Design and Finite Element analysis of Thick walled Laminated Composite Pressure Vessel

Sarada Prasad Parida, Pankaj Charan Jena

Abstract: Composite materials in general offer a high potential for manufacturing of structures with featuring an interesting mechanical performance, mainly with regards to specific stiffness, specific strength, damage tolerance and energy absorption capability. In current analysis, glass fibre reinforced in epoxy resin to form a laminated composite walled pressure vessel(filament winding) is considered for design. The purpose of this work is primarily to perform finite element analysis (FEA) of a composite walled pressure vessel (CPV) under different loads. Different design stresses and strains are evaluated using Lame's equation. These outcomes are tabulated and examined with the results of the steel walled pressure vessel used for LPG. It is foundthat CPV is a suitable vessel for LPG storage and it can be replaced current LPG steel walled vessel to CPV.

Keyword: design, cylinder, composite walled, vessel

F_R	Normal force along radial direction
F_Θ	Normal force along Tangential l direction
$F_{R\Theta}$	Shear force
M_R	Bending moment along radial direction
M_Θ	Bending moment along Tangential direction
$M_{R\Theta}$	Bending moment along RΘ plane
σ_{RR}	Radial stress
$\sigma_{\Theta\Theta}$	Tangential stress
$\sigma_{R\Theta}$	Shear stress
Z_k	Thickness of kth layer
Z_{k-1}	Thickness of k-1 th layer
n	Number of layer
$[\varepsilon^0]_{R,\Theta}$	Normal strain component matrix
$[\kappa]_{R,\Theta}$	Shear strain component matrix
q_{rr}, q_{ss}, $q_{\Theta\Theta}$, $q_{r\Theta}$, q_{rs}, $q_{\Theta s}$	Transformed stiffness of orthotropic composite cylinders in respective R, S, Θ directions
q_{ij}	stiffness of individual lamina in i and j directions
[A],[B],[D]	Components of compliance matrix
E_1,E_2	Modulus of elasticity of individual lamina along warp and fill direction
G_{12}	Modulus of rigidity
$\gamma_{12}\gamma_{21}$	Poisions ratio along warp and fill direction
P	Internal pressure
R_o	Outer diameter
R_i	Inner diameter
H	Wall thickness
γ	Poisons ratio
δ_R	Radial displacement

Revised Manuscript Received on July 22, 2019.

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I. INTRODUCTION

Composite materials in general offer a high potential for manufacturing of structures featuring an interesting mechanical performance, mainly with regard to specific stiffness, specific strength, damage tolerance and energy absorption capability Composite pressure vessels were originally developed for aerospace applications. Nowadays, these are utilized in broad field of applications such as water treatment stations and petroleum industry. The current state of the art composite pressure vessels are light, safe.

The purpose of this work is primarily to perform finite element study of composite pressure vessel subjected to various constraints of loads and to investigate the possibility of replacing current LPG steel vessels with cpvs. The analysis is carried out using the finite element method.

Tauchert [1] optimized fiber distribution in cylindrical fiber reinforced composite pressure vessel using minimum strain energy criterion. They have presented results by considering variation of radii, elastic moduls, and global volume fractions. Ecklod[2] used anisotropic elastic theory to study the effect uniaxial and combined loading on filament wound thick composite cylinder. Adaliet la.[3] optimized the burst pressure with respect to weight for different fiber orientation and thickness using membrane theory of shells. Cohen et al. [4-5] studied and presented the effect volume fraction of fiber, stacking sequence of laminate, winding time and tension with failure pressure. for the purpose authors developed a computer program and validated with the experimental investigation. Xu and Yu[6] conducted shake down analysis and determined the elasto-plastic stress limits for thick walled cylinders subjected to internal pressure. Naser and Osama [7] have stated that the composite LPG cylinders are as replacements of conventional steel cylinder by ANSYS with lower stress level and higher displacement. Antunes et al. [8] made glass polypropelene pressure vessel by filament winding process cascaded with thin layer of steel to study the burst pressure by FEM. Yue and Li[9] modelled composite cylinders for CNG storage and evaluated deformed cloud diagrams for stress and strain when subjected to different internal pressures. Taheri [10] studied and presented the various manufacturing techniques used for the manufacturing of fiber reinforced composites used as pipes and risers in oil and gas industry. Lepikhin et al. [12] presented an overview of correlations of stress-strain with different parameter for anisotropic composite cylinders in dynamic loading from different experimental studies. Hemmatnezhad et al. [13] fabricated GFRP composite cylinders by filament winding process and determined the dynamic characteristics in vibration theoretically based on Sanders' thin shell theory and by FEM.

Guz et al.[14] reviewed the practical applications of thick composite pipes subjected to outer pressure in oil and gas industry and analytically demonstrated the failure analysis by stress distribution through the wall thickness for different lay ups of fibres. Davies et al. [14] demonstrated the use of glass/epoxy and carbon/epoxy composite pressure vessel in underwater applications with implosion pressure of 600bar in 6000m depth. Ahmad and Hoa[15] experimentally determined the flexural stiffness of thick walled tubes indigenously manufactured by fiber placement machine. Ahmadi [16] used Reddy's layer wise theory and approached an analytical method to determine inter-laminar stresses from elastic equations subjected to uniform and non-uniform internal pressure. Ramos et al. [17] studied the mechanical behaviour of thick anisotropic fiber reinforced composite cylinder analytically by exact 3-D elastic solution approach and the results obtained were compared with the results of FEA study. Arhant et al. [18] designed and fabricated thermoplastic composite pressure vessels and presented that thermoplastic composites pressure vessels in undersea application can be the replacements of thermoset composites. For validity of the result the experimental data are matched with the results obtained from FEA study for different stacking sequence of fiber and internal pressure.

II. MODELLING OF THICK WALLED CYLINDERS

The pressurevessels or gas cylinders which are generally used for storing fluids i.e. liquid or gas under pressure are of thick cylinders. In this case the cylinder wall is taken as of four layered composite material. The whole procedure of study is presented through the following flow chart (Figure1). The stress strain relationship for an orthotropic composite material can be determined using laminated shell theory. Shells are three dimensional bodies closed by curved surface as shown in the Figure 2.

Table-I: Elastic Properties of Epoxy –Glass

Material	Properties	Values
Glass fiber	Fiber longitudinal modulus in l direction E_{fl}(GPa)	78
	Fiber transverse modulus in t direction E_{ft}GPa	78
	Fiber shear modulus G_f (Gpa)	30
	Density ρ_f (kg/m3)	2650
	Fiber Poisson ratio $\nu_f \ell t$	0.3
Epoxy resin	Elastic modulus E (Gpa)	4
	Shear modulus G (Gpa)	1.43
	Density ρ_m(kg/m3)	1250
	Poisson ratio ν	0.4

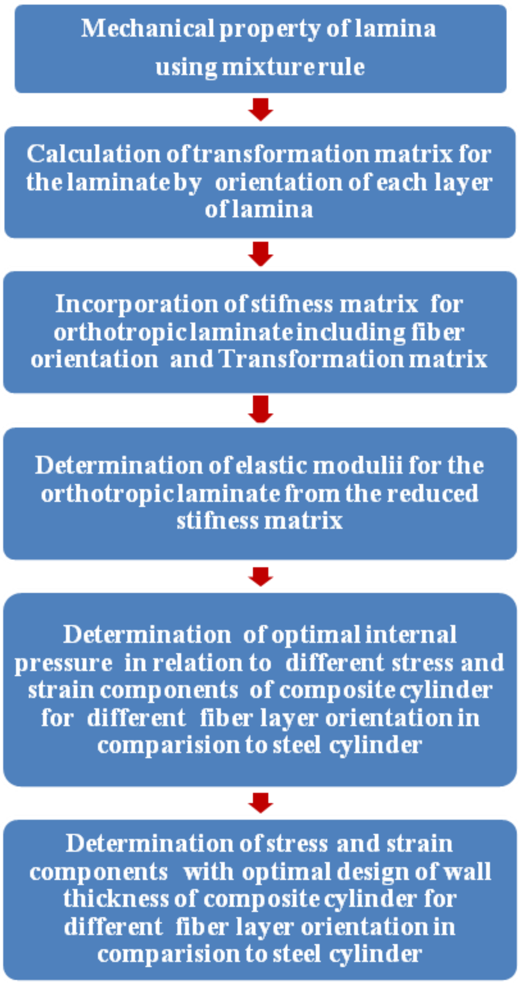

Fig 1: Detail steps of current analysis in flow chart.

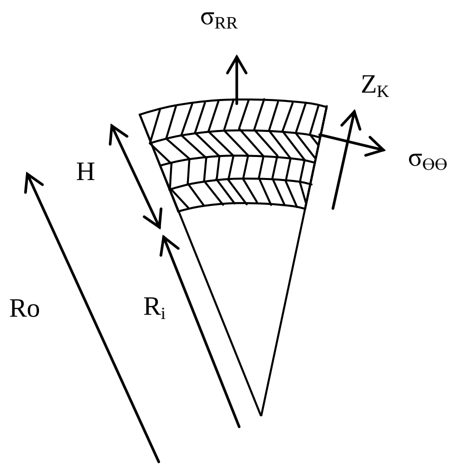

Fig 2: Schematic view of orthotropic composite walled cylinder.

$$\begin{bmatrix} F_R \\ F_\Theta \\ F_{R\Theta} \end{bmatrix} = \sum_{I=1}^{n} \int_{Z_{k-1}}^{n} \begin{bmatrix} \sigma_R \\ \sigma_\Theta \\ \sigma_{R\Theta} \end{bmatrix} zdz \quad (1)$$

Retrieval Number J98310881019/2019©BEIESP
DOI: 10.35940/ijitee.J9831.0881019

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$$\begin{bmatrix} M_R \\ M_\Theta \\ M_{R\Theta} \end{bmatrix} = \sum_{I=1}^{n} \int_{Z_{k-1}}^{n} \begin{bmatrix} \sigma_R \\ \sigma_\Theta \\ \sigma_{R\Theta} \end{bmatrix} zdz \qquad (2)$$

$$[F]_{R,\Theta} = \left[\sum [q]_{R,\Theta}^{k} \int_{k_{k-1}}^{k} (z_k - z_{k-1}) \right] \left[\varepsilon^0 \right]_{R,\Theta}$$

$$+\frac{1}{2}\left[\sum [q]_{R,\Theta}^{k} \int_{k_{k-1}}^{k} (z_k^{\ 2} - z_{k-1}^{\ 2}) \right] \left[\varepsilon^0 \right]_{R,\Theta} \qquad (3)$$

$$\left[F_{R,\Theta} \right] = [A]_{R,\Theta}[\varepsilon^0]_{R,\Theta} + [B]_{R,\Theta}[k]_{R,\Theta} \qquad (4)$$

$$\left[M_{R,\Theta} \right] = [B]_{R,\Theta}[\varepsilon^0]_{R,\Theta} + [D]_{R,\Theta}[k]_{R,\Theta} \qquad (5)$$

The laminate compliance matrix is given by $A_{ij} = \sum_{k=1}^{n} q_{ij}^{\ k} \left(z_k - z_{k-1} \right)$ (6)

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} q_{ij}^{\ k} \left(z^2_{\ k} - z^2_{\ k-1} \right) \qquad (7)$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} q_{ij}^{\ k} \left(z^3_{\ k} - z^3_{\ k-1} \right) \qquad (8)$$

where

$$q_{RR} = c^4 q_{11} + s^4 q_{22} + 2c^2 s^2 q_{12} + 4c^2 s^2 q_{66}$$

$$q_{\Theta\Theta} = s^4 q_{11} + c^4 q_{22} + 2c^2 s^2 q_{12} + 4c^2 s^2 q_{66}$$

$$q_{Rs} = c^3 s q_{11} - s^3 c q_{22} - cs(c^2 - s^2) q_{12}$$
$$-2cs(c^2 - s^2) q_{12} q_{66}$$

$$q_{ss} = c^2 s^2 q_{11} - c^2 s^2 s q_{22} - 2c^2 s^2 s q_{12}$$
$$+(c^2 + s^2) q_{12} q_{66}$$

$$q_{\Theta s} = s^3 c q_{11} - c^3 s q_{22} - cs(c^2 - s^2) q_{12}$$
$$-2cs(c^2 - s^2) q_{12} q_{66}$$

$$q_{11} = \frac{E_1}{1-\gamma_{12}\gamma_{21}}$$

$$q_{22} = \frac{E_2}{1-\gamma_{12}\gamma_{21}} \quad q_{12} = q_{21} = \frac{\gamma_{21}E_1}{1-\gamma_{12}\gamma_{21}} = \frac{\gamma_{12}E_2}{1-\gamma_{12}\gamma_{21}}$$

$$q_{66} = G_{12}$$

$$\begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} F \\ M \end{bmatrix}$$

$$[a] = [A]^{-1} - \left\{ \left[B^* \right] \times \left[D^* \right]^{-1} \right\} \left[C^* \right]$$

$$[b] = [B] \times \left[D^* \right]^{-1}$$

$$[c] = -\left[D^* \right]^{-1} \times \left[C^* \right]$$

$$[d] = \left[D^* \right]^{-1}$$

$$B^* = -[A]^{-1} \times [B]$$
$$C^* = [B] \times [A]^{-1}$$
$$D^* = [D] - \left\{ [B] \times [A]^{-1} \right\} [B]$$

In this case the composite cylinder is of four layers of lamina. Hence it may be assumed as a thick composite cylinder. The tangential and radial stresses components may be written using lames equation as;

$$\sigma_{\Theta\Theta} = \frac{R_i^2 R_o^2}{z^2} \left(\frac{P}{R_o^2 - R_o^2} \right) - \left(\frac{PR_i^2}{R_o^2 - R_o^2} \right) \qquad (9)$$

$$\sigma_{RR} = \left(\frac{PR_i^2}{R_o^2 - R_i^2} \right) - \frac{R_i^2 R_o^2}{z^2} \left(\frac{P}{R_o^2 - R_i^2} \right) \qquad (10)$$

$$\sigma_{R\Theta} = \left(\frac{PR_o^2}{R_o^2 - R_i^2} \right)$$

Maximum wall thickness is given by

$$H = R_i \left[\sqrt{\frac{\sigma_{\Theta\Theta} + P}{\sigma_{\Theta\Theta} - P}} - 1 \right] \qquad (11)$$

Also the strain displacement relationship for a thick cylinder can be expressed as

$$\delta_R = PR_O \left[\sum_{i=1}^{k} \frac{1}{E_i} \left(\frac{R_{i+1}^{\ 2} + R_i^{\ 2}}{R_{i+1}^{\ 2} - R_i^{\ 2}} + \gamma \right) \right]$$
$$+PR_O \left[\sum_{i=1}^{k} \frac{1}{E_i} \left(\frac{R_{i+1}^{\ 2} + R_i^{\ 2}}{R_{i+1}^{\ 2} - R_i^{\ 2}} - \gamma \right) \right] \qquad (12)$$

III. NUMERICAL MODELLING

The beams were discretized using solid Tet 8 node 285 finite elements, available in ANSYS14.0. It consists of 8 nodes and several numbers of layers varying according to the requirement. In this particular study the element is designed as four layers of equal thickness. This type of symmetry is called as mirror symmetry. Four possible orientations of plies of 0˚, 90˚and 45˚ of the four layers are manipulated. The choice of solid Tet 8 node 285 element types is assumed to be valid as the composite material taken as a layered one.

A thick cylinder of internal diameter of 128mm and 160mm external diameter with 360 mm length and semi spherical end are taken for the study. The mechanical properties of the constituent materials taken for the study are presented through Table-I.

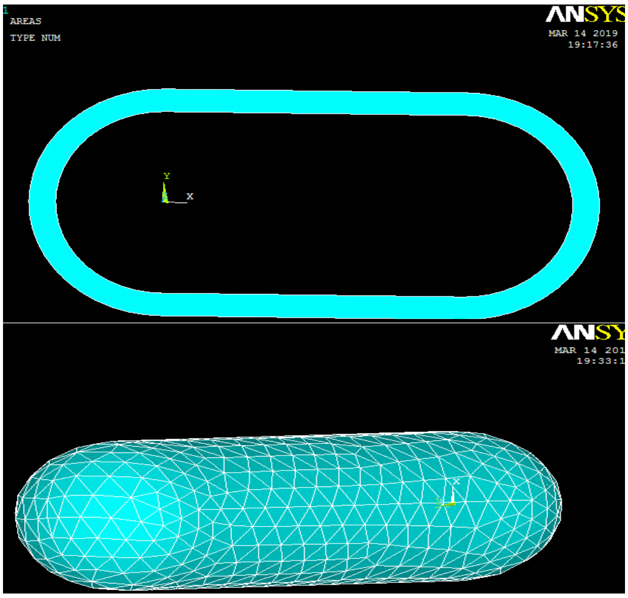

Fig 3(a):FEA model of pressure vessel.

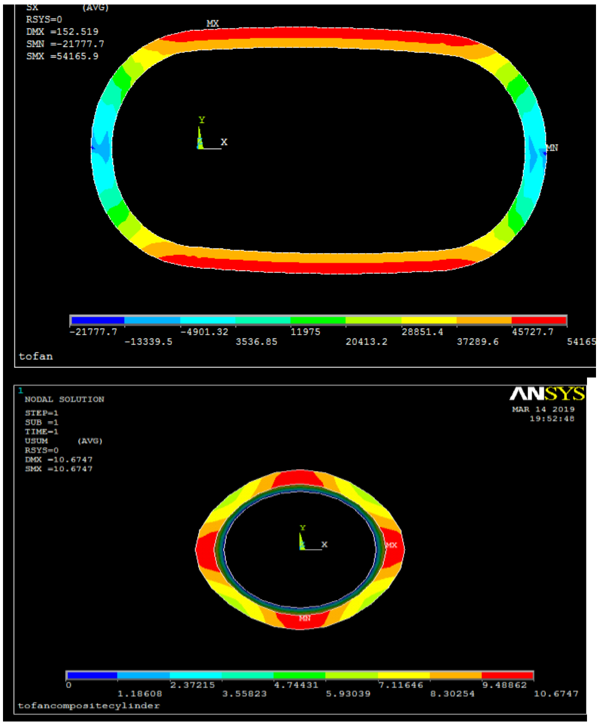

Fig3(b): Shows the radial displacements of FEA models of Pressure vessel.

IV. RESULT AND DISCUSSION

For the comparative study of the steel thick cylinder with the composite cylinder, an internal pressure of 120MPa is taken. Also, it is tried to find the best configuration of the fibre orientation among the designed four fiber orientations of 0º,45º and 90º the composite cylinders from here known as the sample cylinders and are presented in the Table. The results obtained are presented in Table-II.

The variation of hoop stress, radial stress, major principal stress, minor principal stress, resultant stress intensity and von misses stress intensity for the thick cylinders of different composite sample cylinder and steel cylinder subjected to 120MPa internal pressure are presented in Fig.4. From the graph it is very much clear that thick wall steel cylinder has higher properties than the other test specimens in all aspect of the study. However from other four composite cylinders sample-4 having ±(0 º /90 º) fibre orientation has superior property with less stress intensity. So the composite cylinder with ±(0 º /90 º) may be taken for the study.

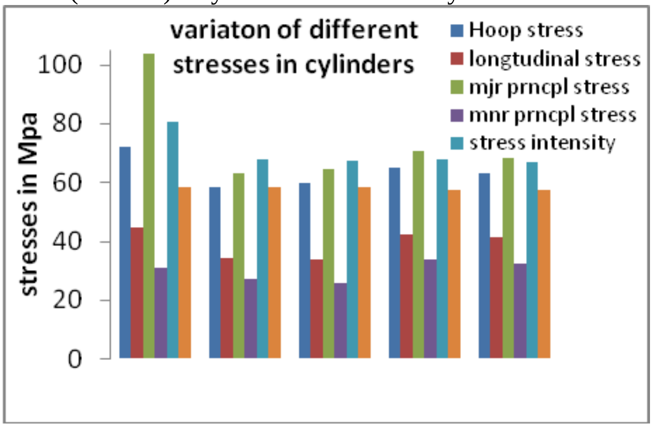

Fig. 4: variation of stress for different cylinder samples.

Fig.5 represents the longitudinal displacement of four composite cylinders samples along with the thick-walled steel cylinder. From the graph it can be observed that all of the samples are nearly equal longitudinal displacement. Hence the effect of fibre orientation does not play any important role on longitudinal displacement of the cylinders. Change of internal pressure also causes the change in observed stress parameters and longitudinal displacement of the thick cylinders. For the study the internal pressures are varied from 100MPa to 170MPa and the change in stress values and longitudinal displacement of thick steel cylinder and composite cylinder are determined. Figure 6and Figure 7represent the variation of hoop stress, longitudinal stress, three mutual principal stresses, resultant stress intensity and von misses stress intensity with change in internal pressures from 100MPa to 170MPa for steel cylinder and composite cylinder. From both of the graph it is quite clear that with increase in internal pressure different types of stresses developed inside the cylinder also increases. However, von misses stress intensity increases rapidly or more exponentially than other stress components.

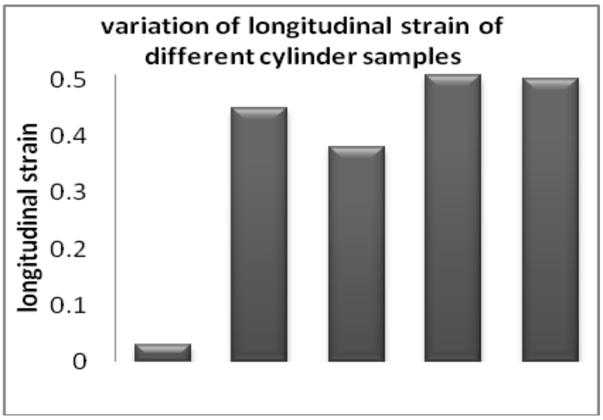

Fig.5: variations of longitudinal strain for different cylinder samples.

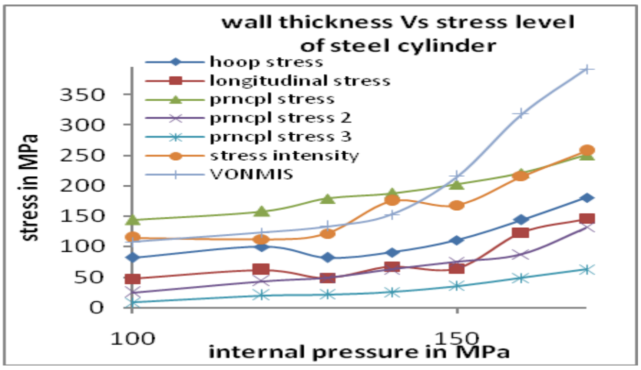

Fig.6: variation of internal pressure on steel cylinder.

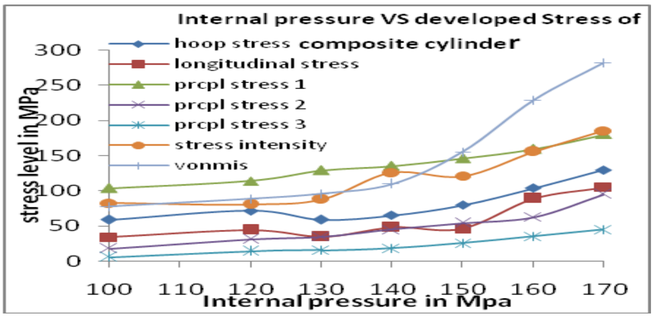

Fig.7: variation of stresses with internal pressure of composite cylinder.

Figure 8 represents the varation of the lpngitudinal displacement with the variationa of internal pressure both for composite cylinder and steel cylinder. From the curve it is quite clear that with increase in internal presure, longitudinal displacement increases. Also from the graph it can be seen that the longitudinal displacement increases gradully upto 130MPa internal pressure. Then further increase in internal pressure longitudinal displacement increases rapidly or exponenttially. The effect of wall thickness on the stresses developed in the cylinder subjected to 120MPa internal pressure is studied. for the study the wall thickness of the cylinders is taken as 4mm, 6mm, 8mm, 10mm, 12mm, 14mm and 16mm respectively. Figure 9 represents the variation of the different stresses namely hoop stress, longitudinal stress, major principal stress, minor principal stress, resultant stress intensity and vonmisses stress intensity of the steel cylinder with the variation of the wall thickness. It can be seen that with increase in wall thickness the value of hoop stress, longitudinal stress, principal stresses, resultant stress intensity and von misses stress intensity decreases. The same nature of variation of the stresses for the composite cylinder is presented in fig.10.

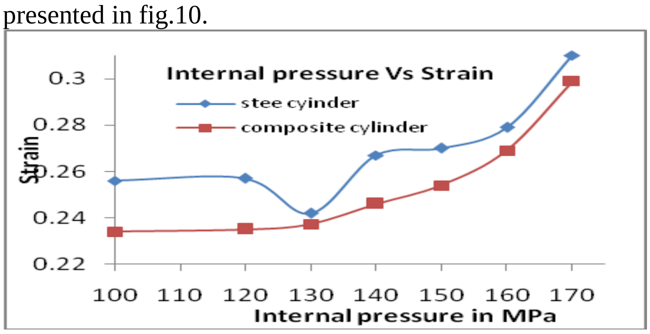

Fig.8: variation of longitudinal displacement with internal pressure.

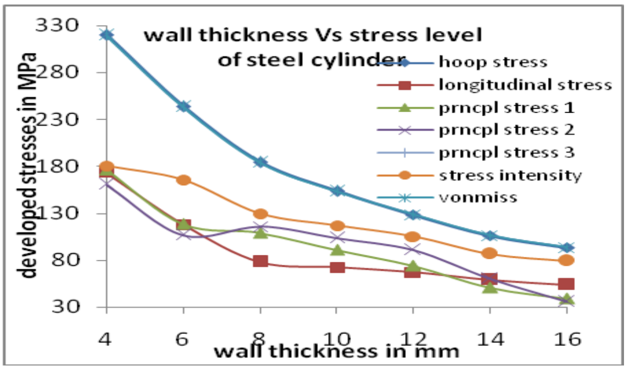

Fig. 9: variation of stresses with wall thickness for steel cylinder.

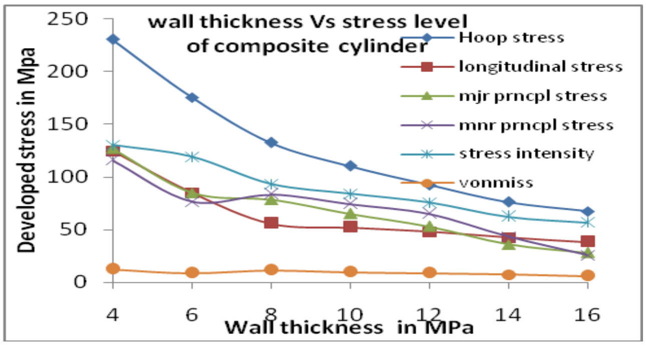

Fig.10: variation of stresses with wall thickness for composite cylinder.

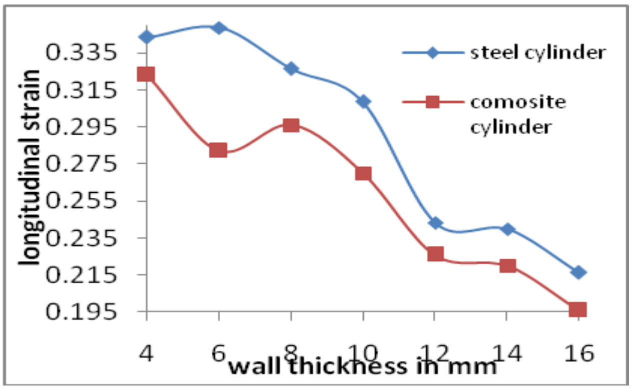

Fig. 11: variations of stresses with wall thickness of composite cylinder. Fig.11represents the variation of the longitudinal displacement of steel and composite cylinder with the variation of the wall thickness.

Table-II. Stresses of steel and composite cylinders. From the graph it is quite clear that with increase in wall thickness of the thick cylinder, the longitudinal displacement decreases rapidly.

Samples		Stresses Developed in the Specimens							Deformation in mm (Δl)
		Normal stress in MPa		Principal stresses in MPa			Stress intensity (SI) in MPa	VonMisses Stress in MPa	
		σ_θ	σ_r	σ_1	σ_2	σ_3			
Steel		72	44.5	104	31	14.2	80.67	58.5	0.03
composite	sample-1(0 º /45 º)$_{2s}$	58.2	34.07	62.9	27.22	11.89	67.63	58.58	0.45
	sample-2± (0 º /45 º)	59.8	33.65	64.6	25.6	11.3	67.6	58.5	0.38
	Sample-3(0 º /90 º)2s	65.1	42.5	70.9	33.7	12.82	67.66	57.36	0.508
	Sample-4± (0 º /90 º)	63.2	41.5	68.2	32.5	13.5	66.86	57.58	0.502

IV.CONCLUSION

The steel cylinder has superior property than the composite cylinders. However, it can be observed that von misses stress intensity which plays a crucial role in the design of pressure vessel is nearly equal for the steel cylinder and all composite cylinders. But the compressive stress or hoop stress is quite lower. Also, from all of the fiber orientations taken for the study ± (0 º /90 º) lamina orientation may be considered for the study. All the test samples have negligible and nearly equal longitudinal deformation for all of the internal pressures and wall thicknesses. With increase in internal pressure the developed stress values developed inside the cylinder increases. Also, the longitudinal displacements are found to be increasing with the increase in internal pressures. Also, it is observed that with increase in the wall thickness decreases the developed stress values and longitudinal displacement.

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