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# Structural Performance of Unstiffened Laminated Composite Pressure Vessels

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***ABSTRACT:*** *The use of composite materials improves the performance of the vessel and offers a significant amount of material savings. In this paper buckling analysis of woven fiber reinforced multi layered composite shell under pure internal pressure is conducted and its structural performance is studied. The thickness of pressure vessel is kept constant and number of layers and angle of orientation of each layer is altered. Three composites are considered for the study namely carbon/epoxy, E-glass/ epoxy and S-glass/ epoxy for the tank body. After static and buckling analysis of unstiffened pressure vessels it is concluded that carbon/epoxy laminated composite pressure vessel with 15 numbers of layers at 90° orientation has shown the best performance.*

***KeyWords:****Laminated composite pressure vessels, Number of layers, Angle of orientation*

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## I. INTRODUCTION

Composites are structural material with consist of two or more constituent materials. Laminated composites consist of matrix as binder and fiber as reinforcement. These matrix and fibres combined to form plies called laminae and in these plies the fibres can be oriented in any angle. The laminaes are stacked one over the other to give laminated structure. Laminated structures are used to build ship parts, aeroplane parts and also pressure vessels. So these laminated composite pressure vesselsfind many applications in various fields ranging from households to industrial to aviation. Pressure vessels are very important and they are used to store many liquids under high pressure.The composite materials exhibit high specific strength and high specific modulus resulting in substantial reduction of weight of the components, thus improves efficiency, and results in energy savings. One of the main advantages of composite materials is the flexibility involved in getting the desired strength and stiffness in the direction required.

## II. LITERATURE REVIEW

Alexis A. Krikanov [1999] proposed a new method to design laminated composite pressure vessels under strain and strength constraints. Chang [2000]concluded that Wu failure criteria can yield fairly good results with consistent accuracy for the laminated pressure vessels. Levend Parnas et al. [2002] shown that for composite pressure vessels with a ratio of outer to inner radius, up to 1.1, thin wall and thick wall solutions give similar results in terms of the optimum winding angle, the burst pressure, etc. As the ratio increases, the thick wall analysis is required. Kim et al. [2005]used the semi-geodesic path algorithm to calculate possible winding patterns taking into account the windability and slippage between the fiber and the mandrel surface. Zheng Chuan-xiang et al. [2006] presented new modified Faupel’s formulae for calculating the burst pressure. Error in the calculation is reduced after using the modified Faupel formulae. P. Xu et al. [2009] conduced parametric studies in terms of the effects of different failure criteria are performed and the calculated failure strengths of composite vessels are also compared with the experimental results. E.S. Barboza Neto et al.[2011] investigated the behaviour of pressure vessel liner under burst pressure testing. They concluded that ideal thickness of liner which can with stand the pressure of 2-2.2 MPa lie between 15-16 mm.Haris Hameed Mian et al.[2013] studied optimization of composite material system and lay-up to achieve minimum weight pressure vessel.M Mohan Kumar et al. (2013) conducted buckling analysis of woven glass epoxy laminated composite plate.Amruta M.Kulkarni et al. [2015] calculated burst pressure of liquid petroleum gas cylinder used in household application by using twice elastic slope criteria. S. Sharifi et al [2016]conducted numerical and experimental study on mechanical strength of internally pressurized laminated woven composite shells incorporated with surface-bounded sensors. And it is found that laminated composite shells with WR $[0/ 45]_3$ were preferred choice over WR $[0]_6$.

## III. AIM OF STUDY

- To study the buckling characteristics of carbon /epoxy, E-glass /epoxy and S-glass /epoxy as a material used for pressure vessel
- To study the structural performance of woven fiber reinforced multi layered composite shell, with different fiber orientations under internal pressure
- To study the effect of numbers of layers on the structural behaviour of composite pressure vessel

## IV. NUMERICAL VERIFICATION

To validate the finite element modelling, “Buckling analysis of woven glass epoxy laminated composite plate” by M Mohan Kumar et al. (2013) selected from literature. It is also analysed in finite element software ANSYS 16 and result are found to be explicitly matching. The static, buckling analyses are carried out. The validation summary is tabulated in Table 1.

**Table-1**: Numerical verification results

| Plate description | Critical buckling load by FE analysis (kN) | |
|---|---|---|
| | Present study | M Mohan Kumar et al. (2013) |
| Rectangular Aluminium plate 200mm×300mm×1.6mm | 2.58 kN | 2.52 kN |
| Square Aluminium plate 300mm×300mm×1.6mm | 3.4 kN | 3.24 kN |

## V. METHODOLOGY

To evaluate buckling analysis of fiber reinforced composite pressure vessels with different number of layers and different fiber orientation using finite element modelling in ANSYS workbench 16. Carbon /epoxy, E-glass /epoxy and S-glass /epoxy were chosen for the study. The entire model is generated by and revolving the profile in full circle about the horizontal axis. The model is treated as surface body. To give ply orientation angle layered section is also included in the geometry. The composite pressure vessels are provided with 10, 15, 20 and 25 number of layers to give a total shell thickness of 10mm. That is for 10 numbers of layers each layer is provided with 1mm thickness to have a total shell thickness of 10mm. Each layer is provided with 0°, ±35°, ±45°, ±55°, ±65°, ±75°, ±85°, and 90° oriented symmetric layers. The layer orientation angle, thickness of each layer and material are given in the worksheet provided in the layered section. Von-Mises stress,maximum principle stress and deformation are observed for all composite pressure vessels with different layers and different fiber orientation in static analysis. After static analysis buckling analysis is carried out for composite pressure vessels by varying fiber orientation (0°, ±35°, ±45°, ±55°, ±65°, ±75°, ±85°, and 90°)and number of layers (10, 15,20 and 25) while keeping the thickness constant, buckling analysis is performed. The properties of carbon/epoxy, E glass/epoxy and S glass/epoxy is shown in Table 2.

**Table 2** Properties of composites

| Properties | Carbon /epoxy | E-glass /epoxy | S-glass /epoxy |
|---|---|---|---|
| Fibre volume fraction, $V_f$ | 0.55 | 0.55 | 0.55 |
| Density,$\rho$ (kg/$m^3$) | 1800 | 1855.36 | 2600 |
| Modulus of elasticity in X-direction, $E_1$ (MPa) | 77000 | 22200 | 24500 |
| Modulus of elasticity in Y-direction, $E_2$(MPa) | 75000 | 20300 | 23800 |
| Modulus of elasticity in Z-direction, $E_3$(MPa) | 13800 | 10000 | 11600 |
| Poison’s ratio,$\upsilon_1$ | 0.06 | 0.11 | 0.11 |
| Poison’s ratio,$\upsilon_2$ | 0.37 | 0.17 | 0.20 |
| Poison’s ratio,$\upsilon_3$ | 0.5 | 0.14 | 0.15 |
| Shear modulus in X- direction,$G_1$(MPa) | 6500 | 4500 | 4700 |
| Shear modulus in Y- direction,$G_2$(MPa) | 4100 | 3900 | 3600 |
| Shear modulus in Z- direction,$G_3$(MPa) | 5100 | 3400 | 2600 |

### 5 Modelling

3-D model was built for unstiffened and stiffened shell using ANSYS Workbench software. The modelled shell has the following properties:

| | |
|---|---|
| Cylinder diameter | 670 mm |
| Cylinder height | 1030mm |
| Shell thickness | 10 mm |

The 3D model of composite pressure vessel is shown in Figure 1

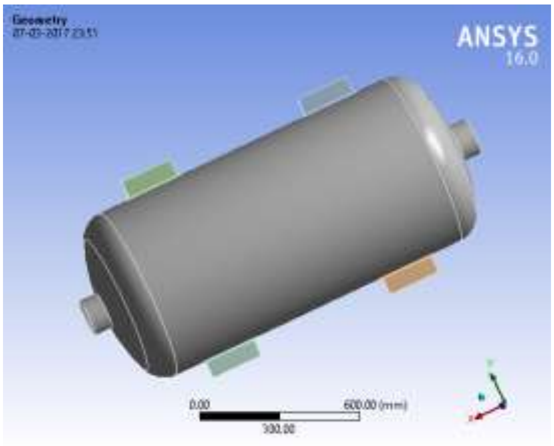


**Figure 1** The 3D model of composite pressure vessel

### 5.1 Meshing

After modelling the entire 3D structure the model is meshed. Individual finite element can be visualised as small pieces of a structure. The elements are connected at points called nodes. Elements must be small enough to give accurate results and large enough to reduce computational effort. SHELL 181 and SOLID 187 are the element type used. The shell structure is modelled by SHELL 181 and support is modelled by SOLID 187. The figure 2 shows the meshed 3D structure.

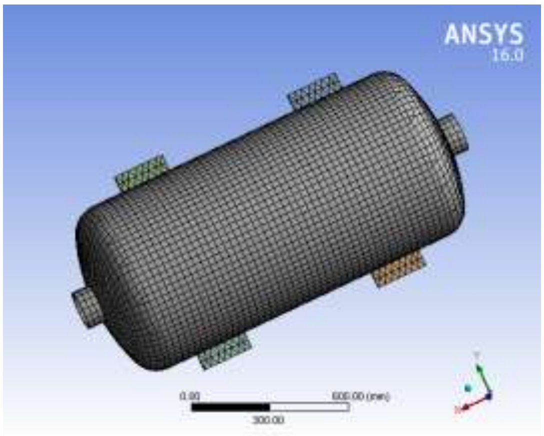


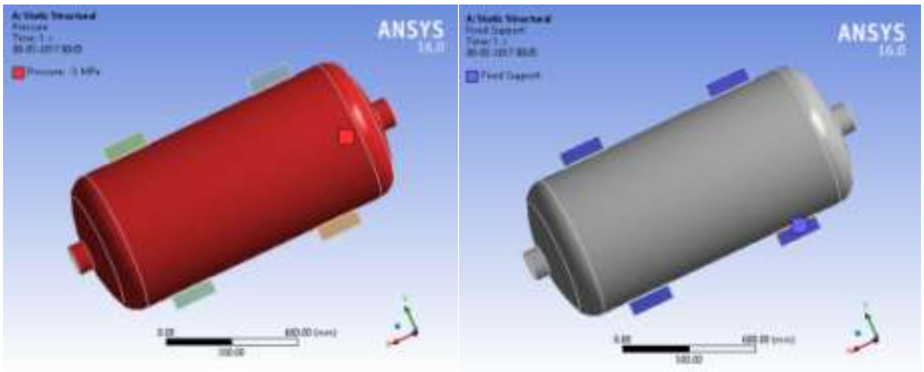
**Figure 2** Finite element model of pressure vessel

### 5.2 Element description

SHELL 181 and SOLID 187 are the element type used. Both the shell structure and stiffeners are modelled by SHELL 181 and support is modelled by SOLID 187. SHELL 181 is suitable for analysing thin to moderately thick shell structures. It is a 4 noded element with 6 degrees of freedom at each node: translation in X, Y, Z directions and rotation about X, Y and Z axes. SHELL 181 is well suited for linear large rotation and large strain non-linear application. SOLID 187 element is a higher order 3-D, 10 node element. It has a quadratic displacement behaviour and well suited to modelling irregular meshes. The element is defined by 10 nodes having 3 degrees of freedom at each node: translation in the nodal X, Y and Z directions. Element has plasticity, hyper elasticity, creep, stress stiffening, large deformation and large strain capabilities.

### 5.3 Loading and boundary condition

The working pressure of pressure vessel is 3MPa. An internal pressure of 3MPa is given in the shell structure and boundary condition is given as shown in figure 3(a) and 3(b) respectively. The boundary condition given is fixed support on the wings of the pressure vessel.



(a) Loading (b)Boundary condition

**Figure 3** Loading and boundary conditions of finite element model

## VI. RESULTS AND DISCUSSION

### 6.1 static analysis

### 6.1.1 Von mises stress

The figure 4 shows the von-mises stress of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers.

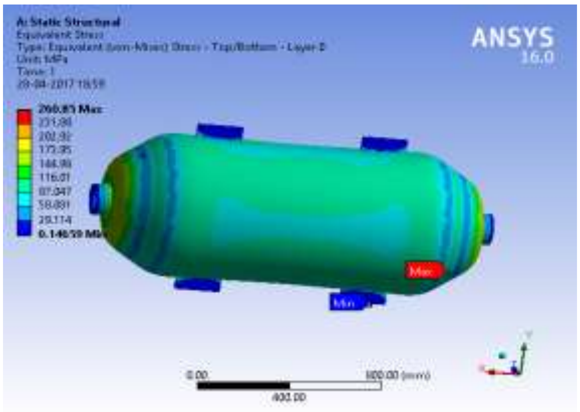


**Figure 4** Von-mises stress contour of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers

For carbon/epoxy von-Mises stress increases up to 45° thereafter it decreases up to 90° for all number of layers. As the number of layer increases, slight difference is observed in the value of von-Mises stress. Von-mises stress is maximum at 45° and minimum at 90° for all number of layers. Von-Mises stress is minimum for 15 numbers of layers compared to other numbers of layers considered. Von- mises stress for 15 numbers of layers is 0.52% less than 10, 20, 25 numbers of layers for 90° orientation. Figure 5 shows the variation of Von-mises stress for different fiber orientation and for different numbers of layers.

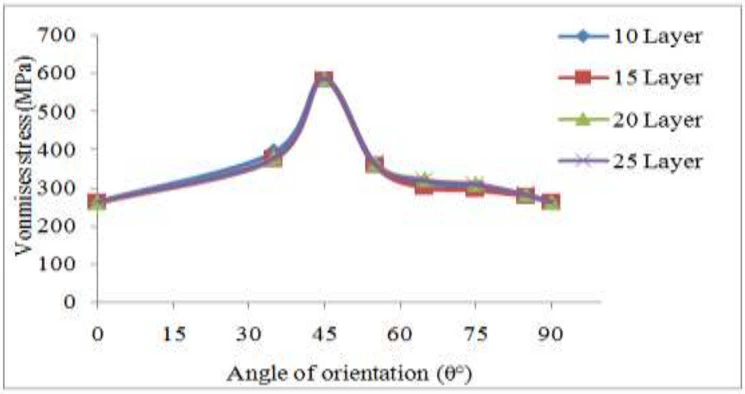


**Figure 5** Variation of von-Mises stress for different fiber orientation for carbon /epoxy

For E glass/epoxy as the angle of orientation increases from 0° to 35° von-mises stress decreases, then von-mises stress reach peak at 45° thereafter it decreases up to 65° and then increases up to 90° for all number of layers. Eventhough von-mises stress is minimum for 15 number of layers compared to 10, 20, 25 number of layers there is only a slight difference observed between their values after 45°. Maximum von-mises stress is at 45° and minimum at 65° for all number of layers. Von-mises stress is 1.17% 2.29% 1.8% lesser for 15 number of layers compared to 10, 20, 25 number of layers respectively for 65° orientation. Figure 6 shows the variation of von-mises stress for different fiber orientation and different numbers of layers.

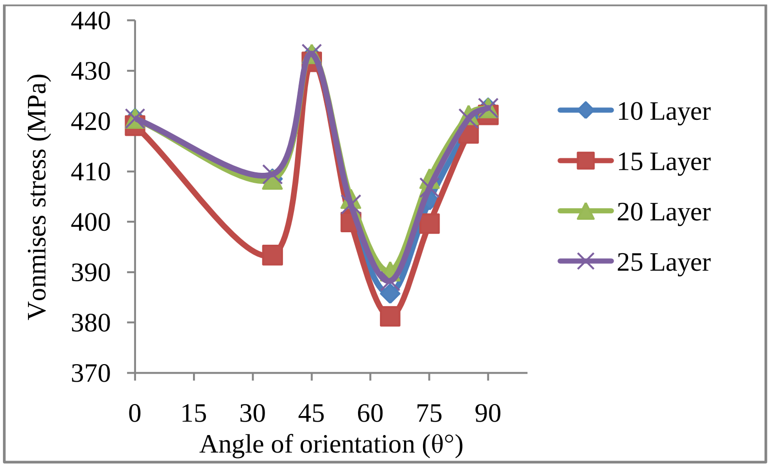


**Figure 6** Variation of von-mises stress contour for different fiber orientation for E glass/epoxy

For S glass epoxy maximum von-mises stress is observed at 90° and minimum at 65°.Von-mises stress is 1.35%, 2.52% and 2.0% lesser for 15 numbers of layers than compared to 10, 20 and 25 numbers of layers respectively corresponding to least stress angle of orientation 65°. Figure7shows the variation of von-mises stress for different fiber orientation and different numbers of layers of S glass epoxy.

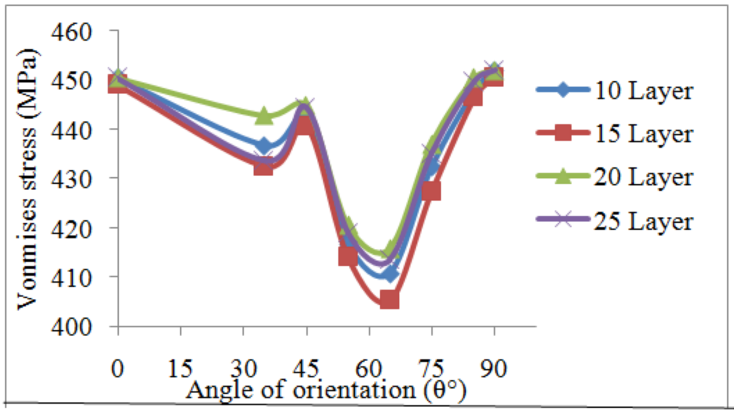


**Figure 7** Variation of von-mises stress for different fiber orientation for S glass/epoxy

### 6.1.2 Maximum principle stress

Figure 8 shows the maximum principle stress of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers.

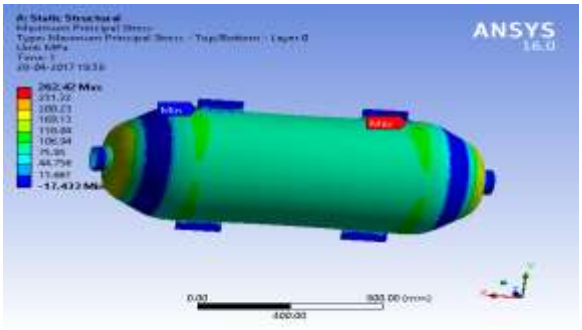


**Figure 8** Maximum principle stress contour of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers

For carbon /epoxy maximum principle stress increases up to 45 then it decreases up to 65° and then slightly increases up to 90°. Principle stress maximum at 45° and minimum at 65°. Figure 9 shows the variation of maximum principle stress for different fiber orientation and different numbers of layers. Maximum principle stress is minimum for 15 numbers of layers compared to 10, 20 and 25 numbers of layers. Maximum principle stress is 1.125%, 1.07%, 0.87 % lesser for 15 numbers of layers compared to 10, 20 and 25 numbers of layers respectively corresponding to 65° orientation.

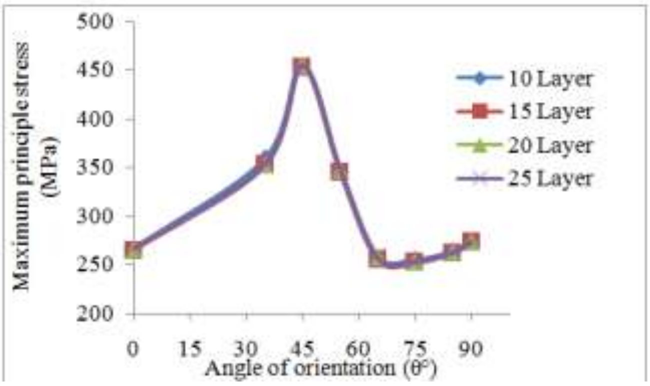


**Figure 9** Variation of maximum principle stress for different fiber orientation for carbon /epoxy

For E glass /epoxy maximum principle stress increases up to 45 then it decreases up to 65° and then it slightly increases up to 90°. Principle stress maximum at 45° and minimum at 65°. Maximum principle stress minimum for 15 numbers of layers for all angle of orientation. Maximum principle stress is 1.129%, 2.35%, 1.83% lesser for 15 numbers of layers compared to 10, 20 and 25 numbers of layers respectively corresponding to 65°orientation. Figure 10 shows the variation of maximum principle stress for different fiber orientation and different numbers of layers.

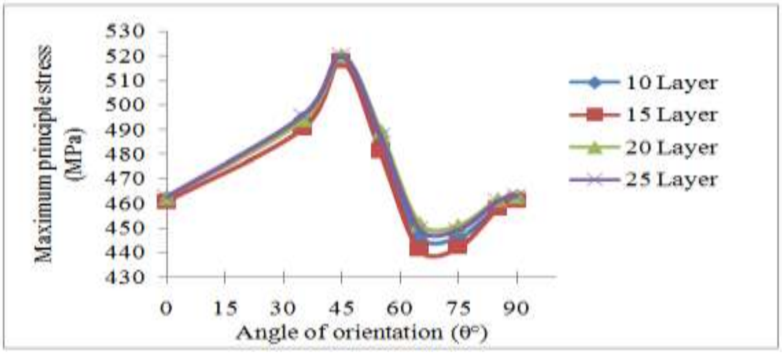


**Figure 10** Variation of maximum principle stress for different fiber orientation for E glass /epoxy

For S glass /epoxy maximum principle stress increases up to 45° then it decreases up to 65° and then it increases up to 90°. Principle stress maximum at 45° and minimum at 65°. Maximum principle stress is minimum for 15 numbers of layers for all angle of orientation. That is the variation is similar to that of E glass /epoxy. Maximum principle stress 1.15%, 2.37%, 1.86% lesser for 15 numbers of layers compared to 10, 20 and 25 numbers of layers respectively corresponding to 65°orientation. Figure 11 shows the variation of maximum principle stress for different fiber orientation and different numbers of layers.

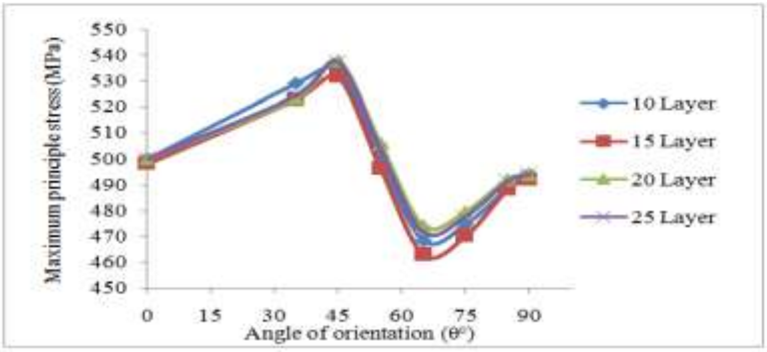


**Figure 11** Variation of maximum principle stress for different fiber orientation for S glass /epoxy

### 6.1.3 Deformation

The figure 12 shows the deformation of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers by performing static analysis.

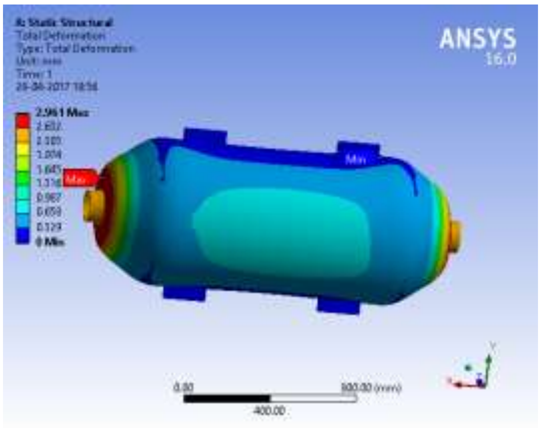


**Figure 12** Deformation contour of static analysis of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers.

Deformation of static analysis of carbon /epoxy laminated composite pressure vessel is observed for different numbers of layers. The figure 13 shows the variation of deformation of static analysis for different angle of orientation with different numbers of layers. The deformation is increases up to 45° thereafter it decreases. The deformation on static analysis is maximum at angle of orientation 45°. We can conclude that the effect is negligibly small while varying the number of layers. This may be due to the fact that this pressure vessel is a thin shell. But comparing the values of deformation on static analysis, pressure vessel with 15 numbers of layers has least deformation than other numbers of layers. That is deformation is 0.58% lesser than other number of layers.

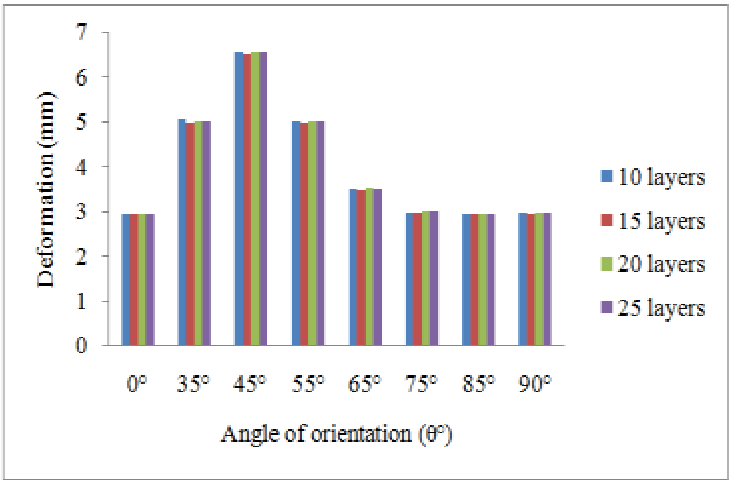


**Figure 13** Variation of deformations for different fiber orientation for carbon /epoxy

Figure 14 shows the variation of deformation on static analysis for different angle of orientation with different numbers of layers. The deformation is increases up to 45° thereafter it decreases. The deformation on static analysis is maximum at angle of orientation 45°. Same effect that have observed for carbon/ epoxy can be seen here. But total deformation of 15 numbers of layers is 0.60% lesser than other number of layers.

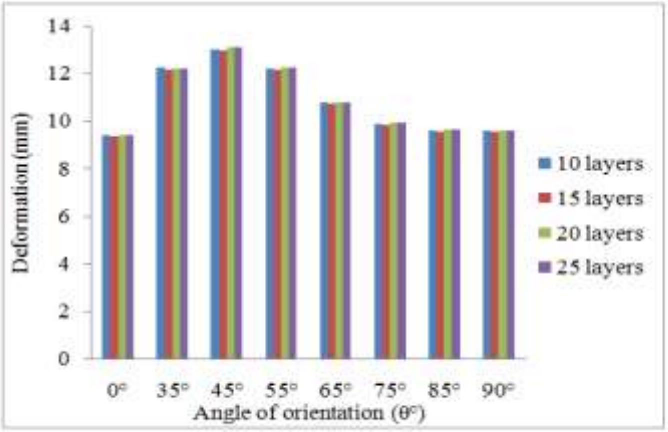


**Figure 14** Variation of deformations for different fiber orientation for E glass/epoxy

Figure 15 shows the variation of deformation on static analysis for different angle of orientation with different numbers of layers. The variation is similar to that observed for carbon/epoxy and E glass/epoxy. The deformation on static analysis is maximum at angle of orientation 45°. Deformation of S glass/epoxy laminated composite pressure vessel with 15 numbers of layers is 0.60% lesser than other number of layers.

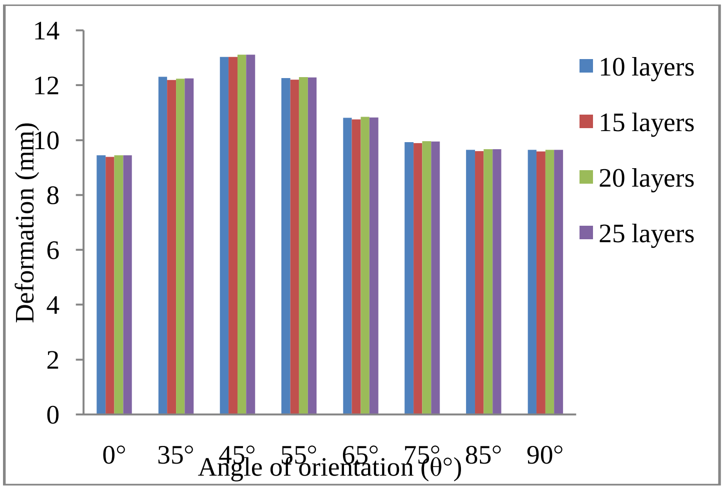


**Figure 15** Variation of deformations for different fiber orientation for S glass/epoxy

### 6.2 BUCKLING ANALYSIS

After static analysis eigen value buckling analysis is done. Buckling analysis is executed for 6 numbers of modes. Total deformation and critical buckling pressures are obtained for 6 modes. Minimum deformation and maximum critical buckling pressure were observed for mode 1.

### 6.2.1 Critical buckling pressure

Figure 16 shows the buckled deformation contour of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers.

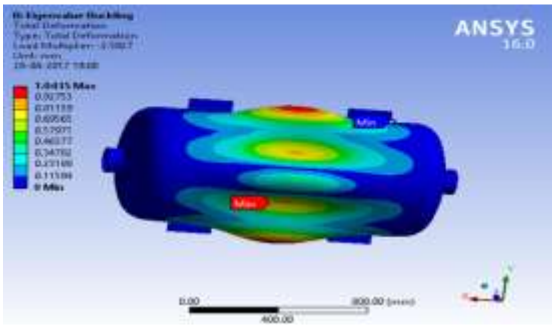


**Figure 16** Buckled deformation contour of 90° oriented carbon/epoxy laminated composite pressure vessel with 15 numbers of layers

Figure 17 shows the variation of critical buckling pressures for carbon/epoxy with different angle of orientation with 10, 15, 20 and 25 numbers of layers. The maximum critical buckling pressure is observed at 90° and minimum critical buckling pressure observed for 45°. Critical buckling pressure is maximum for 15 numbers of layers.

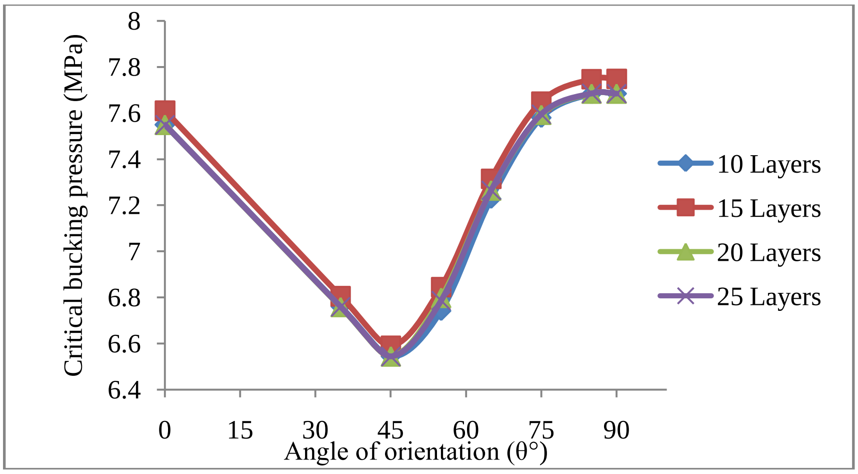


**Figure 17**Variation of critical buckling pressure with respect to angle of orientation for carbon/epoxy

Figure 18 shows the variation of critical buckling pressures for E glass/epoxy with different angle of orientation with 10, 15, 20, and 25 numbers of layers. The maximum critical buckling pressure is observed at 85° and minimum critical buckling pressure observed for 45°.And critical buckling pressure is maximum for 15 numbers of layers.

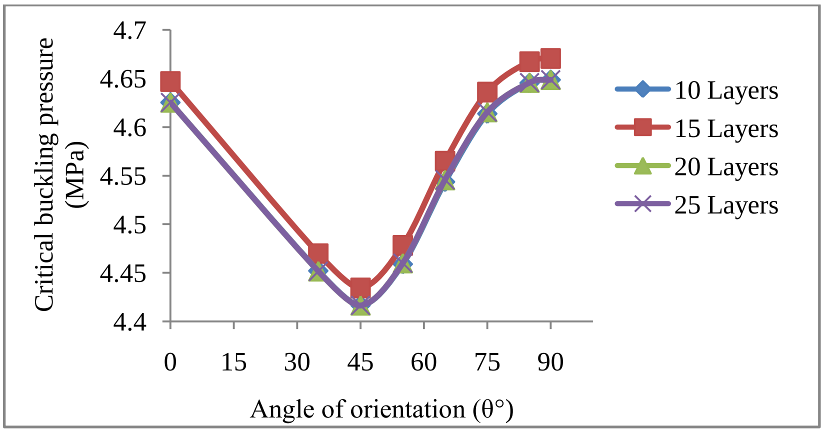


**Figure 18** Variation of critical buckling pressure with respect to angle of orientation for E glass/epoxy

Figure 19 shows the variation of critical buckling pressures for S glass/epoxy with different angle of orientation with 10, 15, 20 and 25 numbers of layers. The critical buckling pressure is observed at 85° and minimum critical buckling pressure observed for 45°. And here also critical buckling pressure is maximum for 15 numbers of layers.

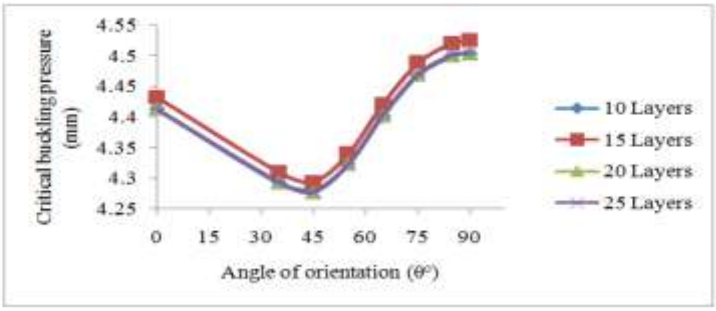


**Figure 19** Variation of critical buckling pressure with respect to angle of orientation for S glass/epoxy

## VII. CONCLUSIONS

1. Maximum critical buckling pressure and minimum stress is for carbon/epoxy than that of E glass and S glass epoxy. And it is observed for composite carbon epoxy pressure vessel with 15 numbers of layers at 90° orientation
- Von-mises stress for carbon epoxy is 34.98% lesser than E glass/ epoxy and 39.22% lesser than S glass/ epoxy corresponding to 15 numbers of layers at 90° fibre orientation
- Maximum principle stress for carbon epoxy is 43.08% lesser than E glass/ epoxy and 46.65% lesser than S glass/ epoxy corresponding to 15 numbers of layers at 90° fibre orientation
- On static analysis the total deformation of carbon /epoxy is 64.87% lesser than E glass/ epoxy and 69.09% lesser than S glass/ epoxy
- Critical buckling pressure for carbon epoxy is 39.72% greater than E glass/ epoxy and 41.59% greater than S glass/ epoxy corresponding to 15 numbers of layers at 90° fibre orientation
2. Composite pressure vessel with 15 numbers of layers found to give least stresses, minimum deformation and maximum critical buckling pressures than that of 10, 20 and 25 numbers of layers.
- For carbon/ epoxy ,von- mises stress for 15 numbers of layers is 0.52%, total deformation is 0.58% lesser than other number of layers at 90° orientation
- On buckling analysis of carbon epoxy with 15 numbers of layers the critical buckling pressure is 0.82% higher than that of 10, 20, 25 numbers of layers
3. Carbon/epoxy,its weight also less (density low) compared to other two composites.
4. So the carbon epoxy pressure vessel with 15 numbers of layers at 90° orientation is best for the tank body.

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