Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 21, No. 2, 2026

Winding Parameter Optimization and Static Strength Analysis of Type IV Hydrogen Storage Cylinders Based on Abaqus-WCM

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Abstract: This study focuses on a 70 MPa Type IV hydrogen storage cylinder and investigates optimization of the fiber-winding process and static-strength behavior through finite element simulation. Based on composite laminate design theory, the thickness distribution of the winding layer in the dome region was predicted. A finite element model consisting of a plastic liner, a metal boss, a carbon-fiber winding layer, and a glass-fiber protective layer was established. The stress distribution of each component under the rated high-pressure condition was systematically analyzed. The results show that the components exhibit good cooperative load-bearing behavior. The stress of the metal boss basically satisfies the strength requirement, and the composite winding layer demonstrates favorable load-bearing capacity.

Keywords: Type IV hydrogen storage cylinder; fiber winding; static strength analysis.

1. Introduction

The world is at an important turning point in the energy transition. In this process, hydrogen is widely regarded as a key energy carrier for achieving the goal of net-zero emissions by 2050 [1].

The development of high-pressure gaseous hydrogen storage cylinders has evolved from all-metal structures to all-composite structures. Each generational transition has been accompanied by reductions in material weight and substantial increases in hydrogen storage density. Hydrogen storage cylinders have progressed from the original all-metal Type I cylinders to all-composite Type IV cylinders [2].

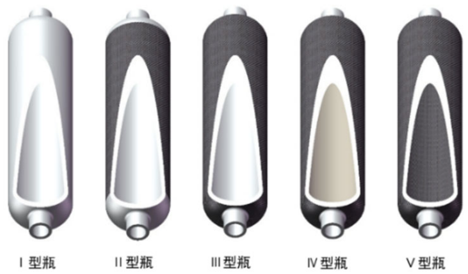

Figure 1. Structural forms and development of Type I to Type V hydrogen storage cylinders

Although Type IV cylinders offer significant advantages, their structural characteristics also impose very high requirements on the manufacturing process. Compared with metal liners, plastic liners have a very low elastic modulus. During carbon-fiber winding, the high winding tension can easily cause liner instability and collapse [3]. Therefore, finite element analysis, especially when combined with Dassault Systemes Wound Composite Modeler (WCM), can be used to perform full-process simulation analysis of hydrogen storage cylinders [4].

2. Main Research Content

Taking a 70 MPa Type IV hydrogen storage cylinder as the research object, this study carries out structural design and simulation-based evaluation on a theoretical basis. The preliminary design of the plastic liner is first completed according to pressure-vessel design theory. The number of winding layers is then calculated, and the winding-layer design of the hydrogen storage cylinder is completed. Based on netting theory, the design calculation of the cylinder winding layer is carried out, and a wound cylinder model is established using the WCM plug-in on the Abaqus platform.

3. Theoretical Basis and Simulation Software

3.1. Basic Theory of Filament-Wound Composite Materials

The filament-winding pattern reflects the placement path of the fiber tow on the mandrel surface and the variation characteristics of the winding angle along the axial position. It not only affects the thickness distribution and load-bearing performance of the composite layer, but also determines the speed-matching relationship among the motion axes of the winding equipment. Therefore, pattern design is an important link between the layup design of hydrogen storage cylinders and the motion control of winding equipment.

For Type IV hydrogen storage cylinders, the geometric curvature of the cylindrical body remains constant, and fibers can generally be laid at an approximately constant winding angle. The dome section is a surface of revolution with continuously varying curvature. When the fiber tow moves in this region, the local winding angle and trajectory curvature vary with the axial position. To avoid fiber slippage, bridging, and local accumulation, the dome winding pattern should also satisfy process requirements such as continuous coverage and stable conformity.

On this basis, this paper starts from the kinematic relationship of filament winding, analyzes geodesic and non-geodesic trajectories, and further establishes criteria for stable fiber placement. This provides a theoretical basis for subsequent winding trajectory planning, process-parameter determination, and equipment motion debugging.

3.2. Preliminary Layup Design Method Based on Netting Theory

Netting theory is a simplified analysis method commonly used in the design of winding layers for composite pressure vessels. This theory equivalently treats the filament-wound layer as a spatial load-bearing network composed of continuous fiber tows. It assumes that the main hoop and axial loads generated by internal pressure are carried by the reinforcing fibers, while the resin matrix mainly bonds the fibers, transfers shear, maintains the fiber position, and ensures integral structural forming. Therefore, in preliminary strength design and layup-parameter calculation, the direct load-bearing contribution of the resin matrix along the fiber direction is usually treated as a secondary factor [5].

However, the reliability of Type IV hydrogen storage cylinders is also affected by liner material behavior, forming quality, and manufacturing defects. Previous studies have shown that the hydrogen permeability and aging behavior of PA6 liner materials influence the long-term sealing reliability of Type IV cylinders [6], while liner welding quality and plastic-liner failure mechanisms are closely related to local deformation, leakage, and interface integrity [7,8]. In addition, composite material selection, preparation process, and defect-induced instability should be considered when evaluating the strength and stability of Type IV cylinders [9,10].

According to the basic idea of netting theory, the design of composite winding layers is usually based on the following two assumptions:

(1) Balanced deformation assumption. Under internal pressure, the fiber network deforms compatibly, and fibers in different directions participate in load bearing according to their placement angles. This allows the fiber strength to be used more fully and keeps the overall structure in a relatively balanced stress state.

(2) Continuous conformity assumption. Before structural failure occurs, the fiber tow maintains continuous contact with the geometric surface of the liner or mandrel. The fiber trajectory remains stably attached to the structural surface without obvious slippage, bridging, or local separation. For a thin-walled cylindrical section (t/R << 1) subjected mainly to internal pressure, membrane theory can be used to obtain the membrane force per unit length of the body section, as shown in Eqs. (1) and (2).

$$N_z = \frac{1}{2} p_b R \tag{1}$$

$$N_\theta = p_b R \tag{2}$$

Considering the typical combination of helical winding and hoop winding in the cylindrical section, static equilibrium is performed on the netting element to obtain the basic relationships of netting theory, as shown in Eqs. (3) and (4).

$$\sigma_{f\alpha} h_{f\alpha} \cos^2 \alpha = \frac{Rp_b}{2} \tag{3}$$

$$\sigma_{f\alpha} h_{f\alpha} \sin^2 \alpha + \sigma_{f\theta} h_{f\theta} = Rp_b \tag{4}$$

When R, p_b, alpha, and the corresponding allowable fiber stresses are given, the equivalent thicknesses of the helical and hoop winding layers can be obtained.

3.3. Layup Design of the Cylindrical Section

The equivalent thickness can be solved from the netting-theory equations. As shown in Eq. (5), the equivalent thickness in the helical direction can be obtained directly.

$$h_{f\alpha} = \frac{Rp_b}{2\sigma_{f\alpha} \cos^2 \alpha} \tag{5}$$

Substituting Eq. (5) into Eq. (4) gives the general expression for the hoop equivalent thickness, as shown in Eq. (6).

$$h_{f\theta} = \frac{Rp_b - \sigma_{f\alpha} h_{f\alpha} \sin^2 \alpha}{\sigma_{f\theta}} \tag{6}$$

When the common simplification is further adopted, namely when the fiber utilization strength or allowable stress of the two fiber systems is expressed by the same symbol, Eq. (6) can be transformed into the form shown in Eq. (7).

$$h_{f\theta} = \frac{\left(2 - \tan^2 \alpha\right) Rp_b}{2\sigma_{f\theta}} \tag{7}$$

The calculation results of netting theory are highly sensitive to the allowable fiber stress. The fiber utilization strength or allowable stress is often converted from the NOL ring tensile strength, and a strength loss or reduction factor is introduced, as shown in Eq. (8).

$$\sigma_f = \frac{\sigma_{\mathrm{NOL}}}{V_f} \cdot \eta \tag{8}$$

where the corresponding terms denote the NOL ring tensile strength, the fiber volume fraction, and the strength loss factor, respectively. The reduction accounts for decreases in fiber strength utilization caused by tension fluctuations, speed fluctuations, curvature variation, defects, and other factors during cylinder forming. If the helical and hoop directions are distinguished, the relationship is expressed as shown in Eq. (9).

$$\sigma_{f\alpha} = \frac{\sigma_{\mathrm{NOL}}}{V_f} \cdot \eta_\alpha, \quad \sigma_{f\theta} = \frac{\sigma_{\mathrm{NOL}}}{V_f} \cdot \eta_\theta \tag{9}$$

In engineering implementation, the calculated thickness needs to be converted into the number of layers. The single-layer equivalent thickness, which is related to material linear density, tow spreading width, and fiber volume fraction, is first determined, and the number of layers is then calculated.

If the fiber linear density is T (mass per unit length), the fiber density is rho_f, and the tow spreading width is b, the single-layer geometric thickness of the fiber can be estimated according to mass conservation, as shown in Eq. (10).

$$t_f = \frac{T}{\rho_f b} \tag{10}$$

Considering the fiber volume fraction in the composite, the single-layer equivalent thickness of the composite can be obtained, as shown in Eq. (11).

$$t_c = \frac{t_f}{V_f} \tag{11}$$

For the helical and hoop directions, the single-layer equivalent thicknesses can be written separately, and the number of layers is calculated as shown in Eq. (12).

$$n_\alpha = \frac{h_{f\alpha}}{t_{c\alpha}}, \quad n_\theta = \frac{h_{f\theta}}{t_{c\theta}} \tag{12}$$

Following the idea of single-layer contribution, superposition, and selection of the minimum value, the contribution of a single layer at a given angle to the axial and hoop burst capacities can be expressed as shown in Eqs. (13) and (14).

$$p_{\alpha i} = \frac{2\sigma_{f\alpha} h_{f\alpha} \cos^2 \alpha_i}{R} \tag{13}$$

$$p_{\theta i} = \frac{\sigma_{f\alpha} h_{f\alpha} \sin^2 \alpha_i + \sigma_{f\theta} h_{f\theta}}{R} \tag{14}$$

The axial contribution is provided by helical winding, while the hoop contribution is provided by hoop winding.

When multiple angles or multiple groups of layers are present, the contributions are linearly superposed according to the number of layers, as shown in Eq. (15).

$$p_\alpha = \sum_i p_{\alpha i} n_i, \quad p_\theta = \sum_i p_{\theta i} n_i \tag{15}$$

The final burst strength is taken as the smaller value between the axial and hoop load-bearing capacities, as shown in Eq. (16).

$$p_b = \min\{p_\alpha, p_\theta\} \tag{16}$$

If the calculated burst pressure does not meet the design requirement, the winding angle, equivalent thickness, or layer allocation should be revised. The iterative process of thickness estimation, layup design, and burst verification is then repeated until the constraints on burst strength and burst mode are satisfied.

3.4. Introduction to Abaqus and the WCM Plug-in

The finite element method (FEM) is a commonly used engineering calculation method for solving complex problems.

Abaqus is a powerful engineering simulation software package that performs well in solving complex engineering and nonlinear problems. The WCM plug-in based on Abaqus is specifically used to study the performance of composite pressure vessels. It can establish a complete finite element model of a composite vessel, directly generate fiber layers according to specified winding parameters, combine them with geometric models of different liners, and assign corresponding material-property data. This improves both simulation accuracy and modeling efficiency. Therefore, the Abaqus WCM plug-in is used to model and analyze the Type IV hydrogen storage cylinder with defined opening parameters.

4. Finite Element Modeling of the Type IV Hydrogen Storage Cylinder

4.1. Structure and Geometric Parameters of the Hydrogen Storage Cylinder

The research object is a 20 L Type IV hydrogen storage cylinder with an all-plastic liner and carbon-fiber winding. The Type IV hydrogen storage cylinder consists of a plastic liner, carbon-fiber winding layer, glass-fiber protective winding layer, metal boss, and other components. In terms of the overall configuration, the cylinder adopts a typical body of revolution. The cylindrical section transitions continuously to the domes on both sides. The overall dimensions are approximately 933 mm in total length and 230 mm in outer diameter after winding. The overall dimensions and appearance of the cylinder are shown in Figure 2.

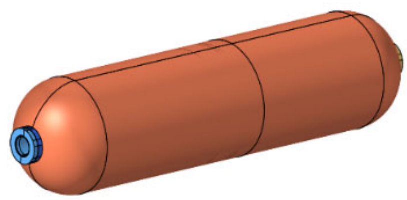

Figure 2. Overall three-dimensional structural model

In practical service, the refueling control strategy of the hydrogen storage system affects the pressure-loading process of the cylinder [11]. At the manufacturing stage, integrated molding of the plastic liner affects dimensional accuracy and provides the geometric basis for subsequent fiber winding [12]. In addition, rapid filling of 70 MPa vehicle-mounted Type IV cylinders may cause temperature rise, indicating the importance of structural verification under high-pressure service conditions [13].

The plastic liner mainly provides gas-tightness and hydrogen-barrier functions. It is not the primary load-bearing component of the hydrogen storage cylinder, but it still directly withstands the internal pressure and transfers the load to the composite winding layer through interface contact. The carbon-fiber composite layer carries most of the hoop and axial loads. The overall structure of the hydrogen storage cylinder is divided into the cylindrical section, dome section, and mouth-connection section. An ellipsoidal structure is adopted at the dome, which can effectively alleviate stress concentration.

4.2. Winding-Layer Modeling Based on WCM

The winding continuum method (WCM) is used to construct the winding-layer model. This method does not require each single fiber layer to be modeled individually and can provide an equivalent model for composite structures consisting of helical and hoop winding. According to the actual winding process, the cylindrical part adopts a combination of hoop winding and helical winding, while the dome region is mainly formed by helical winding to ensure structural continuity in the dome area.

With the development of multi-tow carbon-fiber synchronous helical winding, accurate control of the winding angle, layer sequence, and motion coordination has become increasingly important for ensuring the consistency of the composite winding layer [14].

(1) Establishment of the liner model

First, a geometric model is constructed in Abaqus/CAE to define the basic shape of the pressure-vessel liner.

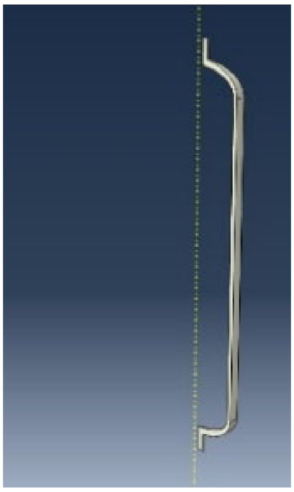

Figure 3. Liner model

(2) Definition and generation of winding-layer parameters

The filament-winding layer model is established using the Layers option. The thickness, angle, and layup sequence of the carbon-fiber and glass-fiber winding layers are designed, as shown in Figure 4.

Winding Pattern	Winding Angle	Thickness	Layers	Tow Width	Single-layer Thickness
Hoop	88.5	0.52	2	20	0.26
Helical	20	0.6	2	18	0.3
Hoop	88.5	1.04	4		
Helical	23	1.2	4		
Hoop	88.5	1.04	4		
Helical	45	1.2	4		
Hoop	88.5	1.04	4		
Helical	30	0.6	2		
Hoop	88.5	1.04	4		
Helical	25	0.6	2		
Hoop	88.5	0.52	2		
Helical	24	0.6	2		
Hoop	88.5	0.52	2		
Helical	20	1.2	4		
Hoop	88.5	1.04	4		
Helical Design	20				
Hoop Design	88.5				

Figure 4. Fiber layup information

(3) Definition of material properties and contact types

Before simulation, the elastic modulus, Poisson's ratio, and other mechanical properties of carbon fiber and the liner material need to be defined. PA6 is used as the plastic liner material, and 6061-T6 aluminum alloy is used for the metal boss. The material-property parameters are shown in Table 1.

Table 1. Material-property parameters

Material property	Unit	6061-T6 aluminum alloy	PA6
Poisson's ratio	-	0.33	0.35
Yield strength	MPa	276	45 - 80
Ultimate strength	MPa	310	60 - 90

(4) Boundary-condition and load settings

Boundary conditions and loads are defined according to the actual operating condition. The axial motion of the pressure vessel, namely the motion in the Y direction, is constrained, and a uniform load is applied to the inner contour surface of the liner.

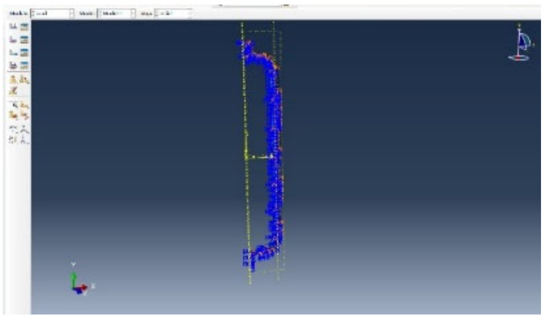

Figure 5. Boundary conditions and load settings

(5) Setup and submission of the job in the analysis step. The analysis step is created, solution parameters are set, the analysis type is selected, stress output is defined, and finally the job is submitted for solution.

5. Simulation Results and Analysis

5.1. Stress Analysis

Under the 70 MPa internal pressure condition, the maximum stress values of the components are shown in Table 2.

Table 2. Analysis results under the 70 MPa pressure condition

Component	Maximum stress (MPa)	Yield strength (MPa)
Boss	163.35	180
Liner	137.5	74

Component	Fiber tensile stress (MPa) Calculated value / allowable value		In-plane fiber shear stress (MPa) Calculated value / allowable value	
Middle fiber layup	985.9	2200	2.85	70
End fiber layup	539.6	2200	23.69	70

Under an internal pressure of 70 MPa, the calculated stresses of each component of the Type IV hydrogen storage cylinder are listed in Table 4.1. As shown in Table 4.1, under the 70 MPa internal pressure, the maximum equivalent stress of the boss is 163.35 MPa, which is lower than the allowable value of 180 MPa and basically satisfies the strength requirement, although the safety margin is relatively small. The maximum stress of the PA6 liner is 137.5 MPa, which is higher than its yield strength of 74 MPa, indicating that local regions may experience yielding. In the composite winding layer, the tensile stresses in the fiber direction in the middle and end fiber layups are 985.9 MPa and 539.6 MPa, respectively, both lower than 2200 MPa. The in-plane shear stresses are 2.85 MPa and 23.69 MPa, respectively, both lower than 70 MPa, indicating that the load-bearing capacity of the winding layer satisfies the requirement.

6. Conclusion

Overall, under the rated internal pressure condition of 70 MPa, the carbon-fiber winding layer can carry the main internal-pressure load. The tensile stress in the fiber direction and the in-plane shear stress do not exceed the corresponding allowable values, indicating that the current layup scheme is reasonably suitable for the composite load-bearing layer. The stress of the metal boss basically satisfies the strength requirement, but the safety margin is small. The local stress of the PA6 liner exceeds the yield strength, indicating that local stress concentration still exists in the mouth-connection region or the liner constraint region. Therefore, it cannot simply be concluded that all components are completely safe. In subsequent work, model verification and structural optimization should focus on the liner-boss connection region.

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