e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:07/Issue:02/February-2025 Impact Factor- 8.187 www.irjmets.com

ENHANCING PERFORMANCE WITH FINITE ELEMENT ANALYSIS-BASED TYPE 4 CNG CYLINDER OPTIMIZATION: MATERIAL AND DESIGN PERSPECTIVES

Vedprakash Marrapa[*1], Dr. Shailesh Gupta[*2], Dr. Gouraw Beohar[*3]
[*1,2,3]Department Of Mechanical Engineering, Shri Ram Institute Of Technology, Jabalpur (M.P.), India.

ABSTRACT

The application of compressed natural gas (CNG) as a cleaner and more efficient fuel is becoming more and more popular worldwide. However, the challenges associated with CNG storage, especially with high-pressure gas cylinders, require innovation in materials and design to ensure safety and performance. This study focuses on the optimization of Type 4 CNG cylinders using Finite Element Analysis (FEA) to enhance material selection, layer configuration, and production processes. We evaluate various composite materials, including epoxy carbon, epoxy E-glass, Kevlar, T700, and boron, under operating conditions up to 73 MPa. The results indicate that Kevlar and T700 perform better than the other materials, with lower deformations and higher safety margins, making them ideal for high-pressure applications. In order to ensure long-term durability and safety, the study emphasizes the significance of strengthening crucial layers, especially under conditions of intense pressure. Additionally, covered are suggestions for design enhancements and the possibilities of alternate fuels like hydrogen.

Keywords: Finite Element Analysis (FEA), Composite Material, Durability Compressed Natural Gas Etc.

I. INTRODUCTION

Since natural gas is widely available and operates safely, it is an environmentally benign energy source. This is a workable remedy for the problem that environmental degradation now poses. Unfortunately, its low density and traffic issues have prevented it from being widely used. The lowest calorific value of natural gas compared to gasoline or diesel is the worst component. Because of this, liquefied natural gas (LNG) was utilized at a very low temperature of around -162°C at normal pressure and compressed natural gas (CNG) was used at a pressure of about 20 MPa at ambient temperature. Methane gas, which is a mixture of ethane, propane, butane, and carbon dioxide, makes up more than 90% of natural gas chemically. Higher engine efficiency, a clean burning behaviour, and a high-octane rating are all associated with higher methane content.

The present situation centres on the development of lightweight compressed natural gas storage containers. Moreover, a composite pressure vessel is less heavy than a metal cylinder. There is enough cruising range in the luggage compartment thanks to the pressure range of 20 to 25 MPa. Because composite cylinders are lightweight and highly durable, they also contribute to increased fuel efficiency. However, mishaps involving high-pressure gas storage, like CNG cylinder leaks and ruptures, are becoming a significant issue. Various manufacturing flaws can result in operational catastrophes even if the ISO 11439 safety standard is in place to guarantee the safe functioning of cylinders. Less room in the layout of the car. Storage containers must be reasonably priced, dependable, and safe. Conventional metallic pressure vessels have high strength-to-weight ratios and poor efficiency. To attain optimal balance and security, a dependable and cost-effective design with enhanced mechanical attributes is necessary. CNG is lighter than gasoline and has a greater autoignition temperature, among other benefits. CNG has an ignition temperature of 700°C. It is less expensive and emits less pollution than gasoline-powered goods. Worldwide, the usage of compressed natural gas (CNG) as an automotive fuel is growing because it has several advantages over gasoline, such as far fewer emissions and cheaper fuel.

Figure 1: 3D View of CNG Cylinder in use

Transport Options:

Short-distance possibilities include low-pressure gas distribution pipelines or injection into the natural gas grid.

Table 1: Type of the cylinder

Gas transport containers (CNG/CBG)	Liquefaction (LNG/LBG)
High-pressure containers (Type I or Type IV) are a cost-effective way to carry biomethane (CBG) to gas stations, industrial units, or grid injection.	Liquefied natural gas (LNG) or liquefied biogas (LBG) can be used for long-distance or specialized applications.

II. LITERARTURE REVIEW

The study by Kashyzadeh et al. (2021) developed a high-fatigue performance cylinder for compressed natural gas using an optimization algorithm. The design improved fatigue life by 2.4 times compared to the initial design, utilizing finite element simulation and RSA. Xiong S, Huang S, Li B et al (2020) The Leak-before-break (LBB) test is an important test for ensuring safety performance verification of CNG-II bottles. A CNG-II gas cylinder ruptured during the LBB test, causing crack growth and failure due to oxide slag inclusions, which are used as fatigue sources during the fatigue test.A study by Tschirschwitz et al. (2019) found that Type IV CNG cylinders showed less critical failure behaviour under fire impingement than Type III cylinders, emphasizing the need for proper safety measures in the use of CNG automotive fuel. The study by Rafiee et al. (2018) predicts burst pressure in composite pressure vessels using progressive damage modelling and stochastic modelling, considering manufacturing uncertainties and fibre volume fraction as random parameters. A study by Tschirschwitz et al. (2018) found that tank failure in installed LPG tanks can pose severe hazards in case of a vehicle fire. The study involved 16 tests with toroidal shaped LPG vehicle tanks, with all failing within a time of less than 5 minutes in a BLEVE explosion. Fragment throwing distances were also observed. A study by Kumar et al. (2017) tested a 70-liter capacity CNG gas cylinder under 730 bar burst pressure, proving safe under specific loading and boundary conditions. Composites are being used to design pressure vessels. Stefana et al. (2016) used bow-tie analysis, FTA, FMEA, and FTA to assess the risk of a Dual Fuel (LNG-Diesel) system in heavy-duty diesel trucks. The analysis identified causes, critical events, and potential accident scenarios, and identified safety measures throughout the system's life cycle. Stojanovic B, Ivanovic L et al. (2015) Composite materials, particularly aluminium alloys, are increasingly used in mechanical constructions due to increased exploitation periods and reduced weights. Hybrid composites with aluminium matrices offer improved mechanical properties, including resistance to wear and specific stiffness. A study by Tahir et al. (2015) found that CNG fuel produces 18.5% less power than gasoline, with a 23% lower heat transfer rate and 20% less pressure inside the cylinder, suggesting improvements are needed for improved engine performance. Chen et al. (2014) utilized a fault tree to analyse the safety and reliability of CNG vehicle energy storage-supply systems, focusing on catch fires and explosions.11). Lie S, Li T et al. (2014)The paper discusses the use of two levels of Failure Assessment Diagram (FAD) to predict the failure pressure of a cracked Type 1 full metal compressed natural gas cylinder, using CTOD, Charpy impact, and tensile coupon tests to determine the fracture toughness and stress-strain curve. Dashtebayaz et al.'s 2014 study on rapid refuelling of a Natural Gas Vehicle (NGV) on-board cylinder reveals a new approach to understanding heat transfer and flow. They developed an equation for foretelling heat transfer rate and a thermodynamic method for predicting pressure and temperature variations.

III. OBJECTIVES

CNG cylinders are crucial for the safety of workers, and their performance can be significantly improved by utilizing cutting-edge materials. These materials can enhance durability, fatigue life, and impact resistance, while also enhancing the arrangement of layers. Production procedures can also impact the mechanical characteristics and functionality of CNG cylinders. To ensure resilience and safety, precise models should be created, and failure analysis should be conducted to identify weak points. Strict safety regulations should be established to ensure the reliability of CNG cylinders. Additionally, long-term performance analysis and the exploration of substitute fuels like hydrogen can help mitigate environmental effects and safety issues.

1. Problem Formulation:

The aim of research focuses on optimizing Type 4 CNG cylinders using Finite Element Analysis (FEA) to enhance material selection, layer configuration, and production processes. FEA will predict burst pressure and analyze failure mechanisms for improved safety. Long-term performance testing and exploration of alternative fuels like hydrogen will also be conducted to improve resilience, efficiency, and environmental impact.

IV. METHODOLOGIES

1. Finite Element Analysis (FEA):

Finite Element Analysis (FEA) is a prevalent technique utilized in contemporary scenarios, employing finite component analysis under diverse conditions. This method divides a workpiece or system into finite elements, incorporating applied forces within specific boundary conditions to generate comprehensive outputs. For instance, in structural analysis, each division of a structure is termed an element. FEA aids engineers in exploring complex component issues and expediting research advancements. Additionally, the Finite Element Method (FEM) emphasizes optimizing the design process for analysis and manufacturing, known as Design for Analysis (DFA) and Design for Manufacturing (DFM). In the Finite Element Method (FEM), DFA (Design for Analysis) and DFM (Design for Manufacturing) focus on optimizing the design process for analysis and manufacturing,

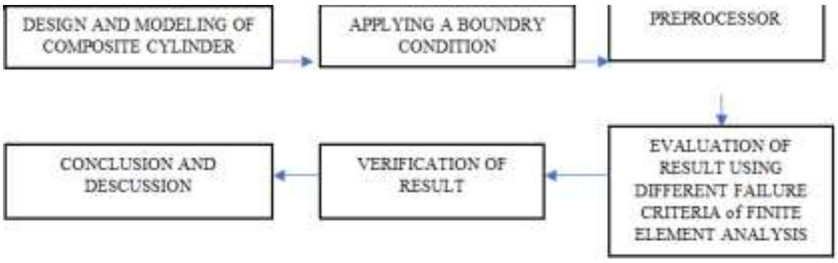


Figure 2: Process Flow Diagram

2. Boundary Conditions:

Different paper inputs have been obtained in order to ensure correctness in the outcomes of the current research study.

Stresses in a thin cylindrical shell due to an internal pressure

The analysis of stresses induced in a thin cylindrical shell are made on the following assumptions:

1. The effect of curvature of the cylinder well is neglected.
2. The tensile stresses are uniformly distributed over the section of the wells.
3. The effect of the restraining action of the head at the end of the pressure vessel is neglected.

3. Geometry:

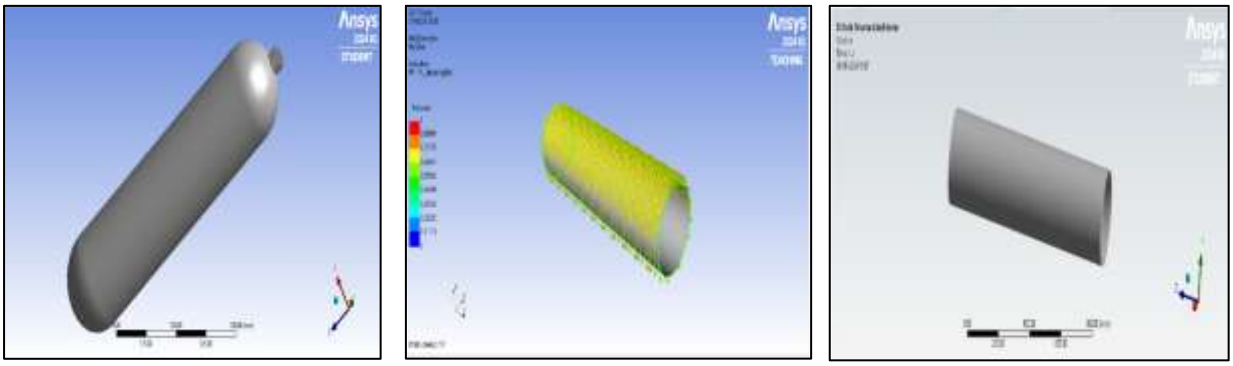


Figure 3: Shown above the geometry of the three views of design

The gas cylinder is designed using composite material, with dimensions including a 1,145 mm body section, 314 mm liner, 7.5 mm wall thickness, and 350 mm outer diameter. The nozzle has dimensions of 56 mm inside diameter, 51 mm length, and 80 mm outer diameter. The end plate has a wall thickness ranging from 7.5 mm to 29 mm. The cylinder consists of 23 layers, with the first layer being a HDPE liner with a thickness of 7.5 mm.

IRJMETS

e-ISSN: 2582-5208

International Research Journal of Modernization in Engineering Technology and Science

(Peer-Reviewed, Open Access, Fully Refereed International Journal)

Volume:07/Issue:02/February-2025 Impact Factor- 8.187 www.irjmets.com

The remaining 22 layers are composed of GFRP helically wound layers (Ply-2 to Ply-11) and GFRP hoop wound layers (Ply-12 to Ply-23). Overall length of the gas cylinder: 1,500 mm.

V. MATERIAL PROPERTIES

Mechanical Property of Material in use:

Table 2: Composite Material Property

Epoxy Carbon UD (230 GPa)									
	Orthotropic Elasticity								
Density kg mm^-3	Young's Modulus X direction MPa	Young's Modulus Y direction MPa	Young's Modulus Z direction MPa	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY MPa	Shear Modulus YZ MPa	Shear Modulus XZ MPa
1.49E-06	1.21E+05	8600	8600	0.27	0.4	0.27	4700	3100	4700
	Orthotropic Strain Limits								
	Tensile X direction	Tensile Y direction	Tensile Z direction	Compressive X direction	Compressive Y direction	Compressive Z direction	Shear XY	Shear YZ	Shear XZ
	1.67E-02	3.20E-03	3.20E-03	-1.08E-02	-1.92E-02	-1.92E-02	1.20E-02	1.10E-02	1.20E-02
	Orthotropic Stress Limits								
	Tensile X direction MPa	Tensile Y direction MPa	Tensile Z direction MPa	Compressive X direction MPa	Compressive Y direction MPa	Compressive Z direction MPa	Shear XY MPa	Shear YZ MPa	Shear XZ MPa
	2231	29	29	-1082	-100	-100	60	32	60
	Thermal Expansion								
Coefficient of Thermal Expansion X Direction C^-1			Coefficient of Thermal Expansion Y Direction C^-1			Coefficient of Thermal Expansion Z Direction C^-1		Zero-Thermal-Strain Reference Temperature C	
-4.70E-07			3.00E-05			3.00E-05		20	

Table:

Puck Constants						
Compressive Inclination XZ	Compressive Inclination YZ	Tensile Inclination XZ	Tensile Inclination YZ	Interface Weakening Factor	Degradation Parameter s	Degradation Parameter M
0.3	0.25	0.35	0.25	0.8	0.5	0.5
Tsai-Wu Constants						
Temperature C	Coupling Coefficient XY		Coupling Coefficient YZ		Coupling Coefficient XZ	
22	-1		-1		-1	

IRJMETS
e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:07/Issue:02/February-2025 Impact Factor- 8.187 www.irjmets.com

Epoxy carbon with material combination:

Table 3: Composite property of material in use

Kevlar				
Density kg mm^-3	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
1.39E-06	75800	0.34	78958	28284
T700				
Density kg mm^-3	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
1800	1.60E+05	0.198	8.83E+04	66778
Boron				
Density kg mm^-3	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
2700	39300	0.2	21833	16375

4. Meshing:

The model's mesh consists of 26,331 nodes and 17,751 elements, generated using physics preferences for optimal accuracy. A 3D mesh with an aspect ratio of 1.02- and 20-mm element size was applied, using a quad-dominant approach.

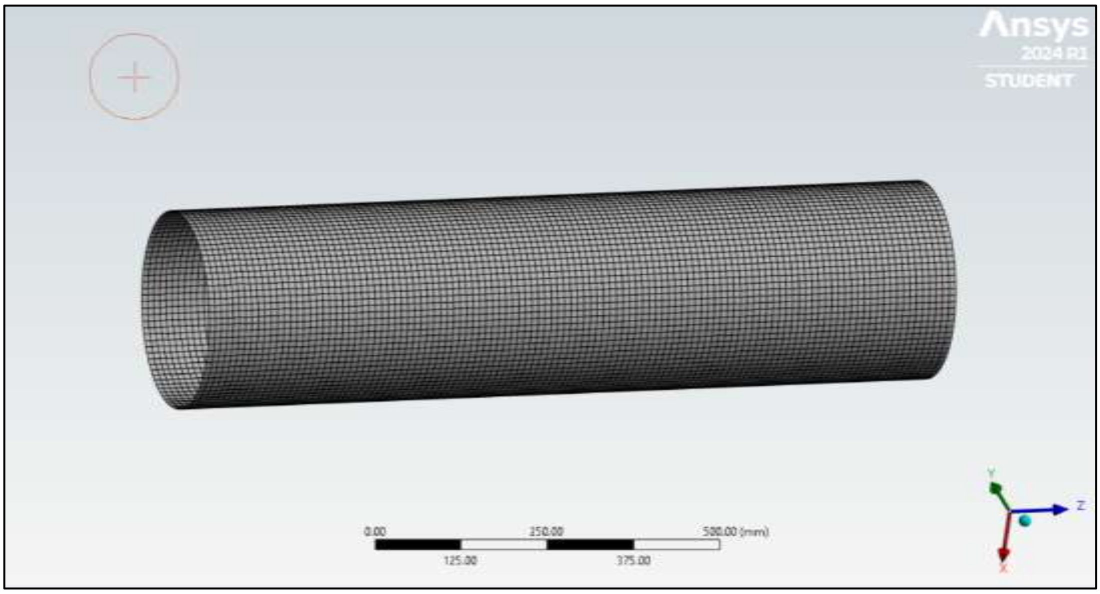


Figure 4: Meshed view of cylindrical model

5. Solver Setup:

One effective numerical technique for analysing how structures and components behave under different loading scenarios is finite element analysis, or FEA. One popular kind of FEA is linear analysis, which assumes that applied loads and consequent deformations have linear connections. The conditions that were applied to the 3D FEA model during analysis are listed below.

Fixed Support:	**Load Criteria:**
The figure shown below shows the fixed support applied at the left end of ring.	The figure shown below shows the Fixed displacement applied on the opposite Z direction.

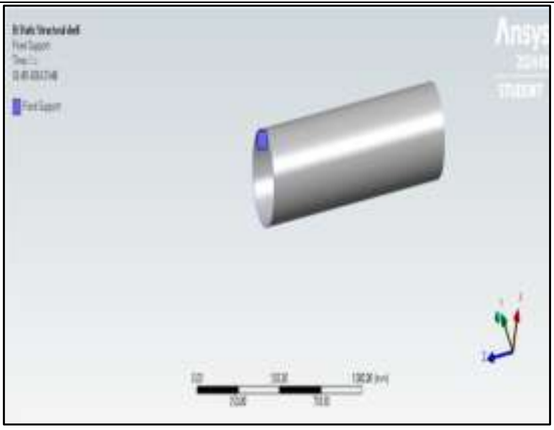


Figure 5: Fixed Support applied on a ring beam

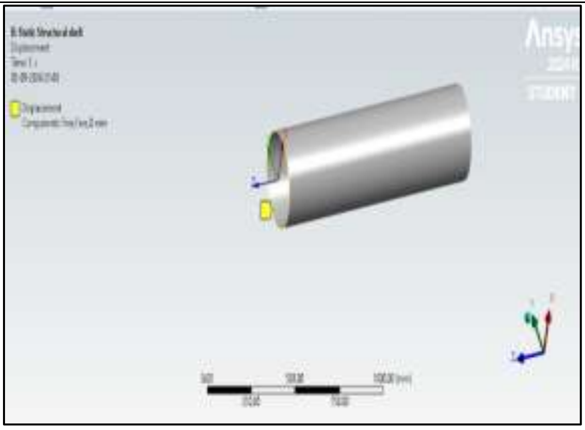


Figure 6: Boundary condition with fixed displacement

6. Load Calculation:

The figure shown below shows the Internal Pressure applied in Y direction that Equally distributed in the internal surface of the cylinder with the three condition.

Operating temperature	Filled medium	Pressure Operating	Pressure (Water test)	Bursting Pressure (Max)
-40°C to 60°C	Natural gas	20 MPa	30 MPa	73 MPa

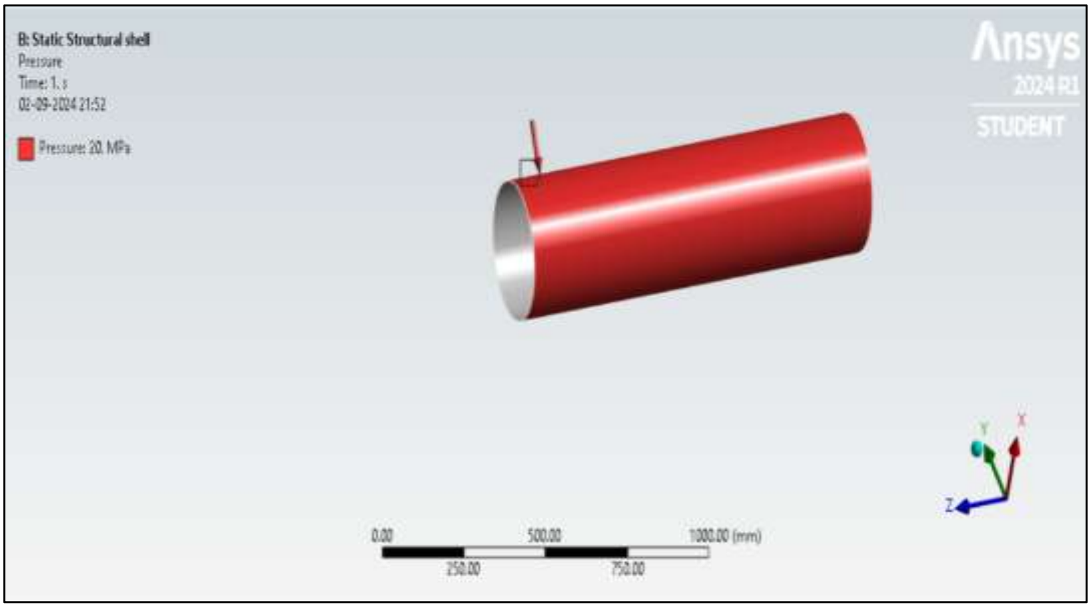
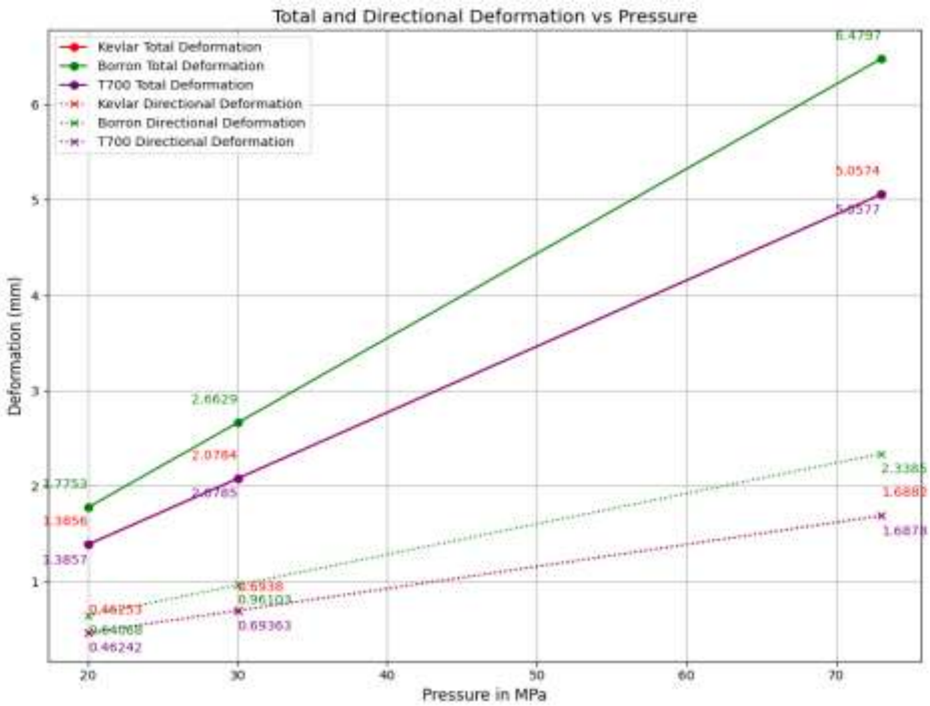


Figure 7: Pressure boundary condition inside of the vessel

7. Comparison of Deformation:

Comparison of Deformation of (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and Kevlar), (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and Boron) and (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and T700):

Comparisons demonstrate the differences in deformation characteristics between the Three material models, indicating variations in total and directional deformations under three Pressure conditions 20MPA, 30MPA and Max Permissible 73MPA respectively. condition.



Graph 1: Total Deformation (mm) & Directional Deformation (mm)

Total Deformation:

- Kevlar: Lower deformations than Boron; Kevlar has 5.0574 mm at 73 MPa while Boron has 6.4797 mm.
- T700: Deformation similar to Kevlar with 5.0577 mm at 73 MPa.

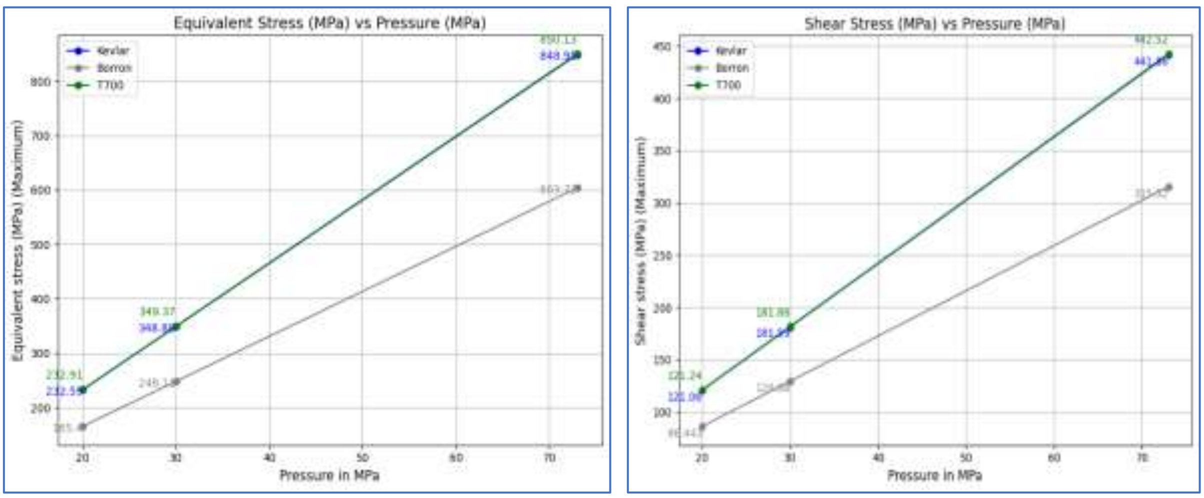
Directional Deformation:

- Very small values for all reinforcements, meaning deformations along specific directions are minimal, especially for Kevlar and T700.

8. Comparison of All Stresses:

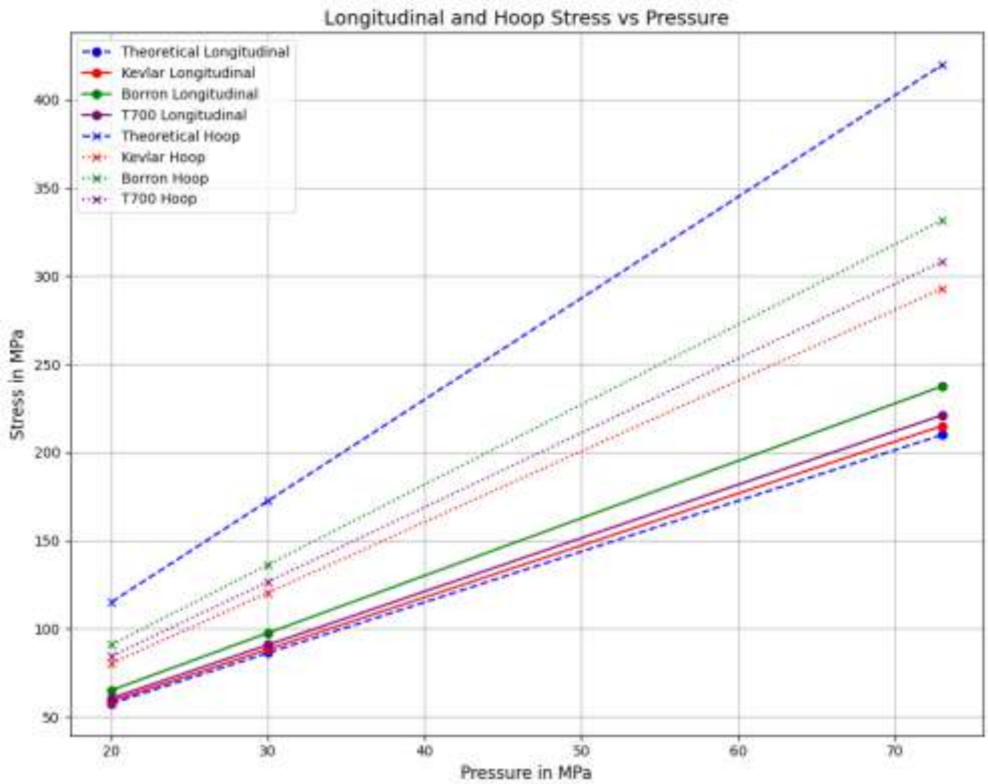
1. Comparison of All Stresses:

The comparison of All Stresses for material models (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and Kevlar), (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and Boron) and (Epoxy carbon UD (230 GPa) prepreg, Epoxy E-Glass UD and T700) reveals significant variations in stress magnitudes under different in three Pressure conditions 20MPA, 30MPA and Max Permissible 73MPA respectively. conditions. In the graph shown below comparison of different stresses:



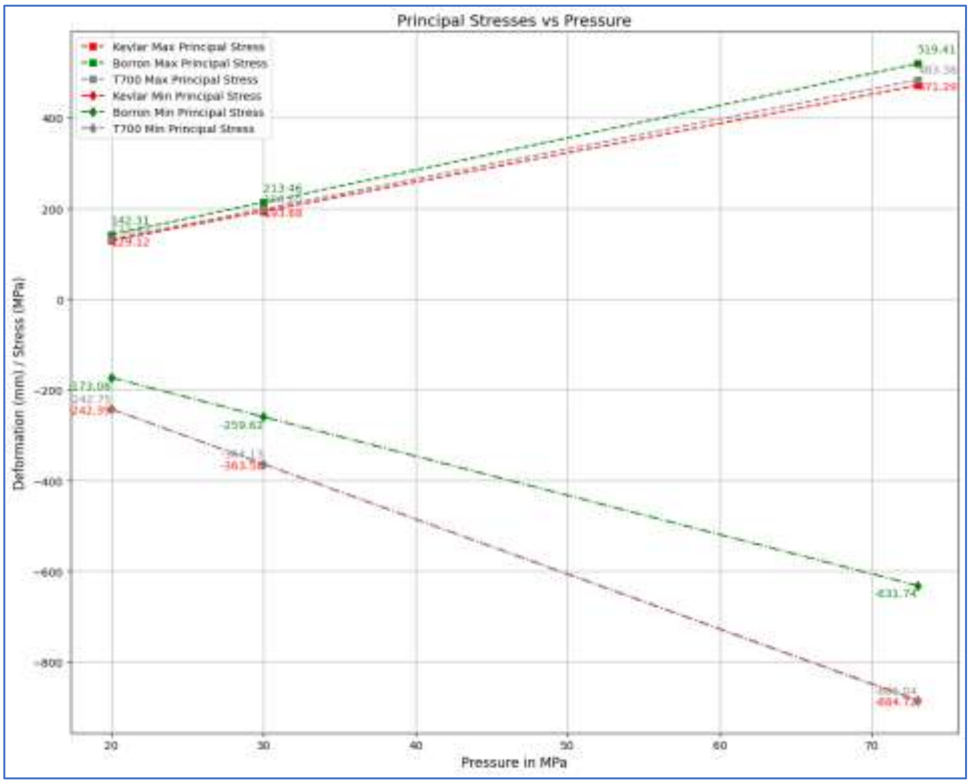
Graph 2: Comparison of Stresses

Shown below the comparison of the Hoop Stress and longitudinal stress in three Pressure conditions 20MPA, 30MPA and Max Permissible 73MPA respectively. condition.



Graph 3: Comparison of All Stresses

Shown below the comparison of the Maximum and Minimum Principal Stress in three Pressure conditions 20MPA, 30MPA and Max Permissible 73MPA respectively. condition.



Graph 4: Comparison of Principal Stresses

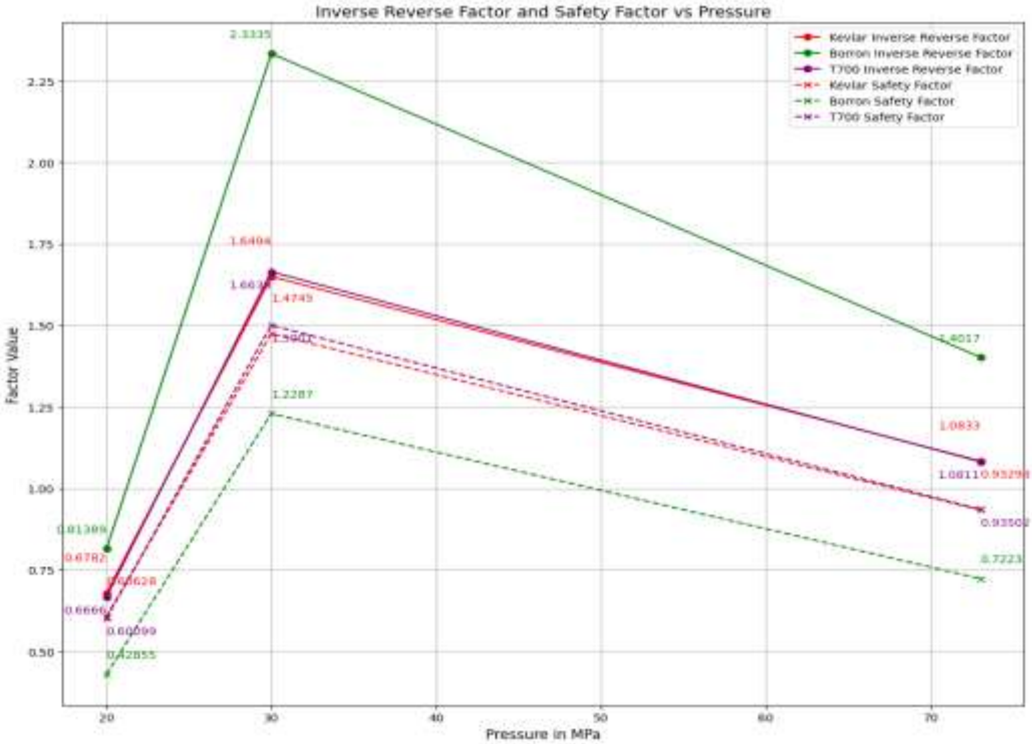
IRJMETS
e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:07/Issue:02/February-2025 Impact Factor- 8.187 www.irjmets.com

2. Comparison of safety factors and Inverse reverse factor:

Shown below the comparison of the safety factors of three loading condition.

1. **Safety Factor (SF):** Now let's talk about the Safety Factor. This is a simple way to see how much stronger a material is compared to what we expect it to handle. It looks at the ultimate strength versus the stress applied:

Safety Factor = (Ultimate Strength) / (Applied Stress)



Graph 5: Comparison of the safety factors

- Kevlar and T700 same performance in stress, deformation and safety factors. Both strong and resilient at high pressure.
- Boron reinforcement more deformation and strain energy, more energy absorption but less longitudinal and hoop stress.

VI. CONCLUSION

Material performance in a cylinder is analyzed using epoxy-carbon and epoxy-glass layers up to 73 MPa for good structural integrity. The Kevlar layer showed improved deformation performance at higher pressures, making it a top choice for important applications. The hoop stress was larger than the longitudinal stress, indicating the need for sufficient safety margins in the design. The material is approaching the edge of allowable limits at the maximum burst pressure of 73 MPa, indicating it is getting close to its critical stress levels. The operating and test pressure range for the cylinder is 20-30 MPa, but careful monitoring and strengthening of crucial layers should be considered when operating close to 73 MPa. The safety margins show a modest or slightly negative margin in some circumstances.

VII. REFERENCES

[1] Chen, D. H., & Fu, C. S. (2014). Safety assessment for CNG vehicle energy storage -supply system. Applied Mechanics and Materials, 668–669, 1646–1650. https://doi.org/10.4028/www.scientific.net/AMM.668-669.1646.

[2] Deymi-Dashtebayaz, M., Farzaneh-Gord, M., Nooralipoor, N., & Rastgar, S. (2014). The full simulation of rapid refueling of a Natural Gas Vehicle on-board cylinder. Journal of Natural Gas Science and Engineering, 21, 1099–1106. https://doi.org/10.1016/j.jngse.2014.11.001

[3] Deymi-Dashtebayaz, M., Gord, M. F., & Rahbari, H. R. (2012). Studying Transmission of Fuel Storage Bank to NGV Cylinder in CNG Fast Filling Station: Vol. XXXIV (Issue 4).

[4] Jeevan Kumar, B., & Madhavi, M. (2017). DESIGN AND STRUCTURAL ANALYSIS OF CNG COMPOSITE GAS CYLINDER. In ijartet.com International Journal of Advanced Research Trends in Engineering and Technology (IJARTET) (Vol. 4). www.ijartet.com

[5] Kashyzadeh, K. R., Koloor, S. S. R., Bidgoli, M. O., Petrů, M., & Asfarjani, A. A. (2021). An optimum fatigue design of polymer composite compressed natural gas tank using hybrid finite element-response surface methods. Polymers, 13(4), 1–15. https://doi.org/10.3390/polym13040483

[6] Kim, E. S., Kim, J. H., Moon, B. S., & Goh, J. M. (2012). Study on the structural safety evaluation for pressure vessel of the cng vehicle using F.E.M. Advanced Materials Research, 569, 598–602. https://doi.org/10.4028/www.scientific.net/AMR.569.598

[7] Lie, S. T., & Li, T. (2014). Failure pressure prediction of a cracked compressed natural gas (CNG) cylinder using failure assessment diagram. Journal of Natural Gas Science and Engineering, 18, 474–483. https://doi.org/10.1016/j.jngse.2014.03.021

[8] Mirzaei, M., Malekan, M., & Sheibani, E. (2013). Failure analysis and finite element simulation of deformation and fracture of an exploded CNG fuel tank. Engineering Failure Analysis, 30, 91–98. https://doi.org/10.1016/j.engfailanal.2013.01.015

[9] Rafiee, R., & Torabi, M. A. (2018). Stochastic prediction of burst pressure in composite pressure vessels. Composite Structures, 185, 573–583. https://doi.org/10.1016/j.compstruct.2017.11.068

[10] Stefana, E., Marciano, F., & Alberti, M. (2016). Qualitative risk assessment of a Dual Fuel (LNG-Diesel) system for heavy-duty trucks. Journal of Loss Prevention in the Process Industries, 39, 39–58. https://doi.org/10.1016/j.jlp.2015.11.007

[11] Stojanović, B., & Ivanović, L. (2015). APPLICATION OF ALUMINIUM HYBRID COMPOSITES IN AUTOMOTIVE INDUSTRY. Tehnicki Vjesnik, 22(1), 247–251. https://doi.org/10.17559/TV-20130905094303

[12] Tahir, M. M., Ali, M. S., Salim, M. A., Bakar, R. A., Fudhail, A. M., Hassan, M. Z., & Abdul Muhaimin, M. S. (2015). Performance analysis of a spark ignition engine using compressed natural gas (CNG) as fuel. Energy Procedia, 68, 355–362. https://doi.org/10.1016/j.egypro.2015.03.266