# Numerical Investigation on Strength of Isotropic and Laminated Composite Pressure Vessel

**Venkata Narayana Yenugula and Raja Shekhar Bhukya**

**Abstract** Cylindrical pressure vessels are being used in different industrial applications like power plants, chemical and processes plants to store and use fluids and liquids. The thermal, fatigue and static stress analysis has been carried out on cylindrical pressure vessels for a given geometry with different materials. Buckling analysis also carried out to find the satiability of the cylindrical pressure vessel with hemispherical domes. The generalized finite element code with Ansys is used to perform the above analysis. The static analysis is to determine the stress, deformation and strain. Fatigue analysis is performed to determine life, damage and safety factor of the pressure vessel using AISI-1513 steel, carbon fiber and E-glass fiber-reinforced materials. Thermal analysis has been carried out to find the temperature gradients and rate of heat transfer per unit area of the pressure vessel using AISI-1513 steel, carbon fiber and E-glass fiber materials. Buckling analysis of pressure vessel has been carried out with AISI-1513 steel and with the laminated composite material. Comparisons are made after performing static, fatigue and thermal analysis with different materials.

**Keywords** Pressure vessel · Static analysis · Buckling analysis · Factor of safety · Fatigue analysis and carbon fiber

## 1 Introduction

Metals as well as composite pressure vessels were designed for holding gases and liquids at substantially very high pressure. Historically, it was evident that improper design of pressure vessels causes fatal accidents and hazardous environment in plants during development of pressure vessels and their operations. Consequently, design, developments and operations of pressure vessels are controlled and monitored by some accredited engineering departments supported by legislations. Due to this reason, definition and development procedures of pressure vessels vary for different

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countries. The design parameters which influence the safety of pressure vessels are maximum working pressure, minimum temperature, safety factor and corrosion allowances for metallic pressure vessels. Leak-proof development and manufacturing pressure vessels decrease extensive damage of property, and also physical injuries can be avoided. General theoretical shapes of pressure vessels are cylindrical pressure vessels, spherical and cone-shaped pressure vessels. Spherical vessels are stronger among other shapes, but development and manufacturing are very complicated. Pressure vessels material should consist of more ductility and toughness to withstand different pressure variations during operation [1, 2]. Pressure vessels manufactured with metals are less preferable in automotive, aerospace industries and gas and oil refinery industries because of having more weight to strength factor and more corrosion characteristics. These companies are in demand with lightweight materials (high strength to weight ratio) such as carbon fiber and glass fiber-reinforced materials. Composite materials are used for increasing performance of different structures due to having more strength to weight ratio and replacing conventional metal material [3–5].

Kharat. A et al. [6] carried out literature review on stress analysis of composite pressure vessels and concluded that ASTM and other codes sufficient enough to give solutions for regular-shape pressure vessels with higher factor of safety. But pressure vessels with non-standard shapes with geometric discontinuities with limit loads and stress concentration are not possible to analyze with the above codes. Abdalla et al. [7] studied and formulated analytically optimum shape and thickness of the pressure vessel and observed that the solutions were admitted only for additional constraints. Raja et al. [8] made an attempt to evaluate the bursting pressure of filament wounded pressure vessel with different layup sequences using commercially available finite element software, Ansys. Abdolreza. T et al. [9] done critical review on pressure vessel analysis based on ASTM pressure vessel code and observed that it is essential to choose suitable analytical procedure to design and analysis of different pressure vessels. In industrial applications, fiber-reinforced composite shells and pressure vessels undergo high operating pressure throughout their life cycle. Generally, 15–300 MPa pressure range is used for high pressure vessels

## 2 Methodology of Paper

Based on the radius ($r$) to thickness ratio ($t$), there are two types of approaches in design of pressure vessels analysis. First method: if the r/t ratio is more than 20, we need to go for structural stability analysis, otherwise elasticity approach need to be followed. The geometry of the pressure vessel is as follows: overall length = 1732 mm**,** thickness = 15 mm and radius = 335 mm was taken for performing analysis. Buckling analysis is one of the most important collapse modes of the pressure vessel. The first one is that pressure vessel code usually only provided design method by rules to protect against global bulking of shell under conventional loads, such as external pressure or axial compression load.

**Table 1** AISI-1513 steel mechanical properties

| Name of the property | Property value |
|---|---|
| Modulus of elasticity | $200 \times 10^5$ N/mm$^2$ |
| Poisson's ratio | 0.29 |
| Shear modulus | $80 \times 10^5$ N/mm$^2$ |
| Ultimate tensile strength | $36010^5$ N/mm$^2$–480 N/mm$^2$ |
| Tensile strength, yield | $215 \times 10^5$ N/mm$^2$ |

The material properties of the pressure vessel are as shown in Table 1. The internal pressure used for the above analysis was 15 N/mm$^2$ with different boundary conditions. The *r*/*t* ratio of the pressure vessel considered here is 22. In this work, the analysis of geometric failure and material failure was carried out using generalized finite element software, Ansys. The 2D drawing which gives the overall dimensions of the pressure vessel is shown in Fig. 1. To get the overall idea about the pressure vessel, solid modeling was developed by using CATIA as shown in Fig. 2.

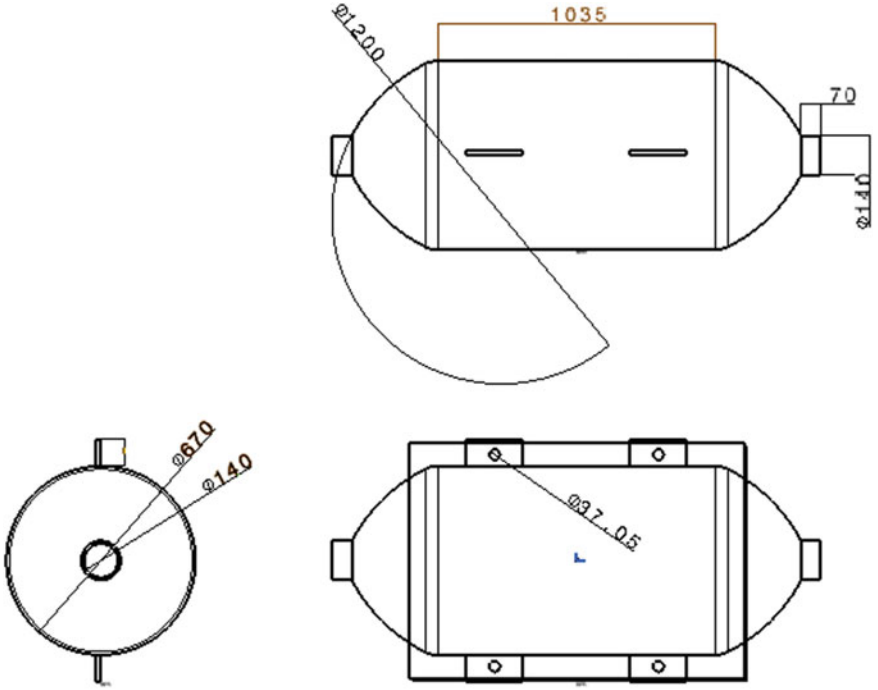

**Fig. 1** 2D model of pressure vessel

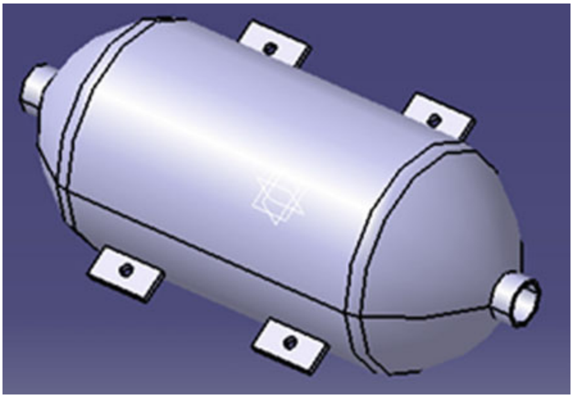

**Fig. 2** Solid model of pressure vessel

## 2.1 Buckling Analysis of Pressure Vessel Using Ansys

For modeling purpose, a shell 281 element is being selected among the available element library of Ansys. The eight-nodded shell element 281 having six degrees of freedom at each node is used in buckling analysis of pressure vessel. The boundary conditions used for the buckling analysis of isotropic and laminated composite (CFRP) pressure vessel is shown in Fig. 3.

The linear buckling analysis was carried out with different materials (AISI-1513 steel and carbon fiber-reinforced plastics—CFRP) and following boundary conditions as shown in Fig. 3.

1. Both ends of the pressure vessel fixed

$$Ux = Uy = Uz = Rx = Ry = Rz = 0 \tag{1}$$

2. Fixed at four points on cylindrical portion

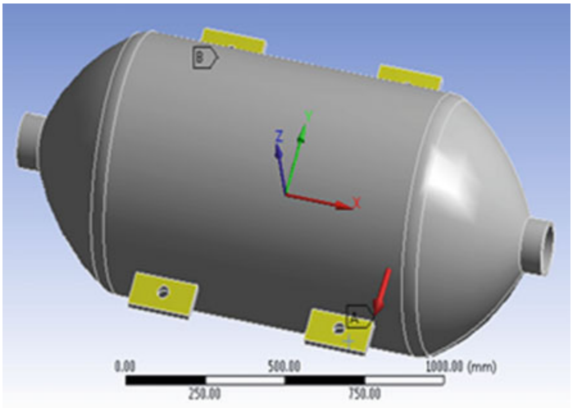

**Fig. 3** Boundary conditions on cylindrical portion

**Table 2** **(a)** CFRP mechanical properties, **(b)** GFRP mechanical properties

| **(a)** | | |
|---|---|---|
| Name of the property | Direction | Property value |
| Modulus of Elasticity in longitudinal direction | $E_1$ | $2.7 \times 10^5$ N/mm$^2$ |
| Modulus of Elasticity in transverse direction | $E_2$ | $5.2 \times 10^3$ N/mm$^2$ |
| Shear modulus | $G_{12}$ | $2.6 \times 10^3$ N/mm$^2$ |
| Poisson's ratio | $\nu_{12}$ | 0.25 |
| **(b)** | | |
| Modulus of Elasticity in longitudinal direction | $E_1$ | $1.0.64 \times 10^5$ N/mm$^2$ |
| Modulus of Elasticity in transverse direction | $E_2$ | $1.27 \times 10^3$ N/mm$^2$ |
| Shear modulus | $G_{12}$ | $3.0 \times 10^3$ N/mm$^2$ |
| Poisson's ratio | $\nu_{12}$ | 0.20 |

$$Ux = Uy = Uz = Rx = Ry = 0 \tag{2}$$

The above boundary conditions were as per the horizontal pressure vessel realistic conditions. The material properties of the steel (AISI-1513 steel) and the CFRP-laminated composite material is as shown in Tables 1 and 2, respectively. The CFRP-laminated composite material is widely used in civil and offshore applications; generally, it is a quasi-isotropic material having four fundamental elastic constants. Other five elastic constants for this material used to find using empirical formulas in order to convert this in to orthotropic material.

The quasi-isotropic angle-ply (v/v)5s, where *v*=,45°, orientation with 1.5-mm layer thickness of the carbon fiber-reinforced plastic material was used for investigation of the buckling analysis.

The results of linear buckling analysis of pressure vessels using generalized finite element software, Ansys with two different materials (isotropic and laminated composite material) and two different boundary conditions are as shown in Table 3. It is evident that the buckling factors for the steel pressure vessels are more than CFRP material pressure vessel. It is also observed that the critical buckling pressures for the steel pressure vessels are more than the applied pressure than the CFRP pressure for a given boundary condition of the finite element model. Generally, it is also known that if BLF (buckling load factor) <1 pressure vessel loses its geometry rather than elastic failure. The critical pressures (Pcr) of the isotropic pressure vessel are observed to

**Table 3** Buckling load factors and critical loads

| SN | Material | Lay-up sequence | B.C'S | BLF | $P_{cr}$ |
|---|---|---|---|---|---|
| 1 | Steel | – | Fixed-Ends | 1.93 | 20.42 |
| 2 | Steel | – | Fixed on cylinder | 1.36 | 28.95 |
| 3 | CFRP | $(45°/\text{-}45°)_{5\ s}$ | Fixed-Ends | 0.37 | 5.59 |
| 4 | CFRP | $(45°/\text{-}45°)_{5\ s}$ | Fixed on cylinder | 0.51 | 7.63 |

be more than the applied pressure (15 N/mm$^2$). 1705 mm effective length, 15 mm thickness and 15 MPa internal pressure was considered for buckling of isotropic and laminated composite pressure vessels. The buckling factors and critical pressures of laminated pressure vessels were observed to be less than the AISI-1513 steel.

The first fundamental mode shape of CFRP pressure vessel and AISI-1513 steel pressure vessels with fixed end boundary conditions are shown in Fig. 3. Fig. 4a shows the first mode shape and critical buckling load (5.59 MPa) of CFRP material pressure vessel. Fig. 4b shows the first mode shape and critical buckling load (20.42 MPa) of AISI-1513 steel pressure vessel. The buckling analysis was carried out with the effective length of the pressure vessel using Ansys, and other attachments were removed (Fig. 4).

### *2.2 Static, Fatigue and Thermal Analysis of Pressure Vessel*

The fatigue analysis has been carried out to find out the life, damage and safety factor of the pressure vessel after completing the static analysis. Fatigue analysis has been carried out with three different materials. The fatigue analysis results are shown in Figs. 5 and 6. Thermal analysis was carried out to find the temperature distribution and heat flux of the internal pressure vessel subjected to operating temperature and air convection as boundary conditions. In present work, 300 °C operating temperature, air convection, 30 °C ambient temperature and 2200 W/m$^2$ °C air film coefficient were considered. The results were evaluated for AISI-1513 steel pressure vessel and other two composite materials also.

## 3 Results and Discussions

### *3.1 Static Analysis*

Buckling analysis of pressure vessel with different boundary conditions and three different materials was carried out using finite element software, Ansys. Table 3 depicts the comparison of critical pressure of both AISI-1513 steel and CFRP pressure vessel. It has been observed that the critical pressure and buckling load factors of AISI-1513 steel are more than the composite pressure vessels.

The static analysis has been carried out on both AISI-1513 steel and composite pressure vessels. It is evident that the results of both AISI-1513 steel and the composite pressure vessel show that the induced stresses are well below the allowable stresses for a given boundary condition and geometry. Table 4 and Fig. 5 present the results of static analysis. E-Glass fiber has major contribution followed by AISI-1513 steel and carbon fiber. Deformation is low at AISI-1513 steel followed by E-Glass fiber and carbon fiber composite.

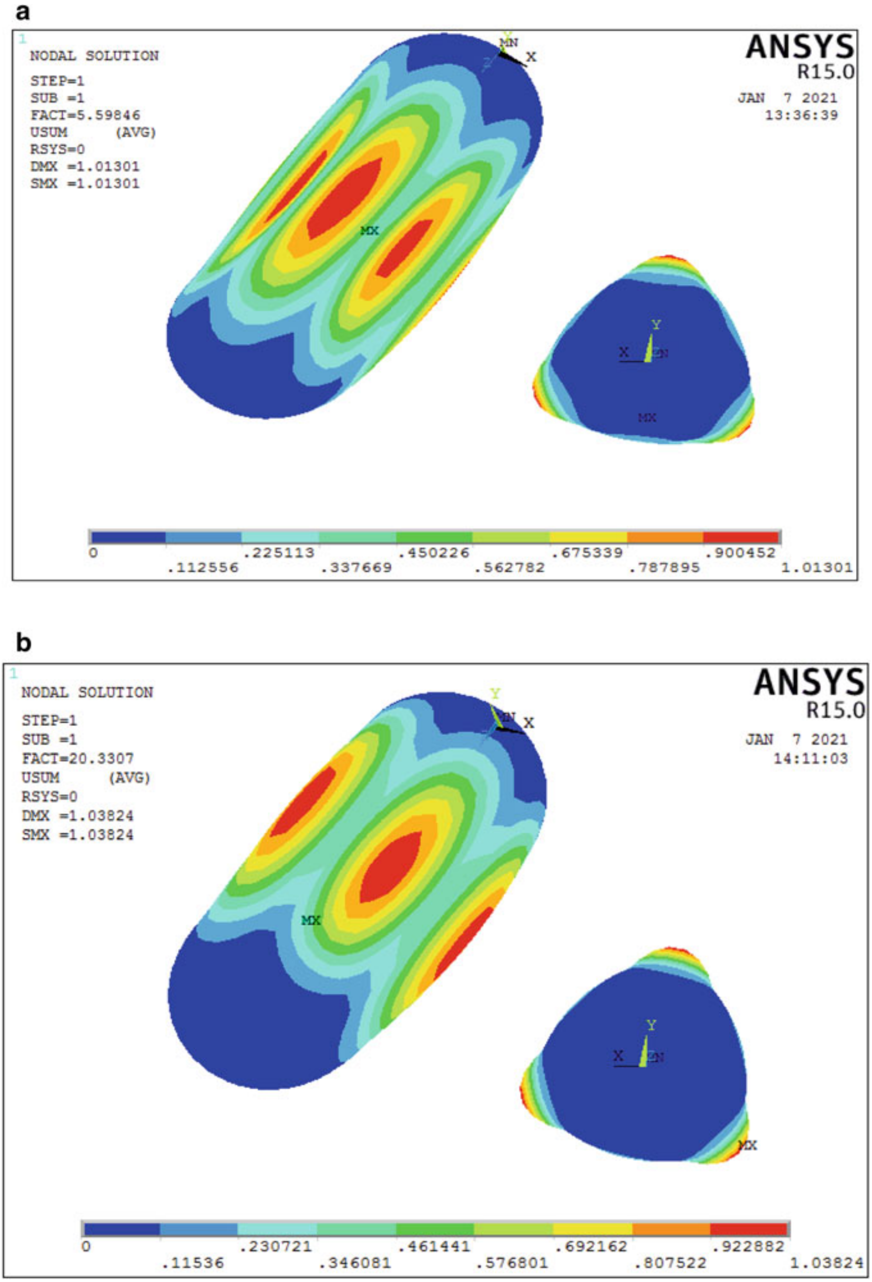

**Fig. 4** **(a)** CFRP-fixed ends, **(b)** Isotropic (steel)-fixed ends

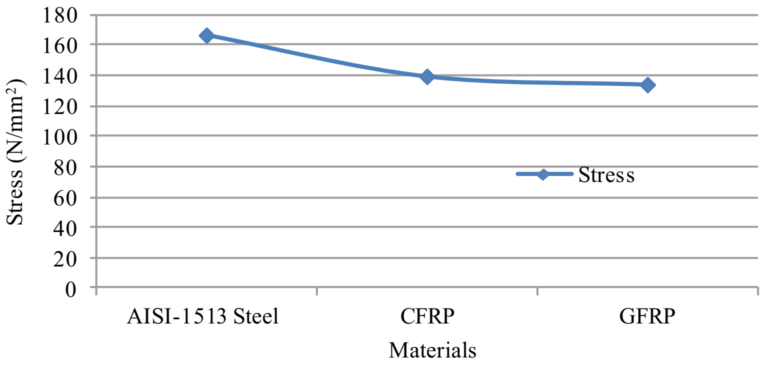

**Fig. 5** Static analysis stress versus materials

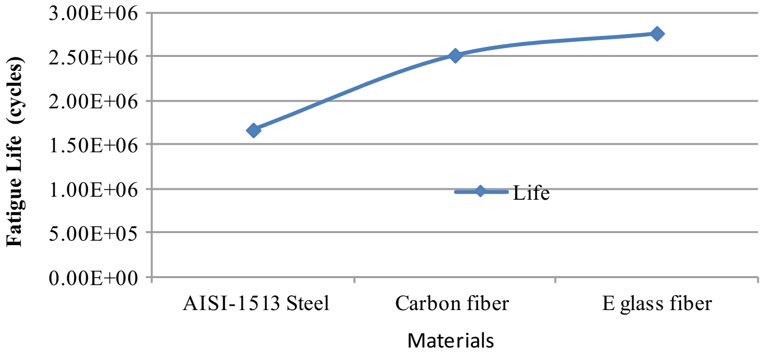

**Fig. 6** Fatigue analysis life and materials

**Table 4** Static analysis results

| Material | Deformation (mm) | Stress (N/mm$^2$) | Strain |
|---|---|---|---|
| Steel | 0.23452 | 166.73 | 0.00083952 |
| CFRP | 0.57623 | 139.64 | 0.0020695 |
| GFRP | 0.49539 | 134.21 | 0.0017375 |

## *3.2 Fatigue Analysis*

Fatigue analysis results were shown in Table 5, Figs. 6 and 7. Life of pressure vessel is good at E-glass fiber composite has major contribution followed by carbon fiber composite material and AISI-1513 steel. Damage is also low for E-glass fiber when compared to carbon fiber and AISI-1513 steel. Safety of pressure vessel is good for E-glass fiber material.

**Table 5** Fatigue analysis results

| Material | Temperature distribution (°C) | Heat flux (w/m$^2$) |
|---|---|---|
| AISI-1513 steel | 29.886 | 0.51658 |
| Carbon fiber | 30.00 | 0.59580 |
| E glass fiber | 30.002 | 0.86702 |

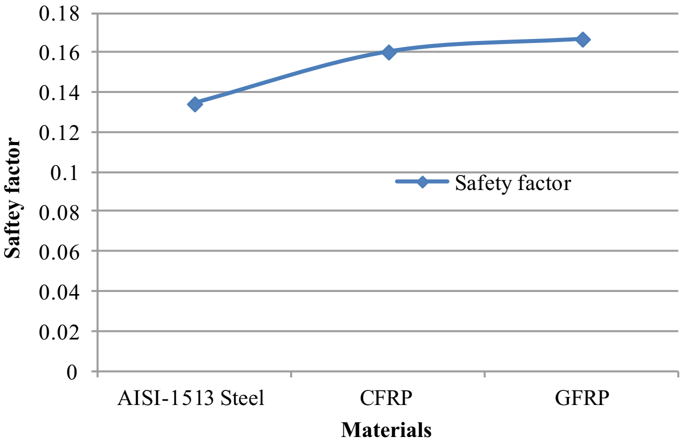

**Fig. 7** Safety graph

**Table 6** Thermal analysis results

| Material | Life | Damage | Safety factor |
|---|---|---|---|
| Steel | 1.67e$^6$ | 1323.9 | 0.13442 |
| CFRP | 2.52e$^6$ | 834.72 | 0.16051 |
| GFRP | 2.77e$^6$ | 752.99 | 0.16699 |

## *3.3 Thermal Analysis*

By observing the thermal analysis results Table 6 and Fig. 8, the heat dissipation is more for E-glass fiber material when compared to AISI-1513 steel and carbon fiber materials.

## *3.4 Linear Layer Analysis*

Table 7 and Fig. 9 present the results of linear layer analysis carbon-reinforced plastics material. In the linear layer analysis results, the stress values are less at 12 layers stacking pressure vessel model when compared to conventional model.

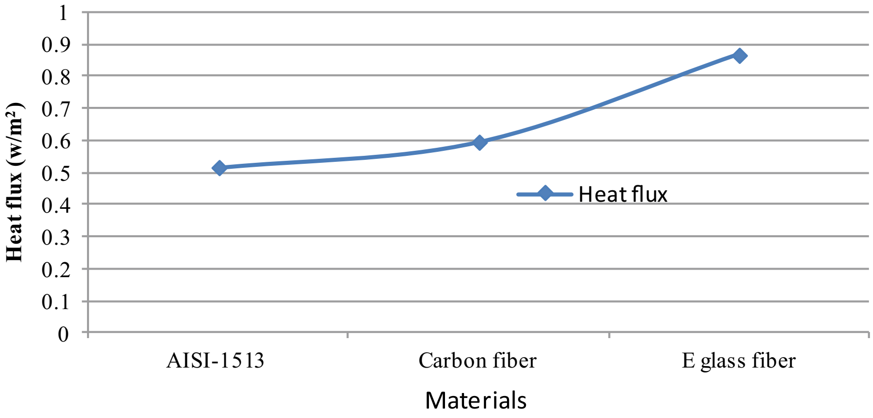

**Fig. 8** Heat flux graph

**Table 7** Linear layer analysis results

| Layer stacking | Deformation (mm) | Stress (N/mm$^2$) | Strain |
|---|---|---|---|
| 3 layers | 5.2012 | 199.35 | 0.01534 |
| 6 layers | 1.462 | 141.05 | 0.032109 |
| 9 layers | 6.248 | 138.68 | 0.01028 |
| 12 layers | 5.6307 | 101.8 | 0.008944 |

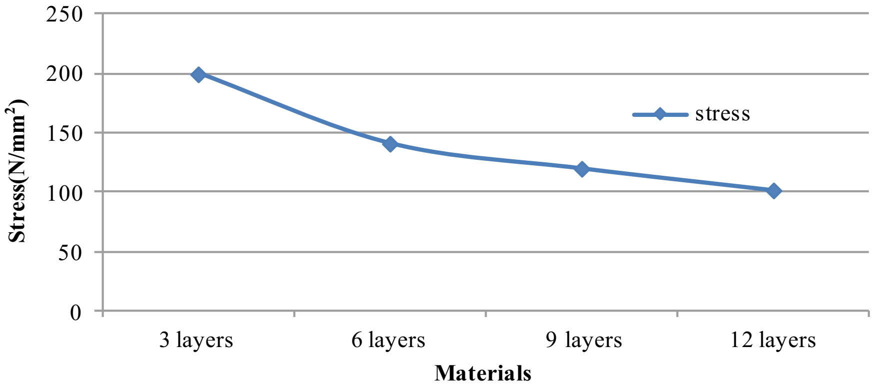

**Fig. 9** Layer analysis graph

## 4 Conclusions

Analysis of pressure vessels subjected to internal pressure has been carried out with different material and different loads for given geometry. The following conclusions are made after performing analysis using generalized finite element software, Ansys.

1. The static analysis has been carried out with different materials for given boundary conditions and pressure, and it has been observed that the induced stress value for E-glass fiber pressure vessel is 134.21 N/mm$^2$, whereas the stress values for AISI-1513 steel and carbon fiber-reinforced plastic pressure vessel are 166.73 N/mm$^2$ and 139.64 N/mm$^2$, respectively.
2. After performing fatigue analysis, it is also observed that GFRP (glass fiber-reinforced plastic) pressure vessels has more life (2.77e$^6$ cycles) than other materials, i.e., 2.52e$^6$ cycles for CFRP and 1.67e$^6$ cycles for steel pressure vessels.
3. It is also evident from the thermal analysis results that the heat dissipation is more (0.86702 w/m$^2$) for E-glass material in comparison with AISI-1513 steel (0.51658 w/m$^2$) and carbon fiber (0.51658 w/m$^2$) pressure vessels.
4. After observing all above results, it has been concluded that GFRP (glass fiber-reinforced plastic) pressure vessels is more suitable for this radius to thickness ratio and for given load and displacement boundary conditions.

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