THERMO-STRUCTURAL ANALYSIS AND LIFE CYCLE EVALUATION WITH OPTIMIZATION OF SEPARATION PLATE IN PRESSURE VESSEL

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MAY - 2018

DECLARATION

This is to certify that

i) The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (CAD/CAM) at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgment has been made in the text to all other material used.

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I, Jaykumar M. Patel, Roll No.16MMCC13, give undertaking that the Major Project entitled "Thermo-Structural Analysis and Life Cycle Evaluation with Optimization of Separation Plate in Pressure Vessel" submitted by me, towards the fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (CAD/CAM) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere, it will result in severe disciplinary action.

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This is to certify that the Major Project entitled "**Thermo-Structural Analysis and Life Cycle Evaluation with Optimization of Separation Plate in Pressure Vessel**" submitted by **Mr. Patel Jaykumar Maheshbhai (16MMCC13)** towards the fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (CAD/CAM) of Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge haven't been submitted to any other university or institution for the award of any degree or diploma.

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ABSTRACT

Pressure vessels are being used in many industries. Ammonia converter is also one kind of pressure vessel. It is being used for the production of ammonia in fertilizer industries and some other industries. It is one of the most required product in the world.

Ammonia converter is horizontal pressure vessel which has three to five compartment filled with catalyst bed. There is a different type of chemical processes taken place in each compartment. So, separation plate is being used to separate the compartments. The catalyst is being used to increase the speed of the chemical reaction which is also supported by a separation plate. Due to the exothermic reaction, this catalyst bed generates a different temperature in each compartment. It results in structural and thermal stresses in the separation plate.

The structural and thermal loads make the separation plate a crucial part of the converter basket. The design of separation plate has been carried out and same has been verified for safety. The thermo-structural analysis of the separation plate has been carried out and cause of high-stress concentration have been evaluated, then the various changes in the design have been made for stress reduction. Each design has been analyzed using FEA software and the optimum design has been selected. The fatigue life cycle evaluation has been carried out using ASME guidelines.

Keywords: Pressure vessel, Separation plate, Optimization.

ABBREVIATIONS

L&T – Larsen and Toubro

FEA – Finite Element Analysis

ASME – American Society of Mechanical Engineer

DBF - Design by Formula

DBA - Design by Analysis

MAWP - Maximum Allowable Working Pressure

CAD – Computer Aided Design

CSG - Constructive Solid Geometry

BR - Boundary representation

NOMENCLATURE

K - Stress Concentration Factor

t – Thickness of Plate

H – Height of Stiffener

w – Width of Segment

P_m - General primary membrane equivalent stress

P_L - Local primary membrane equivalent stress

P_b - Primary bending equivalent stress

Q - Secondary equivalent stress

P_2 – Pressure on Bottom Catalyst Support Plate

P_3 – Pressure Difference around Separation Plate

P_4 – Pressure on Top Catalyst Support Plate

P_i – Design Pressure on Basket Shell

P_b – Pressure Acting on the Shell

T_o – Operating Temperature of Separation Plate

T_d – Design Temperature of Separation Plate

D – Diameter of Plate

ID_s – Inner Diameter of Shell

υ – Poison's Ratio

E – Modulus of Elasticity

δ – Allowable Deflection for Structural Loading

M – Moment at Specific Point

F – Force on Specific Point

CG – Centre of Gravity

I_{xx} – Inertia About X Axis

Z - Section Modulus

Y – CG Location from Reference

TABLE OF CONTENTS

Page No.

LIST OF FIGURES **Page No.**

LIST OF TABLES

Page No.

CHAPTER 1

INTRODUCTION

1.1 PRESSURE VESSEL

The pressure vessel is a closed sealed cylinder shaped vessel for storage of gaseous, liquids or solid products for the period of the interval between productions.

Pressure Vessels are defined in ASME Section VIII, Division 1 "Pressure Vessels are containers for the containment of pressure either external or internal. The pressure may be obtained from an external source, or by the application of heat from a direct or indirect source, or any combination thereof". [1]

1.2 AMMONIA

1.2.1 Introduction

Ammonia (NH3) is colorless, pungent gas. It is the composition of one nitrogen and three hydrogen atoms. It is the stable compound of hydrogen and nitrogen and it also used for the production of many commercially important nitrogen compounds. The chemical structure of ammonia is shown in figure 1.1 below. [2]

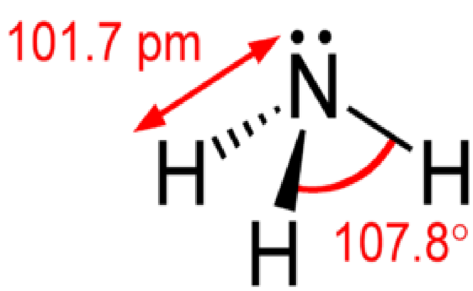


Figure 1.1 Chemical Structure of Ammonia [2]

1.2.2 Ammonia Production

1. Chemical Formulation
   - H_2O → $H_2 + O_2$ (Electrolysis)
   - $N_2 + 3H_2$ → $2NH_3$ (Haber process)

2. Methods used for Production
    1. Gasification
    2. Conversion of CO
    3. Gas purification
    4. Synthesis

1.2.3 Application of Ammonia

1. As a Fertilizer
2. As a Cleaner
3. For Fermentation Purpose
4. Antimicrobial agent for food products
5. Refrigeration – R717
6. As a remedy of gaseous emissions
7. As a fuel
8. In Textile Industries
9. As a Lifting gas
10. Woodworking

1.2.4 India in Production of Ammonia

From overall worldwide production, India produces 8.9% of the ammonia. It is second in the world to produce ammonia after China. India has around 32 plants at 25 different locations and the number of the plants is increasing with time. The total installed capacity of India to produce ammonia is about 13.4 million tonnes per annum. [2] In India, ammonia is being produced using four different types of raw materials

1. Naphtha (example IFFCO, cost of the project – 205 Crores)
2. Crude oils (example NFL, cost of the project – 223 Crores)
3. Coal (example FCI, cost of the project – 218 Crores)
4. Natural gas (example RCF, cost of the project - 166 Crores)

1.3 AMMONIA CONVERTER

It is a patented product with patent number US4452760 & US4696799. [3] [4]

The main function of this converter is to make all chemical processes possible to produce ammonia in a single unit. The outer construction of the ammonia basket shown in figure 1.2.

Though gas flow in this process has no uniform direction as shown in figure 1.3, it is placed horizontally that gives the gas flow a zigzag motion stage by stage.

Figure 1.2 Ammonia Converter Basket [5]

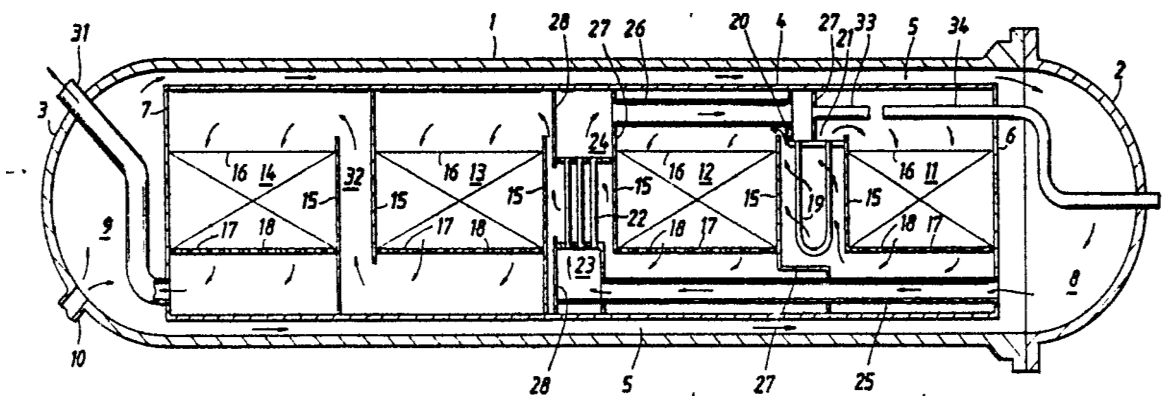


Figure 1.3 Inside Ammonia Converter Basket [3]

1.3.1 Type of Ammonia Converter

1. Classification based on the type of gas flow
   i) Axial Gas Flow Converter
   - Gas flow axially in the pressure shell through the catalyst.

   ii) Radial Gas Flow Converter
   - Gas flow radially in the pressure shell through the catalyst
   - Low-pressure drop

2. Classification based on the number of bed used
   i) Number of bed varied from 1 to 5
3. Classification based on interbed cooling
   i) Quench
   ii) The heat exchanger also called Interchanger
   iii) Not Available

1.3.2 Components of Ammonia Converter

Components of any reactor are being called as reactor internals. Internals used in the ammonia converter are listed below: [5]

1. Cylindrical pressure vessel

The pressure vessel is the big cylindrical structure with special attachments like nozzles, manways and support rings. It is the main component of the converter as it provides the structural support to all other internals and withstands the internal pressure of the vessel. It also provides thermal insulation to the whole process if required. The nozzles and the thermocouples are mounted on this pressure vessel.

2. Catalyst bed for converter basket

The catalyst is used to increase the chemical process. They help to improve efficiency, save time and increase the production. To mount the catalyst at the required position the basket is used where the catalyst is filled. The gas or liquid passes through that bed.

3. Catalyst support grid

Catalyst support grid is used to stop motion of the catalyst while continuing the motion of gas and liquid. It has a wire which has a distance lower than the catalyst size so the gas and liquid can pass through it but the catalyst cannot pass through it. The overall dead load of the catalyst is sustained by the catalyst support grid.

4. Separation plate

Separation plate has multiple functions. The main function of the separation plate is to separate the chemical processes running inside the vessel. There are multiple processes going on inside the vessel in a different compartment. The separation plate helps to separate them. It also gives support to the catalyst support grid and resists the retaining force acting on it due to the catalyst. It also resists the pressure difference and temperature difference.

5. Interbed Interchanger

Interbed Interchanger is not used in all type of ammonia converter but due to exothermic reaction in some type of the converter temperature of the gas reaches to 545 ^{o}C which is needed to be decreased for next process and the same time the inlet gas which is to cold needed to be heated to increase the efficiency of the particular chemical process. To use that generated heat and increased the efficiency of the basket Interchanger is being used.

6. Pressure shell covers

It is the support plate of the vessel which is mostly in the semi-spherical shaped which helps to provide the space to insert all the internals of the vessel. After installation of all the internals, some of the shell covers are welded and some shell covers are bolted to the vessel. [4]

1.3.3 Separation Plate

Separation plate is a crucial part of ammonia converter basket. It is used to separate the two processes inside the reactor. It also provides the structural support for the catalyst bed. The separation plate helps to Separate two compartment of the ammonia converter basket. Separation plate withstands all the thermal and structural loads like temperature difference, pressure differences, self-weight of component and dead weight of the catalyst. The bed 1 in the ammonia converter basket has the critical separation plate as it sustains the highest loading like highest temperature and pressure difference. So it is required to be considered for failure. [5]

The figure 1.4 shown here is the schematic of the separation plate, the slot at bottom side is provided to allow the gases coming from the catalyst bed passes to the second compartment. There is a heat exchanger between those compartments which reduces the temperature of the gases. The hole at the top of the separation plate is for the pipes which are passing through the separation plate. The horizontal stiffeners are provided to support the catalyst grid and vertical stiffeners are given to support the plate from thermal expansion and the bending.

The gas flow diagram in figure 1.5 shows the details that how gas passes through different compartments and components. This diagram helps to understand the role of separation plate. As shown in this diagram the gas enters into the inner shell from the end of the inner vessel pipe. It passes through pipes and reaches to the box from where it transferred to the interchanger where it is preheated and then it crosses the separation plate through the holes provided on the top of separation plate. [5]

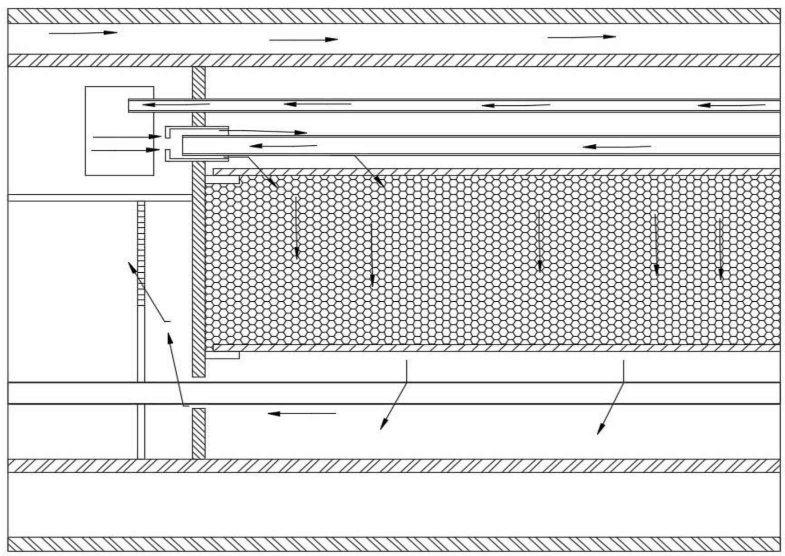


Figure 1.4 Gas Flow Diagram [3]

After entering the bed 1 it passes through the top grid and enters the region of catalyst where the exothermic reaction happens due to chemical processes between gases which result into a generation of the high value of heat energy. Due to that generated heat, the temperature of the gas increases. After that chemical process, the gas passes through bottom catalyst support grid, which is provided to support and preserve the catalyst. Then the gas passes through the slots provided in the plate and reaches to the interchanger. Where the heat is being transferred to the upcoming gas from the pipe, which is going to enter the catalyst bed.

1.4 PROBLEM DEFINITION

Ammonia Basket (separation plate) operates at high temperature (545^{o}C) and subjected to complex loading like thermal stresses due to highly constrained geometry, the differential pressure across catalyst beds, static head of operating fluid, fixed loads of internal parts, thermal loads due to the exothermic reaction of the process gas with the catalyst.

Separation plate between catalyst beds, which is subjected to complex loadings as above, is of intricate shape with many of stress risers, stiffeners, cut out for gas flow.

1.5 OBJECTIVES OF THE PROJECT

1. To design a separation plate considering specification
2. To analyze various designs using FEA program
3. To optimize the design of separation plate
4. To evaluate the life of separation plate

1.6 METHODOLOGY

As the first step of the project, a theoretical study has been carried out to understand the problem and to gather knowledge about ammonia converter, loading conditions, understanding a separation plate, materials, and manufacturing. Then the design calculation process of the separation plate has been simplified. The design has been changed and optimized with the aim of stress reduction. The fatigue life cycle has been evaluated. The result of the evaluation has been presented and discussed.

1.7 DISSERTATION ORGANIZATION

Chapter 1: Introduction

It contains an Introduction of ammonia, ammonia converter basket, separation plate, Problem Statement, and Objectives.

Chapter 2: Literature Review

This chapter contains the study carried out through various research papers regarding Design of circular plate, retaining force, Structural analysis, optimization of the plate, Elastic-plastic analysis, and Fatigue analysis.

Chapter 3: Design of Separation Plate

In this chapter, the different design constraints, the loading and design calculations have been carried out to define the unconstrained values of the components. The design safety check has been carried out by simplifying the structure.

Chapter 4: Finite Element Analysis and Optimization

This chapter contains different design cases of separation plate. The different result has been obtained for each case and the best case has been selected for further analysis. Then the plate has been optimized to reduce more stresses and to reduce material consumptions.

Chapter 5: Fatigue Life Cycle Analysis

This chapter contains the calculation of the fatigue life cycle of the separation plate for two cases (Elastic Analysis and Elastic-Plastic Analysis) using ASME guideline. The result has been compared with the specifications.

CHAPTER 2

LITERATURE REVIEW

2.1 AMMONIA CONVERTER

Patents and Presentation [5] is the source of details regarding the ammonia converter. The study of this sources gave the details regarding the design of the vessel. The design data like operation pressure, operation temperature, design pressure, design temperature, pressure differences, the volume of bed, the density of catalyst etc. were given. The schematic of the converter basket gave the structural details. There was some guideline regarding design procedure which must be followed.

Patent US4696799 [3] related to horizontal converters for exothermic, catalytic synthesis of ammonia from hydrogen and nitrogen. The study of this patent helped to understand the structure of the ammonia converter and helped to understand the working of the ammonia converter basket. The flow pattern of the gas was important to study for better understanding the function of separation plate.

Patent US4452760 [4] helped to understand the importance of the heat exchanger which is also called as interchanger provided after the first bed. Though it causes temperature changes and it affects the strength of separation plate by generating thermal stresses inside plate.

2.2 RETAINING FORCE

Collins [7] gave details regarding the Rankine theory in the book of failure of materials in mechanical design. It is a stress field solution that predicts active and passive earth pressure. The same theory can be used as the catalyst retaining force acting on the separation plate.

Kuai et al. [8] checked Several typical existing calculation methods of earth pressure considering displacement was introduced and compared; typical methods were used to calculate the condition of laboratory tests and the result was compared with Rankine earth pressure results in the paper ‘The Study on Earth Pressure against Retaining Wall Considering Displacement Plate’. It concluded that the Rankine earth pressure theory is reasonable to be taken into consideration.

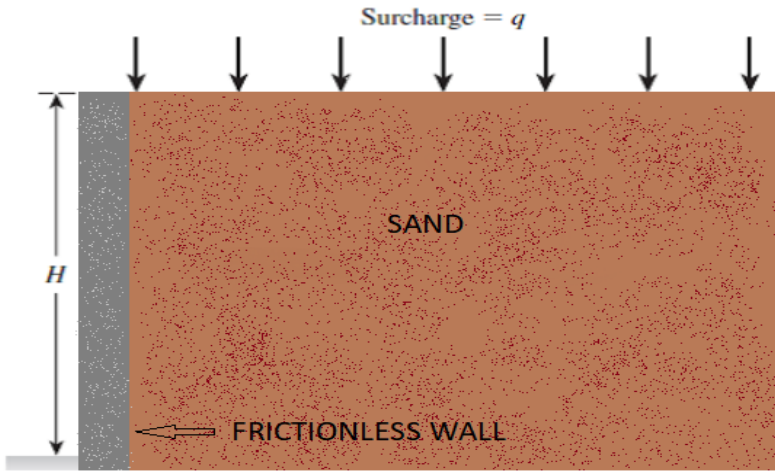


Figure 2.1 Retaining Force [9]

Rajapakse [9] explained all about the retaining forces in the book of geotechnical engineering calculations and rules of thumb. Figure 2.1 shows the concept of the earth retaining force. The different type of loading conditions and useful expressions and formulas was given in the book helped to calculate retaining force due to catalyst on separation plate.

2.3 STRUCTURAL ANALYSIS OF PLATE

Gujar and Ladhane [10] mentioned that deflection value of thin circular plate decreases with increase in thickness, in paper ‘bending analysis of simply supported and clamped circular plate’. This was because of the thin plate in which shear deformation was not considered. The plate was thick then the effect of shear deformation was more pronounced and the results obtained may vary. The results of deflection obtained from the analytical method and ANSYS for 200mm and 500 mm thickness of plate (Both for simply supported and clamped plate with UDL) show greater variation due to the thickness of the plate.

The contour of the deformation and stress is shown in figure 2.2. The study showed that analytical, and FEA result was a mismatch as the thickness of plate increases. In this case of separation plate thickness of plate would be limited to 200 or 300 mm, so we can trust the analytical equations to calculate minimum thickness of the plate.

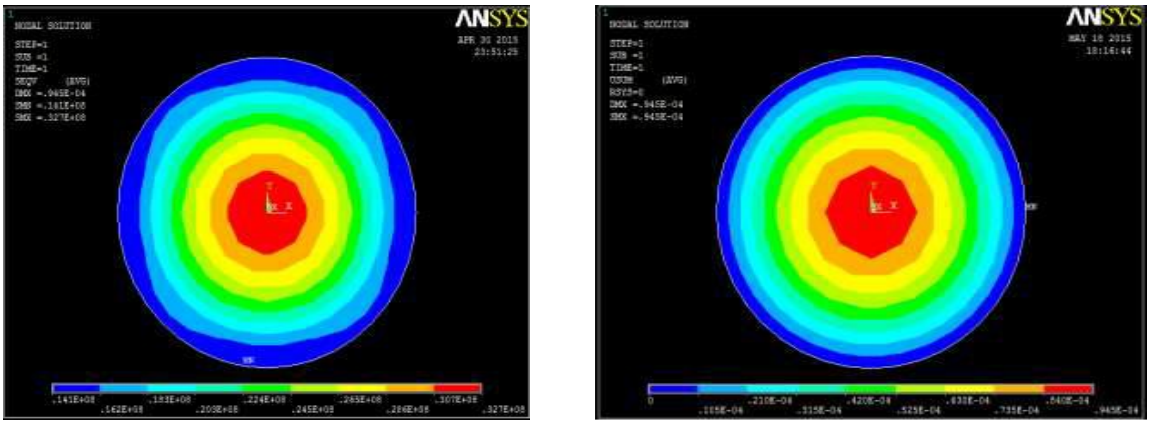


Figure 2.2 Deformation of Plate [9]

Santos [11] studied stress concentration in the paper 'Determination of stress concentration factors on flat plates of structural steel'. It helped to understand the stress concentration factor. Paper confirms the use of finite element software for obtaining the stress concentration factors for flat plates with a central hole and subjected to axial load. It statistically demonstrated that there were no significant differences between the theoretical data and data obtained through simulation. The maximum calculated errors between all data were 5.42%. So it signifies that FEA can be used to validate the stress concentration factor for any case.

The stress concentration factor for static load condition could be calculated as the ratio of the actual maximum stress to the average stress as per below equation,

$$k = \frac{Actual\ maximum\ stress}{Average\ stress}$$

Jones [12] derived some expression regarding the plate in the paper 'Impulsive loading of a simply supported circular plate'. The main objective of the paper was to derive the membrane and bending stresses generated in the plate which was simply supported and deformed due to loading.

Paik et al. [13] explained the biaxial bending of the plate in the paper 'Large deflection orthotropic plate approach to developing ultimate strength formulations for stiffened panels under combined biaxial compression/tension and lateral pressure'. The author mentioned that to restrain biaxial bending one needs to provide stiffeners in both directions. The ultimate strength of the plate can be found by considering all the stiffeners as single stiffener has lower ultimate strength but the combination of stiffeners gives an accurate result. Figure 2.3 shows the bi-axial bending of the plate without stiffeners.

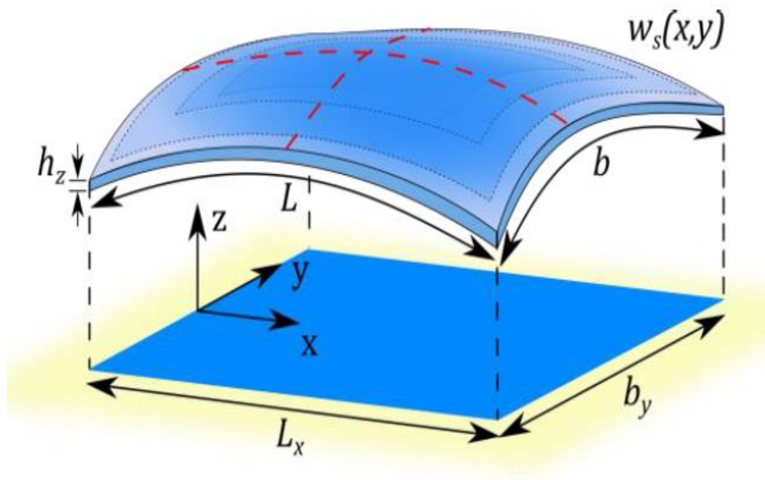


Figure 2.3 Bi-Axial Bending of Plate [14]

Pini et al. [14] concluded the two-dimensional bending of the plate in the paper 'How two-dimensional bending can extraordinarily stiffen thin sheets'. Two-dimensional bending was explained with the example in the paper. The same phenomena have been followed in the separation plate.

2.4 OPTIMIZATION OF PLATE

Optimization is the process of reducing unnecessary variables of the design and maximize the required variable. To resist all loads, the plate has to be thick. The higher thickness results in higher cost of material, high rate of production, and transportation. So the thickness of plate must be optimized. Simitses [15] explained about the use of stiffeners in the paper 'optimal vs. the stiffened circular plate'. The paper explained the chances of instability in case of bad location of the stiffeners. The book of Bending Response of Plates and Optimum Design by Massachusetts Institute of Technology [16] explained a different method for stiffener design one of them was equivalent thickness where the inertia of the plate has been made equivalent with the stiffeners and the plate was assumed to be an only load-sharing element.

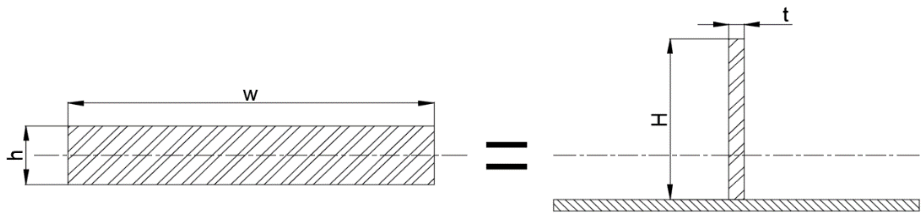


Figure 2.4 Inertia Equivalence Method [16]

For that case, considering the figure 2.4 and the Equivalent inertia method, let the inertia of plate is equal to the inertia of stiffener.

$$\frac{w * h^3}{12} = \frac{t * H^3}{12}$$

$$H = \sqrt[3]{\frac{w * h^3}{t}}$$

The plate in figure 2.5 has the same case as separation plate but it is rectangular and has only three stiffeners but the deformation shows that the stiffeners deform in opposite direction from each other. Adding the horizontal gusset to the support stiffener can help to decrease the deformation.

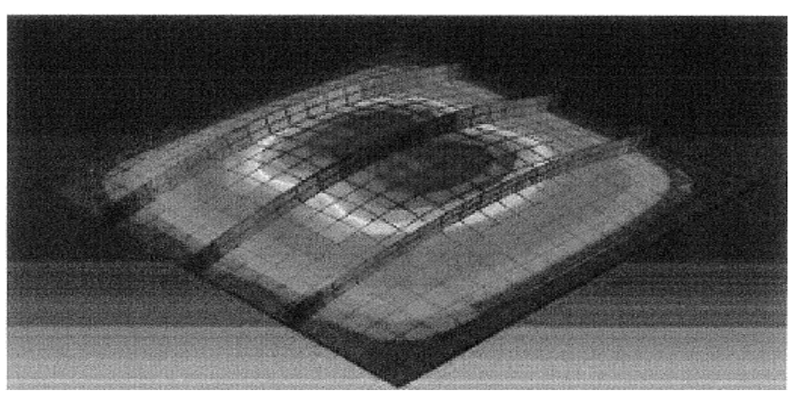


Figure 2.5 Stiffener on Plate [16]

2.5 LINEARIZATION OF STRESSES

Miranda et al. [17] deliberated the importance and the methods of linearization of stresses in the analysis. The FEA result showed von-mises stresses which were resultant of the different forces. In case of the pressure vessel, ASME code for boiler and pressure vessel section VIII division 2 [18] is being followed which helped to calculate and compare the linearize stresses.

Linearization was done at the point of maximum stress on the vessel. The von-mises stress has different unique components of stress which should be analyzed. The components of the stress are listed below.

1. General primary membrane equivalent stress – P_m
2. Local primary membrane equivalent stress – P_L
3. Primary bending equivalent stress – P_b
4. Secondary equivalent stress – Q

The stress and the limit conditions are given in ASME code mentioned in table 2-1 below.

Stress	Limit	
P_L	≤	1.5 * S
P_m	≤	S
P_l+P_b+Q	≤	3 * S

Table 2-1 Stresses and Limit Condition

2.6 FATIGUE LIFE

G. Chen et al. [19] analyzed total strained control low cycle fatigue in the paper "Low cycle fatigue and creep-fatigue interaction behavior of Nickel base superalloy GH4169 at an elevated temperature of 650°C". The study showed that in LCF, only finite fatigue life is possible and it should be analyzed using LCF criteria. The study showed that small increment of stresses gave large increment in strain in case of the stresses are close to yield limit. The main criteria for LCF are "static load carrying capacity must not be exceeded the limit". This must be checked separately.

The study of Part 5 of ASME boiler and pressure vessel code gave the details regarding the criteria and the methods of fatigue life cycle calculations. In Annexure 3.F of ASME gave an equation for the number of design cycles, N. It can be computed from Equation below or Table 3-F.9 of the ASME code based on the stress amplitude, S_a which is determined in accordance with Part 5 of ASME code.

$$N = 10^X$$

Where,

$$X = \frac{C1 + C3 * Y + C5 * Y^2 + C7 * Y^3 + C9 + Y^4 + C11 * Y^5}{1 + C2 * Y + C4 * Y^2 + C6 * Y^3 + C8 + Y^4 + C10 * Y^5}$$

$$Y = \left(\frac{Sa}{Cus}\right)\left(\frac{Efc}{Et}\right)$$

S_a = Stress Amplitude

E_{fc} = Modulus of elasticity at room temperature

E_t = Modulus of elasticity at max. design temperature

C_{us} = conversion factor

2.7 SUMMARY

The literature study has been carried out to discover the different possibilities of the ammonia converter basket. It contributed to understand the detail construction and working of ammonia converter basket. It facilitated to recognize the utilities of a separation plate in pressure vessels.

The study regarding the retaining force has been carried out to understand its significance on separation plate. The approaches to calculating retaining force have been found and same has been applied during load calculations. The equations to evaluate the retaining force has been considered from the literature.

The different aspects of the structural analysis of plate have been observed. The type of deflection and stress generation in the circular plate has been deliberated. The literature survey has confirmed that the analytical and finite element analysis methods are precise. It confirmed that FEA can be reliable to analyze the plate.

The study of literature, related to stiffeners has confirmed the use of stiffener to reduce the thickness of plate which can be used to optimize the plate. The concept of bi-axial bending of the plate has been studied which is the main cause of extreme bending and stresses. This concept has been applied during the optimization of the plate.

The study of literature regarding linearization of stresses facilitated to recognize the significance of linearization. It provided the information regarding the various kinds of stresses and the limit cases for that stresses to be considered during the post-processing of results.

The method for generation of load histogram has been studied in the mentioned papers. The study gave a better understanding of low cycle fatigue. The equation for calculation of the fatigue life cycle has been deliberated.

CHAPTER 3

DESIGN OF SEPARATION PLATE

In this chapter, the different design constraints have been discussed. The load acting on separation plate has been calculated and design calculations have been carried out to define the unconstrained values of the components. The design safety check has been carried out by simplifying the structure of separation plate.

3.1 DESIGN PROCEDURE

Design of pressure vessel is mainly done by following two procedure:

1. Design by formula (DBF):

Design by the formula is to calculate basic dimensions for components using formulas and basic rules according to given standards. In Pressure vessel basically, ASME codes are being used.

DBA method is used in the design of high-pressure equipment widely. Any pressure vessel code is concerned with this approach. It is simple to use. The formulas, values, and rules have evolved over many years and represent the safe approach to design pressure vessel. This method helps to ensure that the component is safe against all possible failure modes such as collapse, plastic deformation, buckling, brittle fracture, and Ratcheting. Some formulas and rules are also based on elastic analysis and elastic-plastic analysis.

Though DBF approach is relatively simple and safe to use, it has some limitations.

Availability of formulas and rules are only for some standard geometries. Only some geometries are covered by the respective standard. This causes some limits on the designer, as nonstandard geometries and loadings become difficult to analyze. Furthermore, the results obtained by DBF have a tendency to be over conservative and results in designs may not be competitive. [18]

2. Design by Analysis (DBA):

Design by analysis uses stress analysis method. The maximum load acting on the designed component is determined by performing a stress analysis.

In 90's, these methods were only focused on linear stress analysis because nonlinear analysis requires a high level of computer resources. However, as computers became more and more powerful nonlinear analysis has become more popular. Today the Finite Element Method is the popular approach for DBA. That has been used to analyze separation plate. [19]

3.2 PRESSURE VESSEL DESIGN TERMINOLOGY

1) Design Thickness:

The total of the specified thickness calculated by the formula given in the Code and also includes corrosion allowance.

2) Nominal Thickness:

The nominal thickness is that the thickness hand-pick as commercially on the market and provided to the manufacturer.

3) Design Temperature:

The component needs to design for this specified temperature. But while the component is designed considering some minimum design temperature and while the operating condition of the component this temperature limit shall not be crossed.

4) Operating Temperature:

The temperature is the temperature which is being maintained in the vessel. It is the temperature at which the component will be operated. That temperature is considered as operating temperature for the specified components.

5) Design Pressure:

Vessels shall be designed for a minimum of the foremost severe condition of coincident pressure and temperature expected in operation.

6) Operating Pressure:

The pressure at the top of the vessel at which it normally operates. It shall be lower than the MAWP, design pressure, or the set pressure of any pressure relieving device.

7) Maximum Allowable Working Pressure:

The MAWP is the maximum allowable working pressure on the vessel during its normal operating position at a specified temperature, usually, the temperature is the design temperature. The MAWP is required to be stamped on the nameplate of the pressure vessel. Its value is taken for the ‘hot and corroded’ condition.

3.3 MATERIAL PROPERTY

For any kind of design process, the material selection is the crucial part. As it directly affects the cost, strength, efficiency, workability, availability and the life of the component.

The material used in the separation plate is INCONEL® 600. It is a nonmagnetic, nickel-based high-temperature alloy. It has a property to withstand the load at high temperature so it is mostly used in high-temperature applications. It has high strength with hot and cold workability and it is corrosion resistant so it is an ideal material for the ammonia converter basket separation plate. As it is working at high temperature and it is going to be in contact with different chemicals where its corrosion resistant property will help to improve its life. Some application of the Inconel® 600 are listed below:

1. Ethylene dichloride crackers
2. Furnace trays, mufflers, hangers
3. Gasoline stabilizer production
4. Pressure Vessel

Properties of Inconel 600 & SS 304 [20]

	SS 304	Inconel 600	Unit
Density	8060	8470.1	Kg/m^3
Melting Range	1400-1455	1354-1413	ºC
Specific Heat	500	444	J/kg-C
Allowable Stress	114.8 @ 315 °C	112.32 @ 530 °C	MPa
Tensile Strength	505	725	MPa
Yield Strength	215	345	MPa

Temperature (ºC)	Modulus of Elasticity (MPa)	
	SS 304	**Inconel 600**
25	195000	213000
100	189000	209000
150	186000	206000
200	183000	203000
250	179000	201000
300	176000	198000
350	172000	195000
400	169000	192000
450	165000	189000
500	160000	186000
550	156000	182000

Temp. (ºC)	Co-Efficient of Thermal Expansion (mm/mm/ºC)		Thermal Conductivity (W/m ºC)	
	SS 304	**Inconel 600**	**SS 304**	**Inconel 600**
20	$1.53x10^5$	$1.23x10^5$	14.8	14.9
50	$1.56x10^5$	$1.25x10^5$	15.3	15.2
75	$1.59x10^5$	$1.27x10^5$	15.8	15.5
100	$1.62x10^5$	$1.28x10^5$	16.2	15.9
125	$1.64x10^5$	0.000013	16.6	16.2
150	$1.66x10^5$	$1.32x10^5$	17	16.6
175	$1.68x10^5$	$1.33x10^5$	17.5	17
200	$1.70x10^5$	$1.35x10^5$	17.9	17.3
250	$1.74x10^5$	$1.37x10^5$	18.6	18.1
275	$1.75x10^5$	$1.38x10^5$	19	18.5
300	$1.77x10^5$	$1.40x10^5$	19.4	18.9
325	$1.78x10^5$	$1.41x10^5$	19.8	19.3
350	$1.79x10^5$	$1.42x10^5$	20.1	19.7
375	$1.80x10^5$	$1.43x10^5$	20.5	20.1
400	$1.81x10^5$	$1.44x10^5$	20.5	20.5
425	$1.82x10^5$	$1.45x10^5$	21.2	20.9
450	$1.83x10^5$	$1.46x10^5$	21.5	21.3
475	$1.84x10^5$	$1.47x10^5$	21.9	21.7
500	$1.84x10^5$	$1.48x10^5$	22.2	22.1
525	$1.85x10^5$	$1.49x10^5$	23.6	22.6
550	$1.86x10^5$	$1.50x10^5$	22.9	23

Table 3-1 Material Property

3.4 LOADS ACTING ON SEPARATION PLATE

To design any component load acting on that components needs to be calculated. The different kind of load acting on the separation plate is listed and calculated. [5]

1. Static load due to the weight of the catalyst
   i) Density of catalyst = 3300 kg/m^3
   ii) Catalyst volume = 16.4 m^3
2. Pressure differences
   i) Pressure differences between different section of the bed
   ii) Most of the pressure differences has been already given
3. Retaining force
   i) Retaining force acting on the separation plate due to the catalyst
   ii) It is important to load needs to be considered for safe design of component
4. Load due to thermal expansion
   i) Temperature change is the crucial part as a variation of temperature is high
   ii) The structural load due to thermal expansion
5. Thermal load
   i) Temperature changes generate thermal stress in the plate
   ii) It also affects the material property

3.4.1 Area of the Plate Segments

A. Notations used:

1) A = 650 mm
2) B = 600 mm
3) C = 675 mm
4) D = 825 mm
5) E = 1500 mm
6) F = 575 mm
7) $OD = 3000$ mm
8) X = $\frac{E}{2}$ = 750 mm

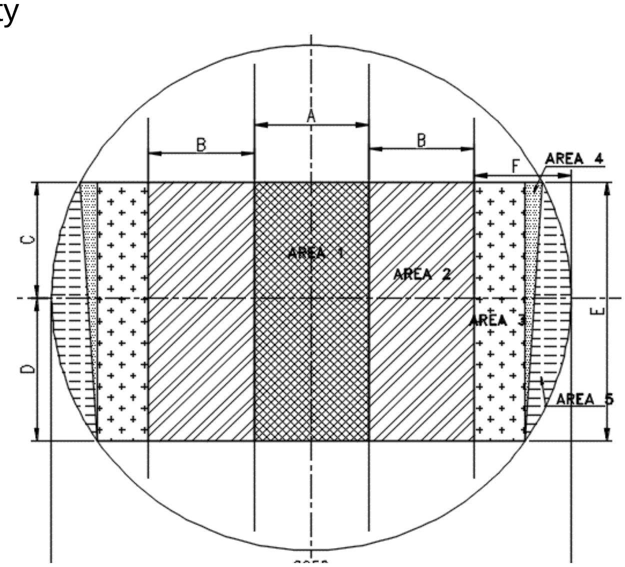


Figure 3.1 Segmentation of Plate

9) G = $\sqrt{(R^2 - X^{2)}}$ = 1299 mm

10) H = $G - \frac{A}{2} - B$ = 374 mm

11) $\theta = 2 * tan^{-1}\left(\frac{X}{G}\right)$ = 1.047 rad

B. Calculated Area:

1) $Area\ 1 = A * E = 975000$ mm^2
2) $Area\ 2 = B * E$ = 900000 mm^2
3) $Area\ (3 + 4) = H * E = 561057$ mm^2
4) $Area\ 5 = \frac{(\theta - sin\,\theta) * R^2}{2}$ = 203818 mm^2
5) **Total area of Retaining = Ar = 4304751 mm^2**
6) **Total area of Plate = $\frac{\pi * D^4}{4}$ = 7068583 mm^2**

3.4.2 Pressure difference between Separation Plate (P_3)

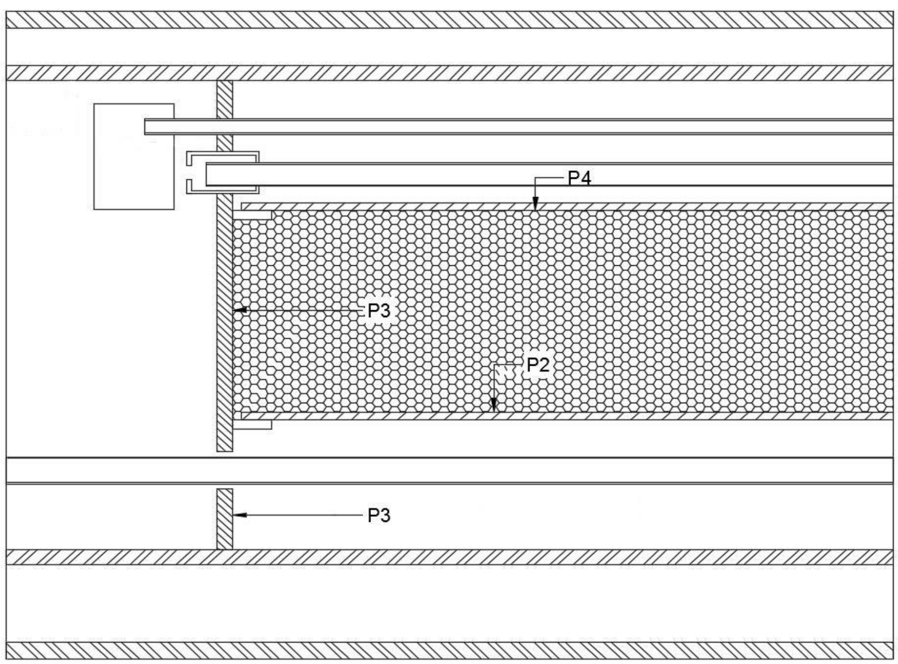


Figure 3.2 Loads Acting on Separation Plate [5]

(Considering pressure difference and retaining force)

1) Angle of Repose (Ø) = 30^o = 0.52 rad
2) Area of Retaining (A_r) = 4304752 mm^2

3) k = $\frac{1-\sin\emptyset}{1+\sin\emptyset}$ = 0.33

4) Diameter (D)=3000 mm

5) Catalyst Height (h) = 1500 mm

6) Catalyst Density (ρ) = $3.3*10^{-6}$ kg/mm^3 = $3.21*10^{-5}$ N/mm^3

7) Pressure difference on the top grid (P_{4a}) = 0.020 MPa

8) Retaining pressure due to vertical load (P_a) = $P4a * k$ = 0.00667 MPa

9) Retaining Force due to vertical load (F_a) = $Pa * D * h$ = 30018 N

10) Retaining Pressure due to Catalyst (P_b) = $\rho * h * k$ = 0.0161 MPa

11) Retaining force due to Catalyst (F_b) = $\frac{Pb*h*D}{2}$ = 36442 N

12) Total Retaining force (F_r) = 66460 N

13) Moment at point of retention (F_y) = $\left(Fa * \frac{h}{2}\right) + \left(Fb * \frac{h}{3}\right)$ = 40734773

14) Point of Retention = $\frac{Fy}{Fr}$ = 613 mm

15) Total Retaining Pressure on plate (P_{3a}) = $\frac{F}{Ar}$ = 0.0154 MPa

16) Pressure difference (P_{3b}) = 0.204 MPa

17) Total Pressure on separation plate (P_3) = P3a +P3b = 0.2194 MPa

3.4.3 Pressure due to catalyst on bottom catalyst support plate (P_2)

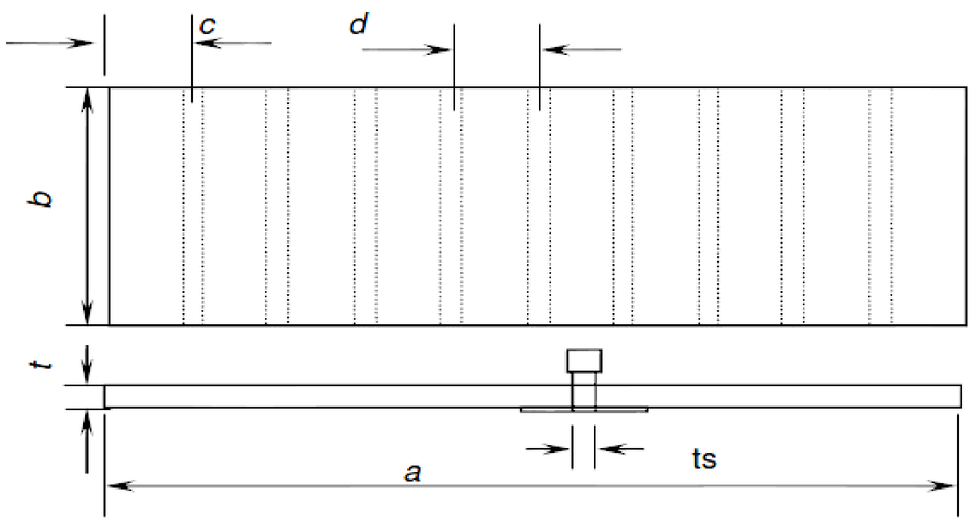


Figure 3.3 Bottom Catalyst Support Plate

1) Catalyst Density (ρ) = 3.3*10-6 kg/mm3 = 3.21*10-5 N/mm3
2) Volume of bed 1 (V_1) = 16.5 * 10^9 kg/mm^3
3) Force due to Weight of catalyst (W_1) = $\rho * V1$ = 54450 kg = 534155 N
4) b = 2400 mm
5) c = 500 mm
6) Force on single plate due to catalyst weight (F_{2a}) = $\frac{W1}{8}$ = 66769 N
7) Pressure difference between Grid (P_{2b}) = 0.160 MPa
8) Area of segment of single plate (A_s) = c * b = 1200000 mm^2
9) Force on single plate segment due to pressure difference (F2b) = $P2a * As$ = 192000 N
10) Force due to Self-weight of Grid (F_{2c}) = 2250 N
11) Total load on single plate segment (F_2) = $\mathrm{F2a} + \mathrm{F2b} + \mathrm{F2c}$ = 261019 N
12) Total load on bottom Support plate (F_{2s}) = $\frac{F2}{2}$ = 130510 N
13) Length of bottom support plate (L_s) = 3350 mm
14) Width of bottom support plate (W_s) = 70 mm
15) Area of bottom Support Plate (A_s) = $Ls * WS$ = 234500 mm^2
16) **Total pressure on bottom support plate (P_2) = $\frac{F2s}{As}$ = 0.5565 MPa**

3.4.4 Pressure on the top catalyst bed support plate (P_4)

1) Width of Top Distributor Grid (W_t) = 1550 mm
2) Length of Top Distributor Grid (L_t) = 2400 mm
3) Width Of Top Support Plate (W_{ts}) = 100 mm
4) Length Of Top Support Plate (L_{ts}) = 2350 mm
5) Pressure Difference (P_{4a}) = 0.02 MPa
6) Total Area of Distributor Grid (A_d) = $Wt * Lt$ = 3720000 mm^2
7) Total Area of Holes (A_h) = 98500 mm^2
8) Total Effective Area (A_e) =$Ad - Ah$ = 3621500 mm^2
9) Force due to pressure difference (F_t) = $Ae * p4a$ = 72430 N
10) Force on top support plate (F_{4a}) = $\frac{Ft}{2}$ = 36215 N

11) Self-Weight of Grid (F_{4b}) = 3387 N

12) Area Of Top Support Plate (A_{ts}) = $Wts * Lts$ = 235000 mm^2

13) **Pressure acting on top support plate (P_4) = $\frac{F4a + F4b}{Ats}$ = 0.1685 MPa**

3.4.5 Calculated loads:

1) Total Pressure on separation plate (P_3) = 0.2194 MPa
2) Total pressure on bottom support plate (P_2) = 0.5565 MPa
3) Pressure acting on top support plate (P_4) = 0.1685 MPa

3.5 DESIGN OF SEPARATION PLATE

3.5.1 Input Design Data

A. Construction code:

ASME code section VIII, Division 1, 2015 edition

B. Loads:

1) P_3 = pressure difference between separation plate = 0.2194 MPa
2) P_4 = pressure difference between top catalyst support grid = 0.1685 MPa
3) P_2 = pressure difference between bottom catalyst support bed = 0.5565 MPa
4) P_b = pressure acting on the shell = 0.323 MPa
5) T_o = operating temperature of separation plate =530 ^oC
6) T_d = design temperature of separation plate =545 ^oC

C. Default Dimensions to be Maintained:

1) ID_S= inner diameter of shell =3000 mm
2) Dimension of Slot, location & diameter of holes are given
3) Volume of catalyst bed = 16.4 m^3
4) Density of catalyst = 3300 Kg/m^3

3.5.2 Design of Plate

3.5.2.1 Calculation of Thickness of Separation Plate

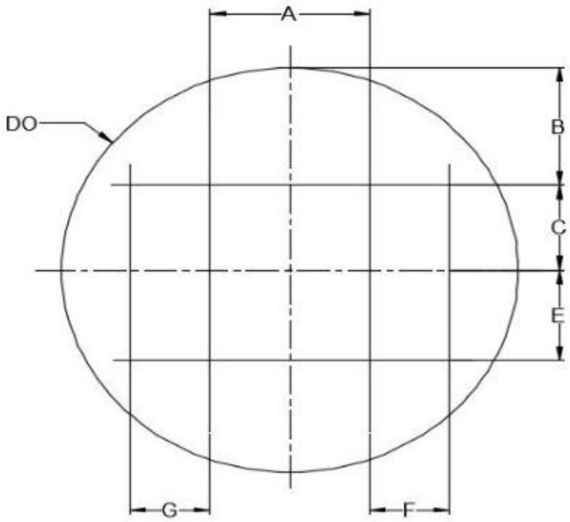


Figure 3.5 Plate with Stiffener Support

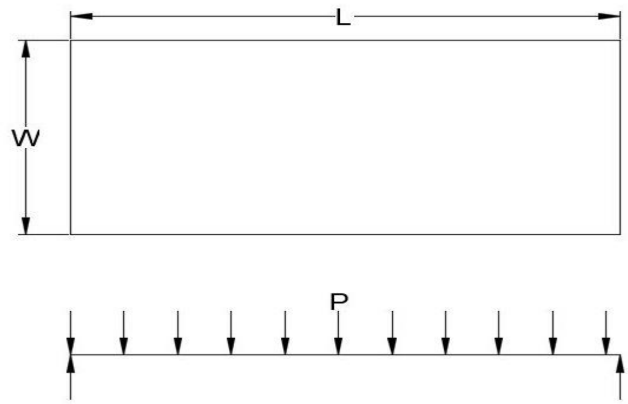


Figure 3.4 Plate Supported At All Edges (UDL)

A. Notations:

1) A = 650 mm
2) B = 775 mm
3) C = 675 mm
4) E = 825 mm
5) F = 600 mm
6) G = 600 mm
7) Do = 3000 mm

B. Input data:

1) Allowable stress (s) = 192 MPa
2) Total pressure on separation plate (P_3) = 0.2194 MPa
3) Temperature = 545 ^{o}C

C. Area 1

1) Length (L_1) = 1550 mm
2) Width (W_1) = 550 mm
3) X = $\frac{L1}{W1}$ = 2.8

4) B = $\frac{0.75}{\left(1.61*\left(\frac{W1}{L1}\right)^{3}+1\right)}$ = 0.6996

5) Minimum Thickness = $w1 * \sqrt{\left(\frac{p*\beta}{s}\right)}$ = 15.95 mm

D. Area 2

1) Length (L_2) = 1550 mm
2) Width (W_2) = 650 mm
3) X = $\frac{L2}{W2}$ = 2.38
4) B = $\frac{0.75}{\left(1.61*\left(\frac{W2}{L2}\right)^{3}+1\right)}$ = 0.6704
5) Minimum Thickness = $w2 * \sqrt{\left(\frac{p*\beta}{s}\right)}$ = 18.46 mm

E. Area 3

1) Length (L_3) = 1550 mm
2) Width (W_3) = 600 mm
3) X = $\frac{L3}{W3}$ = 2.583
4) B = $\frac{0.75}{\left(1.61*\left(\frac{W3}{L3}\right)^{3}+1\right)}$ = 0.6859
5) Minimum Thickness = $w3 * \sqrt{\left(\frac{p*\beta}{s}\right)}$ = 17.236 mm

F. Area 4

1) Length (L_4) = 775 mm
2) Width (W_4) = 650 mm
3) X = $\frac{L4}{W4}$ = 1.19
4) B = $\frac{0.75}{\left(1.61*\left(\frac{W4}{L4}\right)^{3}+1\right)}$ = 0.384
5) Minimum Thickness = $w4 * \sqrt{\left(\frac{p*\beta}{s}\right)}$ = 13.98 mm

Considering the availability of material and the manufacturing aspects the thickness of the plate is considered 20 mm which is adequate. [21]

3.5.2.2 Design of Plate with Stiffeners

A. Calculation of thickness of the separation plate without stiffeners

Separation plate resists the different type of loads on it. The highest value from all the load is the pressure difference and the retaining force. The retaining force is uniformly increasing load from top to bottom but it is taken as the uniformly distributed load with its maximum value. The combination of both loads is taken as a uniformly distributed load for simplicity.

Some assumption has been made to calculate the minimum thickness of the plate.

1. The plate is fixed supported by the reactor shell.
2. The plate is flat and no stiffeners are provided.
3. Only uniformly distributed load acting on the plate.
4. The value of deflection limit has been decided by the designer.
5. The value of R_0 is zero as there is a load acting on the whole plate.

B. Input data:

1) Pressure (P_3) = 0.2194 MPa
2) D = 3000 mm
3) a = $\frac{OD}{2}$ = 1500 mm
4) E = 182000 MPa
5) Design Temperature = 545 ^{o}C
6) υ = 0.3005
7) Allowable deflection (δ) = 0.8 mm

C. Calculated data:

1) D = $\frac{E*t^3}{12*(1-\upsilon^2)}$ = 133377341
2) Minimum thickness (t_{min}) = $\left(\frac{12*P3*a^4*(1-\upsilon^2)}{64*E*\delta}\right)^{\frac{1}{3}}$ = 109.2 mm

* Equation from Roark's formulas for stress and strain [24]

For allowable deflection, the thickness of the plate is 110 mm.

This kind of thick plate cannot be used in industries as it is too heavy and it may cost very high. To optimize the thickness of plate for the same load condition stiffeners must be provided which reduce the requirement of material for the same load carrying capacity. The number of required stiffener decided by the size of a component.

D. Calculation of height of stiffeners

Separation plate is divided into four segments to simplify the analytical calculations. In the four segments, only two types of segment need to be designed as other two are identical. As there can be more or fewer stiffeners can be used then four but more stiffeners can cause the interference with other components of the vessel and it also blocks the slot made for the transfer of gases and it may bock the way of pipes so increasing number of stiffeners is not preferable. For decreasing number of stiffeners, the load sharing capacity will decrease. The plate having more thickness is to withstand more load compared to the current condition. It causes more cost of material and increases the overall weight.

So, the four stiffeners are best for this size of separation plate. The locations of this stiffeners are at an identical distance. To improve the design, some design changes can be proposed but that changes may affect the performance of reactor as an area of the slot may change.

Some assumption has been made to calculate the height of stiffeners.

1. The stiffeners are fixed and supported by the reactor shell at the end.
2. The number of stiffeners are four.
3. Only uniformly distributed load acting on the stiffeners.
4. The stiffeners and the plate designed before have an equal maximum moment of inertia.
5. All the loads are acting only on the stiffeners, the plate of thickness 20 mm just transfer all the load to the stiffeners.

E. For segment 1:

1) Width of segment (w_1) = 600 mm
2) Thickness of segment (h_1) = 110 mm
3) Thickness of stiffener (t_1) = 30 mm

$$H = \sqrt[3]{\frac{w1 * h1^3}{t1}}$$

= 298 mm ~ 300 mm

F. For segment 2:

1) Width of segment (w_2) = 625 mm
2) Thickness of segment (h_2) = 110 mm
3) Thickness of stiffener (t_2) = 30 mm

$$H = \sqrt[3]{\frac{w2 * h2^3}{t2}}$$

= 302.6 mm ~ 300 mm

As there are four segments of the circular plate but due to the symmetric shape of the plate, the calculation of only two segment will be sufficient. For both segments, the 300 mm height of stiffener will be sufficient.

3.6 SAFETY CHECK

3.6.1 For segment 1

The cross-section of the segment 1 is shown in figure 3.6. The plan view of the segment also shown in figure 3.7.

The loading condition on the beam is uniformly distributed load and uniformly varying load. The calculations of the beam are as follow:

A. Notations:

1) Width of plate (W_1) = 625 mm
2) Width of flange (W_2) = 80 mm
3) Thickness of plate (T_1) = 20 mm
4) Thickness of stiffener (T_2) = 30 mm
5) Thickness of flange (T_3) = 25 mm
6) Length of beam 1 (L_1) = 2788 mm
7) Length of retention (L_A) = 1500 mm
8) Height of stiffener (H_1) = 300 mm

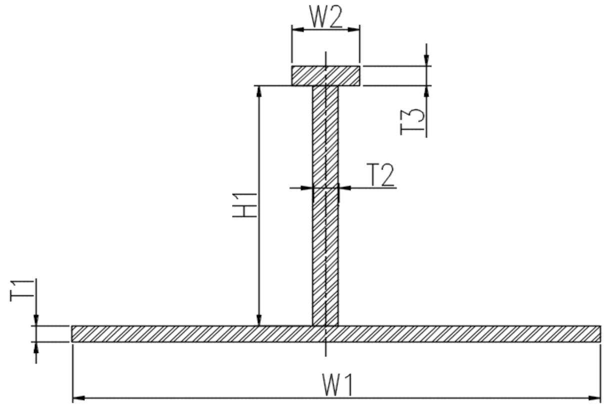


Figure 3.6 Cross Section of Segment 1

B. Design data

1) Modulus of elasticity (E) = 182000 MPa
2) Design temperature (T) = 545 ^{o}C
3) Uniform pressure (UDL) = 0.204 MPa
4) Uniform pressure * W_1 = 127.5 N/mm
5) Catalyst pressure (UVL) = 0.01553 MPa
6) Catalyst pressure * W_1 = 9.706 N/mm

C. Reaction forces and maximum bending moment

1) Force due to UDL = 284835 N
2) Force due to UVL = 7280 N
3) Moment at point E (M_1) = 258284 N-mm
4) Moment at point F (M_2) = 853997 N-mm

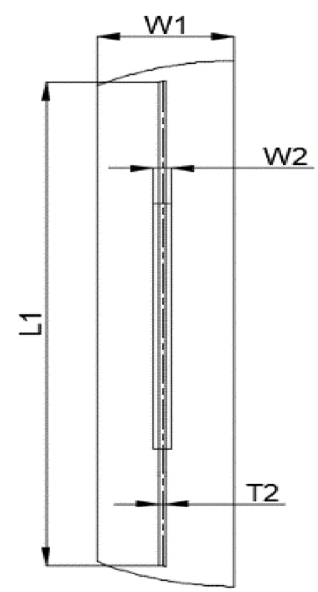


Figure 3.7 Schematic of Segment 1

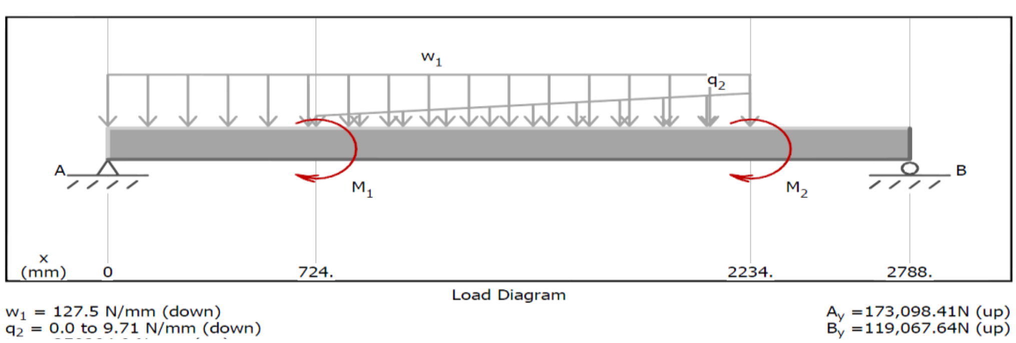


Figure 3.8 Loading Conditions for segment 1

5) F_a = 173070 N
6) F_b = 119045 N
7) Maximum bending moment = 1.17 * 10^8 N-mm
8) Point of Maximum bending moment = 1324 mm

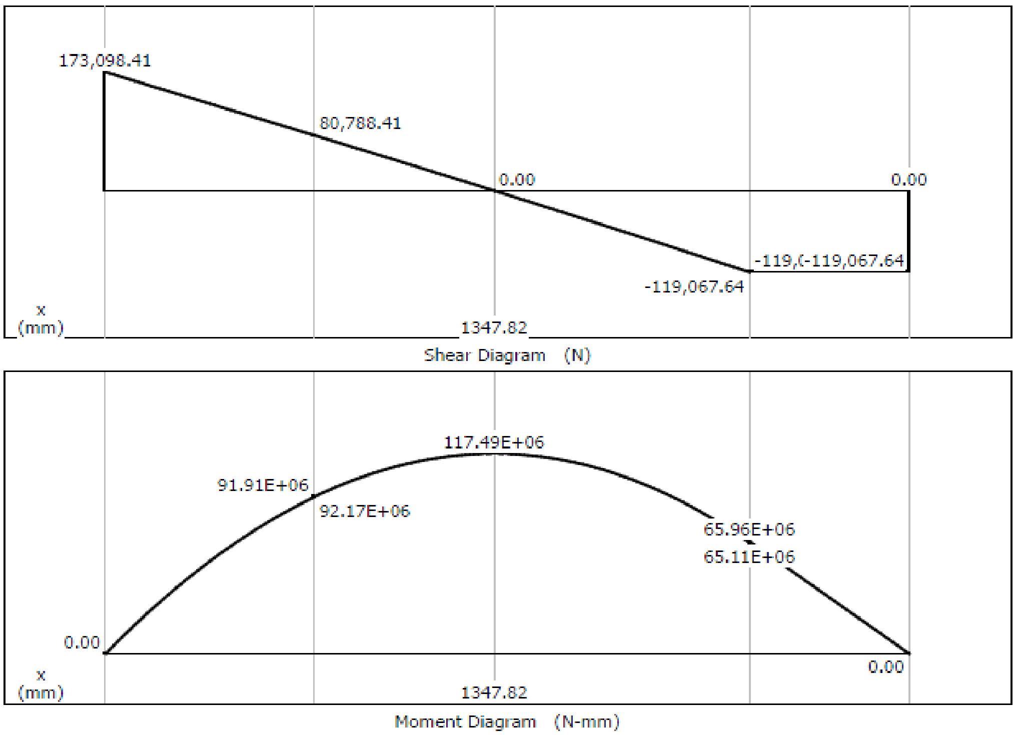


Figure 3.9 Sear Force and Bending Moment Diagram

D. Inertia calculation

1) Area 1 = W_1*T_1 = 12500 mm^2
2) Area 2 = H_1*T_1 = 9000 mm^2
3) Area 3 = W_2*T_2 = 2000 mm^2
4) $y_1 = \frac{T1}{2}$ =10 mm
5) $y_2 = \frac{H1}{2} + y1$ = 170 mm
6) $y_3 = \frac{T2}{2} + y1 + y2$ = 332.5 mm
7) CG = $\frac{(Area\ 1*y1)+(Area\ 2*y2)+(Area\ 3*y3)}{Area\ 1+Area\ 2+Area\ 3}$ = 98.72 mm

Area	I_G	H	h^2	$A*h^2$	I
	mm^4	Mm	mm^2	mm^4	mm^4
1	416667	88.7	7872	98398031	98814697
2	67500000	71.3	5080	45723178	113223178
3	104167	233.8	54651	109302993	109407160

I_{xx}	321445035.5	mm^4
y	246.3	mm
Z	1305219.582	
Bending stress	89.7	MPa

Table 3-2 Inertia & Stress Calculation for Segment 1

- As allowable stress is 92 MPa the design is safe.

3.6.2 For segment 2

The cross-section of the segment 2 is shown in the figure 3.10 below with the legends. The plan view of the segment also shown in the figure 3.11.

The loading condition on the beam is uniformly distributed load and uniformly varying load. The calculations of the beam are as follow:

A. Notations:

1) Width of plate (W_3) = 600 mm
2) Thickness of flange (T_1) = 20 mm
3) Thickness of stiffener (T_4) = 30 mm
4) Length of beam 2 (L_3) = 2200 mm
5) Length of retention (LA) = 1535 mm
6) Height of stiffener (H_1) = 300 mm

B. Design data

1) Modulus of elasticity (E) = 182000 MPa
2) Design temperature (T) = 545 ^oC
3) Uniform pressure (UDL) = 0.204 MPa
4) Uniform pressure * W_1 = 122.4 N/mm^2

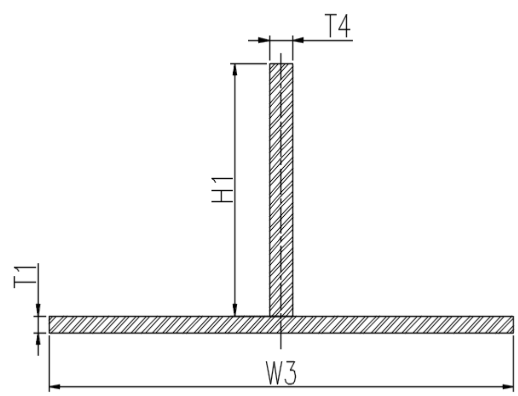


Figure 3.10 Cross Section of Segment 2

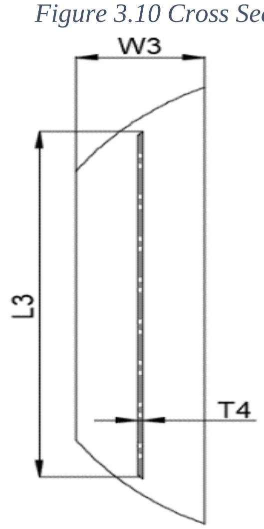


Figure 3.11 Schematic of Segment 2

5) Catalyst pressure (UVL) = 0.01553 MPa

6) Catalyst pressure * W1 = 9.32 N/mm

C. Reaction forces and maximum bending moment

1) Force due to UDL = 230846 N

2) Force due to UVL = 6989 N

3) Moment at point E (M_1) = 247953 N-mm

4) Moment at point F (M_2) = 1093116 N-mm

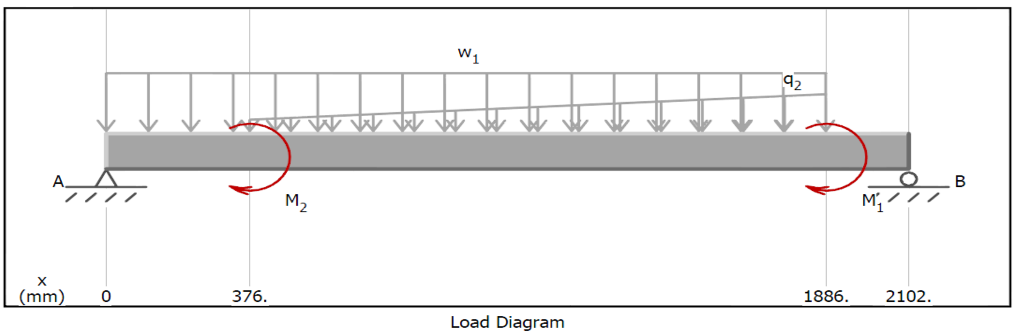


Figure 3.12 Loading Condition for Segment 2

5) F_a = 129027 N

6) F_b = 108809 N

7) Maximum bending moment = 0.690 * 10^8 N-mm

8) Point of Maximum bending moment = 1023 mm

D. Inertia calculation

1) Area 1 = W_1*T_1 = 12000 mm^2

2) Area 2 = H_1*T_1 = 9000 mm^2

3) $y_1 = \frac{T1}{2}$ =10 mm

4) $y_2 = \frac{H1}{2} + y1$ = 170 mm

5) CG = $\frac{(Area\ 1 * y1)+(Area\ 2 * y2)}{Area\ 1 + Area\ 2}$ = 78.57 mm

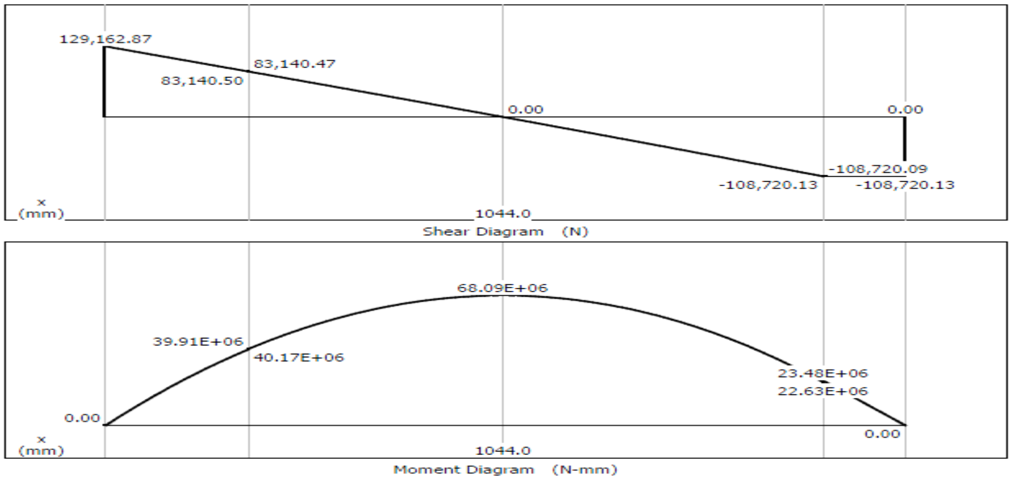


Figure 3.13 Shear Force and Bending Moment Diagram

Area	I_G	H	h^2	$A*h^2$	I
	mm^4	Mm	mm^2	mm^4	mm^4
1	400000	68.6	4702.041	56424489.8	56824490
2	67500000	91.4	8359.184	75232653.06	142732653.1

I_{xx}	199557143	mm^4
y	241	mm
Z	826568	
Bending stress	83.4	MPa

Table 3-3 Inertia & Stress Calculation for Segment 2

- As allowable stress is 92 MPa the design is safe

3.6.3 Welding Safety Check

Welding between Plate and Stiffener is very important. The stresses generated in the weld needs to be calculated for design safety. The groove-type welding with a fillet at the outer side has been proposed which gives a better performance during high loading condition.

h1	*88.7*
h2	71.28
h3	233.8
L	*2788*
I_{xx}	*321445035*
UDL	*127.5*

Table 3-4 Input Data for Welding

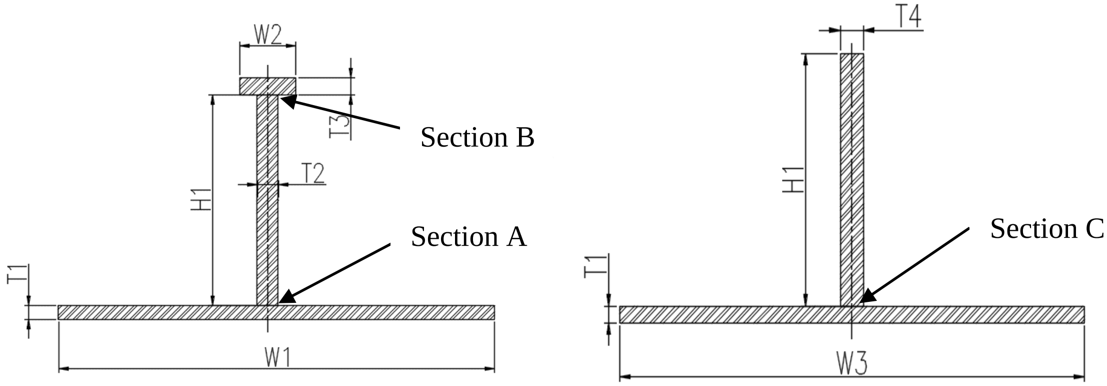


Figure 3.14 Stiffener Weld Section Details

Load on Stiffener	S	177735	N
Weld root width	W = (2* 0.7* 8)	11.312	mm
Maximum Stress Limit		132.27	N/mm²
At Section A			
Stress in Stiffener	$\sigma fa = \frac{S * W1 * h1}{Ixx * T1}$	0.9809	N/mm²
Stress-induced in the weld	$\frac{\sigma fa * W1}{w}$	54.195	N/mm²
WELD JOINT IS SAFE			

At Section B			
Stress in Stiffener	$\sigma fa = \frac{S * H1 * h2}{Ixx * T2}$	11.82	N/mm²
Stress-induced in the weld	$\frac{\sigma fa * T2}{w}$	31.669	N/mm²
WELD JOINT IS SAFE			

At Section C			
Stress in Stiffener	$\sigma fa = \frac{S * W2 * h3}{Ixx * T3}$	3.2315	N/mm²
Stress-induced in the weld	$\frac{\sigma fa * W2}{w}$	23.082	N/mm²
WELD JOINT IS SAFE			

Table 3-5 Welding Calculations

➢ The Result shows that fillet weld of 8 mm will be adequate for given loading condition.

CHAPTER 4

FINITE ELEMENT ANALYSIS AND OPTIMIZATION

4.1 INTRODUCTION

The chapter contains the detailed analysis and optimization of the separation plate. The structural analysis of the separation plate has been carried out then the design modification done for stress reduction. Then the thermo-structural analysis has been performed and the result of thermo-structural analysis has been discussed. The elastic-plastic analysis of the plate has been performed. The scope of the elimination of support plate has been searched and found solution has been analyzed. The result has been deliberated following ASME guideline.

4.1.1 Structural Analysis

Structural loads, displacements, supports, stresses, reactions, etc. are necessary to perform structural analysis. The structural analysis can be done by strength of material approach and the finite element approach. The strength of the material is an analytical approach which can be used for a simple problem. In case of the complex structure if an analytical approach requires then the structure needs to be simplified. But the finite element method is the best method for a complex structure. It gives an accurate answer, and it requires less time compare to analytical method. The FEA approach strictly depends on the processing power of the computer as the whole analysis done on the computer using specialized finite element analysis program. The time depends on the complexity and the size of the structure. [19]

4.1.2 Thermo-Structural Analysis

The thermo-structural analysis is a technique used in the thermal analysis, a branch of materials science which studies the change of material properties with the change of temperature. [19]

The change in material property due to change in temperature has been considered in the structural analysis. During the analysis Modulus of Elasticity and the Thermal Expansion of the material needs to be considered for specific temperature scale. That gives a more accurate result for particular thermal boundary conditions.

4.1.3 Design Improvement Using FEA

Finite element analysis considering mentioned boundary condition has been performed. The first design was proposed design which has a high value of stress concentration at some specific points which were a lot more than the yield level of the material. The step by step improvement in the structural design of separation plate has been done which has been explained below. The cad model has been prepared as shown in figure 4.2 then, meshing has been performed as shown in figure 4.3. The quality of mesh limit has been mentioned in table 4-1. Then the boundary conditions have been given to the model, and the structural analysis has been done in the Ansys 16.

4.1.4 Load Cases

Case 1. Structural Load Case (Design Pressure, Dead Weight, Self-Weight)

Case 2. Thermal and Structural Load Case (Operating Temperature, Design Pressure, Dead Weight, Self-Weight)

4.2 PARAMETRIC MODELING

Parametric modeling is the modeling of the geometry according to the dimensional parameters. Parametric is defined as a dimension's ability to change the dimensions of geometry as soon as the dimension value is changed without changing its basic shape. Parametric modeling can be done using the computer software specially made for parametric modeling. Computer software has the ability to make object model attributes like actual physical behavior. Parametric models use feature-based modeling design tools to change the system attributes. Most important features of parametric modeling are that attributes which interlink automatically and change their values relatively. In the other word, parametric modeling facilitates the designer to define the shapes of the component which is always same. [19]

For example, to modify a 3D solid, the designer has to change the length, the width, and the height. But, with parametric modeling, the designer needs to alter one parameter than the other two parameters will get adjusted automatically.

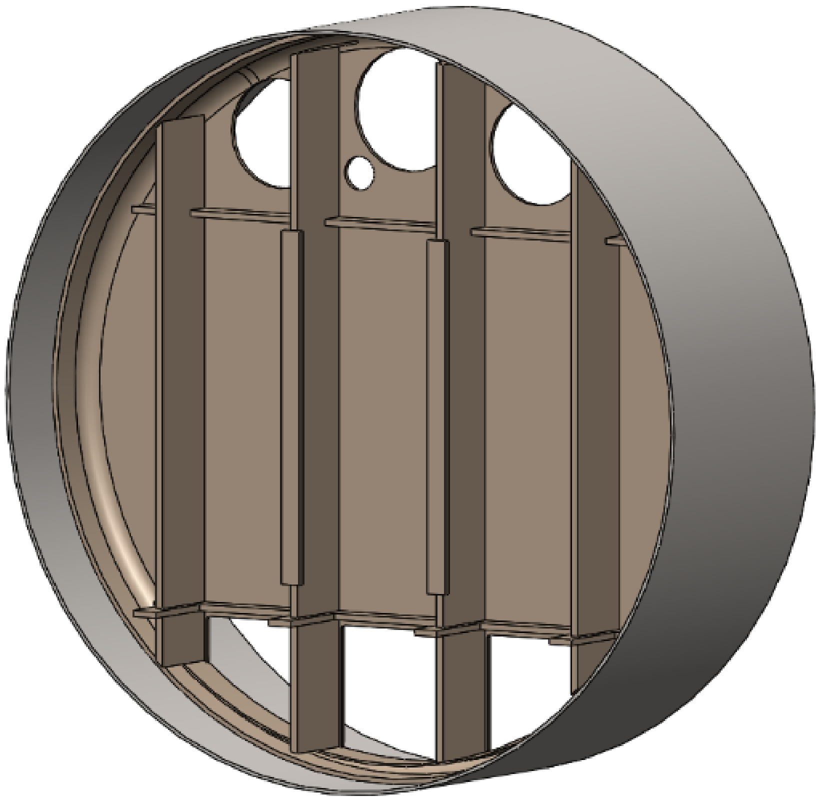


Figure 4.1 CAD Mode of Separation Plate

4.3 MESHING OF SEPARATION PLATE

4.3.1 Introduction

The basic concept of FEA is to complete the calculation for the only finite number of points and then generate the results for the entire volume and surface (Component). Every component has infinite points and that results in infinite degrees of freedom which cannot be possible to solve. In Finite Element analysis, meshing reduces the degrees of freedom from infinite to finite as shown in figure 4.1. [19]

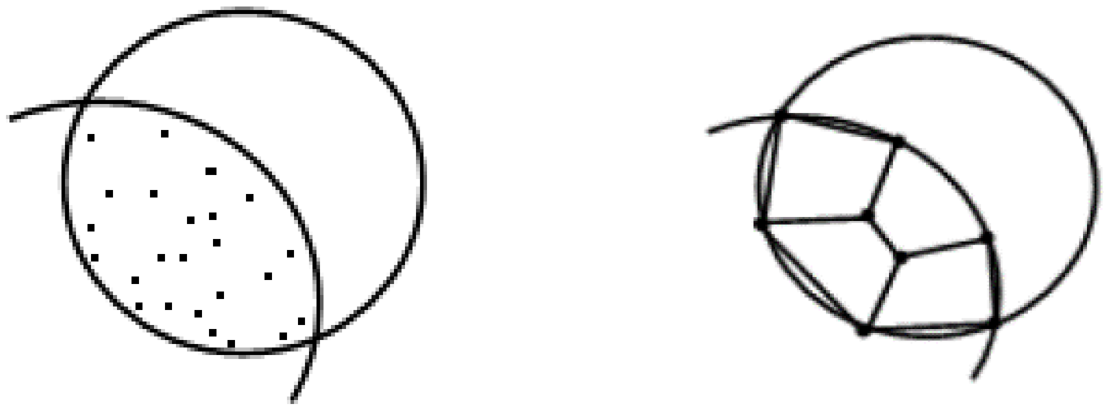


Figure 4.2 Importance of Meshing [19]

No. of Point = ∞	No. of Point = 8
DOF per point = 6	DOF per point = 6
Total equations = ∞	Total equations = 48

4.3.2 Selection of Element Type

Structural analysis can be done using a different method. If the specimen is simple plate then the 2D mesh can be helpful to easily evaluate results. If the specimen is beam type then 1D mesh can be sufficient to evaluate the accurate result in shortest time. But in case of complex shapes like the plate with different shape of support, the 3D mesh is best to get an accurate result. As in this case, many points exist where stress concentration can be possible which can propagate a crack and that can result in failure of the component so for this case in project 3D mesh was selected.

For 3D mesh there are different meshing type can be used as a pyramid, prism, and brick. The analyst needs to select the best type of mesh from that available mesh type. For structural analysis brick type of mesh is advisable for faster and accurate result. So the Brick type of meshing was done using Ansys workbench 16. [19]

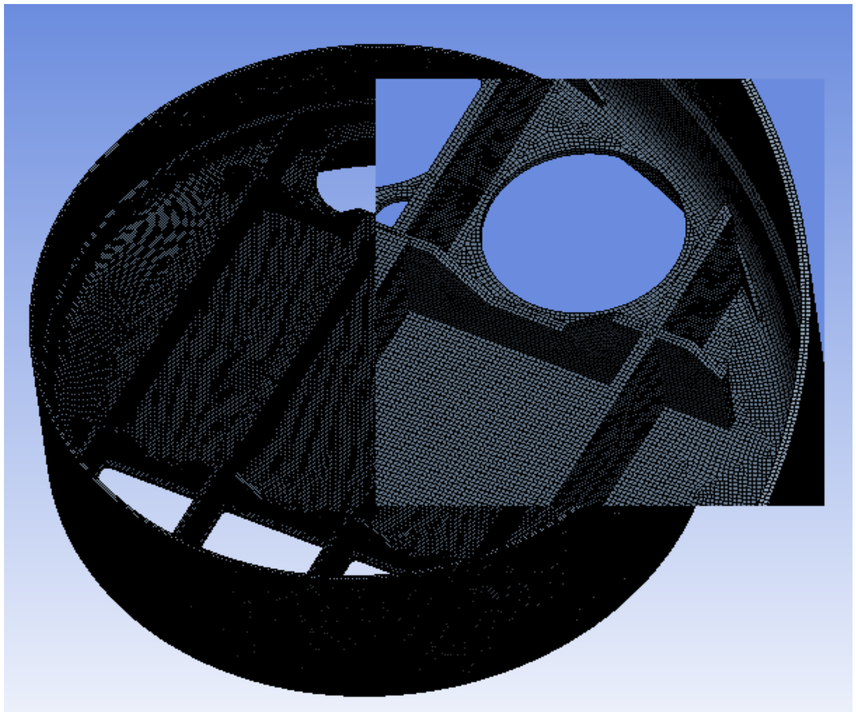


Figure 4.3 Meshing of Separation Plate

4.3.3 Meshing Quality

Element Size	5 mm	For support plate
	10 mm	Other
Mesh type	Hex Element Solid 287	Quad/Tria
Relevance center	Fine	-
Transition Ratio	0.272	-
Growth Rate	1.1	-
Total Elements	434603	-
Total Nodes	445585	-
	Ideal	Mesh
Element Quality	1	0.766
Aspect Ratio	1 (A < 5)	3.93
Jacobian Ratio	1 (A > 0.5)	1.4
Warping Factor	0 (A < 0.4)	0.061415
Skewness	0.25 — 0.5	0.35

Table 4-1 Quality of Meshing

4.4 BOUNDARY CONDITIONS

4.4.1 Values of Boundary Conditions

1. Both ends of the basket shell are constrained in theta direction and one end in the axial direction.
2. Symmetric boundary conditions on applicable symmetrical surfaces.
3. External design pressure on basket shell (Pi) = 0.323 MPa
4. Differential design pressure on separation plate-1 = 0.2194 MPa
5. Load on horizontal stiffener due to differential pressure action on distributor grid = 0.169 MPa
6. Load on support grid stiffener due to the differential pressure across support grid + catalyst pressure on support grid = 0.556 MPa
7. For thermal analysis design temperature for separation plates are 545 ^{o}C
8. For thermo-structural analysis operating temperature for separation plates are 530 ^{o}C

4.4.2 Boundary Conditions

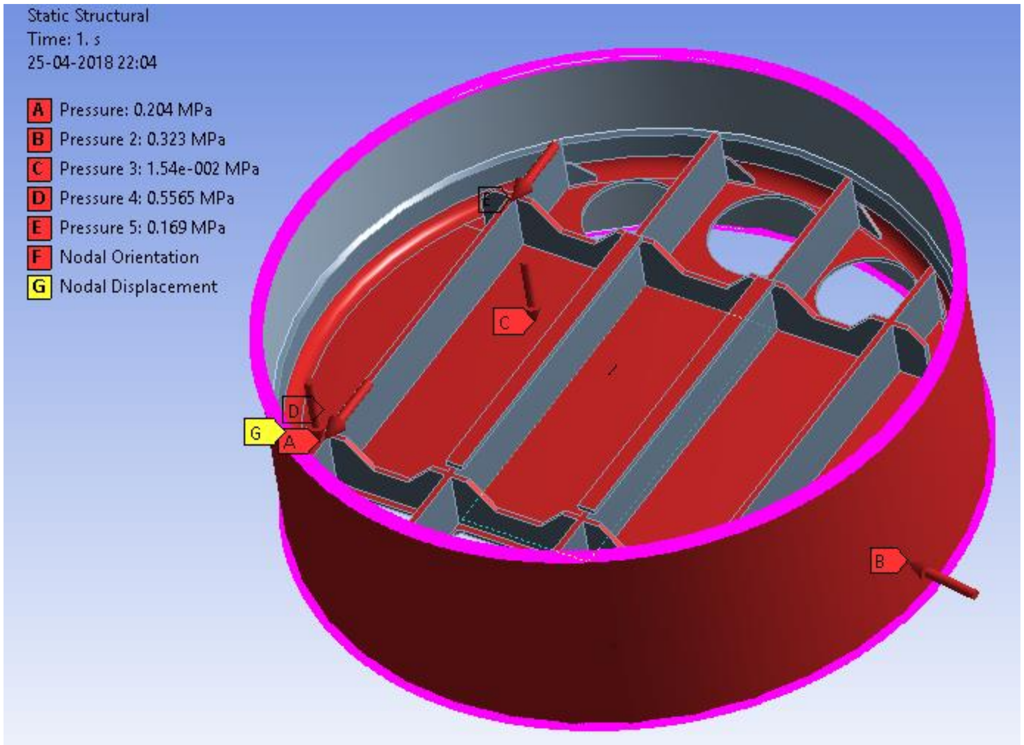


Figure 4.4 Boundary Conditions Applied to Separation Plate & Reactor Shell

4.5 LOAD CASE 1: STRUCTURAL LOAD CASE

In structural load case the design pressure difference, Dead weight of the catalyst, retaining force of the catalyst and the design temperature has been taken into consideration.

The analysis has been carried out for 3 different design cases. The first design case is normal to plate with stiffener, the second design case has support plate at the end of the outer stiffener and the third design case is modified horizontal stiffener with the gussets. All three design has been analyzed using FEA structural analysis and the result has been compared.

4.5.1 Option-1: Existing Design

The load case for this Design case is same as explained before. The stress and deformation plot are generated and shown in figure 4.5 & figure 4.6 simultaneously.

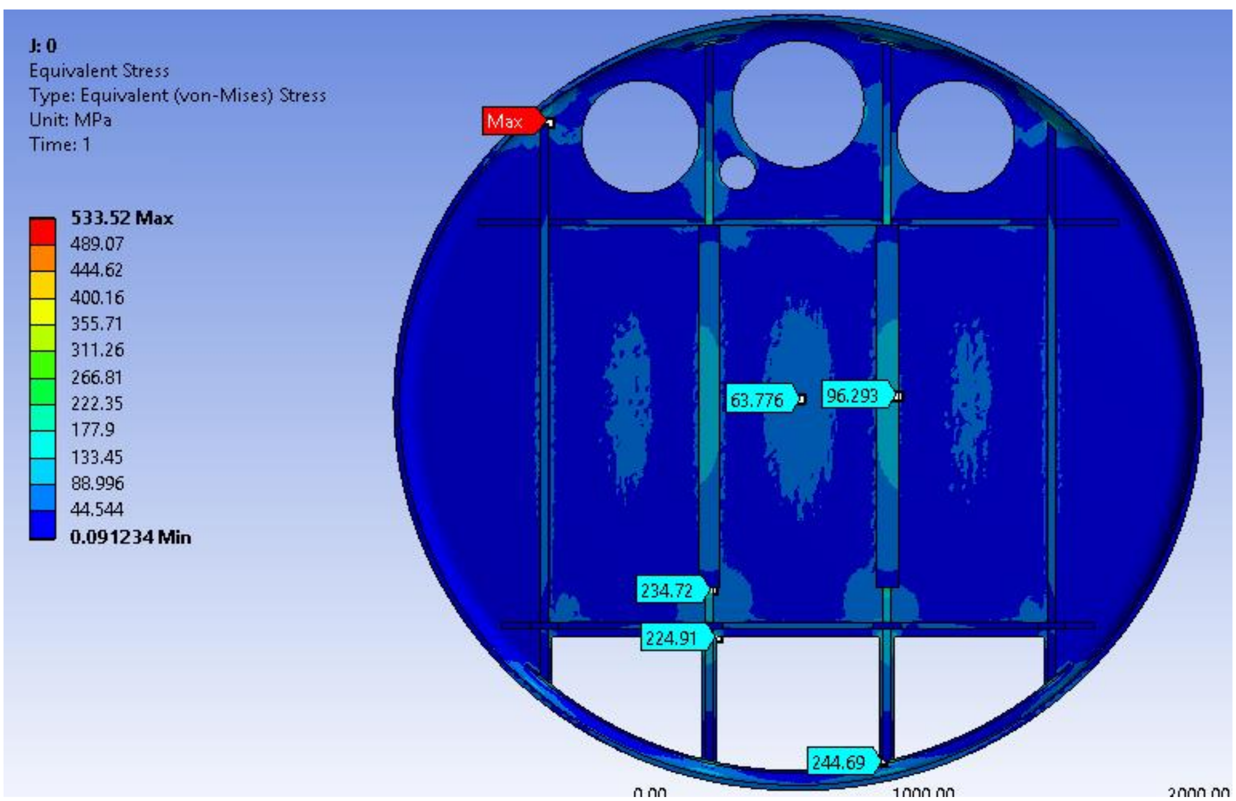


Figure 4.5 Existing Design Stress Distribution

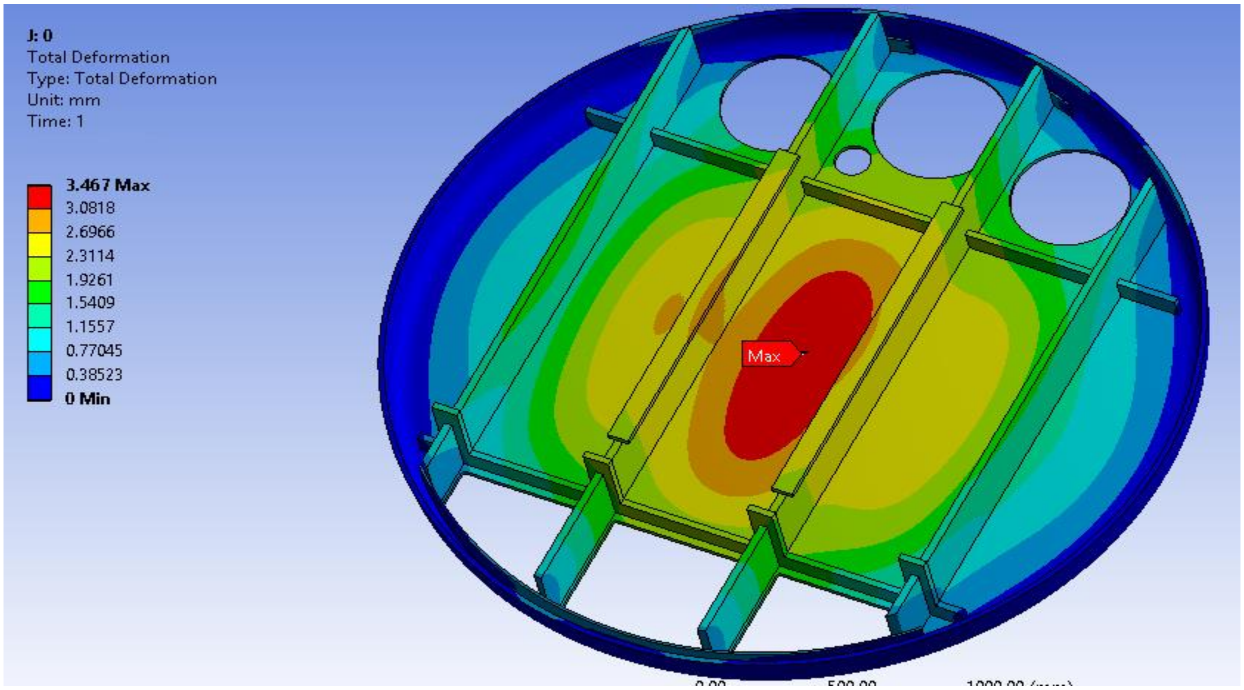


Figure 4.6 Existing Design Deformation

Result:

The existing design has been evaluated for structural loading, but the peak stresses were very high (533 MPa) as shown in figure 4.5. So it is advisable to reduce the stress by improving the design. This result shows 96 MPa of stresses at the midpoint of stiffener which is very close to the analytical calculation. So it can be concluded that meshing done for analysis is adequate for an accurate result.

4.5.2 Option-2: Support Plate at Outer Stiffener

In this case, the support plate at the outer stiffener has been used to reduce the peak stresses (Refer figure 4.7 Red mark rectangle) as the design case 1 show the peak stresses at that junction. The support plate will help to reduce stress generation at that junction. The meshing and loading cases are same as used in design case 1. The stress and deformation plot is shown in figure 4.7 & figure 4.8 simultaneously.

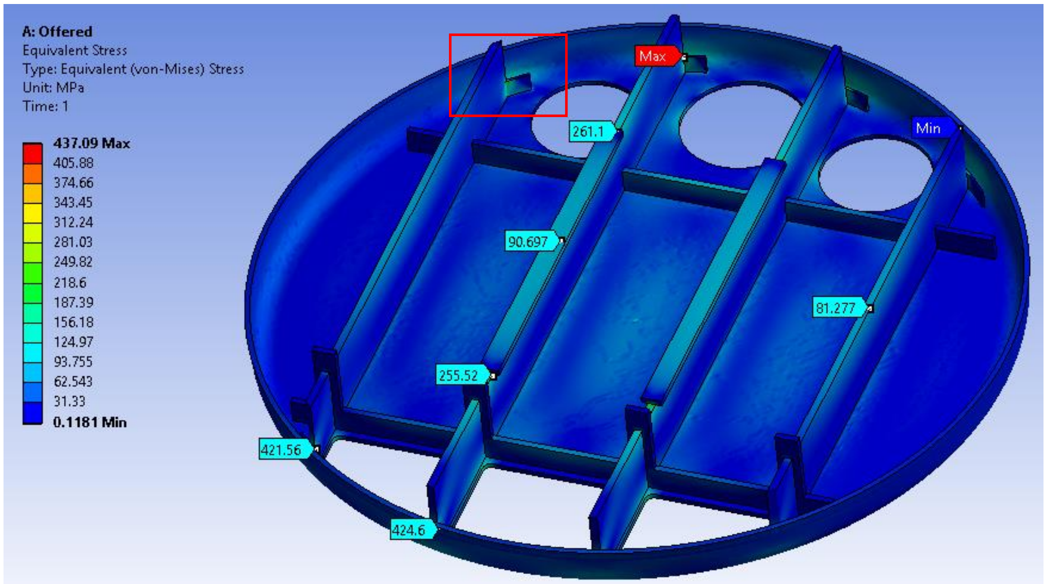


Figure 4.7 Support Plate at Outer Stiffener Stress Pattern

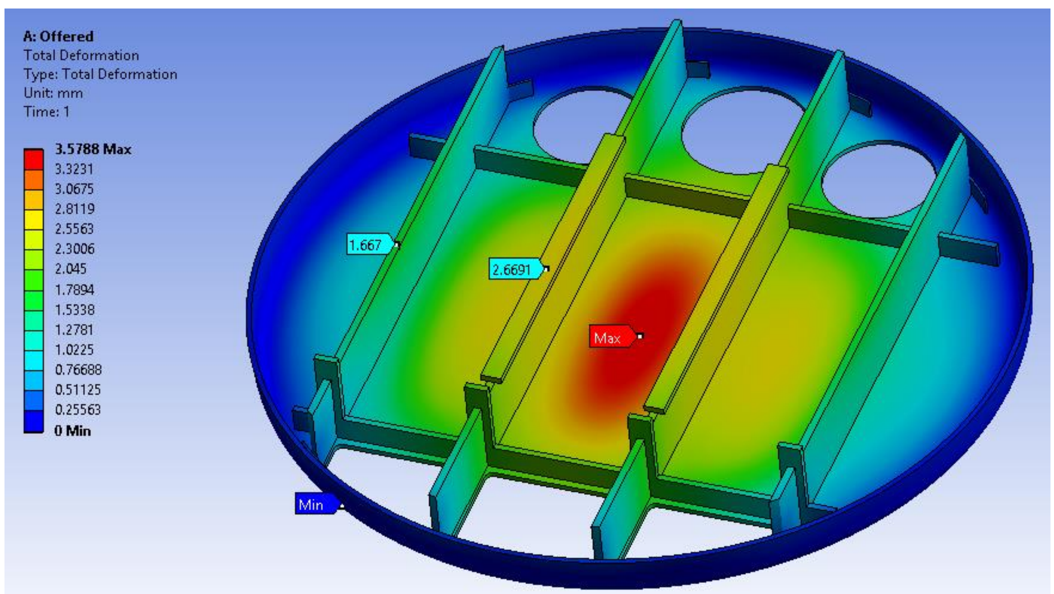


Figure 4.8 Support Plate at Outer Stiffener Deformation

Result:

The support plate at the outer stiffener has contributed to reducing the stress from 533 MPa to 437 MPa shown in figure 4.7 but it was not satisfactory so the concept of bi-axial bending has been considered in case 3 and the design has been modified accordingly.

4.5.3 Option-3: Horizontal Stiffener with Gusset

The circular plate is stiffened vertically by vertical stiffeners but the absence of horizontal stiffener allows the plate to bend around vertical axis this was the main cause of deformation of the vertical stiffener in the horizontal direction which results into high bending stresses and high peak stresses. The figure 4.9 below is the scale model of the deformation of the plate. Scale model helps to understand the pattern of the deformation.

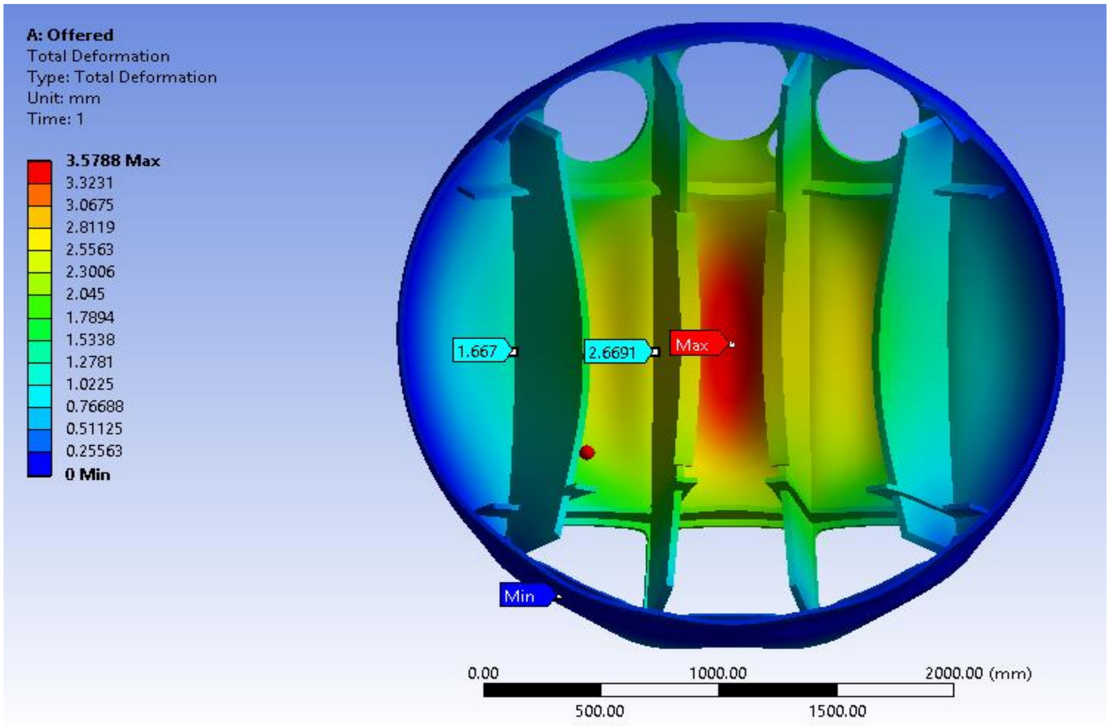


Figure 4.9 Bi-Axial Bending (Scale 1:290)

The use of horizontal stiffener with gusset resist the bending of the vertical stiffener and that resist the bending of the circular plate also as shown in figure 4.10. The design has been analyzed with same boundary condition and meshing conditions. The stress and deformation plot is shown in figure 4.10 & figure 4.11.

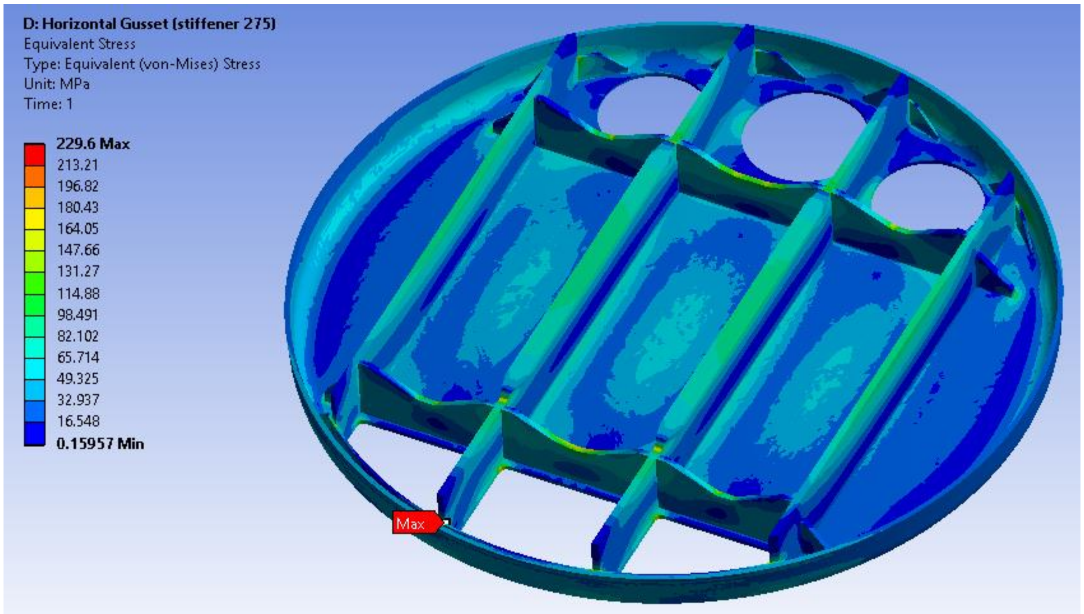


Figure 4.10 With Horizontal Stiffener Stress Distribution

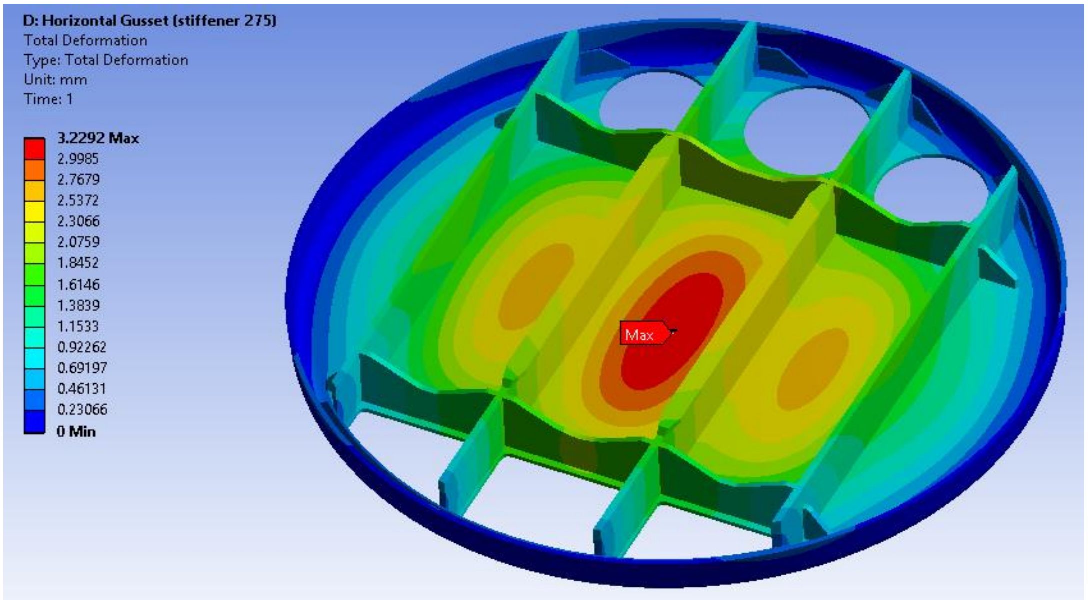


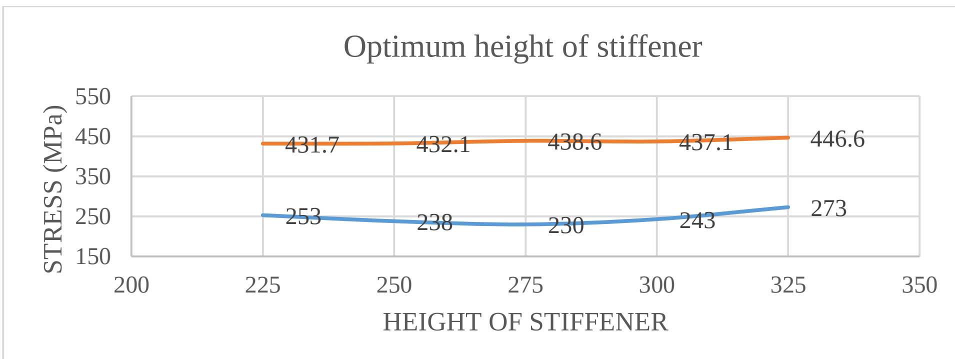
Figure 4.11 With Horizontal Stiffener Deformation

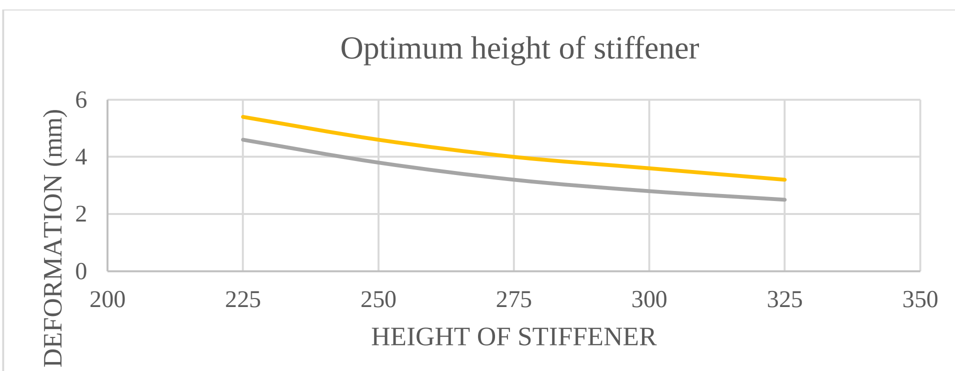
4.5.4 Results for Different Height of Stiffeners

The peak stresses generated in the plate are still high so the two design cases of the plate are analyzed again with different height of stiffener with a height of 225 mm to 325 mm and the pattern of the stress generation has been observed and analyzed.

Cases	Height of Stiffener	Deformation	Stress
	Mm	mm	MPa
Existing Design	325	3.2	446.6
	300	3.6	437.1
	275	4	438.6
	250	4.6	432.1
	225	5.4	431.7
Plate with Horizontal Gusset	325	2.5	273
	300	2.8	243
	275	3.2	230
	250	3.8	238
	225	4.6	253

Table 4-2 Results of Different Height of Stiffeners





As shown in table 4.2 the optimum solution found is the plate with horizontal gusset with the stiffener height of 275 mm. That gives least stress generation at least material utilization compare to the existing design.

The peak stresses generated in the plate are more than allowable stress limit. So, As per ASME Boiler and Pressure Vessel section VIII, Division-2, Paragraph 5.5.3 the linearization of stresses has been performed and the results of the stress linearization is shown in table 4-3. The allowable limit as per ASME is also mentioned in table 4.3.

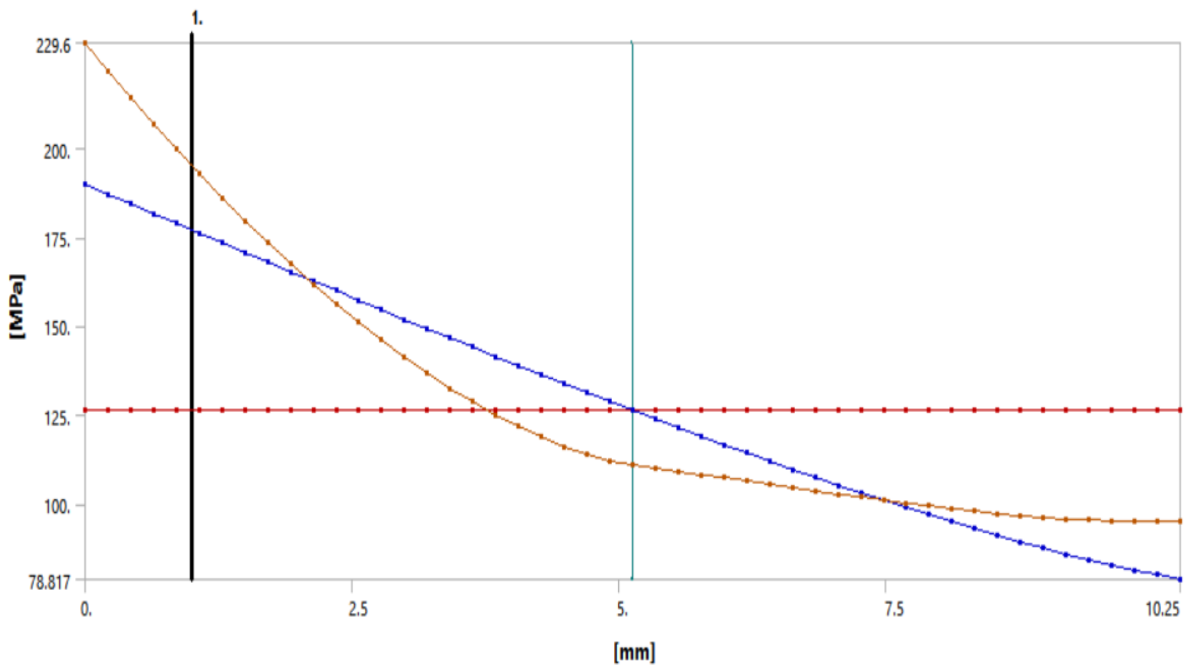


Figure 4.12 Linearization of stresses

Stress type	Stress (MPa)	limit
Membrane (Pl)	126.35	1.5 * σ_{all} = 138
Membrane + Bending (Pl + Pb+ Q)	189.95	3 * σ_{all} = 276

Table 4-3 Structural Load Case Linearization of Stresses

The table 4-3 shows that the stresses induced are less than the ASME guideline. So the Height of stiffener, Thickness of stiffener, Thickness of plate is adequate for Load case 1.

4.6 LOAD CASE: 2 THERMO-STRUCTURAL LOAD CASE

The second load case is thermo-structural load case. It is the crucial case as it is a combination of thermal load and structural load. In this case, temperature varies between various contact parts so the thermal expansion is critical. Due to thermal expansion and structural load stresses, the value of stress generated is high. The figure 4.13 & figure 4.14 below shows stress and deformation plot.

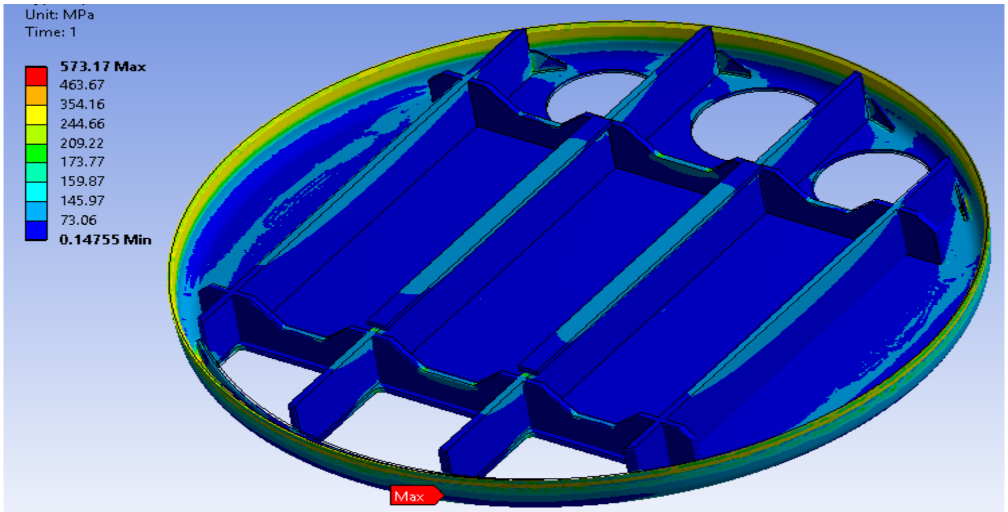


Figure 4.13 Thermo-Structural Stress Distribution

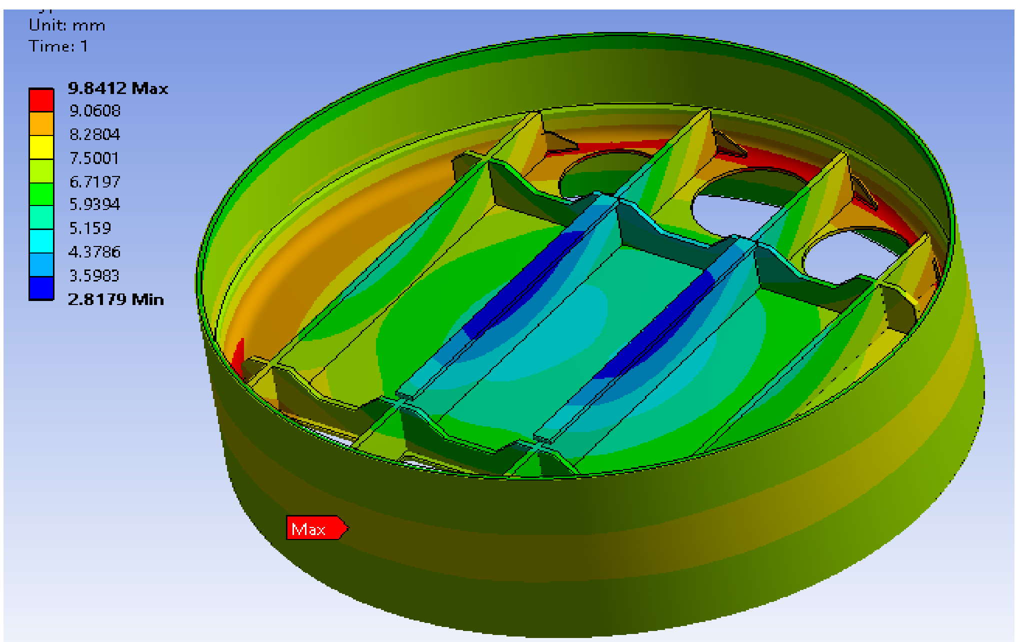


Figure 4.14 Thermo-Structural Deformation

Result:

Stress type	Stress (MPa)	limit
Membrane (Pl)	110	1.5 * σ_{all} = 138
Membrane + Bending (Pl + Q)	407	Min (3 * σ_{all} = 276 , 2*S_y = 384)

Table 4-4 Thermo-Structural Analysis Linearization

The peak stresses generated during thermo-structural analysis has crossed the allowable limit. Thus, Following ASME guidelines the linearization of stresses has been performed at some places where an abrupt change in geometry present. The table 4.4 shows that the result of linearized stress value, in that case, local membrane stress is in limit condition but the membrane + bending crosses the allowable limit. In such a case, the Elastic-Plastic analysis required to be performed.

4.7 ELASTIC-PLASTIC ANALYSIS OF SEPARATION PLATE

4.7.1 Introduction:

Plasticity can be defined as the property which enables a material to be deformed permanently and continuously without any rupture during the application of stresses exceeding yield limit of the material.

In the linear-elastic plastic analysis, the stresses are directly proportional to strain up to the yield point of the material. Beyond the yield point, this relation no longer applies and plasticity effects required to be considered. At this stage, the material exhibits non-linear strain hardening and permanent deformations start to be taken place. During the unloading, stress is assumed to take place linearly and parallel to the loading line. [22]

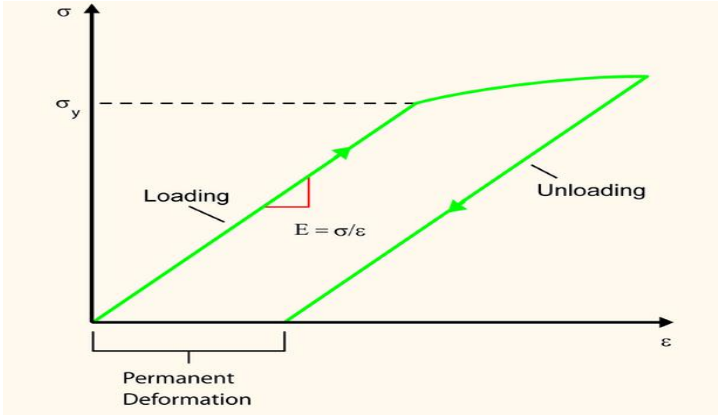


Figure 4.15 Elastic-Plastic Curve [22]

4.7.2 Bilinear Hardening

The material is assumed to be linear elastic up to yield point. Beyond yield, the material exhibits linear plastic deformation.

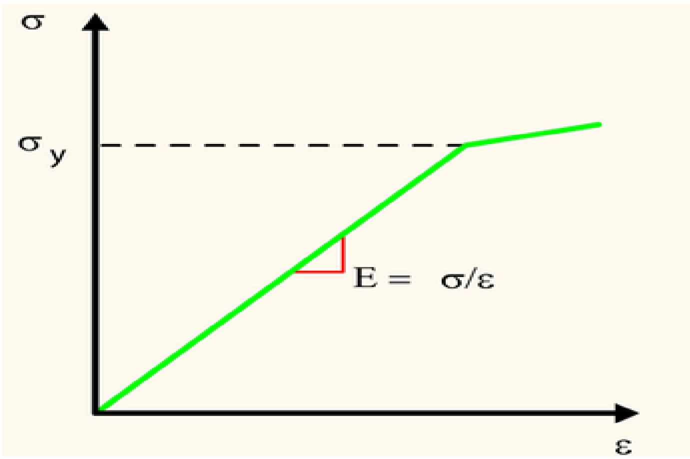


Figure 4.16 Bilinear Hardening [22]

4.7.3 FEA of Plate with Vertical Support Plate

The same design has been evaluated with the different material property which is bi-linear material property. In this analysis, the plastic deformation of the body is being taken into consideration. The stress and deformation plot found below:

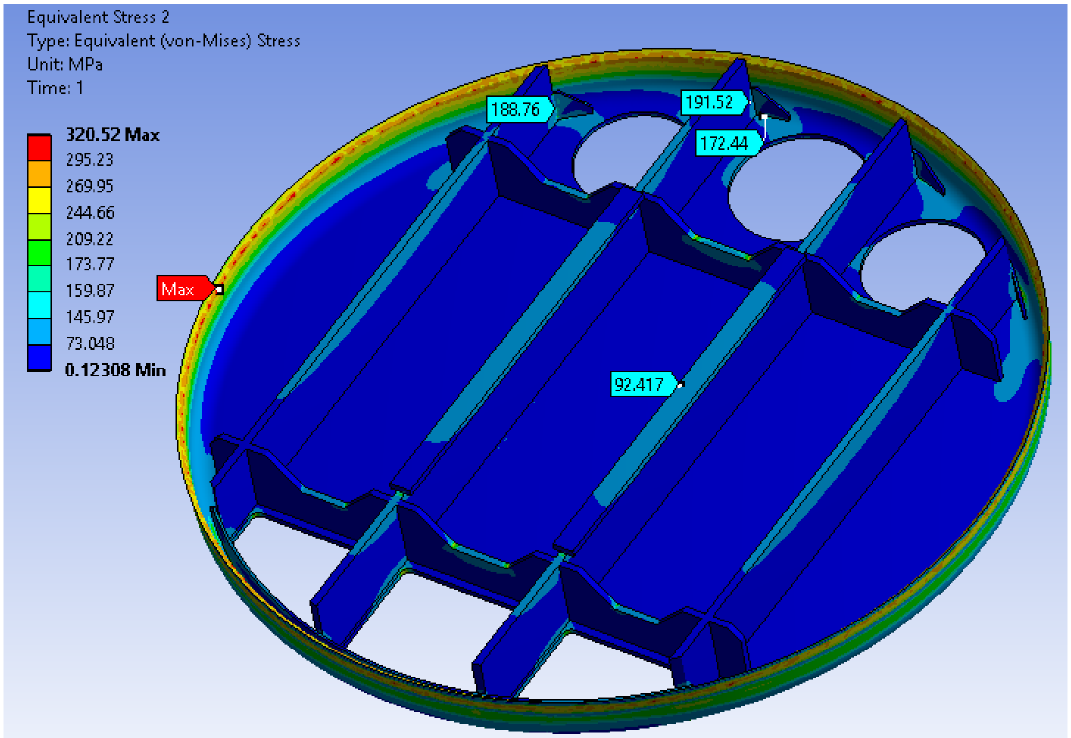


Figure 4.17 Vertical Support Plate Elastic-Plastic Stress Pattern

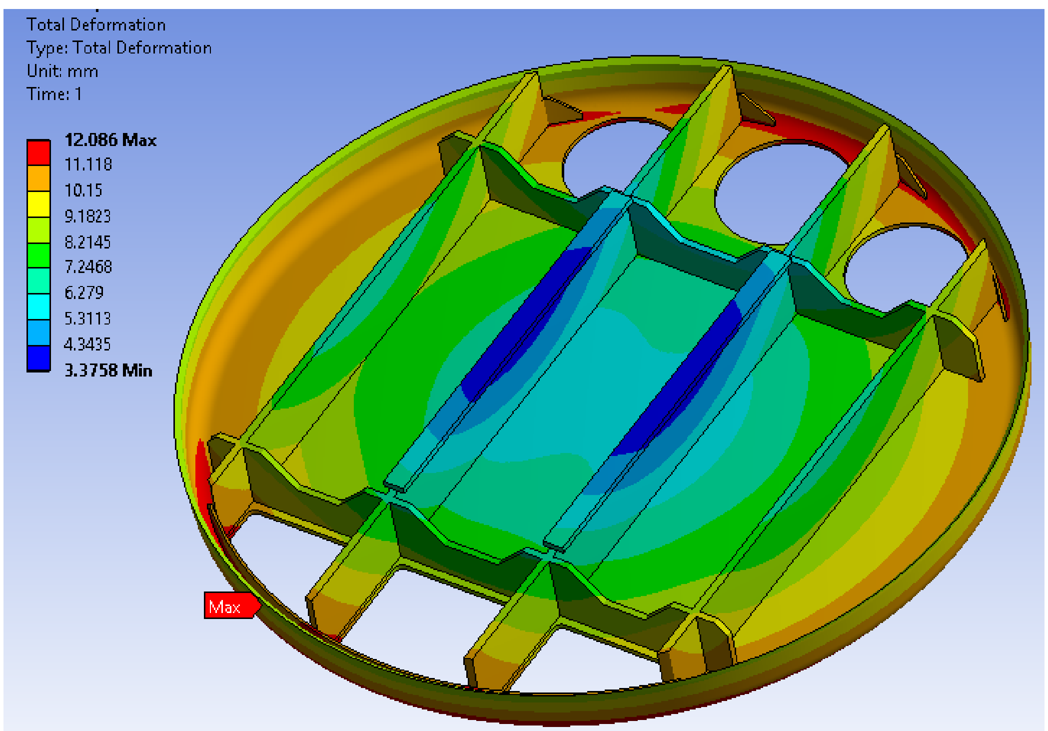


Figure 4.18 Vertical Support Plate Elastic-Plastic Deformation

Stress type	Stress (MPa)	limit
	SCL 1	limit
Membrane (Pl)	114.11	1.5 * σ_{all} = 138
Membrane + Bending (Pl + Q)	257.03	Min (3 * σ_{all} = 276 , 2*Sy = 384)

Table 4-5 Stress Elastic-Plastic Result for Vertical Support Plate

The peak stresses generated during thermo-structural elastic-plastic analysis has crossed the allowable limit. Thus, Following ASME guidelines the linearization of stresses has been performed at some places where an abrupt change in geometry present. The table 4.5 shows that the result of linearized stress value for local membrane stress and membrane + bending are in limit condition. In such a case, the Elastic-Plastic analysis shows the design is adequate for given loading condition,

4.7.4 Elimination of Support Plate

The support plate is very difficult from a fabrication point of view due to limited access. It is advisable to remove support plate but there should be other provision to reduce the stresses as shown earlier that stresses increase when support plate removed. So it was required to search for a scope of other technique which can improve the design. Some design changes can be done. [5]

1) Change the length of the stiffener
2) Remove support plate and make stiffener free (increased the value of stress)
3) Use aligned support at the end of stiffener (Sustain the peak load of stiffener at the end)
4) Provide tapper at the end of the beam (Provide flexibility to deform and help to absorb energy by deforming it – Not by resisting it)

4.7.5 FEA of Plate with Horizontal Support Plate

The horizontal stiffener with tapered stiffener has been designed and analyzed for same cases and the result found as below:

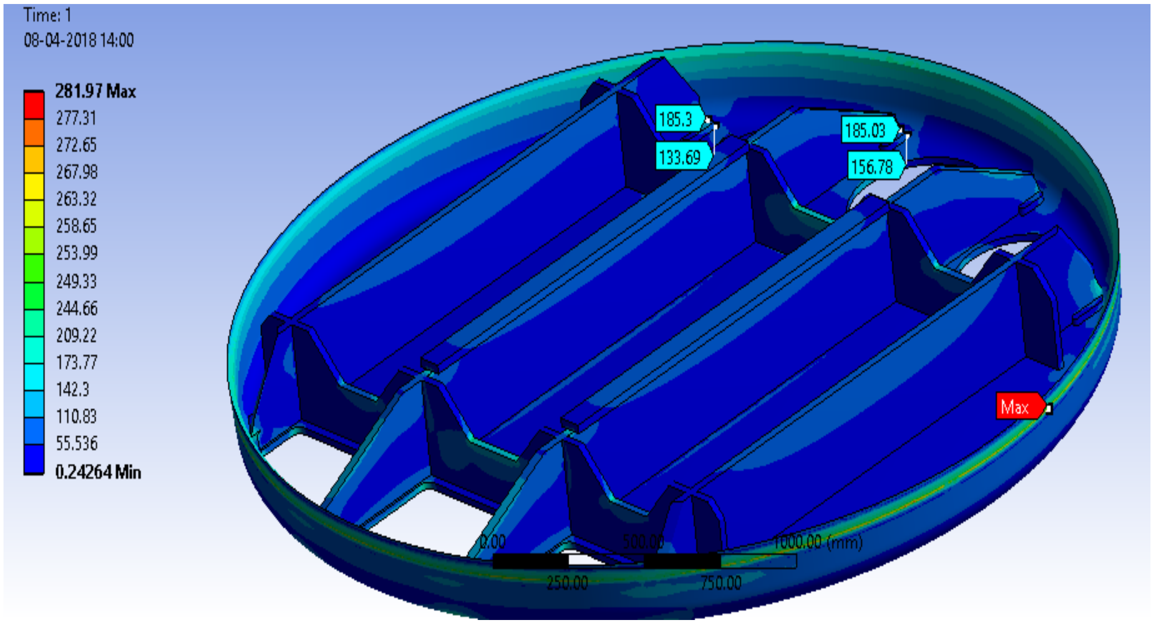


Figure 4.19 Horizontal Support Plate Elastic-Plastic Stress Pattern

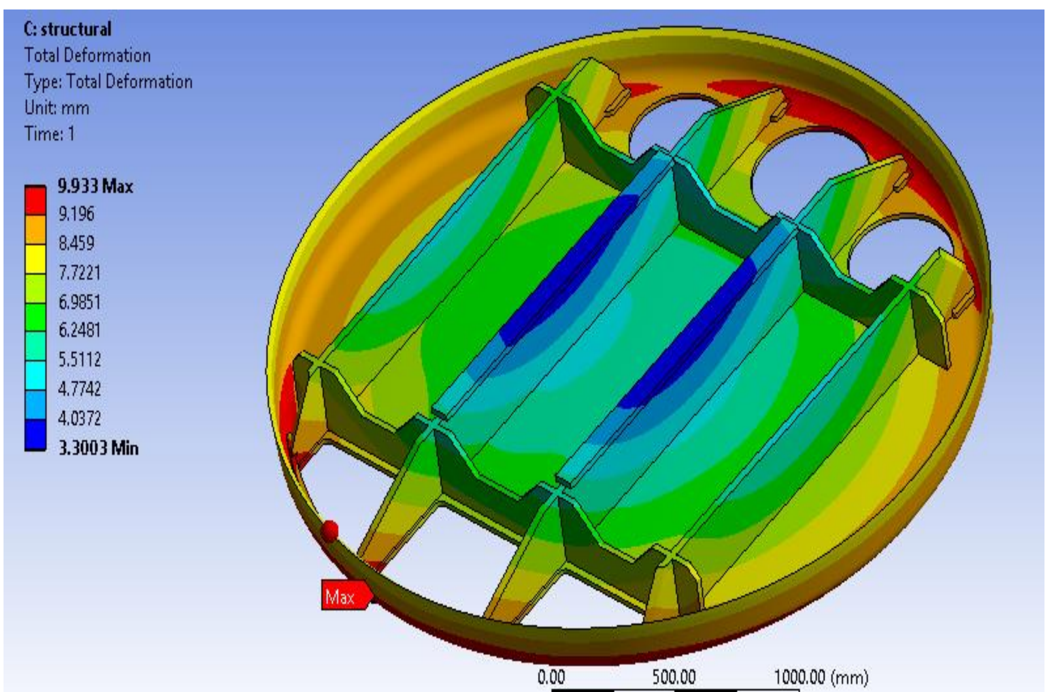


Figure 4.20 Horizontal Support Plate Elastic-Plastic Deformation

Stress type	Stress (MPa)	limit
	SCL 1	limit
Membrane (Pl)	129.58	1.5 * σ_{all} = 138
Membrane + Bending (Pl + Q)	170.7	Min (3 * σ_{all} = 276 , 2*Sy = 384)

Table 4-6 Stress Elastic-Plastic Result for Horizontal Support Plate

The peak stresses generated during thermo-structural elastic-plastic analysis has crossed the allowable limit. Thus, Following ASME guidelines the linearization of stresses has been performed at some places where an abrupt change in geometry present. The table 4.6 shows that the result of linearized stress value for local membrane stress and membrane + bending are in limit condition. In such a case, the Elastic-Plastic analysis shows the design is adequate for given loading condition,

4.7.6 Result of Elastic-Plastic Analysis of Separation Plate

The peak stresses during Thermo-structural analysis found more than allowable Stress limit so Elastic-plastic analysis has been performed. In this case, the analysis gave maximum stress value more than allowable limit so again linearization of stress has been performed and that shows stresses are in limit condition. So the height and thickness of Plate and Stiffener are adequate. The elastic-plastic analysis of both design vertical support plate and horizontal support plate has been evaluated by linearization. The result shows the design is adequate for loading conditions.

CHAPTER 5

FATIGUE LIFE CYCLE ANALYSIS

The low cycle fatigue is mainly applicable to the devices on which very large loads are applied. Typical examples of low cycle fatigue is a pressure vessel. A fatigue failure mostly begins at a local discontinuity and when the stress at the discontinuity exceeds elastic limit there is a plastic strain.

The cyclic plastic strain is responsible for crack propagation and fracture. When plastic strain occurs, the service life of material decreases, often it is not more than 10^4 cycles in low-cycle fatigue range. The research of low-cycle fatigue was traditionally done for pressure vessels, power machinery that is exposed to a high-temperature heat source which induces thermal expansion (thermal stress) to the structure. [23]

5.1 LOAD HISTORY

Figure 5.1 shows the fatigue loading histogram which explains the cyclic loading condition of the separation plate. The reactor works for months and then it shut down for maintenance purpose again it being started after maintenance. Due to this process, the temperature of plate fluctuates from 0^oC to 545^oC and structural loads also fluctuates. That load fluctuations generate the stress fluctuation which is shown in figure below. [18]

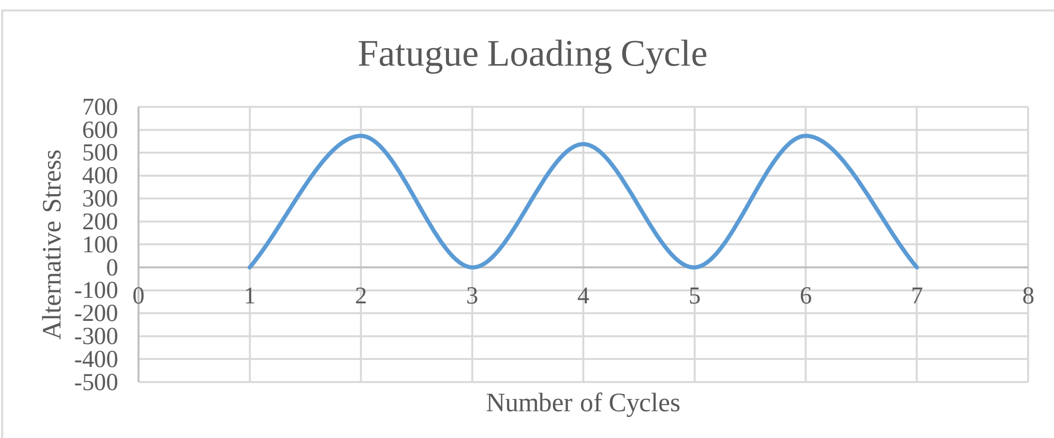


Figure 5.1 Fatigue Loading Histogram

5.2 FATIGUE LIFE CALCULATION FOR ELASTIC ANALYSIS

S	Stress Range	573	MPa
S_a	Alternating stress amplitude (K_f x K_e x S /2)	955	MPa
S_m	Stress Intensity	114	MPa
S_{ps}	Allowable Primary + Secondary stress	342	MPa

For Inconel 600			
m	Constant	1.7	
n	Constant	0.3	
K_e	S_n > m x S_{ps} So, K_e = 1/n	3.333333	From 5.5.3.2
S_a	Allowable Stress	92	MPa
K_f	Fatigue strength reduction factor	1	
S_y	Yield stress @ design temp	192	MPa

From Cl.3.F.1.2 & Table 3.F.3, Section VIII Div.2. 2016 [18]	
C1	7.52
C2	0.01
C3	-1.17E-01
C4	-5.34E-04
C5	-1.16E-04
C6	5.27E-06
C7	1.13E-05
C8	-1.69E-09
C9	-1.70E-08
C10	-4.76E-12
C11	4.36E-12

E_{fc}	Modulus of elasticity at room temperature	195000	MPa
E_t	Modulus of elasticity at max. design temperature	183600	MPa
C_{us}	conversion factor	6.89	
Y	$\left(\frac{Sa}{Cus}\right)\left(\frac{Efc}{Et}\right)$	147.11	Eq 3.F.3 of code
X	$\frac{C1 + C3 * Y + C5 * Y^2 + C7 * Y^3 + C9 + Y^4 + C11 * Y^5}{1 + C2 * Y + C4 * Y^2 + C6 * Y^3 + C8 + Y^4 + C10 * Y^5}$	2.45	
N	Number of Allowable cycles (10^x)	283	

N @545ºC	Number of allowable cycles (10^x (427/T)^(427/T))	233	From the modified equation 3.F.1

Table 5-1 Elastic Fatigue Calculation

5.3 FATIGUE LIFE CALCULATION FOR ELASTIC-PLASTIC ANALYSIS

ε	Strain Range	0.0017648	mm/mm
S_a	Alternating stress amplitude (Kf x Etc x ε/2)	574	MPa
Sm	Stress Intensity	114	MPa
S_{ps}	Allowable Primary + Secondary stress	342	MPa

For Inconel 600			
m	Constant	1.7	
n	Constant	0.3	
K_e	$S_n > m \times S_{ps}$ So, $K_e = 1/n$	3.333333	From 5.5.3.2
S_a	Allowable Stress	92	MPa
K_f	Fatigue strength reduction factor	1	
S_y	Yield stress @ design temp	192	MPa

From Cl.3.F.1.2 & Table 3.F.3, Section VIII Div.2. 2016 [18]	
C1	7.52
C2	0.01
C3	-1.17E-01
C4	-5.34E-04
C5	-1.16E-04
C6	5.27E-06
C7	1.13E-05
C8	-1.69E-09
C9	-1.70E-08
C10	-4.76E-12
C11	4.36E-12

E_{fc}	Modulus of elasticity at room temperature.	195000	MPa
E_t	Modulus of elasticity at max. design temperature	183600	MPa
C_{us}	conversion factor	6.89	

Y	$\left(\frac{Sa}{Cus}\right)\left(\frac{Efc}{Et}\right)$	88.35	Eq 3.F.3 of code
X	$\frac{C1 + C3 * Y + C5 * Y^2 + C7 * Y^3 + C9 + Y^4 + C11 * Y^5}{1 + C2 * Y + C4 * Y^2 + C6 * Y^3 + C8 + Y^4 + C10 * Y^5}$	2.50	
N	Number of Allowable cycles (10^x)	320	
N @545ºC	Number of allowable cycles (10^x (427/T)^(427/T))	264	From the modified equation 3.F.1

Table 5-2 Elastic-Plastic Fatigue Calculation

5.4 RESULT OF FATIGUE LIFE CALCULATIONS

Fatigue analysis has done to calculate allowable useful life cycle of the separation plate against the designed cycles. The values for fatigue strength and penalty factors were taken as per the ASME guidelines. Evaluated fatigue life of the separation plate is 233 cycles for elastic analysis and 264 cycles for elastic-plastic analysis. The evaluated life cycle is higher than the required life cycle of the separation plate. So design is adequate.

CHAPTER 6

CONCLUSION

A literature review has been carried out for a better understanding of ammonia converter and separation plate. The loads acting on the plate has been calculated and the design calculation of the plate has been carried out and then the structural finite element analysis has been performed on the designed plate. The design has been modified to reduce the structural stresses. The results have been compared, and the optimum design has been selected for further development.

The thermo-structural finite element analysis has been performed on the structural optimized plate. The results have been analyzed which found that exceeded the limit stresses. So as per ASME guideline, Elastic-Plastic analysis has been performed and the result found adequate. Then the Fatigue life calculation has been carried out using ASME guideline for elastic and elastic-plastic both cases and same has also been found satisfactory compared to specifications. The new concept of horizontal stiffener support plate has been found to be satisfactory.

In selected optimum design, structural stresses have been reduced by 47%. The horizontal stiffener has added some weight which is less than 1.5% of the overall weight of Plate. Adding 1.5% of weight in the plate has given 47% of the reduction in von-mises stresses thus, the optimized design is preferable.

The Thermo-structural elastic-plastic analysis result has confirmed that the design is adequate for particular loading conditions. The fatigue life of the separation plate has been found adequate for particular loading histogram.

CHAPTER 7

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