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Advances in Design and Fabrication of Fiber-Reinforced Polymer Composite Bottles for Aerospace Applications

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Abstract. The increasing demand for lightweight and high-performance pressure vessels in aerospace applications has prompted a shift from conventional metallic cylinders to fiber-reinforced polymer (FRP) composites. This study explores the design, development, and fabrication of FRP bottles, emphasizing the use of high-modulus, high-strength materials such as E-Glass, carbon, and Kevlar fibers, alongside epoxy resins as the matrix. The project employs Classical Lamination Theory and the Tsai-Wu first ply failure criterion to evaluate the structural integrity and safety factors of the composite bottles. Findings reveal that carbon fiber reinforcement yields the lowest weight for specified pressure and volume, while the optimal winding angle of 54-55 degrees minimizes thickness and enhances performance. Experimental validation indicates that the E-glass composite bottle requires increased thickness to meet internal pressure requirements, suggesting potential for further optimization. This research contributes to the advancement of composite materials in aerospace applications, highlighting their advantages in weight reduction, corrosion resistance, and design flexibility.

Introduction

Composite pressure vessels are important storage devices in the renewable energy sector for storing compressed natural gas (CNG) [1]. Fuel containers used in commercial and aerospace applications in the world today are manufactured from conventional monolithic materials. These metallic cylinders range from small bottles of a few centimeters in diameter to large storage tanks, which are heavy, reliable in service, and relatively low-cost. With the advancements in new technology, the need for lighter cylinders with lower losses is gaining importance, thereby resulting in the development and use of composite cylinders made of various reinforcements such as glass, carbon, or aramid fibres, with metallic or non-metallic liners.

The composite cylinders are used for a variety of applications such as traditional aerospace vessels for missiles, spacecrafts and ground support equipment function; fire extinguisher equipment cylinders, life support breathing tanks containing air or oxygen for firemen, rescue workers, miners, aircraft and undersea vehicle crew and passengers medical compressed gas cylinders, automate tanks for compressed natural gases (cars, buses, trucks, etc), industrial compressed gas cylinders, mobile refueling CNG stations, transportation of the CNG and cryogenic tanks[2-4].

Fibre-reinforced polymer composites (FRP) are a type of fibre-reinforced composite (FRC) in which the fibres (reinforcements) are dispersed in the polymer matrix that binds them together and facilitate stress transfer between the reinforcement[5-6]. Glass and carbon are the most used reinforcement fibres in composite pressure vessels[7]. Epoxies are polymeric resins exhibiting excellent dimensional stability, fatigue resistance, adhesion to reinforcements, high-temperature resistance, and low shrinkage [8-11]. In addition to low cost, the high strength-to-weight ratio makes the polymer matrix composite an ideal material for various engineering applications. Of the different fabrication techniques of PMC, filament winding (FW) emerges as an efficient, cost-effective method for fabricating axisymmetric products[12]. The foregoing paragraph emphasizes

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the need to replace the existing heavy, high-pressure gas cylinders made from steel with lightweight materials, such as polymeric composites.

Materials and Methodology

The present work concerns the design and development of FRP gas bottle to store inert gas at high pressure. A multidirectional laminate is made by stacking many laminae of 0.125 mm thick at different orientation angles and at a particular distance from the midplane in the laminate, depending on the loading conditions. The laminate code is used to designate the stacking sequence of the lamina. The program is coded in C, making use of stress and failure analysis for a general multidirectional laminate applying the first ply failure proposed by Tsai-Wu. The FRP composite pressure vessel is designed using the classical lamination theory. The pressure on the walls of the gas bottle is calculated from the pressure acting internally and the internal diameter of the gas bottle. The unit load acting on the elements of the cylindrical shell along the axial and the hoop direction is then calculated. The bottle is assumed to be cylindrically orthotropic. Of the different types of architecture available, the cross-ply $[0_m / 90_n]s$, angle ply $[\pm\theta]_{ns}$, and $[90_m/\pm\theta_n]_s$ laminates have been considered for the present investigation. In $[0_m / 90_n]s$ laminates, the choice of m & n for the optimum weight has been reached by trying different values of m & n around the initial guesses until the sum (m + n) is minimized. $[\pm\theta]_{ns}$ and $[90_m/\pm\theta_n]$ laminate involve only one variable θ for optimization. The safety factors are computed for the basic laminate for three different materials and the unit thickness h_0= 6t. The weight of the bottle is computed from the density and volume using the equation

$$Weight = 2\pi rl\rho t \quad (1)$$

Where p =pressure, r= radius of the pressure vessel, l = length of the glass bottle, ρ = Density of the material used, t is the thickness of the laminate. The stiffness matrix, laminate stress, and safety factor are obtained using the program.

The glass bottles are fabricated using a three-axis filament winding machine. 2 bottles are fabricated, one with an aluminum liner and E-glass fiber reinforcement, and the other with a polypropylene liner and carbon as the reinforcement. 10 creels were employed to carry out the winding at $\pm$54°. After preliminary checks of fiber tension and winding angle, the winding was completed in 2 hours. The bottle was then cured in the oven at 120°C for about 2 hours, and an additional layer of 2 mm was added to protect the bottle against damage during handling. The cured bottle was taken out and cooled to room temperature. The irregularities were removed using the Emery paper.

The dimensions of the bottles are checked along with visual examination for any defects such as air pockets, misalignment, dry patches, etc. The bottle is subjected to internal pressures of 125, 199, and 375 bars in steps. Strain measurements are carried out at 3 pressures using foil-type rosette gauges, mounted at different locations on the bottle as shown in Fig.1.

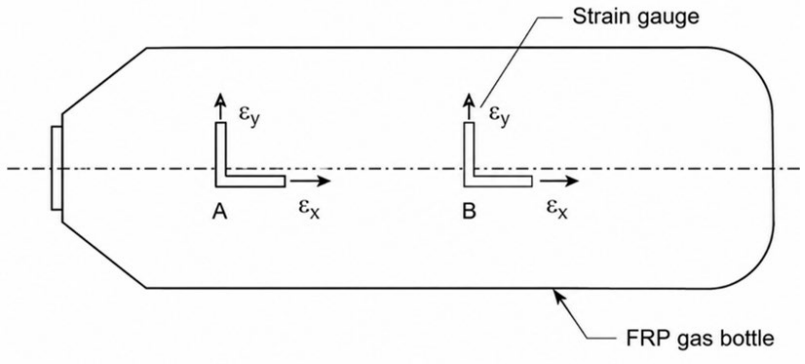


Fig.1. Strain gauge location on the FRP glass bottle

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Results and discussion

The output of the developed program and the comparison with the published results [13] are presented in Table 1.

Table1: Comparison of the program results with published results

Properties	Computer Program Results			Published Results		
Laminate Strains × 10^{-3}	ε_x^0	ε_y^0	ε_{xy}^0	ε_x^0	ε_y^0	ε_{xy}^0
	1.622	0.692	1.845	1.62	0.69	1.85
Safety Factor of Each Ply	0°	90°	45°	0°	90°	45°
	2.424165	1.928621	1.784678	2.42	1.93	1.79
On-axis Strain of i-th Ply	$\varepsilon_1 \times 10^{-3}$	$\varepsilon_2 \times 10^{-3}$	$\varepsilon_{12} \times 10^{-3}$	$\varepsilon_1 \times 10^{-3}$	$\varepsilon_2 \times 10^{-3}$	$\varepsilon_{12} \times 10^{-3}$
for θ = 0°	1.622	0.6924	-1.845	1.62	0.69	-1.85
for θ = 90°	0.692	1.622	1.845	0.69	1.62	1.85
for θ = 45°	0.234	2.080	-0.93	0.24	2.08	-0.93
On-axis Stress of the i-th Ply	σ_1 (MPa)	σ_2 (MPa)	σ_{12} (MPa)	σ_1 (MPa)	σ_2 (MPa)	σ_{12} (MPa)
for θ = 0°	296.99	11.86	-13.23	297	12	-13
for θ = 90°	130.59	18.79	13.23	131	19	13
for θ = 45°	48.67	22.20	-6.68	49	22	-7
Off-axis Ply Stress	σ_x (MPa)	σ_y (MPa)	σ_{xy} (MPa)	σ_x (MPa)	σ_y (MPa)	σ_{xy} (MPa)
for θ = 0°	296.99	11.86	-13.23	297	12	-13
for θ = 90°	18.792	130.59	-13.23	19	131	-13
for θ = 45°	42.10	28.76	13.23	42	29	13

The result shows the accuracy of the programme. The gas bottle designs were carried out using 3 different architectures along with 3 different reinforcements. Process optimization for the layout has been carried out by using the program. The allowable laminate thickness is determined and plotted against the lamination angle. It was found that the optimum angle θ corresponding to the minimum thickness of the fiber considered lies in the range between 54° to 55° has shown in Fig.2. The weight of the bottle, computed from the density and the volume, is represented in Table2.

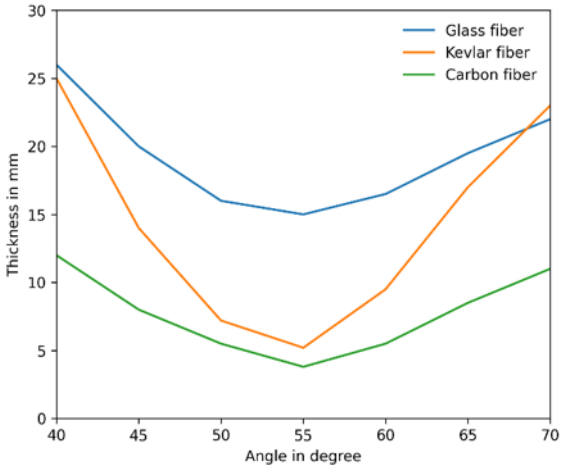


Fig.2. Effect of lamination angle on allowable thickness in a pressure vessel

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Table 2: Comparison of Weight for the different fibres

Material	Lay-Up	Weight [kg]	Safety Factor at Working Pressure
E-glass/Epoxy	[±54]30s	6.679	3.089989
	$[90_{40}/\pm54_{20}]s$	8.906	3.015241
	$[O_{27}/90_{54}]s$	9.017	3.109375
Carbon/Epoxy	[±54]7s	1.191	2.783114
	$[90_8/\pm54_8]s$	2.042	2.795794
	$[O_6/90_{12}]s$	1.531	3.204707
Kevlar/Epoxy	[±54]9s	1.337	3.217912
	$[90_{13}/\pm54_{13}]s$	2.898	2.981206
	$[O_7/90_{14}]s$	1.56	3.048108

Strains measured at location B are shown in Table 3 and Table 4. The values of strain in the axial and hoop directions have been plotted against the internal pressure. It is observed that the measured hoop strains are lower than the calculated values, and hence the failure of fiber in the hoop direction is ruled out.

At proof pressure of 199 bar, the micro strain developed is 1810 against 1516. This indicates the failure of the bottle in the axial direction, which is confirmed by the leak observed during the test. Therefore, the bottle should be wound with more number of layers of the E glass fiber.

In the case of the carbon epoxy bottle, the experimental values of strains are less than the calculated values at any specified pressure. This indicates that the bottle is safe until a pressure of 130 bar. It is also confirmed by the fact that no leak was observed during the testing.

Table3: Strain and Safety Factor for Polypropylene-Lined Carbon/Epoxy Composite Bottle $[\mathbf{90_8/\pm54_{10}}]_s$

Pressure [bar]	Strain [μm/m]	Predicted	Experimental	Factor of Safety	Remarks
100	ε_x	845.77	789	6.991	No leak
	ε_y	463.46	455		
130	ε_x	1099.50	924	5.37	No leak
	ε_y	602.505	577		
375	ε_x	3171.646	Test could not be conducted due to lack of facility	1.8644	—
	ε_y	1737.995			

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Table 4: Strain and Safety Factor for Aluminium-Lined E-glass/Epoxy Composite Bottle $[\pm 54_{20}]_s$

Pressure [bar]	Strain [µm/m]	Predicted	Experimental	Factor of Safety	Remarks
Working, 125	ε_x	952.4165	1010	2.059991	No failure
	ε_y	3361.489	2150		
Proof, 199	ε_x	1516.247	1810	1.293965	Leakage observed after 10 min
	ε_y	5351.490	3920		
Burst, 375	ε_x	2857.247	Could not be measured; test terminated at 199 bar	0.686639	Nil
	ε_y	952.4165			

Conclusions

Carbon fibre reinforced polymer (CFRP) gas bottles exhibited the lowest weight among the E-glass, carbon, and aramid reinforced composite designs for the same pressure and storage volume requirements. Carbon/epoxy composite bottles fabricated using a high-temperature-grade epoxy resin required a relatively low wall thickness ranging from 3.1 mm to 6.1 mm, depending on the laminate configuration. Among the laminate architectures investigated, the angle-ply layup ([±54°]) resulted in the minimum bottle weight while satisfying the structural design requirements. Fibre winding angles in the range of 54°–55° provided the most efficient load-carrying capability, leading to the minimum required laminate thickness irrespective of the fibre type. The E-glass composite bottle with a 10 mm wall thickness was found to be inadequate for meeting the specified internal pressure requirements. To satisfy the pressure design criteria, the E-glass composite bottle thickness had to be increased to approximately 15 mm through the addition of extra ±54° winding layers. The study demonstrates that carbon fibre reinforced composite pressure vessels offer superior structural efficiency and significant weight savings compared with E-glass and aramid counterparts. The lightweight characteristics of CFRP pressure vessels make them highly suitable for aerospace applications, where weight reduction directly contributes to improved payload capacity, flight endurance, and mission performance.

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