Design and Optimization of a Double-Layer Composite Pressure Vessel Structure

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Authors' contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Original Research Article

ABSTRACT

Ballast tank is the main pressure component of underwater intelligent equipment, material selection and structural design are important factors restricting its diversified functions. In order to realize the functional application and lightweight of underwater ballast tank, the structure and materials of ballast tanks were studied. The design uses carbon fiber resin matrix composite material as the shell and titanium alloy material as the inner liner to prepare the underwater double-layer cylindrical water-tight structure ballast tanks. The fiber layer is selected as the layering scheme of [90°/90°/0°]s. The weight can be reduced by 23% compared to the ballast made of titanium alloy. Based on Abaqus finite element analysis software, the actual working conditions of the ballast tank are simulated, and the analysis shows that the cylinder meets the strength requirements. At the same time, the stability of the cylinder is studied, and the critical load of the instability of the double-layer underwater ballast tank is 22.15MPa by buckling analysis. The physical object was processed, and the pressure experiment of 1.5MPa and 2MPa was carried out on the physical object. The experimental results met the requirements of strength and stiffness.

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1. INTRODUCTION

As humanity continues to exploit ocean resources, the demand for underwater intelligent equipment has concurrently increased. Among these, the pressure-resistant chamber components are crucial pressure-bearing devices [1]. Traditionally, the materials used for underwater pressure chamber hulls have been primarily metals, which have a high density-to-volume ratio, thereby impacting the spatial utilization and long-endurance requirements of underwater intelligent equipment. With the successful application of fiber-reinforced composites in military, aerospace, and other fields, carbon fiber resin-based composites have gradually been adopted for underwater equipment as well [2-5]. Carbon fiber composites exhibit high specific strength, high specific modulus, fatigue resistance, and a lower density-to-volume ratio [6], aligning well with the material requirements for deep-sea intelligent equipment. Carbon fiber ballast is an important development in the field of structural engineering, especially in applications requiring high strength and lightweight, as well as excellent durability under certain conditions.

Pengfei Wang et al. designed a composite pressure vessel for underwater applications at depths of 1000 meters, achieving a weight reduction of 34% compared to aluminum alloy pressure vessels [7]. Bin Li and colleagues employed a synergistic optimization method based on ply parameters to optimize the design of composite pressure vessels, resulting in a 20.57% reduction in structural weight [8]. These results indicate that carbon fiber composites are a crucial avenue for achieving lightweight deep-sea pressure vessels.

To obtain the lightweight study of the ballast capsule under the condition of various performance requirements, carbon fiber resin matrix composite material as the shell and titanium alloy material is used as the lining to prepare the double cylindrical watertight ballast capsule. The mechanical performance of the carbon fiber composite under load is designed using Abaqus finite element analysis software. The study determines the lay-up scheme for the carbon fiber resin composite and utilizes filament winding techniques to manufacture the cylindrical pressure vessel hull. Hydrostatic tests are conducted on the designed and fabricated pressure vessel to obtain products that meet the required pressure resistance specifications. This research provides a practical foundation and theoretical basis for the development of underwater intelligent devices.

2. DESIGN OF BALLAST STRUCTURE

2.1 Ballast Structure

Previously developed and deployed underwater pressure vessels in China predominantly featured single-layer metal structures, which fail to meet the stringent requirements of low weight, high strength, and long lifespan. With the advancement of advanced composite material pressure vessels in electric vehicles and rocket engine systems, their application in underwater intelligent equipment has become feasible. Consequently, the designed composite underwater pressure vessel consists of a double-layer structure, with an outer shell made of carbon fiber resin-based composite material and an inner lining made of titanium alloy [9-11]. Research indicates that for every 0.1mm reduction in the thickness of the metal lining, the mass of the composite pressure vessel decreases by 3%-6%. Accordingly, this design employs an ultra-thin metal lining, with a thickness ≤ 1mm, for the underwater pressure vessel. Given that the metal lining must not only provide sealing but also bear internal pressure and high-temperature conditions, the thickness is preliminarily set at 1mm. The double-layer underwater pressure vessel structure can prevent gas or liquid leakage, enhance the fracture toughness of the material, and offer higher load-bearing capacity, meeting the demands of various operational conditions. This significantly reduces the weight of underwater intelligent equipment. The overall structure of the pressure vessel is shown in Fig. 1 (1 represents the end cap, 2 represents the titanium alloy inner shell, and 3 represents the carbon fiber composite outer shell).
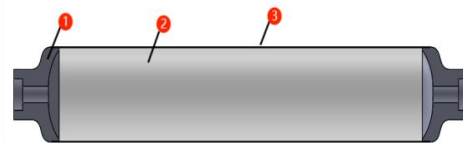
Fig.1. Structural drawing of a double pressure chamber

2.2 Fibrous Material

Compared to all-metal pressure vessels, composite material pressure vessels offer numerous advantages, including lighter weight, better stiffness, higher vessel characteristic

coefficients, longer operational lifespans under load, and a safe failure mode characterized by leakage before bursting [12]. In addition to these benefits, fiber composites also exhibit excellent mechanical properties such as vibration damping and noise reduction. Common fibers include glass fiber, aramid fiber, and carbon fiber. Table 1 presents a comparison of the basic properties of these fiber materials, while Table 2 details the basic properties of carbon fibers developed by Toray Industries, Japan [13].

The data in the tables indicate that carbon fiber composites exhibit superior performance in terms of strength and modulus, while also possessing a lower density-to-volume ratio. The use of carbon fiber materials aligns perfectly with the requirements for deep-sea intelligent equipment. Therefore, this paper selects T700 carbon fiber as the reinforcing material.

2.3 Lining Material

The primary materials constituting composite pressure vessels are metallic and non-metallic liners. As liners, they need to bear internal pressure while having a relatively low elastic modulus, allowing deformation under pressure to effectively transfer the load to the external fiber layer, thereby preventing shell failure. Given the operational requirements, the designed underwater pressure vessel liner must withstand instantaneous high-temperature exposure and possess long cyclic life and anti-permeation characteristics. Consequently, a metallic material is selected for the liner.The inclusion of a metallic liner facilitates the filament winding process for the fiber layer, eliminating the need for demolding post-manufacture. Titanium alloy is chosen as the liner material due to its favorable weight-to-volume ratio, superior specific strength, specific modulus, high-temperature resistance,

and excellent tensile strength and yield limit. These properties make titanium alloy an ideal choice for the pressure vessel liner [14].

2.4 Structural Parameter Design

(1) The main body length of the pressure vessel:500mm。
(2) The inner diameter of the titanium alloy inner shell: Φ 100mm ; the outer diameter of the titanium alloy inner shell:Φ102mm。
(3) The inner diameter of the carbon fiber resin composite outer shell: Φ 102mm ; the outer diameter of the carbon fiber resin composite outer shell:Φ110mm

The weight of the double-layer pressure vessel is 5.85kg, which represents a 23% reduction in weight compared to a pure titanium alloy cylinder of the same dimensions.

3. MOLDING PROCESS OF BALLAST TANK

3.1 Fiber Layer Forming Method

Carbon fiber resin-based composites can be fabricated using various filament winding techniques. This design employs wet filament winding, which allows for precise control of fiber pre-tension, resulting in high fiber volume content and outstanding mechanical properties [15].

Unlike the structural design of metallic materials, composite material structures require optimization of the lay-up method used. The performance of the final formed cabin body will also vary greatly depending on the way of ballast is laid.In this study, the composite lay-up module of Abaqus finite element analysis software will be utilized to analyze the lay-up sequence and angles of the carbon fiber composite. Three lay-up schemes will be set up: [90°/90°/0°], [-45°/90°/45°/0°/-45 °/0 °/45°/0 °], and [0 °/45 °/90 °/-45 ° /0 ° /45 ° /90 ° /-45 °]. By applying external pressure to the ballast cylinder of different layering schemes through Abaqus, the maximum stress generated by each layering scheme under external pressure is analyzed, and the results are shown in Figs. 2.

Table 1. Fiber material contrast

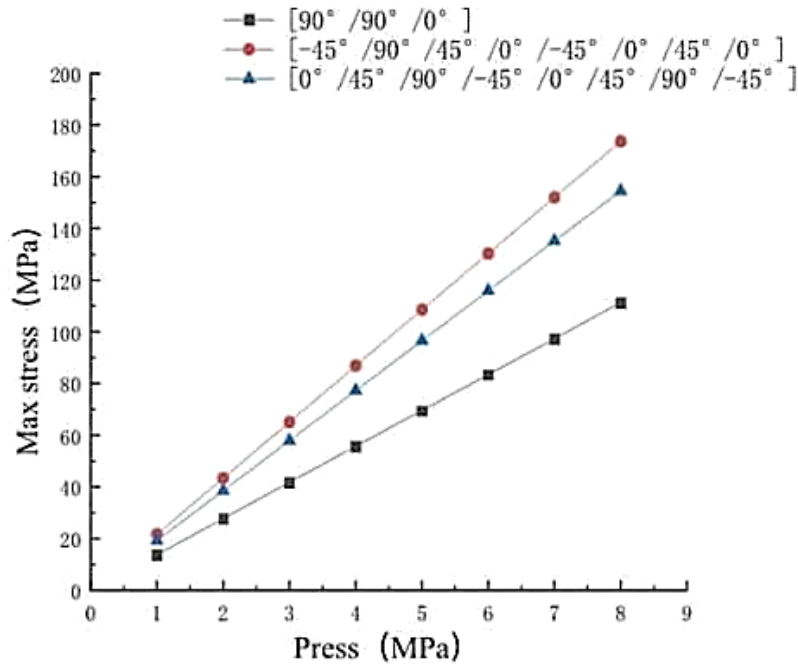| Material type	Density/ (g/cm3)	Modul us/GPa	Intensity/M Pa	Elongation/%
Carbon fiber T700s	1.8	230	4900	2.1
Quartz	2.20	69	3400	-
E-glass	2.55	81.3	3440	4.8
Nomex	2.0	7.5	485	3.5

Fig. 2. Maximum stress of different lay-up schemes Based on the analysis, the [90 ° /90 ° /0°]s lay-up scheme was selected

4. FINITE ELEMENT ANALYSIS

Abaqus, recognized for its high reliability as a finite element analysis software, is capable of conducting finite element analysis on highly complex models and handling various linear and nonlinear problems [16]. Based on Abaqus finite element analysis software, a three-dimensional model of the double-layer pressure vessel hull was established.

4.1 Material Property Definition

Unlike ordinary metallic materials, carbon fiber composites exhibit multidirectional and anisotropic characteristics [17]. When the same force is applied in each of its principal material directions, the resulting tensile or compressive deformation varies, leading to different elastic moduli in each direction. Additionally, the shear modulus of orthotropic materials is independent of their Poisson's ratio and elastic modulus, necessitating nine independent engineering constants to fully define the stress-strain relationship of triaxially orthotropic materials [18]. The specific parameters of the carbon fiber composite and titanium alloy materials are presented in Tables 2 and 3, respectively, with units in MPa.

Table 2. Engineering constant parameter

E_x	115000
E_y	6430
E_z	6430
V_{xy}	0.28
V_{yz}	0.34
V_{xz}	0.28
G_{xy}	6000
G_{yz}	4800
G_{xz}	6000

Table 3. Titanium alloy material parameter

Materials	Titanium alloy TC6
Density/(g/cm3)	4.5
Modulus of elasticity/MPa	0.34
Poisson's ratio	107800

4.2 Actual Condition Analysis

4.2.1 Simulation analysis of external pressure of cylinder subjected to static water

Using Abaqus software, the strength of the designed double-layer pressure vessel cylinder was analyzed under a 2000m deep-sea environment. The analysis involved constraining the circumferential displacement at the bottom end face of the pressure cylinder and the

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circumferential and radial displacements at the other end. During the simulation, the hydrostatic pressure applied a uniform circumferential external pressure (PC) and axial pressure (PA), each of 20 MPa, to the pressure vessel, as shown in Fig. 3. The simulation analysis yielded the maximum stress values and deformation of the pressure vessel. The analysis results are presented in Figs. 4 and 5.

As shown in the figures, the pressure vessel is in a compressed state with relatively uniform stress distribution. The maximum stress is 269.1 MPa, the minimum stress is 244.8 MPa, and the maximum strain is 0.00045. Due to the effects of localized constraints, the maximum stress concentration occurs at the front end of the cylinder. The stress values obtained from the simulation analysis are all below the material's strength limits, indicating that the double-layer pressure vessel has sufficient safety margins to withstand external pressure in deep-sea environments.

4.2.2 Simulation analysis of cylinder under internal pressure and axial tension

The pressure vessel cylinder can be used as a protective casing for a launcher. When items are propelled from the cylinder interior by an ignition device, dynamic loads are generated within the cylinder, causing axial displacement. This section simulates such conditions by applying an internal pressure of 2 MPa to the titanium alloy interior and an axial tensile force of 30 MPa to the front end of the main body [19]. The analysis examines the stress and strain behavior of the pressure vessel under the combined effects of axial tensile force and internal pressure. The resulting analysis contour plots are shown in Figs. 6 and 7.
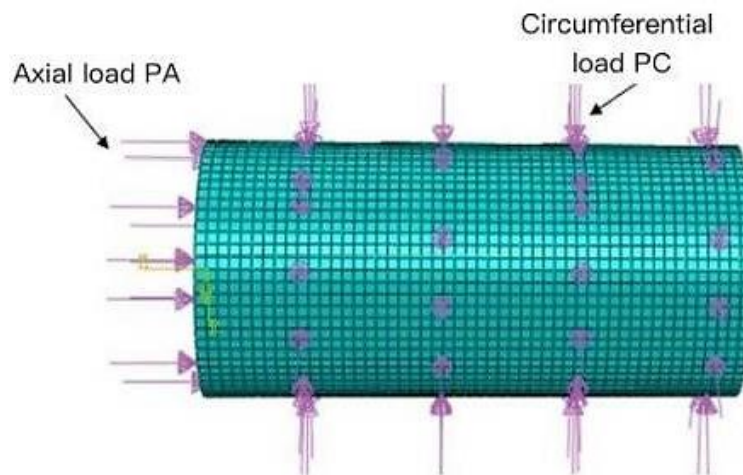

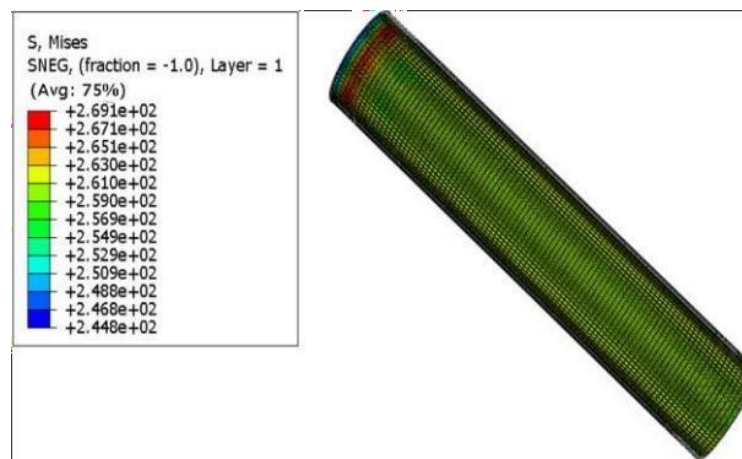**Fig. 3. Loaded under static water external pressure**

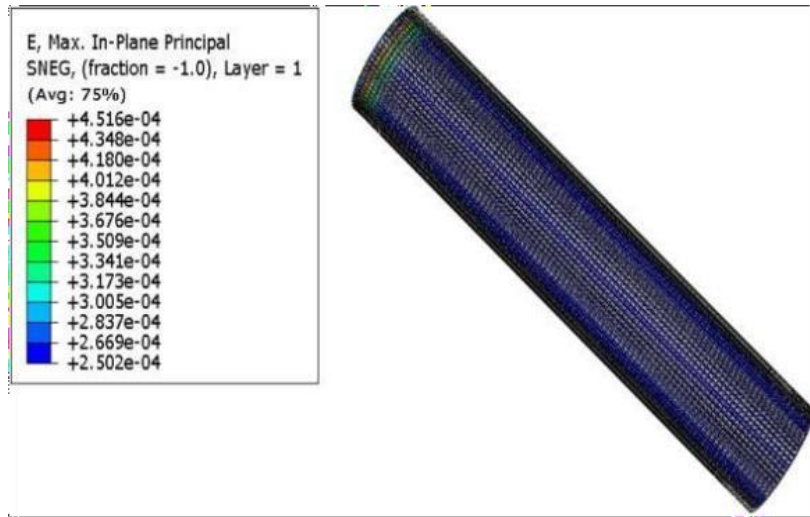**Fig. 4. Nephogram of external stress under static water**

Fig. 5. Hydrostatic external pressure strain cloud image
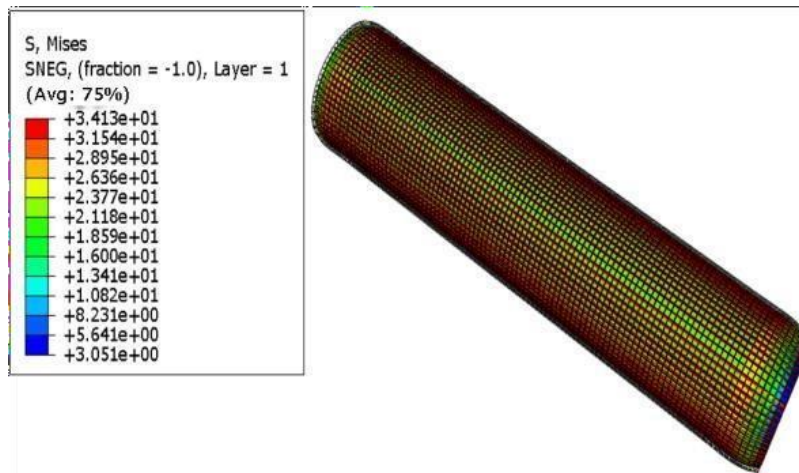

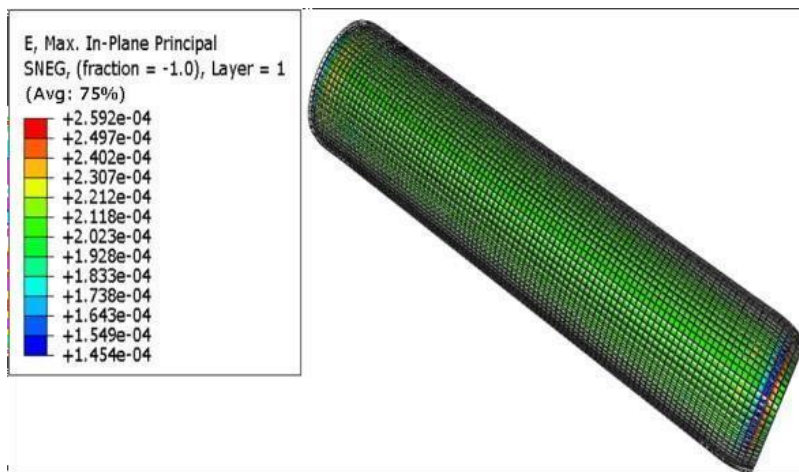**Fig. 6. Stress cloud image under internal pressure and axial tension**

Fig. 7. Strain cloud image under internal pressure and axial tension

From the figure, it can be observed that the maximum stress in the pressure vessel is 34.13MPa and the maximum strain is 0.000259, which is well below the material failure threshold. The internal pressure is primarily borne by the titanium alloy liner. This is due to the high yield strength and moderate elastic modulus of the titanium alloy liner, which allows it to undergo expansion deformation under operational conditions. This deformation effectively transfers the load to the fiber layer. Additionally, after the pressure is released, the liner helps prevent the entire pressure vessel from collapsing inward or failing.

4.2.3 Ballast lining subjected to transient high -temperature erosion

In composite pressure vessels, the liner primarily serves a sealing function and is typically not considered for load-bearing capacity. However, under actual operating conditions, the liner remains in a plastic state when subjected to internal or external loads. To evaluate whether the metallic liner can withstand high-temperature conditions, the design must be tested under an internal transient temperature of 800°C (0.6 seconds). The stress and strain variations in the liner are examined, as illustrated in Figs. 8 and 9.

As an isotropic material, the failure strength of titanium alloy depends on its yield strength. According to the "Submarine Structural Design Calculation Methods," the expression used for verifying its strength is as follows:

$$\leq 0.85 \tag{1}$$

In the expression: - Yield strength, in MPa.

From Fig. 8, it can be seen that under the conditions of 800°C and internal pressure, the maximum stress in the cylinder is 215.7 MPa, which indicates that there will be no failure in strength or stiffness.
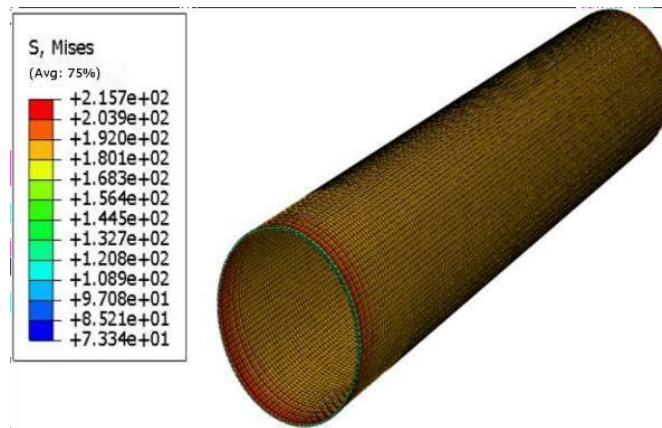

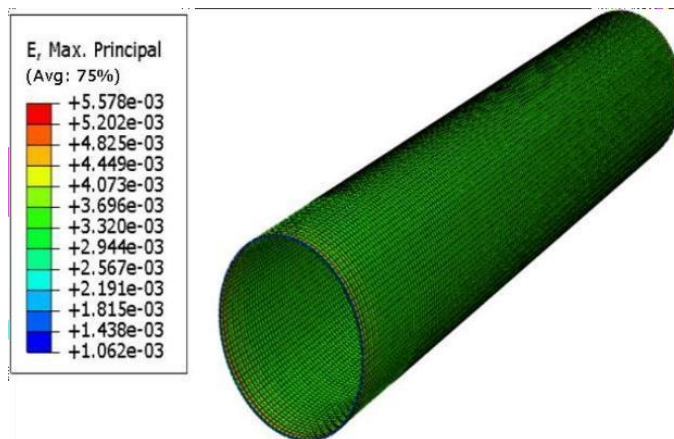**Fig. 8 Stress nephogram of titaniumalloy**

Fig. 9. Strain cloud image of titanium alloy

4.3 Stability Analysis

Linear buckling analysis is used to study the buckling performance of a structure under external loads. In this analysis, equilibrium equations are established based on the structure's initial configuration at each stage of

load application. When the load reaches a critical value, the structure's configuration abruptly shifts to a different equilibrium state. This conclusion assumes that the structure behaves linearly, disregarding material plasticity and geometric nonlinearity effects, meaning that the structure can be described using linear elasticity theory under small deformations.

As shown in Equation (1), linear buckling analysis employs the eigenvalue method to obtain the buckling load factors and buckling modes.

$$([K]) + \lambda_i[S])\{\psi_i\} = \{0\} \tag{2}$$

In the expression: [K]、[S] is constant
λ_i-Buckling load factor
-Bucking mode shape

Linear buckling analysis was performed using ABAQUS to determine the critical load and instability modes of the pressure vessel cylinder. The simulation applied a uniform external pressure of 2.5 MPa to the cylinder and constrained the displacement at both ends [20]. A linear perturbation buckling analysis step was set up, with the liner material modeled using C3D8R elements and the fiber layer modeled using SC8R shell elements. The first four modes were extracted to observe the instability modes and the corresponding eigenvalues at the point of instability, which were used to calculate the critical load of the pressure vessel. The results of the simulation analysis are shown in Fig. 10.
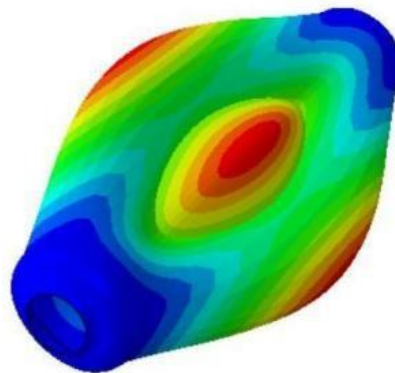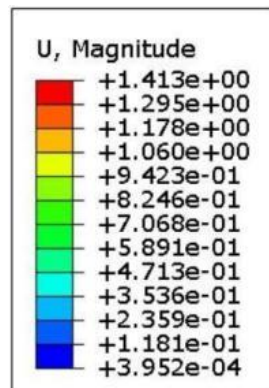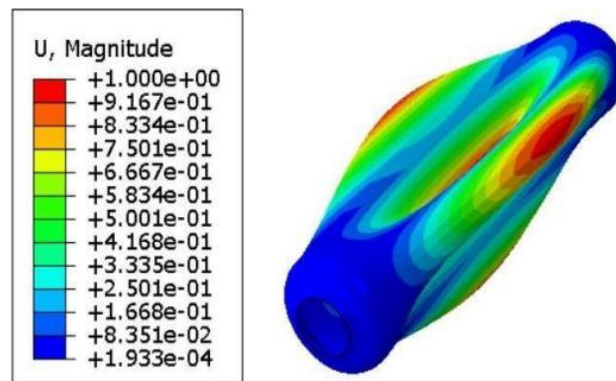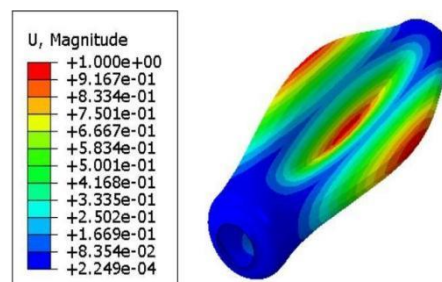

(a) First mode
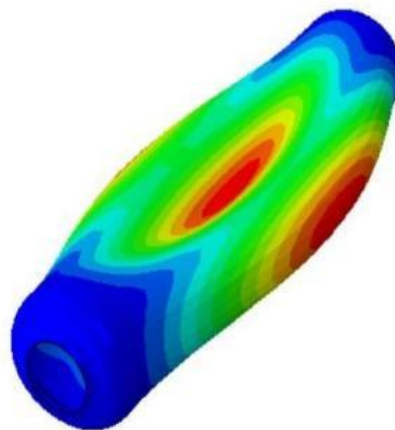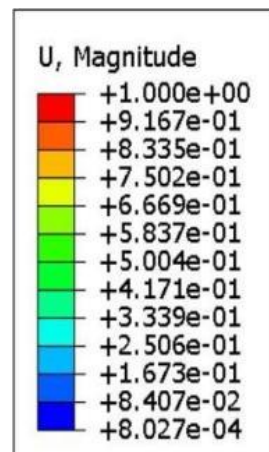
(b)Second mode

(c)Third mode

(d) Fourth mode

Fig.10. The first four stage buckling modes of a double-deck ballast tank

Table 4. The first four buckling eigenvalues and instability waves

Stability parameter	Eigenvalue	Destabilizing wave
First mode	8.8589	4
Second mode	8.8999	4
Third mode	13.597	6
Fourth mode	13.710	6

The eigenvalues and instability modes for each order is shown in Table 4.

From the Table 4, it is evident that the eigenvalue for the first mode of the double-layer pressure vessel is 8.8589. The calculation method for the critical load is as follows.

$$p_{cr} = \lambda p \qquad (2)$$

In the expression：

p_{cr}-Critical pressure，in MPa；λ-Eigenvalue；p-External pressure，in MPa

The critical load was calculated to be 22.15 MPa, indicating that the cylinder will experience instability when subjected to an external pressure of 22.15 MPa. This suggests that the shell will primarily undergo stability failure rather than strength failure when it fails.

5. SAMPLE MAKING AND TESTING

To obtain the actual parameters and sealing performance of the pressure vessel under internal pressure and to verify the accuracy and reliability of the ABAQUS simulation, a physical prototype of the pressure vessel was developed for analysis. The prototype features a carbon fiber reinforced polymer shell with a [90 ° /90 ° /0 °]s layup scheme, manufactured using wet winding technology. The sealing method employs O-ring seals to ensure water and gas tightness inside the cylinder. The O-rings are positioned on the surfaces near the bolts on both ends of the end caps, as shown in the detailed dimensions in Fig. 11.
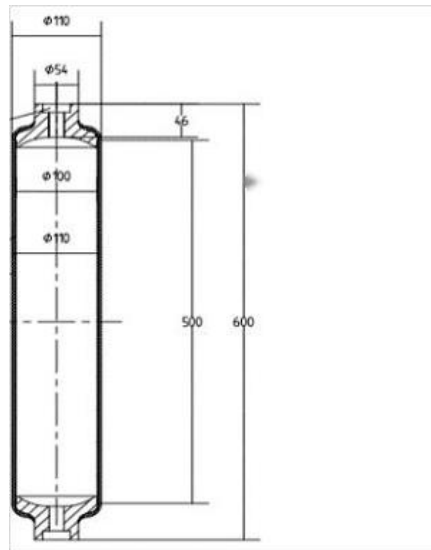
Fig.11. Physical size drawing

5.1 Hydrostatic Test

To assess whether the pressure vessel cylinder would fail and to verify the reliability of the ABAQUS finite element analysis software, a hydrostatic pressure test was conducted on the completed pressure vessel shell by national standards for pressure vessels [21]. The physical prototype is shown in Fig. 12.

5.2 Loading Test

The pressure vessel was subjected to a hydrostatic pressure load according to national standards. The test involved a stepwise pressurization process. Initially, the pressure was increased to 1.5 MPa and held for 3 minutes, as shown in Fig. 12.

Fig.13. 1.5MPa test

The pressure was then increased to the target pressure of 2 MPa. The pressure gauge readings stabilized, and after the test, no leaks were detected in the pressure vessel. The hydrostatic pressure test was successful.

Fig.12. Experimental objects

Fig.14. 2MPa test

5.3 Experimental Result

During the experimental process, the pressure vessel demonstrated good strength and stability, with no signs of damage or instability in the shell. It met the requirements for water and gas tightness, indicating that the pressure vessel satisfies the performance criteria. This confirms the feasibility of both the structural design and the simulation calculations.

6. CONCLUSION

This paper verifies the reliability of a composite material-based double-layer underwater pressure vessel from five aspects: structural design, material selection, molding process, simulation analysis under actual operating conditions, and hydrostatic testing. The use of a carbon fiber reinforced polymer shell and a titanium alloy liner for the pressure vessel demonstrates clear advantages.

1. Compared to traditional metal underwater pressure vessels, this design is lighter, with a weight reduction of 23% compared to fully titanium alloy pressure vessels.
2. The application of ultra-thin liner materials is influenced not only by their intrinsic properties but also by the pre-tensioning of the fiber layers, which requires further investigation.
3. The vessel exhibits excellent strength and stability, capable of withstanding more complex loading conditions while ensuring material stability.
4. For thin-walled cylindrical structures, stiffness failure precedes strength failure; thus, the stability of the pressure vessel should be prioritized in underwater intelligent devices deployed at greater depths.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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