# Design & Stress Analysis of a Hoop Wrapped CNG Composite Vessel with an SAE- 4135 Low Alloy Steel Liner

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**ABSTRACT – Fibre reinforced composite material is widely used in various industrial sectors where weight reduction is required without hampering the strength. In this project, an attempt has been made to replace the conventional CNG tank by composite material. The composite CNG cylinder involves a liner hoop wrapped with a fibre impregnated in suitable resin. The liner material used is that of a conventional Type-I CNG cylinder viz. SAE 4135 low alloy steel as per IS 15490. The cylinder liner is manufactured from hot or cold rolled seamless tube formed by metal spinning. The composite material used for hoop winding is e-glass fibre impregnated in epoxy resin. The cylinder has been fabricated using hoop filament winding technique. The vessel has been validated experimentally by conducting hydraulic test. Experimental stress analysis using strain gauges for the composite CNG cylinder is compared with that of conventional cylinder. The metal liner has been designed and fabricated for 50% of the design pressure, while the thickness of the filament winding is determined by using ANSYS software.**

***Keywords:-*** **CNG vessel, Strain Measurement, Composite, Glass Fibre-Epoxy, Hoop wrapped, Hydrotest, Ansys.**

## INTRODUCTION :-

The use of fiber reinforced and polymer-based composites have been increasing. One area in which the advantages of composite materials, such as high stiffness and strength, can be utilized is that of pressure vessels.

There are basically two approaches to the implementation of composite materials in high pressure vessels: (a) to reinforce a thin metal liner with composite overwrap and (b) to use a thick metal liner reinforced with composite overwrap. The choice of metal for the liners is required whenever the vessel is designed to contain gas under high pressure, in order to prevent diffusion through the wall, or when it is designed to contain liquid under severe temperature conditions. In both cases elastomeric liners are not suitable. Thin liners are not considered to contribute to the load carrying capacity of the vessel, in contrast to thick liners that may support from one-third to one-half of the internal pressure load of the vessel.

Metal liners are normally made of elastoplastic materials with a large plastic range such as 6061-T6 aluminum. The fibers of the composite material can be carbon, glass or kevlar. One of the advantages of combining a load-bearing metal liner with composite over-wrap is achieved by introducing internal stresses (compression in the liner and tension in the fibers) before putting the vessel to service. This process which is known as 'autofrettage' in metal working, is termed 'sizing' in the composite pressure vessel industry. After fabrication, a sizing pressure, higher than the operating pressure, is applied such that the metal liner is plastically deformed whereas the composite reinforcement is in its elastic range. The elastic unloading of the vessel leaves the liner in compression and the composite reinforcement in tension. Later, in subsequent loading cycles, the entire pressure vessel operates in the enhanced elastic range. The weight saving that can be reached, with load-bearing metal liner reinforced with composite overwrap, compared to all metal vessel, is about 50%.

## LITERATURE REVIEW :-

L. Varga ,A. Nagy have made a CNG storage tank for gas operated vehicles out of thin walled aluminium liners with a glass/epoxy reinforcement overwind. The hybrid construction makes it possible to utilize the higher tensile strength of the glass reinforcement. The methodology involved in achieving this using analytical techniques has been given in the paper.[1]

MCS IS using an Araldite hot curing epoxy system for the production of high strength, composite CNG tanks for performance and endurance vehicles. The MCS technology is based on a carbon fibre epoxy matrix system. The composite fuel tanks are said to be over 55% lighter than the steel cylinders typically used as compressed natural gas (CNG) fuel tanks. MCS chose Araldite LY 564 low viscosity epoxy resin, Aradur 917 anhydride hardener and 960-1 Accelerator from Huntsman Advanced Materials. Used in the filament winding process, this hot curing epoxy system helps to produce structural parts and components that are lightweight and extremely durable. [2]

ISO 11119 specifies requirements for composite gas cylinders up to and including 450 litres water capacity, for the storage and conveyance of compressed or liquefied gases with test pressures up to and including 650 bar. The cylinders are constructed in the form of a seamless metallic liner over-wrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a resin matrix, or steel wire, to provide circumferential reinforcement.[3]

ISO 11439:2000 specifies minimum requirements for serially produced light-weight refillable gas cylinders intended only for the on-board storage of high pressure compressed natural gas as a fuel for automotive vehicles to which the cylinders are to be fixed. This International Standard covers cylinders of any steel, aluminium or non-metallic material construction, using any design or method of manufacture suitable for the specified service conditions.[4]

BarbozaNeto, Chludzinski, investigated the behavior under burst pressure testing of a pressure vessel liner. The liner was produced with a polymer blend of 95 wt.% low linear density polyethylene (LLDPE) and 5 wt.% of high density polyethylene (HDPE). The liner is to be used in an all–composite carbon/epoxy compressed natural gas (CNG) shell, manufactured by the filament winding process, with variable composite thickness. Experimental hydrostatic tests were conducted on reduced scale and actual liner models. Design and failure prediction of the composite laminate shell and the polymeric liner were conducted based on Tsai-Wu and von Mises criteria, respectively, using commercial Finite Element Analysis (FEA) software. [5]

Zhong Yue adopted FEA software to conduct numerical simulation of all-composite CNG cylinders, and used a top-down modeling approach to model cylinders, obtaining the cloud diagrams of stress and strain under operating pressure, test pressure and bursting pressure.[6]

## NEED OF ANALYSIS :-

Currently used CNG tanks in vehicles are made purely out of metal, and the CNG being stored at 200 bar, the shell is of thicker size, which makes the tank heavy. This causes extra load on the rear suspension springs; and thereby increases dead weight. For a vehicle which is later fitted with CNG kit, the rear suspension springs are not designed to cater that extra dead weight of storage tank, leading to poor suspension of vehicle.

Hence there is a need to come up with a light weight storage vessel for CNG, still maintaining the required strength. Also, the lighter CNG tank can be used for 2-wheelers.

## OBJECTIVE : -

- Experimental stress analysis of conventional CNG cylinder by conducting hydrotest
- Design & fabrication of composite CNG liner
- Thickness calculation of reinforcement Glass fibre/Epoxy shell thickness using ANSYS
- To design solid model cylinder in software.
- Importing it in FEA software & conducting finite element analysis.
- Hoop Wrapping the sidewalls of cylinder by filament winding method
- To test the worthiness of composite vessel through experimental tests

## METHODOLOGY :-

A composite CNG tank for a light motor vehicle is manufactured. The tank capacity is 30litres, the liner for the cylinder is made out of low alloy stainless steel manufactured from hot or cold rolled seamless tube formed by metal spinning and the composite material used is e-glass fibre with epoxy resin as the matrix solution. Due to the heavy cost involved in manufacturing of a completely new cylinder liner, the already available conventional cylinder is machined to obtain the required liner thickness. The fibres are hoop wrapped around the metal liner using filament winding technique. First of all pressure vessel liner is designed as per the ASME standard and modelled. The thickness of the composite material is determined through the simulation by carrying out by trial and error method.

The vessel will be experimentally validated by conducting ‘Hydrostatic pressure test’.

## DESIGN PROCESS :-

## Process Parameter & Material Selection

As per IS 15935:2011 Composite Cylinders for on-board storage of Compressed Natural Gas(CNG) as a Fuel for Automotive material chosen is as follows

<u>Liner Material-</u> SAE 4135 low alloy steel

Table 1. Chemical Composition of SAE-4135

| Sr. No. | Parameter | Value (%) |
|---|---|---|
| 1 | Carbon (C) | 0.33 |
| 2 | Manganese (Mn) | 0.76 |
| 3 | Silicon (Si) | 0.26 |
| 4 | Sulphur (S) | 0.002 |
| 5 | Phosphorus (P) | 0.016 |
| 6 | Chromium (Cr) | 1.09 |
| 7 | Molybdenum (Mo) | 0.21 |

Table 2. The mechanical Properties of SAE-4135 steel

| Sr. No. | Parameter / Description | Value |
|---|---|---|
| 1 | Ultimate Tensile Stress ($N/mm^2$) | 980.25 |
| 2 | Yield Stress ($N/mm^2$) | 979.37 |
| 3 | Elongation % | 14.70 |
| 4 | Youngs Modulus | 262 GPa |
| 5 | Density | 7700 $kg/m^3$ |
| 6 | Hardness | 285 BHN |

Table 3. The mechanical properties of glass fibre/ epoxy composite laminated board

| | | |
|---|---|---|
| Transversal Stretching | Strength (MPa) | 380 |
| | Elastic Modulus (GPa) | 20.6 |
| | Poisson’s Ratio | 0.117 |
| | Max. Strain | 334 |
| Longitudinal Stretching | Strength | 334 |
| | Elastic Modulus (GPa) | 17.2 |
| | Poisson’s Ratio | 0.112 |
| | Max. Strain (%) | 2.47 |

## LINER DESIGN

As per IS 15935 (2011) Composite Cylinders for on-board Storage of Compressed Natural Gas (CNG) as a Fuel for Automotive Vehicle, the metal liner shall have a minimum actual burst pressure of 260 bar. The minimum actual burst pressure of the finished cylinder shall be not less than the values given in Table 2.

Table 4. Minimum Actual Burst values for metal-lined Hoop Wrapped Cylinders

| Sr. No. | Fibre Type | Stress Ratio | Burst Pressure (bar) |
|---|---|---|---|
| 1 | Glass | 2.75 | 500 |
| 2 | Aramid | 2.35 | 470 |
| 3 | Carbon | 2.35 | 470 |

The composite cylinder shall be manufactured from a seamless metallic liner overwrapped with continuous filament windings.

The wall thickness of the cylindrical liner of the cylinder may be calculated by following formulae

$$f = \frac{P_h\,(1.3\,D_o^2 + 0.4\,D_i^2)}{100\,(D_o^2 - D_i^2)} \qquad (1)$$

Where f = maximum allowable wall stress at hydrostatic test pressure

$$= \frac{5}{6} \times R_e$$

$$= \frac{5}{6} \times 832 \text{ MPa}$$

$$= 693 \text{ MPa}$$

$R_e$ = minimum value of yield strength = 0.85 x yield strength
= 0.85 x 979 MPa
= 832 MPa

$P_h$ = hydrostatic test pressure

$$= \frac{5}{3} \times \text{working pressure}$$

$$= \frac{5}{3} \times 10$$

$$= 16 \text{ MPa}$$

Substituting these values in equation (1)

$$391.6 = \frac{16\,[1.3\,x\,226^2 + 0.4\,(226 - 2t)^2]}{[226^2 - (226 - 2t)^2]}$$

$$22 = \frac{86829.2 + 1.6t^2 - 361.6t}{-4t^2 + 904t}$$

$$-88t^2 + 19888t = 86829.2 + 1.6t^2 - 361.6t$$

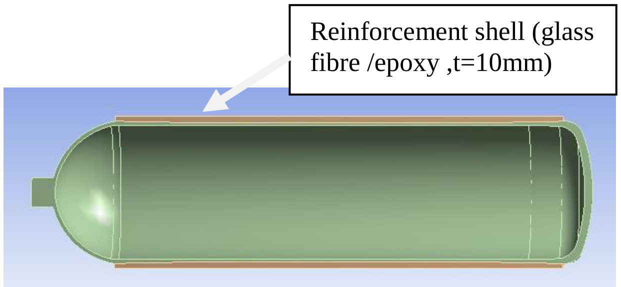
$$-89.6t^2 + 20249.6t - 86829.2 = 0$$

$$t = 4.37 \text{ mm}$$

Therefore taking t= 4.5 mm

## 6.2 COMPOSITE REINFORCEMENT SHELL DESIGN

The thickness of the composite material is determined through the simulation by carrying out a trial and error method.




## EXPERIMENTAL SETUP

The experimental set-up consists of following parts

- Steel Cylinder
- Composite cylinder
- Foil type Strain gauges (350 ohms, gauge factor 2.1, polyamide base)
- Hydraulic Booster Pump
- Dewesoft Data Acquisistion Module
- Pressure gauge indicator
- Test fluid reservoir

Experimental Stress Analysis of Conventional (metal) CNG vessel

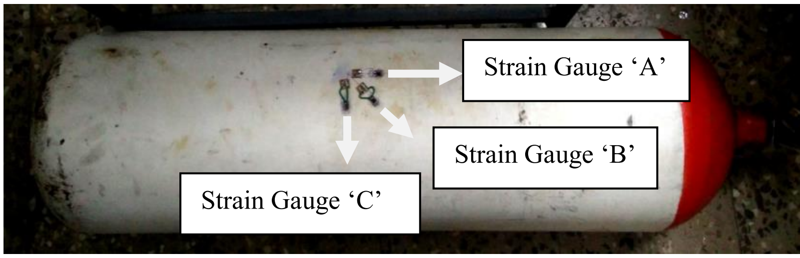



Fig 1. Rectangular strain gauge rosette pasted on the shell on all metal CNG vessel

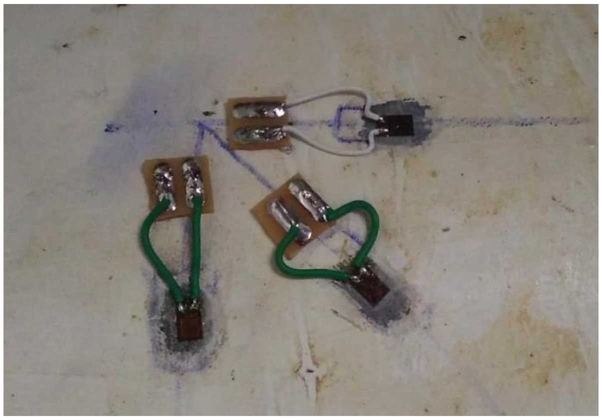


Fig 2. Enlarged view of strain gauges

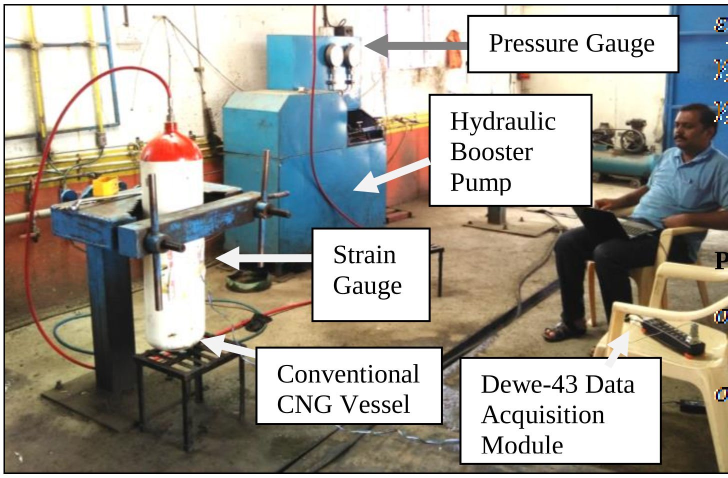



Fig 3. Experimental stress analysis of conventional CNG vessel by applying hydrostatic pressure

Table 5 :- Strains measured for conventional CNG vessel at various hydrostatic pressure

| Pressure (bar) | Strain Gauge No. | Strain (µm/m) |
|---|---|---|
| 100 | A | 123 |
| | B | 395 |
| | C | 730 |
| 200 | A | 315 |
| | B | 840 |
| | C | 1545 |
| 250 | A | 407 |
| | B | 1065 |
| | C | 1920 |
| 300 | A | 505 |
| | B | 1290 |
| | C | 2280 |

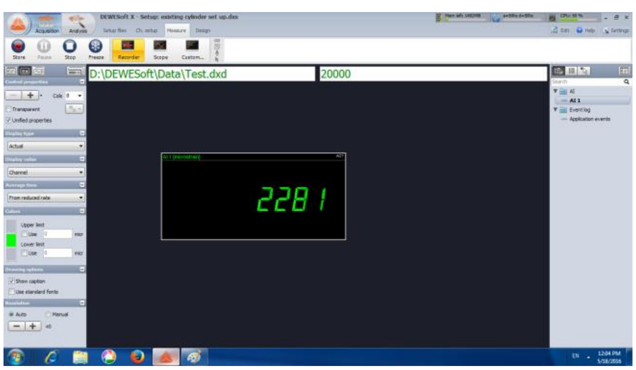



Fig 4. Snapshot of strain gauge 'C' reading at 300 bar hydrostatic pressure taken using DEWE-soft software.

**Calculation of Principal Stress & shear strain deduced from the strains obtained**

For 300 bar pressure,

$$\varepsilon_a = 505\ ,\varepsilon_b = 1290, \varepsilon_c = 2280$$

$$\varepsilon_x = 505$$

$$\varepsilon_y = 2280$$

$$\gamma_{xy} = 2\varepsilon_b - \varepsilon_a - \varepsilon_c$$

$$\gamma_{xy} = 2(1290) - 505 - 2280$$

$$= -205\mu$$

**Principal Stress**

$$\sigma_x = \frac{E}{1-\vartheta^2}(\varepsilon_x + \vartheta\varepsilon_y)$$

$$\sigma_x = \frac{262\ x\ 10^9}{1-(0.29)^2}[505 + (0.29\ x\ 2280)]\ x\ 10^{-6}$$

$$\sigma_x = 333.6\ MPa$$

$$\sigma_y = \frac{E}{1-\vartheta^2}(\varepsilon_y + \vartheta\varepsilon_x)$$

$$\sigma_y = \frac{262\ x\ 10^9}{1-(0.29)^2}[2280 + (0.29\ x\ 505)]\ x\ 10^{-6}$$

$$\sigma_x = 694\ MPa$$

**Maximum Shear Strain**

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

$$= \frac{694 - 0}{2}$$

$$= 347\ MPa$$

**Finite Element Results for Composite CNG vessel**

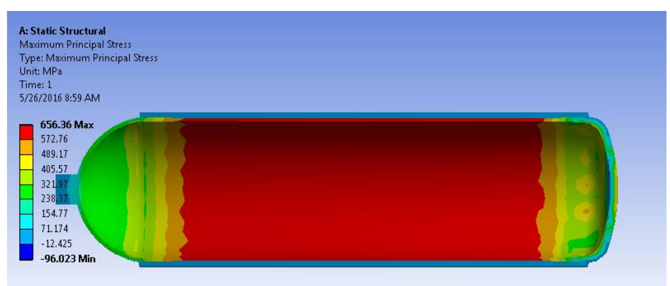



Fig 5. Maximum Principal Stresses for composite CNG vessel

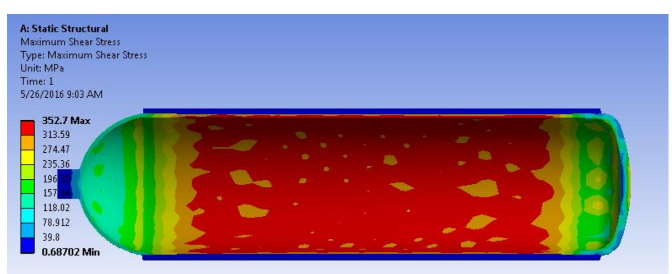



Fig. 6 Maximum Shear Stress for composite CNG vessel

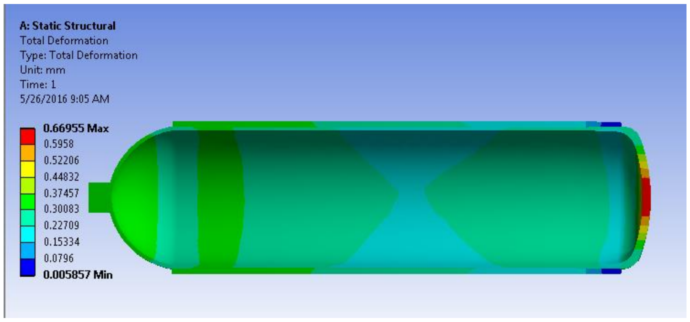



Fig. 7. Total Deformation for CNG composite vessel

**RESULT & DISCUSSION :-**

| | Steel CNG Cylinder | Composite CNG cylinder |
|---|---|---|
| | Results | |
| | Experimental | Software |
| Maximum Principal Stress (MPa) | 694 | 656 |
| Maximum Shear Stress (MPa) | 347 | 352 |
| Total Deformation (mm) | 0.7 | 0.6 |
| Weight (kg) | 35.2 | 30 |

**CONCLUSION:-**

Results show that the composite pressure vessel developed the least stresses when compared to other models such as steel pressure vessel. The results also shows that weight of the composite vessel is lower than that of steel vessel. The corrosion resistance of the composite pressure vessel is more than that of steel pressure vessel so as to increase life of the vessel.

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