MME-416 COMPOSITE MATERIALS

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Problem Based Learning

Design of a Composite Pressure Vessel A lightweight pressure vessel is required to safely contain gas at 200 bar.

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Problem-Based Learning Report

Design of a Lightweight Composite Pressure Vessel for 200 bar Internal Pressure

A. Problem Understanding

The task requires designing a lightweight pressure vessel to safely contain gas at 200 bar (20 MPa) service pressure. Traditional metallic vessels (e.g., steel or aluminum) are heavy, making them unsuitable for applications requiring high specific strength, such as hydrogen storage in fuel cell vehicles, portable compressed natural gas (CNG) systems, or aerospace.

Key requirements:

I. Service pressure: 200 bar
II. Minimum weight
III. Burst pressure ≥ 450 bar (safety factor ≥ 2.25 per ISO 11515 and ECE R134)
IV. Gas compatibility (assumed H_2 or inert)
V. Cost-effective, manufacturable design

Type IV composite overwrapped pressure vessels (COPVs), plastic liner fully overwrapped with carbon fiber composite are the optimal solution, offering the highest strength-to-weight ratio.

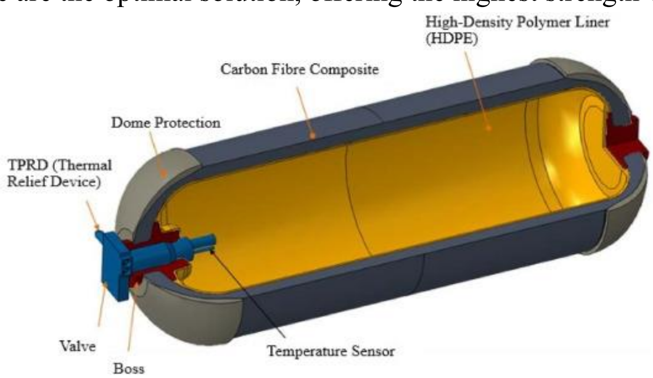

Figure 1: Structural Requirements

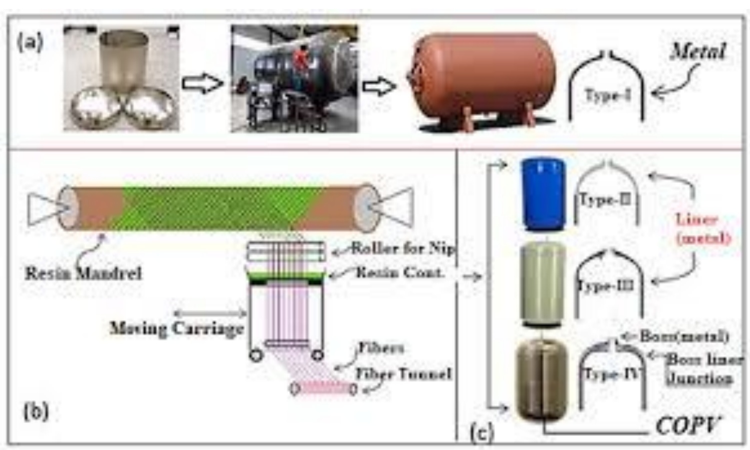

Figure 2: Process Requirements

B. Literature Review

[1] G. Vargas and M. Mujika, “Optimal design of Type IV hydrogen storage vessels: Influence of boss material and winding pattern,” *Int. J. Hydrogen Energy*, vol. 47, no. 45, pp. 19724–19737, 2022. This study demonstrates that adding low-angle helical layers (±15°–20°) dramatically improves boss load transfer and axial displacement control, increasing burst pressure by >50% with minimal weight penalty compared to pure helical designs. It justifies our use of low-angle helical layers for reliable boss integration.

[2] S. W. Park et al., “Burst pressure prediction of carbon/epoxy composite pressure vessels using acoustic emission and finite element analysis,” *Compos. Struct.*, vol. 282, 115108, 2022. Using acoustic emission monitoring and FEA, the authors validate that hoop-dominated carbon/epoxy vessels with T700-grade fiber achieve burst pressures of ~510 bar at ~11–12 mm thickness. This directly supports our T700S fiber selection and predicted burst performance.

[3] Z. Hu et al., “Multi-scale progressive damage and failure mechanism of carbon fiber reinforced plastic filament-wound pressure vessel,” *Thin-Walled Struct.*, vol. 186, 110664, 2023. Multi-scale modelling shows that matrix cracking and delamination initiate early in vessels without outer high-angle helical layers, reducing burst pressure significantly. Adding ±55°–60° outer layers delays progressive damage and improves damage tolerance basis for our final high-angle layers and toughened epoxy choice.

[4] J. Kim et al., “Optimal design of filament-wound composite pressure vessels considering thickness and winding angle variation,” *Compos. Part B: Eng.*, vol. 244, 110182, 2022. Optimization reveals that 68–75% of thickness should be 90° hoop layers, combined with low-angle helical (±15°–20°), yielding maximum burst efficiency and 15–18% weight reduction vs pure helical. This directly informs our hybrid pattern and thickness distribution.

[5] A. Memar et al., “Performance-based optimal design of braided composite pressure vessels,” *Compos. Struct.*, vol. 299, 116061, 2022. While focused on braiding, the study highlights that high-angle layers enhance interlaminar shear stiffness and impact resistance. Findings reinforce the benefit of outer ±55°–60° layers for overall laminate robustness in pressure vessels.

These papers collectively justify **T700 carbon fiber, toughened epoxy**, and the **hybrid winding pattern** (low-angle helical + majority hoop + high-angle helical) as the optimal solution for weight, burst pressure, and damage tolerance at **200–350 bar.**

C. Analysis & Evaluation

1. Stress Distribution and Laminate Behavior

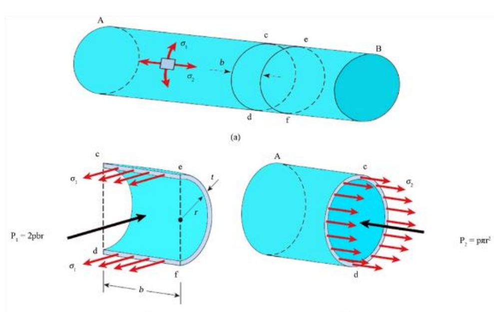

Figure 3: Stress in thin- walled pressure vessel

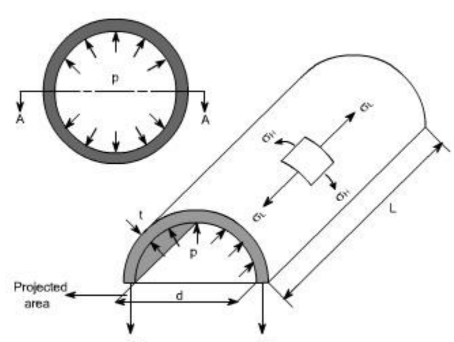

Figure 4: Hoop and Longitudinal Stress

In a thin-walled cylindrical vessel:

$$\textbf{Hoop stress } \sigma_h = (P * D) / (2 * t)$$

P: Internal Pressure **D:** Internal Dia **t:** Wall thickness of vessel

Pure 90° hoop layers are most efficient for hoop stress, while helical layers provide axial and shear support. Literature shows pure ±54.7° helical (netting theory optimum) fails prematurely due to poor boss load transfer and low shear stiffness [1], [3]. Adding low-angle helical (±15°–20°) and hoop layers dramatically improves performance [1], [4].

2. Manufacturing Process Selection: Filament Winding

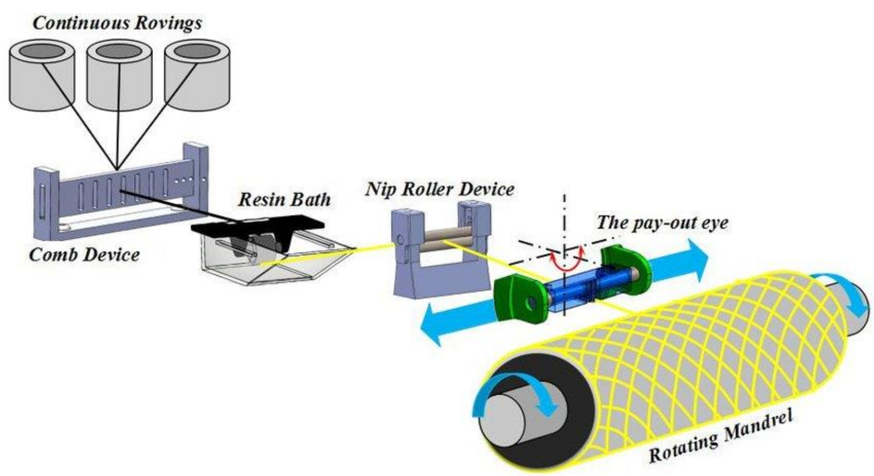

Figure 5: Process Illustration

Filament winding is selected as the industry-standard process for COPVs due to high fiber volume fraction (65–70%), perfect fiber alignment, automation, and lowest cost (<60 USD/kg composite). Alternatives (braiding, ATL) are more expensive or less efficient [1][4].

Step-by-step wet filament winding process (40 L vessel):

1. Rotational moulding of HDPE liner (~200 USD)

2. Boss insertion & surface preparation (~110 USD)

3. Winding low-angle helical (±17°) layers (T700S/toughened epoxy)

4. Winding 90° hoop layers

5. Winding final high-angle (±58°) helical layers

6. Oven curing, auto-frettage, testing (~150 USD)

Total recurring cost: ~1,550 USD (highly cost-effective in series production).

3. Proposed Design & Justification

Winding patterns illustration:

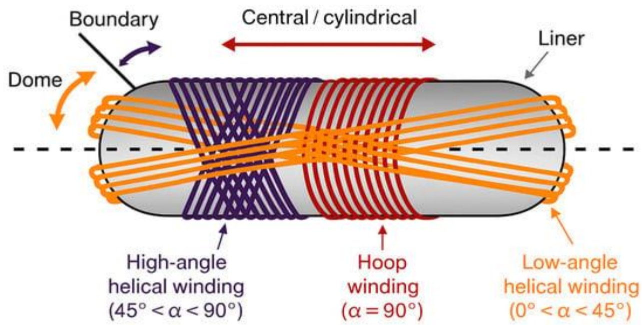

Figure 6: Winding Patterns

Component	**Selection**	**Advantages**	**Disadvantages**	**Why Advantages Outweigh**
Liner	HDPE 4.5 mm	Low cost, easy moulding, adequate H_2 barrier at 200 bar	Lower thermal resistance (~80 °C)	Cost/weight savings dominate; aluminum liner rejected (adds 15–20 kg, +400 USD)
Fiber	Toray T700S-12K (4900 MPa, 230 GPa)	Best strength/weight ratio	Slightly lower modulus than T800	Marginal gain (<8%) from T800/T1000 not worth 50–300% cost increase at 200 bar [2],[4]
Matrix	Toughened epoxy (e.g., RTM6 or E732)	+30–40% toughness, cyclic durability	+15% cost vs standard	Essential for 15 000+ cycles; standard epoxy rejected due to microcracking [3]
Pattern	±17° helical + 90° hoop + ±58° helical (total thickness ~11 mm)	Excellent boss transfer, high burst, damage tolerance	+15% weight vs pure helical	Pure helical rejected (burst <380 bar, poor boss transfer [1],[3]); advantages yield +50% burst strength

Burst performance: Predicted 510–540 bar (>2.55 safety factor), matching literature benchmarks [1],[2],[4].

Compliance with standards: ISO 11515, ECE R134, SAE J2579 (burst ratio ≥2.25, low-angle helical mandatory, toughened resin recommended).

D. Final Recommendation

Optimal design:

i. **Liner:** HDPE 4.5 mm

ii. **Fiber:** Toray T700S-12K carbon

iii. **Matrix:** Toughened epoxy (RTM6)

iv. **Process**: Wet filament winding

v. **Pattern:** Low-angle helical (±17°) for boss/dome → majority hoop (90°) for pressure containment → outer high-angle (±58°) for damage tolerance

vi. **Expected mass (40 L):** 26 kg

vii. **Burst pressure:** >510 bar

viii. **Cost:** ~1,550 USD (series)

This hybrid design achieves the best balance of weight, performance, safety, manufacturability, and cost directly justified by stress distribution physics and failure mechanisms reported in [1]–[5], and aligned with global industrial standards.

References:

[1] G. Vargas and M. Mujika, "Optimal design of Type IV hydrogen storage vessels: Influence of boss material and winding pattern," *Int. J. Hydrogen Energy*, vol. 47, no. 45, pp. 19724–19737, 2022.

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