell.

5. Analyses of Model

Analysis of model is performed in accordance with ASME code⁸. A thermo-mechanical system, in ANSYS Work- bench 15, is used to perform analyses. Two cases, as listed below, are considered, so that the effect of providing hotbox at skirt to shell junction can be observed.

- Case 1 : Model Without Hotbox
- Case 2 : Model With Hotbox

Firstly, Steady State Thermal analysis is performed at design temperature to obtain temperature gradient through the length of skirt.

The solution of SST is then imported in SS system, to get induced thermal stress. Also, various load combinations comprising of internal pressure, dead weight and seismic shear force and bending moment are applied, and stresses induced due to these are evaluated at different stress classification lines and are limited to ASME code allowable limits, as discussed in Section 6.2.

5.1 Results of Analyses

5.1.1 Steady State Thermal Analysis

Figure 5 shows temperature distribution across the shell and insulation, for the first case, i.e., model without hotbox. Figure 6(a) shows the temperature gradient through the length of skirt. It illustrates that when hotbox is not provided, there is more thermal concentration at y-ring, which leads to higher induced thermal stress. Figure 6(b) illustrates a temperature ($^{\circ}\text{C}$) versus length of skirt (mm) graph for the same.

Figure 7 shows temperature distribution across the shell and insulation for these condcase, i.e., model with hotbox. Figure 8(a) shows the temperature gradient through the length of skirt. It illustrates that when hotbox is provided, temperature concentration at y-ring is reduced, due to radiative heat transfer inside hotbox. Figure 8(b) illustrates a temperature ($^{\circ}\text{C}$) versus length of skirt (mm) graph for the same

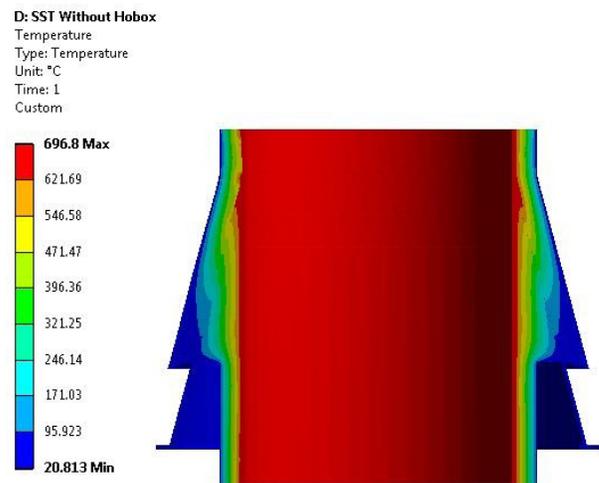


Figure 5. Temperature Distribution across Vessel for Case 1.

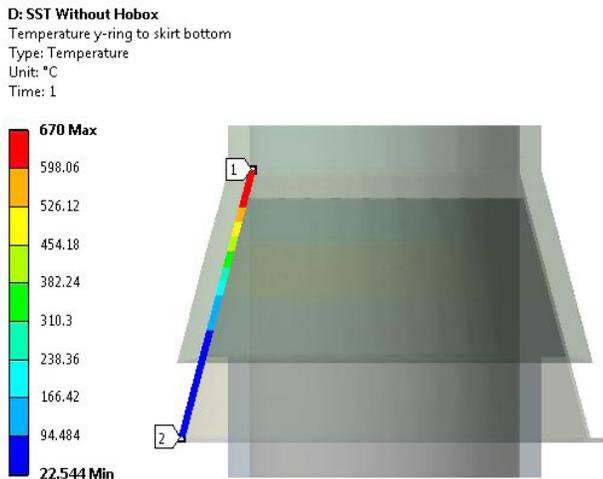


Figure 6(a). Temperature Variation along the Length of Skirt for Case 1.

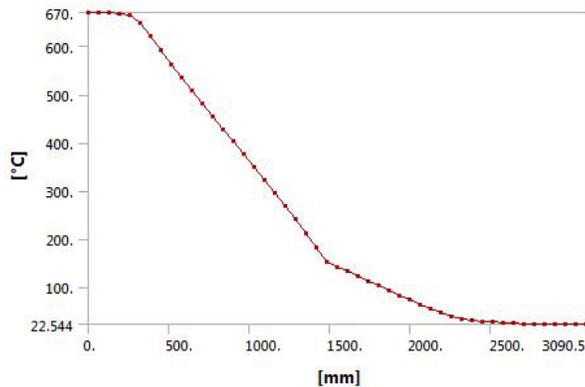


Figure 6(b). Graph representing Temperature Variation along the Length of Skirt for Case 1.

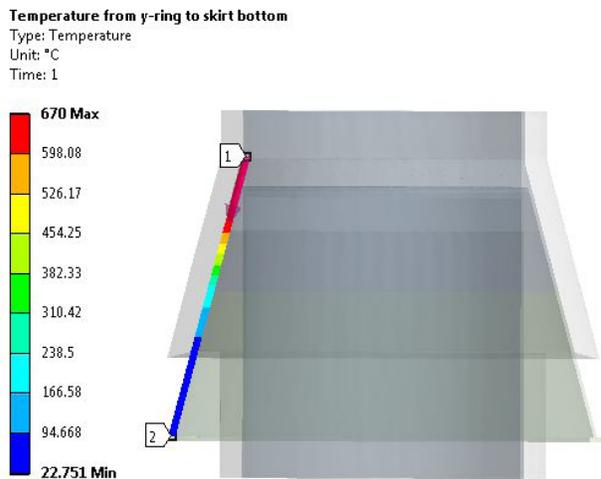


Figure 8(a). Temperature Variation along the Length of Skirt for Case 2.

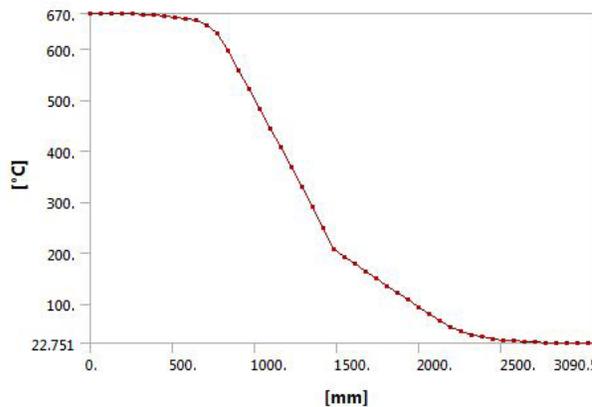


Figure 8(b). Graph representing Temperature Variation along the Length of Skirt for Case 2.

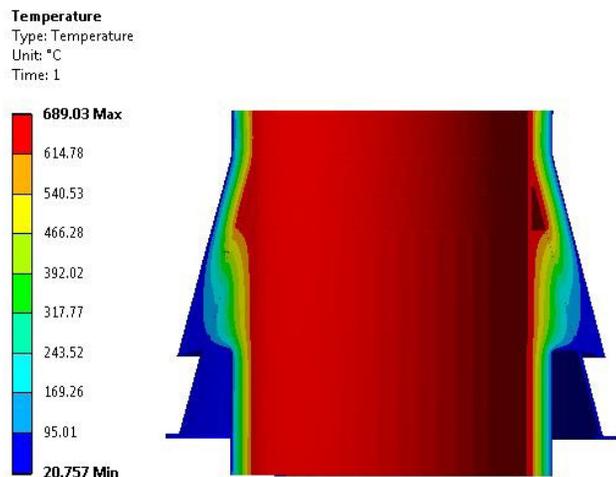


Figure 7. Temperature Distribution across Vessel for Case 2.

5.1.2 Static Structural Analysis

Figure 9 shows the equivalent Von-misses stress induced at the junction, when hotbox is not provided. It can be observed that, due to high temperature concentration, a thermal stress as high as 442.8 MPa is induced at the Y-ring, which is much higher than the code allowable stress.

Figure 10 shows the equivalent Von-misses stress induced at the junction, when hotbox is provided. The maximum stress is seemed to be dropped down to approx. 35 MPa at y-ring. Also, the location of maximum stress is shifted from y-ring to the skirt top part-skirt bottom part junction, and is found to be with in the allowable limit.

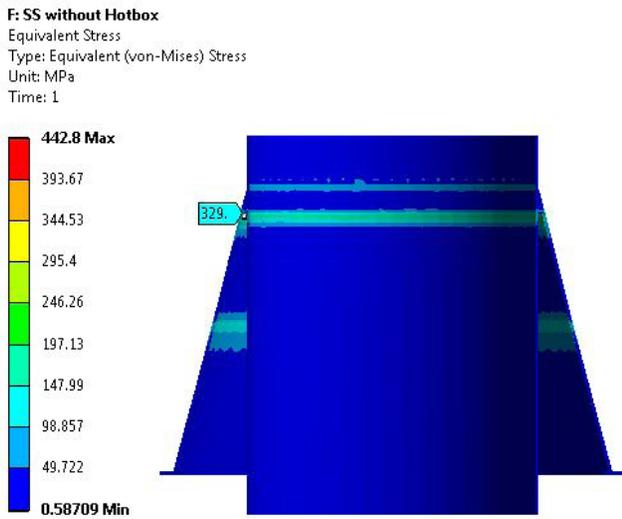


Figure 9. Equivalent Von-mises stress for Case 1.

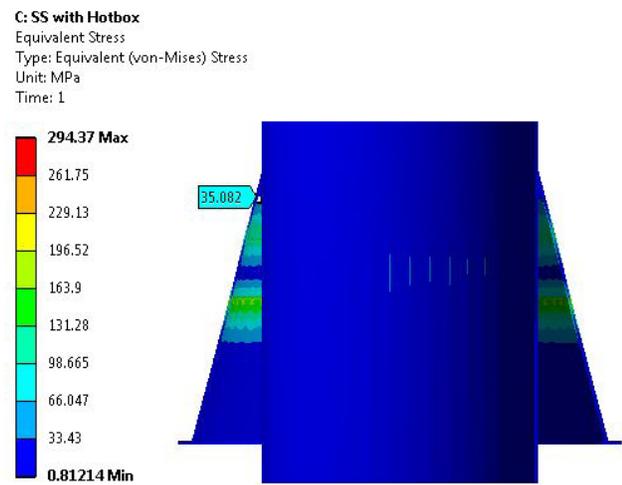


Figure 10. Equivalent Von-mises stress for Case 2.

The above results proves that by providing hotbox at skirt to shell junction, thermal stress concentration at such a critical junction in vessel is reduced appreciably and stress induced is also less than the allowable limit.

6. Stress Linearization

The stresses induced in a solid body due to application of load consists of six components, which needs to be assigned to a class of stress, as specified in ASME codes, namely, primary, secondary and peak stresses, to limit them to respective allowable limits, provided in ASME Section VIII Division 2. This is done by stress linearization. The total

stress distribution is linearized on a stress component basis and is used to evaluate the equivalent stress. Membrane and bending stresses are developed on the cross-section through the thickness of shell. These sections are called stress classification planes (SCPs). A stress classification line (SCL) is obtained by reducing the two opposite sides of SCP to an infinitesimal length. These SCLs must be normal to either maximum stress component or to the mid-surface of the section, and are generally selected at local structural or material discontinuities to analyze vessel against plastic collapse and local failure⁹.

6.1 Stress Classification Lines

Figure 11 shows the locations at which SCLs are selected, and Table 4 enlists the same.

Table 4. Locations of SCLs

Sr. No.	Stress Classification Line	Location
1	SCL 1	Top shell to y-ring junction
2	SCL 2	Y-ring to skirt junction
3	SCL 3	Y-ring to lower shell junction
4	SCL 4	Skirt top part to skirt bottom junction
5	SCL 5	Location in shell at a distance $2.5\sqrt{Rt}$

Note: SCLs 1, 2 & 3 are taken at structural discontinuities. SCL 4 is taken at material discontinuity, i.e., stainless steel to carbon steel junction of skirt, and SCL 5 is taken at a distance greater than $2.5\sqrt{Rt}$, from the discontinuities in shell, to find general membrane stress produced in shell and check mesh sensitivity, by comparing this to the theoretically calculated value of membrane stress.

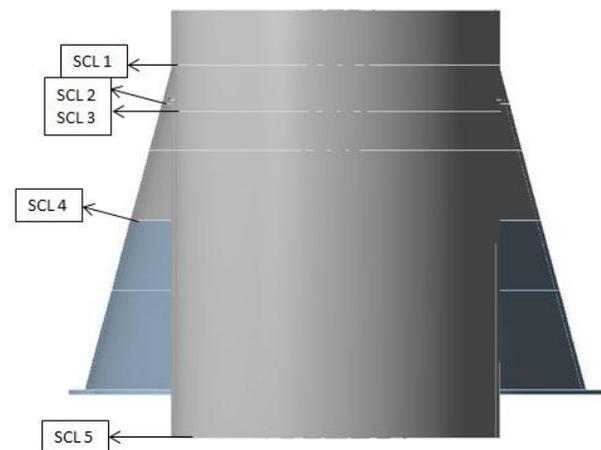


Figure 11. Stress Classification Lines.

6.2 Load Combinations and Stresses Induced

Four load combinations as mentioned in⁹, and listed below, are considered, and stresses induced due to these at the selected SCLs are limited to the code allowable stresses.

The four load combinations are:

- Load Combination 1 : P + W
- Load Combination 2 : P + W + T
- Load Combination 1 : 0.6 W + 0.7E
- Load Combination 1 : 0.9 P + W + 0.7E

The induced stresses due to these load combinations at SCLs, and the allowable limits as per¹⁰ are listed in tables.

1 Load Combination 1

Table 5 shows the maximum allowable limits for load combination 1.

Table 5. Stresses due to load combination 1

Sr.No.	Stress Classification Line	Category of stress	Max. Induced Stress (MPa)	Max. Allowable Stress (MPa)
1	SCL 1	PL	20.858	1.5 S = 51.99
		PL + Pb	21.342	1.5 S = 51.99
		$\sigma_1 + \sigma_2 + \sigma_3$	39.55642	4 S = 138.64
2	SCL 2	PL	11.743	1.5 S = 51.99
		PL + Pb	15.952	1.5 S = 51.99
		$\sigma_1 + \sigma_2 + \sigma_3$	22.1763669	4 S = 138.64
3	SCL 3	PL	17.962	1.5 S = 51.99
		PL + Pb	20.816	1.5 S = 51.99
		$\sigma_1 + \sigma_2 + \sigma_3$	40.51227	4 S = 138.649
4	SCL 4	PL	1.1192	1.5 S = 51.99
		PL + Pb	1.3269	1.5 S = 51.99
		$\sigma_1 + \sigma_2 + \sigma_3$	-0.6845232	4 S = 138.64

Here, PL and PL+Pb are limited to 1.5S, for protection against plastic collapse, and $\sigma_1 + \sigma_2 + \sigma_3$ is limited to 4 S, for protection against local failure.

Figures 12(a), (b), (c), (d) shows the linearized equivalent stress (MPa) v/s thickness of junction (mm) plots at SCLs for Load Combination 1.

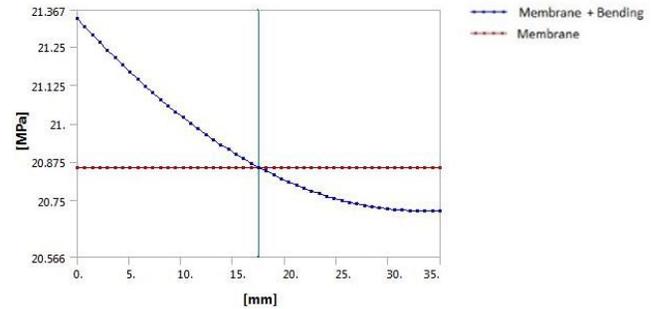


Figure 12(a). Stress v/s Length of SCL1 plot for Load Combination 1.

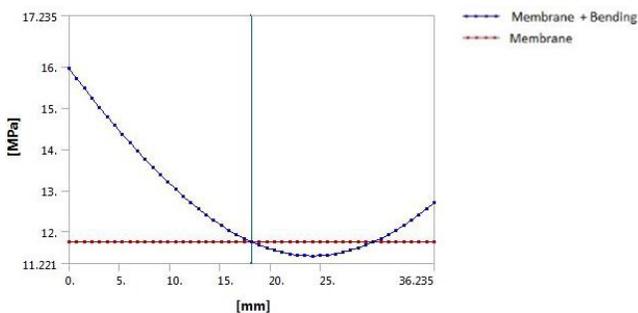


Figure 12(b). Stress v/s Length of SCL2 plot for Load Combination 1.

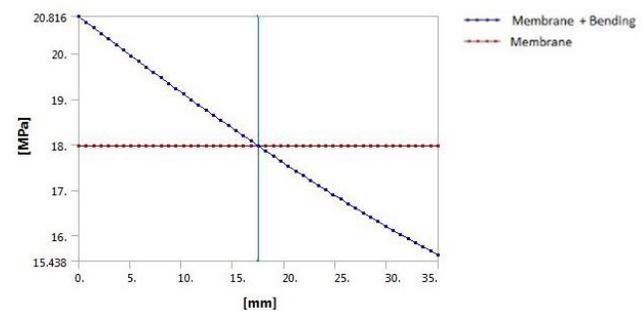


Figure 12(c). Stress v/s Length of SCL3 plot for Load Combination 1.

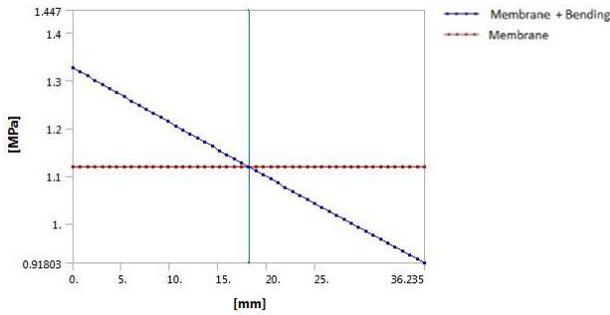


Figure 12(d). Stress v/s Length of SCL4 plot for Load Combination 1.

2 Load Combination 2

Table 6 shows the maximum allowable limits for load combination 2.

Table 6. Stresses due to load combination 2

Sr. No.	Stress Classification Line	Category of stress	Max. Induced Stress (MPa)	Max. Allowable Stress (MPa)
1	SCL 1	PL + Pb + Q	21.977	3 S = 103.9
2	SCL 2	PL + Pb + Q	35.254	3 S = 103.9
3	SCL 3	PL + Pb + Q	21.04	3 S = 103.9
4	SCL 4	PL + Pb + Q	190.34	3 S _{min.*} = 414

*The temperature obtained at skirt top part to skirt bottom part is approx. 65°C. The minimum of the allowable stresses for SA-240 and SA-516, at this temperature is considered for calculation.

Figures 13(a), 13(b), 13(c) and 13(d) shows the linearized equivalent stress (MPa) v/s thickness of junction (mm) plots at SCLs for Load Combination 2.

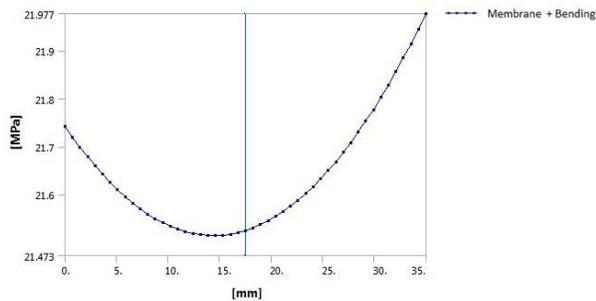


Figure 13(a). Stress v/s Length of SCL1 plot for Load Combination 2.

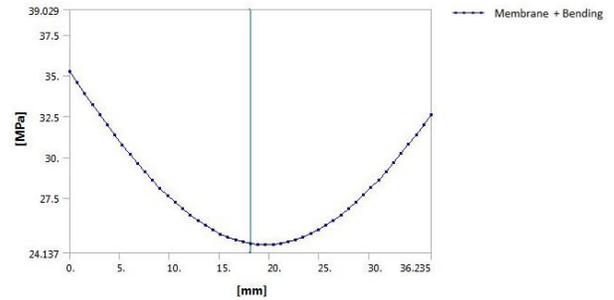


Figure 13(b). Stress v/s Length of SCL2 plot for Load Combination 2.

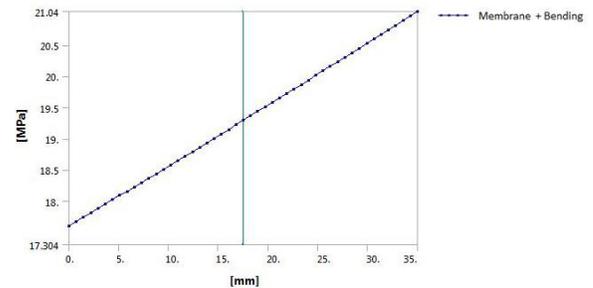


Figure 13(c). Stress v/s Length of SCL3 plot for Load Combination 2.

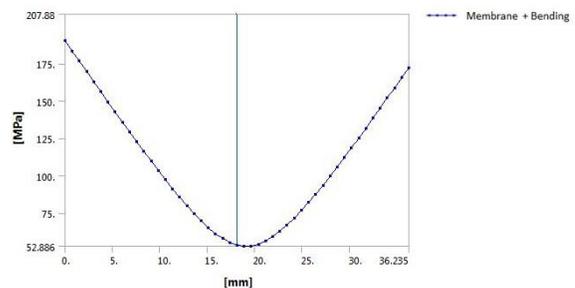


Figure 13(d). Stress v/s Length of SCL4 plot for Load Combination 2.

3 Load Combination 3

Table 7 shows the maximum allowable limits for load combination 3.

Table 7. Stresses due to load combination 3

Sr. No.	Stress Classification Line	Category of stress	Max. Induced Stress (MPa)	Max. Allowable Stress (MPa)
1	SCL 5	Pm	1.2689	S = 34.66

Figure 14 shows the linearized equivalent stress (MPa) v/s thickness of junction (mm) plots at SCLs for Load Combination 3.

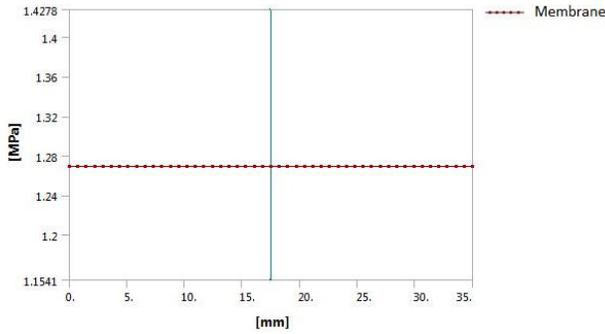


Figure 14. Stress v/s Length of SCL4 plot for Load Combination 3.

4 Load Combination 4

Table 8 shows the maximum allowable limits for load combination 4.

Table 8. Stresses due to load combination 4

Sr. No.	Stress Classification Line	Category of stress	Max. Induced Stress (MPa)	Max. Allowable Stress (MPa)
1	SCL 5	Pm	22.494	S = 34.66

Figure 15 shows the linearized equivalent stress (MPa) v/s thickness of junction (mm) plots at SCLs for Load Combination 4.

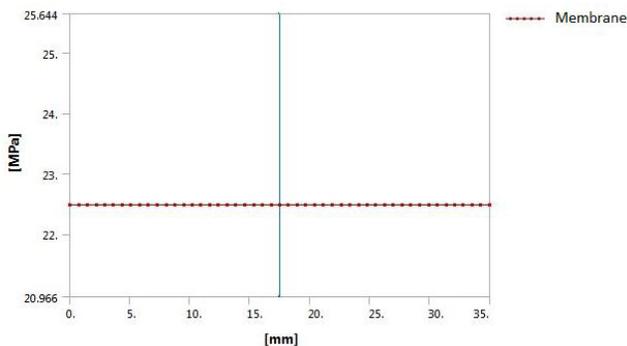


Figure 15. Stress v/s Length of SCL4 plot for Load Combination 4.

7. Theoretical Validation of Results Obtained

The results obtained by Finite Element Analysis are theoretical validated for mesh sensitivity check and the

force reaction obtained at fixed support, that is, base ring.

7.1 Mesh Sensitivity Check

Theoretical circumferential stress,

$$\sigma_{th} = \frac{PD}{2t} \tag{1}$$

From equation 1,

$$\sigma_{th} = 28.657 \text{ MPa}$$

In FEA, Induced circumferential stress at SCL-5 = 27.609 MPa

Percentage error = 3.67 %, which is less than 5% (i.e., allowable limit).

Since the induced circumferential stress (membrane stress) obtained by FEA is approximately equal to the theoretical value of circumferential stress, it proves that the meshing done is good enough to provide a better approximation of results.

7.2 Global Equilibrium Check

Total weight of vessel = 425146.4682 N

In FEA,

Reaction force at fixed support = 425150 N

Percentage error = $8.307 \times 10^{-4} \%$
 $\approx 0\%$

In ANSYS Workbench, the reaction force at the base ring (i.e., fixed support) is approximately equal to the total weight of vessel. This proves that a global equilibrium of forces on vessel is achieved during analysis.

8. Conclusion

The above finite element analysis shows that, providing hotbox at skirt to shell junction in a pressure vessel results in appreciable reduction of thermal stress concentration at this critical junction. The value of maximum equivalent von-mises stress is found to be dropped down from 442.8MPa to 35MPa at y-ring. Different load combinations are considered to ensure safe working of vessel under several operating conditions. Also, the induced stresses are linearized at SCLs, taken at regions of material and geometric discontinuities in vessel, and are limited to the code allowable stress, for protection of vessel against plastic collapse and local failure.

9. References

1. Kolekar D, Jewargi SS. Stress analysis of pressure vessel with different type of end connections by fea. *International Journal of Innovative Research in Science, Engineering and Technology*. 2015; 4(5):2769–75. Crossref
2. Chandra NP, Belkar SB. Analytical study of coke drum skirt support hot box. *International Journal of Emerging Science and Engineering*. 2014; 2(9):7–11.
3. Alexander C, Boswell R. Techniques For Modeling Thermal and Mechanical Stresses Generated in Catalytic Cracker and Coke Drum Hot- Boxes, *Proceedings of ASME Pressure Vessels and Piping Conference*, Denver, Colorado, USA: 2005. p. 527–37. Crossref
4. Sagar P, Sachin TS, Barve. Finite element analysis of skirt to dished junction in a pressure vessel. *International Journal of Modern Engineering Research*. 2013; 3(4):1–4.
5. Attar PR, Agiwale MC. Analysis of dished head and skirt joint of pressure vessel using fea method. *International Journal of Recent Technology and Engineering (IJRTE)*. 2015; 23(1):49–52.
6. Makwana MM, Parmar G, Badi M. Thermal analysis of different attachment of skirt to dished end joint of stainless steel vessel. *International Journal for Scientific Research Development*. 2016; 4(3):826–8.
7. Pan J, Chen X, Jun C. Comparison of different analysis design methods in the calculation of hydrogenation reactor skirt structure, *Proceedings of ASME 2014 pressure vessels and piping conference*, Anaheim, California, USA: 2014. p. 1–5. Crossref
8. ASME Boiler and Pressure Vessel Committee on Pressure Vessels. 8 Division 2, Alternative Rules, Rules for Construction of Pressure Vessels. Addison-Wesley; 2010.
9. ASME Boiler and Pressure Vessel Committee on Pressure Vessels. Linearization of Stress Results for Stress Classification. In 8 Division 2, Alternative Rules, Rules for Construction of Pressure Vessels. Addison-Wesley; 2010.
10. ASME Boiler and Pressure Vessel Committee on Pressure Vessels II Part D, Properties (Metric) Materials. Addison-Wesley; 2010.