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Design and analysis of composite overwrapped pressure vessel with analysis of various overwrapping pattern

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ABSTRACT

In this paper, Designing and Analysis of Composite Overwrapped Pressure vessel (COPV) is done. Metallic liner of titanium alloy is used with composite material, namely Epoxy Carbon woven, for developing a Composite pressure vessel. Furthermore, Structural performance of Composite pressure vessel under different load condition is investigated on ANSYS and compared with a metallic pressure vessel made up of structural steel of same dimensions. Based on the result of analysis, a more lightweight and pressure bearing composite overwrapped pressure vessel (COPV) is proposed. In this paper, effect of different winding pattern like (35°/-35°), (0°/90°) with varying angles of fiber orientation of composite material over the metallic liner is also investigated. Hence, finally, composite overwrapped pressure vessel with metallic liner and with appropriate winding pattern of composite material is achieved.

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KEYWORDS: Composite overwrapped pressure vessel, Metallic Liner, ANSYS, Structural performance.

1. INTRODUCTION

Apressure vessel is a container that is used to store fluid under pressure which is different from ambient pressure. They have been manufactured in different shapes and sizes for various application purposes in industries. Conventionally, pressure vessels are manufactured using metals but using metal leads to significant increase in total weight of pressure vessel. Heavy pressure vessels are strong and durable but they are hard to move and are not suitable for use in light weight application, for example, in space craft and aircraft industries. Composite materials can be used for lightweight constructions due to its unique properties instead of metals and appropriate selection of composite material for construction of pressure vessel can lead to development of a pressure vessel with comparable performance. A composite overwrapped pressure vessel (COPV) is developed for similar purpose which is a vessel that consists of a metal or plastic liner over which the composite material is overwrapped to contain the pressurized fluid. The liner acts as a barrier between the fluid and composite and prevents leakage through micro cracks of composite matrix. Liner also prevents the chemical degradation of composite due to the fluid stored in pressure vessel. Generally, the primary advantage of composite overwrapped pressure vessel is the weight reduction that is approximately equal to 50% of earlier metallic pressure vessels weight.

There are various types of Pressure vessels;
Type I: Full metallic pressure vessel.
Type II: Metallic liner with hoop-wrapped composite pressure vessel.
Type III: Metallic liner with fully overwrapped composite PressureVessel.
Type IV: Polymer lined composite pressure vessel.
Type V: Liner less composite pressure vessel.

Composite pressure vessel is a composite structure where the fibers gives tensile strength and the matrix takes shear load. Matrix in the composite also acts as an adhesive that holds the successive fiber layers. Liner acts as a barrier over which the composite is wrapped and it may be made up of a plastic or a metal. A strong liner in a pressure vessel shares the pressure acting on it along with fibers.

There are many differences between the composite overwrapped pressure vessel and metal vessels. Few of the significant ones are like composites like carbon, Kevlar and glass will see reduction in burst strength due to impact. Composites fails by stress rupture when holding the pressure in the structure during operation well below the ultimate limit. But apart from differences, metallic pressure vessel and composite overwrapped pressure vessel have their own unique advantages. For higher efficiency and light-weight applications, the COPV offers significant advantage, where one of the advantages is approximately one-half the weight reduction as of a comparable metal tank. The all-metal vessel, while possibly heavier, offers the advantage of low manufacturing cost, easy verification of fracture control by analysis, and a simple, more straightforward design.

In a COPV, the fiber is applied in form of ribbons of multiple fibers that goes through a bath for resin application. This ribbon of fiber and resin is wound on the liner in various overwrapping patterns. The pressure vessel liner and dispensing head for the fibers ribbon move relative to one another in such a way so that fiber is overwrapped on the liner in various patterns. The winding process consists of various critical factors, such as content of resin, configuration of fiber, the pattern of the wrap relative to the axis of the liner etc. The resin is then cured (dry and harden) at an elevated temperature.

After post-cure inspections, the vessel is autofretaged, which results in improved structural performance. Autofretage is a process where the composite pressure vessel is pressurized above the yield strength of liner which leads to permanent deformation of liner. Since the vessel is permanently expanded now, at the time of depressurization, a tensile strain (or stress) remains in the fiber composite because of the enlarged liner and as a result compressive strain is induced in the liner.

The residual strain in the liner increases cycle life of overall cylinder. The autofretage of the wrapped liner may serve as a proof test.

STRUCTURE OF PAPER

The paper is organized as follows: In Section 1, the introduction of the paper is provided along with the structure, important terms, objectives and overall description. In Section 2 we discuss literature review. In Section 3 we have discussed about designing procedure. Section 4 shares information about the theoretical calculations. Section 5tells us about the simulation details. Section 6 tells us about theresults of paper. Section 7 includes discussion and concludes the paper with acknowledgement and references.

OBJECTIVES

Conventionally used metallic pressure vessel have advantages like simpler design and testing methods but their heavy weight is a huge disadvantage which restricts their use in light weight application like aircraft and spacecraft application. This paper aims to resolve the issue of metallic pressure vessel by proposing a composite overwrapped pressure vessel with liner of titanium alloy and composite material of carbon epoxy woven prepreg, with weight reduction and increased burst pressure as compared with metallic pressure vessel of same dimension.

2. LITERATURE REVIEW

Wang and Lin [1] analyzed stresses in composite cylindrical shells rotating with a constant speed about their longitudinal axis. Jaunky*et al*. [2] developed a design strategy for optimal design of composite grid-stiffened cylinders subjected to global and local buckling constraints and strength constraints.Tam *et al*. [3] designed and manufactured a composite overwrapped pressure tank assembly for commercial aircraft.

Krishnamurthy and Mahajan [4] studied Impact response and damage in laminated composite cylindrical shells.

Velosa*et al*. [5] studied and developed a new generation of filament wound composite pressure cylinder for large scale market application. Kaneko *et al*. [6] studied and discussed impact analysis of pressurized fiber-reinforced plastic (FRP) cylinders by simulation, using the finite element method under transverse impact loading. Mclaughlan*et al*. [7] gave a comprehensive review of composite overwrapped pressure vessel. BarbozaNeto*et al*. [8] investigated the behavior under burst pressure testing of a pressure vessel liner. Experimented and numerical analyzed LLDPE/HDPE liner for a composite pressure vessel. Yongming*et al*. [9] studied fiber hoop-wrapped composite cylinders impact resistance and evaluated cylinder's impact resistance performance with various parameters. Francescato*et al*. [10] compared different optimal design methods for producing two-angle filament-wound structures able to withstand under internal pressure. Hocine*et al*. [11] analyzed Failure Pressures of Composite Cylinders with a Polymer Liner of Type IV CNG Vessels and investigated effect of the order of the circumferential winding on the stacking sequence.

Mujeeb Iqbal *et al*. [12] designed and Analyzed stresses in FRP Composite pressure vessel. Chauhan and Awasthi. [13] Designed and analyzed high pressure composite vessels in order to increase the strength.Krishna Mohan *et al*. [14] developed analytical model for the Prediction of the minimum buckling load with / without stiffener composite shell of continuous angle ply laminas for investigation. Compared result for different approaches.Halawa and Al-Huniti [16] designed and analyzed Carbon/Epoxy Composite Pressure vessel to maintain structural integrity under moisture effect.Park *et al*. [17] performed an optimization analysis and evaluated a high-pressure hydrogen storage vessel to improve the reliability of the structure, and simultaneously conducted fatigue assessment of all patterns derived from the optimization analysis process.

Zu*et al*. [18] proposed a novel design approach to generate winding paths for composite pressure vessels with unequal dome parts.Alam*et al*. [19] Designed and developed a filament wound composite overwrapped pressure vessel.Regassa*et al*. [20] investigated the burst performance of a type III composite overwrapped pressure vessel (COPV) using finite element methods for different orientation of composite.Rahul *et al*. [21] a detailed review on various works carried by the researchers to evaluate the performance of composite overwrapped pressure vessels under various design and environmental factors.

3. DESIGNING

Structural steel is used for analysing a metallic pressure vessel of prescribed design. For composite pressure vessel of same design parameter, Titanium Alloy (Ti-6Al-4V) is used for liner and Epoxy Carbon Woven (395 Gpa) Prepreg is used as a composite material. Following are the tables of property for used materials.

Table 1: Material Data

Properties	**Titanium Alloy (Ti-6Al-4V)** (For liner)	**Structural Steel** (For metallic Pressure vessel)
Density	4.62 g/cm³	7.85 g/cm³
Tensile yield strength	930 Mpa	250 MPa
Compressive yield strength	930 MPa	250 MPa
Ultimate tensile strength	1070 MPa	460 MPa
Young's Modulus	96 GPa	210 GPa
Poisson's ratio	0.36	0.3

Table 2: Composite Material data

Epoxy Carbon Woven (395 GPa) Prepreg. (For Composite Material)	
Density	Density
Young's Modulus in X-Direction	Young's Modulus in X-Direction
Young's Modulus in Y-Direction	Young's Modulus in Y-Direction
Young's Modulus in Z-Direction	Young's Modulus in Z-Direction
Poisson's Ratio in XY	Poisson's Ratio in XY
Poisson's Ratio in YZ	Poisson's Ratio in YZ
Poisson's Ratio in XZ	Poisson's Ratio in XZ
Tensile stress limit in X-Direction	Tensile stress limit in X-Direction
Tensile stress limit in Y-Direction	Tensile stress limit in Y-Direction
Tensile stress limit in Z-Direction	Tensile stress limit in Z-Direction

Composite overwrapped pressure vessel are made up of multiple layers of composite material wound over a liner. In our case, the liner is of titanium alloy and the composite material is of carbon epoxy woven (395 GPa) Prepreg. Multi-layered pressure vessel are used for higher pressure application. Objective of the modelling is to obtain a composite pressure vessel with high pressure resistance and significant weight reduction as compared with its metallic counterpart.

- **Reference solid wall pressure vessel**

Following dimensions are from an existing solid wall pressure vessel designed to ASME code Section VIII division I. Based on these input parameter, shell thickness of the vessel, burst pressure of the vessel, hemispherical end thickness and other parameters are theoretically calculated. Finally, these parameters are used to validate the result of simulation done on ANSYS 19.2 by matching the values.

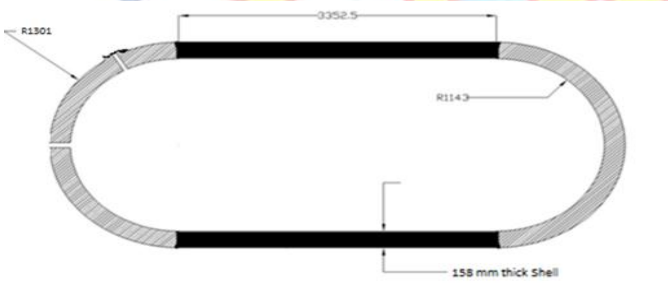

Figure 2: Reference metallic pressure vessel

First, Designing of the all metallic pressure vessel is done according to the previously specified dimensions. This is done on ANSYS Space claim. After the designing of all metal pressure vessel, design of COPV is made with liner of appropriate dimension, Composite layering is done using ACP (Pre). In the Composite layering, layer thickness, fiber material, number of layers and orientation of composite being used [*(35°/-35°), (0°/90°)*]is defined.

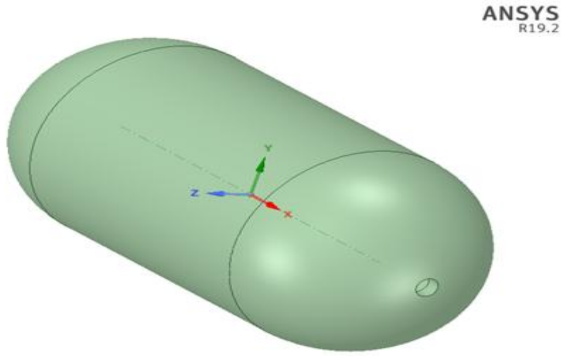

Figure 3: Model of Pressure vessel

- **Dimension of the Composite Pressure vessel**
  Liner Thickness = 62mm
  Length of the cylinder = 3352.5mm
  Internal Radius = 1143 mm
  Overall Composite Layer Thickness = 96mm
  Individual Layer thickness = 4mm
  Number of Layers = 24
- **Dimension of the all metallic pressure vessel**
  Thickness of vessel = 158 mm
  Length of the cylinder = 3352.5 mm
  Internal Radius = 1143 mm
  Dished-End thickness = 158 mm

Using ACP (Pre), composite layering is defined. Liner material assigned to Titanium alloy whereas the composite layer used is Carbon Epoxy Woven Prepreg.

- **Winding Pattern [35⁰/-35⁰]**

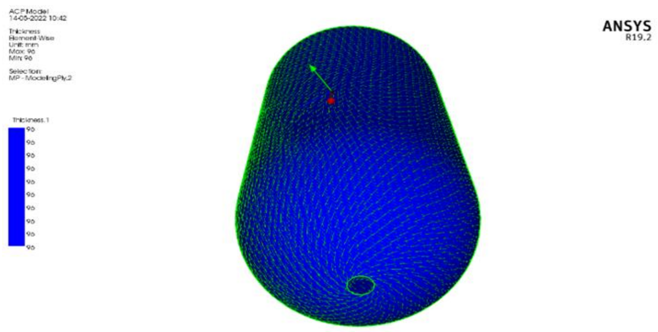

Figure 3: Layer orientation of -35^0

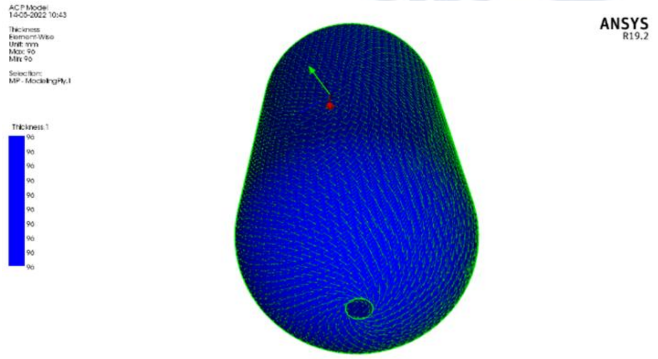

Figure 4: Layer orientation of 35^0

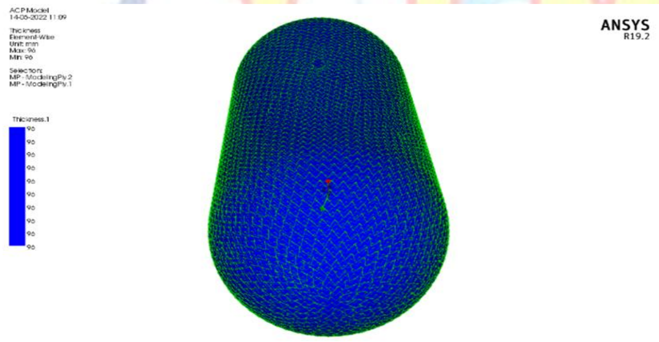

Figure 4: Overall Layer orientation

Table 3: Layering detail for [35^0/-35^0]

Name	Ply material	Ply angle	Number of layers	Thickness
Modelin gPly.1	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.2	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.3	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.4	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.5	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.6	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.7	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.8	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.9	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.10	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.11	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.12	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.13	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.14	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.15	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.16	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.17	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.18	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.19	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.20	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.21	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.22	fabrics/Carbon Epoxy Woven	-35	1	4mm
Modelin gPly.23	fabrics/Carbon Epoxy Woven	35	1	4mm
Modelin gPly.24	fabrics/Carbon Epoxy Woven	-35	1	4mm

- **Winding pattern [0^0/90^0]**

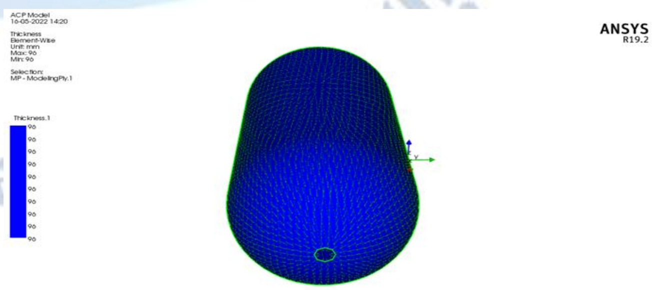

Figure 5: Layer orientation of 0^0

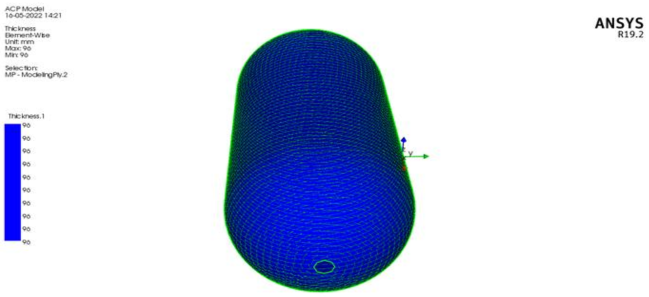

Figure 6: Layer orientation of 90⁰

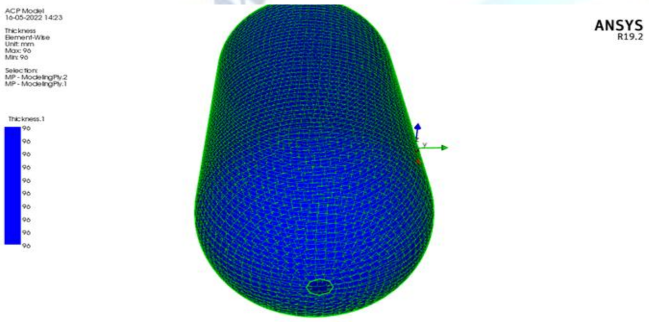

Figure 7: Overall layer orientation

Table 4: Layering details for [0⁰/90⁰]

Name	Ply material	Ply angle	Number of layers	Thickness
ModelingPly.1	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.2	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.3	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.4	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.5	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.6	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.7	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.8	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.9	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.10	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.11	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.12	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.13	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.14	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.15	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.16	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.17	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.18	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.19	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.20	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.21	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.22	fabrics/Carbon woven epoxy	90	1	4mm
ModelingPly.23	fabrics/Carbon woven epoxy	0	1	4mm
ModelingPly.24	fabrics/Carbon woven epoxy	90	1	4mm

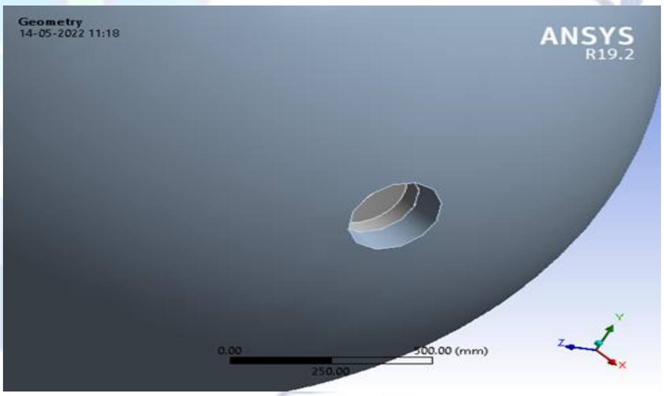

Figure 8: Composite layering over liner

4. THEORETICAL CALCULATION

Table 5: Design Input Data

Design Pressure	P	21 Mpa, Hydrostatic
Design Temperature	T	21°C
Design Code	-	ASME Sec: VIII Div:01
Inside Radius of Vessel	R_i	1143 mm

Inside Diameter of Vessel	D_i	2286 mm
Joint Efficiency	J	1
Safety Factor	F.S	3
Corrosion Allowance	C.A	3 mm

Theoretical calculation is done for reference metallic pressure vessel made up of structural steel in our case. All formulas used for obtaining specified parameters are suggested by ASME Boiler and pressure vessel code section III, division I. [22] Obtained values are matched with result of simulation-01 to validate the results of ANSYS.

- **Thickness of vessel (t)**

$$t = \frac{P * R_i}{S * J - 0.6P} + C.A$$

t = 154.79 + 3 = 158 mm (Rounded off)

- **Thickness of Dished End (t_d)**

$t_d = \frac{P*R_i}{2*S*J-0.2*P}$+ C.A= 76mm

Adopted t_d = 158mm

- **Hydrostatic Test Pressure (P_H)**

P_H = 1.3 * Design pressure

= 1.3 *21 = 27.3 N/mm^2

- **Stress developed in Vessel (S_H) during Hydro static testing.**

$S_H = \frac{P_H*R_i+0.6*P_H*t}{t}$ = 214 N/mm^2

S_H is less than Yield Strength *i.e*250 MPa

- **Stress developed in Dished End ($S_{H,D}$) during Hydrostatic testing.**

$S_{H,D} = \frac{P_H*R_i+0.2*P_H*t}{2*t}$ = 101.5 N/mm^2

$S_{H,D}$is less than Yield Strength i.e. 250 MPa.

- **Bursting Pressure (P_B)**

P_B = UTS * $\frac{K^2-1}{K^2+1}$

Where:

K= $\frac{D_{outer}}{D_{inner}}$= 1.14

So, P_B = 59.9 N/mm^2

- **Stress developed in vessel (S_v) at burst pressure.**

$S_v = \frac{P_B*R_i+0.6*P_B*t}{t}$ = 469.2 MPa

- **Stress developed in dished end (S_D) at burst pressure.**

$S_D = \frac{P_B*R_i+0.2*P_B*t}{2t}$ = 222.6 MPa

- **Hoops stress (σ_{hoop})**

$\sigma_{hoop} = P_B \frac{(R_i+\frac{t}{2})}{t}$= 463.27 MPA

5. SIMULATION

After the designing stage, prepared model is assigned materials and meshing is generated which divides the entire model into finite number of elements which is then analyzed individually under various load conditions. In our case, analysis is primarily done in Static Structural part of ANSYS where we did structural analysis of the model under a load condition.

Structural Analysis: A Structural analysis comprises of analyzing deformation, stresses and displacements generated in the structure during various load conditions.

In this paper, three different structural analysis is done, which are namely;

- **Simulation 1:**

Objective: Structural Analysis of all metal pressure vessel made up of Structural Steel. **Pressure** = 21 MPa is applied and results are observed.

- **Simulation 2:**

Objective: Structural Analysis of Composite Overwrapped pressure vessel having liner of titanium alloy and composite layering of Carbon Epoxy Woven Prepreg. **Pressure** = 21 Mpa is applied for winding pattern of **[35°/-35°].**Failure criteria based on Tsai-Wu Criteria.

- **Simulation 3:**

Objective: Structural Analysis of Composite overwrapped pressure vessel with different overwrapping pattern of Composite material over liner. Winding patterns under consideration are [35°/-35°] and [0°/90°].

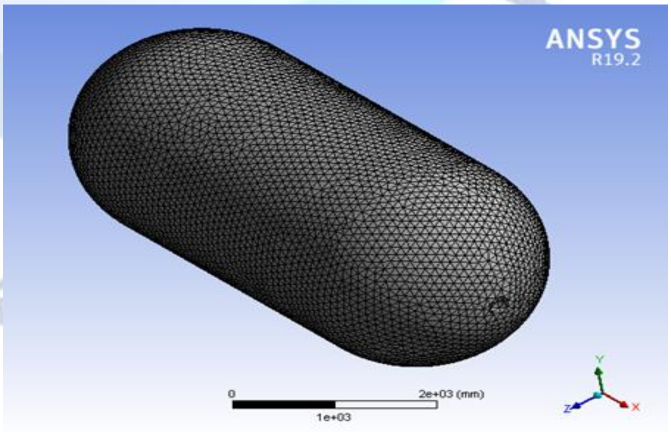

Figure 9: Meshing in liner

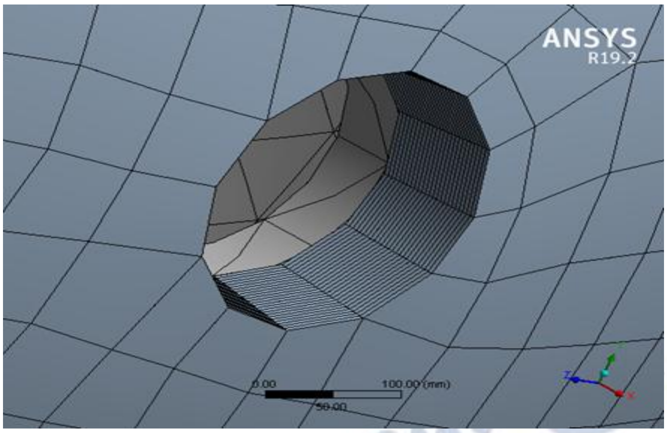

Figure 10: Meshing in composite liner

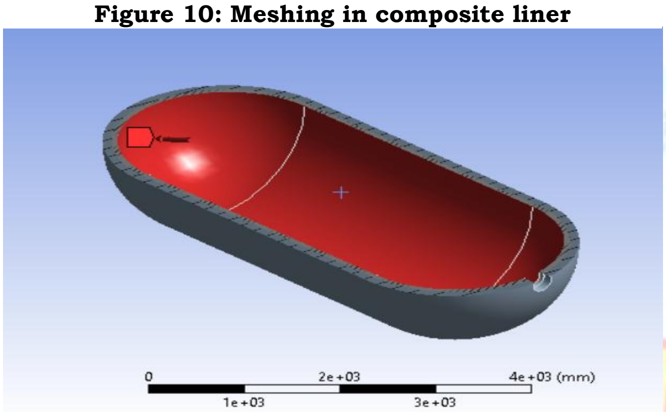

Figure 11: Applied pressure direction

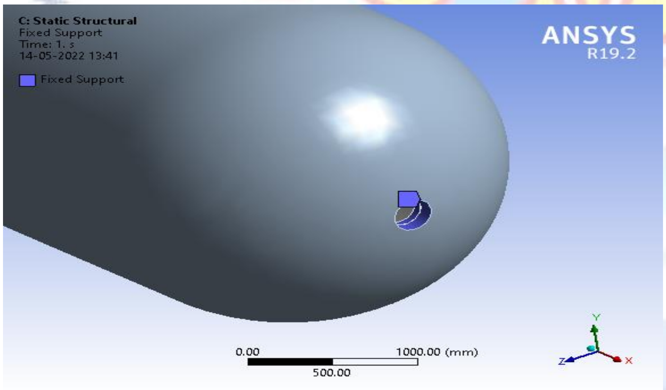

Figure 12: Fixed support

6. RESULTS

- Simulation 1:

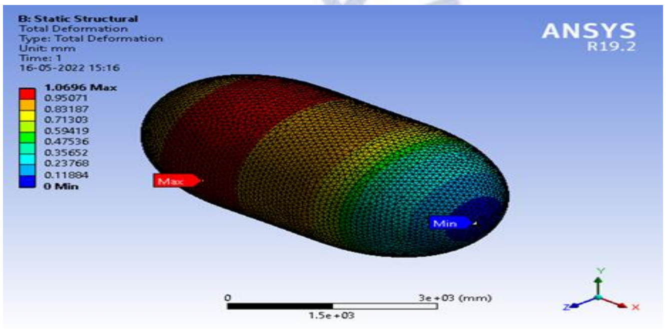

Figure 13: Total deformation

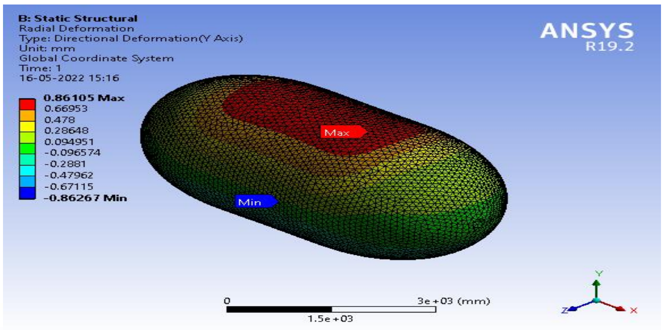

Figure 14: Radial deformation

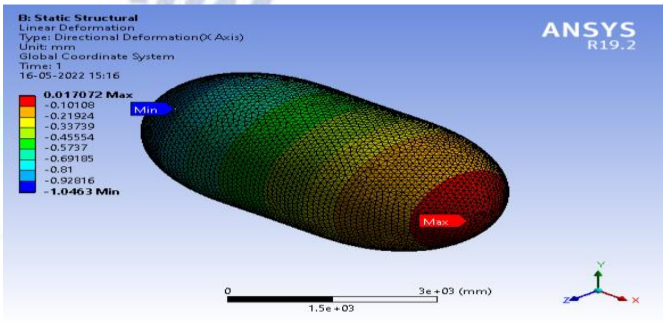

Figure 15: Longitudinal deformation

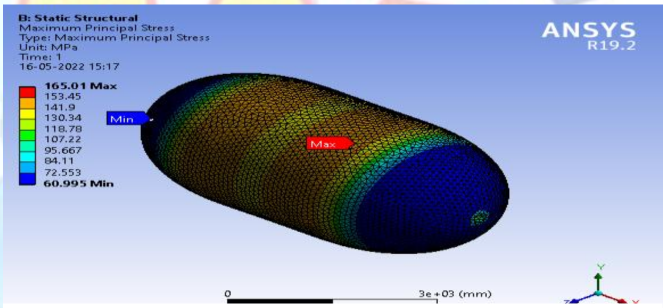

Figure 16: Maximum principal stress

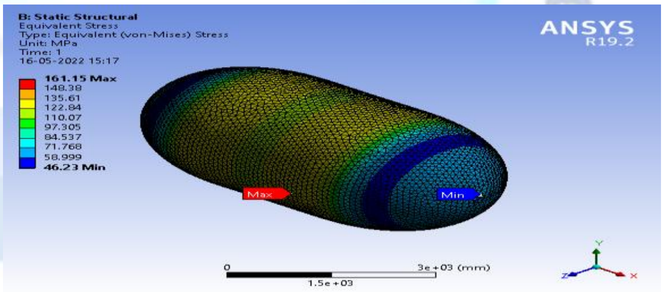

Figure 17: Equivalent stress

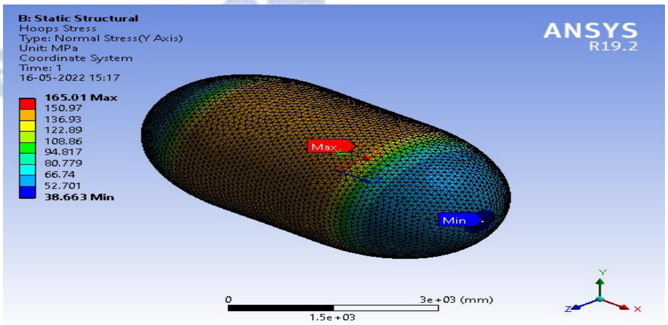

Figure 18: Hoops stress

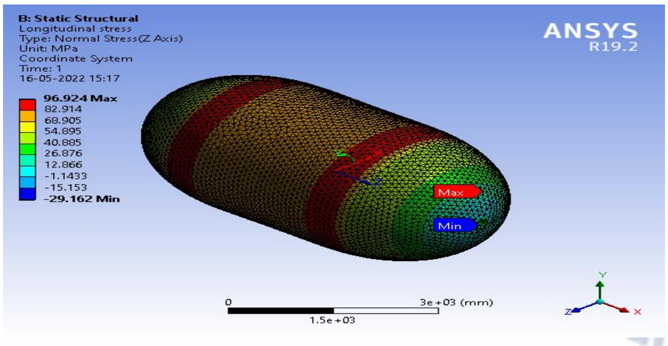

Figure 19: Longitudinal stress

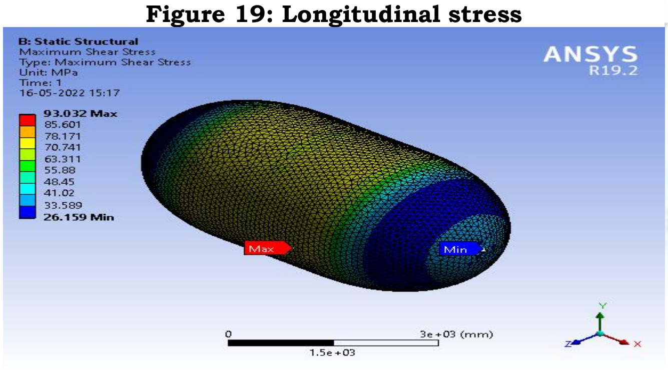

Figure 20: Maximum shear stress

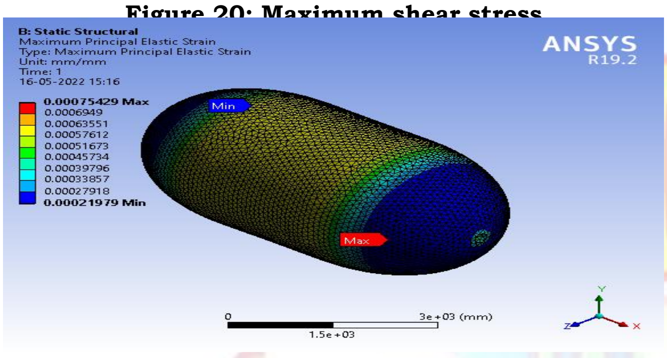

Figure 21: Maximum principal elastic strain

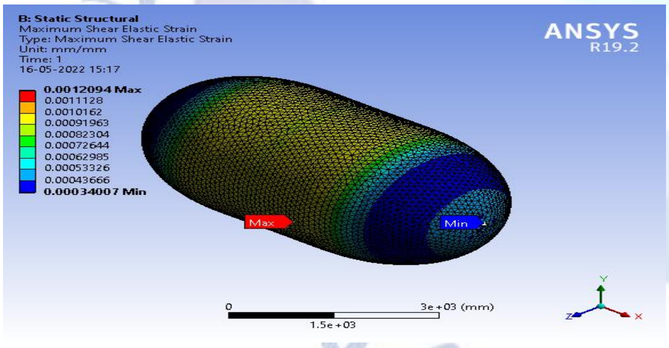

Figure 22: Maximum shear elastic strain

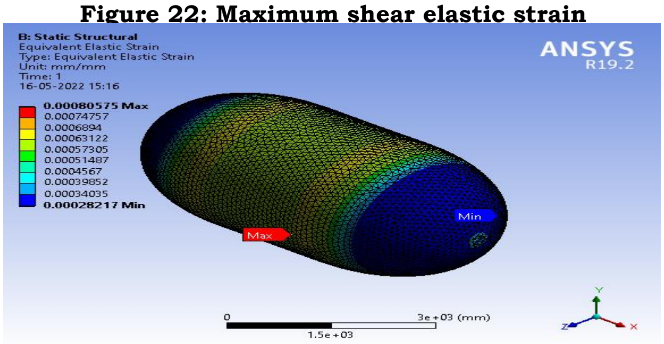

Figure 23: Equivalent elastic strain

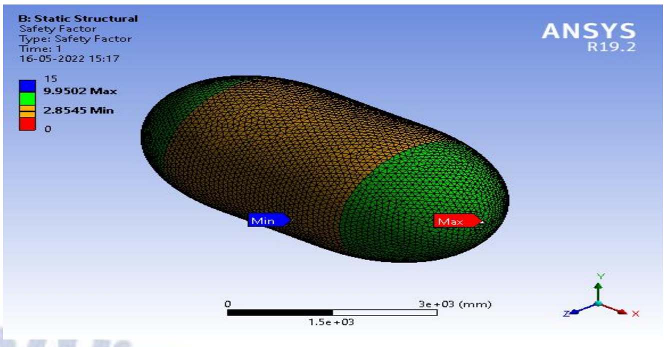

Figure 24: Factor of safety

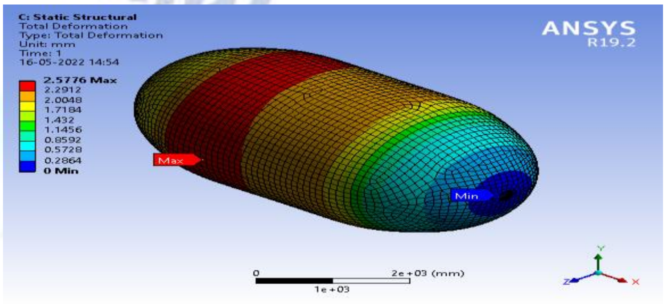

Figure 25: Total Deformation

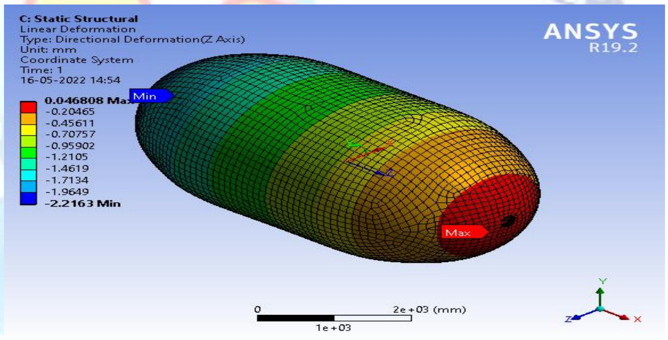

Figure 26: Longitudinal Deformation

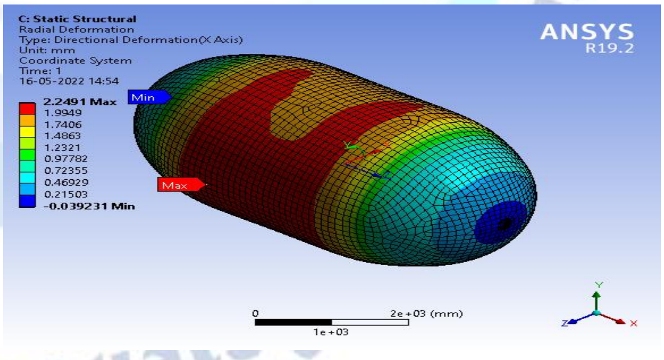

Figure 27: Radial Deformation

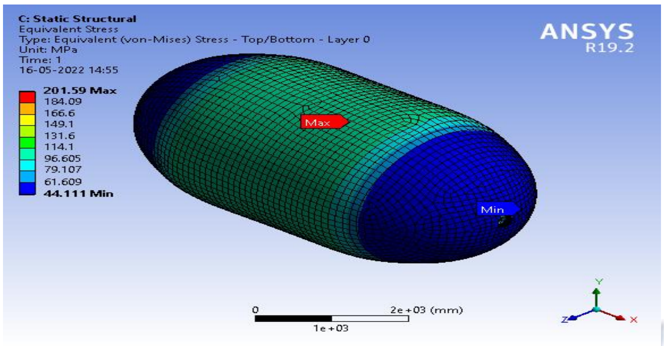

Figure 28: Equivalent stress

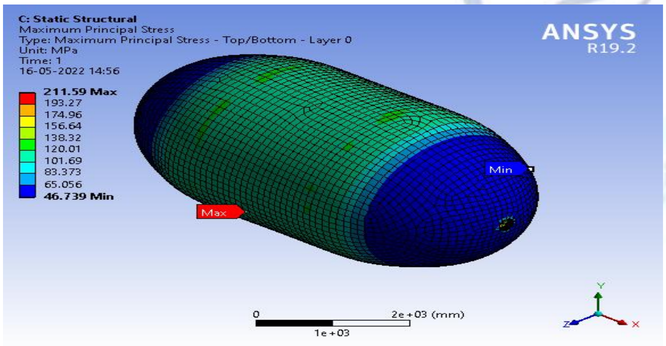

Figure 29: Maximum principal stress

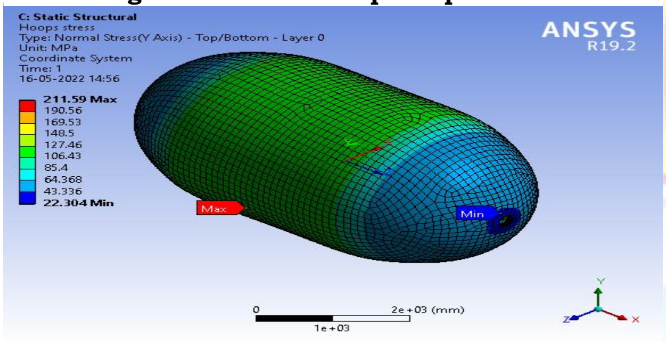

Figure 30: Hoops stress

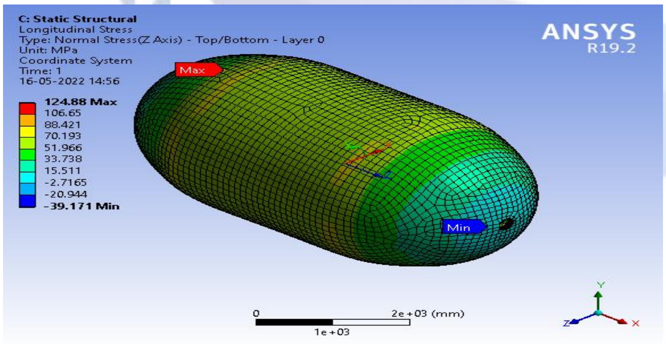

Figure 31: Longitudinal stress

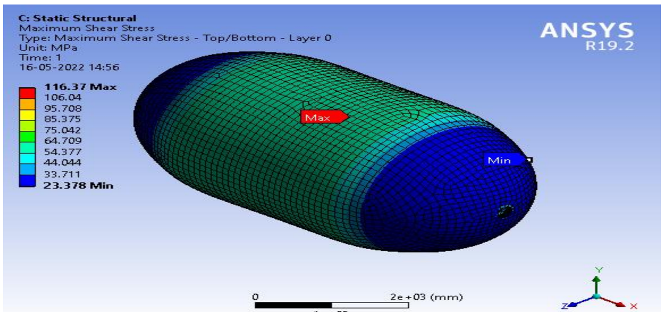

Figure 32: Maximum shear stress

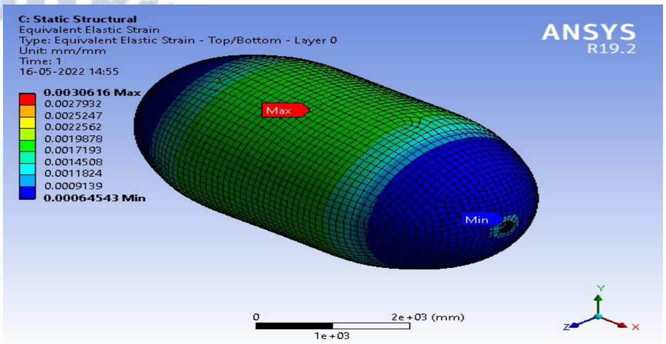

Figure 33: Equivalent Elastic strain

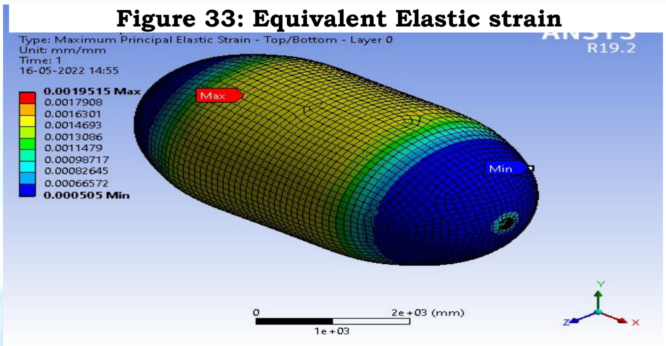

Figure 34: Maximum principal elastic strain

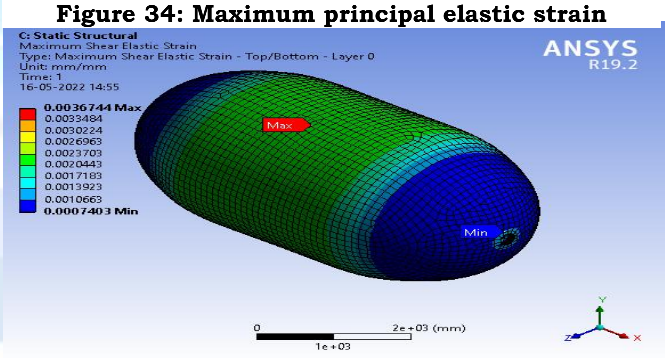

Figure 35: Maximum Shear Elastic strain

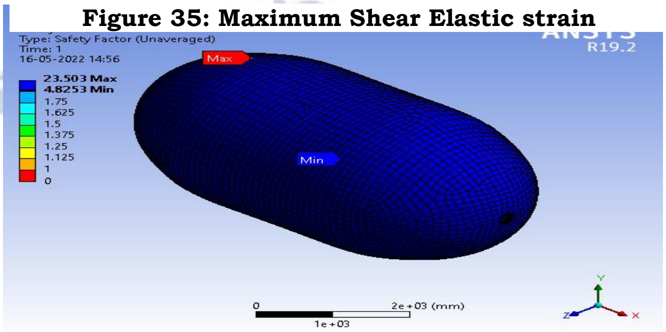

Figure 36: Factor of Safety

- Simulation 3:

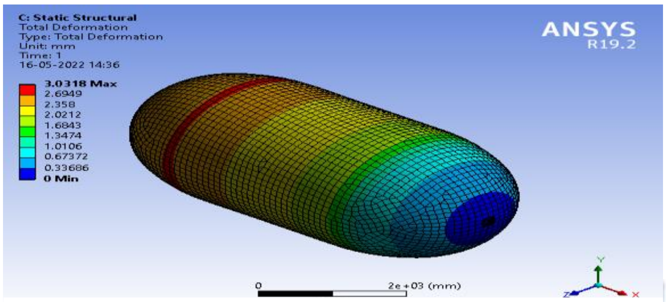

Figure 37: Total Deformation

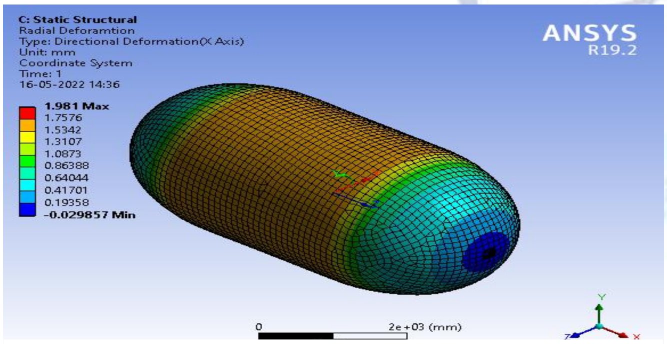

Figure 38: Radial Deformation

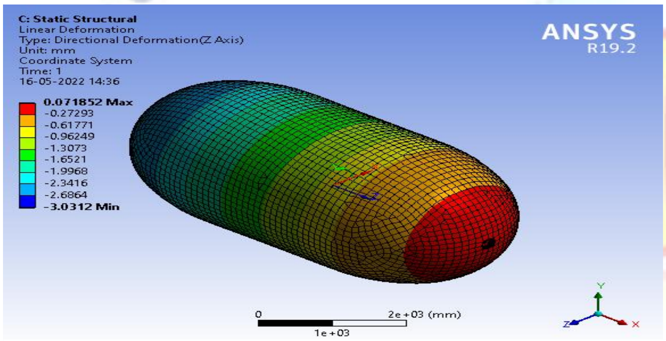

Figure 39: Longitudinal Deformation

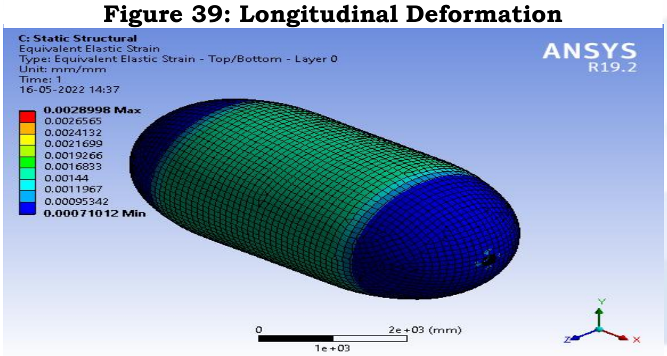

Figure 40: Equivalent Elastic Strain

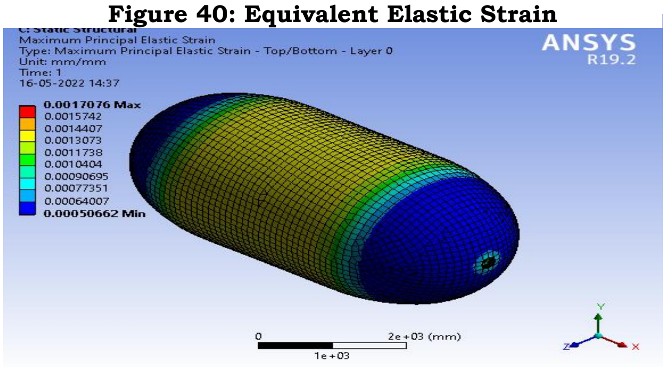

Figure 41: Maximum Principal Elastic strain

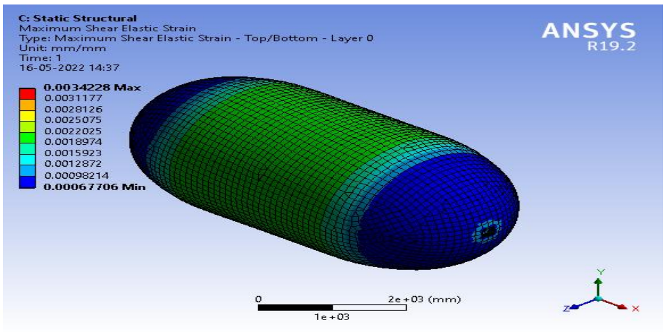

Figure 42: Maximum Shear Elastic Strain

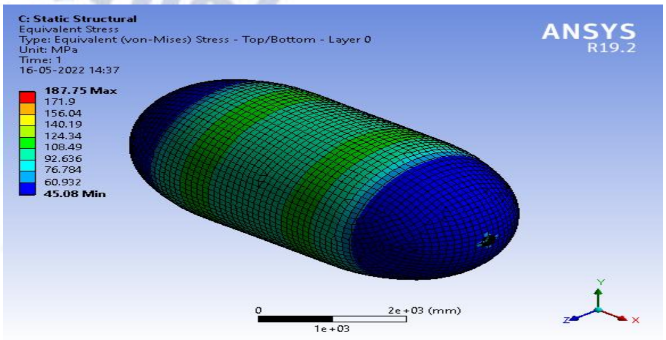

Figure 43: Equivalent Stress

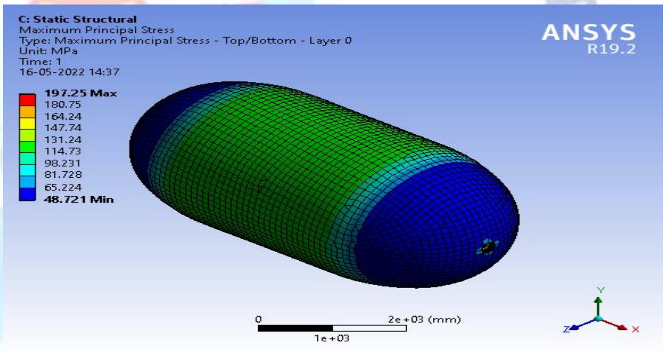

Figure 44: Maximum Principal Stress

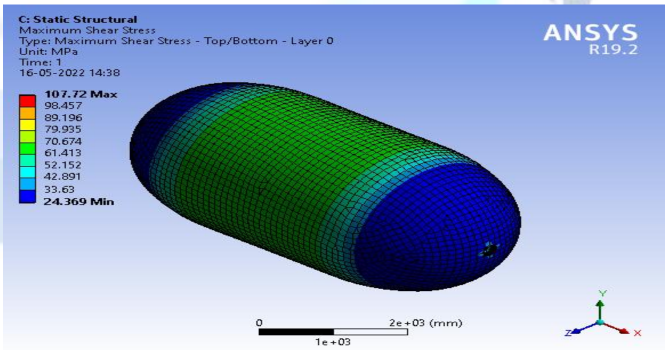

Figure 45: Maximum Shear Stress

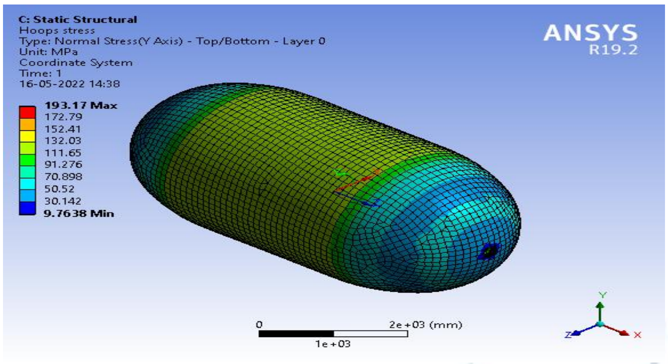

Figure 46: Hoops Stress

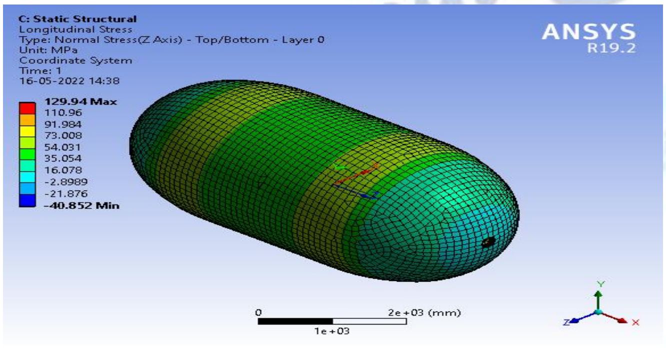

Figure 47: Longitudinal Stress

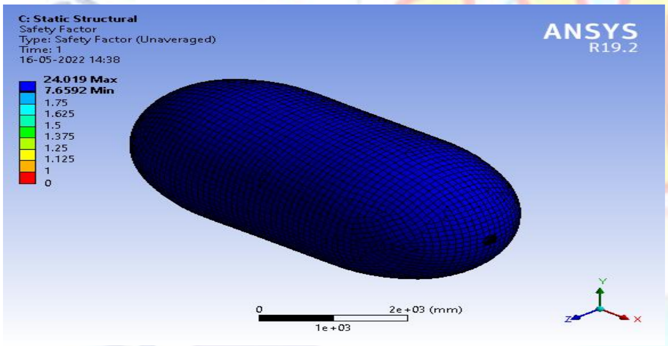

Figure 48: Factor of Safety

Table 6: Comparison of results of simulation 1 and simulation 2

Parameters	**All Metal Pressure vessel (Structural Steel)**	**COPV [-35°/35°] (liner: Titanium Alloy) (Composite: Carbon Epoxy Woven Prepreg.)**
Total Deformation	1.069 mm	2.577 mm
Radial Deformation	0.861 mm	2.249 mm
Longitudinal Deformation	0.017 mm	0.046 mm
Maximum Principal Stress	165.01 MPa	211.59 MPa
Equivalent stress	161.15 MPa	201.59 MPa
Hoops Stress	165.01 MPa	211.59 MPa
Longitudinal Stress	96.92 MPa	124.88 MPa
Maximum Shear Stress	93.03 MPa	116.37 MPa
Equivalent Elastic Strain	0.0008	0.0031
Maximum Principal Strain	0.0007	0.0019
Maximum Shear Strain	0.0012	0.0036
Applied Pressure	21 MPa	21 MPa
Factor of Safety [Min]	2.85	4.82
Burst Pressure	59.9 MPa	101 MPa
Weight	55173 Kg	18576 Kg

Table 7: Comparison of results of simulation 2 and simulation 3

Parameters	**COPV [0°/90°] (liner: Titanium Alloy) (Composite: Carbon Epoxy Woven Prepreg.)**	**COPV [-35°/35°] (liner: Titanium Alloy) (Composite: Carbon Epoxy Woven Prepreg.)**
Total Deformation	3.031 mm	2.577 mm
Radial Deformation	1.981 mm	2.249 mm
Longitudinal Deformation	0.072 mm	0.046 mm
Maximum Principal Stress	197.25 MPa	211.59 MPa
Equivalent stress	187.75 MPa	201.59 MPa
Hoops Stress	193.17 MPa	211.59 MPa
Longitudinal Stress	129.94 MPa	124.88 MPa
Maximum Shear Stress	107.72 MPa	116.37 MPa
Equivalent Elastic Strain	0.0028	0.0031
Maximum Principal Strain	0.0017	0.0019
Maximum Shear Strain	0.0034	0.0036
Applied Pressure	21 MPa	21 MPa
Factor of Safety [Min]	7.65	4.82
Burst Pressure	160 MPa	101 MPa

7. DISCUSSION

- The results of Simulation – 01 is compared with the theoretically calculated data of an existing pressure vessel made to ASME BPVC Code Section VIII

Division 1. Comparison of data showed that the result of the simulation done on ANSYS R19.2 is correct with minimal error and it can be used for further analysis of COPV.

- Based on ASME BPVC Code Section VIII Division 1, required minimum factor of safety for the pressure vessel is 3. Based on this safety factor, operating pressure of designed COPV is compared with metallic pressure vessel. Both types of COPV with winding pattern of [35°/-35°] and [0°/90°] showed betterment of operating pressure.

	Metallic Pressure Vessel	COPV [35°/-35°]	COPV [0°/90°]
Operating Pressure	20 MPa	33.67 MPa	53.33 MPa

- Designed composite overwrapped pressure vessel fulfilled one of its major objectives of being lightweight than its metallic counterpart. By achieving weight reduction, various issues related with transportation and light weight application of Metallic Pressure vessel is solved.

	Metallic Pressure Vessel	Composite overwrapped pressure vessel	Percentage Weight reduction
Weight (in Kg)	55173 Kg	18576 Kg	66.33%

This weight reduction is achieved by using materials with strong mechanical properties but lighter density. In designed COPV, liner is made up of Titanium alloy having density of 4.62 g/cm^3 and Epoxy Carbon composite with density of 1.48 g/cm^3 as compared to structural steel with 7.85 g/cm^3.

- Designed composite pressure vessel showed improved resistance to applied pressure as the burst pressure i.e. pressure where pressure vessel will fail to operate or simply burst, is also significantly increased in case of COPV as compared to its metallic counterpart. This is due to the excellent strength of titanium alloy liner and carbon epoxy composite which together resists the pressure applied to them.

	Metallic Pressure vessel	COPV [35°/-35°]	COPV [0°/90°]
Burst Pressure (in MPa)	59.9 MPa	101 MPa	160 MPa

- In Simulation -3, effect of different winding pattern is analyzed. Surprisingly, angle of winding affects the overall performance of composite overwrapped pressure vessel. Although, the total deformation in COPV with angle of orientation as [0°/90°] is high, it showed remarkable improvement (see table 7) of many parameters as compared to its counterpart with angle of orientation as [35°/-35°], one of the major parameter being burst pressure. The change in angle improved burst pressure by **58.41%**. As a result, factor of safety also increased and strength of overall COPV also increased. This is due to the directional property of Carbon Epoxy Woven Prepreg. This composite has tensile stress limit in X, Y, Z-directions as 850 MPa, 850 MPa, and 50 MPa respectively. Hence, [0/90] orientation took advantage of tensile stress limit in X and Y-directions.

8. CONCLUSION

- Composite overwrapped pressure vessel made up of titanium alloy liner and having composite material of Epoxy carbon woven prepreg is designed and analysed. Based on the results, this model of Composite overwrapped pressure vessel is lighter in weight with **66.33%** of total weight reduction as compared with metallic pressure vessel of same dimension.
- Designed composite overwrapped pressure vessel has also shown improvement in overall burst pressure, As COPV with [35°/-35°] orientation with Burst pressure of 101 MPa showing **68.61%** improvement and COPV with [0°/90°] orientation with burst pressure of 160 MPa showing **167%** improvement over the initial burst pressure of 59.9 MPa of the reference metallic pressure vessel.
- Winding pattern of composite over the liner in composite overwrapped pressure vessel also affect the overall performance of designed vessel. Based on the result of Simulation-3, winding pattern of [0o/90o] showed more better results in performance than the winding pattern of [35o/-35o]. Major Improvement includes, less stress generation, more burst pressure, improved factor of safety. Although the total deformation was slightly more in the [0o/90o] pattern as compared with [35o/-35o] pattern.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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