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Finite Element Analysis of All Composite CNG Cylinders

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Abstract

It is the need of time to ensure the safe operation of compressed natural gas (CNG) cylinders under adverse conditions; the extremities should be predicted under which these cylinders continue to operate without failing. A comprehensive modelling approach in order to predict the behavior and failure of CNG cylinders under various loading conditions has been proposed using Finite Element (FE) Software-ANSYS. In the present investigation two different materials viz. glass/epoxy and carbon/epoxy are used separately and in combination with different patterns of helical and hoop windings, for outer reinforced layers of all composite gas cylinder. Cloud diagram of stress and strain under operating pressure, test pressure and burst pressure are obtained and discussed in detail. The material of the innermost layer of the cylinder i.e. liner should be selected reasonably as it serves as the gas permeation barrier.

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*Keywords:*CNG; composite; finite element; ANSYS; helical; hoop; liner

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1. Introduction

Escalating cost of petrol and diesel prices have forced many transportation companies and vehicles owner to search for an alternative energy. Compressed Natural Gas (CNG) appeared to be a possible choice. Gas cylinder is the heavier portion of alternative fuel system which adds to the weight of the vehicle. All composite-gas cylinder, if-used; reduces the weight of the vehicle and thus reduces the fuel consumption (Paul et al. (2014)). There has been a gradual shift from usage of Type-1 steel cylinders to all composite-gas cylinders.

All composite cylinders provide substantial weight reduction, zero damage to ultra violet/chemical impurities, high impact strength, zero corrosion irrespective of fuel, infinite fatigue life and highest cycle life etc. All

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composite-gas cylinders are made of high density polyethylene (HDPE) liner which acts as natural gas permeation barrier and outer layers are of carbon/epoxy composite laminate wrapped on the liner which gives it pressure bearing capacity (Yue and Li (2012)). Composite cylinder accidents often lead to disastrous consequences, therefore a good design idea and the mechanical calculation will be the precondition for the cylinder safety. The effective way to reduce the accidents is by finding out the causes and the reasons of failure quickly and improving equipment safety and reliability. From safety point of view, none of the composite gas cylinders will leave any fragments on bursting due to external impact and force. However the existing design process doesn't ensure complete safety of all composite-gas cylinders and thus needs further improvement. In the present study a comprehensive FEA on all composites CNG gas cylinder under various operating condition has been conducted and the effect of change in reinforcing material along with its winding process, on its performance has been dealt in detail.

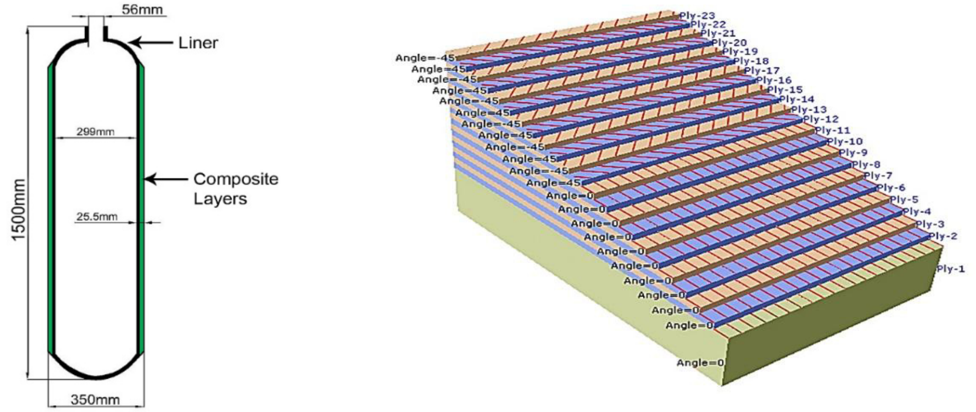
2. Problem statement

The accident cases in Henan Province and Sichuan Province during 2004-05 in which the composite cylinders got burst had put a question mark on safety (Yue and Li (2012)). From 11,843 pieces of 90-L all composite gas cylinders in Beijing, only 3,574 pieces i.e. 31.2% passed the inspection and about 84.85% of total gas cylinders are found with liner defects of bulging and crazing (Xia (2010)). Thus it has become need of the time to study and analyze typical all composite gas cylinders and explore all possible failure trends due to localized loading and internal pressure. Towards this end an investigation has been carried out to test the strength of composite cylinder using different reinforcing materials for outer reinforcing layers and there method of windings.

3. Finite element simulation of all composite gas cylinders

3.1. Dimensions and Structure of all composite-gas cylinder

The dimensions of the liner of a 90-L all-composite gas cylinder were as follows: length of body section of cylinder 1,145 mm; liner outside diameter 314 mm; cylinder nozzle inside diameter of 56 mm; length of cylinder nozzle 51 mm; wall thickness of cylinder body 7.5 mm; cylinder nozzle outside diameter 80 mm; and wall thickness at end plate, gradually increasing from 7.5 mm to 29 mm. With outer reinforcement layer wounded. The dimensions of the gas cylinder: overall length is 1,500 mm; outside diameter of cylinder body section is 350 mm as shown in Fig. 1(a) (Yue and Li (2012)). The cylinder consists of total 23 layers in which first layers is a liner made up of HDPE (Ply-1) having thickness 7.5mm with properties of HDPE as shown in Table 1 while the remaining 22 layers consists of 10 sub-layers (Ply-2 to Ply-11) of GFRP helically windings having thickness 0.9 mm each and 12 sub-layers (Ply-12 to Ply-23) of GFRP hoop windings having thickness 0.75 mm each as shown in Fig. 1(b).



(a) (b)

Fig.1. (a) Dimensions of all composite-gas cylinder; (b) Graphical representation of material layers, orientation, sequence.

3.2. Material Definition

The innermost layer is made of High density polyethylene (HDPE) and is called Liner. The properties of HDPE are given below in the Table 1 (Zhang (2009)).

Table 1. Material Property of HDPE Liner.

Density (g/cm^3)	**Tensile Strength (MPa)**	**Elastic Modulus (GPa)**	**Poisson's ratio**
0.92-0.95	10-16	69.2	0.499

The mechanical properties of glass/epoxy and carbon/epoxy laminated composite board used as the outer reinforcement layers are depicted in Table.2.

Table2. Mechanical properties of glass/epoxy and carbon/epoxy laminated composite board.

Property	**Unidirectional Glass/Epoxy (Yue and Li (2012))**	**T300/976 Graphite/Epoxy (Zhao and Cho (2007))**
In-plane longitudinal modulus (GPa)	20.6	156
In-plane transverse modulus (GPa)	17.2	9.09
In-plane shear modulus(GPa)	17.3	6.96
In-plane Poisson's ratio	0.117	0.228
Out-of-plane Poisson's ratio	0.112	0.400
Out-of-plane Poisson's ratio	0.114	0.400
Longitudinal tensile strength (MPa)	380	1520
Transverse tensile strength(MPa)	334	45

3.3. Load and Boundary Conditions

Tests were performed at three different pressures i.e. operating pressure of 20 MPa, water test pressure of 30 MPa and design bursting pressure of 73 MPa (Table 3) and hoop constraint is applied at the end of the cylinder.

Table 3: Operating conditions of all-composite gas cylinder (Yue and Li (2012)).

Operating temperature	**Operating pressure**	**Filled medium**	**Water test pressure**	**Design bursting pressure**
-40ºC to 60ºC	20 MPa	Natural gas	30 MPa	73 MPa

3.4. Meshing

All composite gas cylinders is meshed using 8 node brick element with element size of 16mm which results in the meshing of cylinder with total 2634 nodes and 2534 elements as shown in Fig.2. Three dimension 8 noded brick element were found to be the most applicable element for this analysis as brick elements have the ability to incorporate midside nodes (producing 21-node elements) and several material models. Eight-node element means, every element consists of 8 nodes. However, the model was found insensitive to further refinement of mesh.

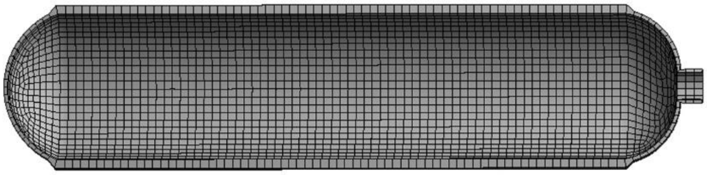


Fig.2. Meshing of all composite gas cylinder.

4.0 Results and Discussions

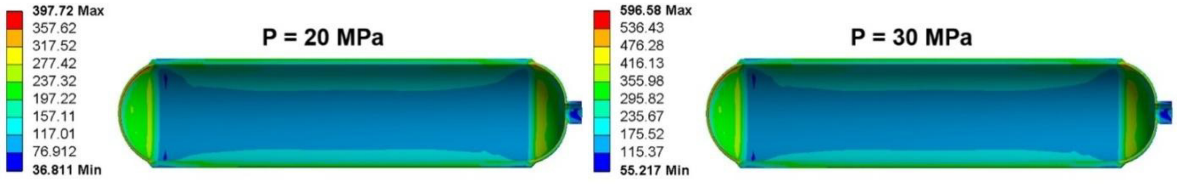
4.1 Validation

The theoretical value of Von Mises stress of the gas cylinder under operating pressure of 20 MPa, water test pressure of 30 MPa and design bursting pressure of 73 MPa was found to be 619 MPa (Yue and Li (2012)) and is given by the following equation 1 of fourth strength theory

$$\sigma = \sqrt{\frac{1}{2}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]} = 619 MPa \qquad (1)$$

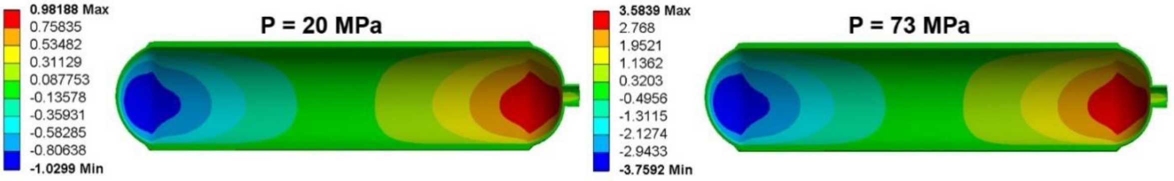
where $\sigma_1 = 380$ MPa, $\sigma_2 = 334$ MPa, $\sigma_3 = 0$

Fig.3. (a, b) represents the Mises stress cloud diagram of all composite gas cylinder under pressure of 20 MPa and 30 MPa. The maximum stress of the gas cylinder under pressure 20 MPa and 30 MPa was found to be 397.72 MPa and 596.58 MPa respectively which is far less than 619 MPa and hence the safety performance requirement for all composite gas cylinders can be ensured. Now for pressure range of 73 MPa the maximum stress was found to be 1451.7 MPa which exceeds the allowable stress. The maximum stress under the above said all pressure values were found to be at the interface of head and cylindrical section.



(a) (b)

Fig. 3. Mises Stress Cloud Diagram of all composite gas cylinder under (a) 20 MPa; (b) 30 MPa.



(a) (b)

Fig.4. Axial Deformation of all composite gas cylinder under (a) 20 MPa; (b) 73 MPa.

The deformation cloud diagram of all composite gas cylinder under pressure of 20 MPa and 73 MPa has been shown in Fig. 4(a, b) and it was found that the tendency of maximum deformation occurs nearby the nozzle tip area.

Table 4: Validation of Present Analysis.

Pressure	**Maximum Von-Mises Stress Results (MPa)**		**Axial Deformation Results (mm)**	
	Present	**Literature(Yue and Li (2012))**	**Present**	**Literature (Yue and Li (2012))**
20 MPa	397.72	398	0.98	0.81
30 MPa	596.58	597	1.47	1.00
73 MPa	1451.7	1450	3.58	2.98

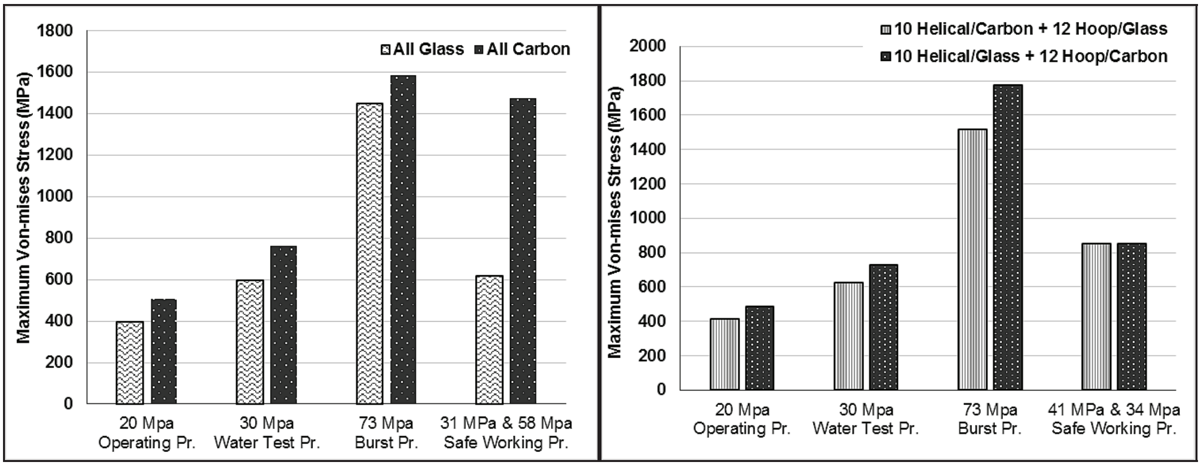
4.2 Parametric Study

In order to ascertain the operation of all composite gas cylinders under various operating conditions, an exhaustive parametric study has been conducted where the material of laminated composite board was taken as T300/976 Graphite/Epoxy in one case and the combination of glass and carbon fibre has been adopted in the second case. Another important change was done in the winding of sub-layers which includes the combination of helical and hoop wound sub-layers.

4.2.1. Material of outer reinforcement layers

In order to visualize the effect of change in material of outer 22 reinforcement layers on the performance of cylinder, T300/976 Graphite/Epoxy was chosen and its properties are mentioned in Table 4.

As per Von Mises theory, the safe working stress using equation 1 for all carbon fibre gas cylinder was found to be 1498 MPa and for combination of both glass and carbon fibre it was found to be 870.85 MPa.



(a) (b)

Fig.5. Effect of different pressures on maximum Von-Mises stress (a) sub-layer material and (b) sub-layer winding material.

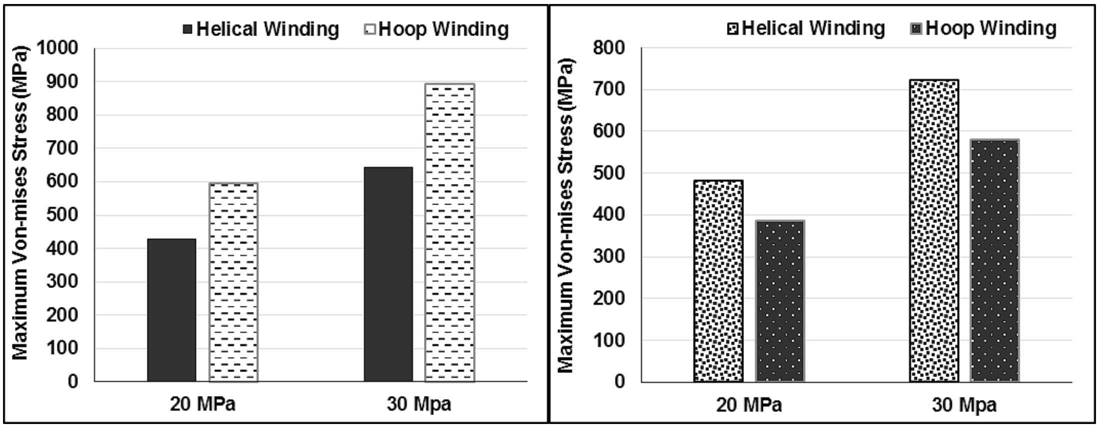
Fig. 5(a) represents the stress level comparison for all glass and all carbon outer 22 reinforcement layers. It can be seen that by the application of carbon fibres as reinforcement, the stress level of gas cylinder, under all pressure range (20 MPa, 30 MPa and 73 MPa) has considerably increased. Also the safe working pressure which was 31 MPa, in case of glass fibre has increased to 58 MPa for carbon fibre reinforcement.

Fig. 5(b)represents the stress level comparison for the cylinder whose outer reinforcement layers have been manufactured respectively with the combination of 10 Carbon with helical windings/12 Glass layers with hoop windings and vice versa. It is clear from the above figure that the involvement of carbon as reinforcement tends to increase the stress resisting capability of all composite gas cylinders.

4.2.2. Winding of outer reinforcement layers

Initially for the validation purpose with outer reinforcement of GF/EP, 10 helically wound sub-layers with thickness of 0.9 mm each and 12 hoop wound sub-layers with thickness of 0.75 mm each of were designed and tested. Also significant variation on the stress level can be achieved by changing the orientation of fibers (Nirbhay et at. (2014)).

Figure 6(a) and (b) represents the variation of stress level for all carbon and all glass layers respectively with all helical and hoop wound sub-layers.



(a) (b)

Fig. 6.Effects of different pressures on maximum Von-Mises stress on (a) all carbon layers and (b) all glass layers.

Hoop winding for all carbon outer-reinforced layers were found to be more effective in terms of stress bearing capacity as compared to helical windings. Similarly, in case of all glass outer-reinforced layers, hoop windings again prove to be successful over helical windings.

5. Conclusion

The following conclusions can be drawn from the above investigation:

i. The increase in the accidents related to bursting of cylinders generates the need of reconsideration in modelling approach; keeping in mind, various parameters such as material selection of cylinder, method of winding used during cylinder manufacturing and optimum combination of both the parameters.
ii. The stress bearing capacity of all composite gas cylinders was found to increase considerably by the involvement of carbon fibres while an intermediate stress level was achieved by using the combination of glass and carbon fibres as a reinforcing material. However, as far as the winding pattern is considered, hoop wound sub-layers are found to be successful as compared to helical windings.
iii. The scope of the present research can be further extended to the material selection for the liner of all composite gas cylinders. The structural design of the cylinder requires further improvement as the level of stresses was found to be high in the transition area from the body of the cylinder to the nozzle.

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