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DESIGN AND ANALYSIS OF LPG CYLINDER

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Abstract – LPG cylinder is a kind of pressure vessel that requires high tensile and compressive strength to store pressurised gases. This study aims at reduction of weight of Liquid petroleum gas cylinder. The commonly used material for the manufacturing of LPG cylinder is steel. But the steel is heavier and has got some safety problems. In addition to this the steel progressively corrodes. So there arises a need to rectify these problems using some other alternatives. In this journal different alternatives are examined and an appropriate material is selected. The finite element analysis of Liquefied Petroleum Gas (LPG) cylinders made of Steel, Aluminium 6061T6 alloy, Aluminium 5052-H38 alloy has been carried out. The models are made in CATIA V5 R20 and are imported to ANSYS. Finite element analysis of cylinder subjected to internal pressure is performed. The analysis done in ANSYS is compared with classical mathematical formulations. Calculations are performed to determine the weight of the cylinders and the least weighed material is chosen for the new LPG cylinder. The cost estimation is also performed to check the economic viability of the new LPG cylinder.

Keywords: LPG cylinder, Steel, Al 6061 T6, Al 5052-H38, ANSYS, CATIA

1. Introduction

Liquefied Petroleum Gas, LPG (propane or butane) is a colour less liquid which readily evaporates into a gas. It is used as a fuel in heating appliances and vehicles. It is now increasingly used as an aerosol propellant and a refrigerant, replacing chlorofluorocarbons in an effort to reduce damage to the ozone layer. LPG is composed of the following hydrocarbons: propane, propylene, butane or butylene. LPG is stored and handled as a liquid when under pressure inside a LPG gas container. When compressed moderately at normal temperature, it becomes liquid. When gas is withdrawn, the pressure drops and the liquid reverts to gas. This means that it can be transported and stored as liquid and burnt as gas.

LPG is odourless but a stench agent is added to assist in its detection in case of leakage. The odourant used in LPG is ethyl mercaptan, which owns a distinctive and unpleasant odour. Ethyl mercaptan is selected because it is non-corrosive, has low sulphur content and possesses a boiling point very near that of LPG.

Jaroslav Mackerle [1] gives finite element methods (FEMs) applied for the analysis of pressure vessel structures and piping from the theoretical as well as practical. E.0. Bergman [2] states that the external loads applied to vertical pressure vessels produce axial loading and bending moments on the vessel. The design method to be used depends on whether the longitudinal stress in the shell is tension or compression, and on whether the vessel is subjected to internal or external pressure. Design procedures for pressure vessel by H. Mayer, H.L.Stark and S. Ambrose [3] concludes that practical difficulties arise for the designer in the fatigue analysis of welds in pressure vessels. Kumar.S and B. Pradhan [4], studied about the safety aspects FRP cylinder and they noted that FRP cylinders are having greater strength compared to that of ordinary steel cylinders. They concluded that FRP gas cylinders doesn't explode (Leak before fail approach) due to porosity formation of materials. Levend Parnas and Nuran Katirci, [5] analytical procedure is developed to design and predict the behaviour of fiber-reinforced composite pressure vessels under combined mechanical and hydrothermal loading. Yogesh Borse and Avadesh K. Sharma [6] present the finite element modelling and Analysis of Pressure vessels with different end connections i.e. Hemispherical, Ellipsoidal & Toro spherical. T.Ashok and A. Harikrishna [7] studied about the stresses and deformations due to pressure loadings inside a composite cylinder. Finite element analysis of glass fibre cylinder is carried out. From their studies significant weight savings were obtained for the GFRP cylinder. The variations in the stress and deformations values according to the fibre orientation were are studied.

1.1 Low carbon steel cylinder

The steel cylinders are manufactured either in two piece or three piece construction as shown in Fig.1. Body parts of a cylinder are explained in this Fig.1. In two piece construction, cylinders are fabricated by welding two domed ends directly together. A three piece cylinder is fabricated by joining two domed ends to a cylindrical body. The domed ends can be tori-Spherical, Semi ellipsoidal or Hemi-spherical in shape as shown in Fig.2

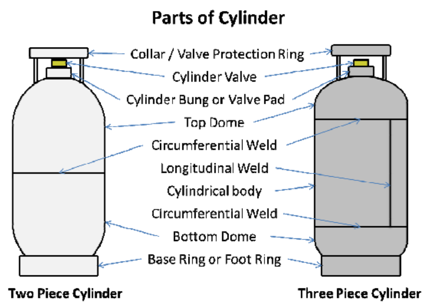

Fig.1 Parts of Cylinder

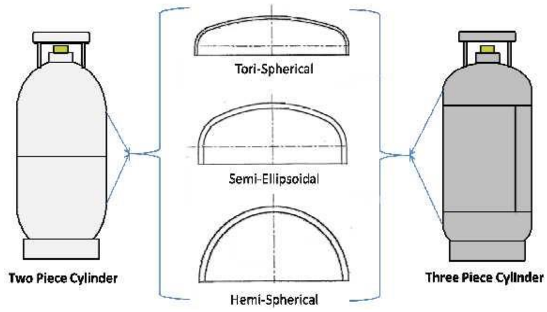

Fig.2 Types of domes in two and three piece cylinder

1.2 Aluminium alloy 6061-T6 cylinder

This is the least expensive and most versatile of the heat-treatable aluminium alloys. It has most of the good qualities of aluminium. It offers a range of good mechanical properties and good corrosion resistance. It can be fabricated by most of the commonly used techniques. In the annealed condition it has good workability. It is welded by all methods and can be furnace brazed. It is available in the clad form ("Alclad") with a thin surface layer of high purity aluminium to improve both appearance and corrosion resistance.

6061 is highly weldable, for example using tungsten inert gas welding (TIG) or metal inert gas welding (MIG). Typically, after welding, the properties near the weld are those of 6061-O, a loss of strength of around 80%. The material can be re-heat-treated to restore -T4 or -T6 temper for the whole piece. After welding, the material can naturally age and restore some of its strength as well.

1.2.1 Use of aluminium 6061-T6

a) Construction of aircraft structures, such as wings and fuselages
b) Yacht construction, including small utility boats.
c) Automotive parts, such as wheel spacers and scuba divers.
d) The manufacture of aluminium cans for the packaging of foodstuffs and beverages.

1.3 Aluminium 5052 H38 cylinder

This is the highest strength alloy of the more common non heat-treatable grades. Fatigue strength of aluminium 5052 h38 is higher than most aluminium alloys. In addition this grade has particularly good resistance to marine atmosphere and salt water corrosion. It has excellent workability. It may be drawn or formed into intricate shapes and its slightly greater strength in the annealed condition minimizes tearing that occurs in 1100 and 3003

1.3.1 Applications

a) Used in a wide variety of applications from aircraft components to home appliances, Marine and transportation industry parts.

b) Heavy duty cooking utensils equipment for bulk processing of food.

2. Design calculations and analysis

2.1 Low carbon steel cylinder

The currently used material for LPG cylinder is low carbon steel .The low carbon steel cylinder is designed according to the Indian Standards (IS 3196)

2.1.1 Thickness required for steel cylinder considering internal pressure

Material – IS 3196 /HR (Low carbon steel)

t=thickness of the cylinder

σ_t – Yield strength of low carbon steel - 250MPa

D_i = Internal diameter = 314.4mm

P_i = internal pressure = 25kgf/mm^2

2.1.2 Thickness required for the cylindrical portion

$$t = \frac{P_i D_i}{2\sigma_t} = \frac{1.2*314.4}{2*250} = 0.754 \text{ mm} \tag{1}$$

2.1.3 Thickness required for the end dome

$$t = \frac{P_i D_i}{4\sigma_t} = \frac{1.2 * 314.4}{4 * 250} = 0.37725mm \tag{2}$$

Taking greater among the both, t = $0.75456mm$

2.1.4 Thickness required for steel cylinder considering internal & external pressure

$$t = \frac{P_h D_i}{(200 * 0.8 * J * R_e) - P_h} \quad \text{(IS 3196)} \tag{3}$$

Where,

P_h = Test pressure = 25kgf/mm^2

J = Weld joint factor = 0.9 (for non-radiographed welded joint)

R_e = Yield strength = 250MPa = 25.48kgf/mm^2

$$\therefore t = \frac{25 * 314.4}{(200 * 0.8 * 0.9 * 25.48) - 25} = 2.156mm$$

2.1.5 Additional thickness requirement

Corrosion allowance = 0.2mm

Transportation allowance =0.1mm

2.1.6 Total thickness requirements

Total thickness t = thickness + allowances

$\therefore t = 2.156 + 0.2 + 0.1 = 2.456mm \therefore t \cong 2.5mm$

2.1.7 Stress calculation for steel cylinder

Longitudinal stress

$$\sigma_L = \frac{P_i D_i}{4t} = \frac{1.2 * 314.4}{4 * 2.5} = 37.728MPa \tag{4}$$

Hoop stress

$$\sigma_H = \frac{P_i D_i}{2t} = \frac{1.2 * 314.4}{2 * 2.5} = 75.45MPa \tag{5}$$

Von-mises stress

$$\sigma_V = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \tag{6}$$

$$= \sqrt{37.23^2 + 75.46^2 - (37.73 * 75.46)} = 65.05\ N/mm^2$$

Longitudinal Deformation

$$\delta = \frac{Pr^2(1-\vartheta)}{2Et} \tag{7}$$

$$= \frac{1.2 * \left(\frac{314.4}{2}\right)^2 * (1-0.3)}{2 * 2.5 * 207 * 10^3} = 0.02mm$$

2.1.8 Volume of steel cylinder

r_o= outer radius of the cylinder

r_i = internal radius of the cylinder

h = height of the cylindrical portion

V = volume of the cylinder

Volume of cylindrical portion = $\pi h(r_o^2 - r_i^2)$ (8)

$$V_{cyl} = \pi * 368 * \left[\left(\frac{319.4}{2}\right)^2 - \left(\frac{314.4}{2}\right)^2\right] = 915925.05mm^3$$

Volume of spherical portion

$$V_{sp} = \frac{4}{3} * \pi * (r_o^3 - r_i^3) \tag{9}$$

$$= \frac{4}{3} * \pi * \left[\left(\frac{319.4}{2}\right)^3 - \left(\frac{314.4}{2}\right)^3\right] = 788757.26mm^3$$

Total volume of the steel LPG cylinder

$$= 915925.05 + 788757.26 = 1704682.31\ mm^3$$

2.1.9 Mass of steel LPG cylinder

Mass of steel LPG cylinder = density of the cylinder * volume of the cylinder

Density of IS 3196 low carbon steel = $7850\ kg/m^3$

Volume of steel LPG cylinder = $1704682.31 * 10^{-9} m^3$

$\therefore$ mass of steel cylinder $= 7850 * 1704682.31 * 10^{-9} = 13.38\ kg$

$\therefore$ the weight of steel cylinder without considering VP ring, valve, bung, foot ring and coatings = 13.38kg

2.1.10 Modelling of steel cylinder

The cylinder is modelled in CATIA V5 R20 the cylinder is modelled for a thickness of 2.5mm.

2.1.11 Analysis of steel cylinder

The analysis of the cylinder is carried out in ANSYS 14.5. The various stages in the ANSYS analysis are described below.

1. The static structural analysis is performed for the steel cylinder. In the static structural analysis the default engineering data is of structural steel. The modifications required for low carbon steel is made by editing the static structural part.
2. Discretization: the LPG gas model divided into no. of parts using triangular elements. Depending upon the requirements of accuracy of result of fitness of mesh was varying. More finer was the mesh more accurate were the results. The mesh size used for the analysis of the cylinder is 0.01mm.
3. In the "Setup" the foot ring is assigned as fixed support, and internal pressure is given by hiding the lateral surface of the cylinder. Here foot ring is assigned as the fixed support since it is an external part attached to the cylindrical shell portion and is not subjected to any internal pressure.

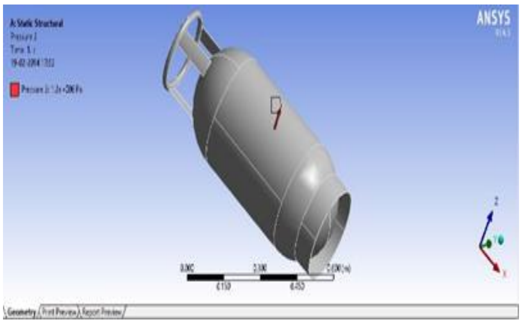

Fig 3: Pressure applied

4. In the "Solution" longitudinal deformation, hoop stress, longitudinal stress, shear stress and von-mises stress are selected for analysis.

5. The result is obtained by updating the results.

From the analysis performed in the ANSYS the results are obtained as shown in the figure

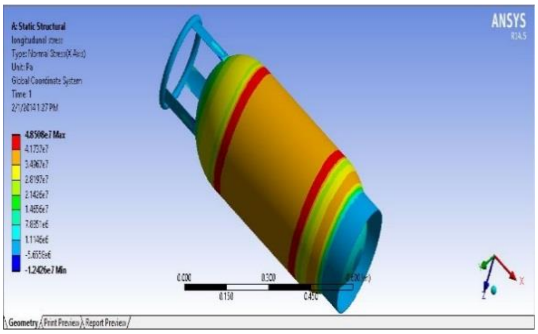

Fig 4: Longitudinal stress

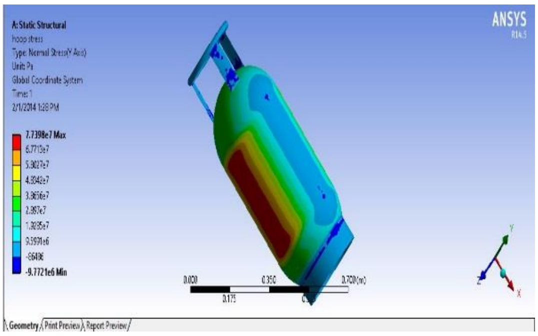

Fig 5: Hoop stress

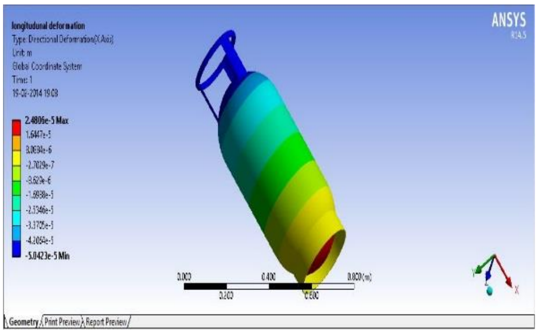

Fig 6: Longitudinal deformation

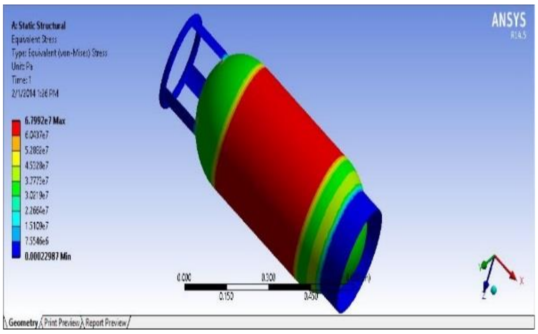

Fig 7: Von-mises stress

2.1.12 Cost estimation

Approximate cost of low carbon steel cylinder will be = Rs 1132

2.2 Aluminium 6061 T6 alloy cylinder

2.2.1 Thickness requirement considering internal pressure

Material – Al 6061 T6 alloy
σ_t – Yield strength Aluminium 6061 T6 alloy - 280MPa
Thickness required for the cylindrical portion

$$t = \frac{P_i D_i}{2\sigma_t} = \frac{1.2 * 314.4}{2 * 280} = 0.674mm \tag{10}$$

Thickness required for the end dome

$$t = \frac{P_i D_i}{4\sigma_t} = \frac{1.2 * 314.4}{4 * 280} = 0.336\ mm \tag{11}$$

Taking greater among the both, t = 0.674mm

2.2.2 Thickness requirement considering internal & external pressure

The thickness equation considering both the internal and external pressure is given as

$$t= \frac{D_i}{2}\left[1-\sqrt{\frac{10FZR_e-\sqrt{3}*P_h}{10FZR_e}}\right] \qquad [ISO\ 7866] \qquad (12)$$

Where,

P_h = Hydrostatic test pressure in bar above atmospheric pressure = 60 bar
D_i = Internal diameter of the cylinder = 314.4mm
R_e = Yield strength = 279MPa
R_g = Ultimate strength=310 MPa
Z= Stress reduction factor = 1
F is the value lesser among $\frac{1.65}{R_e/R_g}$ and 0.95

$\frac{1.65}{R_e/R_g} = \frac{1.65}{279/310}$ = 1.876

Therefore *F* will be the value lesser among 1.876

$$\therefore F = 0.95$$

$$\therefore t = \frac{314.4}{2}\left[1-\sqrt{\frac{10*0.95*1*279-\sqrt{3}*\ 60}{10*0.95*1*279}}\right] = 3.08mm$$

2.2.3 Stress calculation for Al 6061 T6 alloy cylinder

Young's modulus, E =71 GPa
Thickness of cylinder = 3.1mm

Longitudinal stress

$$\sigma_L = \frac{P_iD_i}{4t} = \frac{1.2*314.4}{4*3.1} = 30.43MPa \qquad (13)$$

Hoop stress

$$\sigma_H = \frac{P_iD_i}{2t} = \frac{1.2*314.4}{2*3.1} = 60.85MPa \qquad (14)$$

Von-mises stress

$$\sigma_V = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \qquad (15)$$

$$= \sqrt{30.43^2 + 60.85^2 - (30.43 * 60.85)} = 52.69\ N/mm^2$$

Longitudinal Deformation

$$\delta = \frac{Pr^2(1-\vartheta)}{2Et} \tag{16}$$

$$= \frac{1.2 * \left(\frac{314.4}{2}\right)^2 * (1-0.33)}{2 * 3.1 * 71 * 10^3}$$

$$= 0.0451mm$$

2.2.4 Calculation of volume of Al 6061 T6 cylinder

Volume of cylindrical portion

$$V_{cyl} = \pi h(r_o^2 - r_i^2) \tag{17}$$

$$V_{cyl} = \pi * 368 * \left[\left(\frac{320.6}{2}\right)^2 - \left(\frac{314.4}{2}\right)^2\right] = 1137897.43\ mm^3$$

Volume of spherical portion,

$$Vsp = \frac{4}{3} * \pi * (r_o^3 - r_i^3) \tag{18}$$

$$V_{sp} = \frac{4}{3} * \pi * \left[\left(\frac{320.6}{2}\right)^3 - \left(\frac{314.4}{2}\right)^3\right] = 981776.94\ mm^3$$

Total volume of the aluminium 6061 T6 LPG cylinder

$$= 1137897.43 + 981776.94 = 2119674.37\ mm^3$$

2.2.5 Calculation of mass of Al 6061 T6 cylinder

Mass of aluminium alloy LPG cylinder = density of the cylinder * volume of the cylinder
Density of Al6061 T6 cylinder = $2770\ kg/m^3$
Volume of Al6061 T6 cylinder = $2119674.37 * 10^{-9} m^3$
∴ mass of aluminium 6061 T6 cylinder = $2680 * 2119674.37 * 10^{-9} = 5.87\ kg$

The weight of Al 6061 T6 cylinder without considering the foot ring, VP ring, valve, bung, foot ring and coatings =5.87 kg

The ansys analysis results obtained is shown below

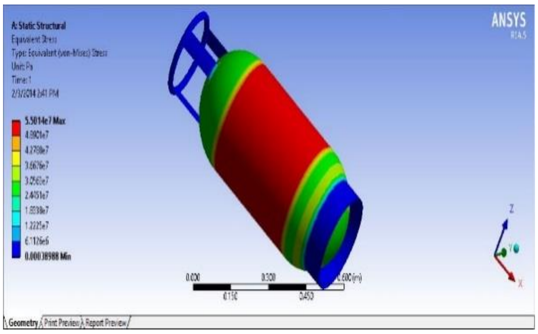

Fig 8: Equivalent stress

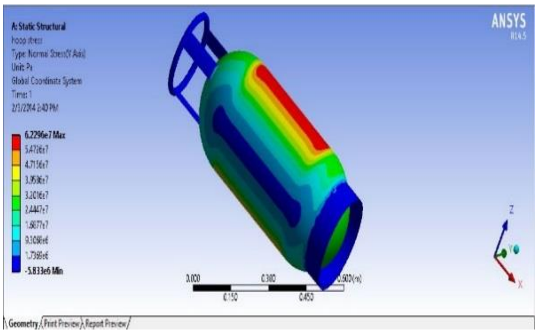

Fig 9: Hoop stress

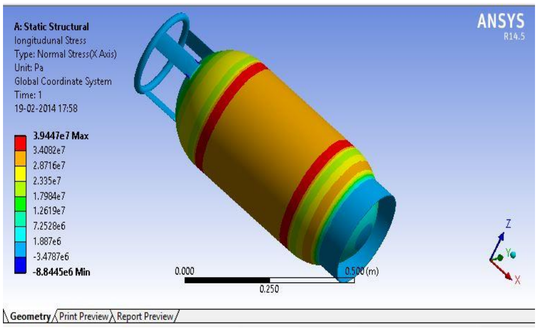

Fig 10: Longitudinal stress

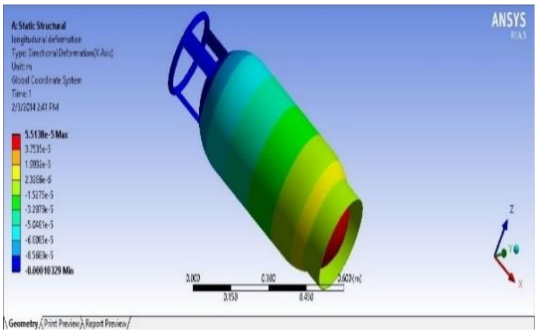

Fig 11: Longitudinal deformation

2.2.6 Cost estimation

Approximate cost of aluminium 6061 t6 cylinder will be = Rs 1356

2.3 Aluminium 5052 H38 alloy cylinder

2.3.1 Thickness requirement considering internal pressure

Thickness required for the cylindrical portion

$$t = \frac{P_i D_i}{2\sigma_t} = \frac{1.2 * 314.4}{2 * 255} = 0.73976mm \quad (19)$$

Thickness required for the end dome

$$t = \frac{P_i D_i}{4\sigma_t} = \frac{1.2 * 314.4}{4 * 255} = 0.3698mm \quad (20)$$

Taking greater among the both, t = 0.7397mm

2.3.2 Thickness required for Al 5052 – H38 alloy considering internal & external pressure

$$t = \frac{D_i}{2}\left[1 - \sqrt{\frac{10FZR_e - \sqrt{3} *\ P_h}{10FZR_e}}\right] \tag{21}$$

where,

P_h = Hydrostatic test pressure in bar above atmospheric pressure = 60 bar

D_i = Internal diameter of the cylinder = 314.4mm

F = Value lesser among $\frac{1.65}{R_e/R_g}$ and 0.95

here,

R_e = Yield strength = 255MPa

R_g = 290 MPa

$$\therefore \frac{1.65}{R_e/R_g} = \frac{1.65}{255/290} = 1.876$$

$$\therefore F = 0.95$$

Z= Stress reduction factor = 1

$$= \frac{314.4}{2}\left[1 - \sqrt{\frac{10 * 0.95 * 1 * 255 - \sqrt{3} *\ 60}{10 * 0.95 * 1 * 255}}\right] = 3.4mm$$

2.3.3 Stress calculation for Al 5052 H38 alloy cylinder

Young's modulus, E =70.3Gpa

Thickness of cylinder = 3.4mm

Longitudinal stress

$$\sigma_L = \frac{P_i D_i}{4t} = \frac{1.2 * 314.4}{4 * 3.4} = 27.74MPa \tag{22}$$

Hoop stress

$$\sigma_H = \frac{P_i D_i}{2t} = \frac{1.2 * 314.4}{2 * 3.4} = 55.48MPa \tag{23}$$

Von-mises stress

$$\sigma_V = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \tag{24}$$

$$= \sqrt{27.74^2 + 55.48^2 - (27.74 * 55.48)} = 48.05\ N/mm^2$$

Longitudinal Deformation

$$\delta = \frac{Pr^2(1-\vartheta)}{2Et} \tag{25}$$

$$= \frac{1.2 * \left(\frac{314.4}{2}\right)^2 * (1-0.33)}{2 * 3.4 * 70.3 * 10^3} = 0.041mm$$

2.3.4 Volume of Al 5052 H-38 cylinder

$$\text{Volume of cylindrical portion} = \pi h(r_o^2 - r_i^2) \tag{26}$$

$$V_{cyl} = \pi * 368 * \left[\left(\frac{321.2}{2}\right)^2 - \left(\frac{314.4}{2}\right)^2\right] = 1249195.759\ mm^3$$

$$\text{Volume of spherical portion} = \frac{4}{3} * \pi * (r_o^3 - r_i^3) \tag{27}$$

$$V_{sp} = \frac{4}{3} * \pi * \left[\left(\frac{321.2}{2}\right)^3 - \left(\frac{314.4}{2}\right)^3\right] = 1078830.323\ mm^3$$

Total volume of the aluminium 5052 H38 cylinder

$$1249195.759 + 1078830.32 \ = \ 2328026.08 \, mm^3$$

2.3.5 Mass of Al 5052 H38 cylinder

Mass of Al5052 H38 cylinder = density of the cylinder * volume of the cylinder

Density of Al5052 H38 cylinder = 2680 kg/m^3

Volume of Al5052 H38 cylinder $= 2328026.082 * 10^{-9} m^3$

$\therefore$ Mass of Al5052 H38 cylinder $= \ 2680 * 2328026.082 * 10^{-9} = 6.2391 \, kg$

$\therefore$ The weight of Al5052 H38 cylinder without considering VP ring, valve, bung, foot ring and coatings $= 6.2391$kg

the ansys analysis results obtained is shown below

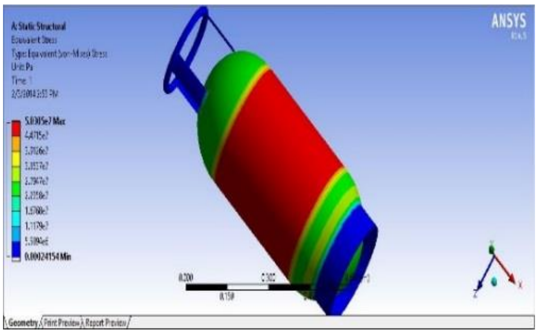

Fig 12: Equivalent stress

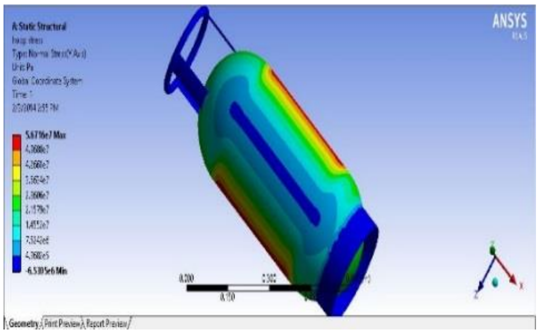

Fig 13: Hoop stress

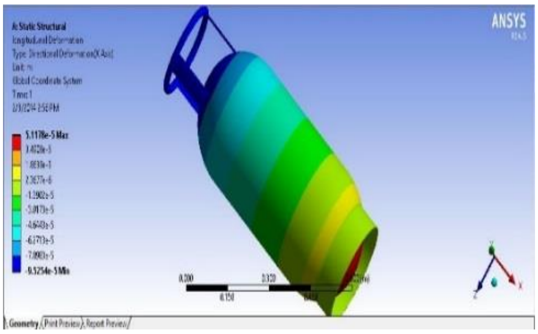

Fig 14: Longitudinal deformation

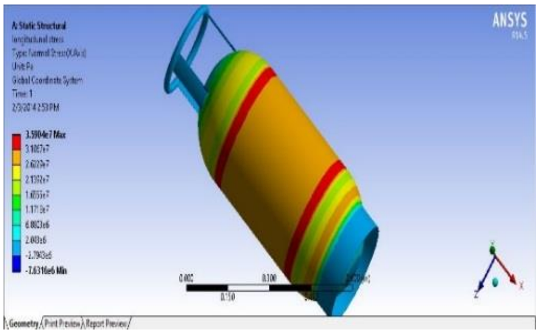

Fig 15: Longitudinal stress

2.3.6 Cost estimation

Approximate cost of aluminium 5052 H38 cylinder will be = Rs 1278

2.4 Result

The results obtained from the ansys analysis of the various cylinders is given in the following table.

Table 1: Ansys Analysis Results

Cylinder	Ansys results			
	Longitudinal stress	Hoop stress	Von-mises stress	Longitudinal deformation
steel cylinder	48.50 MPa	77.39 MPa	67.99 MPa	0.02 mm
Al 6061 T6 cylinder	39.44 MPa	62.29 MPa	55.01 MPa	0.05 mm
Al 5052 H38 cylinder	35.9 MPa	56.71 MPa	50.30 MPa	0.05 mm

2.5 Conclusion

From the analysis both aluminium alloys are suitable for replacing steel cylinders these cylinders would withstand more stress compared to the steel cylinder. The life time of these cylinders will be double compared to the steel cylinder because of their less corrosion rate.

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