ABSTRACT

The Transportation sector is main emitter of harmful substances, including greenhouse gases. These gases cause of health issues like Asthma, Bronchitis and a bunch of other respiratory issues. Diesel vehicles tends to higher emissions of NO_2 and other greenhouse gases. These emissions can be reduced by 80% using Compressed Natural Gas vehicles. Compared to diesel vehicles CNG vehicles emits lower HC, NO_2 and CO gases. Exhaust after-treatments reduces most of the emissions in CNG vehicles. As CNG is better for environment and good for vehicle engines, it is highly advisable to use in transportation sector. Technical aspects of CNG properties, storage, safety problems and its effect on engine performance, efficiency, emissions and barriers to natural gas vehicles adaptation are to be considered for developing CNG cylinders.

The present work deals with design of Type 4 CNG cylinder by using ANSYS Workbench. The main objective of design involves in improving safey and increasing the strength, which were used for storage of CNG. The design of the CNG cylinder is methodized using Finite Element Analysis for least chances of fiber slippage or breakage. Model is developed using ANSYS design modeler in order to determine the structural analysis and vibrational analysis to set optimum values for safety use. The shape and the thickness of the cylinder was investigated with the aim of optimizing the type 4 CNG storage vessel by using Finite Element Analysis technique. Stresses and deformations in different directions under static structural analysis and natural frequencies and mode shapes from the free vibration analysis are calculated using Carbon Epoxy, E-glass Epoxy, Kevlar Epoxy and Hybrid Epoxy materials. The recommended material is selected based on the results under static and free vibration analysis.

Chapter 1

Introduction

1.1 Introduction

Supporting sustainable development is connected with the broader exploitation of alternative fuels, including renewables, in the transportation sector, especially for urban areas as noted in the literature review. The transportation sector is the main emitter of harmful substances, including greenhouse gases. Policies aimed at reducing private vehicles use are failing because they do not incorporate the reality of the human propensity for desiring accessibility and comfort. In order to minimize the negative effects of conventional fuels on the environment, Alternative fuels such as Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) should be encouraged. CNG Cylinders are essential for storage, transport and usage of CNG as fuel in vehicles. Technical aspects of CNG properties, storage, safety problems and its effect on engine performance, efficiency, emissions and barriers to natural gas vehicles adaptation are to be considered for developing CNG cylinders.

1.2 Compressed Natural Gas

CNG is a natural gas under pressure which remains clear, odorless, and non-corrosive. It also can be used as a cheaper, greener, and more efficient alternative to the traditional petrol and diesel vehicles. Natural Gas is not a liquid. It is safer than petrol and diesel. It has no color and is lighter than air. CNG is a petrol-based fuel gas. It is a non-toxic and clean-burning gas. It is a mixture of hydrocarbons that mostly consists of methane. CNG and LNG are two types of natural gas currently used in vehicles.

CNG, in its raw form, comes from the ground. Natural gas is found near oil wells during extraction. The name “Compressed Natural Gas” comes from the fact that CNG is compressed to a pressure of 200 to 250 Kg/cm^2. It has been reduced to less than 1% of its original volume at standard atmospheric pressure. It is popularly used in vehicles as a fuel however, vehicles must first be modified. CNG conversion kits and CNG cylinders need to be installed in regular vehicles to make them CNG compatible. Vehicles that are compatible with CNG produce significantly less pollution. CNG is far superior to petrol because it is both cleaner and more cost-effective.

The first experiments with compressed gases took place in France in the mid-eighteenth century. Initially, natural gas became a transport fuel during the First World War. In the 1960s, Columbia Natural Gas of Ohio tested a CNG carrier. The ship was to carry compressed natural gas in vertical pressure bottles; however, this design failed because of the high cost of the pressure vessels. Since then, several attempts were made to develop a commercially viable CNG carrier.

In the past five years, several competing CNG ocean transport designs have evolved. Following the 1990s, many countries began to adopt CNG fuel in vehicles, as well as its requirements. Iran, Pakistan, Argentina, Brazil, and China have the largest number of cars powered by compressed natural gas in the world. Since 2008, the market for CNG and LPG has grown due to increased gasoline prices and the desire to reduce air pollution. By 2011, there were almost 14.8 million natural gas vehicles in use around the globe.

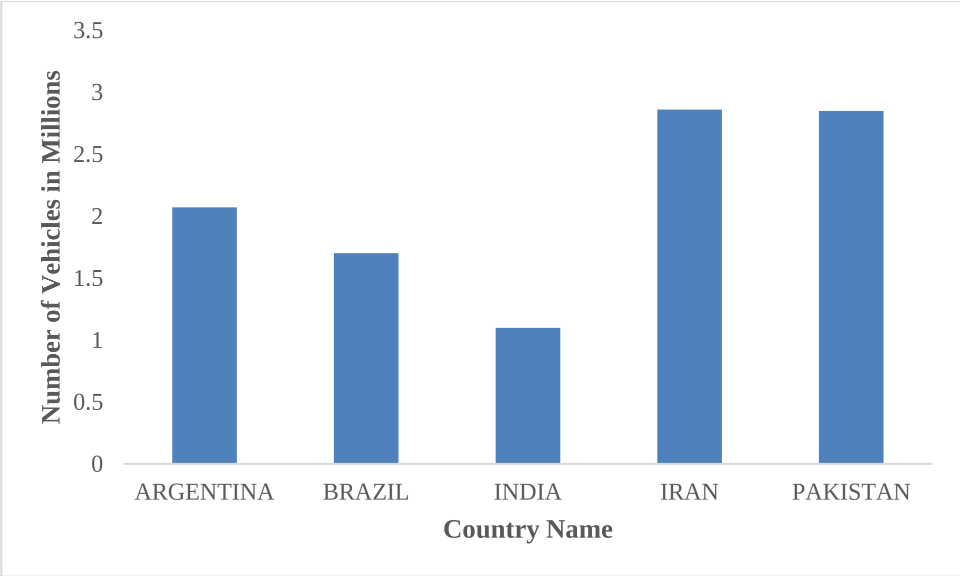


Figure 1.1 CNG cars uses in different countries

In regard to the need for cost-effectiveness and reducing potential difficulties in the future, compressed natural gas is an alternative fuel to conventional fuels. It is being popularly used and its demand is increasing which leads to the conclusion that they are much safer and in response to environmental concerns.

1.2.1 Properties of CNG

The natural gas became a promising alternative fuel since it is highly abundant in the world, produces less emissions.

- The state of the CNG is gaseous and it is an odorless, colorless, and tasteless gas. However, a chemical called methyl mercaptan is added to detect gas leaks.
- It is a highly combustible gas and a fossil fuel. It has a low flammability range and high ignition temperature.
- CNG is a mixture of simple hydrocarbon compounds especially Methane (CH_4) with small amounts of ethane, butane, pentane, and propane.
- The gas has a high calorific value because it is free of any kind of toxicity.
- The byproducts of CNG after burning are water vapor and carbon dioxide.

- CNG and other natural gases are 60% lighter than air.

Table 1.1 Properties of CNG

Properties	Description
Appearance	Colorless gas
Odor	Pungent odor
Boiling Point	-162ºC
Flash point	-187ºC
Auto ignition temperature	537ºC

1.2.2 Advantages and Disadvantages of CNG

Advantages of CNG

- When burned, compressed natural gas releases a number of pollutants that is far lower than that produced by gasoline or oil.
- CNG emits fewer greenhouse gases and thus has a lower carbon footprint. Reports say that CNG has about 28% fewer greenhouse gas emissions over its entire life cycle than the average gasoline fuel in that market.
- Compared to gasoline and oil, CNG is an eco-friendlier fuel source.
- The primary application of compressed natural gas is in motor vehicles; consequently, the primary advantage of CNG for motor vehicles is that Natural Gas-powered vehicles have lower costs of maintenance compared to vehicles, which are powered by gasoline or diesel.
- In the event of a leak, the potential damage caused by natural gas is significantly less severe than that caused by other fuels.

- Compared to diesel-powered cars, natural gas vehicles may cut noise by as much as 50%, making truck traffic on the street calmer.
- It has low CO2 emissions.
- Natural gas is cheaper when compared to gasoline and it is utilized for transportation, and its benefit is its ability to move large ships over long distances at much lower costs.

Disadvantages of CNG

- Compressed natural gas-powered cars demand more fuel storage space than gasoline-powered vehicles.
- CNG-powered vehicles are not a solution to reducing the carbon foot print when the whole natural gas production, distribution, and vehicle infrastructure are considered.
- The leakage of unburned methane as natural gas is a major problem since methane is the primary component of natural gas is consequently seen as a contributor to global warming.
- The natural gas-powered car has less power output than cars powered by petroleum.
- It has less energy density.

1.2.3 Applications of CNG

The most popular use of CNG is in motor cars. Any existing petrol vehicle can be converted to a dual-fuel petrol/CNG vehicle. Not only can a vehicle run solely on natural gas, but it can also function as a bi-fuel, meaning that it can be fueled by a combination of CNG and another fuel. It is also used in train operations, as it is cheaper than diesel. Natural Gas is not commonly used in trains. Although some trains are diesel-electric based, they have been transformed into natural gas-operated trains. Compressed natural gas is also used in transporting materials via ships. The loaded ships go on short and long trips, proving economical both ways when compared to conventional-based fuels.

1.3 CNG Cylinders

CNG is stored and transported in thick-walled pressurized tanks. These tanks are built in a long cylindrical shape with semi-spherical edges. The shape provides for the equal distribution of stresses from the pressure of the gas.CNG tanks are made of steel, aluminium, or composite materials, there are five types of storage tanks based on the material, namely:

- Type 1
- Type 2
- Type 3
- Type 4
- Type 5

Buyers must understand the applicability of each type and how it suits their needs and usage.

1.3.1 Type 1 Gas Cylinders

Type 1 gas cylinders are usually manufactured from steel or aluminum metals. They are the lowest cost and heaviest cylinder type. This makes them most suitable for static applications and high-volume industrial use. Type 1 cylinders are less suitable for applications where low weights and portability is required. Suitable applications include: Scuba, Modified atmosphere packaging (MAP), Onsite industrial/manufacturing, Laboratories.

1.3.2 Type 2 Gas Cylinders

Type 2gas cylinders are made from aluminum, hoop-wrapped with carbon fiber. They are significantly lighter than Type 1 cylinders, but still significantly heavier than Type 3 carbon composite cylinders. Type 2 cylinders are suitable for a variety of applications where cost is more important than low weight and high pressure. Suitable applications include: Medical oxygen (in a healthcare setting), Laboratory (high volume use)

1.3.3 Type 3 Gas Cylinders

Type 3 gas cylinders feature a thin and lightweight aluminum liner, fully overwrapped with carbon composite. Type 3 cylinders offer significant weight savings over Type 2 cylinders (up to 30%). They can also be filled to higher pressures (up to 300bar), so they can offer increased capacity for the same size cylinder. Type 3 lightweight gas cylinders are ideal for applications where portability and capacity are important such as for home oxygen therapy and for medical oxygen cylinders in ambulances. Suitable applications include: Ambulatory oxygen, Portable field testing, Drone/UAVs, Fuel cell applications, Aerospace and military, Calibration.

1.3.4 Type 4 Gas Cylinders

Type 4 gas cylinders are made primarily from carbon composite, with a polymer liner. They are the lightest and most expensive cylinders available on the market today. The key benefit of Type 4 is the low weight, which makes them most suitable for infrequent use applications where maximum portability is required. The downsides of Type 4 cylinders are that they are less robust and resistant to damage. In addition, the polymer lining does not provide an impermeable barrier, making them prone to leakage. Suitable applications include: Portable field testing, Calibration, Military.

1.3.5 Type 5 Gas Cylinders

Type 5 cylinders, also known as Liner less composite cylinders, are not widely available yet. These are the next generation of gas cylinders, and currently, they are only used in the most advanced military and aerospace applications. They are unlikely to be widely available on the commercial market for a few years.

1.4 Composite Materials

Composite materials are created from individual materials. These individual materials are known as constituent materials, and there are two main categories of it. One is the matrix (binder) and the other reinforcement. Epoxy resin is used as the matrix (binder) and different reinforcement materials are being used to design the CNG composite cylinder. Epoxy resins are also known as polyepoxides, which are a class of reactive polymers.

The Carbon composite materials considered in this article for designing CNG Cylinder are

- Kevlar Epoxy
- Carbon Epoxy
- Graphite Epoxy

1.4.1 Kevlar Epoxy

Kevlar is a strong, heat-resistant synthetic fiber which was developed by Stephanie Kwolek at DuPont in 1965, the high-strength material was first used commercially in the early 1970s as a replacement for steel in racing tires. It is typically spun into ropes or fabric sheets that can be used as such, or as an ingredient in composite material components. When Kevlar is spun, the resulting fiber has a tensile strength of about 3,620 MPa and a relative density of 1.38 g/cm^3. The polymer owes its high strength to the many inter-chain bonds.

Fig 1.2 Kevlar Fibers

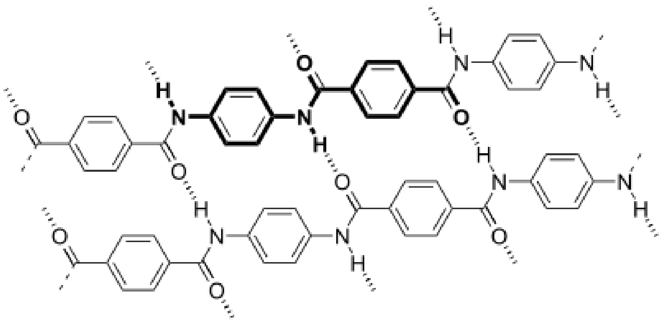


Fig 1.3 Molecular structure of Kevlar

1.4.2 Carbon Epoxy

Carbon fibers are fibers about 5 to 10 micrometers in diameter and composed mostly of carbon atoms. Carbon fibers have several advantages: high stiffness, high tensile strength, high strength to weight ratio, high chemical resistance, high-temperature tolerance, and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military, motorsports, and other competition sports.

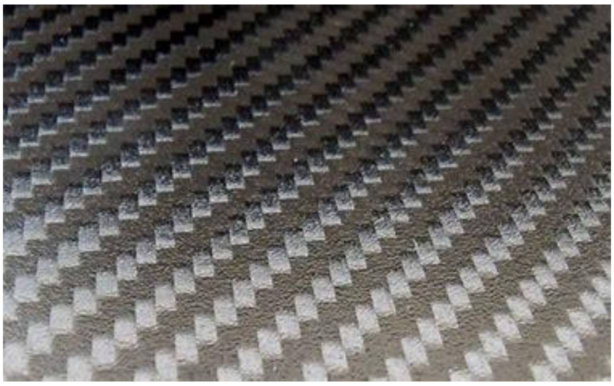


Fig 1.4 Carbon Fiber Epoxy sheet.

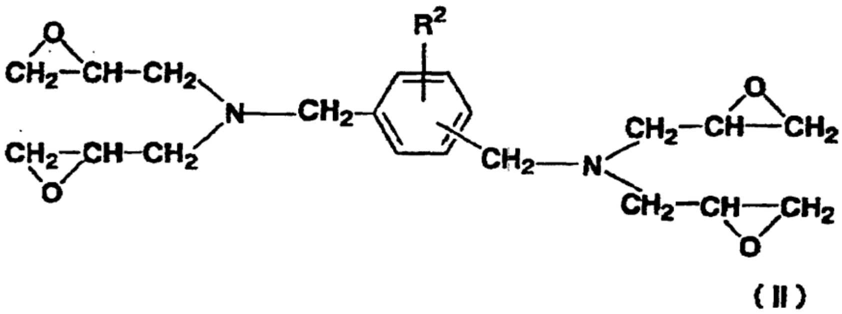


Fig 1.5 Molecular structure of Carbon Epoxy composite.

1.4.3 Graphite Epoxy

Graphite–epoxy is the most popular composite material applied to spacecraft structures. Strength and rigidity are provided by graphite fibers which are imbedded in an epoxy matrix. Material properties can be tailored, by selecting orientations and contents of graphite fibers, for strength, rigidity, and thermal expansion. Because the thermal expansion ratio of a graphite fiber is very small, and sometimes negative, a virtually zero expansion material at least in one direction can be fabricated.

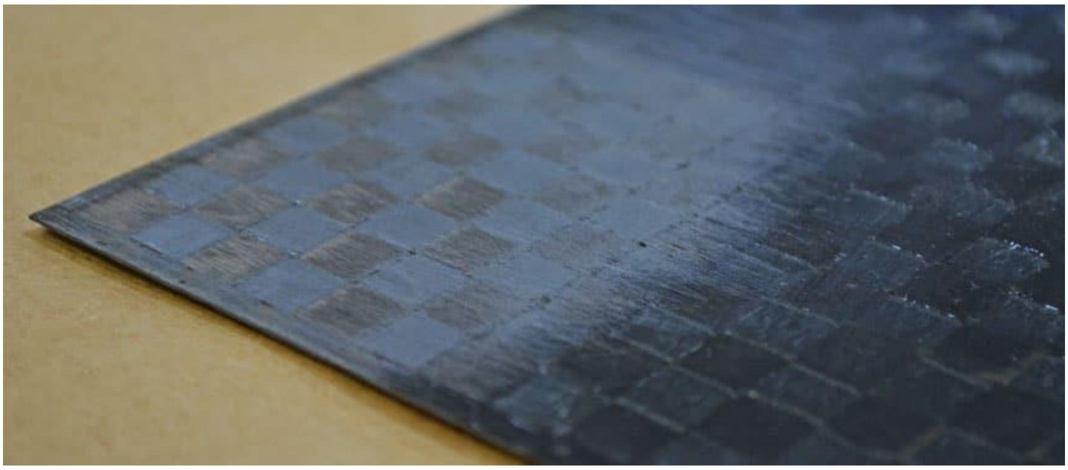


Fig 1.6 Graphite Epoxy composite.

1.5 Selection of CNG Cylinder

The main factors to be considered when specifying gas cylinders for a certain application, are:

- Cost
- Cylinder weight
- Pressure/capacity
- Durability
- Lifespan

1.5.1 Applications of CNG Cylinder

Laboratory and Scientific

Type 1 and Type 2 cylinders are suitable for a wide variety of in-lab applications, where portability isn't required. For field work, equipment testing and calibration applications, Type 3 and in some cases Type 4 cylinders are likely to be more practical, thanks to their lower weights.

1.5.2 Aerospace, UAV and Military

For any kind of flight application, weight matters. Every kg counts, and for that reason, Type 3, Type 4 and Type 5 cylinders are the most suitable, depending on the application. For drone use, Type3cylinders can provide a more resilient and robust solution than Type 4. Type 3 cylinders are also most suitable for the aviation industry, where they have full regulatory approval.

1.5.3 Firefighting

Type 4 cylinders have been used in firefighting, but concerns over durability and impact resistance means they are less suitable for use in dangerous environments. They are light in weight and can handle the high pressures exerted by the gases and chemicals inside the fire extinguisher.

1.6 ISO Standards

Gas cylinders of high pressure for the on-board storage of natural gas as a fuel for automotive vehicles. This standard was last reviewed and confirmed in 2019. Therefore, this version remains current**.** ISO 11439:2013 specifies minimum requirements for 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. The service conditions do not cover external loadings that can arise from vehicle collisions, etc. ISO 11439:2013 covers cylinders of any seamless steel, seamless aluminum alloy or non-metallic material construction, using any design or method of manufacture suitable for the specified service conditions. It does not cover cylinders of stainless steel. ISO 11439:2013 uses 200 bar as a reference working pressure, but other working pressures can be used Cylinders covered by the ISO-11439:2013 are designated Type 1, Type 2, Type 3 and Type4.

1.7 Problem Identification

The demand of energy increasing day by day and it is necessary to develop new way to distribute the energy using economic feasibility. The transport and storage of natural gas or methane has been one of the impediments to natural gas utilization. Pipeline transport is associated with large upfront capital requirements, long pay-back periods and inflexibility once constructed. Similarly, the transport (and storage) of methane as a liquid in form of cryogenically liquefied natural gas (LNG) is capital (and energy) intensive but potentially offers a certain degree of flexibility to sellers and buyers. Another option for natural gas transport/storage is compressed natural gas (CNG).

1.8 Objectives

The present work deals with an objective of designing the CNG cylinder and analyzed for optimum conditions.

- The shape and thickness of the cylinder is to be investigated with the aim of optimizing the type 4 CNG storage vessels by using finite element analysis technique.
- To select the suitable material for developing CNG cylinder.
- To study the structural analysis of CNG cylinder.
- To know the vibrational analysis of the modal.

1.9 Methodology

- Design of Type 4 CNG cylinder by using ANSYS design modeler.
- Structural analysis of the composite CNG cylinder by using ANSYS work bench.
- Vibrational analysis of the composite CNG cylinder by using ANSYS work bench.

1.10 Layout of the Thesis

Chapter 1, Presents the introduction of the CNG cylinder, history of the CNG cylinder, advantages and disadvantages of CNG cylinder, properties of the CNG cylinder, types of CNG cylinder. Objectives and methodology of the project work presented.

Chapter 2, describes the study's on the literature related CNG cylinder and Structural Analysis of CNG cylinders. Gaps were identified from the literature.

Chapter 3, explained the design of the CNG cylinder, Geometry of the Cylinder, Meshing the CNG cylinder.

Chapter 4 & 5, analyzes the structural analysis and vibration analysis of CNG cylinder using ACP Pre tool in ANSYS workbench.

Chapter 6, presents the conclusions and future scope of the work.

1.11 Summary

In this chapter, introduction and history of CNG is presented. The cylinders which are used for storage and transport of CNG are discussed in detail. Materials used to design the CNG cylinder and their properties are discussed. The objectives and methodology of the work is presented. The related Literature has been reviewed in Chapter 2.

Chapter 2

Literature Review

2.1 Introduction

The transportation sector is main emitter of harmful substances, including greenhouse gases. These gases cause of health issues like Asthma, Bronchitis and a bunch of other respiratory issues. Diesel vehicle tends to higher emissions of NO_2 and other greenhouse gases. These emissions can be reduced by 80% using Compressed Natural gas vehicles. Compared to diesel vehicle CNG vehicle emits lower HC, NO_2 and CO gases. Exhaust after-treatments reduces most of the emissions in CNG vehicles. As CNG is better for environment and good for vehicle engines, it is highly advisable to use in transportation sector. So, it is necessary to do structural analysis on CNG cylinders for safety, environmental and economic feasibility.

2.2 Studies on CNG Cylinder

Tadeusz Dyr et.al.,[1] described, the availability of alternative fuels for transportation means using renewable energy is an essential factor for achieving sustainable development. Natural gas use is increasing, and it ranks as one of the most often consumed alternative fuels for public transportation and is leading to improved air quality in urban areas, enabling cleaner production in the transport sector. The investment and maintenance costs for buses fuelled by CNG are higher than for diesel buses. Notably, the use of CNG buses can reduce fuel costs. These factors have a significant influence on the financial effectiveness of deploying CNG buses for public transport. Replacing diesel buses with CNG buses in urban transport reduces the emission of toxic substances and greenhouse gases.

M. Imranet.al.,[2] discussed, the increasing urbanization and industrialization have led to a phenomenal growth in transportation demand worldwide, coupled with a concentration of vehicles in metropolitan cities. With regard to increasingly stringent emission legislation natural gas is gaining interest as a transportation fuel with worldwide over 19 million natural gas vehicles in operation. Technical aspects of compressed natural gas properties, storage, safety problems and its effect on engine performance, efficiency, emissions and barriers to natural gas vehicles adaptation are discussed in detail. The main indicators selected for the comparative assessment of natural gas as vehicular fuel are: economic, emission performance and safety aspect. The results showed that CNG has several advantages over both diesel and gasoline fuel, including considerable emission and cost reductions.

M.I. Khan et.al.,[3] evaluated, that road transport produces significant amounts of CO_2 by using crude oil as primary energy source. A reduction of CO_2 emissions can be achieved by implementing alternative fuel chains. NG-based hydrogen applied in fuel cell vehicles (FCVs) lead to largest CO_2 emission reductions (up to 40% compared to current practice). However, large implementation barriers for this option are foreseen, both technically and in terms of network change. Two different transition strategies are discussed to gradually make the transition to these preferred fuel chains. Important transition technologies that are the backbone of these routes are traditional engine technology fueled by compressed NG and a FCV fueled by gasoline. The first is preferred in terms of carbon emissions. This furthermore indicate that an innovation in the conventional chain, the diesel hybrid vehicle, is more efficient than many NG-based chains. This option scores well in terms of carbon emissions and implementation barriers and is a very strong option for the future.

S.Bernardino et.al.,[4] prescribed, a comprehensive comparison of emissions from vehicles fueled with diesel or compressed natural gas (CNG) was developed from 25 reports on transit buses, school buses, refuse trucks, and passenger cars. Emissions for most compounds were highest for untreated exhaust emissions and lowest for treated exhaust. CNG buses without after-treatment had the highest emissions of carbon monoxide, hydrocarbons, non-methane hydrocarbons (NMHC), volatile organic compounds (VOCs; e.g., benzene, butadiene, ethylene, etc.), and carbonyl compounds (e.g., formaldehyde, acetaldehyde, acrolein). Diesel buses without after-treatment had the highest emissions of particulate matter and polycyclic aromatic hydrocarbons (PAHs). Exhaust after-treatments reduced most emissions to similar levels in diesel and CNG buses. Diesel school buses had higher CO_2 emissions than the CNG bus. CNG transit buses and passenger cars equipped with three-way catalysts had lower NO_2 emissions than diesel buses.

Jingjinget.al.,[5] presented, that the natural gas (NG) is one of the most important and successful alternative fuels for vehicle. Compared to using gasoline, bi-fuel engine using NG exhibits higher thermal efficiency; produces lower HC, CO and PM emissions and higher NO_2emission. The bi-fuel mode cannot fully exert the advantages of NG. Optimization of structure design for engine chamber, injection parameters including injection timing, injection pressure and multi injection, and lean burn provides a technological route to achieve high efficiency, low emissions and balance between HC and NO_2. Compared to diesel, NG/diesel dual fuel engine exhibits longer ignition delay; has lower thermal efficiency at low and partial loads and higher at medium and high loads; emits higher HC and CO emissions and lower PM and NO_2 emissions. The addition of hydrogen can further improve the thermal efficiency and decrease the HC, CO and PM emissions of NG engine, while significantly increase the NO_2 emission.

Daniel Krentelet.al.,[6] explained, CNG is a widely used automotive fuel in a variety of countries. In case of a vehicle fire where the safety device also malfunctions, a failure of the CNG automotive cylinder could occur. Such a cylinder failure is associated with severe hazards for the surrounding environment. Firstly, a comprehensive analysis is done, summarizing various accidents involving CNG automotive cylinders and their consequences. In an extensive experimental program, 21 CNG automotive cylinders with no safety device were tested. Of the

21, burst tests were carried out on five Type 3 and five Type 4 cylinders. Furthermore, fire tests with eight Type 3 and three Type 4 cylinders were conducted. Apart from cylinder pressure, inner temperature and cylinder mantle temperature, the periphery consequences, such as nearfield blast pressure and fragmentation are documented. The maximum measured overpressure due to a Type 3 cylinder failure was P= 0.41 bar. As one key result, it can be stated that the tested Type 4 CNG cylinders showed less critical failure behavior then the Type 3 cylinders under fire impingement.

2.3 Studies on Structural Analysis of CNG Cylinder

PranjaliSharmaet.al.,[7] described, that composite pressure vessels are lightweight structures mainly used in automotive applications, because of their ability to store gaseous energy fuels at high pressures. The development of design methods can reduce the chances of leakage or burst failure in type-4 cylinders for storage of CNG. The design of the pressure vessel is methodized using finite element analysis yielding the least chances of fiber slippage or breakage. The manufacturing technology is optimized to enhance the product performance and reduce the chances of defects during winding. The design methodology is validated by comparing the experimental burst pressure with the theoretical value. The resultant is a high-performing, lightweight, low-cost vessel that is safe for the storage of CNG for on board applications.

M. Madhaviet.al.,[8] evaluated, the filament-wound composite pressure vessels are an important type of high-pressure container that is widely used in the commercial and aerospace industries. The pressure vessels with integrated end domes develop hoop stresses that are twice longitudinal stresses. On the other hand FRP composite materials with their higher specific strength and modulus will result in reduction of weight of the structure. The determination of a proper winding angle and thickness is very important to decrease manufacturing difficulties and to increase structural efficiency. Fibers are principal load carrying members and the surrounding matrix keeps them in the desired location and orientation, acts as a load transfer medium between them and protects them from environmental damage due to elevated temperatures and humidity. The composite pressure vessel consists of a durable plastic liner fully wrapped with epoxy-impregnated carbon fiber.

S Sulaimanaet.al.,[9] explained, the FEA of composite overwrapped pressure vessel (COPV). They studied simulation of aluminum pressure vessel overwrapping by Carbon/Epoxy fiber reinforced polymer (CFRP). FEM was utilized to investigate the effects of winding angle on filament-wound pressure vessel. Burst pressure, maximum shell displacement and the optimum winding angle of the composite vessel under pure internal pressure were determined. An exact elastic solution along with the Tsai-Wu, Tsai-Hill and maximum stress failure criteria were employed for analyzing data. Investigations exposed that the optimum winding angle happens at 55° winding angle.

G. Narayana Naiket.al.,[10] presented, minimum weight design of composite laminates is presented using the failure mechanism based (FMB), maximum stress and Tsai–Wu failure criteria. The objective is to demonstrate the effectiveness of the newly proposed FMB failure criterion (FMBFC) in composite design. The FMBFC considers different failure mechanisms such as fiber breaks, matrix cracks, fiber compressive failure, and matrix crushing which are relevant for different loading conditions. The Tsai–Wu failure criterion over predicts the weight of the laminate by up to 86% in the third quadrant of the failure envelope compared to FMB and maximum stress failure criteria, when the laminate is subjected to compressive–compressive loading. It is found that the FMB and maximum stress failure criteria give comparable weight estimates. The FMBFC can be considered for use in the strength design of composite structures.

Jianhuiet.al.,[11] reported, filament winding is a technology for producing composite parts by winding reinforcing fibers around the mandrel of a desired shape. Products obtained by filament winding have an exceptional strength-to-weight ratio and are suitable for high-pressure vessels such as the fuel tanks of fighters, liquefied natural gas tanks, and torpedo launchers. Filament winding requires a computer numerical control machine for simultaneous control of more than four axes, as well as an exact winding path for its operation. The winding path must be generated such that it causes neither slippage nor bridging (separation of fiber from mandrel) during the winding process and must be continuous even at both ends of mandrel for turnaround operation. In addition, the winding path must be generated to maximize the strength of the part because the strength is determined by the direction of the winding path.

Sarvenaz Ghaffariet.al.,[12] prescribed, there has been a strong demand in using high-modulus (HM) carbon-fiber composites potentially enabling lightweight aircraft structures with significant weight savings. Hybridizing fibers with varying modulus provides an innovative means for improving the fiber-direction compressive strength of composites. Comingling intermediate-modulus (IM) and high-modulus (HM) carbon fibers in HM carbon fiber-reinforced polymer toughened with nano-silica. Comingling IM and HM fibers at the filament level in addition to the matrix nano-sized structural reinforcement throughout the composite, increases compressive strength.

P.J. Hineet.al.,[13] evaluated, validating a new micromechanical modeling scheme for predicting the five independent elastic constants of a unidirectional carbon fiber epoxy resin composite. Finite element calculations were used to validate a much more easily implemented, classical analytical micromechanical approach for predicting the elastic properties of composite materials. For formulating the elastic predictions, the elastic correspondence principle is used to convert the static elastic solutions to their complex steady state elastic forms simply by replacing static elastic modulus of the matrix and the fibers by their complex elastic modulus.

Jianhuiet.al.,[14] describes, filament winding is a technology for producing composite parts by winding reinforcing fibers around the mandrel of a desired shape. Products obtained by filament winding have an exceptional strength-to-weight ratio and are suitable for high-pressure vessels such as the fuel tanks of fighters, liquefied natural gas tanks, and torpedo launchers. Filament winding requires a computer numerical control machine for simultaneous control of more than four axes, as well as an exact winding path for its operation. The winding path must be generated such that it causes neither slippage nor bridging (separation of fiber from mandrel) during the winding process and must be continuous even at both ends of mandrel for turnaround operation. In addition, the winding path must be generated to maximize the strength of the part because the strength is determined by the direction of the winding path.

Dinghua Zhanget.al.,[15] discussed, filament wound isotensoidal structures are recently gaining more attention for designing composite pressure vessels. Governing equation for creating geodesic-isotensoids based on the netting theory and geodesic winding law. The feasible intervals of the isotensoid-based design are also determined. The isotensoid-based dome profiles are determined by solving the governing equation with geometrical and initial winding conditions. When the applied axial load reaches a certain magnitude, the isotensoidal toroids can be obtained by forcing the isotensoid-based dome profile to become closed. The comparisons of the cross-sectional shapes between the isotensoidal dome and the hemispherical dome, and between the isotensoidal toroid and the circular toroid, are performed to demonstrate the preferable performance of the isotensoids. It is concluded that the isotensoid-based design leads to uniform fiber tension throughout the whole shell and the resulting structure can thus be considered as optimal for a pressure vessel. In addition, the isotensoid-based profiles show lower aspect ratios than the conventional vessel profiles.

M. Farzaneh-gordet.al.,[16] invesigated, one of the most important issues regarding Natural Gas Vehicles (NGVs) is the Driving Range, which is defined as capability of a NGV to travel a certain distance after each refueling. The Driving Range is a serious obstacle in the development and growth of NGVs. Thus the necessity of studying the effects of various parameters on the Driving Range could be realized. It is found that the on-board storage capacity and the natural gas heating value have the greatest effect on the Driving Range. The parameters are natural gas composition, engine efficiency and final NGV on-board in-cylinder temperature and pressure. It is found that, the composition has big effects on the Driving Range. As final in-cylinder pressure decreases (or temperature increases), the Driving Range will be increased.

2.4 Identification of gaps

From the studies on structural analysis of CNG cylinder, there is inadequate information related to CNG cylinder. The investigation on mechanical properties on CNG cylinders was limited. Most of the researches were carried on CNG cylinders which are made of Carbon/Epoxy material with zero orientation. The CNG cylinders are made of kelver epoxy graphite epoxy is very limited

2.5 Summary

In this chapter, literature on CNG and structural analysis on CNG cylinder is reviewed. Gaps in the literature were identified. The Design of CNG cylinder has discussed in chapter 3.

Chapter 3

Design of CNG Cylinder

The design modelling is a core part of the product development process and it is first step in simulation process. These models represent actual design details. Geometry is an essential component of engineering simulation and it also links with design and manufacturing.

3.1 Problem Statement

To perform the static and free vibration analysis of the CNG cylinder using realistic loading and boundary conditions for calculating the stresses, deformations, natural frequencies and mode shapes of the structure.

3.2 Geometry

The model of the CNG cylinder designed and modelled in the ANSYS ACP Pre tool student version 2023 R1. The views of the CNG Cylinder are shown in the Fig 3.1.

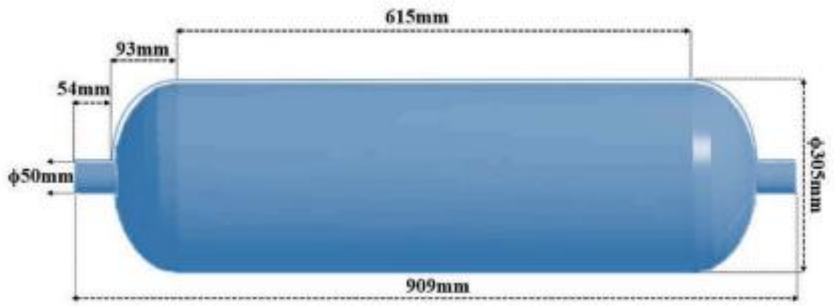


Fig 3.1 CNG Cylinder

3.3 Meshing

Meshing is the process of converting the geometry entities in to the finite elements. The above model of the CNG cylinder is meshed with the shell 181 element which is 4 noded with six degrees of freedom (Linear X, Y, Z & Rotation about X, Y, Z) and diagrammatic representation of four nodded shell element is shown in the Fig 3.2.

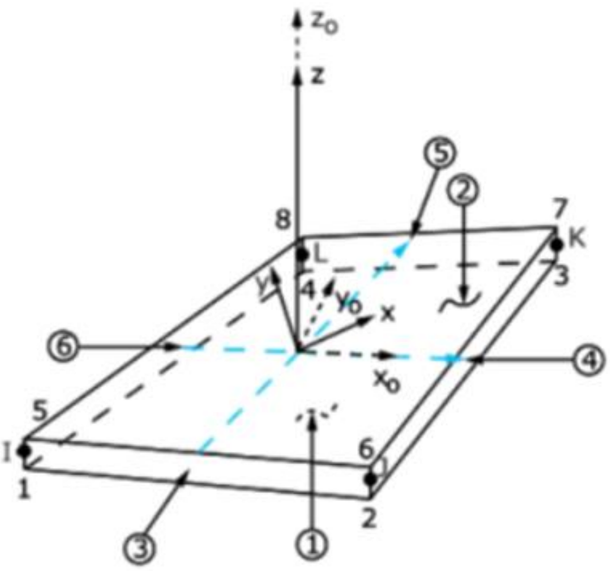


Fig 3.2 Shell

The designed cylindrical model is meshed into 32804 nodes, 32113 elements. With each element size is 5mm and the meshed model is shown in Fig 3.3.

Fig 3.3 Meshed Model

3.4 ACP Pre Tool

In Ansys composite prepost PRE tool, there are five basic steps that are to be considered. For design by layer, the selection of the particles relates where chosen by considering their prophetical

3.4.1 Selection of Fabric Materials

In this analysis, three composite unidirectional materials are considered i.e., Graphite epoxy, Kevlar epoxy and Carbon epoxy. The orthotropic properties of these materials are listed in Table 3.1.

Table 3.1 Material Properties in Uni direction

Property	Kevlar/epoxy	Carbon/epoxy	Graphite/epoxy
Fibre volume ratio	0.60	0.58	0.50
Density (g/cm3)	1.38	1.57	1.59
Longitudinal modulus ,E_1 (GPa)	80	138	294
Transverse modulus, E_2 (GPa)	5.5	8.7	6.4
In plane shear modulus G_{12} (GPa)	2.2	5	4.9
Major Poisson ratio ,υ_{12}	0.34	0.28	0.23
Minor Poisson ratio ,υ_{21}	0.02	0.02	0.01
Longitudinal tensile strength (MPa)	1400	2060	985

The three materials Kevlar/epoxy, Carbon/epoxy, Graphite/epoxy are used for the designing composite cylinder and it is shown in the Fig 3.4.

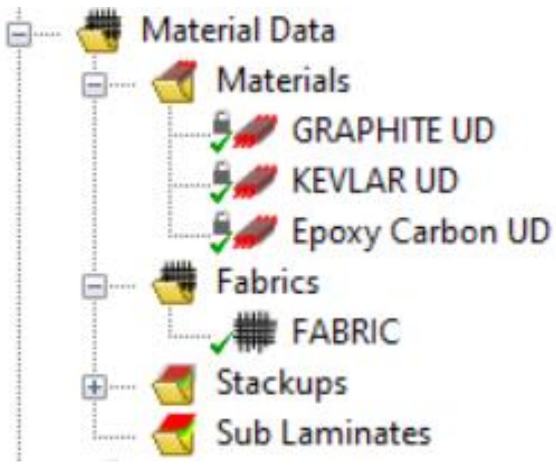


Fig 3.4 Tree Diagram of Material Data

The fabric is made of 1.5 mm thickness by giving the properties shown in Fig 3.5.

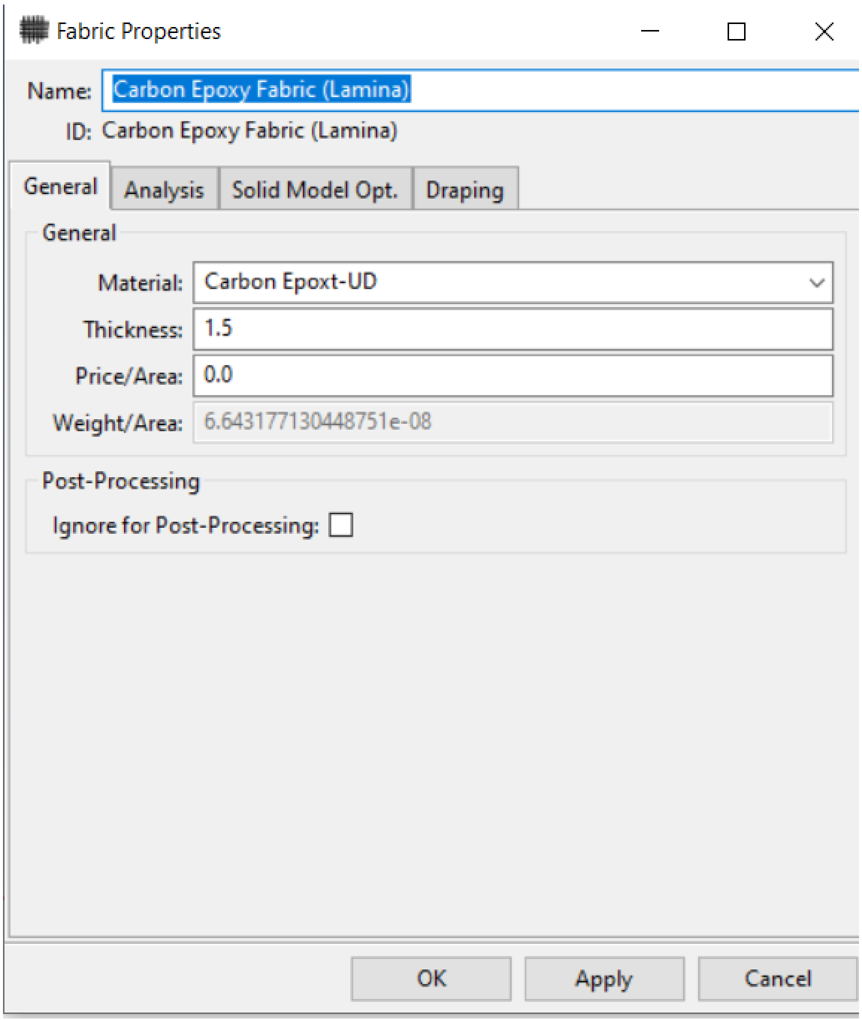


Fig 3.5 Fabric Properties

3.4.2 Stackup

A stackup is made of ten fabric layers. Each of this layer has different orientations, of different angles as shown in Fig 3.6. Each layer has a thickness of 1.5 mm.

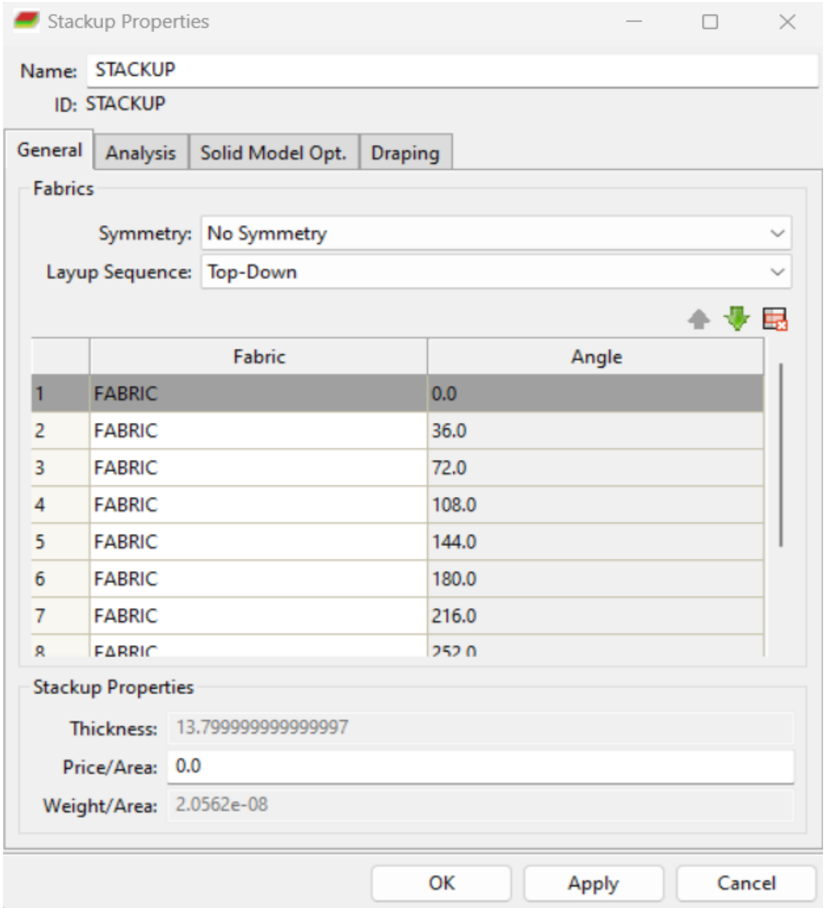


Fig 3.6 Details About Each Fabric Orientation

3.4.3 Rosettes:

Rosettes are the co-ordinate systems that are used to set the reference directions of the oriented selection sets. For this a new origin and directions are given to make a new rosette.

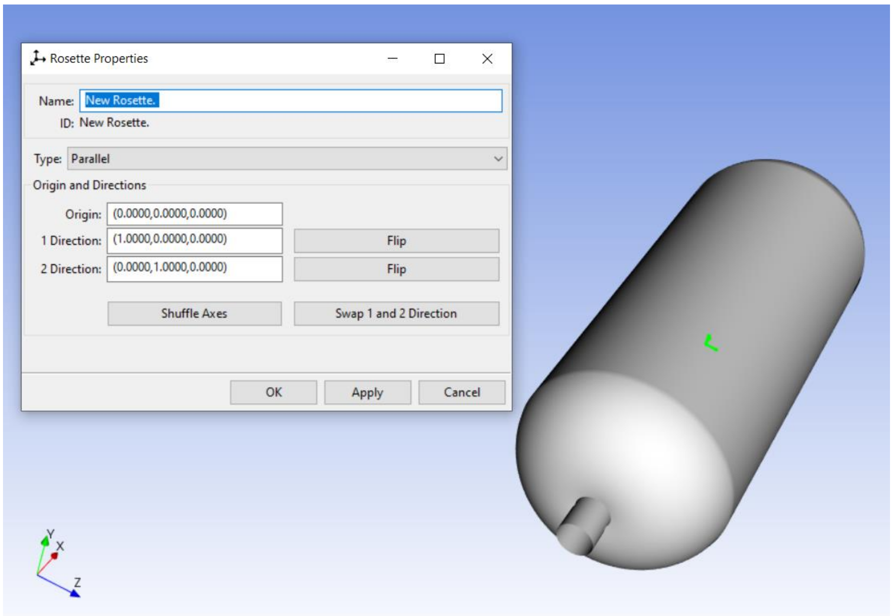


Fig 3.7 Rosette Properties

3.4.4 Oriented Selection Sets

It is used to represent the fibre orientations for particular lamina. For this, first select all the elements in the stackup and the origin point where orientation starts in particular direction as shown in Fig 3.8.

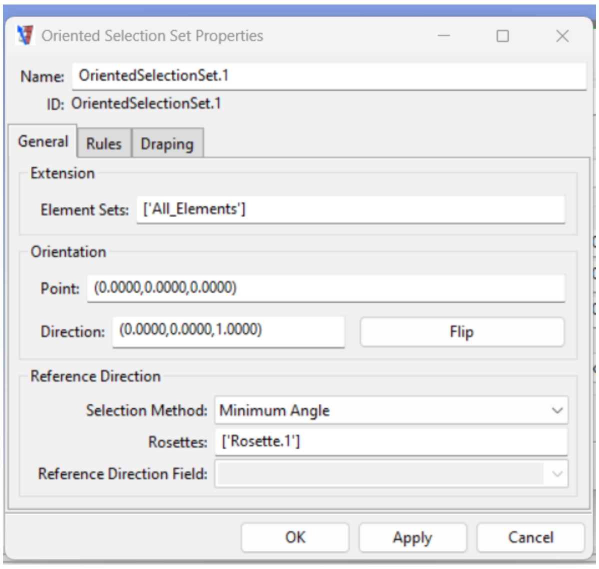


Fig 3.8 Set Properties

3.4.5 Modelling Groups

A new modelling group is created with the following modelling ply properties as shown in Fig 3.9.

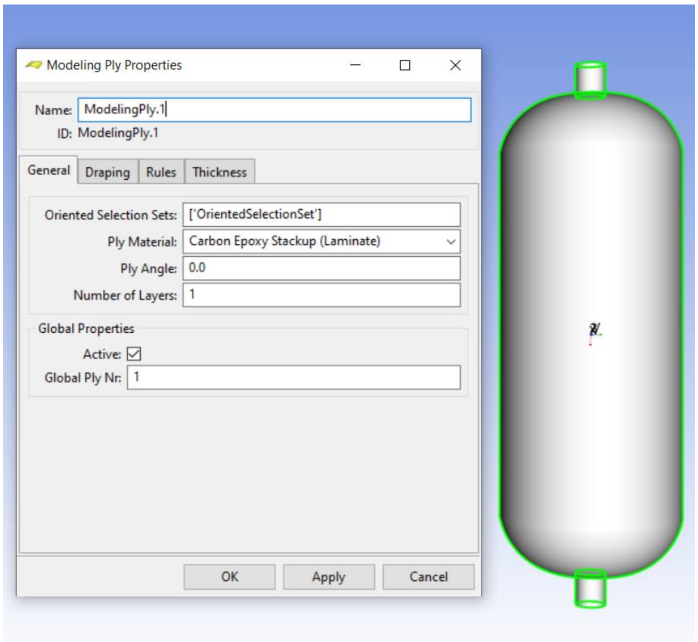


Fig 3.9 Modelling Ply Properties

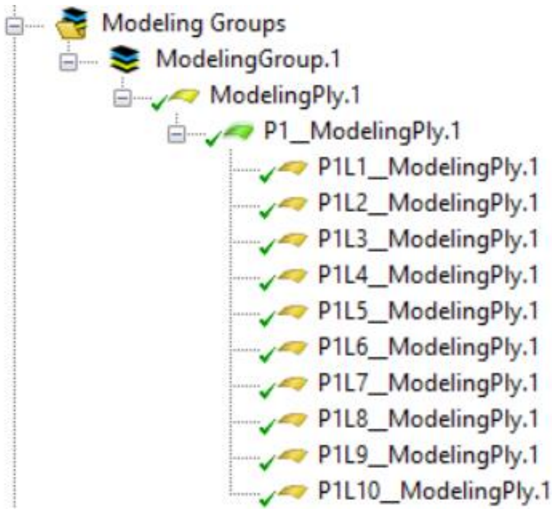


Fig 3.10 Modelling Ply Tree Diagram

The Fig 3.10 shows the information about the ten different layers and also called as modelling ply and its orientations are combined to form a single composite layer.

3.4.6 Solid Models

From the Fig 3.9, different model plys a new solid represented shell cylinder is created as shown in the Fig 3.11.

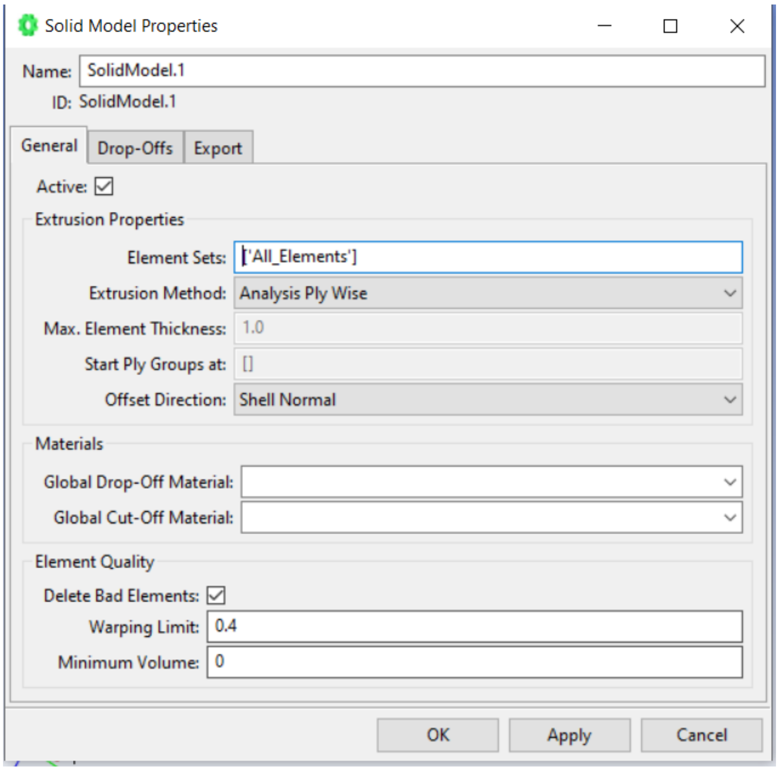


Fig 3.11 Solid Model Properties

The orientations of each layer are shown in Fig 3.12, 3.13, 3.14, 3.15, 3.16.

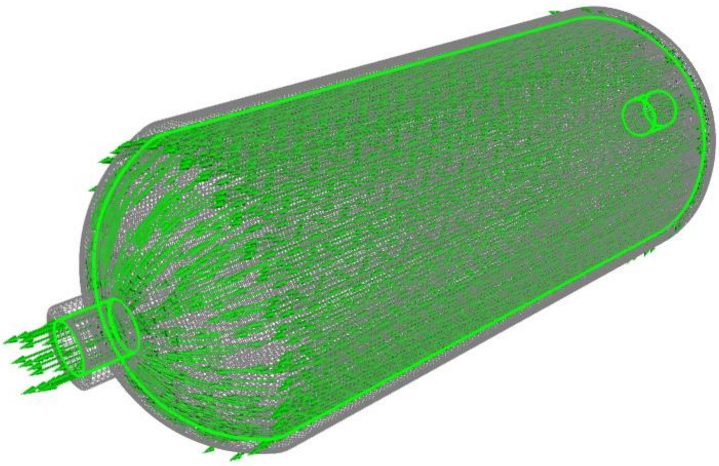


Fig 3.12 0^{0} Fibre Oriented Layer

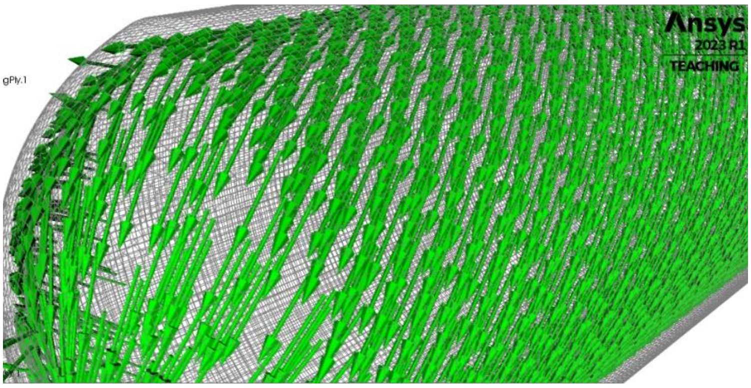


Fig 3.13 36⁰ Fibre Oriented Layer

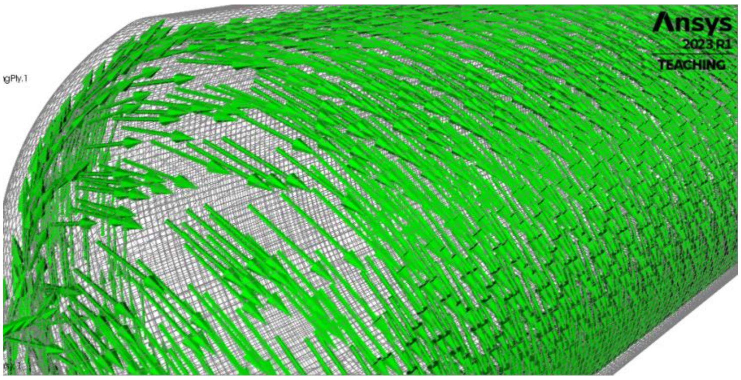


Fig 3.14 72⁰ Fibre Oriented Layer

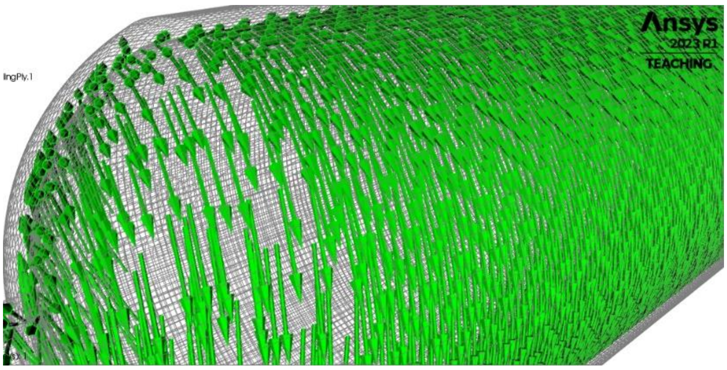


Fig 3.15 108⁰ Fibre Oriented Layer

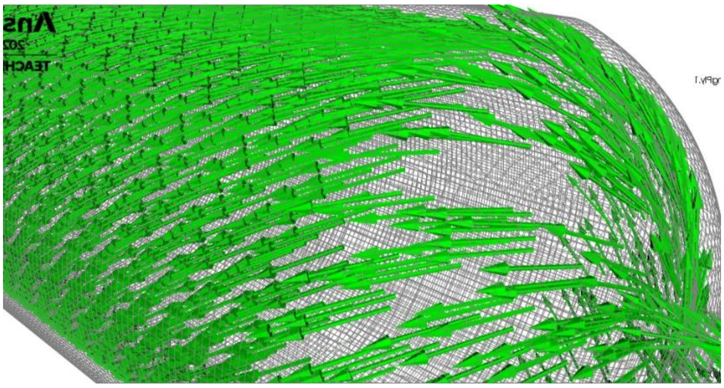


Fig 3.16 144⁰ Fibre Oriented Layer

Similarly, the remaining angles are set to the layers to complete the laminate with 10 lamina's.

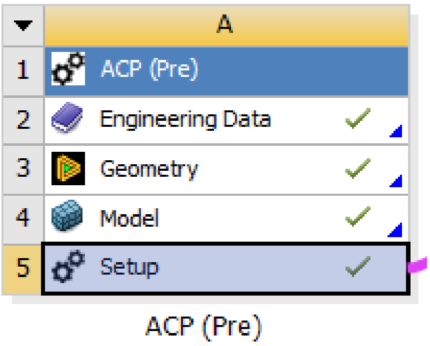


Fig 3.17 Final ACP Pre Component System After Updating

The whole setup for the composite cylinder is created in the ACP Pre tool and it is update in ANSYS Workbench for structural analysis.

The complete tree diagram of ACP (pre) mode is shown in Fig 3.18.

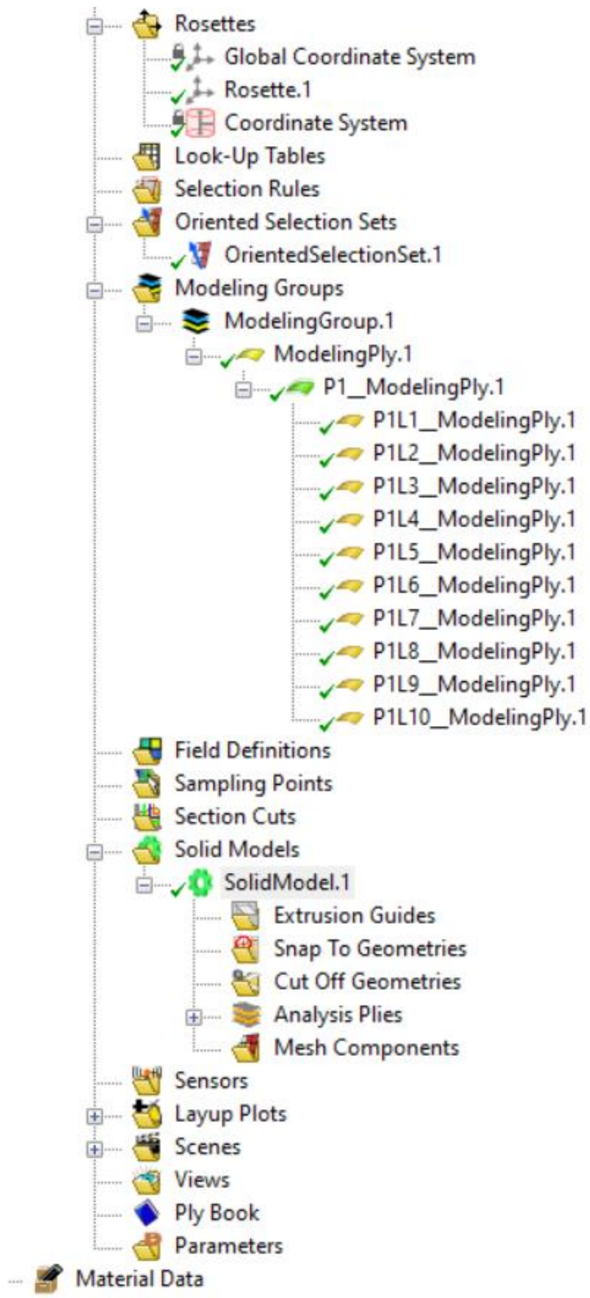


Fig 3.18 Tree Diagram of Complete ACP Pre Component Model

3.5 Theoretical Calculations

Natural gas is a cost-effective, environment-friendly, and abundant source of conventional energy, acting as an asset to humankind because of its sufficient availability and safe operability. It considerably emits less toxic emissions, making its usage an excellent solution for surmounting the current pollution problems. The usage of natural gas in the transportation sector was restricted due to its low energy density. The energy generated by 1000L of natural gas is equivalent to that produced by 1L of gasoline or 1.1L of diesel. Availability of limited storage space restricts fuelling the statutory amount of fuel, providing a small driving range. Therefore, it is either used as CNG stored at 20 MPa pressure at ambient temperature or as LNG at an ultra-low temperature of -162 ^{o}C at atmospheric pressure. Light-weight Type-4 composite pressure vessels are developing for the storage of CNG. CNG stored at a pressure of 20–25 MPa can give the desired driving range in the available cargo space.

The designing of a pressure vessel involves a variety of parameters based on its working pressure, burst pressure, and material properties. The details of the pressure vessel design are determined based on the system properties given in Table 3.2.

Table 3.2 Overall CNG Cylinder Design Details

S. No.	Property	Value
1	Working Pressure	20-25 MPa
2	Burst Pressure	40-45 MPa
3	Volume	52-57 L
4	Standards	ISO 11439
5	Driving range	160 Km
6	Open Radius	25 mm

3.5.1 Diameter

The study aims to design a vessel, which is suitable for storing CNG for a driving range of more than 150 Km. Based on available compositions of natural gas, 5.8–6.4 Kg of natural gas offers a driving range of 100 Km. Due to space restrictions in the available cargo space, the gas is stored at 20 MPa. The gas density at normal temperature and pressure of 20 MPa is reported to be 180 Kg/m3. For a driving range of 160 m, 9.3–10.2 Kg of gas is required which is calculated to be 52–57 L. Therefore; the vessel is designed to store ~57 L of gas at a pressure of 20 MPa; the targeted driving range is estimated to be ~160 Km.

For simplifying the calculations for approximating the vessel diameter, the liner geometry is assumed to contain a cylinder covered with two spherical heads. The diameter of the vessel can be related to the volume of the vessel or the driving range of the vehicle using the equation.

$$D = 0.057(L)^{(1/3)} \tag{3.1}$$

Where D =diameter of vessel

L= targeted driving range

$D=0.057*(160)^{(1/3)}=305.3$ mm

The liner was designed as per these calculations, which yielded the geometry. The geometry comprises a cylinder, an isotensoid head, and port size compatible with the available valves. The composite overwrap is the major load-bearing component of a type 4 vessel. However, the liner must be able to withstand the winding tension. The thickness of the liner depends on its yield stress.

3.5.2 Winding Angle (α)

Clairault condition is used to ensure no fibre slippage at the dome section. Isotensoid curves have varying radii at different dome heights, for which the dome is virtually divided into 8 parts.

$$\sin\alpha = r_0/ R \ (1.2) \tag{3.2}$$

Where, r_0=open radius

R=equator radius=D/2=152.5 mm

α =36°.

Therefore, for the calculations of layer thickness, the minimum value of α is 36°.

3.5.3 Layer Thickness

The preliminary design is formulated using netting analysis; addressing the inner pressure loading of 1.25 times the required load of 20 MPa. The hoop stress plays a vital role in providing strength to the vessel. The NOL ring specimen for determining the hoop strength of the composite was manufacture. The hoop tensile strength of the composite was determined to be 570 MPa. Tensile strength of the engineering materials is reduced by 30%, considering the detrimental effects of unexpected loads, adverse climatic and hydrothermal conditions. The hoop tensile strength,

$\sigma_{\alpha H}$ for the design = 570 – (30% of 570) = 399 MPa.

The helical tensile strength, $\sigma_{f\alpha}$ is 0.8 times the hoop tensile strength with a value of 319.2MPa.

$$t_{helical} = PR/\ 2\sigma_{f\,\alpha}(\cos\alpha)^2 \tag{3.3}$$

$$t_{hoop} = PR(\ 1-(\tan\alpha)^2/\ 2\ )/\ \sigma_H \tag{3.4}$$

Where, α is the minimum winding angle in degrees,

P is the pressure load in MPa,

R is the radius of the cylinder in mm,

$\sigma f\alpha$ is the helical tensile strength in MPa,

$\sigma h\alpha$ is the hoop tensile strength of the composite

$t_{helical} = 25*152.5 /(2*319.2(\cos 36^o)^2) = 7.29$ mm

$t_{hoop} = 25*152.5* (1-((\tan 36^o)^2/ 2))/ 399 = 6.5$ mm

The total thickness is the sum of the hoop and helical thickness=7.29+6.5= 13.79 mm.

3.5.4 Stresses in CNG Cylinder

CNG gas is stored at pressure, 20 MPa at ambient temperature.

Inner radius of cylinder, R=152.5 mm

Outer radius of cylinder = Inner Radius + Thickness=152.5+15.47=167.97 mm.

Tangential stress, σ_t

$$\sigma_t= (r_i^2 p_i*(1+r_o^2/r_i^2))/(r_o^2-r_i^2) \quad (3.5)$$

by substituting, σ_t=373.56 MPa.

Radial stress, σ_r

$$\sigma_r= (r_i^2 p_i*(1-r_o^2/r_i^2))/(r_o^2-r_i^2) \quad (3.6)$$

by substituting, σ_r=350.89 MPa

Von mises stress in cylinder, σ

$$\sigma=(\sigma_t^2+\sigma_r^2-\sigma_t\sigma_r)^{1/2} \quad (3.7)$$

by substituting tangential and radial stresses, σ=361.79 MPa.

3.6 Summary

In this chapter, the whole shell model of the CNG cylinder is designed using ANSYS Workbench. The modelling has been investigated with the composite material. The shell model created in design modeller is converted to a 10 layered composite cylinder using ACP Pre tool. The structural and vibrational analysis of developed model will be presented in chapter 4.

Chapter 4

Structural Analysis of CNG Cylinder

4.1 Introduction

Structural analysis is the determination of the effects of static and dynamic loads on parts, assemblies, and mechanisms in order to avoid failure in the intended use. Colourful terms such as stresses and deformations give us the vivid picture of what can happen when part fail. Ideally, simulation-driven design begins early in the product development process. It helps in finding flaws earlier, extracts cost, speeds up design, and improves the product quality.

Vibration analysis is used to determine the vibration characteristics of linear elastic structures. By these vibrations the natural frequencies of the model are obtained. These frequencies can be compared with the resonating frequencies through which the failure of the model can be analysed.

4.2 Problem Statement

To perform the static structural analysis and vibration analysis on the composite CNG cylinder designed in ANSYS static structural analysis system and modal analysis system.

4.3 Analysis Settings

These are the following methods used in static structural analysis

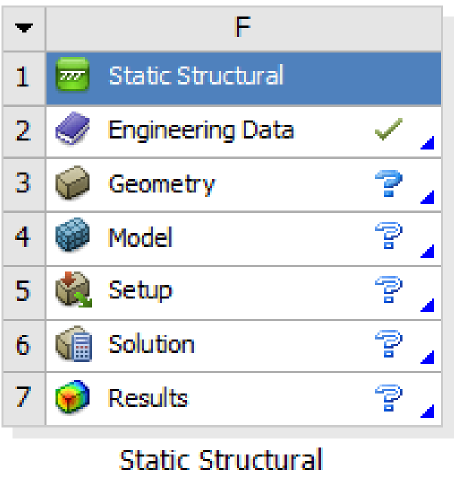


Fig 4.1 Layout of the Structural Analysis System.

4.3.1 Linking of the ACP Pre component system and Static Structural Analysis

The complete setup data from the ACP (Pre) component system is transferred to the model of the static structure, as shown in Fig 4.2.

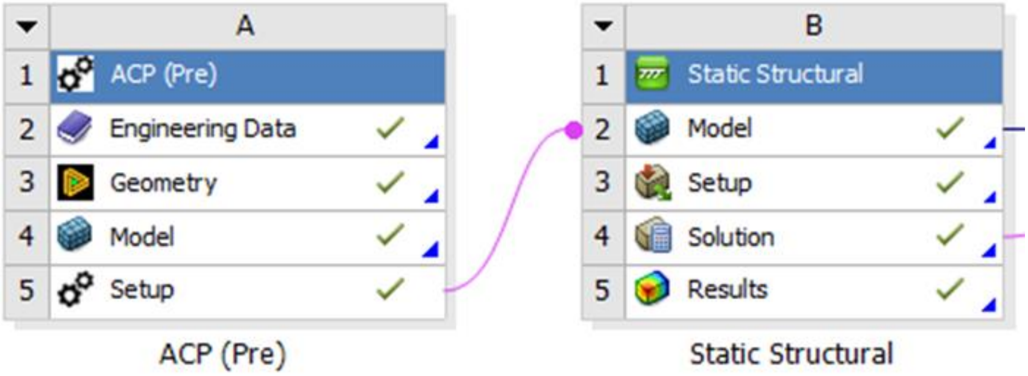
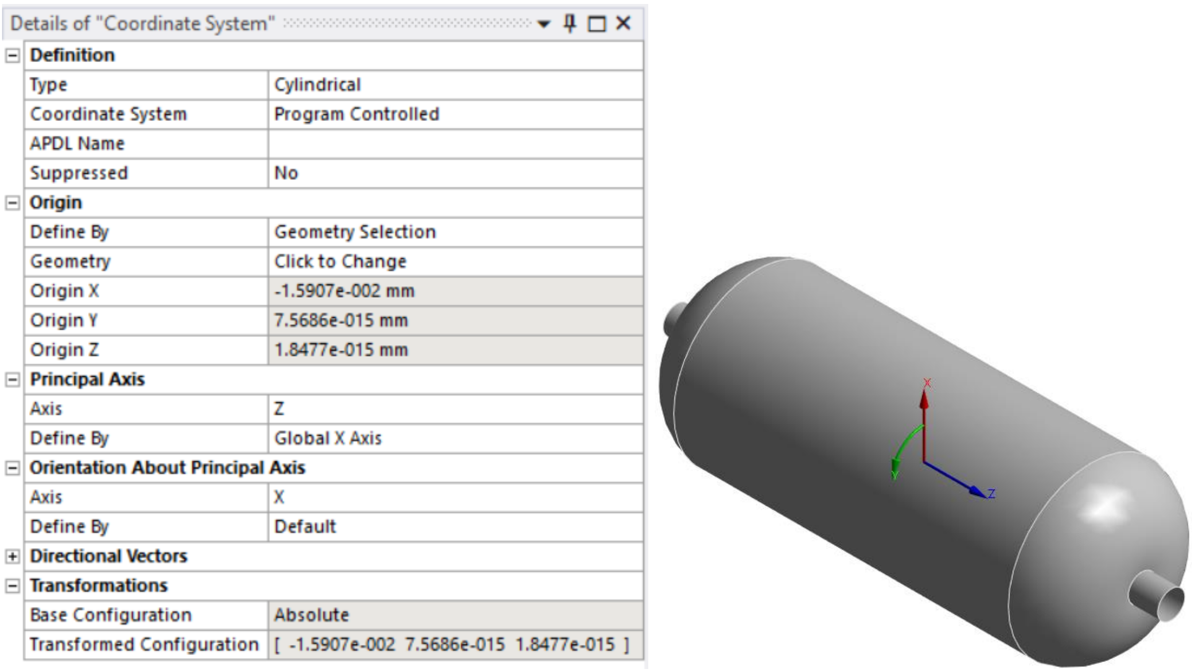


Fig 4.2 Connecting ACP Pre component System and Static Structural

The whole data like the materials used, geometry of the cylinder and complete ACP(Pre) model is transferred (shell model).

4.3.2 Co-ordinate System

The co-ordinate system should be changed from Cartesian co-ordinate system to cylindrical system to get normal stresses and strains. So a new cylindrical coordinate system is created which is shown in Fig 4.3.



Details of "Coordinate System"

Definition	
Type	Cylindrical
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Geometry Selection
Geometry	Click to Change
Origin X	-1.5907e-002 mm
Origin Y	7.5686e-015 mm
Origin Z	1.8477e-015 mm
Principal Axis	
Axis	Z
Define By	Global X Axis
Orientation About Principal Axis	
Axis	X
Define By	Default
Directional Vectors	
Transformations	
Base Configuration	Absolute
Transformed Configuration	[-1.5907e-002 7.5686e-015 1.8477e-015]

Fig 4.3 Arranging the Co-ordinate System

4.3.3 Fixed support

For the considered cylinder, one side of the opening is fixed by inserting the fixed boundary condition in analysis function as shown in the Fig 4.4.

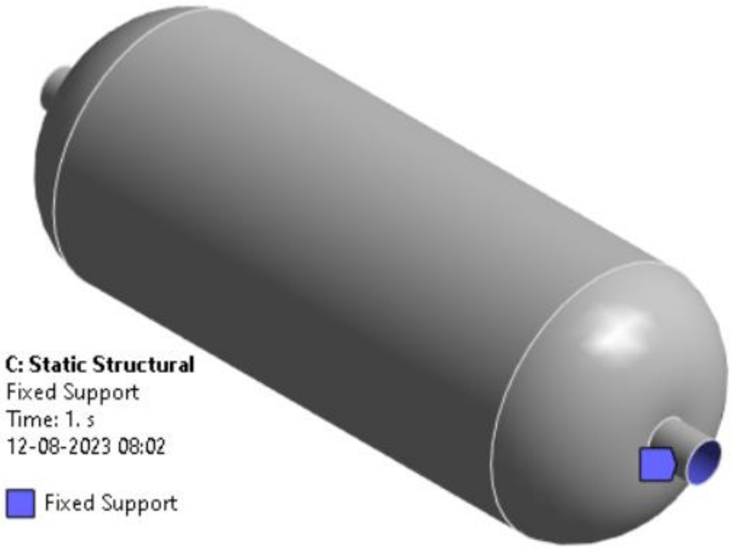


Fig 4.4 One End Fixed Cylinder

4.3.4 Remote Displacement

For a CNG cylinder the working pressure is 20 Mpa. This pressure is applied on the inner surfaces of the cylinder by selecting the geometry and inner surfaces as shown in Fig .4.5.

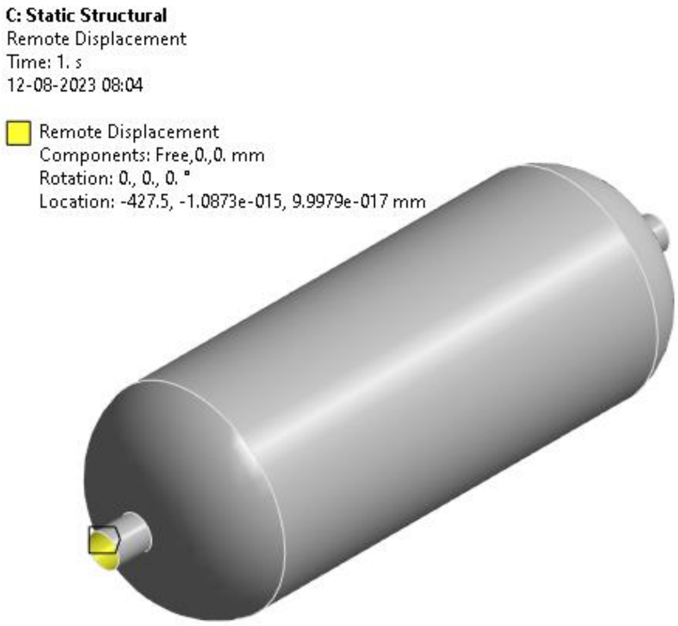


Fig 4.5 working pressure 20 MPa applied on the inner surfaces of the cylinder

4.3.5 Working Pressure

For a CNG cylinder the working pressure is 20 MPa. This pressure is applied on the inner surfaces of the cylinder by selecting the geometry and inner surfaces as shown in Fig .4.5.

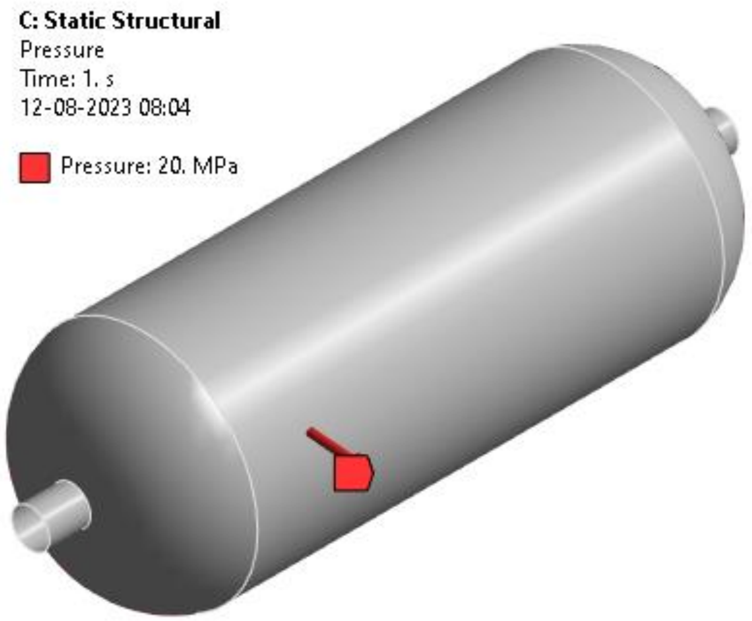


Fig 4.6 Pressure applied on the inner surface of the cylinder

4.4 Static Structural Results

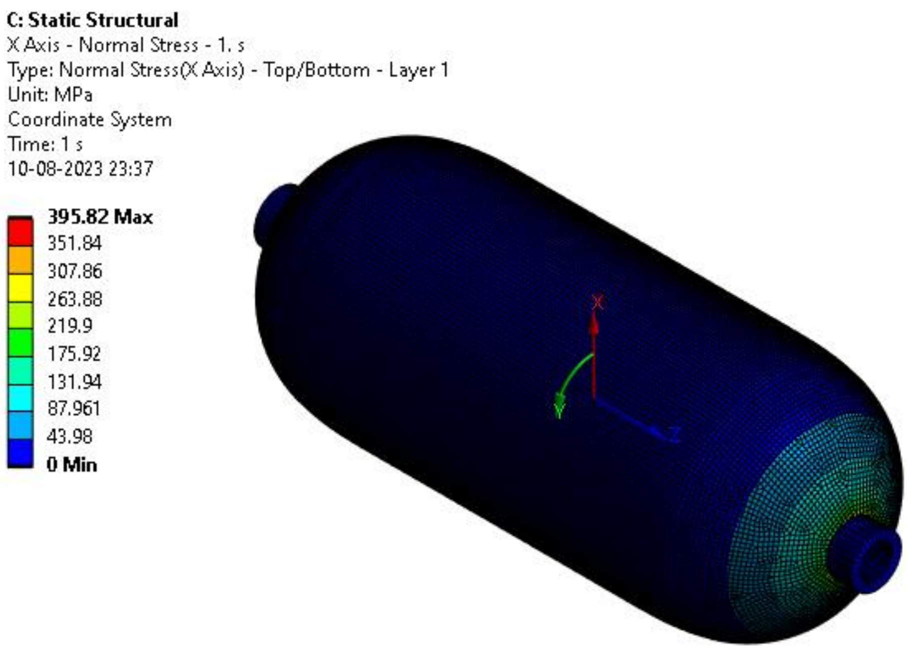


Figure 4.7 Radial Stress in Layer 1 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 395.82 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

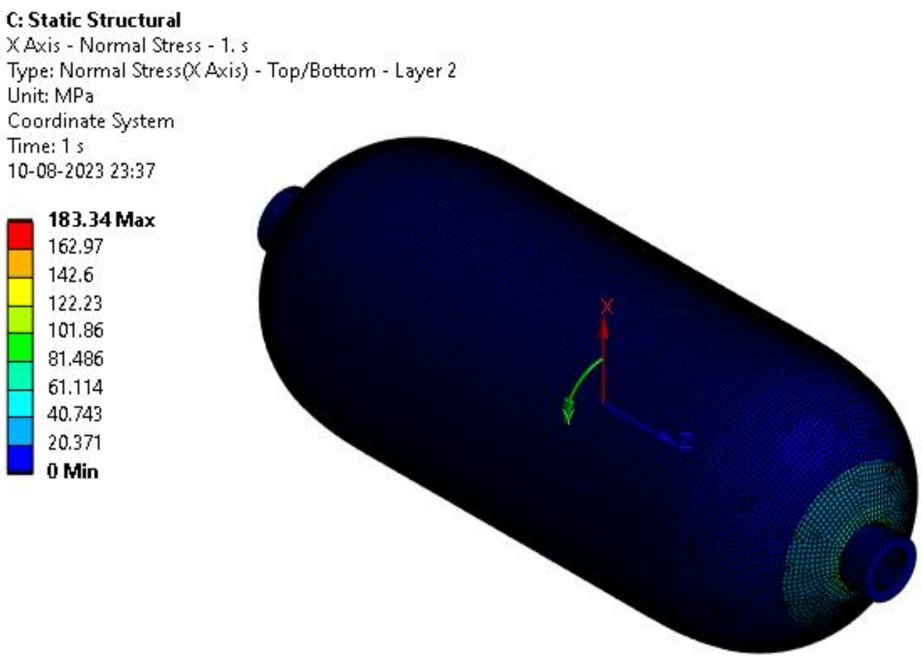


Figure 4.8 Radial Stress in Layer 2 (Carbon Epoxy)

In the second layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 183.34 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

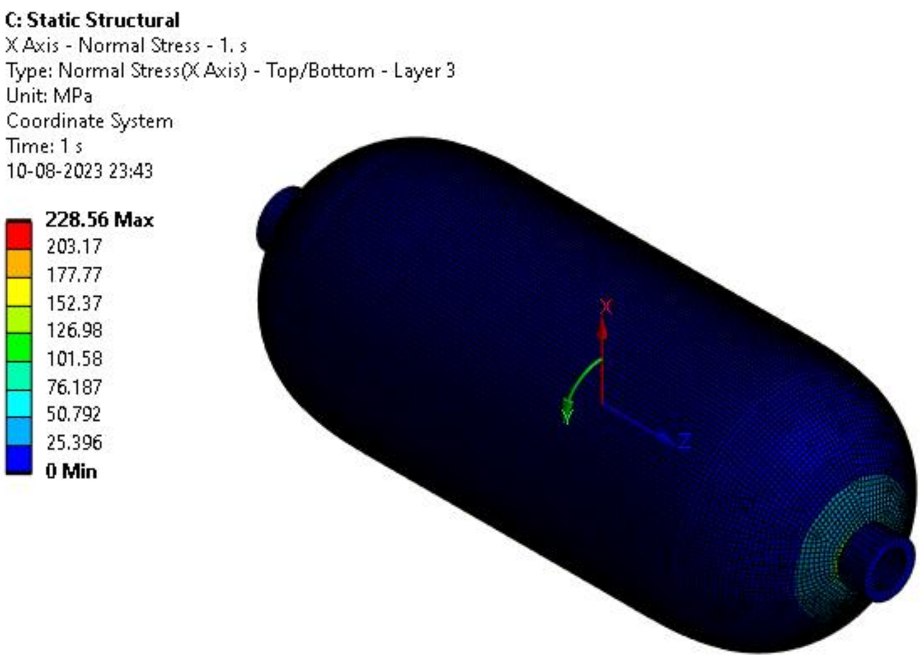


Figure 4.9 Radial Stress in Layer 3 (Carbon Epoxy)

In the third layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 228.56 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

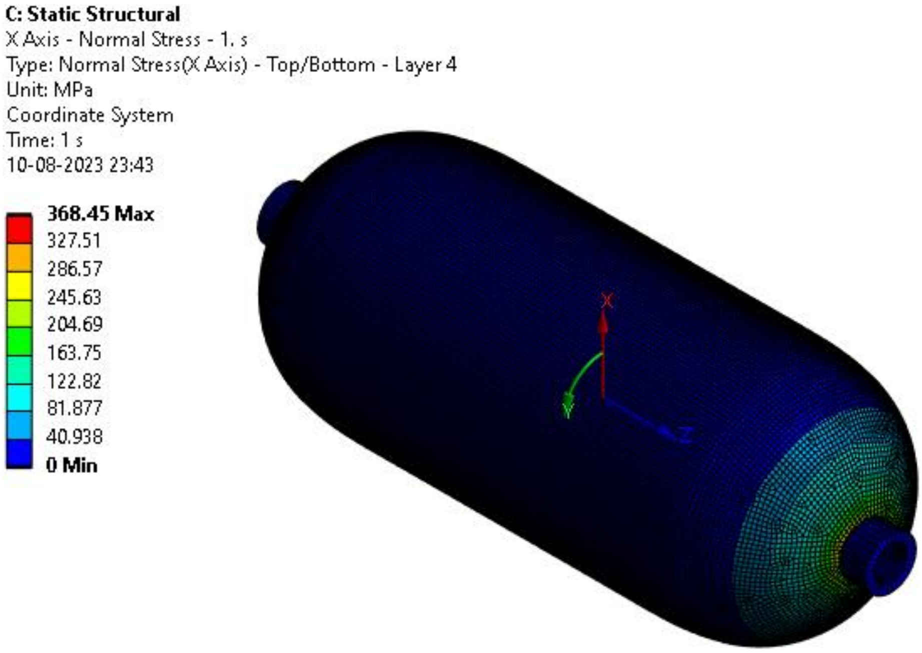


Figure 4.10 Radial Stress in Layer 4 (Carbon Epoxy)

In the fourth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 368.45 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

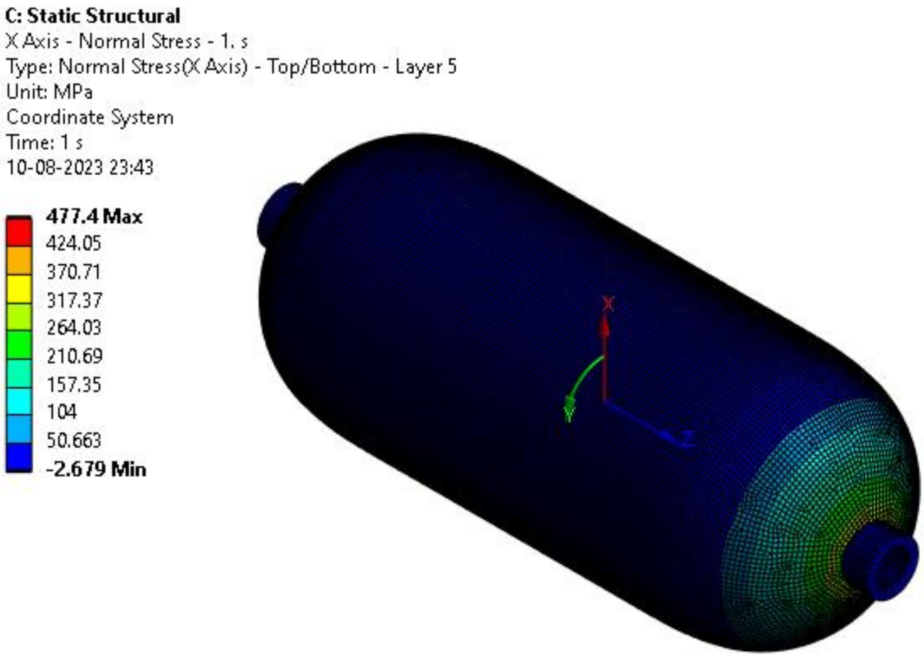


Figure 4.11 Radial Stress in Layer 5 (Carbon Epoxy)

In the fifth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 477.4 MPa in tension and minimum normal stress obtained is -2.679 MPa in compression.

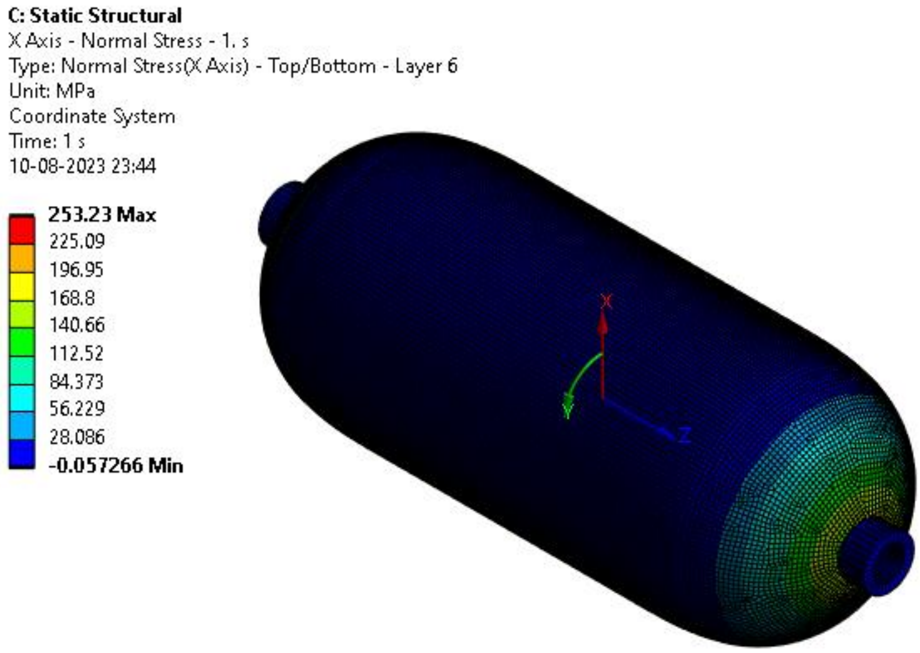


Figure 4.12 Radial Stress in Layer 6 (Carbon Epoxy)

In the Sixth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 253.23 MPa in tension and minimum normal stress obtained is -0.057266 MPa in compression.

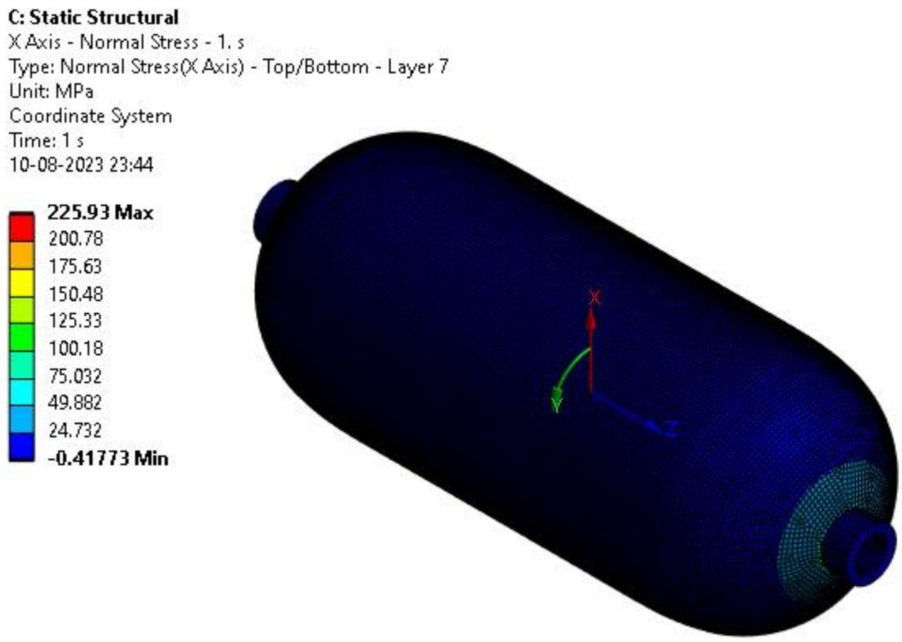


Figure 4.13 Radial Stress in Layer 7 (Carbon Epoxy)

In the Seventh layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 225.93 MPa in tension and minimum normal stress obtained is -0.41773 MPa in compression.

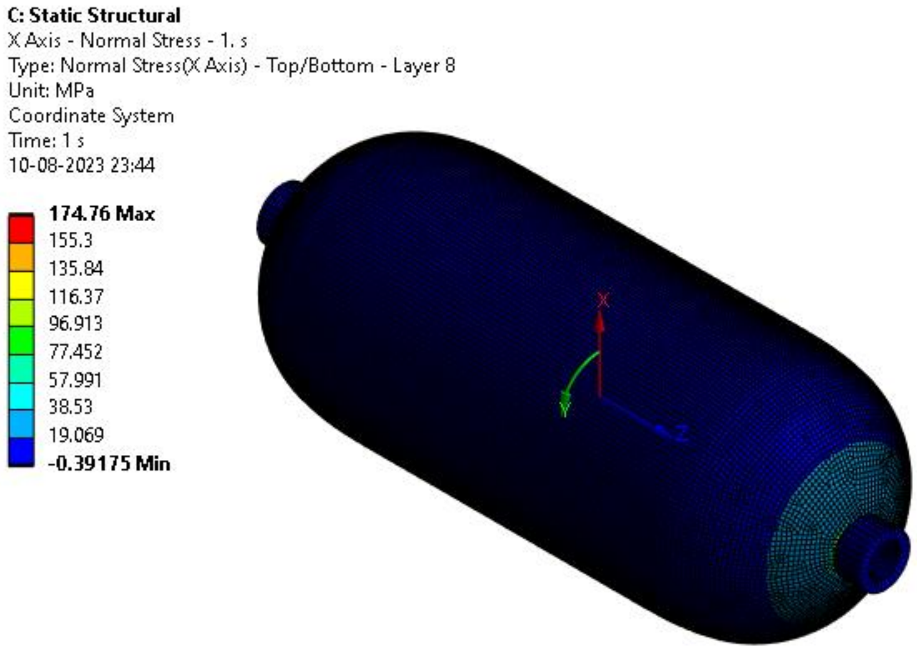


Figure 4.14 Radial Stress in Layer 8 (Carbon Epoxy)

In the Eighth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 174.76 MPa in tension and minimum normal stress obtained is -0.39175 MPa in compression.

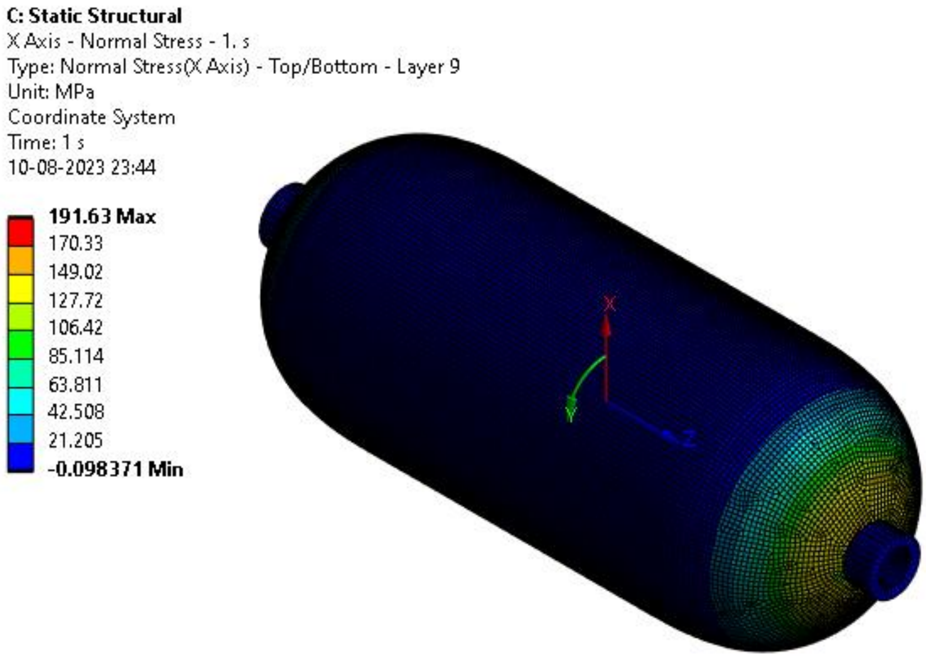


Figure 4.15 Radial Stress in Layer 9 (Carbon Epoxy)

In the ninth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 191.63 MPa in tension and minimum normal stress obtained is -0.0983 MPa in compression.

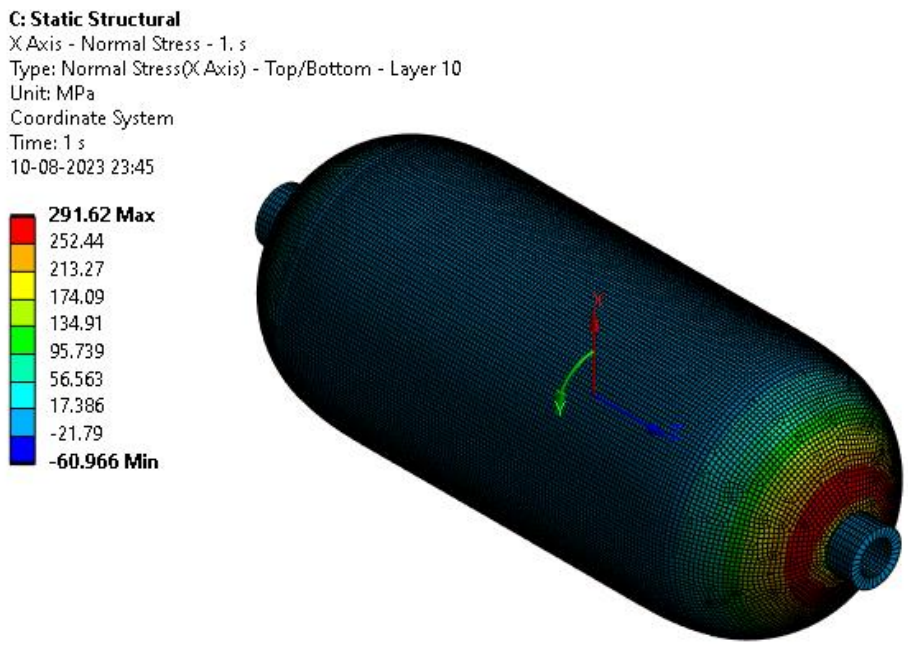


Figure 4.16 Radial Stress in Layer 10 (Carbon Epoxy)

In the tenth layer of the Carbon Epoxy cylinder, along radial direction the maximum stress obtained is 291.62 MPa in tension and minimum normal stress obtained is -60.966 MPa in compression.

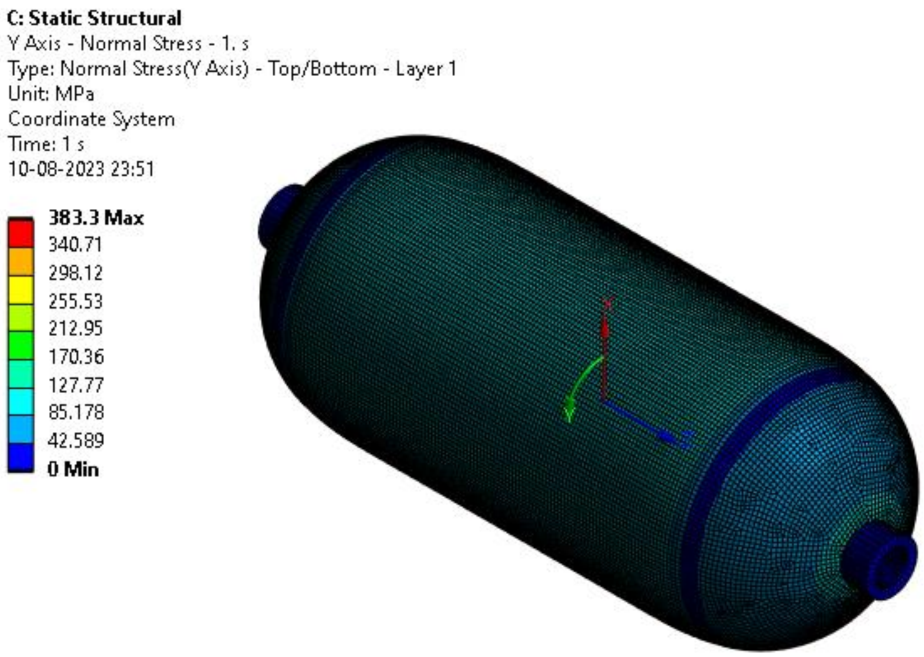


Figure 4.17 Circumferential Stress in Layer 1 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 383.3 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

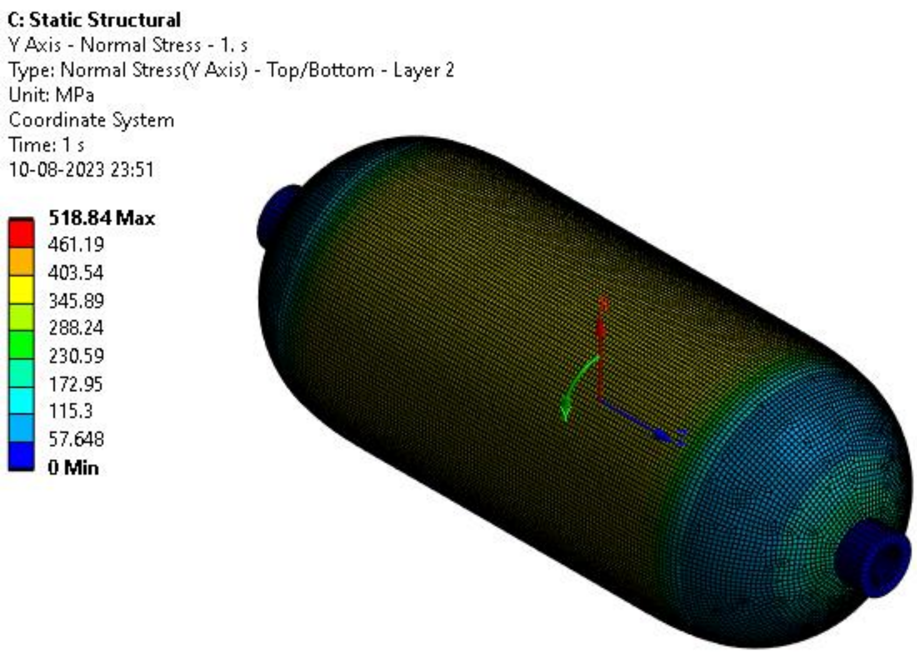


Figure 4.18 Circumferential Stress in Layer 2 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 518.84 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

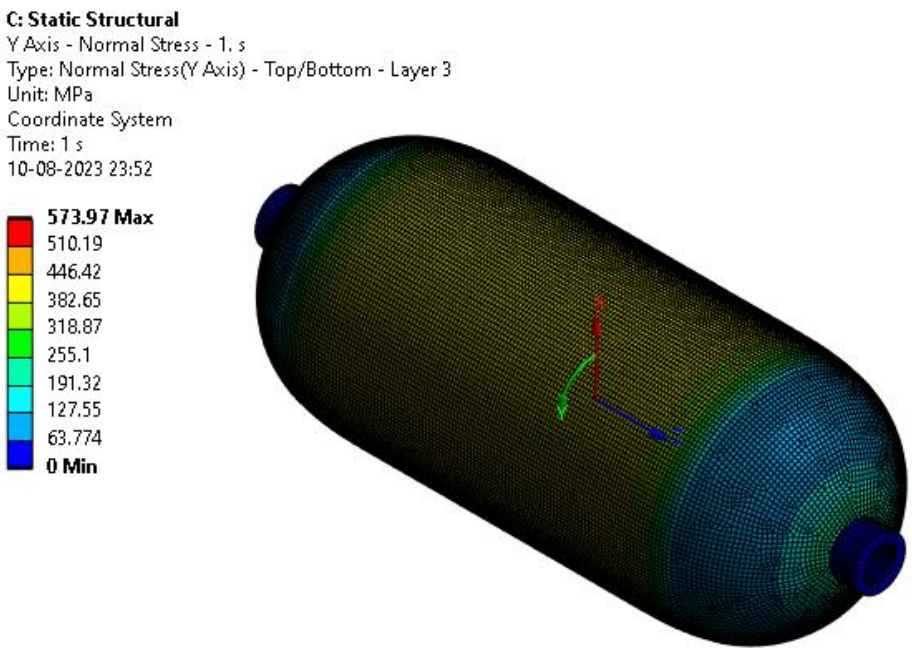


Figure 4.19 Circumferential Stress in Layer 3 (Carbon Epoxy)

In the third layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 573.97 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

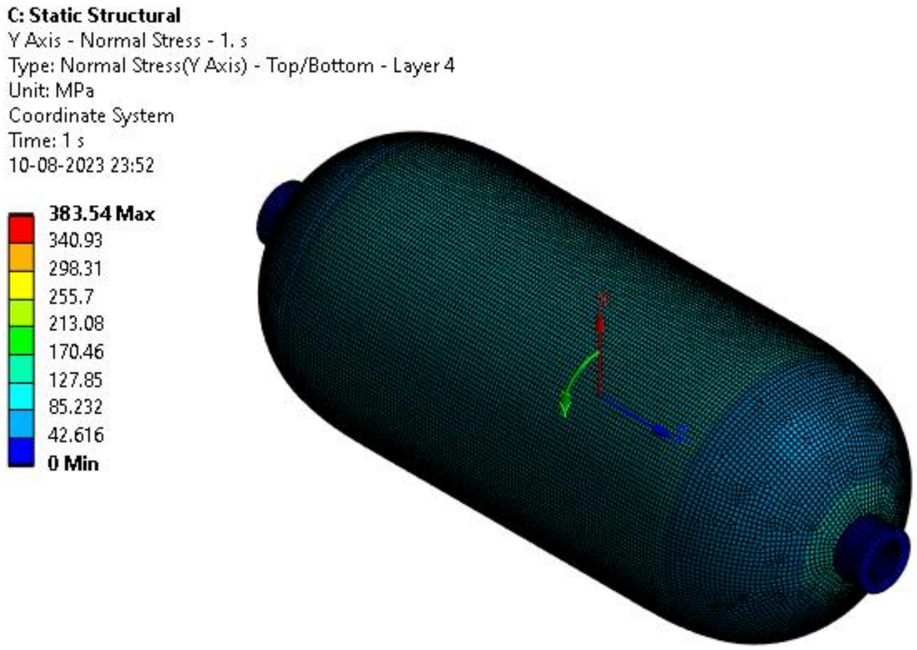


Figure 4.20 Circumferential Stress in Layer 4 (Carbon Epoxy)

In the fourth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 383.54 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

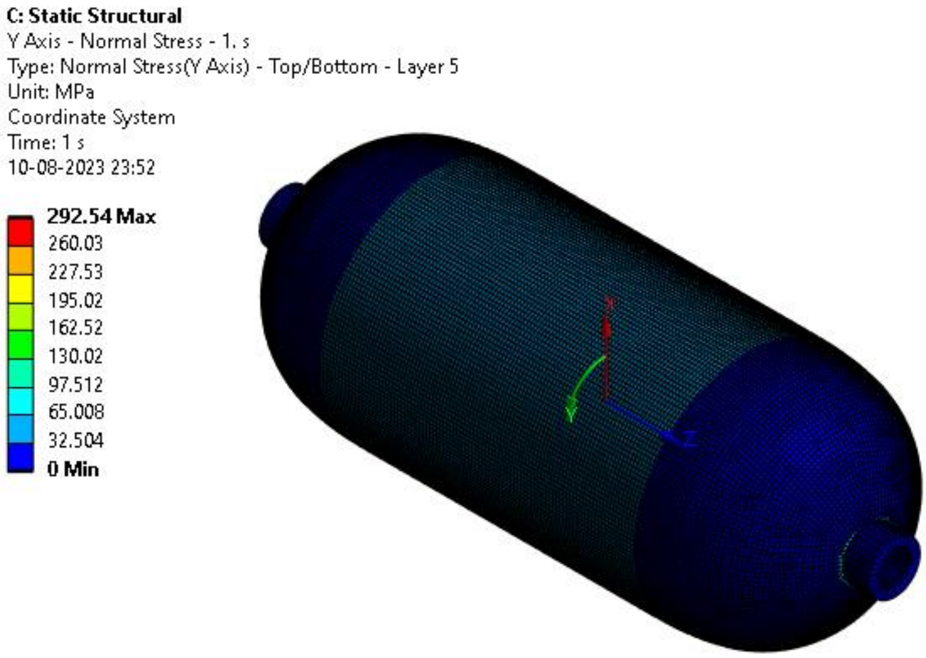


Figure 4.21 Circumferential Stress in Layer 5 (Carbon Epoxy)

In the fifth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 292.54 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

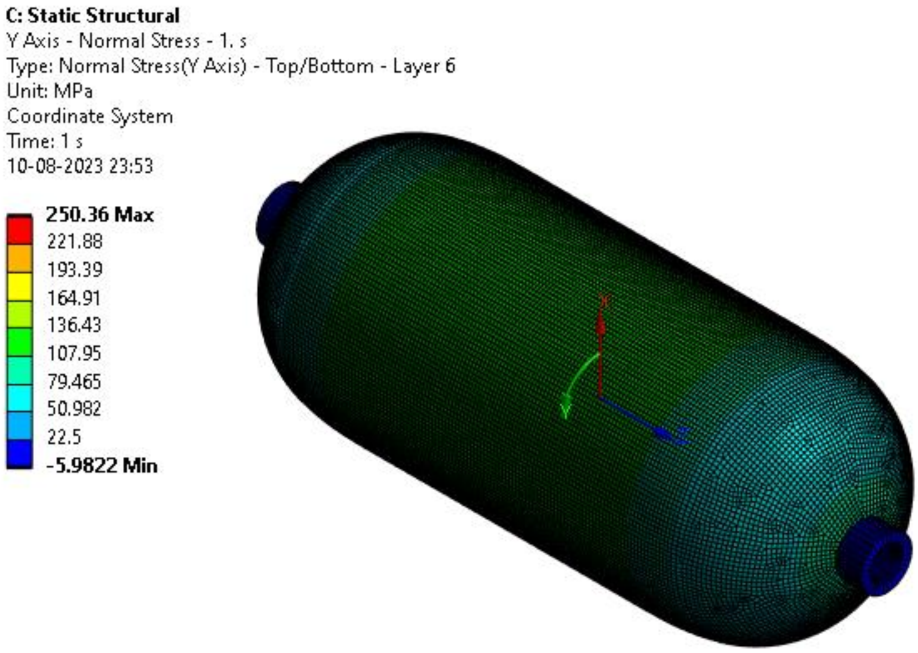


Figure 4.22 Circumferential Stress in Layer 6 (Carbon Epoxy)

In the sixth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 250.36 MPa in tension and minimum normal stress obtained is -5.9822 MPa in compression.

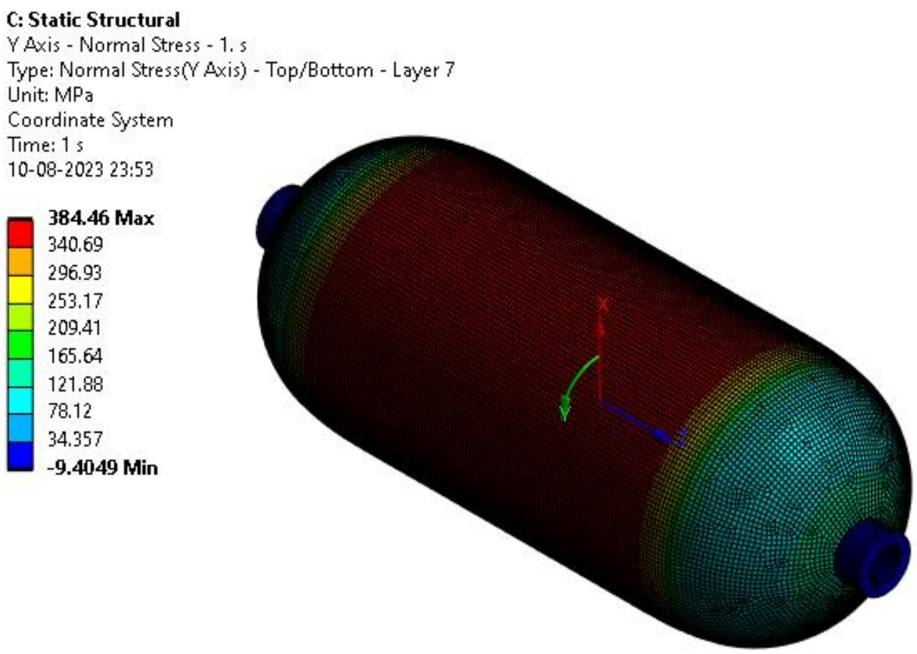


Figure 4.23 Circumferential Stress in Layer 7 (Carbon Epoxy)

In the seventh layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 384.46 MPa in tension and minimum normal stress obtained is -9.4049 MPa in compression.

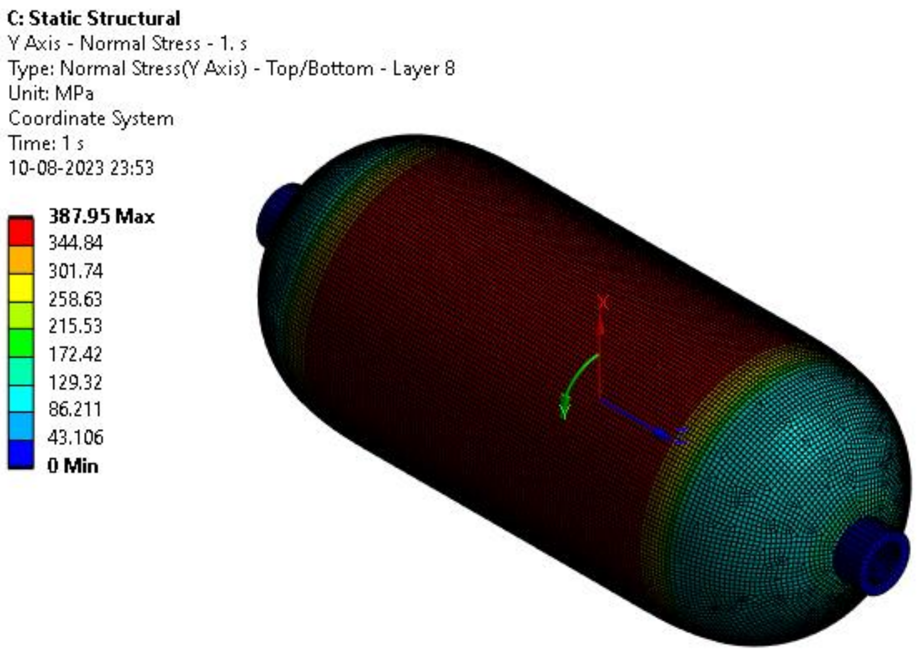


Figure 4.24 Circumferential Stress in Layer 8 (Carbon Epoxy)

In the Eighth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 387.95 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

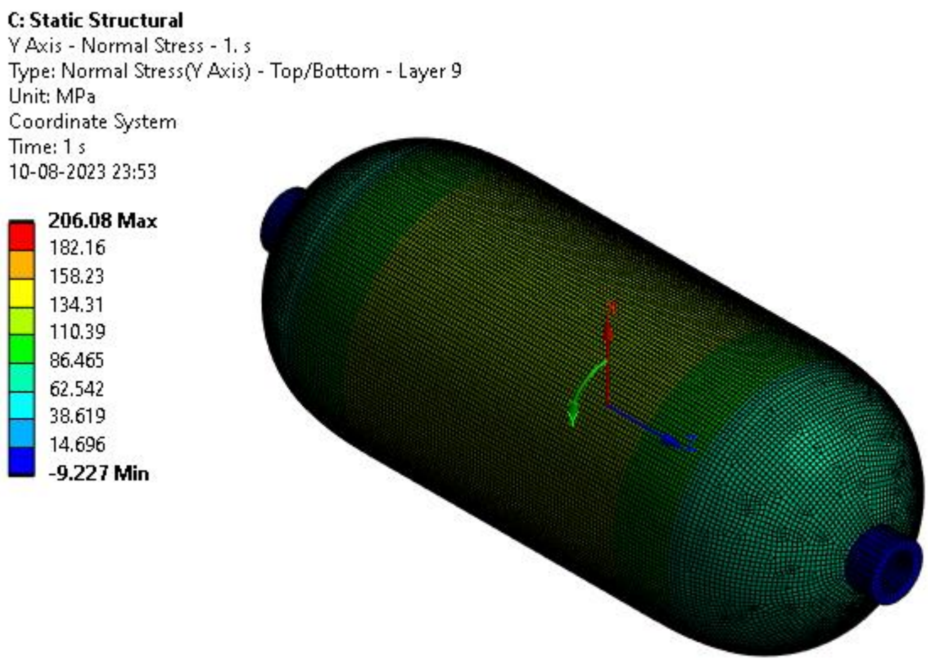


Figure 4.25 Circumferential Stress in Layer 9 (Carbon Epoxy)

In the ninth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 206.08 MPa in tension and minimum normal stress obtained is -9.227 MPa in compression.

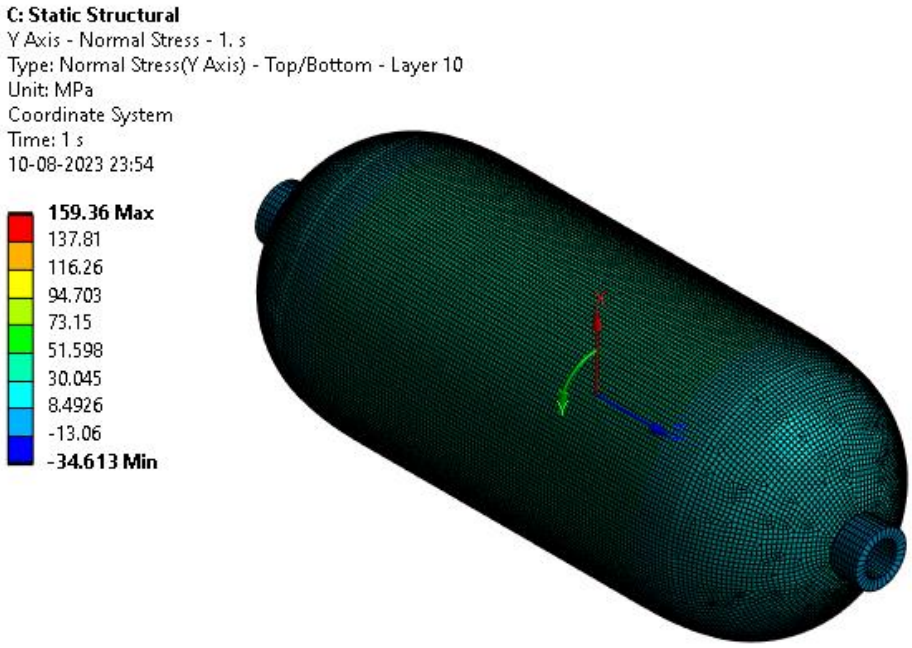


Figure 4.26 Circumferential Stress in Layer 10 (Carbon Epoxy)

In the Tenth layer of the Carbon Epoxy cylinder, along circumferential direction the maximum stress obtained is 159.36 MPa in tension and minimum normal stress obtained is -34.613 MPa in compression.

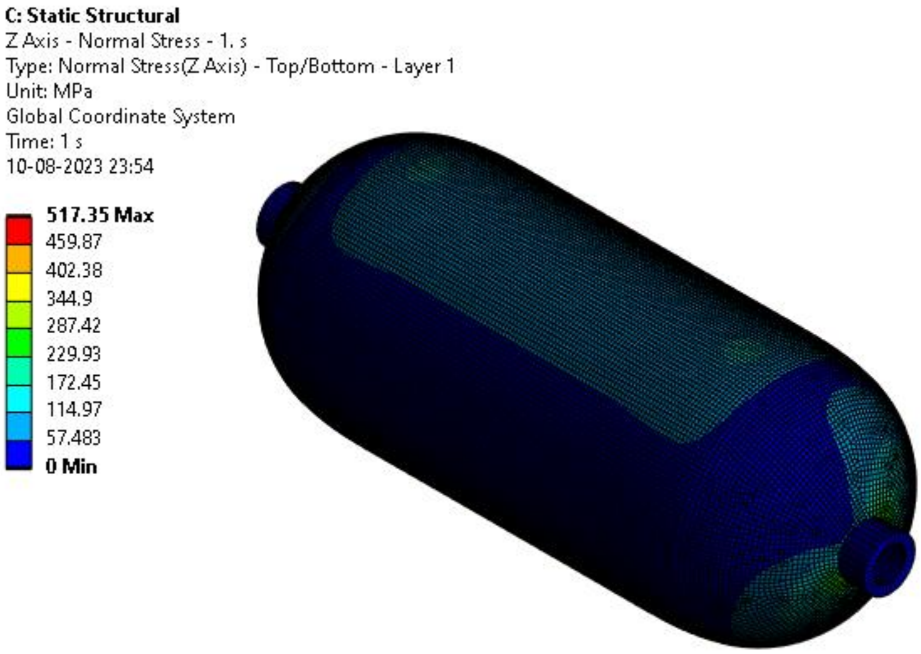


Figure 4.27 Longitudinal Stress in Layer 1 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 517.35 MPa in tension and minimum normal stress obtained is 0 MPa in compression.

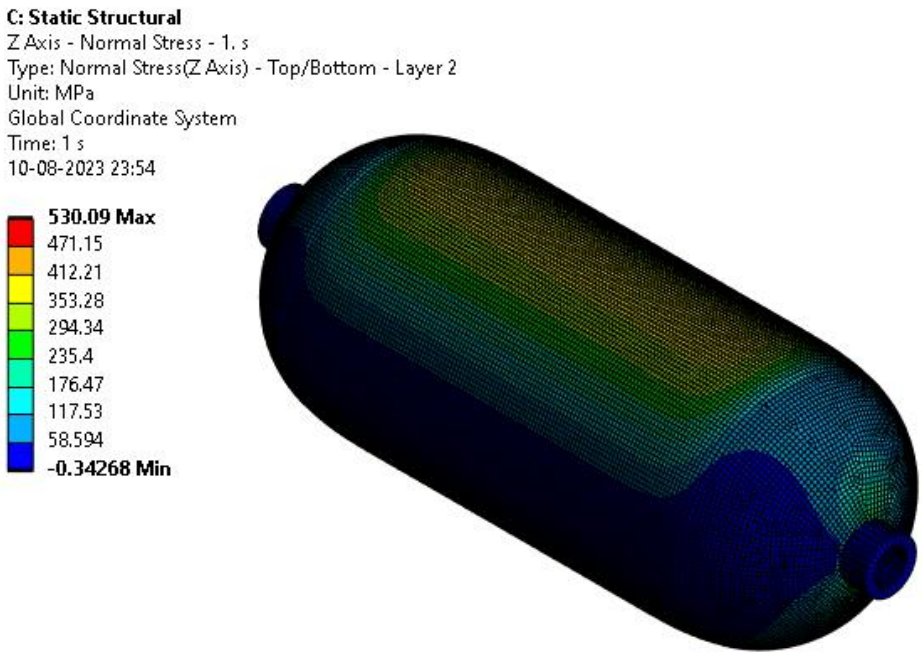


Figure 4.28 Longitudinal Stress in Layer 2 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 530.09 MPa in tension and minimum normal stress obtained is -0.3426 MPa in compression.

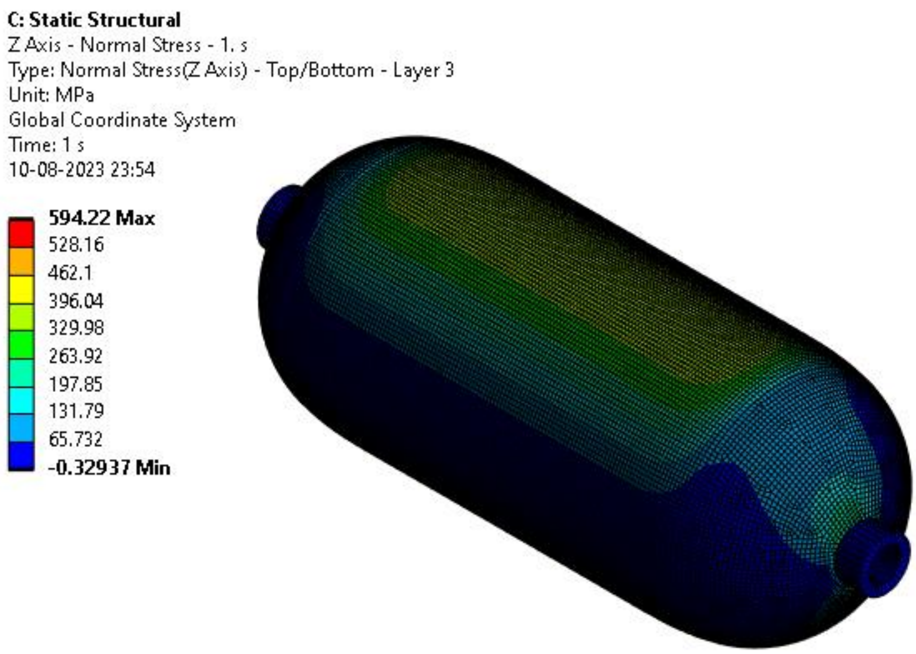


Figure 4.29 Longitudinal Stress in Layer 3 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 594.22 MPa in tension and minimum normal stress obtained is -0.3293 MPa in compression.

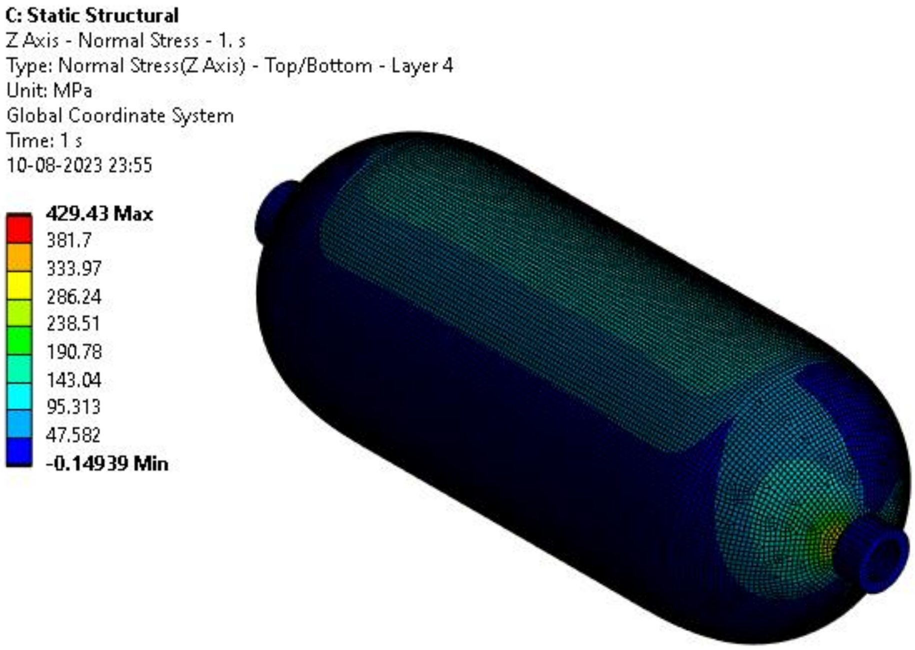


Figure 4.30 Longitudinal Stress in Layer 4 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 429.43 MPa in tension and minimum normal stress obtained is -0.14939 MPa in compression.

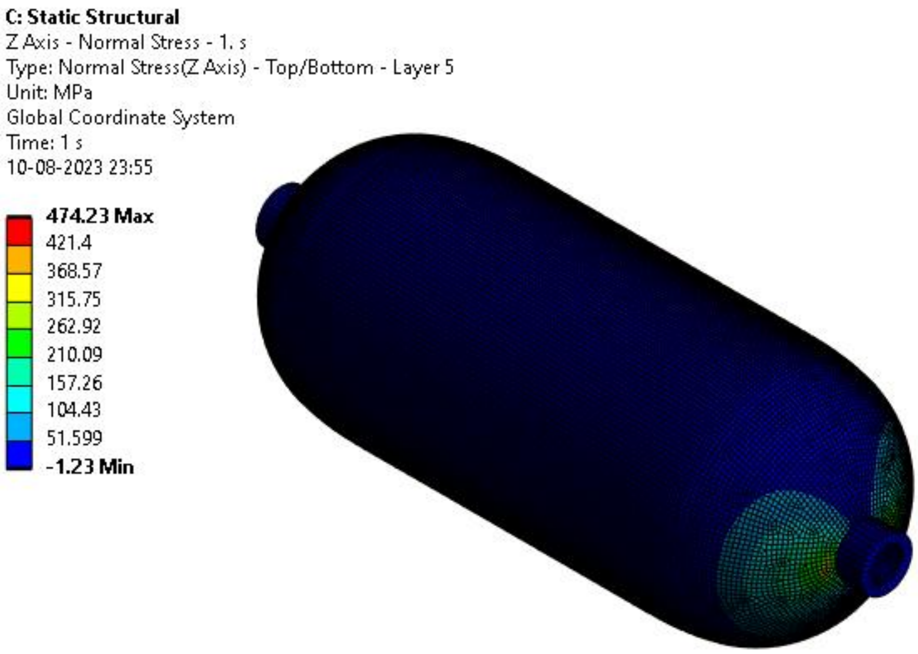


Figure 4.31 Longitudinal Stress in Layer 5 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 474.23 MPa in tension and minimum normal stress obtained is -1.23 MPa in compression.

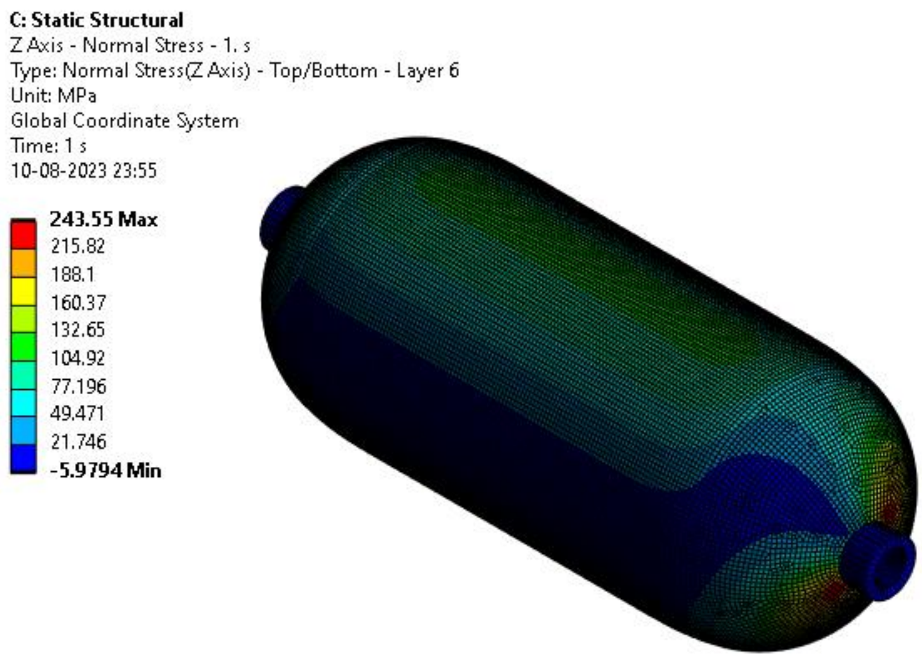


Figure 4.32 Longitudinal Stress in Layer 6 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 243.55 MPa in tension and minimum normal stress obtained is -5.9794 MPa in compression.

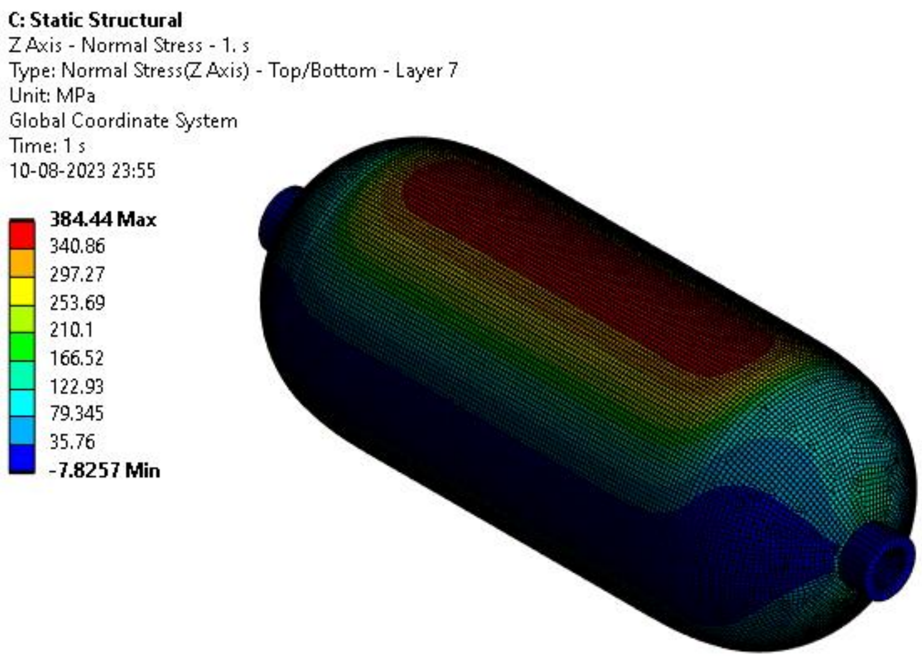


Figure 4.33 Longitudinal Stress in Layer 7 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 384.44 MPa in tension and minimum normal stress obtained is -7.8257 MPa in compression.

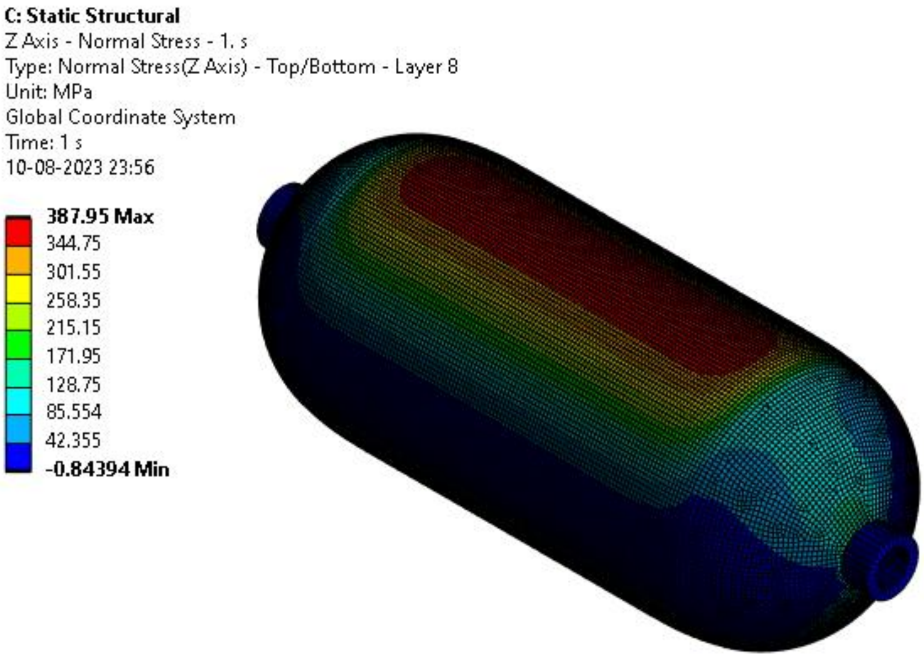


Figure 4.34 Longitudinal Stress in Layer 8 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 387.95 MPa in tension and minimum normal stress obtained is -0.8439 MPa in compression.

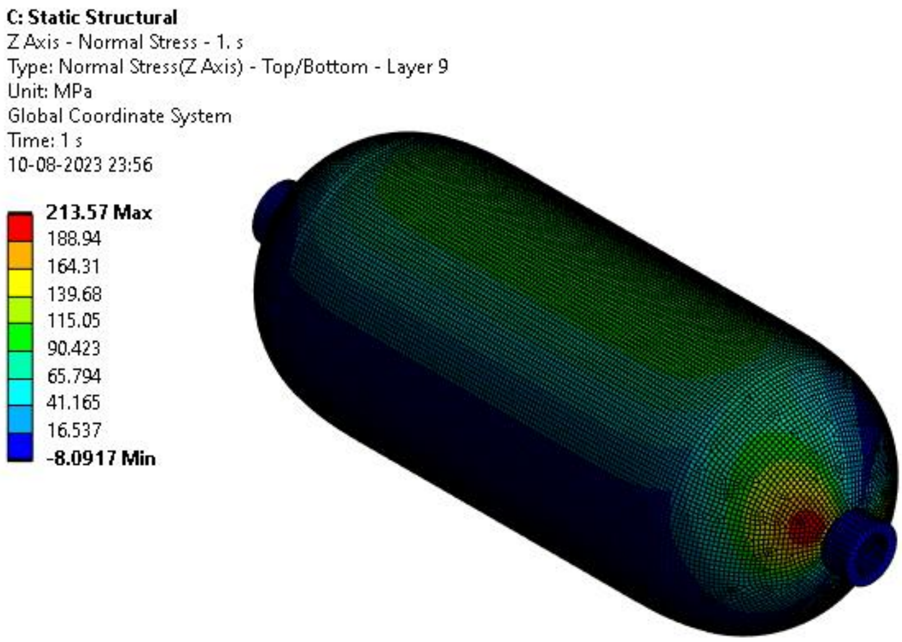


Figure 4.35 Longitudinal Stress in Layer 9 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 213.57 MPa in tension and minimum normal stress obtained is -8.0917 MPa in compression.

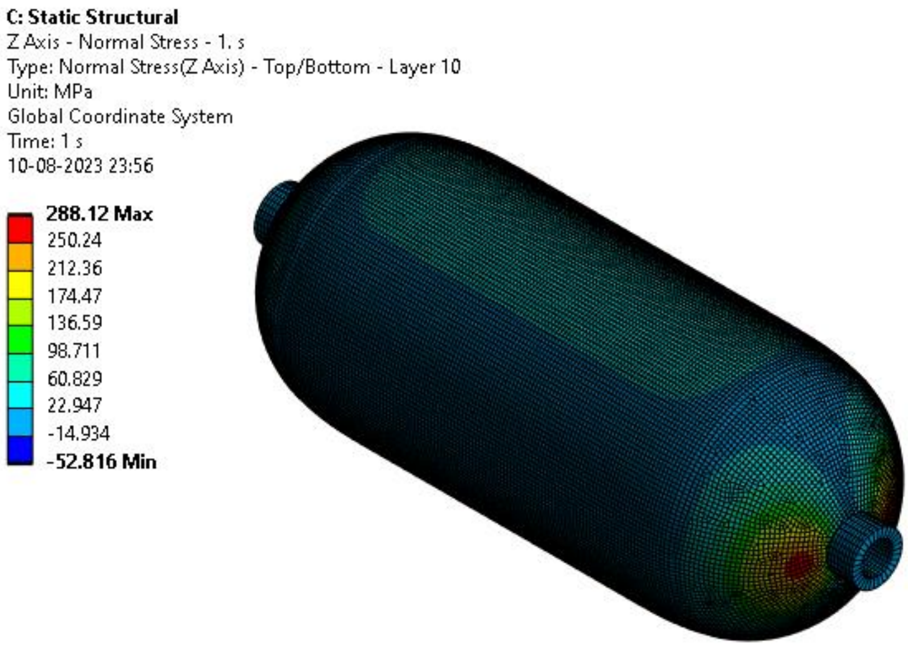


Figure 4.36 Longitudinal Stress in Layer 10 (Carbon Epoxy)

In the first layer of the Carbon Epoxy cylinder, along longitudinal direction the maximum stress obtained is 288.12 MPa in tension and minimum normal stress obtained is -52.816 MPa in compression.

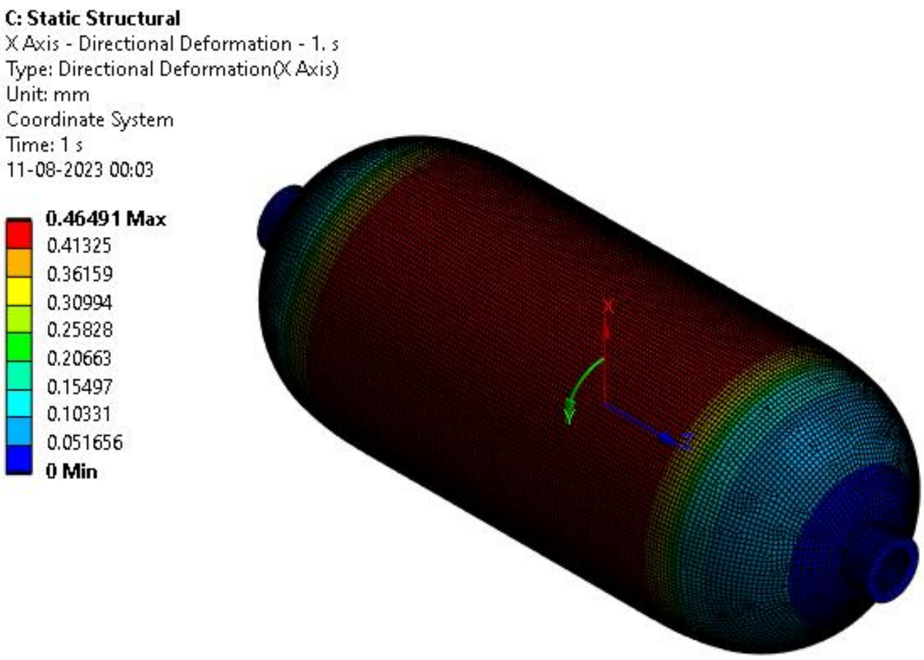


Figure 4.37 Radial Deformation (Carbon Epoxy)

In the Carbon Epoxy cylinder, along radial direction the maximum deformation obtained is 0.46491 mm in tension and minimum normal stress obtained is 0 mm in compression.

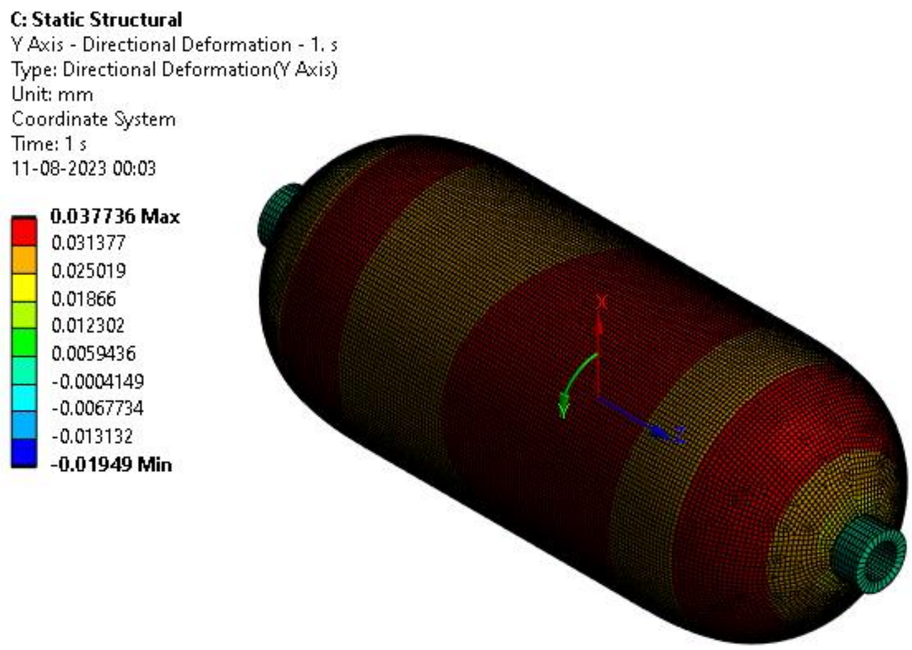


Figure 4.38 Circumferential Deformation (Carbon Epoxy)

In the Carbon Epoxy cylinder, along circumferential direction the maximum deformation obtained is 0.037736 mm in tension and minimum normal stress obtained is -0.01949 mm in compression.

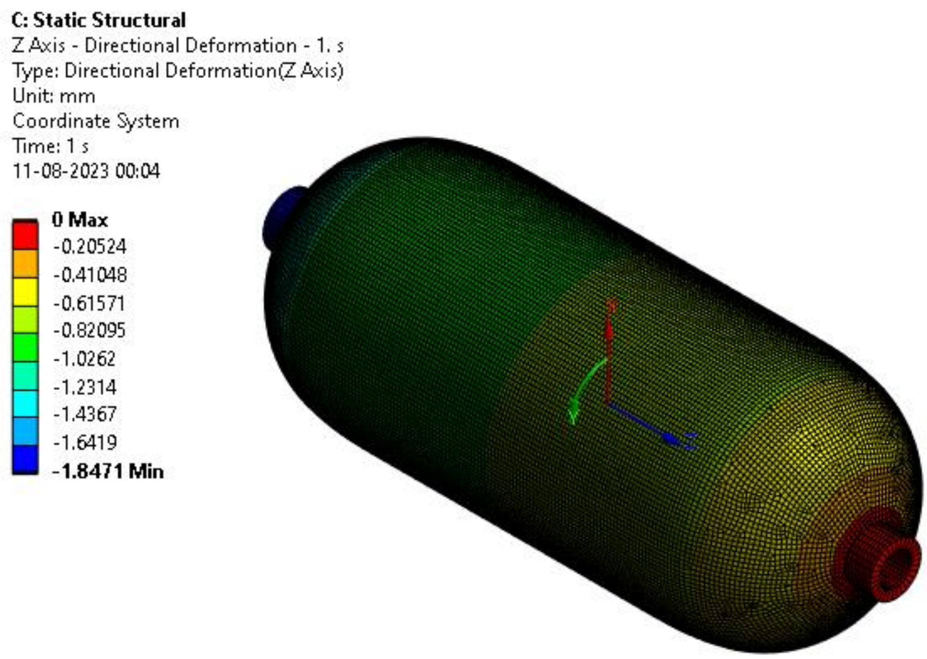


Figure 4.39 Longitudinal Deformation (Carbon Epoxy)

In the Carbon Epoxy cylinder, along longitudinal direction the minimum deformation obtained is 0 mm in tension and maximum deformation obtained is -1.8471 mm in compression.

Similarly, the composite cylinder is assigned with the remaining materials like E-glass Epoxy, Kevlar Epoxy and Hybrid (Carbon + E-Glass + Kevlar Epoxy) and list of results i.e., Maximum stresses with layer wise and directional deformations in radial, circumferential and longitudinal directions are calculated and plotted in the below figures.

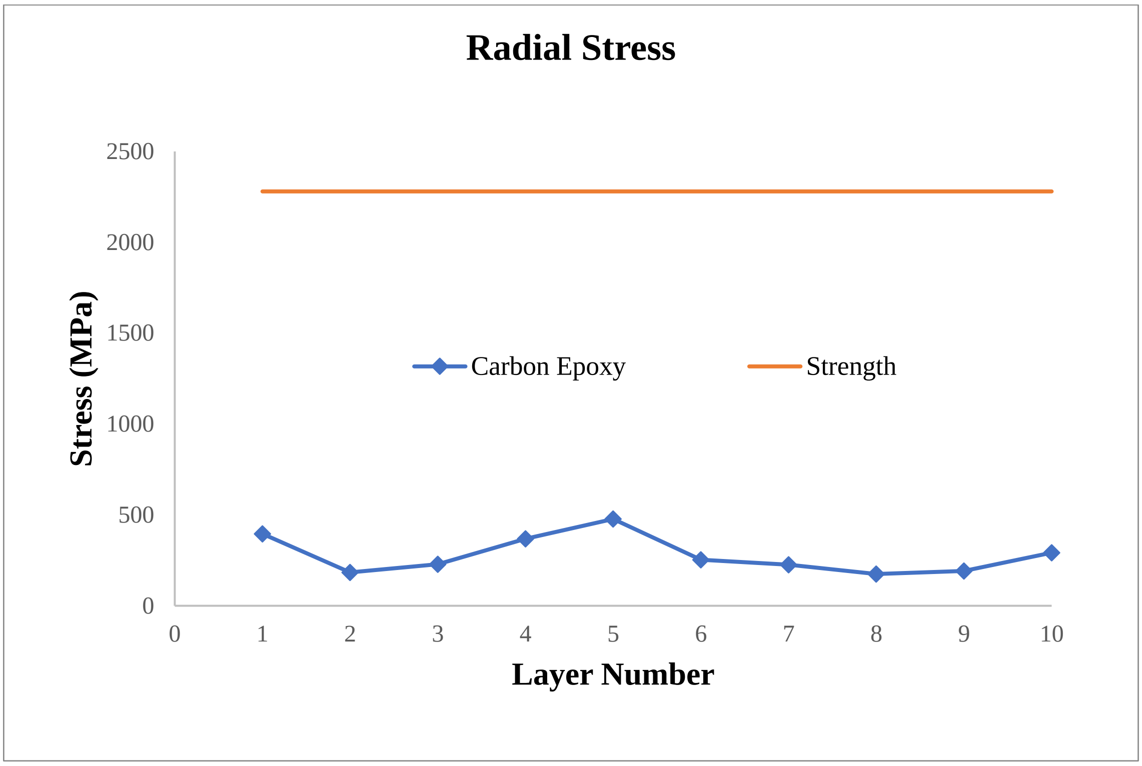


Figure 4.40 Radial Stress of the Composite Cylinder (Carbon Epoxy)

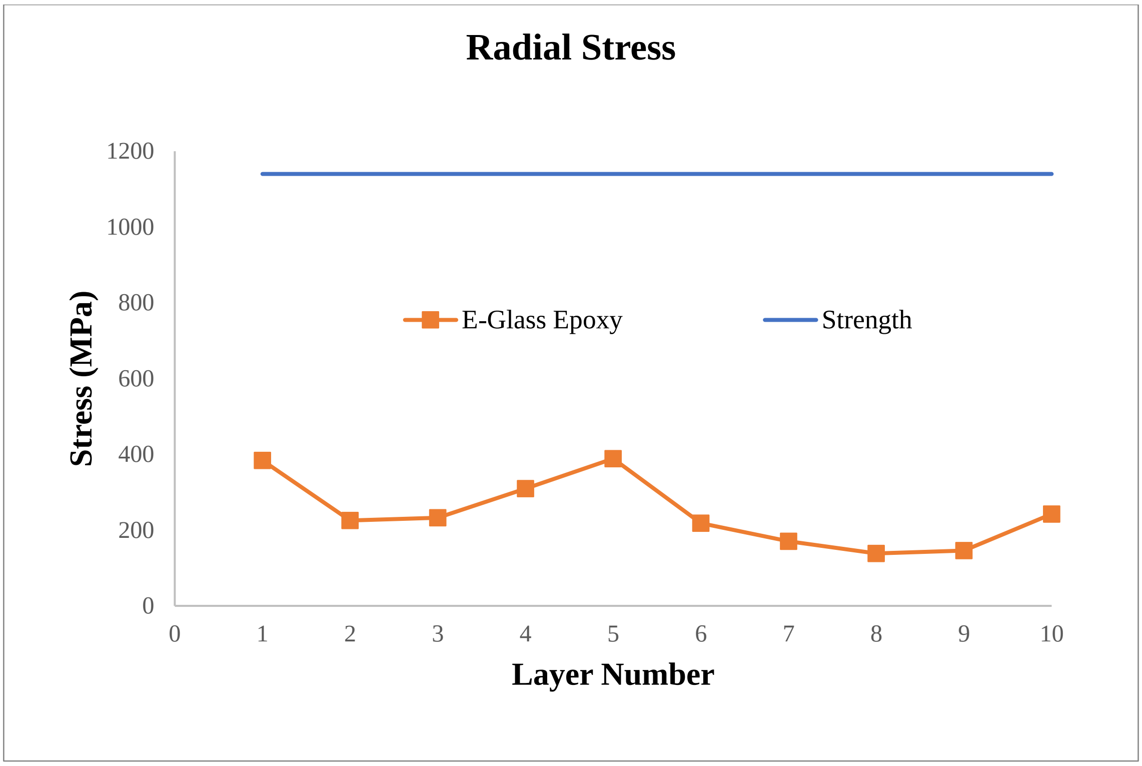


Figure 4.41 Radial Stress of the Composite Cylinder (E-Glass Epoxy)

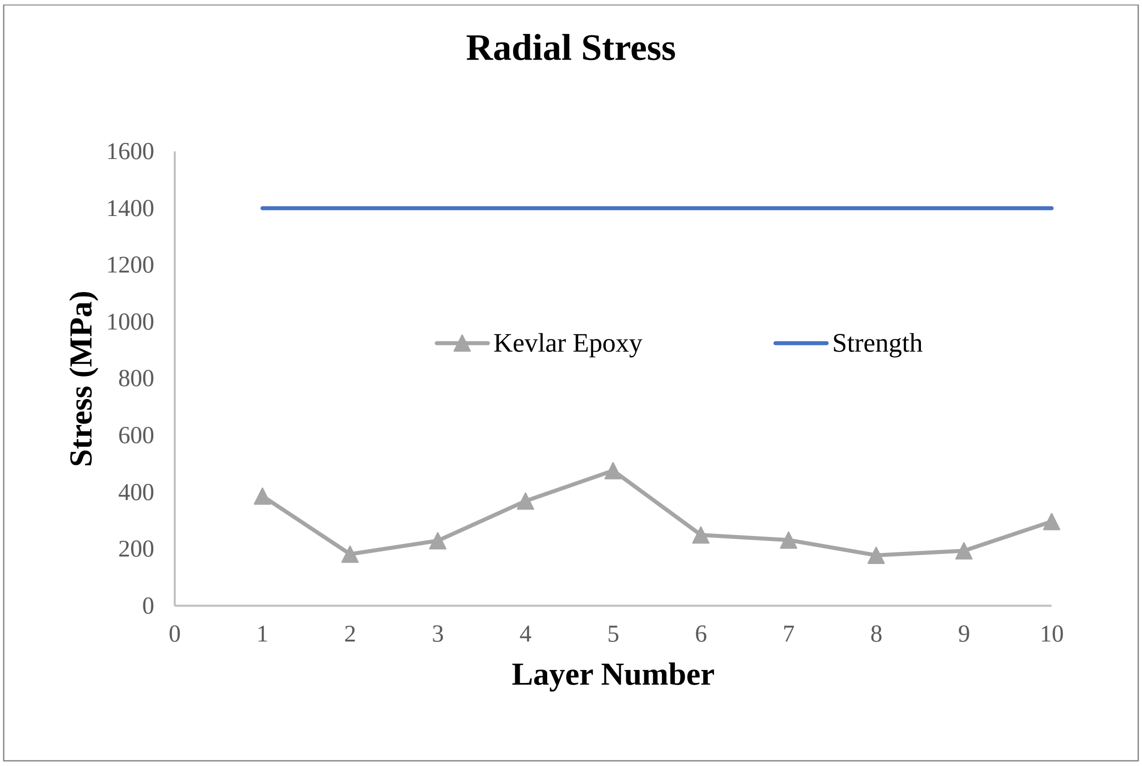


Figure 4.42 Radial Stress of the Composite Cylinder (Kevlar Epoxy)

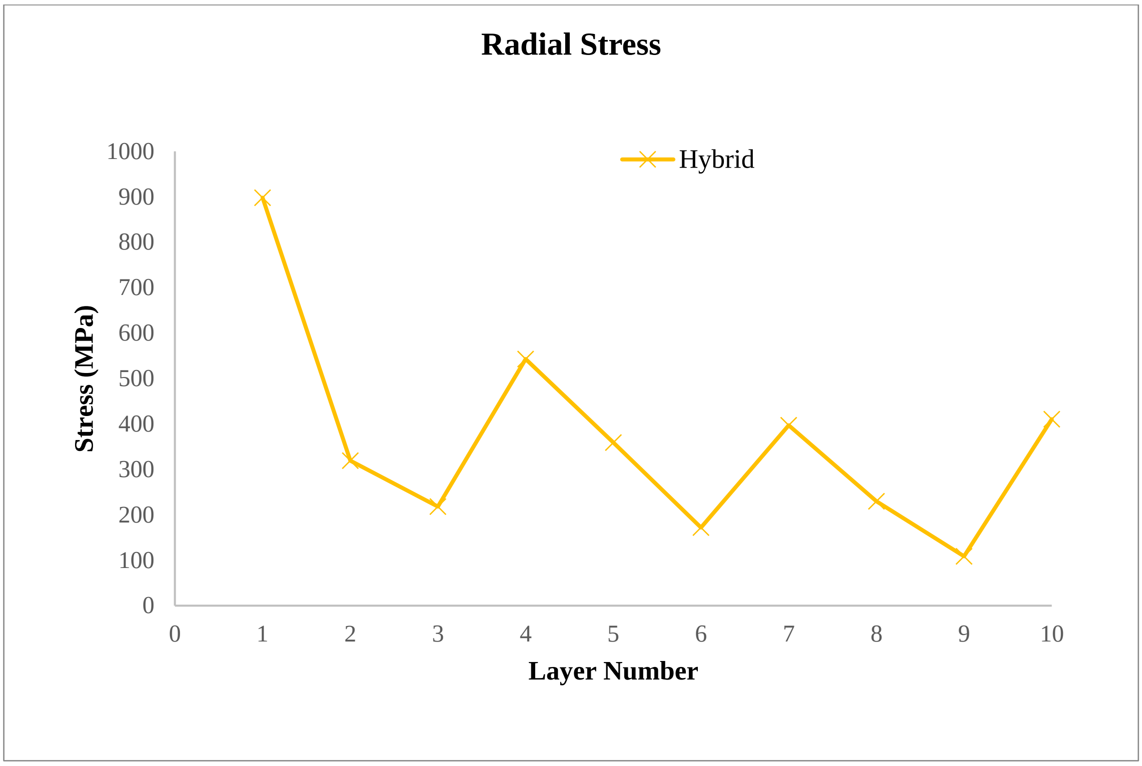


Figure 4.43 Radial Stress of the composite Cylinder (Hybrid)

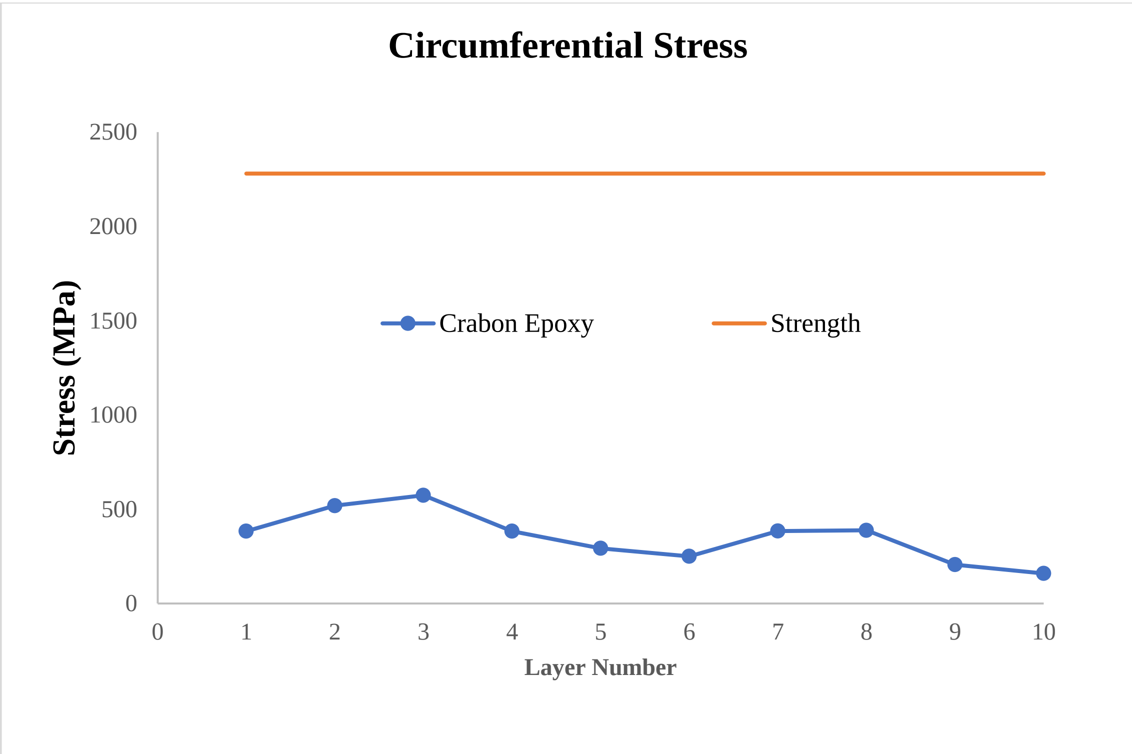


Figure 4.44 Circumferential Stress of the Composite Cylinder (Carbon Epoxy)

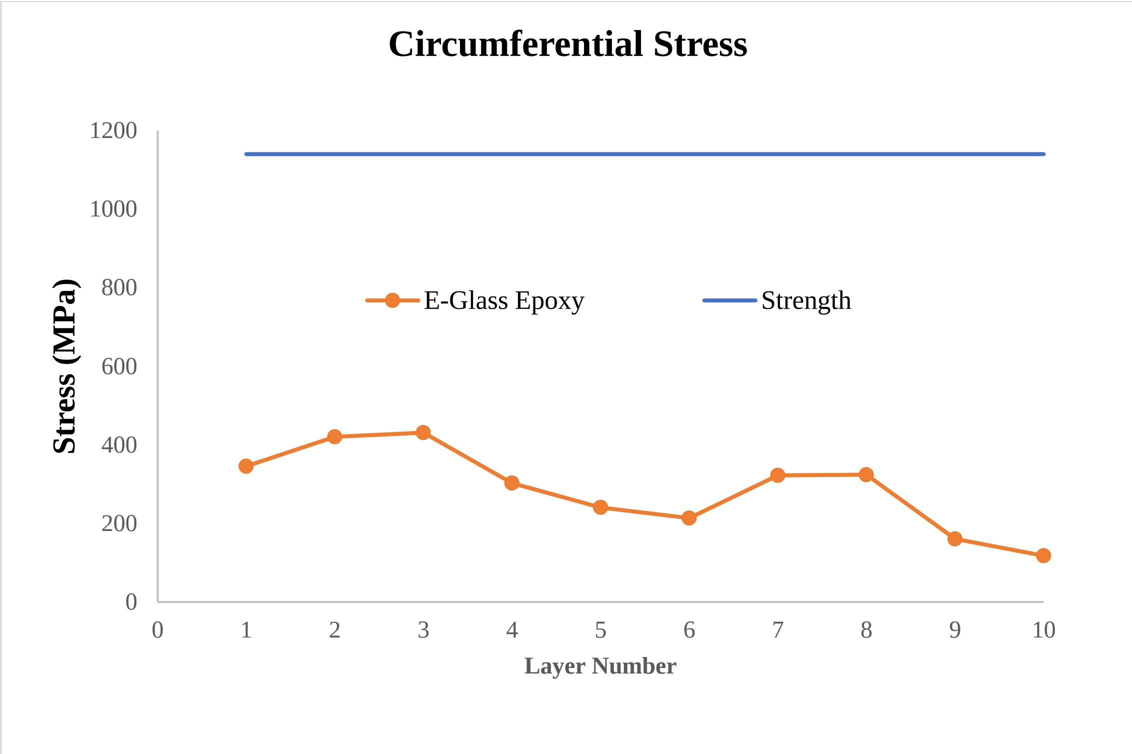


Figure 4.45 Circumferential Stress of the Composite Cylinder (E-Glass Epoxy)

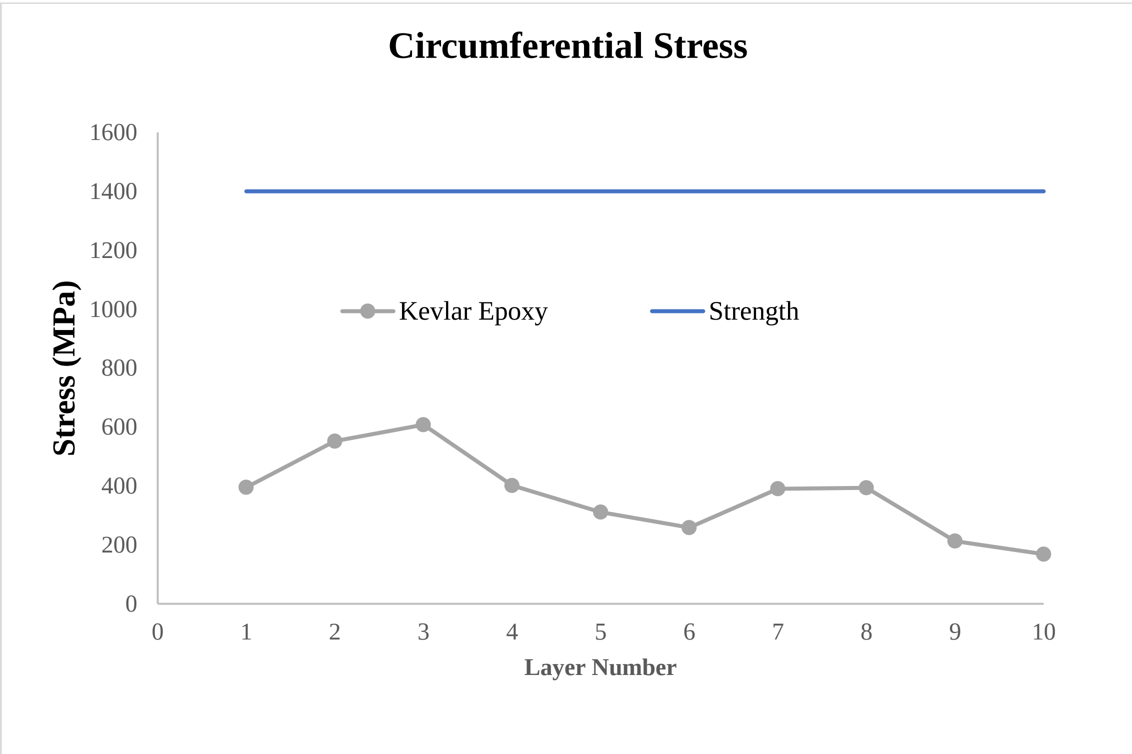


Figure 4.46 Circumferential Stress of the Composite Cylinder (Kevlar Epoxy)

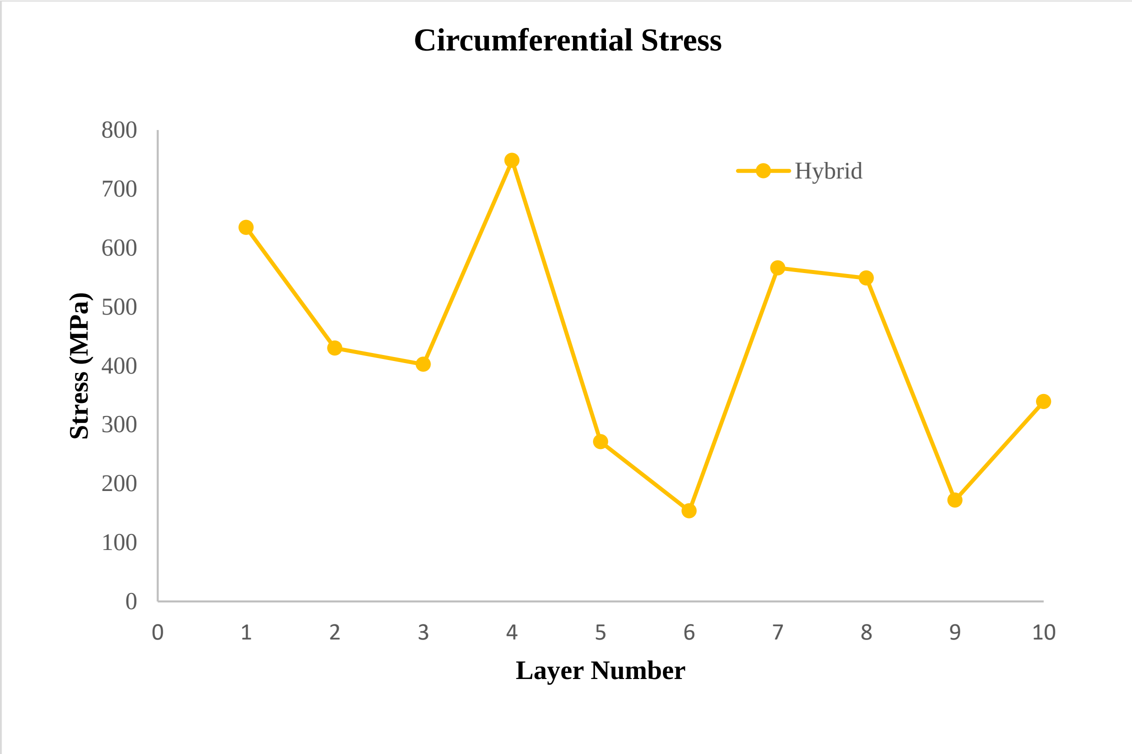


Figure 4.47 Circumferential Stress of the Composite Cylinder (Hybrid)

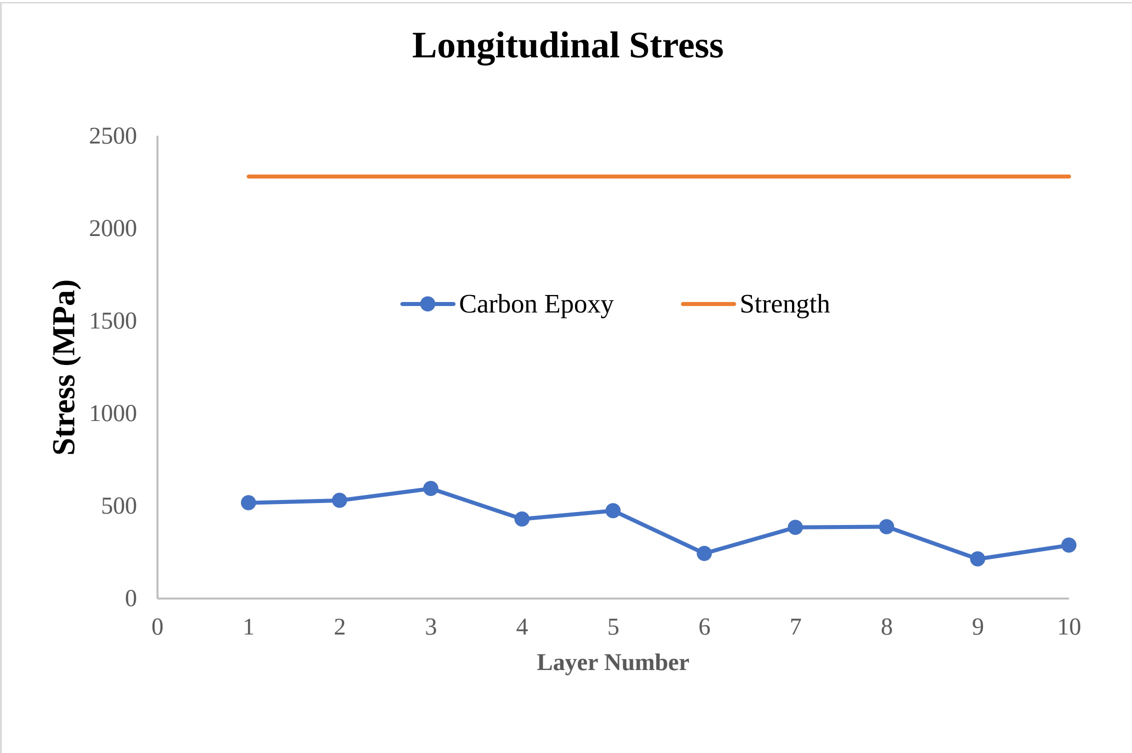


Figure 4.48 Longitudinal Stress of the Composite Cylinder (Carbon Epoxy)

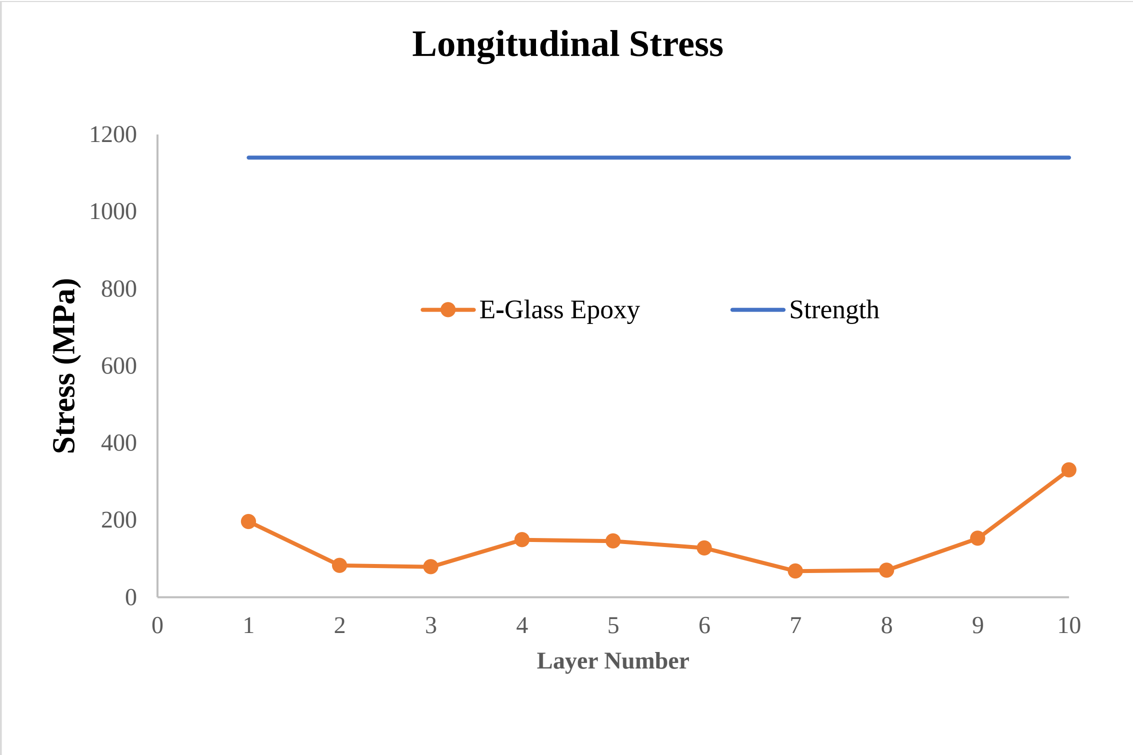


Figure 4.49 Longitudinal Stress of the Composite Cylinder (E-Glass Epoxy)

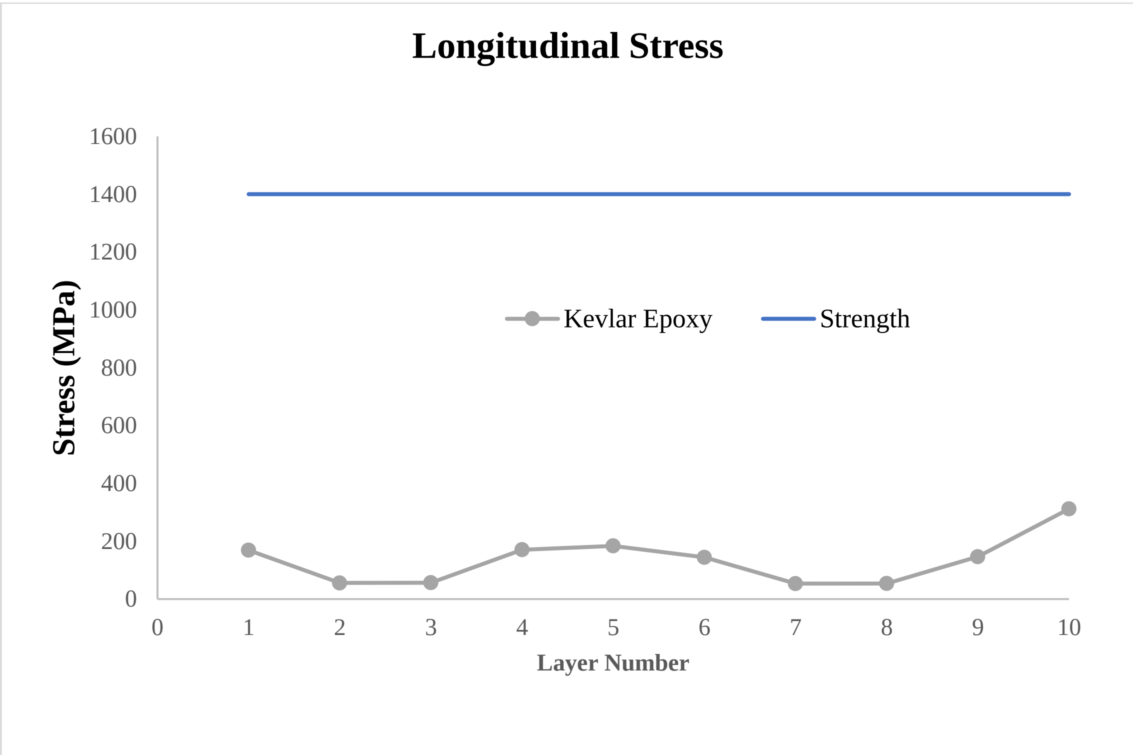


Figure 4.50 Longitudinal Stress of the Composite Cylinder (Kevlar Epoxy)

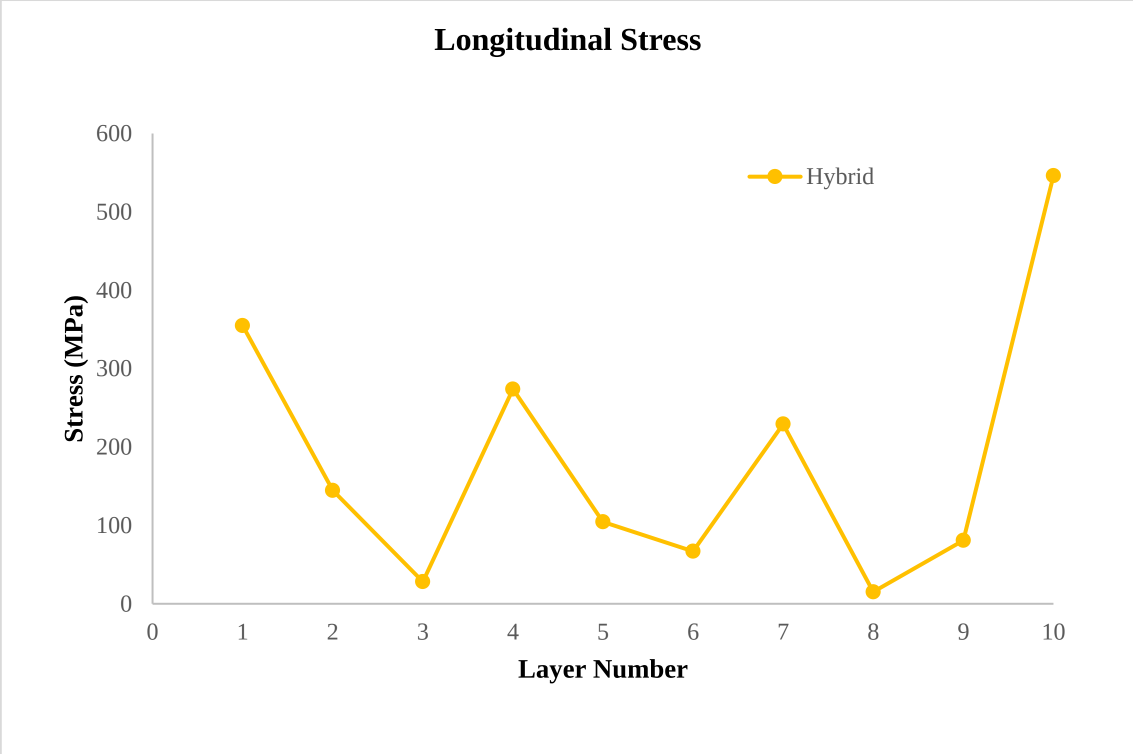


Figure 4.51 Longitudinal Stress of the Composite Cylinder (Hybrid)

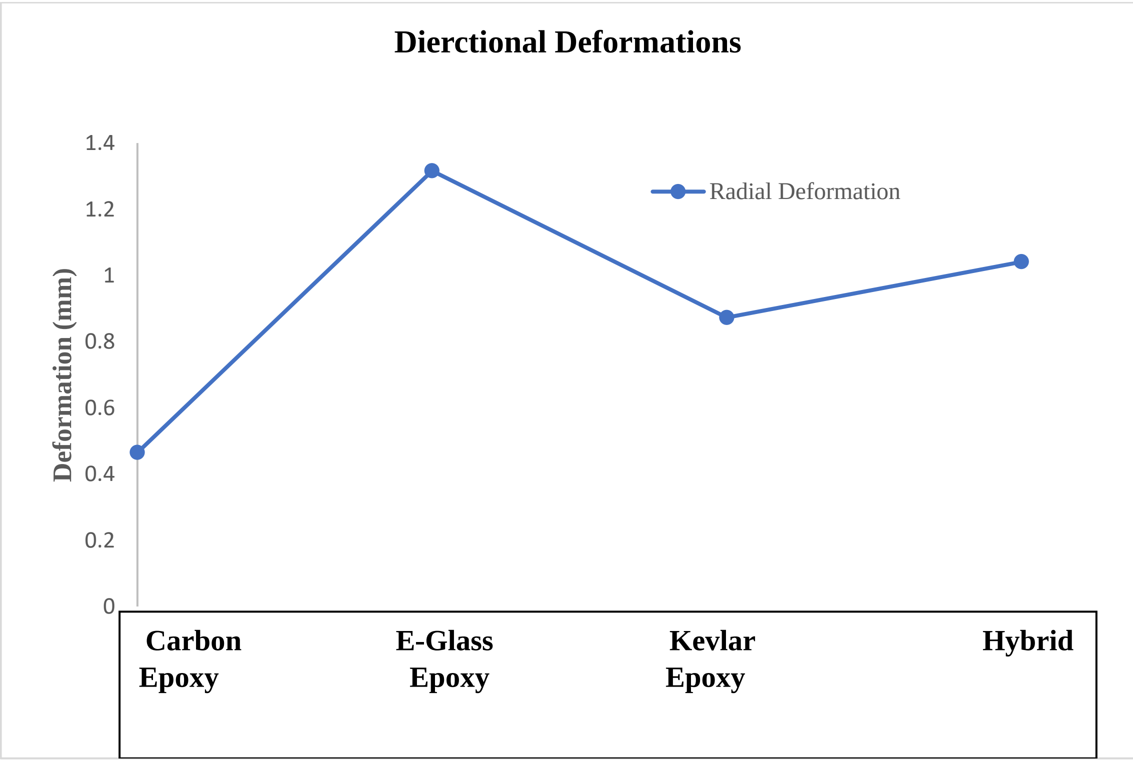


Figure 4.52 Deformations of the Composite Cylinder in Radial Direction

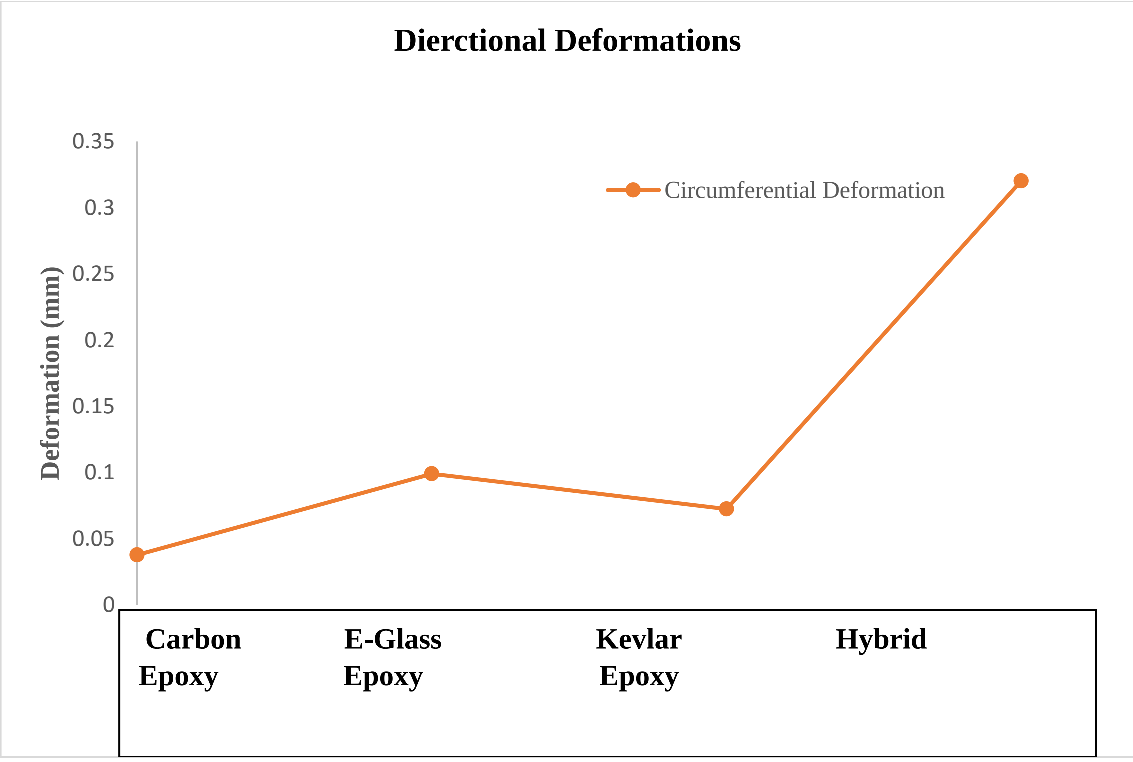


Figure 4.53 Deformations of the Composite Cylinder in Circumferential Direction

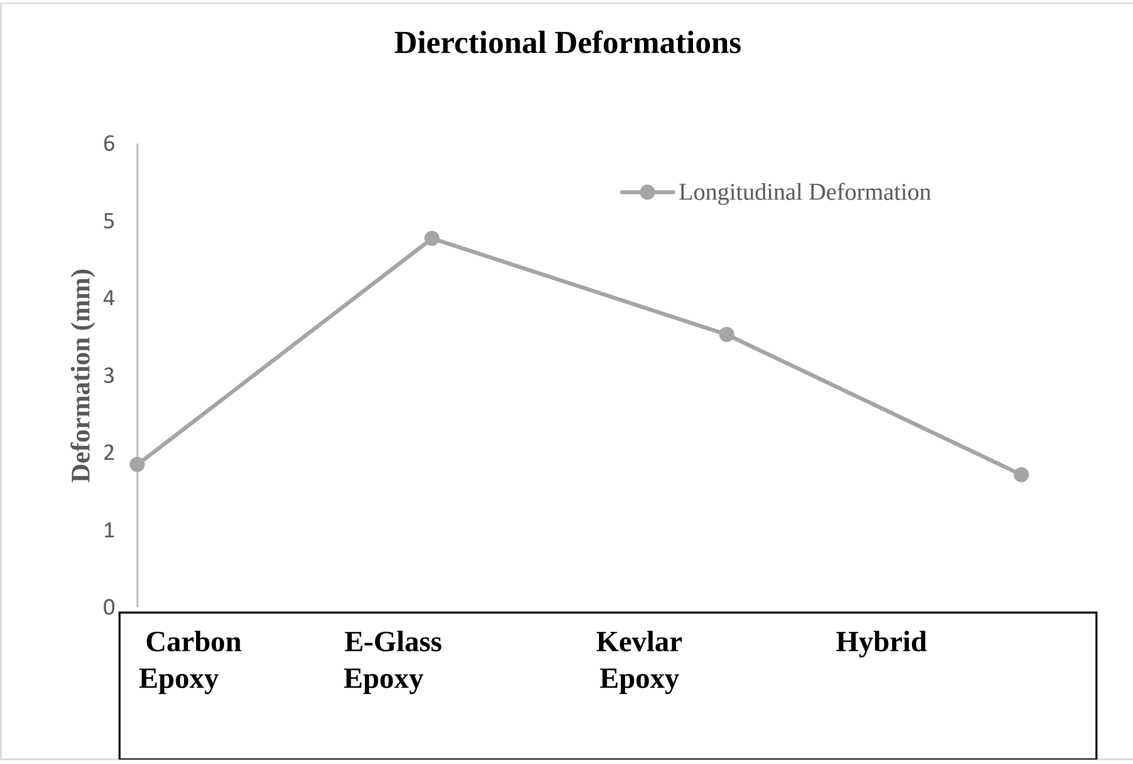


Figure 4.54 Deformations of the Composite Cylinder in Longitudinal Direction

The comparison study between the different materials are discussed below and they magnitudes are represented in the below figures.

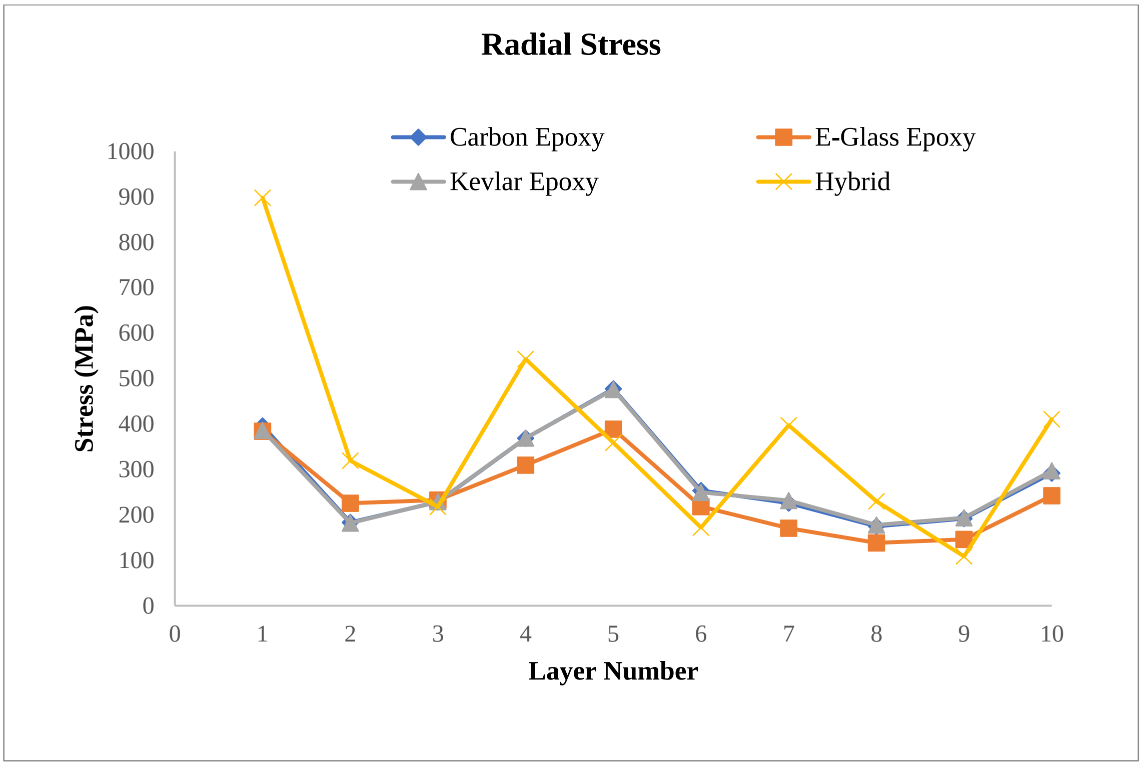


Figure 4.55 Normal stress of the Composite Cylinder in Radial Direction

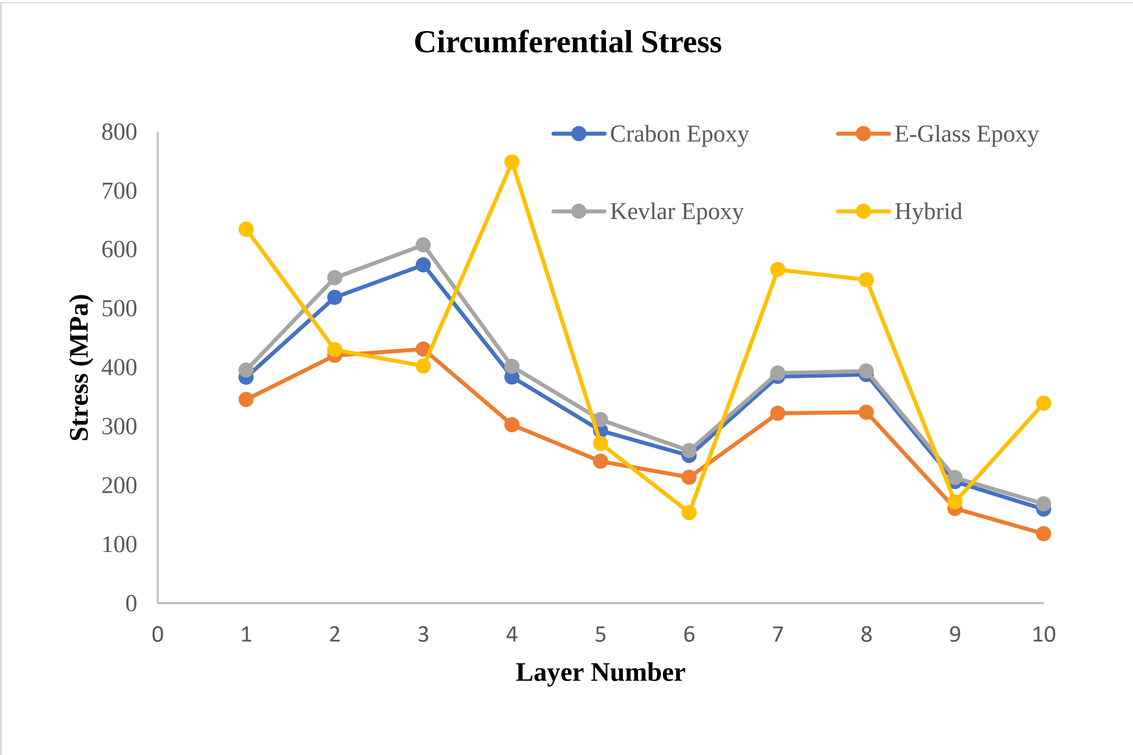


Figure 4.56 Normal stress of the Composite Cylinder in circumferenntial Direction

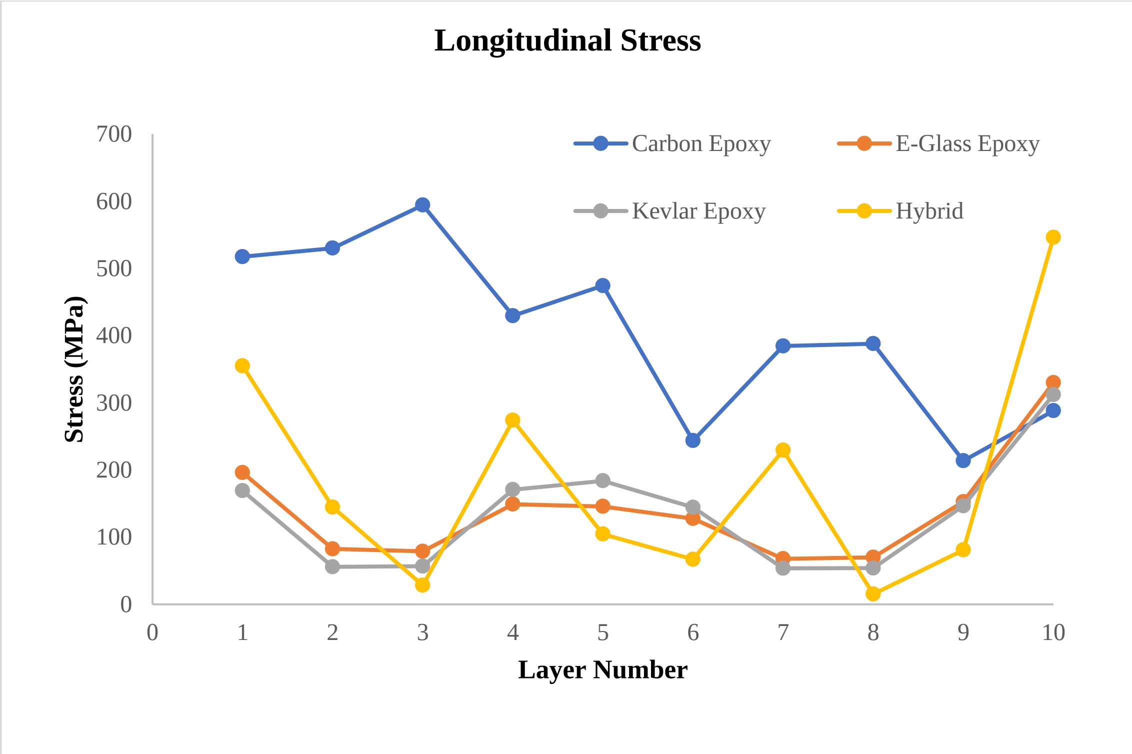


Figure 4.57 Normal stress of the Composite Cylinder in Longitudinal Direction

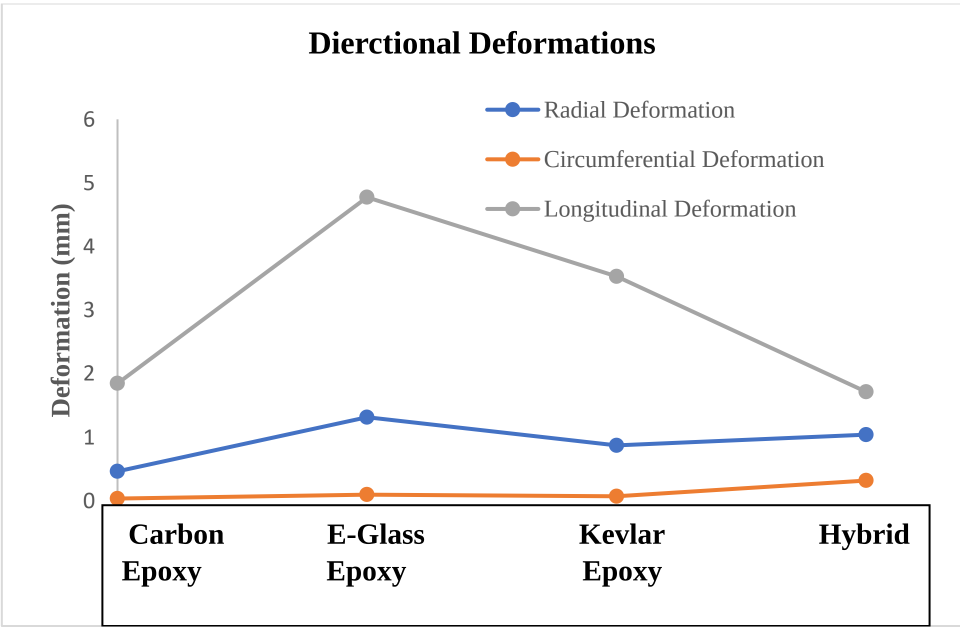


Figure 4.58 Deformations of the Composite Cylinder

4.5 SUMMARY

In this chapter the designed model is structurally analysed for different materials like Carbon epoxy, Graphite/epoxy, Kevlar/epoxy and hybrid composite (Carbon + E-Glass + Kevlar Epoxy). The maximum and minimum normal Stresses and directional deformations are presented.

CHAPTER 5

FREE VIBRATION ANALYSIS OF COMPOSITE CYLINDER

Modal analysis is the fundamental dynamic analysis type, providing the natural frequencies at which a structure will resonate. These natural frequencies are of paramount importance in various engineering fields. Suspensions are usually tuned to have different natural frequencies for passenger cars and race cars.

These are the following requirements for the modal analysis of the composite cylinder.

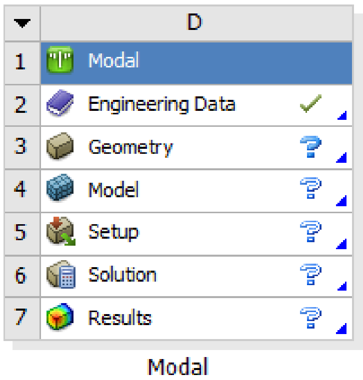


Figure 5.1 Modal analysis system

5.1 Linking the Static Structural system with Modal Analysis systems

The solution data from the static structural analysis is required in the modal analysis. So the complete solution data is transferred to the setup of the modal analysis, as shown in the Fig 4.26.

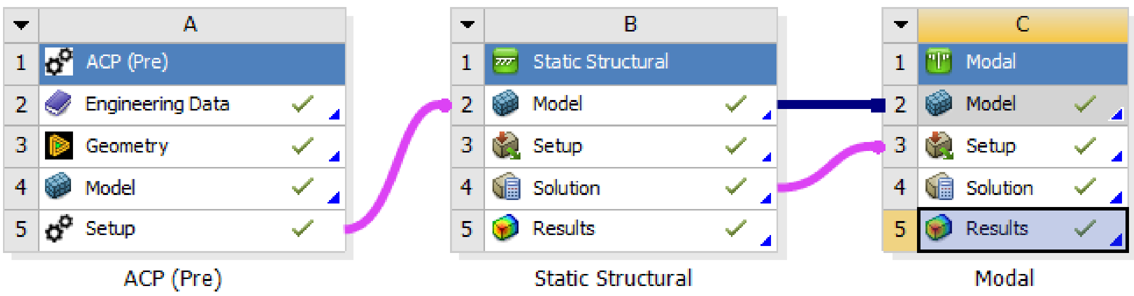


Figure 5.2 Complete setup for modal analysis

From the above step the data like the materials that are used, boundary conditions and results (pre stresses) in the cylinder and all the solutions that are developed in the static structural system is taken into the modal analysis system

5.2 Analysis Settings

In the analysis setting the number of modes that are to be taken into consideration is given .so there 10 modes that are to be considered. The pressure maintained in the cylinder is the 20 MPa which is the working pressure. Each mode represents each loading condition like for tensile loading, compressive loading, twisting, bending etc., these details are given as shown In Fig 4.27.

Options	
Max Modes to Find	10
Limit Search to Range	No
On Demand Expansion Option	Program Controlled
-- On Demand Expansion	No
Spin Softening	Program Controlled
Solver Controls	
Damped	No
Solver Type	Program Controlled
Rotordynamics Controls	
Output Controls	
Analysis Data Management	

Figure 5.3 Analysis setting details

By solving the above data each mode develops its natural frequency under their respective loading conditions. These frequencies of ten modes are listed at pressure of 20 MPa. The maximum frequencies were noticed at 10^{th} mode. This may be due to bending of CNG cylinder about central axis.

5.3 Natural Frequencies and Mode Shapes

Free vibration analysis in performed on the composite cylinder using Carbon Epoxy, E-Glass Epoxy, Kevlar Epoxy and Hybrid (Carbon + E-Glass + Kevlar) materials and list of results i.e., Natural Frequencies and Mode Shapes. The list of natural frequencies of the composite cylinder using carbon epoxy is listed in the below table.

Table 5.1 Natural Frequencies of the Composite Cylinder using Carbon Epoxy

S. No	Mode No.	Frequency (Hz)
1.	1.	70.454
2.	2.	83.156
3.	3.	168.04
4.	4.	168.28
5.	5.	177.62
6.	6.	177.63
7.	7.	302.87
8.	8.	302.87
9.	9.	353.08
10.	10.	353.53

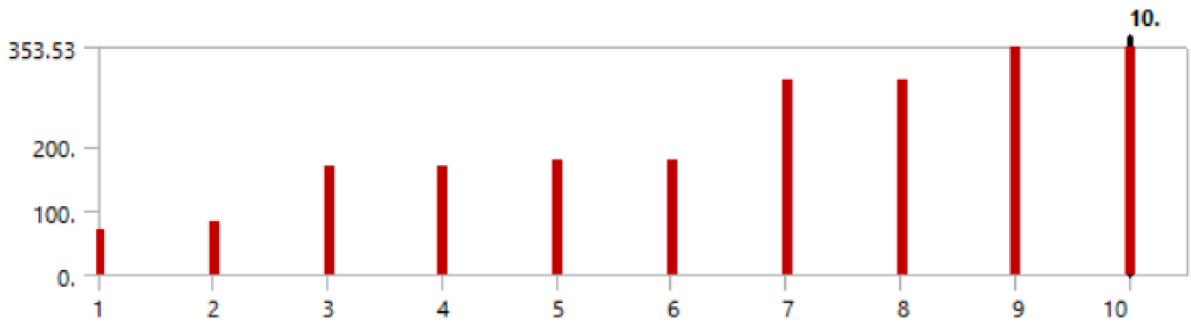


Figure 5.4 Natural frequencies of the cylinder using Carbon Epoxy

The first two mode is about bending about the bending of the cylinder about horizontal and vertical direction about the fixed end. The next mode condition is the twisting about the longitudinal direction. The next one is longitudinal forward movement with respect to fixed end and the fifth mode condition is longitudinal compression. The seventh and eigth mode conditions are longitudinal bending and transverse bending without fixing the ends. The ninth and tenth modes are the transverse compression and expansion of the CNG Cylinder.

The mode shapes of the composite cylinder using carbon epoxy are shown in the below figure.

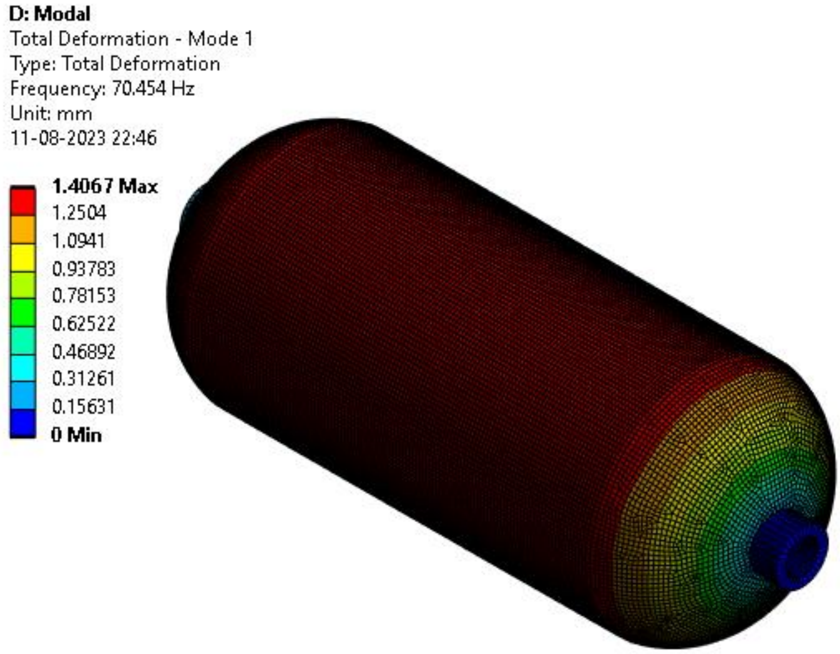


Figure 5.5 First Mode Shape using Carbon Epoxy

The first mode implies the rotation about X-axis i.e., twisting, and the maximum deformation at 70.454 Hz is 1.4067 mm.

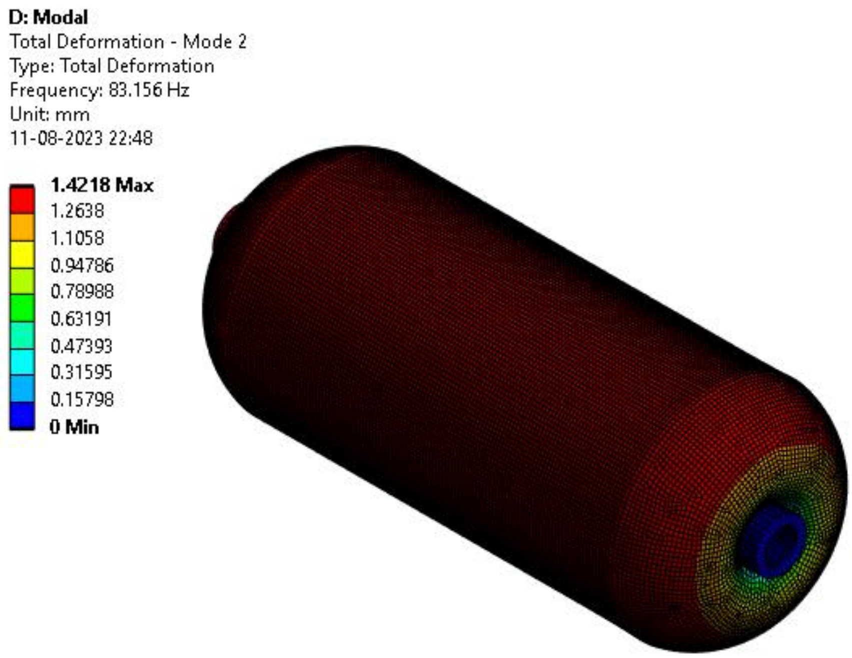


Figure 5.6 Second Mode Shape using Carbon Epoxy

The second mode implies the linear movement in X-axis, and the maximum deformation at 83.156 Hz is 1.4218 mm.

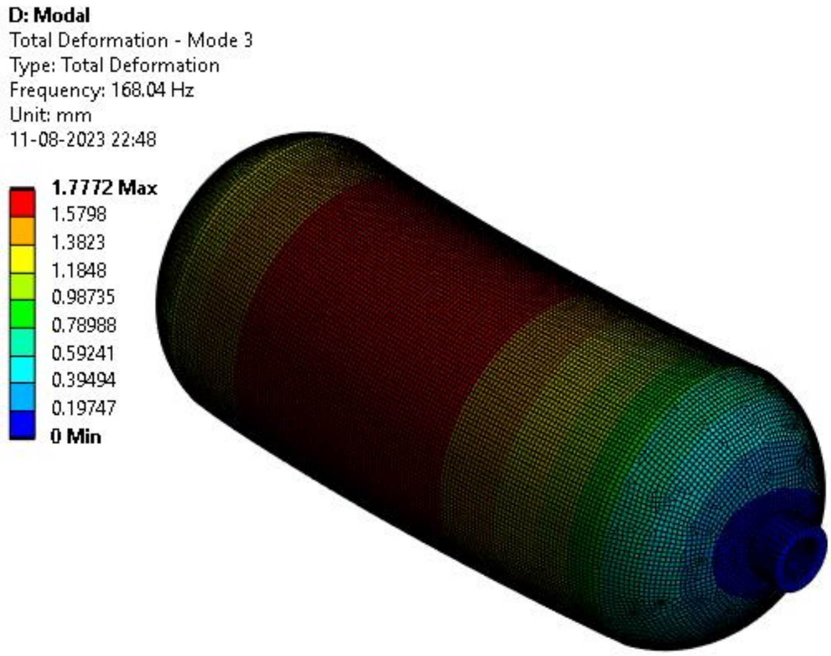


Figure 5.7 Third Mode Shape using Carbon Epoxy

The third mode implies the bending about Z-axis, and the maximum deformation at 168.04 Hz is 1.7772 mm.

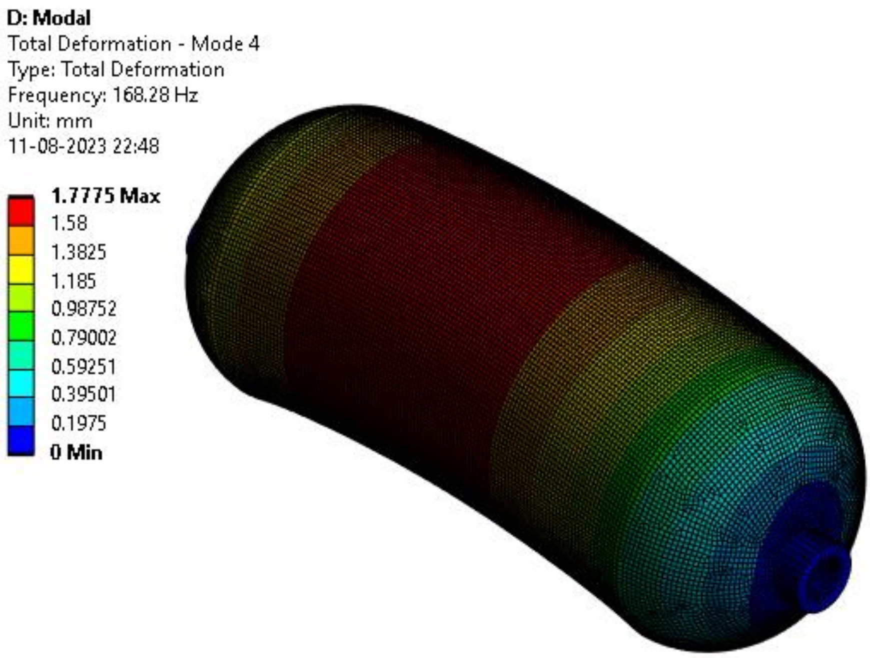


Figure 5.8 Fourth Mode Shape using Carbon Epoxy

The fourth mode implies the bending about Y-axis, and the maximum deformation at 168.28 Hz is 1.7775 mm.

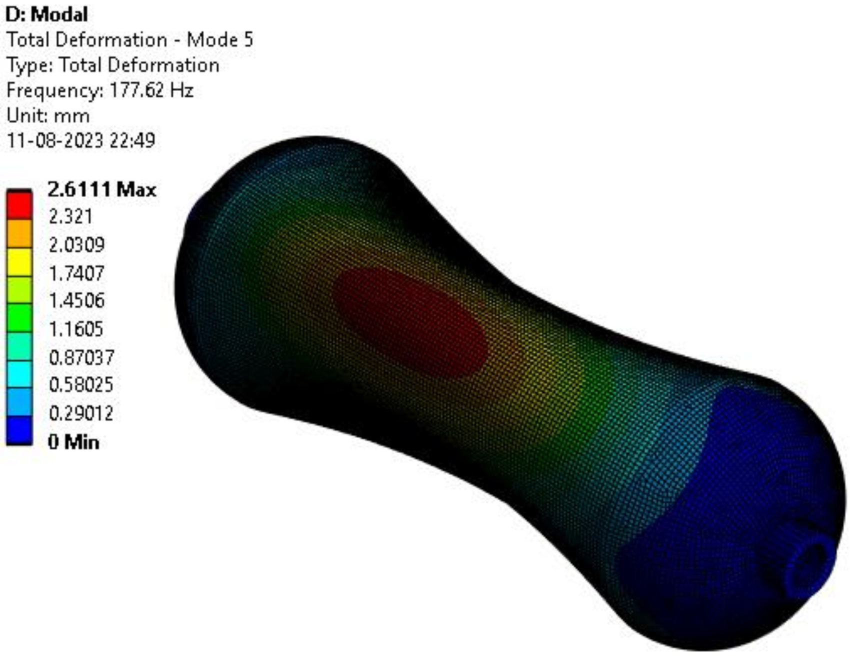


Figure 5.9 Fifth Mode Shape using Carbon Epoxy

The fifth mode implies the bulging mode about diagonals, and the maximum deformation at 177.62 Hz is 2.6111 mm.

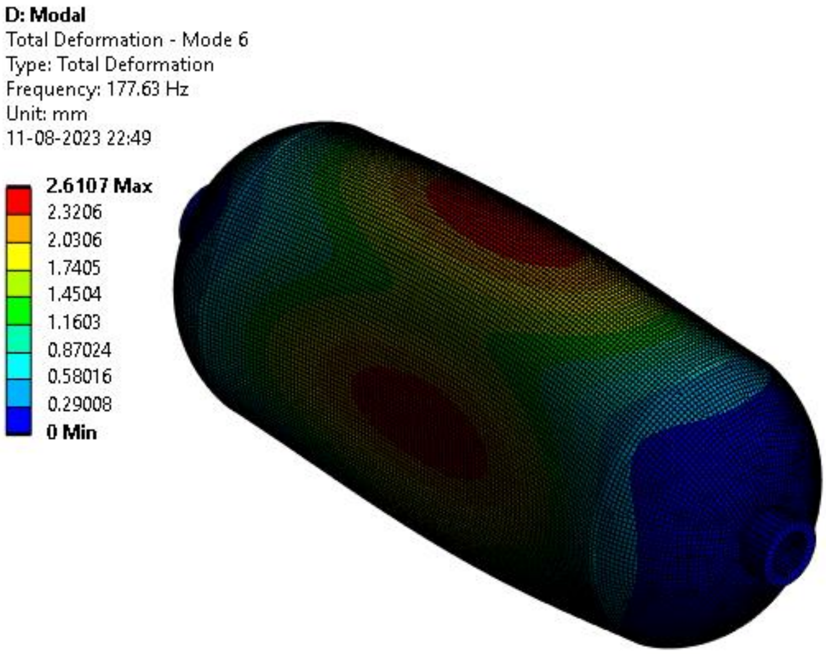


Figure 5.10 Sixth Mode Shape using Carbon Epoxy

The sixth mode implies the bulging mode about Y-axis and Z-axis, and the maximum deformation at 177.63 Hz is 2.6107 mm.

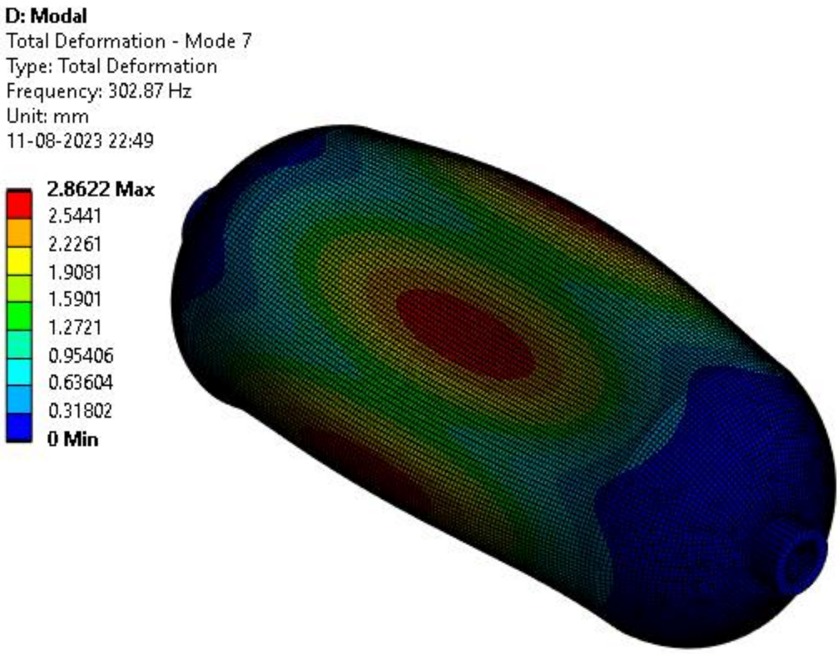


Figure 5.11 Seventh Mode Shape using Carbon Epoxy

The seventh mode implies the bulging mode about diagonals, and the maximum deformation at 302.87 Hz is 2.8622 mm.

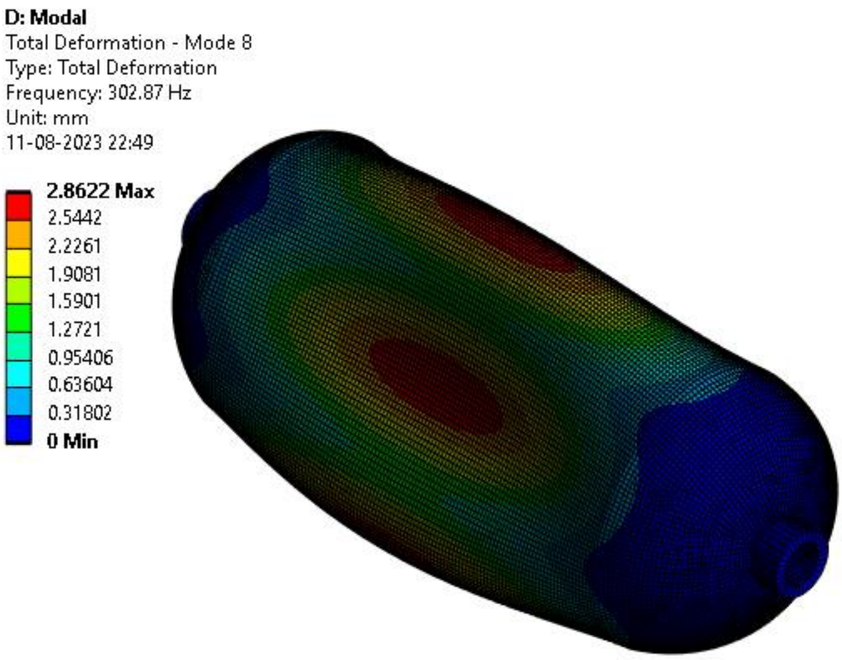


Figure 5.12 Eighth Mode Shape using Carbon Epoxy

The eighth mode implies the bulging mode about diagonals, and the maximum deformation at 302.87 Hz is 2.8622 mm.

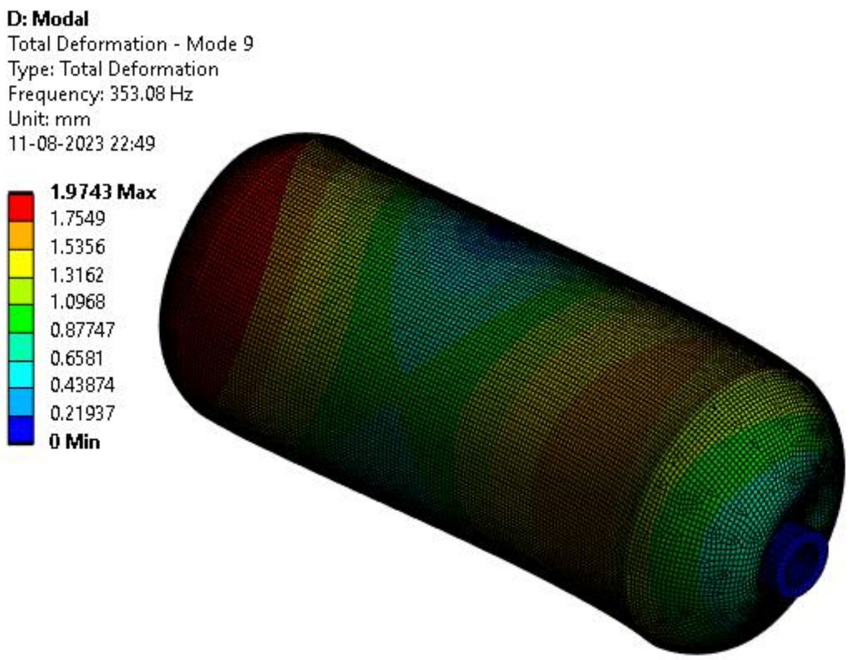


Figure 5.13 Ninth Mode Shape using Carbon Epoxy

The ninth mode implies the bending mode about x-axis, and the maximum deformation at 353.08 Hz is 1.9743 mm.

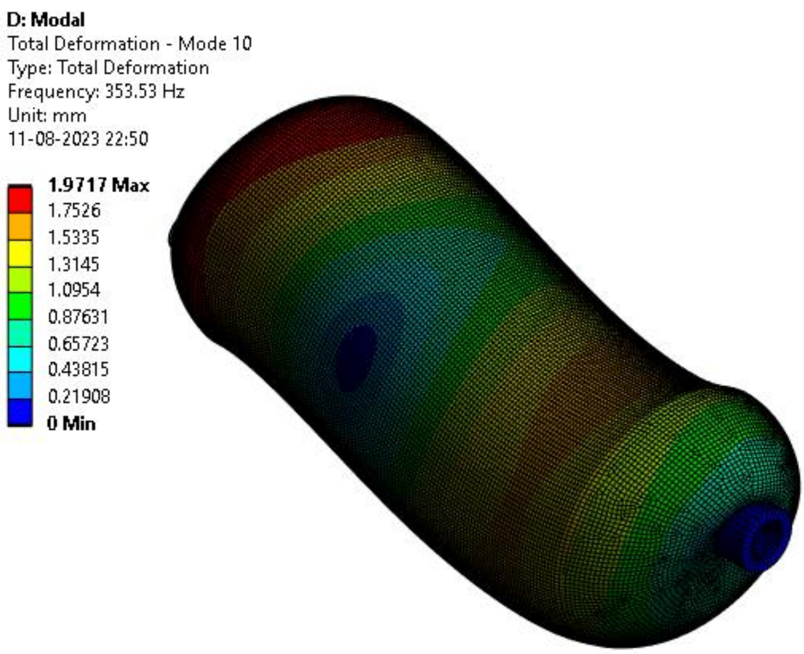


Figure 5.14 Tenth Mode Shape using Carbon Epoxy

The tenth mode implies the bending mode about x-axis, and the maximum deformation at 353.53 Hz is 1.9717 mm.

Similarly, the composite cylinder is assigned with the remaining materials like E-glass Epoxy, Kevlar Epoxy and Hybrid (Carbon + E-Glass + Kevlar Epoxy) and list of results i.e., natural frequencies are calculated and plotted in the below figures.

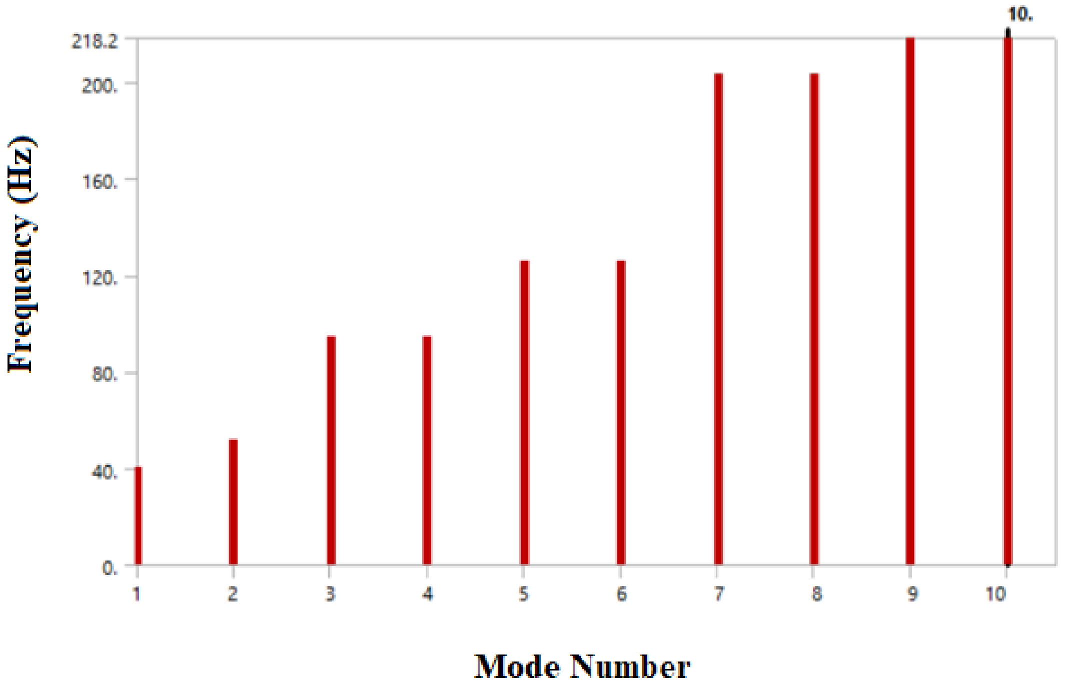


Figure 5.15 Natural frequencies of the cylinder using E-Glass Epoxy

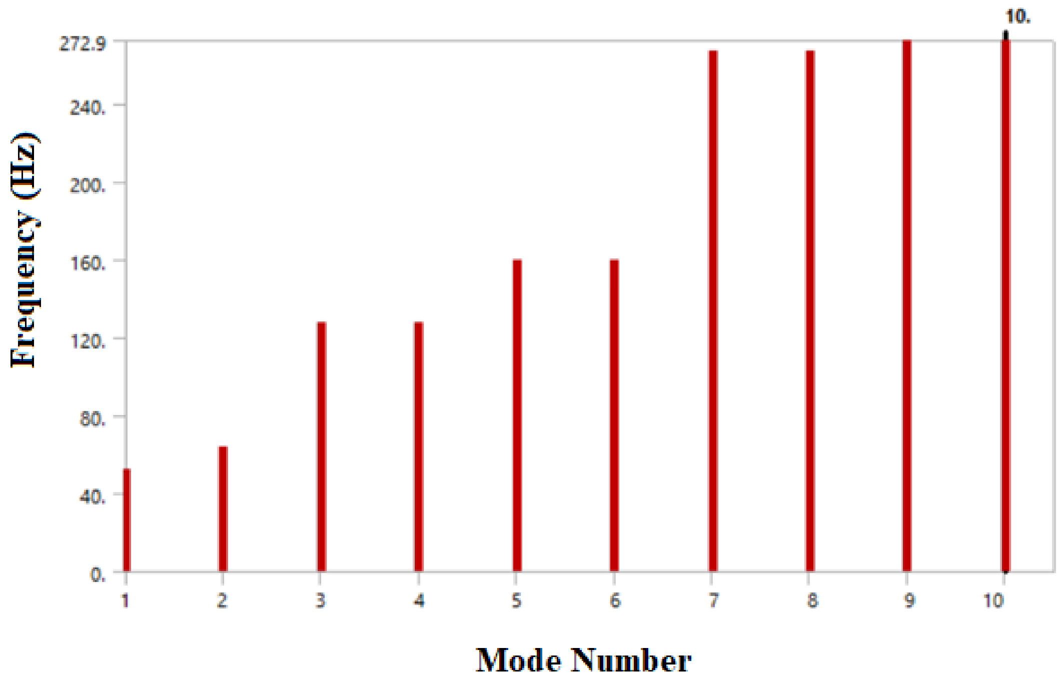


Figure 5.16 Natural frequencies of the cylinder using Kevlar Epoxy

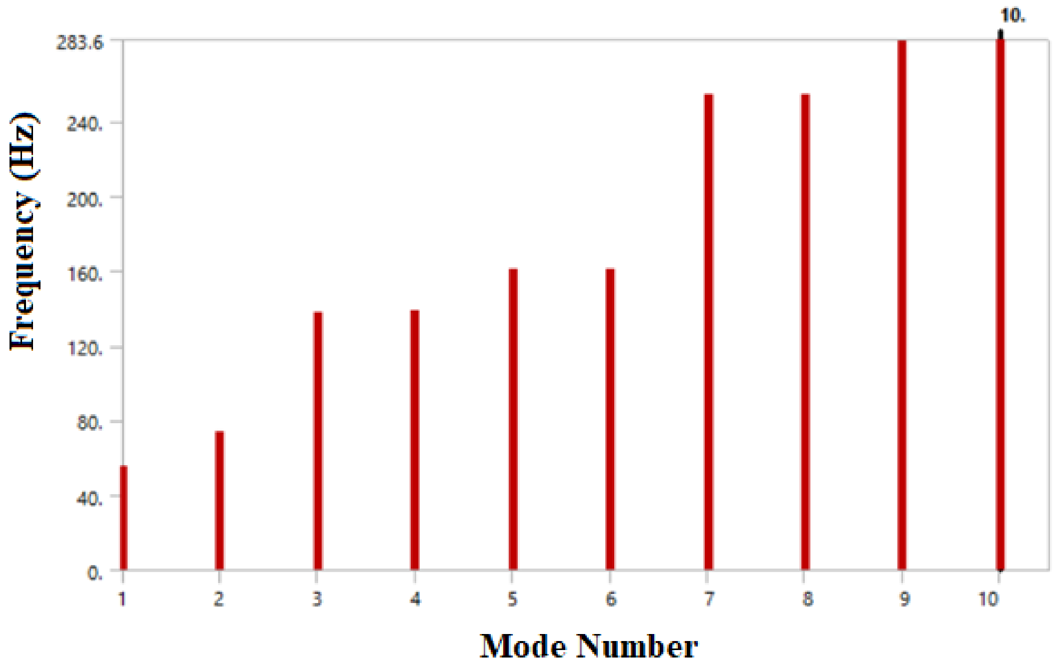


Figure 5.17 Natural frequencies of the cylinder using Hybrid Composite

A comparison study is held on the composite cylinder is assigned with the remaining materials like E-glass Epoxy, Kevlar Epoxy and Hybrid (Carbon + E-Glass + Kevlar Epoxy) and list of results i.e., natural frequencies are calculated and plotted in the below figures.

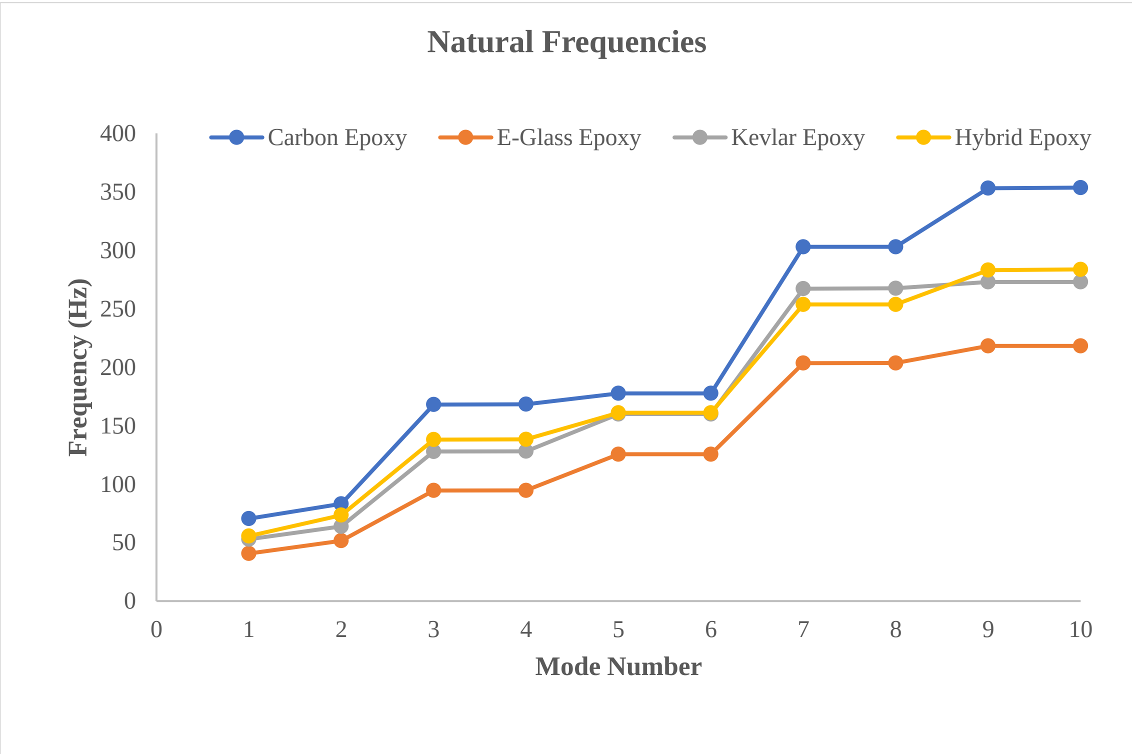


Figure 5.18 Natural frequencies of the cylinder using different materials

From the above graph, it is shown that the carbon epoxy having the high natural frequency values compared to the remaining materials.

5.4 SUMMARY

In this chapter the designed model is structurally analysed for dynamic loads (Free Vibrations) using different materials like Carbon epoxy, Graphite/epoxy, Kevlar/epoxy and hybrid composite (Carbon + E-Glass + Kevlar Epoxy). The natural frequencies and mode shapes are presented in this chapter.

Chapter 6
Conclusions and Future Scope

6.1 Conclusions

The design of Type 4 CNG composite cylinder was developed successfully with standard geometry in design modeller Ansys workbench for the structural and vibration analysis. The materials like Kevlar Epoxy, Carbon Epoxy, E-Glass Epoxy were selected for the high strength with low weight and eco-friendly purpose.

From the structural analysis, the following observations are done.

1. In radial direction, the maximum normal stresses of the CNG cylinder with Hybrid composite possess higher values compared to other materials.
2. CNG cylinder with Carbon Epoxy and Kevlar Epoxy having similar value stresses and CNG cylinder with E-glass epoxy having less stresses.
3. In Circumferential direction, the maximum normal stresses of the CNG cylinder with Hybrid composite possess higher values compared to other materials.
4. CNG cylinder with Carbon Epoxy and Kevlar Epoxy having similar value stresses and CNG cylinder with E-glass epoxy having less stresses.
5. In longitudinal direction, the maximum normal stresses of the CNG cylinder with Carbon Epoxy possess higher values compared to other materials.
6. CNG cylinder with Hybrid composite possess higher values after carbon epoxy, and followed by the E-Glass Epoxy and Kevlar Epoxy.
7. The directional deformations of the CNG cylinder in longitudinal direction having higher values followed by the deformations in radial and circumferential directions.

From the structural analysis, the following observations are done.

1. The natural frequencies of the CNG cylinder are having higher values with carbon epoxy and followed by the Kevlar, hybrid and E-Glass Epoxy.
2. The natural frequencies in 4^{th} and 5^{th} mode of the cylinder having values with all materials.
3. The natural frequencies in 7^{th} and 8^{th} mode of the cylinder having values with all materials.
4. The natural frequencies in 9^{th} and 10^{th} mode of the cylinder having values with all materials.

From the above observations, it is concluded that the carbon epoxy having better performance under static and dynamic loading conditions. Hybrid composite possess in between performance after carbon epoxy and Kevlar and E-glass epoxy composite.

It is recommended to use carbon epoxy under static and dynamic loading conditions using 0/36/72/108/144/180/216/252/288/324 orientated layer angle.

6.2 Future scope

The static analysis of the CNG cylinder was carried in this work. But in practical applications there are some impact forces and sudden jerks experienced by the cylinder while automobile is in motion. The dynamic response will provide more reliability of the analysis. The thermal analysis of the CNG composite cylinder is also a very important characterization for composite material to know the thermal stability.

The future scope may be considered for dynamic analysis and thermal analysis for CNG cylinders with different composite materials.

References

1. Pranjali Sharma Study to methodize the design of safe Type 4 CNG storage vessel using Finite element analysis with experimental validation,
2. T. Dyr, Costs and benefits of using buses fuelled by natural gas in public transport 225 (2019) (2020) 1134–1146,
3. S. Bernardino, Critical review A comparison of emissions from vehicles fueled with diesel or compressed, Nat. Gas 42 (17) (2008) 6437–6445.
4. J. Hine, A.A. Gusev, International Journal of Engineering Science Validating a micromechanical modelling scheme for predicting the five independent viscoelastic constants of unidirectional carbon fibre composites, Int. J. Eng. Sci. 144 (2019) 103133,
5. -A. Makeev, S. Ghaffari, G. Seon, Improving compressive strength of high modulus carbon-fiber reinforced polymeric composites through fiber hybridization, Int. J. Eng. Sci. 142 (2019) 145–157,
6. G.N. Naik, S. Gopalakrishnan, R. Ganguli, Design optimization of composites using genetic algorithms and failure mechanism based failure criterion 83 (2008) 354–367,
7. R. Tschirschwitz, D. Krentel, M. Kluge, E. Askar, K. Habib, H. Kohlhoff, S. Krüger,P.P. Neumann, M. Rudolph, A. Schoppa, S.U. Storm, M. Szczepaniak, Hazards from failure of CNG automotive cylinders in fire, J. Hazard Mater. 367 (July 2018) (2019)
8. J. Fu, J. Yun, Y. Jung, D. Lee, Generation of filament-winding paths for complex axisymmetric shapes based on the principal stress field, Compos. Struct. 161 (2017) 330–339,
9. M. Madhavi, K.V.J. Rao, K.N. Rao, Design and analysis of filament wound composite pressure vessel with integrated-end domes, Defence Sci. J. 59 (1) (2009) 73–81,
10. S. Sulaiman, S. Borazjani, S.H. Tang, Finite element analysis of filament-wound composite pressure vessel under internal pressure, IOP Conf. Ser. Mater. Sci. Eng. 50 (1) (2013),
11. L. Zu, S. Koussios, A. Beukers, D. Zhang, Development of filament wound composite isotensoidal pressure vessels 22 (3) (2014) 227–232

12. M. Imran, T. Yasmin, A. Shakoor, Technical overview of compressed natural gas (CNG) as a transportation fuel 51 (2015) 785–797.
13. T.Dry Costs and benefits of using buses fuelled by using natural gas as public transport , J.Clean. Prod. 225 (2019) (2019) 1134-1146
14. M. Farzaneh-gord, H.R. Rahbari, H. Nikofard, The effect of important parameters on the natural gas vehicles driving range, 2014. April.
15. M.I. Khan, T. Yasmin, A. Shakoor, Technical overview of compressed natural gas (CNG) as a transportation fuel, Renew. Sustain. Energy Rev. 51 (2015) 785–797.