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End Connectors Stress Analysis for Horizontal Pressure Vessel

Sourabh Verma

Abstract*: The gas and oil industry extensively utilizes horizontal pressure vessels to store its primary sources. These vessels are designed to withstand high levels of pressure and to release contents in a controlled manner. Although the sphere-shaped storage container is widely regarded as a better-engineered structure, the ease of manufacturing makes horizontal pressure vessels the preferred choice. This paper presents an in-depth analysis of stress distribution in horizontal pressure vessels with various end connections, including hemispherical, ellipsoidal, flat-head, and torispherical configurations. The study involves both analytical and finite element analysis (FEA) to compare the stress distribution across the aforementioned end connections. Key vessel dimensions, such as internal diameter, vessel thickness, and end connections, have been determined through analytical design. A detailed structural analysis helped determine which of the different end connectors is best suited for industrial use.

Keywords: Horizontal Pressure Vessel, end Connections, FEA Analysis, Structural Analysis, CAD Models

I. INTRODUCTION

Pressure vessels are large static structures that can hold, store, or receive fluids under high pressure. These fluids, often highly hazardous, can experience significant pressure variations inside and outside these tanks. This is why vessels are critical components and hold greater importance in the industry. The pressure inside is typically greater than the pressure outside. As in the case of a steam boiler, the liquid inside the cylinder may change its state or combine with another reagent, as in the case of a chemical reactor. In certain circumstances, pressing factor vessels also have a combination of high pressing factor and high temperature, as well as combustible liquids or profoundly radioactive materials [1]. It is the engineer's responsibility to ensure that no leakage occurs in such hazardous situations. The storage unit must be meticulously designed to withstand the often-extreme operating pressure, highlighting the crucial role of the engineer in maintaining the safety and efficiency of pressure vessels in any industry [2]. Pressure vessels play a crucial role in various industries, including fossil and nuclear power generation, as well as the petrochemical and chemical industries. They are utilized to store and refine crude oil and fuel at service stations [3].

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**Correspondence Author(s)*
Sourabh Verma*, Department of Mechanical Engineering, Bikaner (Rajasthan), India. Email: sourabhv800@gmail.com, ORCID ID: 0009-0004-4509-1935

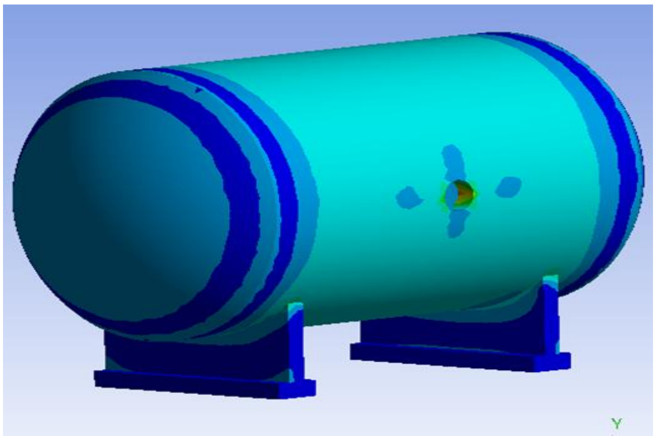

Figure 1: Horizontal Pressure Vessel

The versatile application of pressure vessels and tanks is crucial to industries such as the chemical, petroleum, petrochemical, and nuclear sectors. These vessels are utilized for reactions, separation, and the storage of raw materials. Pressurized equipment is also vital for a wide range of industrial plants for storage and manufacturing processes [1].

Cylindrical vessels are widely utilized due to their efficient use of available space. Boilers, heat exchangers, nuclear reactors, and similar equipment are often designed in a cylindrical shape. These vessels can be constructed with various end connections, such as hemispherical, circular, flat, ellipsoidal, and dish shapes [1].

Hemispherical and flat circular ends are commonly utilized in the construction of internal containers for combustible fossil fuels, water, and milk. Spherical vessels offer the advantage of requiring thinner walls to withstand a given pressure and diameter compared to cylindrical vessels. Consequently, they are frequently employed in the storage of large quantities of gases or liquids, as well as in the construction of containment structures for nuclear facilities [1]. The geometric configuration of the head of a pressure vessel, whether spherical, ellipsoidal, or hemispherical, has a significant impact on the distribution of membrane stress within its cylindrical section.

Pressure vessels are extensively employed across multiple industries, including nuclear and thermal power plants, chemical processing, aerospace, marine exploration, and liquid storage systems [4]. Failure of a pressurized vessel can result in loss of life, health risks, and property damage. Pressure vessels are equipped with various openings of diverse shapes, sizes, and positions to fulfil practical requirements, accommodating sewer vents, handholds, and spouts, ranging from small drain nozzles to openings that match the maximum vessel size.

Gaps are inevitable due to variations in piping measurement scale attachments and accommodate equipment installation, added instrumentation, and material presentation and extraction. Nevertheless, these openings also give rise to high-stress concentration, leading to the potential failure of the pressure vessel. In riveted constructions, these openings introduce geometric discontinuities, commonly known as pressure raisers, manifesting as pressure concentration zones [5].

II. OBJECTIVE

Pressure vessels are frequently subjected to extreme conditions, including high pressure from the fluids they contain. This study focuses on estimating the circumferential (hoop) and longitudinal stresses using the Von Mises criteria. The author's focus is on investigating pressure vessels, specifically analysing the longitudinal and circumferential stresses caused by a maximum fluid pressure of 12 MPa. Additionally, the study determines the equivalent stress on the specific end connector of the pressure vessel and identifies the most suitable head for horizontal pressure vessels.

III. METHODOLOGY

A sequential process has been followed to determine the appropriate end connector for the horizontal pressure vessel. The methodology starts as follows:

A. Literature Survey

The design of a pressure vessel is contingent upon a variety of factors, including pressure, temperature, selected material, corrosion, stress, and numerous other parameters depending on the specific application [3]. Pressure vessel technical papers serve as valuable resources for understanding the intricacies of pressure vessel design, exploring methodologies aimed at minimising failure, and scrutinising critical factors such as material selection, temperature, operating pressure, as well as design and analysis techniques.

B. Mathematical Calculation

Design calculations are performed to determine the thickness of the pressure vessel and the stress induced in the end connectors.

a) Radial and hoop stresses are determined using well-established universal formulas.

b) The Von Mises stress criterion is duly considered for calculations.

C. CAD Model Design

The parts necessary for stress analysis of the end connectors of a horizontal pressure vessel are designed using CAD (Computer-Aided Design) software. This provides a clear picture of the assembly of the horizontal pressure vessel.

D. FEM (Finite Element Method) Analysis

The end connections of the horizontal pressure vessel are analysed using the ANSYS Workbench analysis software. This involves calculating radial and hoop stresses for the cylindrical heads to gain insight into the stress distribution within these components.

E. Data Analysis

The pressure vessel's end connectors undergo theoretical and computational analysis to evaluate their performance under industry-level working conditions. A comparative study of data obtained from both methods is used to validate the most suitable head for the intended application.

F. Result/Tabulation

The study has been structured and documented to showcase the work and methods employed.

IV. DESIGN CALCULATION

The stress on the end connectors of the pressure vessel was calculated through design calculations, which referenced technical research papers and the design data handbook. Carbon steel was chosen as the material for the horizontal pressure vessel due to its widespread use in manufacturing such vessels. Preferred Material – Carbon steel [ASME SA 516 Grade 70]

A. Chemical Composition

The chemical composition of Carbon Steel is represented in Table I.

Table I: Chemical Composition of Carbon Steel

Composition	Percentage (%)
C	0.10/0.22
Si	0.6
Mn	1/1.7
P	0.03
S	0.03
Al	0.02
Cr	0.3
Cu	0.3
Ni	0.3
Mo	0.08
Nb	0.01
Ti	0.03
V	0.02

B. Physical Parameters

Table II below consists of the mechanical properties of the selected material.

Table II: Parameters Associated with the Material

Properties	Value
Density of Material	$7861 kg/m^3$
Modulus of Elasticity	$2x10^5 N/mm^2$
Operating Pressure	120Bar
Inside Diameter	1500mm
Cylinder length	2500mm
Ultimate Tensile Stress	485MPa
Tensile Strength (Yield)	260MPa
Welding Efficiency	1

C. Theoretical Calculations

- Flat Head Calculation [3]

Thickness (t) $= \frac{PR}{SE-0.6P}$ -------- (1)

where,

- P = Pressure
- R = Radius of pressure vessel
- S = Maximum allowable stress
- E = Joint/Weld efficiency

- D = Diameter of pressure vessel
- Hemispherical Head Calculation [3]
- Thickness(t) = $\frac{PR}{2SE-0.2P}$ -------- (2)
- Ellipsoidal Head Calculation [3]
- Thickness(t) = $\frac{PD}{2SE-0.2P}$ -------- (3)
- Tori spherical Head Calculation [3]
- Thickness(t) = $\frac{0.885PL}{SE-0.1P}$ -------- (4)

D. Thickness Calculations

- Flat head:

$$\frac{12 \times 750}{(140 \times 1) - 0.6 \times 12} = 68mm$$

- Hemispherical head:

$$\frac{12 \times 750}{(140 \times 2) - 0.2 \times 12} = 32.42mm$$

- Ellipsoidal head:

$$\frac{12 \times 1500}{(140 \times 2) - 0.2 \times 12} = 64.84mm$$

- Tori spherical head:

$$\frac{0.885 \times 12 \times 1500}{(140 \times 1) - 0.6 \times 12} = 114.76mm$$

E. Thickness Results

Table III: Hand Calculations – Head Thickness

Components	Thickness (mm)
Flat Head	68
Hemispherical Head	32.42
Ellipsoidal Head	64.84
Tori spherical Head	114.76

F. Stress Calculation

Induced Stresses [6]:

Circumferential or Hoop Stress, $\sigma_c = \frac{PD}{2t}$ -------- (5)

Longitudinal Stress, $\sigma_l = \frac{PD}{4t}$ -------- (6)

where, P = Pressure
D = Inside diameter of pressure vessel
t = Thickness

At any point on the circumference of a cylinder shell, there are two mutually perpendicular stresses σ_l and σ_c. The maximum shear stress can be calculated based on these perpendicular stresses.

$\tau_{max} = \frac{\sigma_c - \sigma_l}{2} = \frac{PD}{8t}$ -------- (7)

Van Mises' stress criterion:

$\sigma_v = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 + 3\tau^2}$ -------- (8)

G. Stress-Induced

Table IV: Stresses Associated with Different Heads

Components	Stress (MPa)
Flat Head	128.146
Hemispherical Head	268.146
Ellipsoidal Head	136.159
Tori spherical Head	75.93

H. 3D Modelling Calculation

- Hemispherical Head:
  1. Radius = = $\frac{ID}{2}$ = 750mm.
  2. Blank Diameter = = $\frac{\pi}{2} \times \boldsymbol{ID}$ = 2356mm.
  3. Height = same as radius = 1500mm
- Ellipsoidal head:
  4. Internal diameter = 1500mm.
  5. Straight flange = 50.8mm
  6. Crown radius = 0.9x1D = 1350mm
  7. Overall height = $\frac{1D}{4}$ = 375mm
- Tori spherical head:
  1. Knuckle radius = 150mm.
  2. S.F = 38mm
  3. Height = 296mm
  4. Blank Diameter = 1726mm
  5. Crown Radius = 150mm

V. 3D MODELING

The CAD design modelling presented in this study was conducted using SOLIDWORKS software. The parts were modelled and assembled according to the standard dimensions.

A. Components

i. Hemispherical End Connector

Parameters such as diameter and thickness are crucial for accurately representing the hemispherical end geometry in finite element modelling. It is essential to consider the thickness of the hemispherical end and the diameter of the pressure vessel.

Figure 2: Hemispherical end Connector

ii. Ellipsoidal End Connector

Utilizing an ellipsoidal head reduces the overall length of the vessel. If "X" denotes the length of the hemispherical head, then "$\frac{X}{2}$" represents the length of the ellipsoidal end, leading to a decrease in material costs.

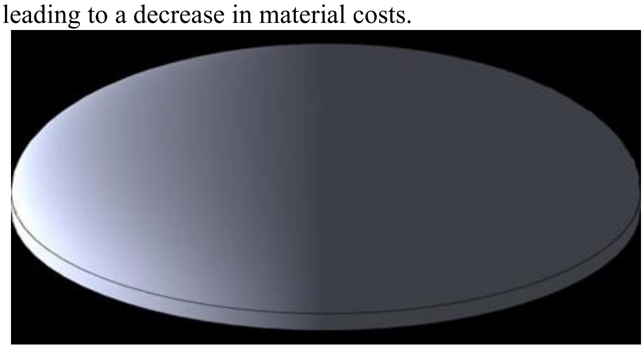

Figure 3: Ellipsoidal Head

iii. Flat Head End Connector

The head of the assembly consists of a toroidal knuckle that is affixed to a flat plate. The design of this type of end is relatively more straightforward compared to other alternatives. Additionally, these ends offer the advantage of being weldable from smaller constituent parts.

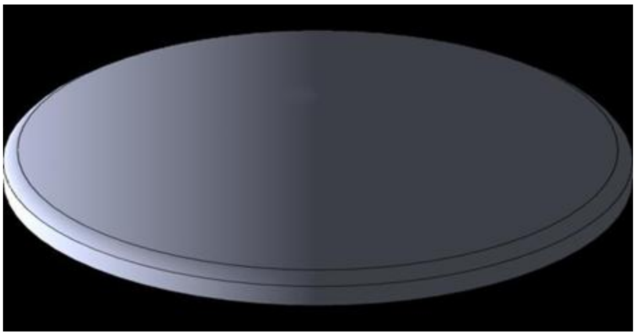

Figure 4: Flat Head End Connector

iv.Tori Spherical Head End Connector

The toroidal spherical heads feature static radius dishes, which are sized based on the toroidal spherical head's structure. The knuckle serves as the interface between the chamber and the dish and is shaped like a toroid.

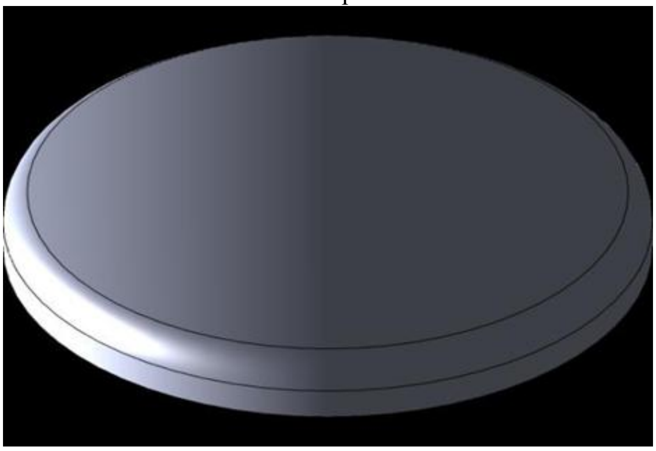

Figure 5: Tori Spherical End Connector

VI. HORIZONTAL PRESSURE VESSEL ASSEMBLED VIEW

The image below shows the complete assembly of each head and the horizontal vessel.

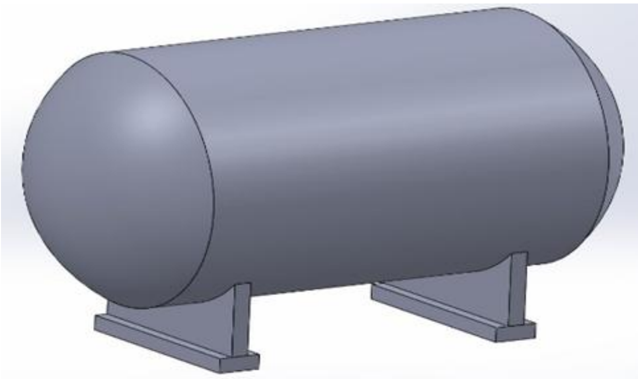

Figure 6: Ellipsoidal Head Vessel

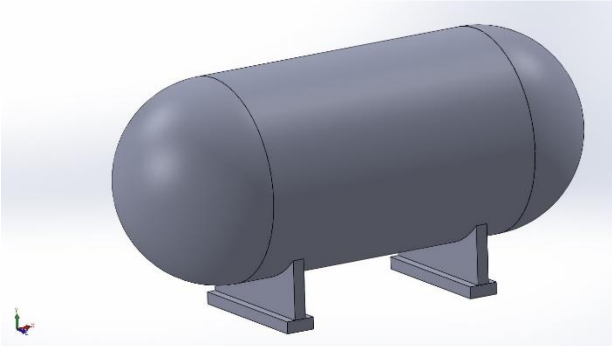

Figure 7: Hemispherical Head Vessel

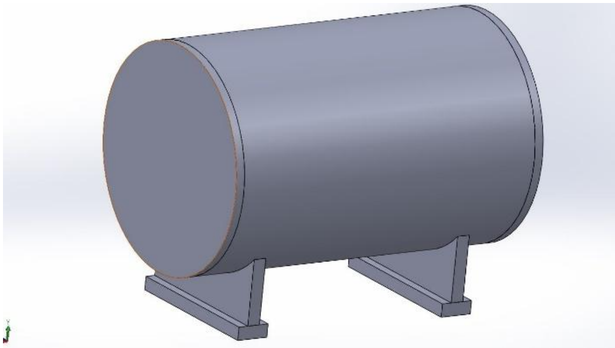

Figure 8: Flat Head Vessel

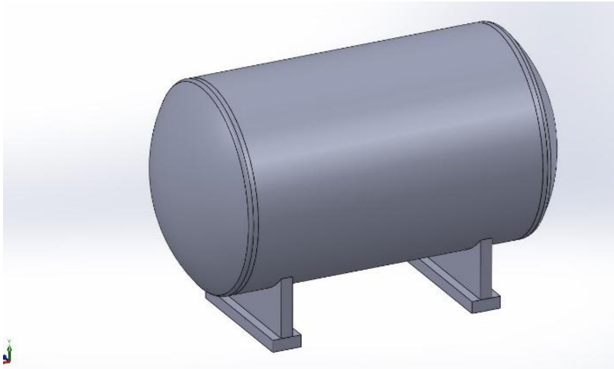

Figure 9: Tori-Spherical Head Vessel

VII. COMPUTATIONAL ANALYSIS

Finite Element Analysis (FEA) software helps to simulate computer models. Although the FEA computational program considers most of the aspects of analysis, it is of utmost importance that users understand the operation and results generated from the software [3].

Ansys simulation software enables the determination of how a product will function in various situations without requiring a physical prototype or conducting crash tests.

A. Stress Analysis of Horizontal Pressure Vessel

All four horizontal vessels are evaluated using the Ansys software program. The stress distribution with different end connectors of a horizontal pressure vessel is computed at an operating pressure of 12MPa. The geometry was produced in SolidWorks and imported into the ANSYS structural analysis study.

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i. Meshing

Mesh generation is a crucial aspect of the simulation process. The mesh significantly impacts the response's accuracy, reliability, and speed [3]. Additionally, generating a mesh typically consumes a significant portion of the time required to obtain results from the simulation.

FEA software employs triangular or quadrilateral cells for two-dimensional bodies and tetrahedral, hexahedral, polyhedral, pyramid, or wedge cells for three-dimensional bodies. Generating structured grids with quadrilateral or hexahedral elements for intricate geometries often requires a significant amount of time. It is evident from Figure 10-13 that the meshes vary on the cylindrical head and around the openings.

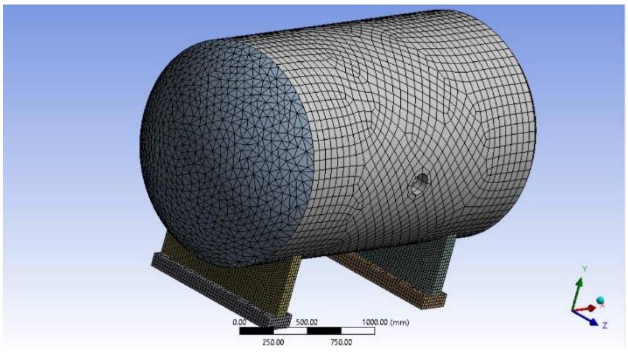

Figure 10: Ellipsoidal Head

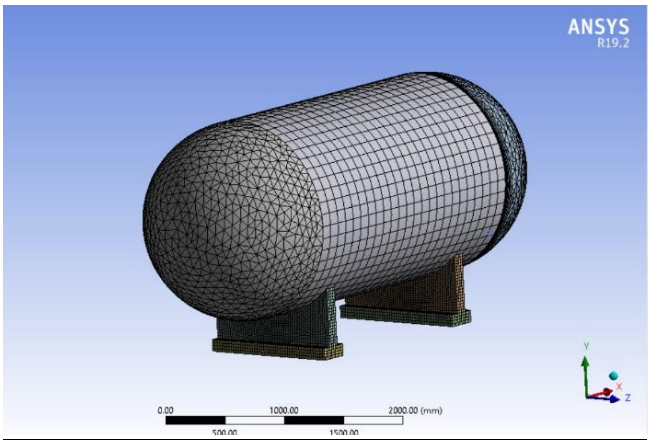

Figure 11: Hemispherical Head

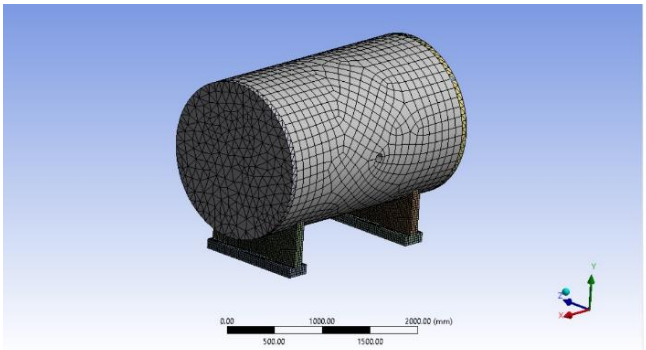

Figure 12: Flat Head

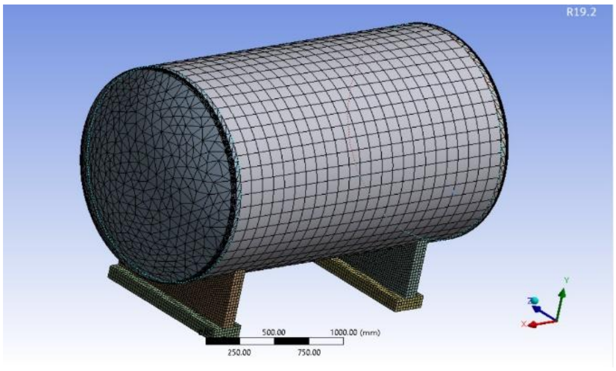

Figure 13: Tori Spherical Head

B. Stress Analysis

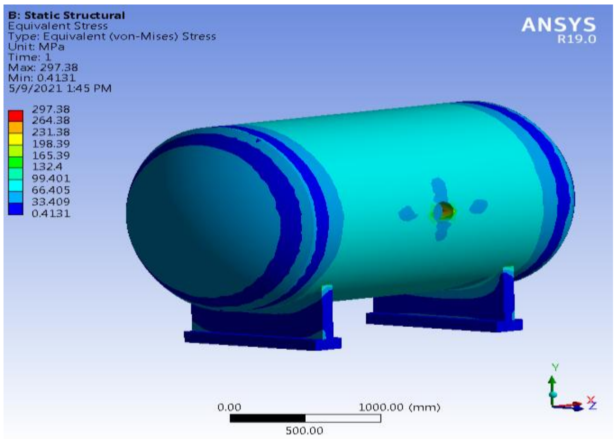

Figure 14: Ellipsoidal Head Analysis

Stress analysis of the horizontal pressure vessel, featuring an ellipsoidal head, determined that the stress induced at the end connector of the pressure vessel reached 132.4 MPa.

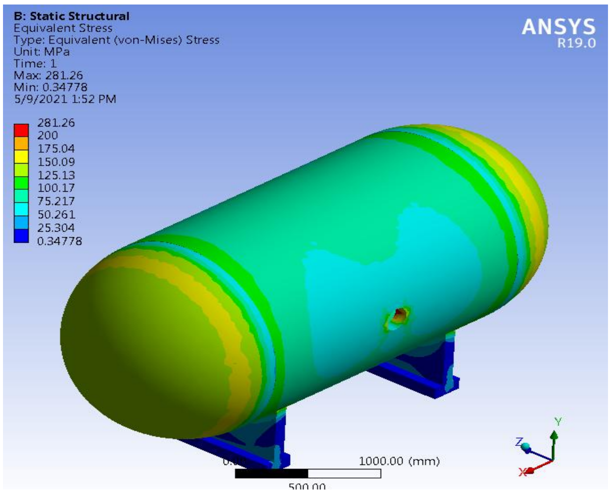

Figure 15: Hemispherical Head Stress Analysis

The stress induced in the hemispherical head was assessed after conducting a stress analysis on the horizontal pressure vessel. It was determined that the stress induced in the end connector at this location amounts to 200MPa.

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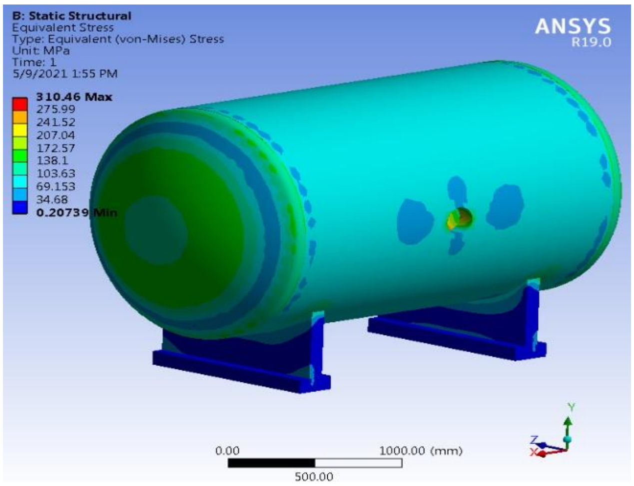

Figure 16: Tori Spherical Head Stress Results

Stress-induced in tori spherical head: The stress analysis report shows that the stress induced in the horizontal pressure vessel with a tori spherical end connector is 69.153 MPa.

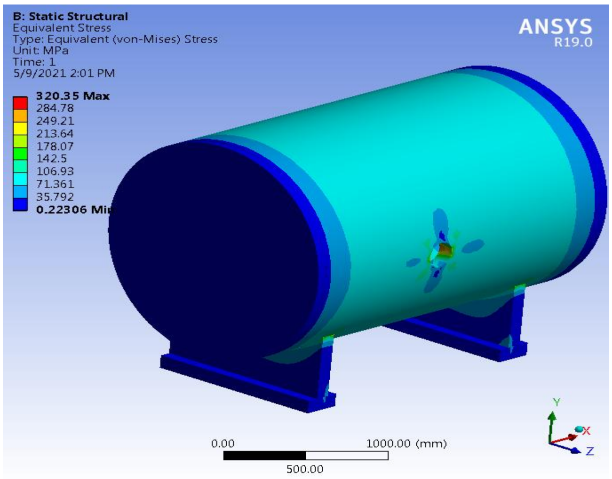

Figure 17: Stress Distribution in Flat Head

Stress analysis of a horizontal pressure vessel with a flat head revealed that the stress induced in this type of end connector is 106.93 MPa.

VIII. RESULTS

Table IV: Stress Distribution Associated with Different Heads

Components	Stress (MPa)
Ellipsoidal Head	132.4
Hemispherical Head	200
Tori spherical Head	69.153
Flat Head	106.93

The above table represents the stress induced in the horizontal pressure vessel's different types of end connectors.

IX. CONCLUSION

An investigation was conducted to analyse the load capacity of a cylindrical vessel head with radial holes. Classical formulas were used to model the stress distribution at the end connectors of cylinders under internal pressure. An analysis was performed to predict the stress behaviour of various end connectors using SolidWorks and ANSYS Workbench software, as per specific requirements.

After examining the stress data for the hemispherical end connection, flat end connection, tori-spherical end connection, and ellipsoidal end connection, it was found that the ellipsoidal head is the most optimal for bearing stress under pressure of 12MPa. Although the hemispherical head has the highest stress-bearing value, the ellipsoidal head is chosen because it is easier to manufacture. Consequently, the ellipsoidal end connection is deemed most suitable for industrial applications.

Stress concentration is a crucial factor to consider for pressure vessels. A literature review on stress concentration at end connectors in pressure vessels is presented, along with a discussion on the stress distribution effect on the various types of end connections in this study.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval or consent to participate, as it presents evidence that is already publicly available.
Availability of Data and Materials	Not relevant.
Authors Contributions	I am the sole author of the article.

REFERENCES

1. P. R. R. G. Rashmi P. Khobragade, "Design & Analysis of Pressure Vessel with Hemispherical & Flat Circular End," IJIRST –International Journal for Innovative Research in Science & Technology, vol. 4, no. 1, pp. 62-84, 2017.
2. N. C. G. a. T.-E.-A. Abu Rayhan Md. Ali, "Optimum Design of Pressure Vessel Subjected to Autofrettage Process," International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering Vol:4, No:10, pp. 1040-1045, 2010.
3. J. S. Digvijay Kolekar, "Stress Analysis of Pressure Vessel with," International Journal of Innovative Research in Science, Engineering and Technology, Vol. 4, Issue 5, pp. 2769-2775, 2015. https://doi.org/10.15680/IJIRSET.2015.0405016
4. T. C. M. Jeyakumar, "Influence of residual stresses on failure pressure of cylindrical pressure vessels," Chinese Journal of Aeronautics, Volume 26, Issue 6, pp. 1415-1421, 2013. https://doi.org/10.1016/j.cja.2013.07.025
5. C. P. V. Shyam R. Gupta, "A Review Paper on Pressure Vessel Design and Analysis," International Journal of Engineering Research & Technology (IJERT), vol. 3, no. 3, pp. 295-300, 2014.
6. B. K. R. K Mahadevan, Design Data Handbook For Mechanical Engineers In SI And Metric Units, CBS Publishers & Distributors Pvt Ltd, India, 2018.

AUTHORS PROFILE

Sourabh Verma earned a bachelor's degree in Mechanical Engineering from PES Institute of Technology, Bengaluru – Electronic City Campus in 2021. Subsequently, completed a master's degree in Mechanical Engineering at Tandon School of Engineering, New York University in 2023. Throughout the academic journey, I have acquired extensive experience across diverse mechanical sectors, encompassing manufacturing, aerospace, automotive, medical, public transportation, and research industries. Additionally, have demonstrated leadership by spearheading a medical startup as a product development engineer, accomplishing the design of a physical product within a remarkably brief period of three and a half months. Maintaining an unwavering commitment to ongoing learning and knowledge acquisition, I continually embrace challenges within the realm of research.

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