Winding Design and Strength Analysis of a Type IV Hydrogen Storage Cylinder Based on Abaqus WCM

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Abstract

This study addresses the composite overwrap design and strength verification of a 70 MPa Type IV high-pressure hydrogen storage cylinder using Abaqus with the WCM plug-in. Based on netting theory, the helical winding angle on the dome and the helical and hoop thicknesses in the cylindrical section are determined. A stepwise polar-opening enlargement strategy combined with cubic spline interpolation is used to optimize the dome fiber-thickness distribution and define a multi-angle layup. The cylinder consists of a PA6 liner, a T700-24K carbon-fiber/epoxy overwrap, and metal bosses. Axial and circumferential symmetries are used to construct a three-dimensional sector model with tie constraints and internal-pressure loading. The results show that polar-opening enlargement markedly mitigates fiber accumulation and reduces the peak dome-overwrap thickness by approximately 24.1 mm. At 70 MPa, the maximum fiber-direction tensile stresses in the cylindrical and dome sections are 995.8 and 559.4 MPa, respectively, both below the allowable tensile strength of 2031 MPa. The proposed layup therefore satisfies the preliminary strength requirement at the rated working pressure and provides a numerical basis for subsequent experimental validation.

Keywords

Finite element analysis; filament winding; strength analysis; Type IV hydrogen storage cylinder.

1. INTRODUCTION

Hydrogen energy is a key energy vector for the global transition toward low-carbon energy systems. In recent years, more than 60 countries and regions have released hydrogen-energy development strategies and promoted diversified applications. By the end of 2024, global hydrogen production and consumption had reached approximately 105 million metric tons [1]. Because hydrogen has a low density and is highly flammable and explosive, safe storage is a fundamental requirement for large-scale application. Hydrogen storage cylinders are core components in storage, transportation, and onboard fuel-supply systems; their material properties, structural strength, and connection reliability directly affect the safety of refueling, transport, and end use.

A Type IV hydrogen storage cylinder consists of a polymer liner, metal bosses, and a composite overwrap. Compared with cylinders using metallic liners, most of the pressure load is carried by the carbon-fiber composite, enabling high-pressure hydrogen storage at a relatively low structural mass. However, fiber steering in the dome, tow convergence near the polar opening, and the ratio between helical and hoop plies in the cylindrical section strongly influence structural efficiency. Consequently, the winding path, winding angle, laminate thickness, and control of local fiber accumulation are key design issues for Type IV cylinders.

Finite element analysis is widely used to evaluate stress distributions and laminate responses before prototype fabrication. Wu [2] numerically investigated the strength and process effects

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of fiber-reinforced thermoplastic containers. Li [3] combined winding-path design with Abaqus analysis to determine process parameters for hydrogen cylinders. Hu et al. [4] performed strength analysis and burst testing of a 70 MPa Type IV cylinder with non-geodesic winding and showed that the winding angle significantly affects the load-carrying capacity of the cylindrical section. Sharma et al. [5] validated a design method for Type-4 composite pressure vessels using experimental burst pressure. Wang et al. [6] and Chen [7] further investigated fiber-thickness prediction and structural design of composite hydrogen storage vessels.

In this study, Abaqus WCM is used as the main analysis platform. Netting theory, cylindrical-section thickness calculations, cubic-spline prediction of dome thickness, and a polar-opening enlargement strategy are combined to define the winding layup. A finite element sector model of the Type IV hydrogen storage cylinder is then established and evaluated at the rated working pressure. The analysis focuses on winding-angle and thickness determination, mitigation of local fiber accumulation in the dome, sector-model construction, and evaluation of fiber-direction stress.

2. WINDING ANGLE AND THICKNESS DESIGN

2.1. Calculation of the Winding Angle

An ellipsoidal dome is adopted for the cylinder. According to netting theory, the stable path of a helical fiber on the dome is related to the polar-opening radius. The winding angle at an arbitrary parallel circle on the dome can be expressed as Eq. (1):

$$\sin\alpha = \frac{r_0}{r} \tag{1}$$

where α is the local helical winding angle on the dome, r_0 is the polar-opening radius, and r is the radius of an arbitrary parallel circle in the dome region. As the fiber path transitions from the polar opening toward the dome equator, r increases and the winding angle varies continuously. When r = R, the helical winding angle α_0 in the cylindrical section is obtained. For the geometry considered here, α_0 = 20.5°. This value is used as the reference angle for subsequent thickness calculations and the allocation of enlarged polar-opening winding angles.

2.2. Winding Thickness in the Cylindrical Section

The cylindrical section uses a combination of helical and hoop winding. Based on the load-sharing relationship of the fibers, the required helical and hoop thicknesses are calculated from Eqs. (2) and (3), respectively:

$$t_{f\alpha} = \frac{Rp_b}{2k\sigma_{fb}\cos^2\alpha} \tag{2}$$

$$t_{f\theta} = \frac{Rp_b(2-\tan^2\alpha)}{2\sigma_{fb}} \tag{3}$$

where p_b is the minimum design burst pressure, k is the fiber strength utilization coefficient, taken as 0.8, and σ_fb is the effective fiber strength. Using the specified design parameters, the calculated helical and hoop winding thicknesses in the cylindrical section are 3.917 mm and 3.846 mm, respectively. Conversion using the single-ply thickness gives theoretical ply counts of approximately 25.639 and 25.172. Considering a fiber volume fraction of 0.6 and the practical requirement for paired winding plies, the final design uses 26 helical plies and 24 hoop plies.

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2.3. Dome-Thickness Prediction and Polar-Opening Enlargement

The fibers transition continuously from the polar opening to the cylindrical section. Geometric convergence causes repeated tow coverage and a rapid increase in thickness near the opening. To describe the thickness variation within a range of two tow-band widths, cubic spline interpolation is applied to discrete winding positions. Its basic form is given by Eq. (4):

$$t(r_i) = m_1 r_i^0 + m_2 r_i^1 + m_3 r_i^2 + m_4 r_i^3 \tag{4}$$

where m_1-m_4 are determined from the thickness and continuity conditions at the polar opening, one-band-width position, and two-band-width position. Outside the two-band-width region, the thickness is smoothly transitioned toward the dome equator according to the geometric relationship. Compared with direct superposition based on an ideal geodesic path, the cubic-spline method provides a more continuous description of dome-thickness variation [6] and is therefore suitable for comparing the effects of different polar-opening enlargement schemes on local fiber accumulation.

After comparing enlargement distances of 0.5, 1.0, 1.5, and 2.0 times the tow-band width, a stepwise enlargement of 1.5 times the band width is adopted. The 26 helical plies are allocated to four winding-angle groups of 20.5°, 26.1°, 32.0°, and 38.3°, and are combined with 24 hoop plies at 90°. The principal winding configuration is summarized in Table 1.

Table 1. Principal winding configuration after polar-opening enlargement

Winding angle / °	Number of plies
20.5	18
26.1	2
32.0	2
38.3	4
90	24

3. FINITE ELEMENT MODELING AND ANALYSIS SETUP

3.1. Computational Model

The rated working pressure of the hydrogen storage cylinder is 70 MPa. The cylindrical section of the liner has a diameter of 200 mm and a length of 700 mm, and the polar-opening diameter of the dome is 35 mm. The main structural components are the metal bosses, polymer liner, cylindrical section, and domes, as shown in Figure 1. The geometry is axisymmetric, which provides the basis for constructing a sector finite element model.

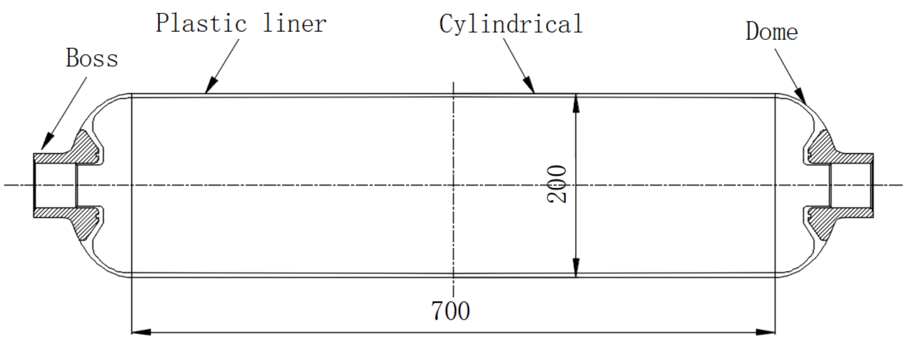

Figure 1. Structural model of the Type IV hydrogen storage cylinder

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3.2. Material Properties

The composite overwrap carries most of the internal-pressure load; therefore, its material properties have a decisive influence on the strength response. T700-24K carbon-fiber/epoxy is used for the overwrap. The prepreg has a density of approximately 1.8 g/cm^3 and a linear density of 1.65 g/m. The effective fiber strength is 3385 MPa, the fiber volume fraction is 60%, the single-ply thickness t_p is 0.255 mm, the spread-tow width is 6 mm, and the total winding-band width is 24 mm. Orthotropic material properties are used in the finite element model, with the main mechanical parameters listed in Table 2.

Table 2. Main mechanical properties of T700 carbon-fiber/epoxy composite

Parameter	Value
E_{11} / GPa	134
$E_{22} = E_{33}$ / GPa	7.42
$G_{12} = G_{23}$ / GPa	3.71
G_{13} / GPa	4.79
ν_{12} / ν_{13} / ν_{23}	0.28 / 0.30 / 0.28
X_t / MPa	2031
X_c / MPa	1250
Y_t = Z_t / MPa	74
Y_c = Z_c / MPa	180
S_{12} / $S_{13} = S_{23}$ / MPa	50 / 90

PA6 is used for the liner. The metal bosses are modeled as an aluminum alloy with a density of 2700 kg/m^3, an elastic modulus of 69 GPa, a Poisson ratio of 0.33, and a yield strength of 0.18 GPa. Because the present study focuses on the fiber-direction stress in the carbon-fiber overwrap, the liner and boss properties are mainly included to represent the overall load-transfer path and the mechanical constraints between components.

3.3. Boundary Conditions and Loading

Because the cylinder geometry, laminate arrangement, and internal-pressure loading are symmetric, a reduced model is used to decrease computational cost. One half of the cylinder is retained in the axial direction, including one dome and the corresponding cylindrical section. In the circumferential direction, 1/36 of the full circumference is modeled, corresponding to a 10° sector. Appropriate axial and circumferential symmetry conditions are imposed on the sector boundaries so that the reduced model reproduces the global mechanical response of the complete cylinder.

Before burst failure, no relative sliding is assumed between the polymer liner and the carbon-fiber overwrap. Tie constraints are therefore assigned to the liner-boss, liner-overwrap, and boss-overwrap interfaces. Following the pressure-loading approach referenced to ISO 11439, internal pressure is progressively applied to the inner surface of the liner, with the numerical loading path extending to 180 MPa. The strength assessment reported here is based primarily on the stress response at the rated working pressure of 70 MPa. The boundary conditions and constraints are illustrated in Figure 2.

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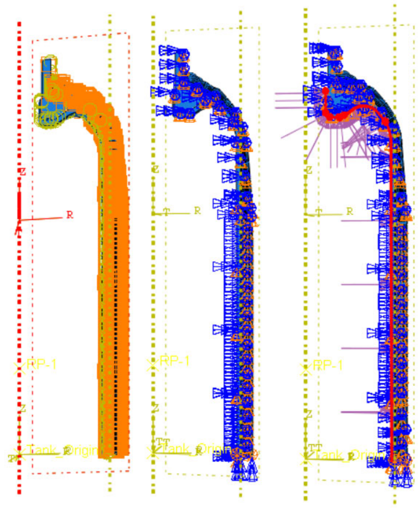

Figure 2. Boundary conditions and constraints of the sector model

4. RESULTS AND DISCUSSION

4.1. Dome-Thickness Distribution

Cubic spline interpolation is used to predict the dome-overwrap thickness before and after polar-opening enlargement. Figure 3 compares the initial polar-opening scheme with the scheme using an enlargement distance of 1.5 times the tow-band width. The initial configuration exhibits a pronounced thickness peak near the polar opening, indicating severe fiber convergence in the small-radius region. After enlargement, the peak is markedly reduced and the thickness gradually transitions toward the cylindrical-section value through the middle of the dome.

The predicted peak thickness of the dome overwrap is reduced by approximately 24.1 mm after polar-opening enlargement. This result indicates that progressively increasing the effective winding angle near the polar opening disperses local tow coverage, produces a more uniform material distribution, and reduces unnecessary thickness accumulation. Because the dome relies mainly on helical fibers to carry the pressure load, a smoother thickness distribution can also help reduce abrupt changes in local stiffness.

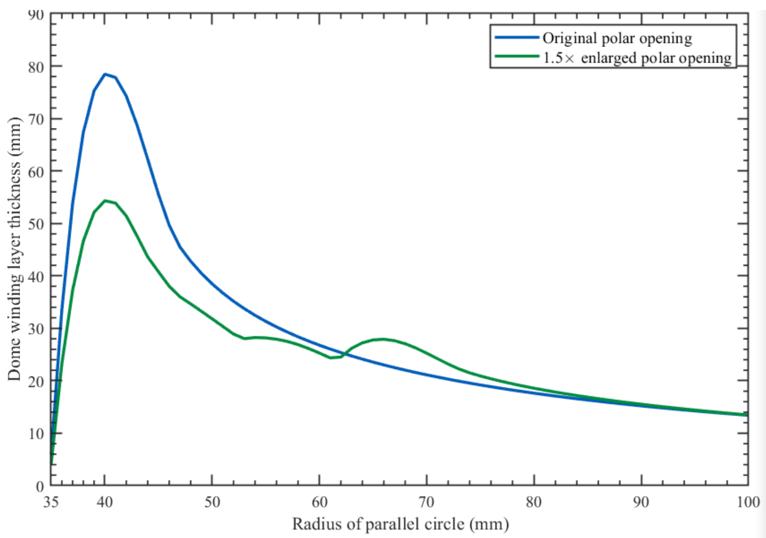

Figure 3. Comparison of dome-overwrap thickness before and after polar-opening enlargement

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4.2. Strength Verification at 70 MPa

At the working pressure of 70 MPa, the cylindrical section is loaded jointly by hoop and helical plies. Because internal pressure generates a relatively high circumferential membrane stress, the hoop plies carry the major portion of the load, while the helical plies also contribute to axial load transfer. The dome has no independent hoop-wound layer and therefore relies primarily on helical fibers at different angles to transfer the internal-pressure load. Consequently, the fiber-direction stress is nonuniform over the dome surface.

The maximum fiber-direction tensile stresses are listed in Table 3. The maximum values are 995.8 MPa in the cylindrical section and 559.4 MPa in the dome, both below the allowable fiber-direction tensile strength of 2031 MPa for the T700/epoxy composite. These values correspond to approximately 49.0% and 27.5% of the allowable strength, respectively. The higher stress occurs in the cylindrical section, which is consistent with the dominant role of the hoop plies in carrying the internal-pressure load.

Table 3. Fiber-direction stress verification at 70 MPa

Region	Calculated / MPa	Allowable / MPa
Cylindrical section	995.8	2031
Dome	559.4	2031

The present strength evaluation is limited to 70 MPa. Although the numerical loading path extends to 180 MPa, complete failure evolution, criterion-based failure pressure, and experimental validation are not available; therefore, no ultimate burst pressure is inferred. Engineering qualification should further consider composite failure, interlaminar damage, liner plasticity, and full-scale burst and pressure-cycle tests.

5. CONCLUSION

Abaqus WCM was used to develop the winding layup, optimize dome thickness, and assess the working-pressure strength of a 70 MPa Type IV hydrogen storage cylinder. The main conclusions are as follows:

(1) Netting theory gives a cylindrical-section helical winding angle of 20.5°. The final design uses 26 helical plies and 24 hoop plies; stepwise polar-opening enlargement distributes the helical plies among 20.5°, 26.1°, 32.0°, and 38.3° and improves fiber placement near the polar opening.

(2) Cubic-spline prediction shows that polar-opening enlargement reduces the peak dome-overwrap thickness by approximately 24.1 mm and produces a smoother thickness transition toward the cylindrical section.

(3) At 70 MPa, the maximum fiber-direction tensile stresses are 995.8 MPa in the cylindrical section and 559.4 MPa in the dome, both below the allowable tensile strength of 2031 MPa. The proposed layup therefore satisfies the preliminary strength requirement at the rated working pressure.

Further validation should include composite progressive-damage analysis together with full-scale burst, pressure-cycle, and manufacturing-deviation tests.

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