# DesignandOptimizationofaDouble-LayerCompositePressureVesselStructure


## Abstract

Ballast tank is the main pressure component of underwater intelligent equipment, material selectionandstructuraldesign areimportantfactors restrictingitsdiversified functions.In orderto realize the functional application and lightweight of underwater ballast tank, the structure and materials of ballast tank 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 underwaterdouble-layer cylindrical water tight structure ballast tank. The fiber layer is selected as thelayering scheme of [90°/90°/0°]s. The weight can be reduced by 23% compared to the ballastmade 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 criticalload 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.



**Keyword:**Underwaterpressurecabin;Lightweight;Double-layerstructure;Carbonfiberresin composite material；Abaqus




## 1.Introduction

As humanity continues to exploit ocean resources, the demand for underwater intelligent equipment has concurrently increased.Among these, the pressure-resistant chambercomponentsarecrucialpressure-bearing devices. The various structural configurations of these chambers determine the specific applications of underwater intelligent equipment, making them an indispensable part of the system[1]. Traditionally,thematerialsusedfor underwater pressure chamber hulls have been primarilymetals,whichhaveahighdensity-to-volume ratio, therebyimpactingthe spatial utilization and long-endurance requirements of underwater intelligent equipment. With the successful application of fiber-reinforced composites in military, aerospace,andotherfields,carbonfiber resin-based composites have gradually been adopted for underwater equipment as well [14-17]. Carbon fiber composites exhibit high specific strength, high specific modulus, fatigue resistance, and a lower density-to-volume ratio[2],aligningwellwiththematerial requirements for deep-sea intelligent equipment.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[3]. Bin Li and colleagues employed a synergistic optimization method based on ply parameters to optimize the design ofcomposite pressure vessels, resulting in a 20.57%reductioninstructuralweight[4].These results indicate that carbon fiber composites are a crucial avenue for achieving lightweight deep-sea pressure vessels.

Thispaperemployscarbonfiber resin-based composites for the outer shell and titanium alloy for the inner lining to fabricatea double-layer cylindrical watertight pressure vessel. The mechanical performance of the carbon fiber composite under load is designed usingAbaqusfinite elementanalysissoftware. 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 requiredpressure resistance specifications. This research provides a practical foundation and theoretical basis for the development of underwater intelligent devices.

## 2 Designofballaststructure

### *2.1 Ballaststructure*

Previously developed and deployed underwater pressure vessels in China predominantly featured single-layer metal structures, which fail to meet the stringent requirementsoflowweight,highstrength,and long lifespan. With the advancement of advancedcompositematerialpressurevessels in electric vehicles and rocket engine systems, their application in underwater intelligent equipmenthasbecomefeasible.Consequently, the designed composite underwater pressure vessel consists of a double-layer structure,withanouter shell madeof carbon fiber resin-based composite material and an inner lining made of titanium alloy [18-20]. Research indicates that for every 0.1mm reduction inthe 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 andhigh-temperatureconditions,thethickness 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 Figure 1 (1 represents the end cap, 2represents the titanium alloy inner shell, and 3 represents the carbon fiber composite outer shell).

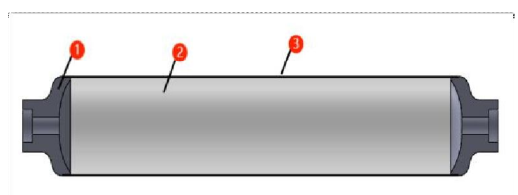



**Fig.1**Structuraldrawingofdoublepressure chamber

### *2.2 Fibrousmaterial*

Compared to all-metal pressure vessels, composite material pressure vessels offer numerousadvantages,includinglighterweight, betterstiffness,highervesselcharacteristic coefficients, longer operational lifespansunder load, and a safe failure mode characterized by leakage before bursting[5]. In addition to these benefits, fiber compositesalso exhibit excellent mechanical properties suchasvibrationdampingandnoisereduction. 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 propertiesofcarbonfibers developedbyToray Industries, Japan[6].

**Table1**Fibermaterialcontrast

| Material type | Density/（g/cm$^3$） | Modulus/GPa | Intensity/MPa | 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 |

Thedatainthetablesindicatethatcarbon 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 Liningmaterial*

The primary materials constituting composite pressure vessels are metallic and non-metallic liners. As liners, they need tobear internal pressure while having arelatively 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 withstandinstantaneoushigh-temperature exposure and possess long cyclic lifeandanti-permeation characteristics. Consequently, ametallic material isselected forthe liner.The inclusion of a metallic liner facilitates the filament winding process for the fiber layer, eliminatingtheneedfordemoldingpost-manufacture. Titanium alloy is chosen as thelinermaterialduetoitsfavorable 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[7].

*1.4Structuralparameterdesign*

(1) The main body length of the pressure vessel:500mm。

(2) The inner diameter of the titanium alloy innershell: Φ100mm; theouterdiameterof the titanium alloy inner shell:Φ102mm。

(3) The innerdiameter of thecarbonfiberresin compositeoutershell: Φ102mm; theouter 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 samedimensions.

**3 Moldingprocessofballasttank**

*3.1 Fiberlayerformingmethod*

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[8].

Unlikethestructuraldesignofmetallic

materials, composite material structures require optimization of the lay-up method used.Thelay-upmethodofthepressurevessel significantly affects the final performance of the vessel. 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 ° ].External pressure will be applied to the pressure vessel cylinder for each lay-up scheme usingAbaqus to analyze the maximum stress generated underexternal pressure.The results are shown inFigure2.

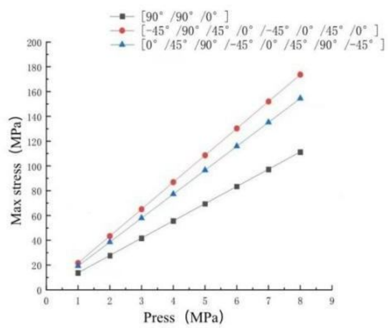



**Fig.2**Maximumstressofdifferentlay-upschemes

Basedontheanalysis,the[90 ° /90 ° /0 ° ]slay-upschemewasselected.

## 4 Finiteelementanalysis

Abaqus,recognizedforitshighreliability as a finite element analysis software, iscapable of conducting finite element analysis on highly complex models and handling various linear and nonlinear problems[9].Based on Abaqus finite element analysis software, a three-dimensional model of the double-layer pressure vessel hull was established.

### *4.1 Materialpropertydefinition*

Unlike ordinary metallic materials, carbon fiber composites exhibit multidirectional and anisotropic characteristics[10]. When the same force is applied in each of its principalmaterial directions, the resulting tensile or compressive deformation varies, leading to different elastic moduli in each direction. Additionally,the shear modulus oforthotropic materials is independent of their Poisson'sratio and elastic modulus, necessitating nine independent engineering constants to fully define the stress-strain relationship oftriaxiallyorthotropicmaterials[11].Thespecific parameters of the carbon fiber composite and titanium alloy materials are presented in Tables 2 and 3, respectively, with units in MPa.

**Table2**Engineeringconstantparameter

| | |
|---|---|
| $E_x$ | 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 |

**Table3**Titaniumalloymaterialparameter

| Materials | |
|---|---|
| | TitaniumalloyTC6 |
| Density/(g/cm$^3$) | 4.5 |
| Modulus of elasticity/MPa | |
| | 107800 Poisson's ratio |
| | 0.34 |

### *4.2 Actualconditionanalysis*

#### *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 cylinderwasanalyzedundera2000mdeepseaenvironment.Theanalysisinvolved

constrainingthecircumferentialdisplacement at the bottom end face of the pressure cylinder and the circumferential and radial displacementsattheotherend.Duringthe simulation,the hydrostaticpressure applied a uniformcircumferentialexternalpressure($P_C$) and axial pressure ( $P_A$), each of 20 MPa, to the pressure vessel, as shown in Figure 3. The simulationanalysisyieldedthemaximum stress values and deformation of the pressure vessel.Theanalysisresultsarepresentedin Figures 4 and 5.

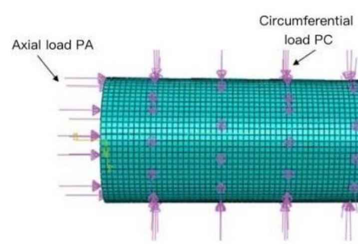



**Fig.3**Loadedunderstaticwaterexternalpressure

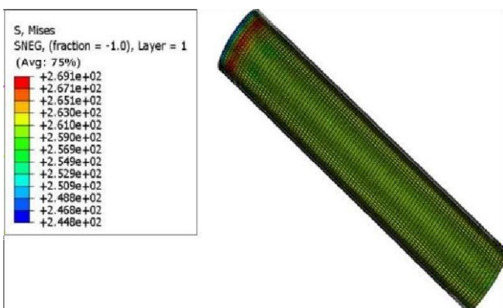


**Fig.4**Nephogramofexternal stressunderstaticwater

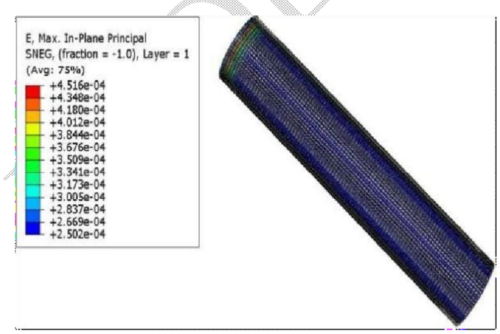


**Fig.5**Hydrostaticexternalpressurestrain cloudimage

Asshowninthefigures,thepressure vessel is in a compressed state with relatively uniformstressdistribution.Themaximum stressis269.1MPa,theminimumstressis 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-layerpressurevesselhassufficientsafetymarginst o 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. The analysis examines the stress and strain behavior of the pressurevessel under the combined effects of axial tensile force and internal pressure. The resulting analysis contour plots are shown in Figures 6 and 7.

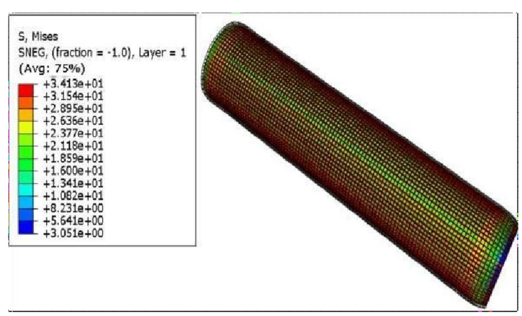


**Fig.6**Stresscloudimageunderinternal pressure and axial tension

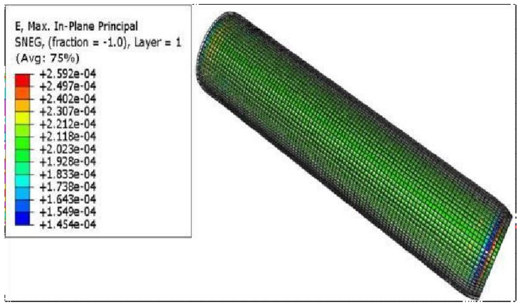



**Fig.7**Straincloudimageunderinternal pressure and axial tension

Fromthefigure,itcanbeobservedthat themaximumstressinthepressurevesselis 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 moderateelasticmodulusofthetitanium alloy liner, which allows it to undergo expansion deformation under operational conditions.This deformation effectively transfersthe load to the fiber layer. Additionally, after the pressureisreleased,theliner helpspreventthe entire pressure vessel from collapsing inward or failing.

*4.2.3 Ballastlining subjectedto transienthigh 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 Figures 8 and 9.

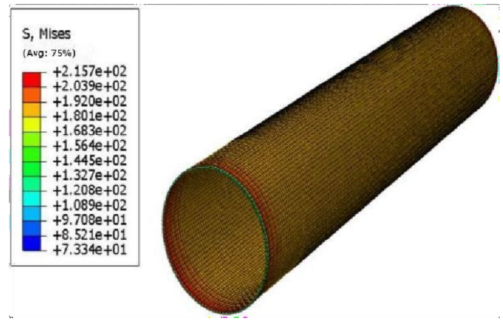



**Fig.8**Stressnephogramoftitanium alloy

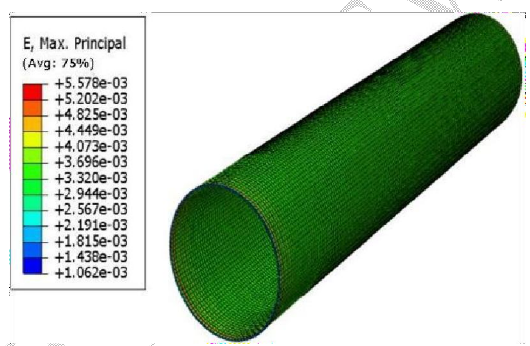



**Fig.9**Straincloudimageoftitaniumalloy

As an isotropic material, the failure strengthoftitaniumalloydependsonitsyield strength. According to the "Submarine Structural Design Calculation Methods," the expressionusedforverifyingitsstrengthisas follows:

$$\leq 0.85 \quad (1)$$

Intheexpression:-Yieldstrength,in MPa.

From Figure 8, it can be seen that under theconditionsof800 ° Candinternalpressure, the maximum stress in the cylinder is 215.7 MPa, which indicates that there will be no failure in strength or stiffness.

*4.3Stabilityanalysis*

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'sinitialconfigurationateachstageof 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), linearbuckling analysis employs the eigenvalue methodtoobtain thebuckling loadfactorsand buckling modes.

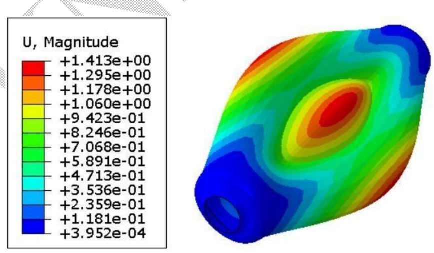
$$([K])+\lambda_i[S])\{\psi_i\}=\{0\} \qquad (2)$$

Intheexpression:[K]、[S] is constant

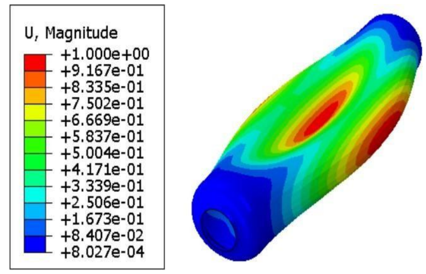
$\lambda_i$-Bucklingloadfactor

-Buckingmodeshape

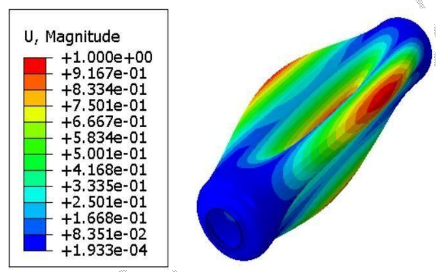
Linear buckling analysis was performed using ABAQUS to determine the critical load and instability modes of the pressure vessel cylinder. The simulation applied a uniform external pressure of 2.5 MPa to the cylinder and constrained the displacement at both ends[12]. A linear perturbation buckling analysis step was set up, with the linermaterial 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 Figure 10.



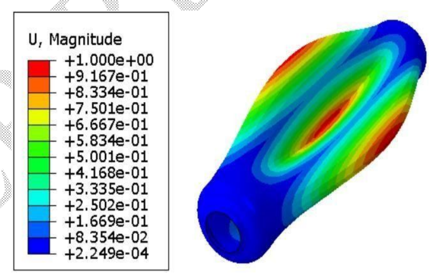

**(a)** Firstmode




**(b)** Second mode




**(c)** Thirdmode




**(d)** Fourthmode

**Fig.10** Thefirstfourstagebucklingmodesofa double-deck ballast tank

Theeigenvaluesandinstabilitymodesfor eachorderareshowninTable 4.

**Table4** Thefirstfourbucklingeigenvaluesand instability waves

| Stabilityparameter | Eigenvalue | Destabilizingwave |
|---|---|---|
| Firstmode | 8.8589 | 4 |
| Secondmode | 8.8999 | 4 |
| Thirdmode | 13.597 | 6 |
| Fourth mode | 13.710 | 6 |

Fromthetableabove,itisevidentthat

the eigenvalue for the first mode of thedouble-layer pressure vessel is 8.8589. The calculation method for the critical load is as follows.

$$_{r}= \quad (2)$$

Intheexpression：

$p_{cr}$-Criticalpressure，inMPa；

λ-Eigenvalue；

p-Externalpressure，inMPa。

Thecriticalloadwascalculatedtobe 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 itfails.

## 5 Samplemakingandtesting

To obtain the actual parameters and sealing performance of the pressure vessel under internal pressure and to verify the accuracyand 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 ° ]slayupscheme, 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 surfacesnear the bolts onboth ends of the end caps, as shown in the detailed dimensions in Figure11

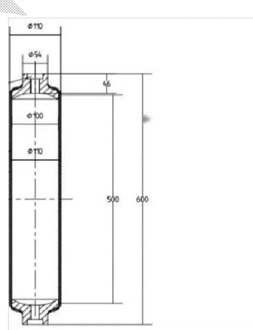


**Fig.11**Physicalsize drawing

### *5.1 Hydrostatictest*

To assess whether the pressure vessel cylinder wouldfail and to verify the reliability of the ABAQUS finite element analysis software, a hydrostatic pressure test was conducted on the completed pressure vessel shellin accordancewith nationalstandardsfor pressure vessels[13]. The physical prototype is shown in Figure 12.

**Fig.12**Experimental objects

### *5.2 Loadingtest*

The pressure vessel was subjected to a hydrostaticpressureloadaccordingtonational 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 Figure 12.

**Fig.13**1.5MPatest

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.14**2MPa test

*5.3 Experimentalresult*

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 shellandatitanium alloylinerforthepressure 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 intrinsicpropertiesbutalsobythepre-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, stiffnessfailureprecedesstrengthfailure;thus, the stability of the pressure vessel should be prioritized in underwater intelligent devices deployed at greater depths.



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