Exploring the Theoretical and FE Aspects of Epoxy Composite Pressure Cylinders in Aerospace Engineering

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Abstract

This paper presents the theoretical design and finite element studies of high-pressure cylinders using different epoxy composites. In general, pressure cylinders are high-pressure shells that are commonly used in aerospace and automobile industries. It is well known that pressure cylinder develops mainly hoop stresses as compared with longitudinal stresses. By comparing with different metals, the fiber-reinforced composite materials result in high specific strength at different pressure conditions. The present work mainly focuses on a detailed understanding of the behavior of the fiber-reinforced composite pressure cylinders operating at different internal pressures.

Keywords: Composite pressure cylinder, Fiber reinforced composites, Hoop stresses, Longitudinal stresses, Ductile failure, Brittle failure

Nomenclature

d	Diameter	σ_t	Longitudinal stress
l	Length	δl	Change in length
t	Thickness	δd	Change in diameter
p	Intensity of max. internal pressure	$\varepsilon 1$	Circumferential strain
$\frac{1}{m}$	Poisson's ratio	$\varepsilon 2$	Longitudinal strain
σ_c	Circumferential stress		

1. Introduction

Nowadays, many materials are available for different applications. It is a big challenge for the selection of the right material and the suitable manufacturing process. We all know that metals exhibit high strength, stiffness, and electrical and thermal conductivity properties. They can also be used for high-temperature applications. Plastics are becoming a more common material nowadays, but due to their poor thermal stability, they can't be used for high-temperature applications. Ceramics will have strong covalent bonds, which give high hardness and thermal stability.

Among all these materials, composite materials exhibit great potential due to reinforcement and matrix phases. The applications of composite materials are gaining good importance due to their high fatigue strength and creep-tensile behaviors.

2. Literature survey

In general, as we all know, there are three types of composites. In particle-reinforced composites, particles of different sizes and shapes are randomly dispersed in the matrix. It increases the modulus of the matrix. Coming to fiber-reinforced composites, the properties mainly depend on fiber properties and the applied load. Based on fiber arrangement, they may be continuous or discontinuous-aligned composites, as shown in Fig. 1. In structural composites, properties mainly depend on design and reinforcement. The common structural composites are shown in Fig. 2(a) & (b).

Tabakov and Summers [1] used the stress function method to determine circumferential, radial and tangential stresses by considering a cylindrical cylinder closed at both ends. Khan [2] has done the stress distribution analysis for a horizontal pressure cylinder with saddle supports. Lei Zu et al. [3] presented a simple methodology with unequal polar openings. Alibeigloo [4] analyzed the free and static vibration features by using differential quadrature methods. Hocine et al. [5] present an analytical and experimental analysis of cylindrical cylinders filled with hydrogen. Rao and Narayana Rao [6] concluded that filament-wound composite pressure cylinders are good for automobile and aerospace industries. Roy and Tsai [7] present an efficient method of design for thick-pressure cylinders made of composite materials. However, many of these studies were not compared with the experimental approach during their analysis.

3. Design of pressure cylinders

According to the dimensions of pressure cylinders, they are mainly thin cylinders or thick cylinders, as mentioned below.

According to the ratio's

$$\frac{t}{d} \leq \frac{1}{10} \quad - Thin\ Cylinder \tag{3.1}$$

$$\frac{t}{d} \geq \frac{1}{10} \quad - Thick\ Cylinder \tag{3.2}$$

In general, thick shells are mainly used for high pressures. Thin cylinders design mainly involves the calculation of thickness (t) as

$$\text{Cylindrical cylinder thickness; } t = \frac{pd}{2\sigma_c} \tag{3.3}$$

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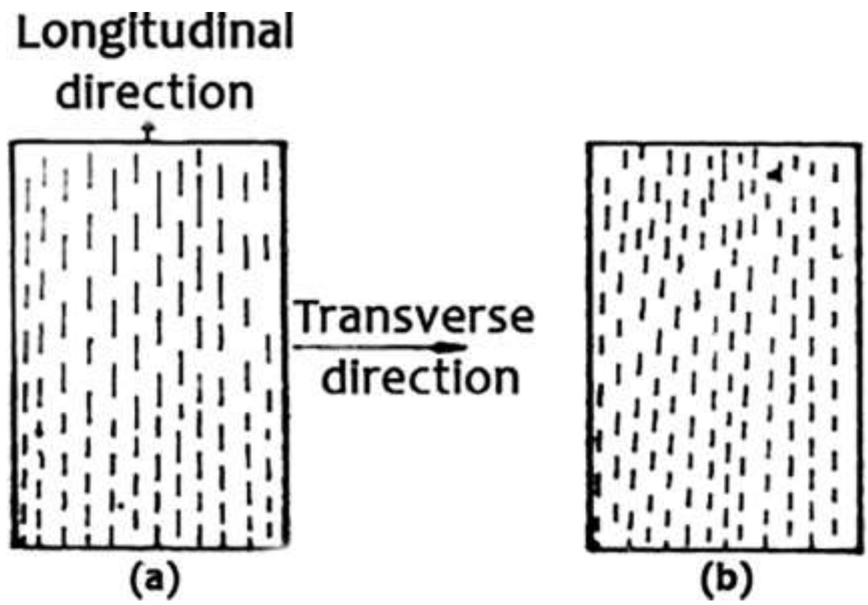

Fig. 1. Illustration of a) Continuous and b) Discontinuous reinforced composites.

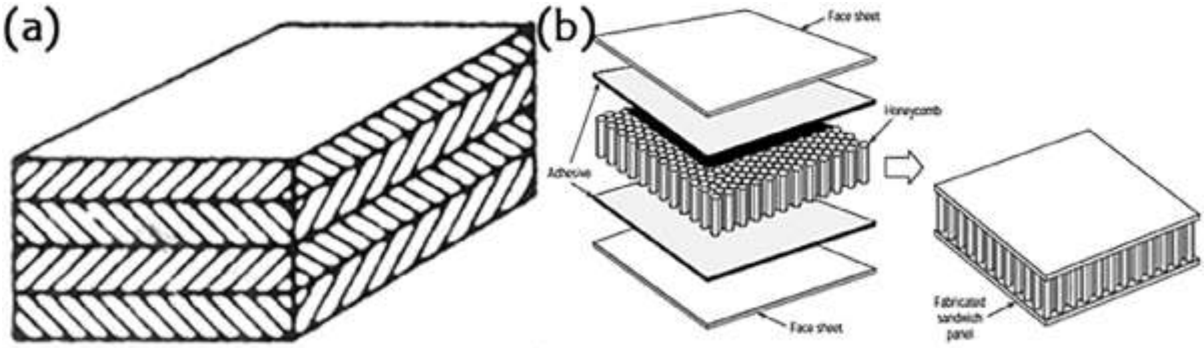

Fig. 2. Illustration of a) Laminated and (b) Sandwich-reinforced composite.

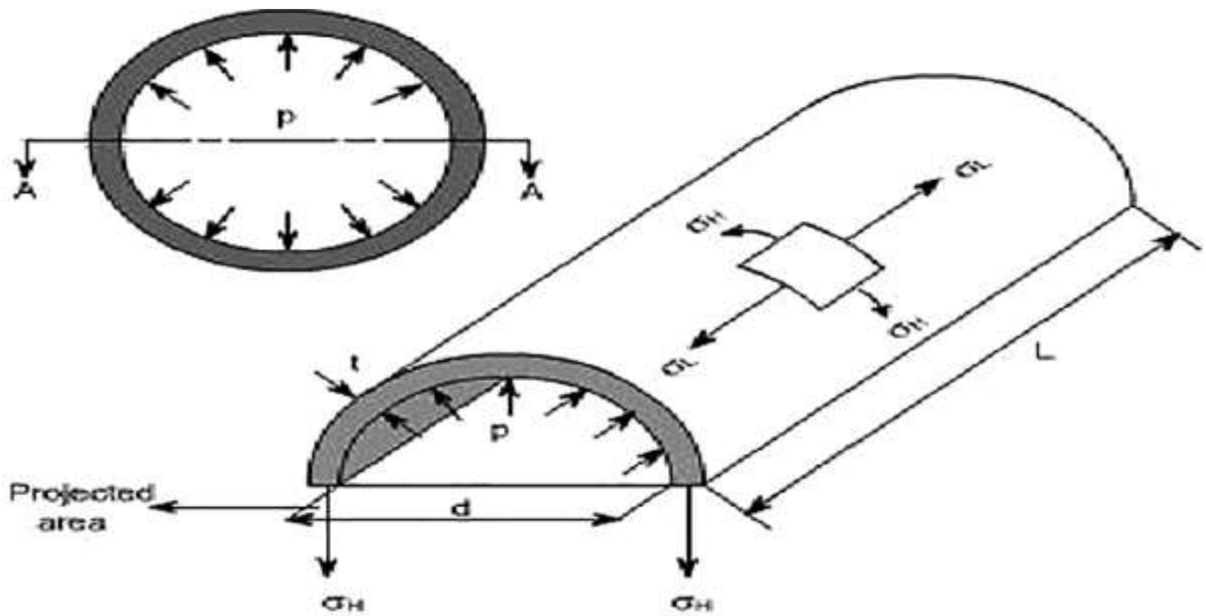

Fig. 3. Internal pressure distribution of cylindrical cylinder.

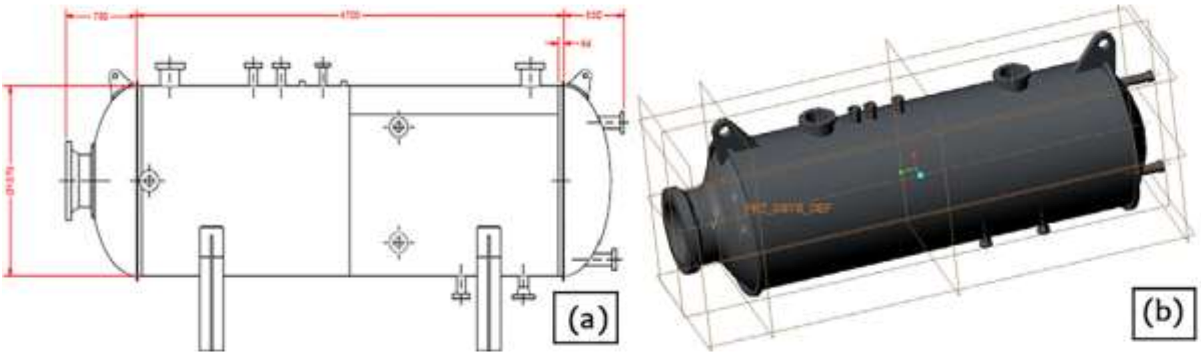

Fig. 4. (a) 2-D Model of pressure cylinder, and (b) Model developed in CREO parametric.

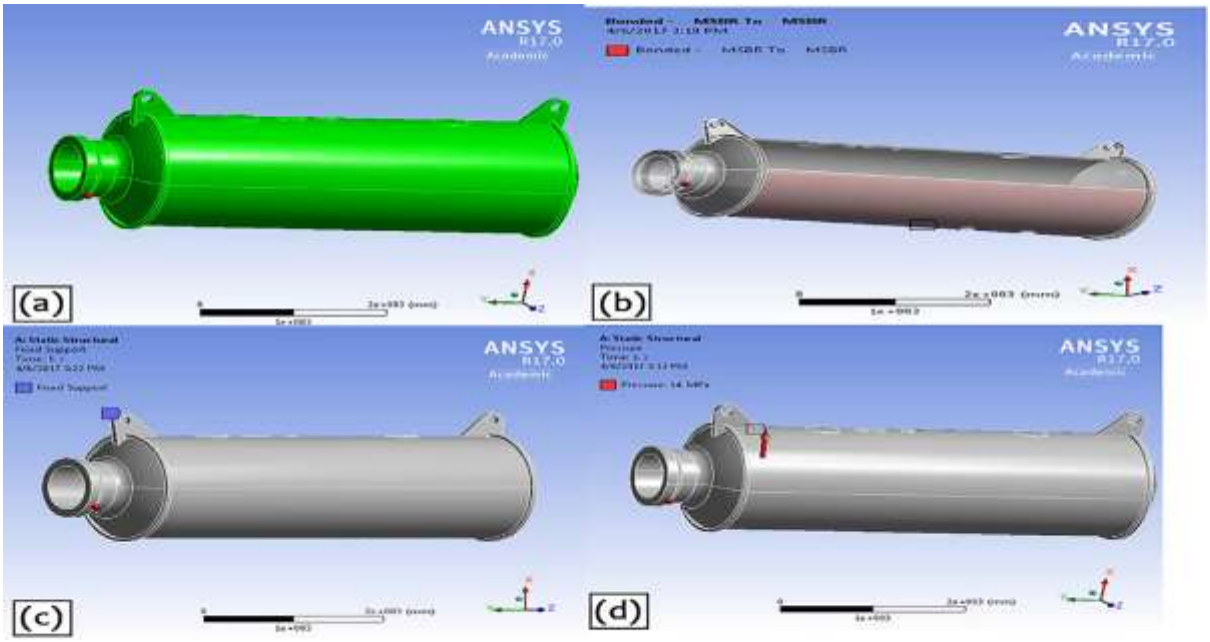

Fig. 5. (a) Pressure cylinder model, (b) Bonded region, (c) Fixed support, and (d) Internal pressure.

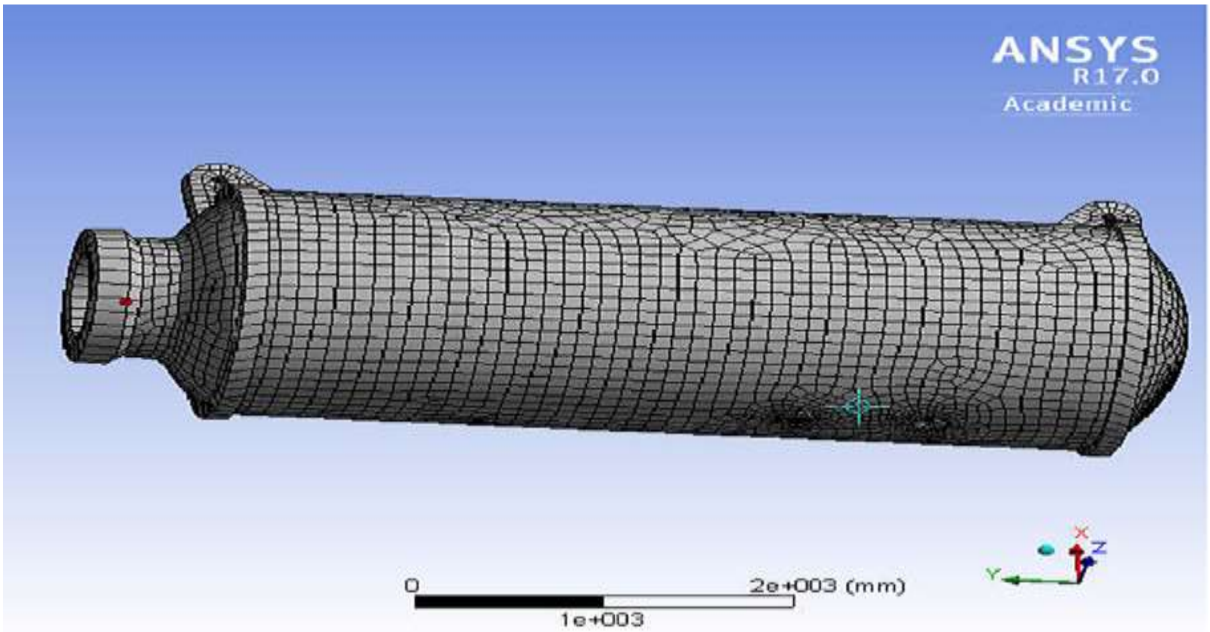

Fig. 6. Pressure cylinder with meshing Model.

The internal pressure distribution of the cylindrical cylinder is shown in Fig.3.

Circumferential stresses will be

$$\sigma_c = \frac{Total\ pressure}{Resisting\ section} = \frac{pdl}{2tl} = \frac{pd}{2t} \qquad (3.4)$$

The longitudinal stresses will be,

$$\sigma_c = \frac{Total\ pressure}{Resisting\ section} = \frac{pd}{4t} \qquad (3.5)$$

Now, changes in diameter and length may be found from the above equations,

$$\delta d = {}^{TM}{}_1 d = \frac{pd}{2tE}\left(1 - \frac{1}{2m}\right) * d \qquad (36)$$

$$\delta l = {}^{TM}{}_2 l = \frac{pdi}{2tE}\left(\frac{1}{2} - \frac{1}{m}\right) \qquad (3.7)$$

Table 1: Comparison of different composite material performance.

S. No	Material	Pressure (MPa)	Weight (kg)	Total deformation (mm)	Equivalent stresses (MPa)	Hoop stresses (MPa)	Longitudinal stresses (MPa)
1	Unidirectional epoxy carbon prepreg (230 GPa)	14	10,467	5.9	556.2	170.9	192.2
2	Unidirectional epoxy carbon Wet (230 GPa)	14	10,664	5.9	567.6	180.3	195.7
3	Unidirectional E-glass epoxy	14	14,049	8.2	354.8	118.6	147.3
4	E-glass epoxy wet	14	12,996	9.4	329.1	112.6	140.9
5	Epoxy resign	14	8148.7	23.4	119.9	42.4	195.7

General materials deformation and stresses.

Table 2

Different metal alloys performance.

S. No	Alloy	Pressure (MPa)	Weight (kg)	Total deformation (mm)	Equivalent stresses (MPa)	Hoop stresses (MPa)	Longitudinal stresses (MPa)
1	Aluminum (Al)	14	19,459	2.2	200	77.3	145.3
2	Copper (Cu)	14	58,305	1.4	200.7	77.5	148.2
3	Structural Steel epoxy	14	55,144	0.8	201.2	76.8	136.7

The weight comparison of different cylinders is tabulated in Table 3, having the same dimensions.

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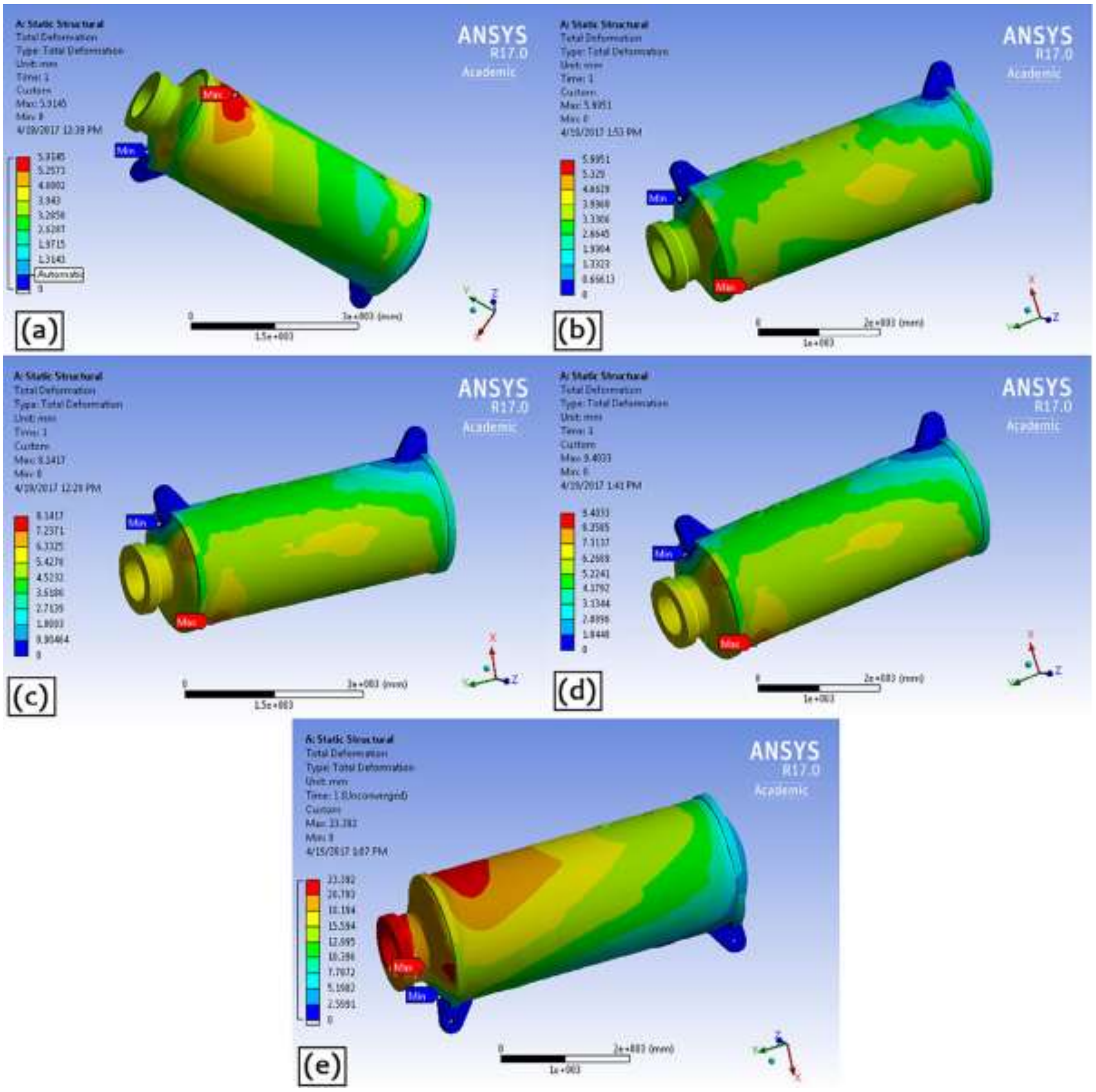

Fig. 7. Results of total deformation contours (a) Unidirectional epoxy carbon prepreg (230 GPa), (b) Unidirectional epoxy carbon Wet (230 GPa), (c) Unidirectional E-glass epoxy, (d) E-glass epoxy wet, and (e) Epoxy resign.

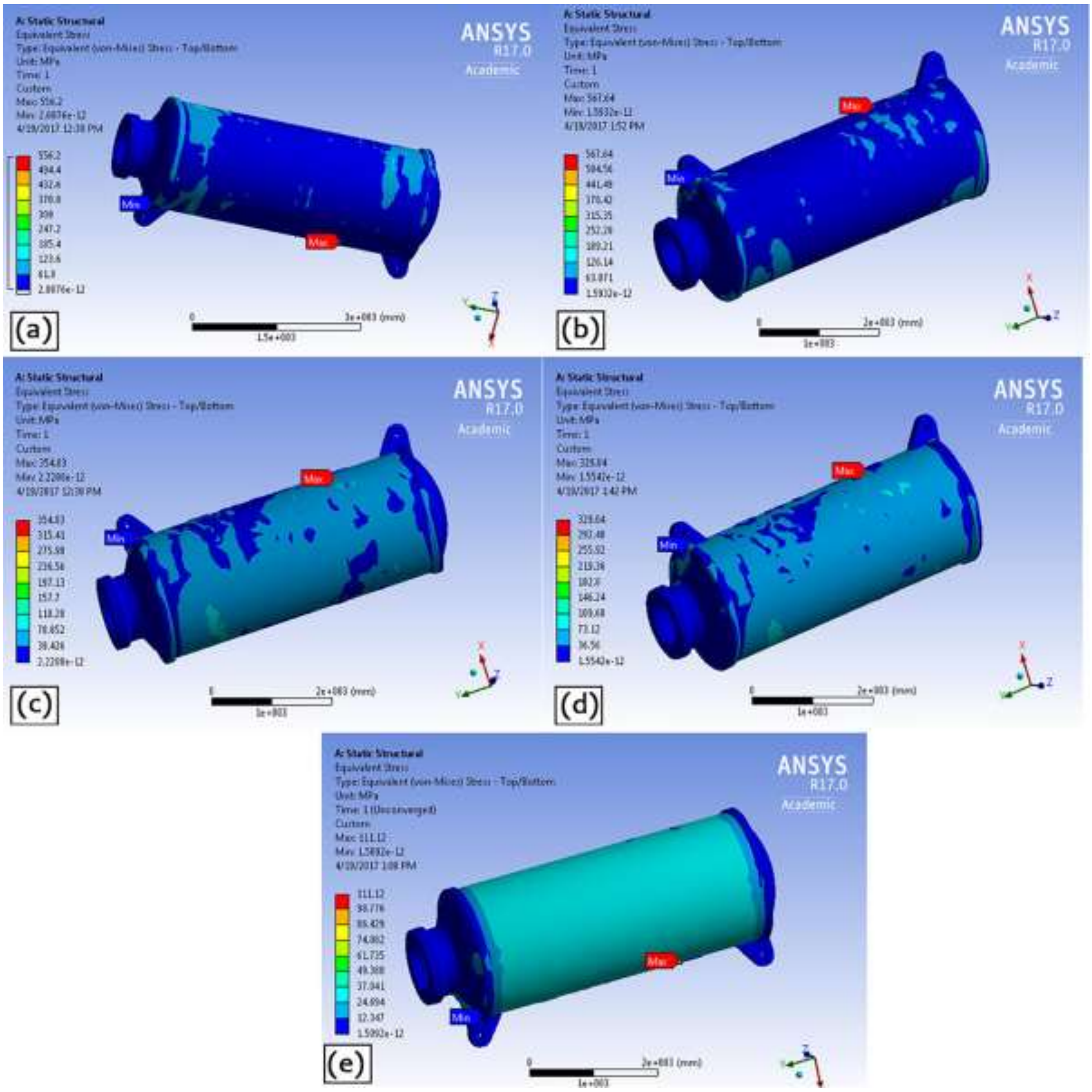

Fig. 8. Results of equivalent stress contours (a) Unidirectional epoxy carbon prepreg (230 GPa), (b) Unidirectional epoxy carbon Wet (230 GPa), (c) Unidirectional E-glass epoxy, (d) E-glass epoxy wet, and (e) Epoxy resign.

4. Geometrical modeling and finite element analysis

Geometrical modeling has been done by using CREO 3.0, as shown in Fig. 4(a) and (b). In ANSYS, element type, material properties, and boundary conditions are assigned at the preprocessor, as shown in Fig. 5(a–d). The dimensions of the pressure cylinder with a thickness of 101.54 mm, an internal pressure of 14 MPa, and a length of 6080 mm are considered as shown in Figs. 5 and 6.

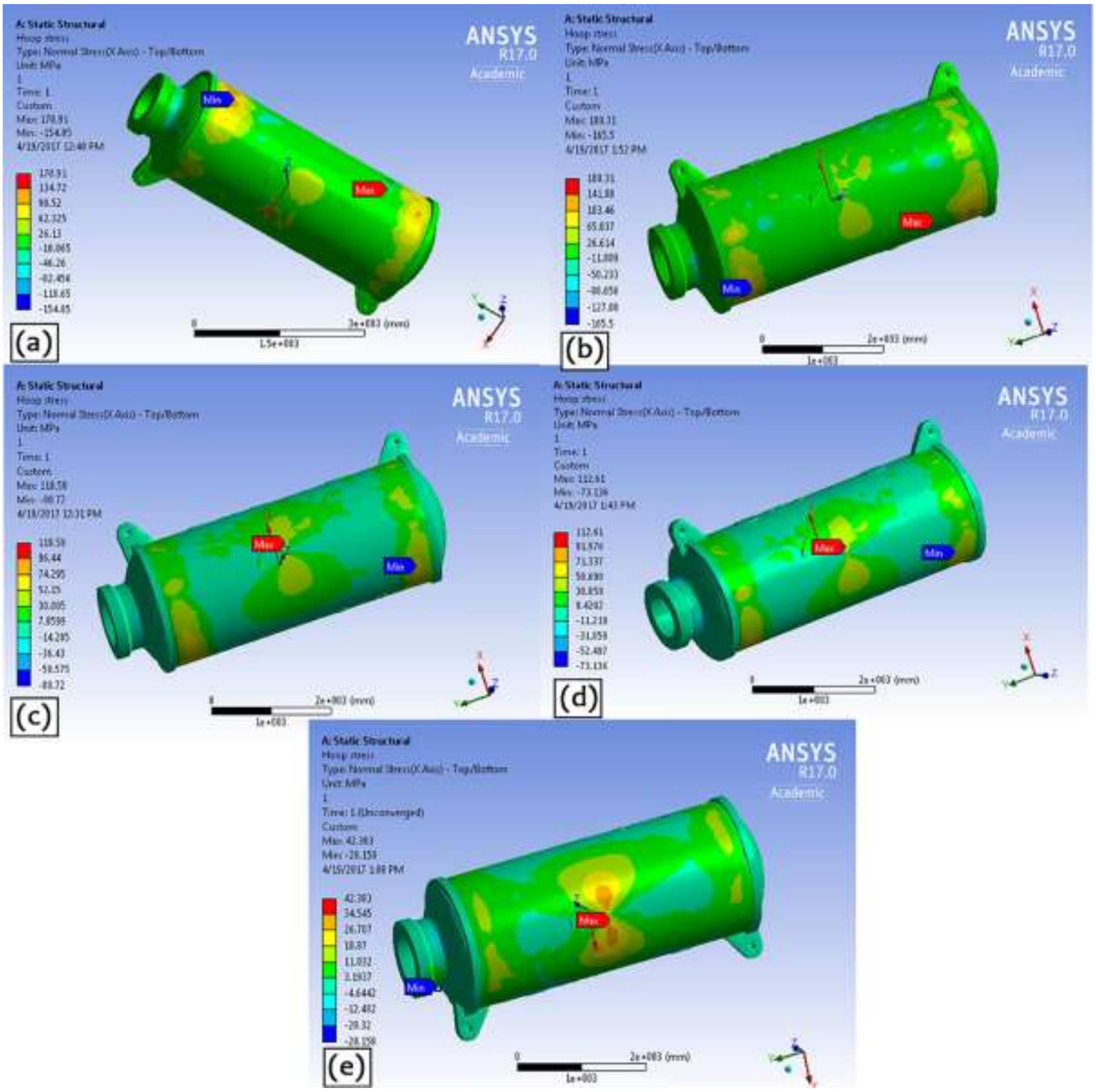

Fig. 9. Results of hoop stress contours (a) Unidirectional epoxy carbon prepreg (230 GPa), (b) Unidirectional epoxy carbon Wet (230 GPa), (c) Unidirectional E-glass epoxy, (d) E-glass epoxy wet, and (e) Epoxy resign.

5. Analysis of composite pressure cylinders

Composite pressure cylinders are made with UD Epoxy Carbon (230GPa) Prepreg, and the results are shown in Tables 1 and 2 and Figs. 7–14. The results show that composite material weight is less as compared with conventional materials like aluminum alloy. Among different composite materials, unidirectional epoxy carbon (230 GPa) Prepreg composites will show less stress and deformation. It is concluded that composite material with the same thickness has less weight as compared to aluminum alloy.

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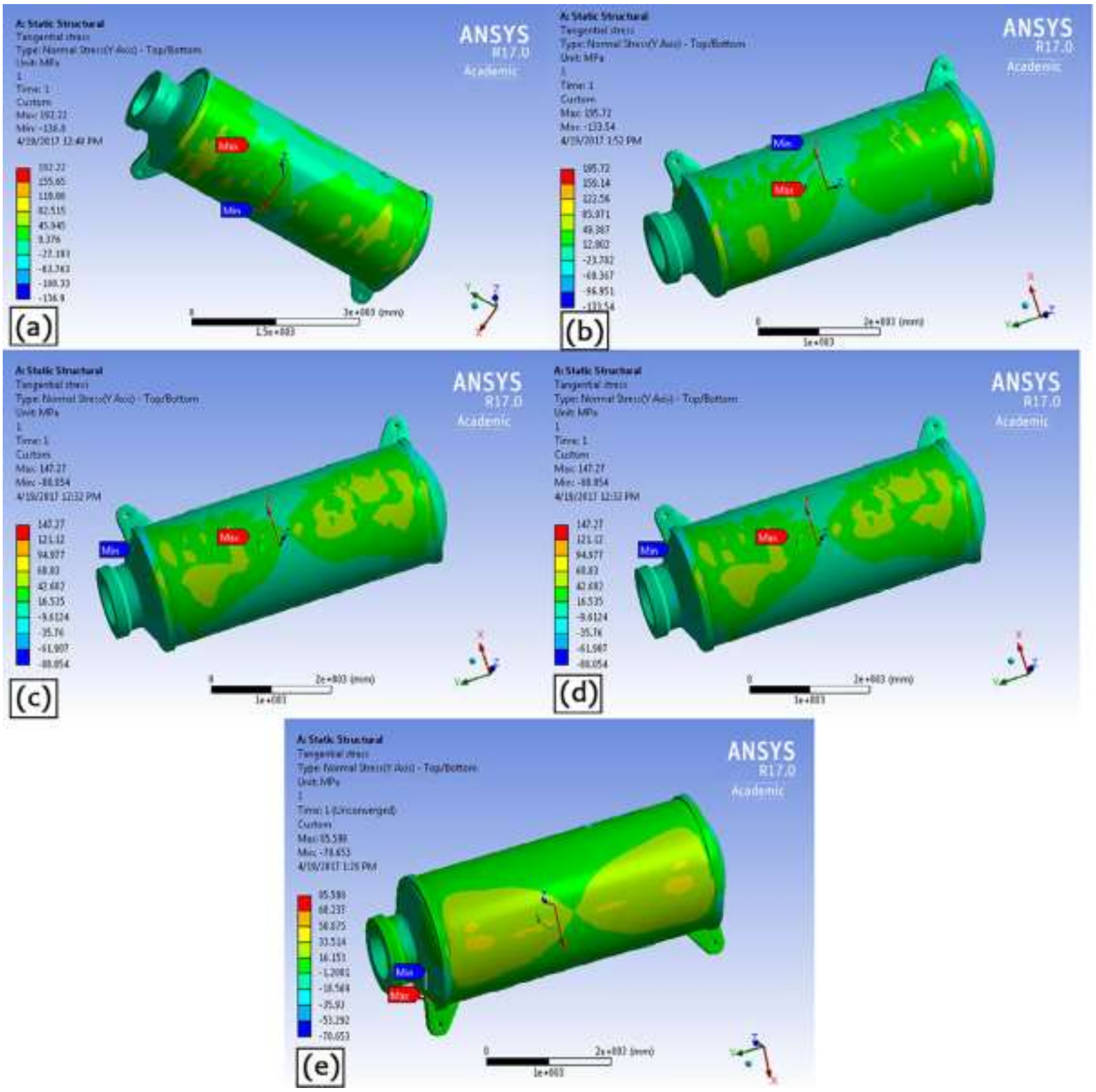

Fig. 10. Results of longitudinal stress contours (a) Unidirectional epoxy carbon prepreg (230 GPa), (b) Unidirectional epoxy carbon Wet (230 GPa), (c) Unidirectional E-glass epoxy, (d) E-glass epoxy wet, and (e) Epoxy resign.

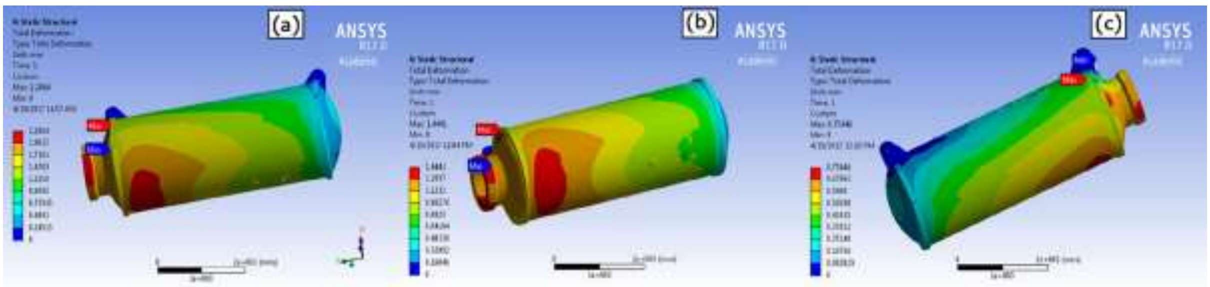

Fig. 11. Results of total deformation contours of alloys (a) Aluminum (Al), (b) Copper (Cu), and (c) Structural steel materials.

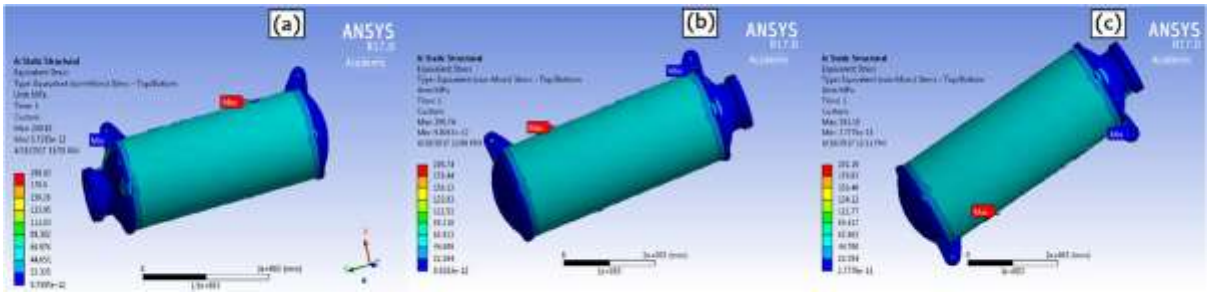

Fig. 12. Results of equivalent stress contours of alloys (a) Aluminum (Al), (b) Copper (Cu), and (c) Structural steel materials.

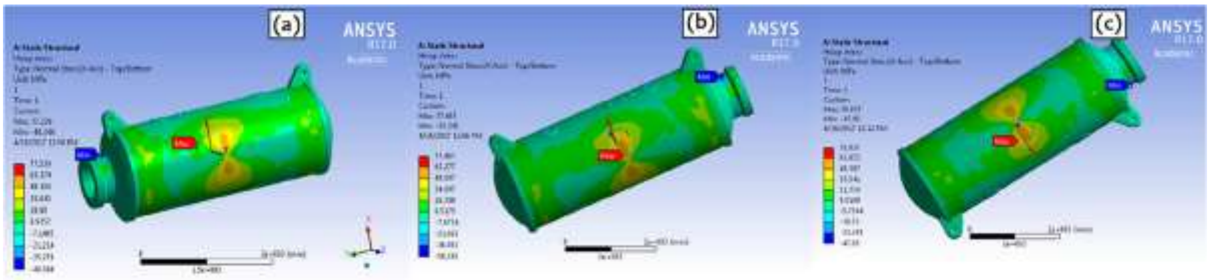

Fig. 13. Results of hoop stress contours of alloys (a) Aluminum (Al), (b) Copper (Cu), and (c) Structural steel materials.

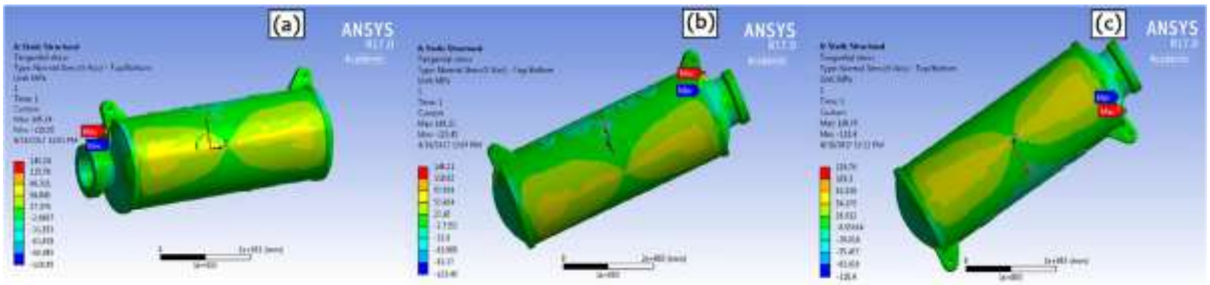

Fig. 14. Results of longitudinal stress contours(a) Aluminum (Al), (b) Copper (Cu), and (c) Structural steel materials.

Table 3: Comparison of unidirectional epoxy carbon and aluminum alloy cylinders.

S. No.	Material	Density (kg/m3)	Thickness (mm)	Diameter (mm)	Volume (m3)	Mass (kg)
1	UD epoxy carbon (230 GPa) Prepreg	1490	101.54	1879	7.0248	10,467
2	Aluminum Alloy	2712	101.54	1879	7.1751	19,459

6. Conclusions

It is concluded that composite materials will have high strength compared with all materials and alloys. For 14 MPa, internal pressures of CNG Auto applications, Composite materials are the best choice. It is also found that UD Epoxy Carbon (230 GPa) Prepreg will have less deformation, as compared to other composites.

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