Strength Analysis of Pressure Vessel by Using Finite Element Approach under the Pressure Loading Condition

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Abstract – *The Pressure vessels are critical components used in various industries to contain liquids, gases, or vapors at elevated pressures. Ensuring their structural integrity and resistance to failure is of paramount importance to prevent catastrophic incidents. The primary objective is to assess the structural behavior of the pressure vessel and identify potential weak points or areas of concern that may be prone to failure. The study involves the utilization of advanced computational tools, particularly finite element analysis (FEA), to simulate the complex mechanical behavior of the pressure vessel. The pressure loading conditions, which simulate the operational environments, are applied to the FEA model to evaluate stress distribution, deformations, and potential failure modes. By employing the finite element method, the study provides detailed insights into stress distribution and deformation patterns within the pressure vessel's components. The FEA results are analyzed to determine the critical stress points and regions where excessive deformations or stress concentrations occur. This information is crucial for identifying potential failure sites and for making informed decisions on design modifications or material selection.*

The study's findings contribute to enhancing the safety and reliability of pressure vessels by providing valuable insights into their structural behavior under pressure loading conditions. The finite element approach serves as a powerful tool to predict potential failure modes, guide design improvements, and optimize the overall performance of pressure vessels. Ultimately, this research aids in ensuring the robustness of pressure vessel designs, thereby mitigating risks associated with potential structural failures and contributing to safer industrial operations.

Key Words: Pressure Vessel, Finite Element Analysis, Ansys, ASME, Stress, ASTM A357.

1. INTRODUCTION

Pressure vessels play a crucial role in various industries, containing substances at significantly different pressures than the surrounding environment. They're essential components in industries such as petrochemicals, oil and gas, chemicals, and food processing. Examples include reactors, flash drums, separators, and heat exchangers. Various standards and regulations govern pressure vessels, ensuring their safety and performance. One of the most widely recognized standards is the ASME Boiler and Pressure Vessel Code (BPVC). This code encompasses the design, construction, installation, testing, inspection, and certification of boilers, pressure vessels, and nuclear power plant components. Within the ASME BPVC, Section VIII specifically addresses pressure vessels and is divided into three divisions:

1. Division I:

- Covers pressure vessels designed to operate with internal or external pressures exceeding 15 psig.
- Can include fired or unfired vessels, with pressure derived from external sources or heating.
- Engineers use a design-by-rule approach based on normal stress theory to ensure safety.

2. Division II: Addresses pressure vessels operating at pressures up to 10,000 psig, whether internal or external.

- Requirements for materials, design, and non-destructive examination are more stringent compared to Division I.
- Engineers employ more detailed calculations and a design-by-analysis approach, allowing for higher stress limits based on maximum distortion energy theory.

3. Division III:

- Pertains to pressure vessels operating above 10,000 psig.
- Specifies mandatory requirements and prohibitions for vessels under these extreme pressure conditions.

The API 510 standard is another important guideline in the realm of pressure vessels. The API 510 - Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration focuses on the ongoing maintenance, inspection, repair, and alteration of pressure vessels that are already in operation. Its primary objective is to ensure the safety, reliability, and continued performance of pressure vessels throughout their service life.

2. LITERATURE SURVEY

Niranjana.S. J and Smit Vishal Patel [1] developed a closed container that adheres to ASME standards, determine the necessary thickness of key components such as the shell, head, nozzle, and leg support, and carry out thorough analyses to ensure structural integrity and safety. The project presents a holistic process for designing and analyzing a vertical pressure vessel using ASME codes and finite element analysis (FEA) techniques. Through the combination of meticulous design, precise modelling, and rigorous analysis, the project not only ensures structural soundness but also highlights the effectiveness of employing FEA in modern engineering practices.

E.S. Barboza Neto et al [2] conducted a study to focus on investigating the performance of a pressure vessel liner subjected to burst pressure testing. The liner was comprised of a polymer blend consisting of 95 wt. % low linear density polyethylene (LLDPE) and 5 wt. % high density polyethylene (HDPE). This liner was intended to be an integral component of a composite pressure vessel designed for containing compressed natural gas (CNG), and it was manufactured using a fiber winding process, with varying composite thickness. In conclusion research addressed the experimental and numerical analysis of a polymeric liner for a composite pressure vessel. By conducting hydrostatic tests, utilizing engineering analysis criteria, and employing FEA software, the study aimed to characterize the liner's performance and suitability for use in composite pressure vessels.

Jitendra Pandey and Prof A. K. Jain [3] carried out research on the performance analysis of a pressure vessel using Finite Element Analysis (FEA) with various stiffener designs. The study aimed to enhance the understanding of the behaviour and structural integrity of a transportation pressure vessel that is commonly used for transporting liquid fuels. The analysis was carried out using the ANSYS software package. The study aimed to enhance the understanding of the pressure vessel's behaviour and provide insights into its structural integrity when used for transporting liquid fuels.

Brijesh Kumar Vishwakarma and Amber Gupta [4] worked on the analysis of pressure vessels intended for storage applications. The review sought to examine the design and analysis aspects of pressure vessels used for storing materials under varying pressure and temperature conditions, with a particular emphasis on material selection. The review aimed to provide valuable insights into the design considerations that influence the behavior and performance of pressure vessels used for storing various substances in industrial settings.

Hazizi and ghalish [5] addressed the critical concerns related to the design and manufacturing of pressure vessels, specifically focusing on the safety aspects associated with the storage of hazardous liquids. The research particularly emphasized the increasing global demand for liquefied petroleum gas (LPG) and the need for safer pressure vessels to accommodate this demand. As the number of LPG facilities grows, the requirement for secure pressure vessels becomes paramount to mitigate potential hazards such as explosions and leakage.

3. PRESENT STUDY

The pressure vessel chosen for this study is a pressure vessel used to hold liquefied petroleum gas (LPG). This pressure vessel has elliptical heads and is designed to be used in a fixed location on a leg support. The pressure vessel will have an inner shell diameter of (d) mm and a shell length of (L) mm, as shown in Fig -1. The overall ability of the tank is driven by the design pressure for the required amount of liquid to be stored. The requirement states 10,000 L of LPG, not exceeding maximum pressure of 1.55 MPa.

Present study is concerned to check the structural integrity of the pressure vessel under pressure loads. Static analysis is performed by taking different material and best material is chosen based on the analysis results. The below is the CAD model pressure vessel used for the study

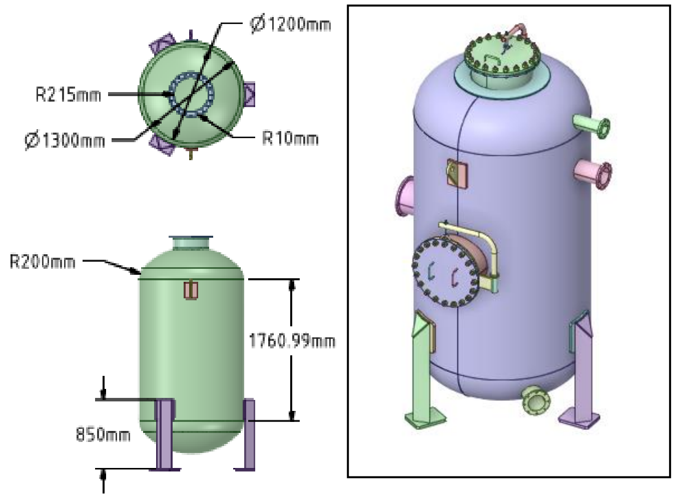

Fig -1: CAD Model of Pressure Vessel

3.1 Material Selection

The study is carried out for three materials SS 304 steel, ASTM A357 steel and Aluminium 3003. The material properties of all the chosen materials are given as shown in the Table -1.

The analysis is performed for all the chosen materials under the static loading condition. Stresses, deformation and Factor of safety is evaluated for both the material and based on safety margins, cost, reliability, availability and safety best material is chosen for further study.

Table -1: Comparison of Material properties

Parameters	SS 304 Steel	ASTM A357	Aluminum 3003
Modulus of Elasticity, GPa	193	200	68.9
Density, kg/m3	8000	7800	2730
Poison ratio	0.29	0.29	0.33
Yield strength, MPa	215	310	185
Ultimate Strength, MPa	505	585	200

4. RESULTS AND DISCUSSION

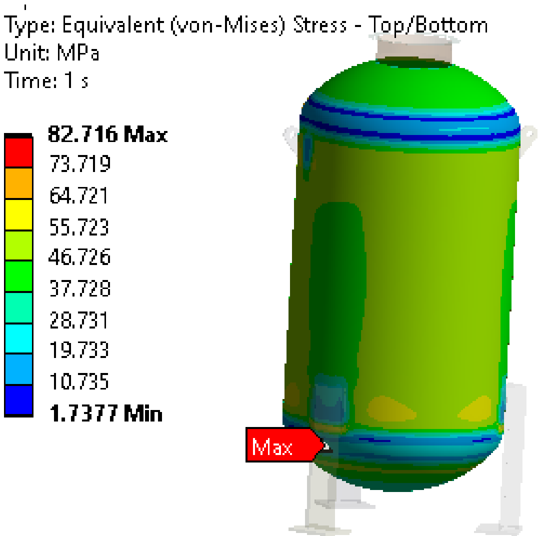

Fig -2: Equivalent stress- SS304 Material

The equivalent stress of 82.7 MPa is observed on the bottom of the pressure vessel for SS304 steel material due to the application of internal pressure of 1.55 MPa. The stresses developed in the pressure vessel are lower than allowable yield strength of the material.

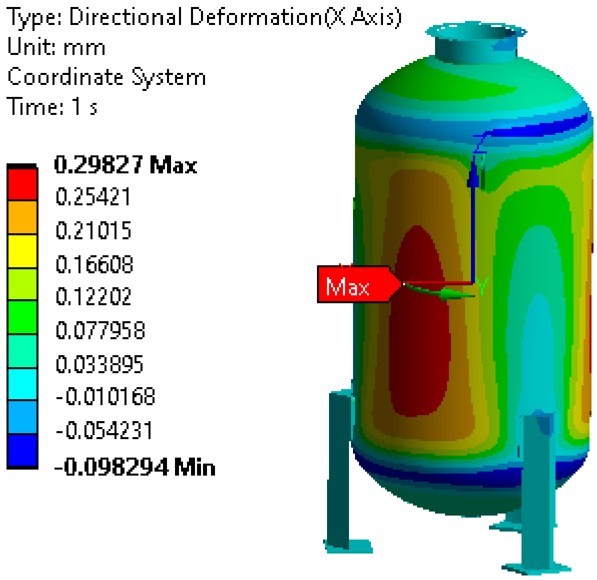

Fig -3: Radial deformation – SS304 Material

The radial deformation of 0.298 mm is observed on the centre of the pressure vessel in the SS 304 steel material due to the application of 1.55 MPa internal pressure.

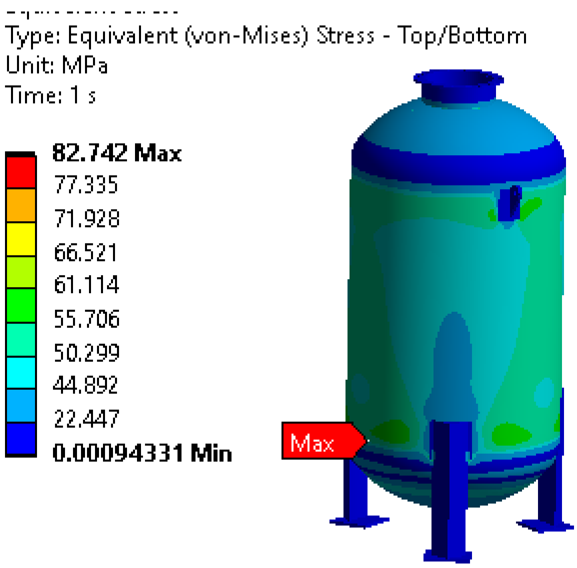

Fig -4: Equivalent stress- ASTM A357

The equivalent stress of 82.7 MPa is observed on the bottom of the pressure vessel for ASTM A357 steel material due to the application of internal pressure of 1.55 MPa. The stresses developed in the pressure vessel are lower than allowable yield strength of the material.

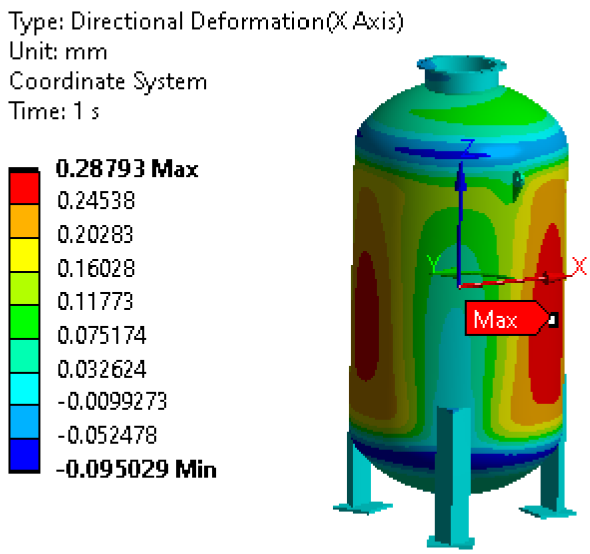

Fig -5: Radial deformation –ASTM A357

The radial deformation of 0.287 mm is observed on the centre of the pressure vessel in the ASTM A357 steel material due to the application of 1.55 MPa internal pressure.

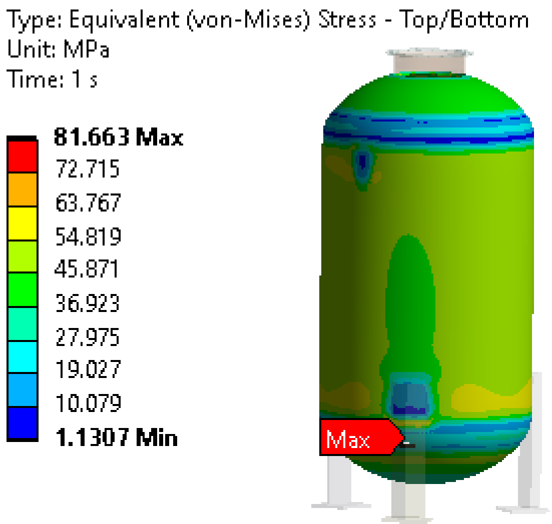

Fig -6: Equivalent stress- Aluminium 3003

The equivalent stress of 81.6 MPa is observed on the bottom of the pressure vessel for Aluminium 3003 material due to the application of internal pressure of 1.55 MPa. The stresses developed in the pressure vessel are lower than allowable yield strength of the material.

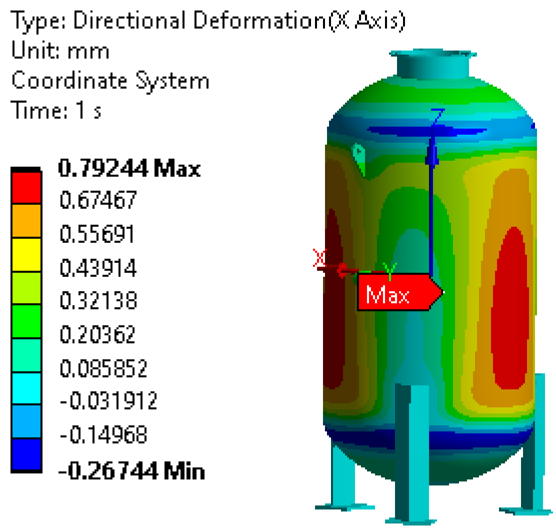

Fig -7: Radial deformation –Aluminium 3003

The radial deformation of 0.792 mm is observed on the centre of the pressure vessel in the Aluminium 3003 material due to the application of 1.55 MPa internal pressure.

Table -2: Comparison of all three Material properties

Parameters	SS 304 Steel	ASTM A357	Aluminum 3003
Modulus of Elasticity, GPa	193	200	68.9
Density, kg/m3	8000	7800	2730
Poison ratio	0.29	0.29	0.33
Yield strength, MPa	215	310	185
Ultimate Strength, MPa	505	585	200
Stress	82.7	82.7	81.6
Deformation	0.298	0.287	0.792
Cost Per Kg	125	75	260
Total Cost	196375	114877.5	139386
FOS for static	2.6	3.7	2.3

The analysis is performed for all three materials under the static loading condition. Stresses, deformation and Factor of safety is evaluated for all the material and based on factor of safety and cost ASTM A357 material chosen.

4.1 Validation of FEA results by Analytical Method

The analytical calculations are carried out by using strength of material approach to validate the results of Simulation done from Ansys. Pressure vessel of thickness 18mm and internal diameter 1300mm is subjected to the internal pressure of 1.55MPa. If Diameter to thickness ratio is greater than20 the cylinder will fall in thin cylinder category. For present case diameter to thickness ratio is 72 which come under thin cylinder category. Circumferential and longitudinal stresses are calculated by using thin theory approach as below

Circumferential Stress

The formula for circumferential stress can be written as following.

σ_c= (PXd)/2Xt MPa……………………….Equation 1

Where:

σ_c = Circumferential/Hoop stress

P = Design pressure

d = Internal diameter

t = Wall thickness

Longitudinal Stress

The formula for longitudinal stress can be written as following.

σ_L= (PXd)/4Xt MPa……………………….Equation 2

Where:

σ_L = Longitudinal stress

P = Design pressure

d = Internal diameter

t = Wall thickness

Table -3: Results of Analytical calculation of stress

Pressure, MPa	1.55
Diameter, mm	1300
Thickness, mm	18
Circumferential Stress, MPa	56
Longitudinal Stress, MPa	28

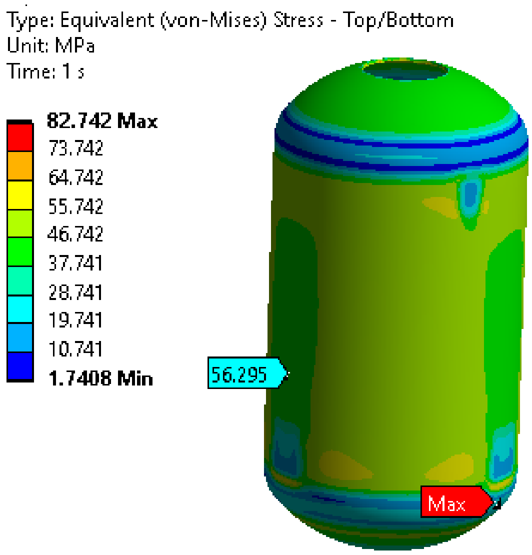

Fig -8: Equivalent Stress Plot of pressure vessel

The equivalent stress of 56.2 MPa is observed on the centre of the pressure vessel under inside acting pressure of 1.55MPa. The results from the simulation are very close to the stresses from analytical approach.

Table -4: FEA and Analytical Results Comparison

Parameters	Stress, MPa
FEA Results	56.2
Analytical approach Results	56
Difference in percentage	0.36

The stresses calculated from analytical calculation is 56MPa are close to the stresses of 56.2 MPa observed from the simulation. Hence it validates the simulation results are in agreement with the analytical results.

5. CONCLUSIONS

Meticulous investigation was conducted to ensure the robustness and efficiency of the pressure vessel design. The process encompassed comprehensive material comparison study was undertaken, assessing SS 304 steel, ASTM A357, and Aluminium 3003. The subsequent analysis involved evaluating all three materials under static loading conditions, wherein stresses, deformations, and the factor of safety were rigorously examined. After a comprehensive evaluation that considered both safety and cost factors, ASTM A357 was chosen as the preferred material.

To assess the structural integrity of the pressure vessel, simulations were conducted using ANSYS Workbench. The static structural analysis revealed significant equivalent von

Mises stresses, maximum principal stresses, and maximum shear stresses, all of which surpassed the yield strength of the material. With the current design thickness yielding a factor of safety of approximately 3.5, The thorough evaluations conducted throughout this study ensure that the pressure vessel design not only meets safety and performance requirements but also undergoes meticulous scrutiny to achieve optimal results in real-world applications.

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