Design and Analysis of a Composite Cylinder for the Storage of Liquefied Gases

A Tripathi[1] Anil Kumar[2] M.K. Chandrakar[3]
[1,2,3]Department of Mechanical Engineering
[1,2,3]Govt. Engineering College Raipur (C.G.), India

Abstract— In recent years there has been an increasing demand from the core industries for the materials possessing high strength to weight ratio. Fiber reinforced composite is one of the latest material posses this property. This paper aims is innovation of alternative materials of Liquid petroleum gas (LPG) cylinder. An LPG cylinder of composite materials is designed and analysis is done using ANSYS software and the comparison is made with existing steel cylinder, on the basis of displacement and Stress produced due to the application of internal pressure to the cylinder. To validate the model the results of stresses and deformation for steel cylinders are compared with the analytical solution available in literature. It was observed that besides less weight, stresses are also less for composite compared to steel cylinder.

Key words: MFRP, FRP, Von-Mises stress, Displacement

I. Introduction

A. *Liquefied Petroleum Gas (LPG)*

LPG (propane or butane) is a colorless liquid which readily evaporates into a gas. It has no smell, although it will normally have an odour added to help detect leaks. When mixed with air, the gas can burn or explode when it meets a source of ignition. It is heavier than air, so it tends to sink towards the ground. LPG is a mixture of commercial butane and commercial propane having both saturated and unsaturated hydrocarbons, Liquefied petroleum gas (LPG),used as domestic cooking gas in around 40% houses of India is a mixture of hydrocarbons . As per government definition “liquefied petroleum gas” means any material that comprises predominantly of any of the following hydrocarbons or mixture of them with vapor pressure not exceeding 16.87 kg/cm^2 (gauge) at 65^{0}C – propane (C_3H_8), propylene(C_3H_6), butane(C_4H_{10}) and butylene (C_4H_8). Domestic cooking gas has a very high energy content (calorific value = 46.1 MJ/KG). LPG is a low carbon emitting hydrocarbon fuel, emitting 19% less CO_2 per kWh than oil and 30% less than coal. The gas can be liquefied at moderate pressure, and can be stored in cylinders as a liquid under pressure and is drawn out and used as gas. This means that it can be transported and stored as liquid and burnt as gas. The expansion ratio of gas from liquid is 270:1 at atmospheric pressure. It is this expansion factor which makes LPG more economical to transport and store large quantities of gaseous fuel in a small container in liquid state. LPG inside a container is in two states of matter, liquid and vapour. The liquid portion of container is in the bottom and the vapour is in the uppermost part of the vessel, i.e. the space above the liquid level. Containers are normally filled 80-85% liquid, leaving a 15-20% vapour space for expansion due to temperature increase.

LP-gas is odorless and non-toxic. A distinct smelling odourant such as ethyl mercaptan is added as a detection agent for all domestic, and for most commercial and industrial LP-gas. The purpose is to introduce sufficient odourant so that the presence of unburnt gas can be readily detected before it reaches a mixture that is flammable and comes in contact with a source of ignition.

B. *Liquefied Petroleum Gas (LPG) Cylinders*

LPG is supplied in pressurized cylinders to keep it liquefied. The LPG (Liquefied Petroleum Gas) Cylinders (fig.1.1), from past many years, are being manufactured in our country from the very conventional metallic material such as steel. The weight of an empty LPG cylinder is called tare weight which is equal to 15.3 kg and it is found printed on the cylinder. Normally a filled cylinder of LPG contains 14.2 kg of gas. The weight of a domestic LPG cylinder that is filled is the sum of the tare weight and weight of LPG in the filled cylinder. So the total weight is 29.5 Kg.

The weight of the cylinder becomes more as density of steel is higher compared to other light weight materials. In household applications, thrust should be given towards use of low density materials so that the weight will come down. With the advancement of low-density materials like Fiber Reinforced Composites, we can think of producing LPG cylinders with composite materials to reduce its weight.

C. *Composite Materials*

Unlike aerospace applications, where weight reduction of a component is of prime requirement, in commercial household applications, reliability/safety as well as weight of the component is given more importance. Keeping the issue of reliability and weight in view, the high-end composite material technology can very well be implemented in design of household LPG cylinders. Any pressure vessel made of metallic materials has a major drawback of severe bursts in worst cases. For example, when gas cylinders catch fire, it explodes heavily creating danger for its users. Whereas, composite gas cylinders doesn’t explode (Leak before fail approach) due to porosity formation of materials. Due to formation of leakage through the thickness, the flames simply start coming out slowly, which is a fail-safe design approach.

D. *History of Composite materials in LPG cylinders*

Bhandavi and Rao [1] established superiority of fiber reinforced plastic over steel. They carried out finite element analysis of composite cylinder and steel cylinder subjected to internal pressure and concluded that the weight of LPG cylinder can be seven enormously by using FRP composites and the stress value are also well within the limit of capability of materials. This gives clear justification for its use in household applications. Ashok and Harikrishna, (2013), stressed in the innovation of alternative materials of liquid petroleum gas (LPG) they carried out elemental analysis of liquid petroleum gas (LPG) made of steel and fiber reinforced plastics(FRP) composite. They used FE analysis package ANSYS to model the shell with FRP composites. They compared weight and variations of stress and deformation for steel, Glass Fiber Reinforced Plastics composites LPG cylinders. Ramkrishna et al. [2] described about the manufacturing of liquefied petroleum gas cylinders their testing under stringent norms before they get certified by Bureau of Indian Standards (BIS) for market use. They mentioned that Cylinders produced on batch from row material specified in Indian Standard and tested before dispatching to market. Rashmi Rekha and Himanshu Shekhar [3] in their article introduce the concept of lighter and transparent fiber glass to be used in domestic cooking gas cylinder. They mentioned that a see through, light weight, safe, eye-catching, environmental friendly cooking gas cylinder made of fiber glass will be an asset for the kitchen of the future. Composite gas cylinder apart from imparting maximized strength and optimized safety, also offer additional advantages like non-corrosive construction, high strength weight ratio, light weight and explosion proof fabrication making this an obvious alternate cooking gas cylinder. Shaikh and Mistry [4] has designed glass fiber reinforced plastic pressure vessel, subjected to internal design pressure of 1.089 kg/cm^2 in accordance with the procedure set out in ASME section A-Design rules. Destructive testing was done to find out the modulus of elasticity and flexural modulus. Corigliano et al. [5] presented results of an experimental and numerical investigation on the mechanical behavior of a composite sandwich primarily designed for naval engineering applications. The skins of the sandwich are made of glass fiber / polymer matrix composits; their interior layers are connected with interwoven threads called piles which cross the sandwich core such core consist of syntactic foam made by hollow glass microsphers embaded in an epoxy matrix. Lakshmi nair [6] did material characterization of FRP of carbon T300/Epoxy for various configurations as per ASTM standards. The design of Laminated Pressure Vessel is described in detail. Netting analysis is used for the calculation of hoop and helical thickness of the Pressure Vessel. A balanced symmetric ply sequence for carbon T300/epoxy is considered for entire Pressure Vessel. Progressive failure analysis of composite Pressure Vessel with geodesic end dome is carried out. The results can be utilized to understand structural characteristics of filament wound Pressure vessels. Sayman [7] develop an explicit analytical formulation anisotropic elasticity theory that determines the behaviour of fibre reinforced composite pressure vessel under hydrothermal loading. The loading is studied for three cases separately which are plain strain case, free ends and pressure vessel cases. He observed that for free ends and pressure vessel cases the vessel is free to expand on the other hand for plain strain case the vessel is prevented to expand. Raju and Rao [8], did design analysis of fiber reinforced multilayered composite shell with optimum fiber orientations; minimum mass under strength constraints for a cylinder under axial loading for static and buckling analysis of pressure vessel has been studied.

II. PROBLEM STATEMENT

LPG is almost the twice the weight of the air it tends to settle down at floor level, particularly in depressions. Hence, care has to be taken in placing the gas installations in the house. Also the fact that 1 cubic centimeter of liquid LPG expand to about 270 cubic centimeters of gaseous LPG , helps it spread very rapidly in the atmosphere.

Hoop Stress, σ_h = (PD)/2t Axial Stress, σ_a =(PD)/4t

Where,

P=Internal Pressure, d= Internal Diameter,
D=External Diameter, t=Thickness.

The design of pressure vessel is entirely reliant upon mechanics of materials. Prediction of the ultimate tensile strength of the design vision is various failure theories. When a building a pressure vessel out of composite materials, some the theories employed to optimize the strength and predict are the "Von-misses theory" and maximum stress and strain theory. The force applied the in the different direction of the pressure vessel are directly related to the magnitude of the pressure.

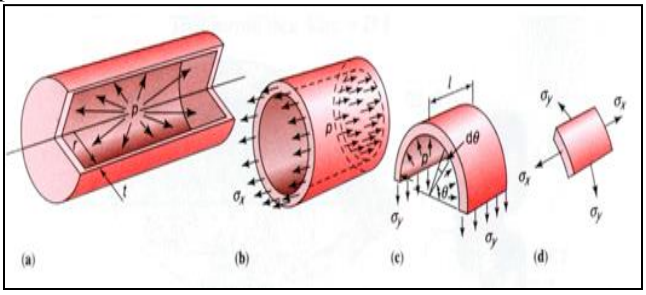

Fig. 1: Hoop Stresses and Axial Stresses
Ref.: www.cmscopoter.in/biog/domestic gas cylinder/

A. Matrices

The purpose of composite material is matrix is to bind the fiber together by virtue of its cohesive and adhesive characteristics to transfer load to and between fibers, and to protect them from environment and handling. In addition to these, the matrix keeps the reinforced fiber in the proper orientation and position so that they can carry the intended loads, distributes the load the more or less evenly among the fiber, provides resistance to crack propagation and damage, and provides all the interlaminar shear strength of the composites. Furthermore, the matrix generally determines the overall service temperature limitation of the composites, and may also control its environmental resistance.

B. Fiber Reinforced Composites

Fiber reinforced composites of material consist of fiber of high strength and modulus embedded in or bonded to matrix with distinct interface between them. In this form, both fiber and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting along. In general, fiber are the principal load carrying members, While the surrounding matrix keeps them, and protects them from environment damage due to elevated temperature and humidity for example. Thus, even though the fibers provide reinforcement for the matrix, the latter also serves number of useful function in a fiber reinforced composite materials.

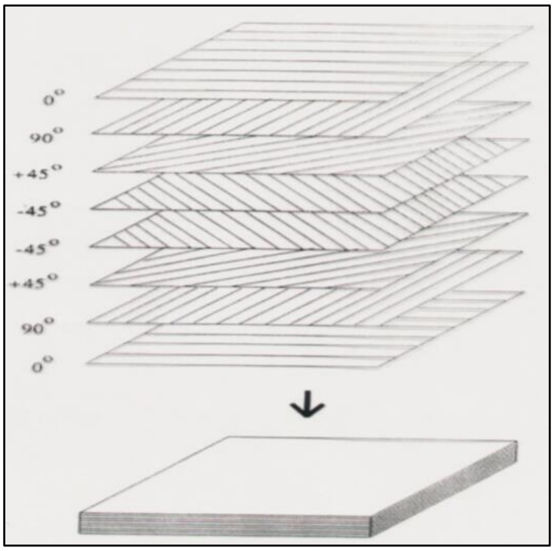

Fig. 2: Some possible ways to orient fibers [Ref: 9]

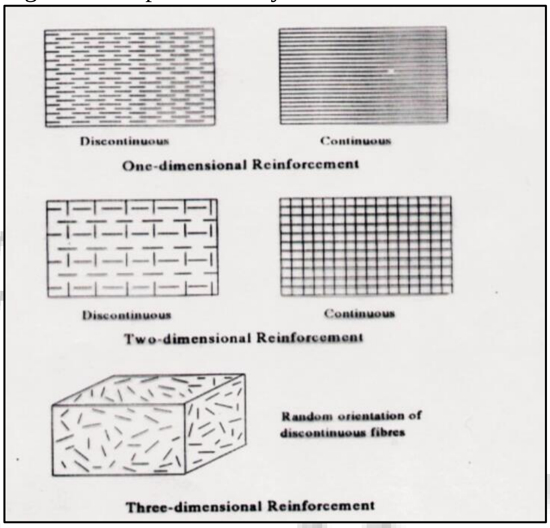

Fig. 3: Typical lamina constitution and fiber orientation. [Ref: 9]

C. *Basic building blocks in fiber reinforced composite*

Manufacturing of composite structure start with the incorporation of large number of fibers into a thin layer of matrix to form a lamina or ply. If continuous fibers are used in making the lamina, they may be arranged either in the uni-directional orientation or in the bi-directional orientation. For a lamina containing uni-directional orientation the composite material has the highest strength and modulus in the longitudinal direction of the fiber. However in the transverse direction its strength and modulus can be very low. For a lamina containing bidirectional fibers, the strength and modulus can be varied by employing different amount as well as different types of fiber in the longitudinal and transverse directions. For a balanced lamina, these properties are the same in the both direction.

III. MASS CALCULATION FOR STEEL CYLINDER

A. *Physical Properties of Low Carbon Steel*

Poisson's Ratio, μ=0.3, Density, ρ=7.8 kg/mm^3, Maximum Pressure, P=25 Mpa

Yield strength, σ= 480 MPa, UTS=800 MPa, Inner Diameter D=314.4mm

B. *Thickness of Low Carbon Steel*

$t = (PD)/\{(200*0.8*J*\sigma)-P\}$ (3.1)

(Where, J= Weld joint factor=0.90)

t=2.19 mm, But, t_{actual}=2.19+0.1+0.2=2.5mm, Hoop Stress, σ_h=PD/2t= (1.2*314.4)/ (2*2.5) =75.45 Mpa (3.2)

Longitudinal stress, σ_l = PD/4t = (1.2*314.4)/ (4*2.5) =37.7 MPa

Von Misses stress

$\sqrt{(\sigma_h^2+\sigma_l^2-\sigma_h*\sigma_l)}$ =65.34 Mpa (3.3)

C. *Analysis of Mass of Steel Cylinder*

Volume of cylinder, $V_1 = \pi (R^2 - r^2)*h$

$= \pi*368*[(319.4/2)^2-(314.4/2)^2]$ =915925.05mm^3

Volume of spherical portion, $V_2=1.33*\pi*(R^3 - r^3)$ $=1.33*\pi*[(319.4/2)^3-(314.4/2)^3]$ =788757.26mm^3

Total Volume=V_1+V_2= 915925.05+788757.26 = 1704682.31mm^3

Mass of cylinder = volume *density = 1704682.31*7850*10$^{(-9)}$ = 13.4Kg (Approx)

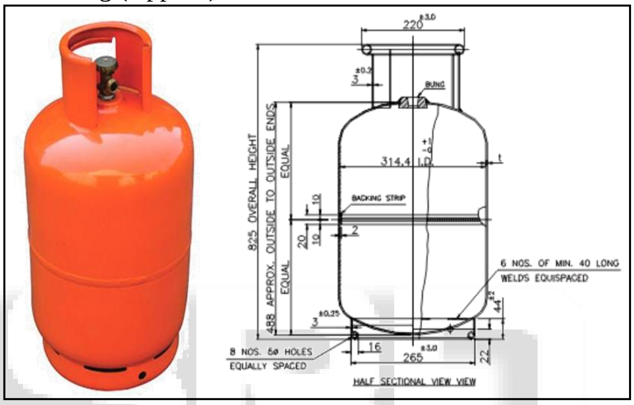

Fig. 4: Specifications of Cylinder

IV. MASS CALCULATION FOR COMPOSITE CYLINDER

A. *Physical properties of Glass fiber (Reinforced)*

Poison's Ratio, μ=0.28,Density , Maximum Pressure P= 25 MPa, ρ=1.8 kg/mm^3

Yield strength, σ=125 MPa, UTS=530 MPa, Inner Diameter D=314.4mm

B. *So, Thickness of composite material*

$t=0.5*D*[1-\sqrt{\{(10*Z*\sigma-P*\sqrt{3})/(10*Z*\sigma)\}}]$ (4.1)

(Where, Z=Stress reduction Factor=1)

t=2.75 mm But, t_{actual}=2.75+0.3=3.1mm

And Hoop Stress, σ_h=PD/2t= (1.2*314.4)/(2*3.1)=60.85 MPa

Longitudinal stress, σ_l=PD/4t=(1.2*314.4)/(4*3.1)=30.42 Mpa

Von Misses stress

$\sqrt{(\sigma_h^2+\sigma_l^2-\sigma_h*\sigma_l)}$ =52.69 Mpa (4.2)

C. *Mass Calculation for Composite Cylinder*

Volume of cylinder, $V_1 = \pi (R^2 - r^2)*h$ $=\pi*368*[(320.6/2)^2-(314.4/2)^2]$ =1137897.426mm^3

Volume of spherical portion, $V_2=1.33*\pi*(R^3 - r^3)$ $=1.33*\pi*[(320.6/2)^3-(314.4/2)^3]$ = 979322.495mm^3

Volume total=V_1+V_2= 1137897.426+979322.495=2117219.921mm^3

Mass of cylinder=volume *density = 2117219.921*1800*10$^{(-9)}$ = 3.81 Kg [Approx]

V. MODELING AND ANALYSIS OF STEEL AND COMPOSITE CYLINDER

The cylinder is modeled in the CATIA. The Cylinder is modeled for steel cylinder thickness of 2.5 and a thickness of 3.1 for composite cylinder. The analysis of the cylinder is carried out in ANSYS 17.2.

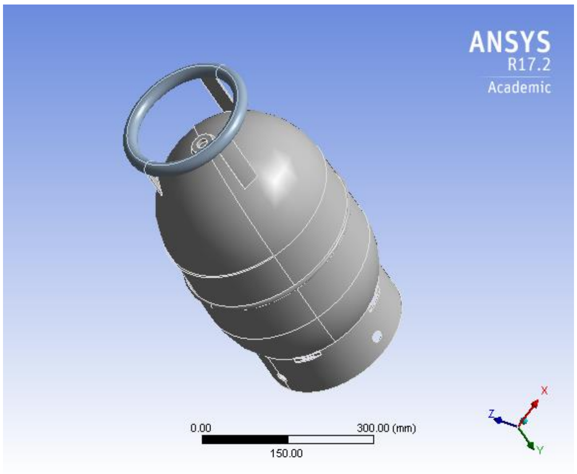

Fig. 5a: Designed LPG cylinders

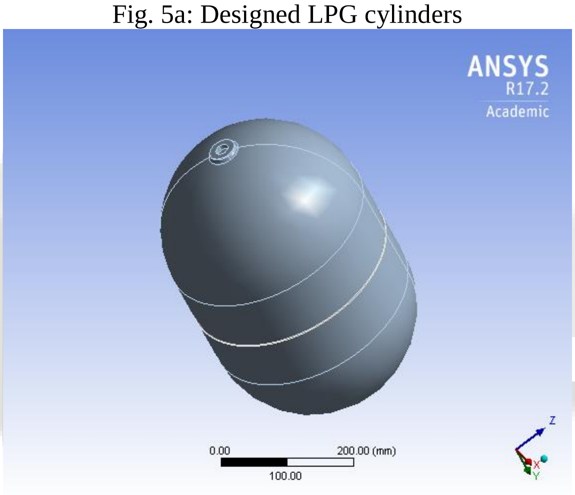

Fig. 5b: Designed LPG cylinders

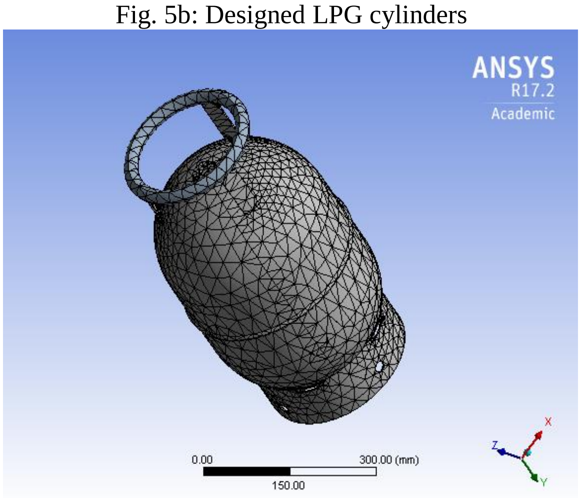

Fig. 6a: Meshed Steel Cylinder

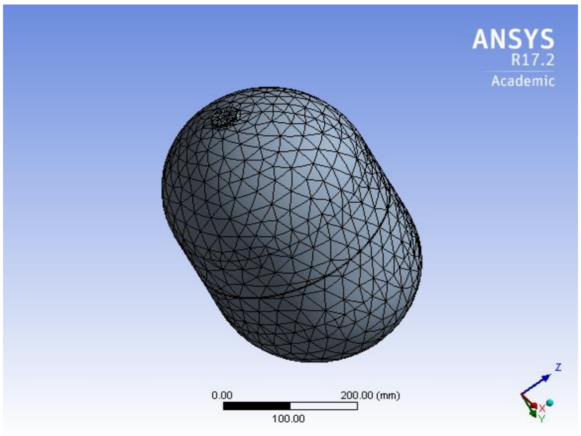

Fig. 6b: Meshed Composite Cylinder

S.NO.	Title	Steel Cylinder	Composite Cylinder
1.	Meshing Size	0.5827 mm	1.9014 mm
2.	Number of Element	7730	4720
3.	Number of Nodes	15837	10161

Table 1: List of Meshing Size, Number of Element and Nodes

VI. ANSYS ANALYSIS

A. *Longitudinal Stresses Analysis*

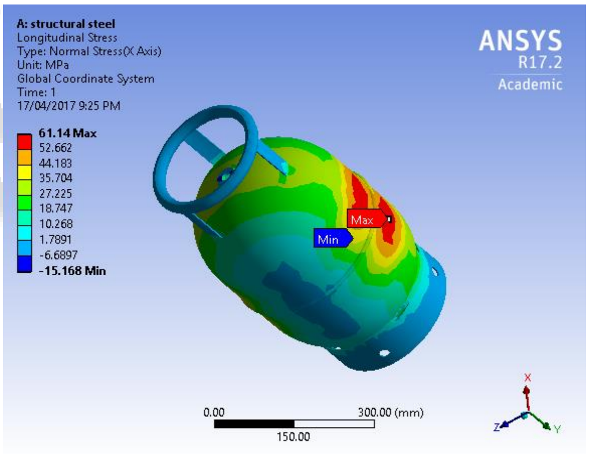

Fig. 7a: Longitudinal stress in Steel Cylinder

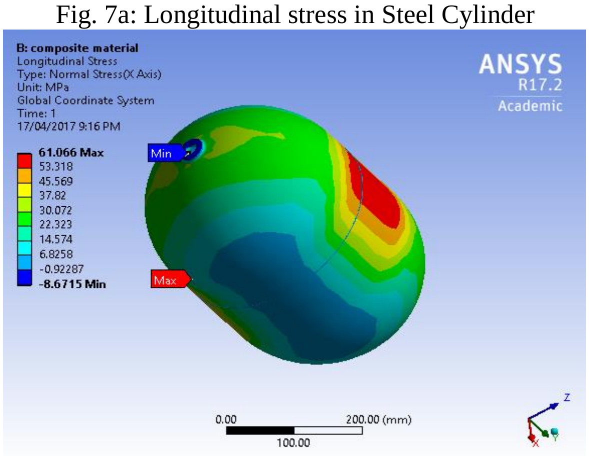

Fig. 7b: Longitudinal stress in composite Cylinder

B. Hoop Stresses Analysis

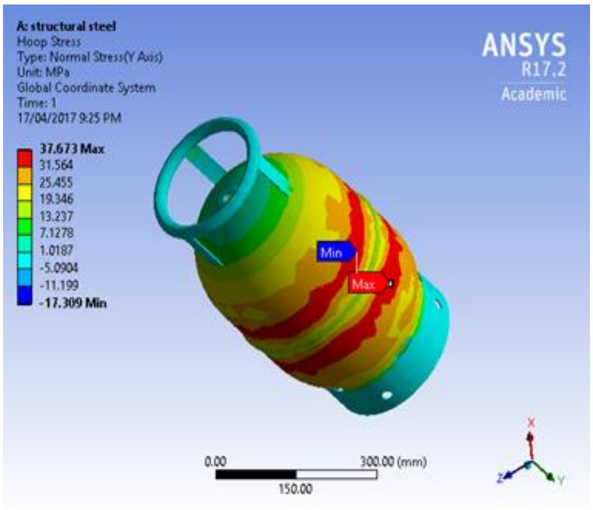

Fig. 8a: Hoop stress in Steel Cylinder

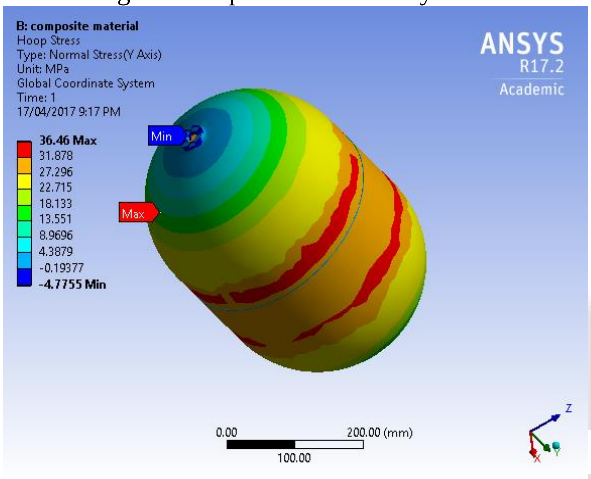

Fig. 8b: Hoop stress in Composite Cylinder

C. Von-misses Stress Analysis

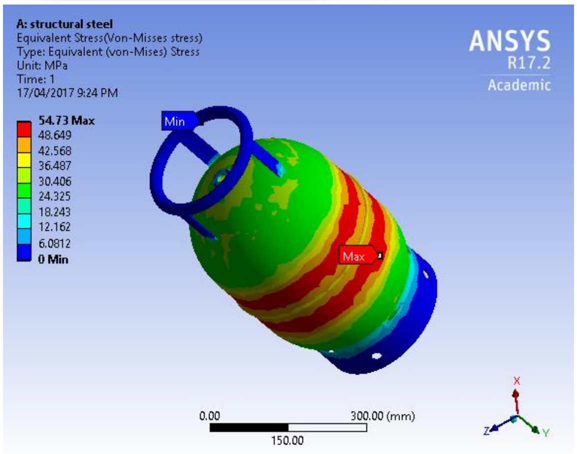

Fig. 9a: Von-misses stress in Steel Cylinder

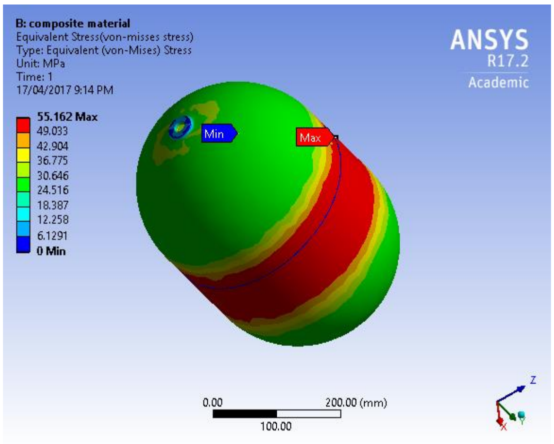

Fig. 9b: Von- misses stress in Composite Cylinder

VII. RESULTS

Results obtained from the analytically and ANSYS analysis of the steel and composite cylinders is given in the table.

S. No.	PROPERTIES	STEEL		COMPOSITE	
		Analytical Method	Finite Element method	Analytical Method	Finite Element Method
1.	Von-misses Stress	65.34 MPa	54.73MPa	60.85 MPa	55.162 MPa
2.	Longitudinal Stress	75.85 MPa	61.14MPa	52.69 MPa	61.066 MPa
3.	Hoop Stress	37.7MPa	37.673 MPa	30.42 MPa	36.46MPa
4.	Weight	131.5N	136.75 N	37.37N	36.98N

Table 2: Result and Comparison

VIII. CONCLUSIONS

Based on the analysis of LPG cylinders made of different materials like steel and composite materials following conclusions have emerged out from the present investigations:

1) The weight of LPG cylinder can be saved enormously by using composites and the stress values are also well within the limit of capability of materials. This gives a clear justification for its use in household applications.
2) 54.5 % light weight.
3) Apart from the weight savings, FRP composite LPG cylinders offer Leak before fail approach of design which may be a design advantage in terms of safety and reliability.
4) The cost of FRP raw materials is definitely more than conventional steel material, but the above two points justify its use for household purpose.
5) Leak before fail approach of design is an advantages in term of safety and reliability.
6) Low electrical conductivity and corrosion resistance.
7) Visual attractiveness and Acoustical insulation.

IX. ACKNOWLEDGMENT

The first author wishes to acknowledge the invaluable assistance given by Dr. A. K. Dubey, Principal and TEQUIP

CELL, G.E.C.Raipur for providing licensed version of ANSYS software for conducting this analysis.

References

[1] Ch.Bandhavi and N.Amar Nageswara Rao, “Design and Analysis of LPG Cylinder using ANSYS Software,” International Journal of Mathematical Sciences Technologies and Humanaties 58, pp 635 – 646, 2012.
[2] Akula Ramakrishna, Nihal A. Siddiqui and P. ojan Lal, 2014 “Development of empirical formulas for LPG cylinder”, International Journal of Applied Engineering and Technology, Vol. 4/1 pp. 54-61, 2014.
[3] Rashmi Rekha and Himanshu Shekah “Composite gas cylinders” Science Reporter, pp 14-15, 2012.
[4] A. Shaikh, Rajiv A. Mistry, “Design of Fiber Reinforced Plastic Pressure Vessel by ASME Section X”, International Journal of Emerging Technology and Advanced Engineering Journal, Volume 4/11, pp. 523-528, 2014.
[5] Alberto Coriglianoa, Egidio Rizzib, Enrico Papaa, “Experimental characterization and numerical simulations of a syntactic-foam/glass-fibre composite sandwich”, Composites Science and Technology, Volume 60/11, pp. 2169–2180, 2000.
[6] Lakshmi Nair, Yezhil Arasu , Indu V S, “Design of Laminated Pressure Vessel”, International Journal of Science and Research, Volume 4/8, pp. 2319-7064, 2015.
[7] Sumeyra sayman, “Analysis of fiber reinforced composite vessel under hygrothermal loading” MS thesis The middle east technical university, 2003.
[8] K Sahitya Raju, Dr. S. Srinivas Rao, “Design optimization of a composite cylindrical pressure vessel using FEA”, International Journal of Scientific and Research Publications, Volume 5/12, pp. 2250-3153, 2015.
[9] T.Ashok and A.Harikrishna, “Analysis of LPG Cylinder Using Composite Materials”, International Journal of Mechanical and Civil Engineering, Vol.9, pp. 33-42, 2013.

