*Original Research Article*

# Design and analysis of underwater double-layer ballast tank prepared with different materials

**Abstract:** As the core component of underwater intelligent equipment, the ballast tank plays a role in pressurizing and protecting internal precision instruments in the entire structure. The design of a more lightweight, stable and stronger ballast tank has become the focus of research.In order to explore the influence of materials on the double-layerstructure ballast tank, the loading hydrostatic pressure of the cylindrical double-layer structure ballast tank made of different materials was numerically studied. Solikworks 3D design software was used to establish a finite element model of ballast tank, and the model was imported into Abaqus finite element analysis software. Different materials of ballast tanks were endowed with different material properties.Then, the actual working conditions of the ballast tank under water are analyzed by finite element method, and the external pressure of 7.5MPa is loaded to analyze the strength and stability of the ballast tank of the same size. The simulation results show that the ballast tank made of carbon fiber composite materialhas the advantage of lightweight, which is 59% less than that of titanium alloy ballast. ; The stability of titanium alloy ballast tank is excellent, and the critical load reaches 14.72MPa. Carbon fiber/titanium alloy ballast absorb the advantages of the two types of ballast has a variety of functions, can be applied to a variety of conditions, compared to titanium alloy ballast weight reduction of 24%. The carbon fiber/titanium alloy ballast tank was prepared, pressurized by 2MPa and held for 12h. The experimental results verified the structural safety and sealing reliability of the ballast tank.

**Keyword:** Ballast tank, double-layer construction,Finiteelementanalysisi， carbon fiber composite material, lightweight.

## 1 INTRODUCTION

When underwater intelligent equipment is operating underwater, it needs to withstand hydrostatic pressure and ensure the normal use of internal precision instruments, which determines that ballast is an important basic form of underwater equipment[1]. The harsh working environment requires that the ballast tank has the characteristics of high strength and high stiffness, and at the same time, its waterproof sealing is crucial[2].Common ballast shapes include spherical, cylindrical, conical, etc. Different structural forms will determine the use of underwater intelligent equipment[3]. At present, most of the ballast tanks used in underwater equipment are single-layer structures, but in order to realize multi-functional applications of submersibles, double-layer ballast tanks have become one of the focuses of future research on submersibles. Hu Zixiao[4] et al. took double-layer reinforced cylindrical shell as the research object and analyzed the influence of reinforced structural design on the strength, stability and ultimate bearing capacity of single-double layer cylindrical shell. Yi[5]et al. proposed that the coating layer can increase the anti-knock performance of double-layer cylindrical shell, which is significantly improved compared with the increase of thickness. Cao Xiaoming[6]et al. proposed an analytical calculation method for the stress and stability of double-layer cylindrical shells, and compared with the finite element results, it is shown that the calculation method has good accuracy.

The material of the ballast tank usually determines the overall performance of the ballast tank. Traditional ballast tanks are mostly made of metal materials, such as titanium alloy, alloy steel, aluminum alloy and so on. However, with the wide application of non-metallic materials in sports equipment, carrier rockets and aircraft, underwater intelligent equipment has gradually taken composite materials as one of the key research objects of forming materials. Ramos[7]et al. analyzed the failure conditions of composite materials and predicted the burst pressure through the Tsai-Wu strength criterion. Huang Zhiliang[8]has carried out mechanical analysis and experimental research on the double-layer cylindrical ballast tank using aluminum alloy, and the results show that the ballast tank shell has sufficient strength and stability. Yang Lu[9]analyzed the mechanical and fatigue characteristics of titanium alloy pressure spherical shell, and designed an equivalent deformation specimen which is expected to replace the whole sphere for test analysis and fatigue life evaluation.

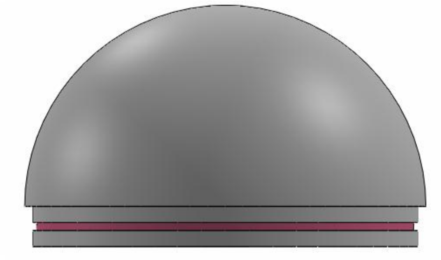
In this paper, Solikworks 3D software will be used to design a small underwater ballast tank with a cylindrical shell length of about 500mm and a diameter of 100mm, both inner and outer layers are 2mm,in which precision instruments can be placed. Based on Abaqus finite element software, different material properties were assigned to the ballast tanks. The mechanical properties of the cylindrical ballast tanks of double carbon fiber composite, double titanium alloy and carbon fiber/titanium alloy were analyzed under 7.5MPa hydrostatic external pressure, and their critical load values were calculated. The differences of ballast tanks prepared with different materials are discussed to provide experience in structural design and material selection for the preparation of large underwater ballast tanks, and to provide scientific and technological support for the development and utilization of underwater resources.

# 2.BALLAST MOLDING DESIGN

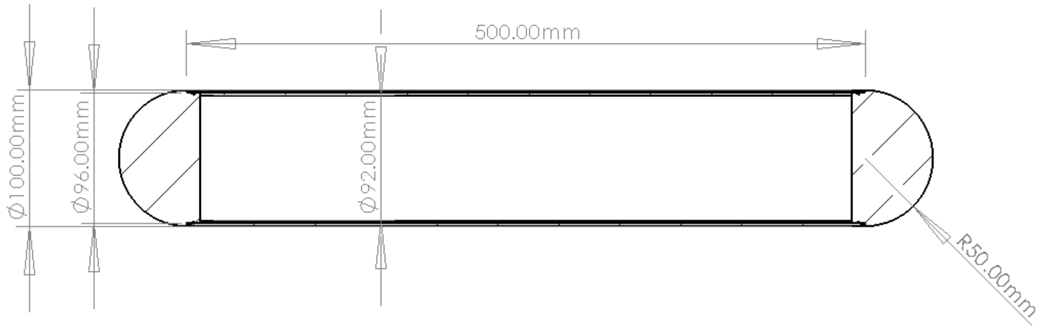
## 2.1.STRUCTURAL DESIGN

At present, many researchers are trying to prepare large deep-water intelligent equipment, and a variety of new ballast structures such as egg-shaped [10]and multi-type have been developed. No matter what kind of structure of the pressure shell, will be subject to certain constraints, including insufficient space utilization, processing and manufacturing difficulties, the structure is not stable enough and a series of problems. Considering the influence of these conditions, the cylindrical structure is still the mainstream structure of the ballast tank. As for the single-layer cylindrical shell, the actual working conditions can be satisfied with the increasing demand of Marine development. When the ballast tank is operating underwater, it will be loaded not only by the hydrostatic pressure, but also by a variety of impact loads. From this, a double-layer cylindrical ballast tank is introduced, which can adapt to a variety of special loads while meeting the strength and stability. In this paper, a simplified model of double-layer cylindrical shell is designed, which does not consider the ribs of the cylindrical shell, and only takes into account the mechanical characteristics of the ballast tank made of different materials. Figure. 1 shows the structure of cylindrical ballast tank.

a Cylindrical shell for ballast



b Ballast ball head




c Dimensional drawing

Fig.1.Ballast structure drawing

As shown in Figure 1, the cylindrical shell of the ballast tank is divided into an inner layer and a shell layer. The thickness of the shell layer is 2mm, the length of the shell is 500mm, the length of the inner layer is 480mm, and the radius of the ball head is 50mm. The connection between the cylindrical shell and the cylindrical shell depends on bolts and welding methods. To prevent the leakage of gas or liquid in the ballast structure and ensure the safety of equipment in the cabin body, O-rings need to be added. The red part of the ball head is where the O-rings are placed. The connection between the inner and outer layers of the double pressure tank is also extremely important. Double carbon fiber and carbon fiber/titanium alloy preparation of the ballast tank based on the grid theory, the use of wet forming process, the continuous fiber soaked in resin in accordance with certain rules on the mold or titanium alloy cylindrical shell[11]. The inner and outer layers of the double-layer titanium alloy cylindrical shell are fixed together by welding.

## 2.2.SELECTION OF BALLAST MATERIAL

Pressure shell materials are mainly made of metal and non-metal materials, and the performance difference between different materials is also large. Titanium alloy and carbon fiber are currently widely used in aerospace, underwater equipment, automotive and other fields of advanced materials, with strong quantization, corrosion resistance and other characteristics. Table 1 shows the main parameters of commonly used materials for various underwater intelligent equipment.

Table 1. Main parameters of commonly used materials

| material type | Density/ ( $g/cm^3$ ) | Modulus /*Gpa* | Strength/*Mpa* | Elongation /% | Yield strength /*Mpa* |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| TC6 | 4.5 | 110 | 1100 | – | 910 |
| Q235 | 7.8 | 190 | 500 | – | 235 |
| Aluminium | 2.7 | 69 | 290 | – | 240 |
| T700CF | 1.8 | 230 | 4900 | 2.1 | – |
| M40 CF | 1.75 | 377 | 4400 | 1.2 | – |
| Glass Fibre | 2.55 | 81.3 | 3440 | 4.8 | – |

According to the above table, it can be concluded that the density of aluminum alloy is the smallest among metal materials, and it is one of the commonly used light metals. The underwater ballast tank prepared by aluminum alloy has the advantage of lightweight, can provide the smallest volume weight ratio, and can maintain stable load loading under the condition of small volume density. In contrast, the steel ballast tank, in the current global context of the pursuit of lightweight intelligent equipment, because of its large density, resulting in the preparation of the submersible weight is too heavy, affecting the range of fields in which it can be applied. However, structural steel is still widely used in submarines such as nuclear submarines because of its good alloy properties, corrosion resistance, and good sealing and high temperature resistance. Compared with the above two materials, titanium alloy has higher yield strength, can meet the needs of the ballast tank carried by the large submersible, the specific strength and the specific modulus are significantly stronger than other metal materials, can be more stable when subjected to underwater explosion impact, and has the characteristics of discharge penetration and long cycle life. Therefore, this paper chooses titanium alloy material to prepare double-layer metal material ballast tank.

As a lightweight material, composite materials have made great progress in all kinds of engineering fields, compared with metal materials, the use of fiber materials processing equipment, lighter weight, while the strength and stiffness are higher. The fatigue failure of metal materials is usually a sudden failure without obvious warning, and the joint surface of the reinforcement and the matrix in the composite material can not only effectively transfer the load, but also the expansion of the cracks in the organization, and improve the fracture toughness of the materia[12]. As shown in Table 1, the three fiber materials can be used as fiber materials for the preparation of underwater ballast tanks, but the current development of glass fiber is still not mature enough, although it has been applied to some land equipment, but to be applied to underwater equipment, more in-depth research is needed. At present, Japan's Toray company is committed to the research of higher strength, greater modulus of carbon fiber, so that it can be more widely used at home and abroad as a fiber reinforcement material for the preparation of underwater vehicles. In this paper, T700 carbon fiber resin composite material is selected to prepare a double-layer ballast tank, and its mechanical properties and load-bearing capacity are analyzed, and compared with metal ballast tanks.

# 3. FINITE-ELEMENT ANALYSIS

ABAQUS is a powerful set of finite element software for engineering simulation, which can carry out finite element work on very complex structural models, and can handle a variety of linear and nonlinear problems. ABAQUS is able to complete both the analysis of a single part and the finite element analysis of the system. Various types of material model libraries can simulate the performance of typical engineering materials such as metal, polymer materials, composite materials, rubber, etc. In addition to solving a large number of (stress/displacement) problems, ABAQUS can also simulate other problems in other engineering fields, such as heat conduction, mass diffusion, fluid mechanics, etc. In this paper, ABAQUS finite element analysis software will be used to carry out finite element analysis of double-layer titanium alloy ballast tank, double-layer carbon fiber composite ballast tank and carbon fiber/titanium alloy pressure ballast tank, respectively, to check the stress and deformation under internal pressure and external pressure.

## 3.1.MATERIAL PROPERTY DEFINITIO

### 3.1.1.TITANIUM ALLOY MATERIAL DEFINITIONT

Any material has the stress-strain relationship shown in Formula 1. In the flexibility matrix, except the diagonal elements, the matrix in other positions all reflect the coupling relationship of the forces in the synchronous direction or in different planes. For metal or metal alloy materials, there is only a tensile coupling relationship, and the engineering constant to measure this coupling is known as Poisson's ratio, whose stiffness matrix contains only two independent engineering constants E and μ. Table 2 shows the material properties of titanium alloy

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11}S_{12}S_{13}S_{14}S_{15}S_{16} \\ S_{12}S_{22}S_{23}S_{24}S_{25}S_{26} \\ S_{13}S_{23}S_{33}S_{34}S_{35}S_{36} \\ S_{14}S_{24}S_{34}S_{44}S_{45}S_{46} \\ S_{15}S_{25}S_{35}S_{45}S_{55}S_{56} \\ S_{16}S_{26}S_{36}S_{46}S_{56}S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix}$$

（ **Error! Bookmark not defined.**）

Formula 1：$\varepsilon_1$、$\varepsilon_2$、$\varepsilon_3$−Tensor shear strain；

$\gamma_{23}$、$\gamma_{13}$、$\gamma_{12}$−Engineering shear strain；

$\sigma_1$、$\sigma_2$、$\sigma_3$−normal stress;

$\tau_{23}$、$\tau_{13}$、$\tau_{12}$−tangential stress.

Table 2.Titanium alloy material parameters

| Material | $\rho$/（*g/cm*$^3$） | Modulus of elasticity/*MPa* | $\mu$ |
|---|---|---|---|
| Titanium alloy | 4.5 | 107800 | 0.34 |

### 3.1.2.CARBON FIBER COMPOSITE MATERIAL DEFINITION

Composite materials are different from metal materials and have the characteristics of anisotropy. Generally, composite monolayers exhibit orthogonal anisotropy in their material principal direction. When the same force is applied in the main direction of each material, the amount of tensile or compressive deformation is different, so each direction has different elastic modulus, and similarly, Poisson's ratio in each direction is also different. Table 3 shows the material parameters of carbon fiber composites。

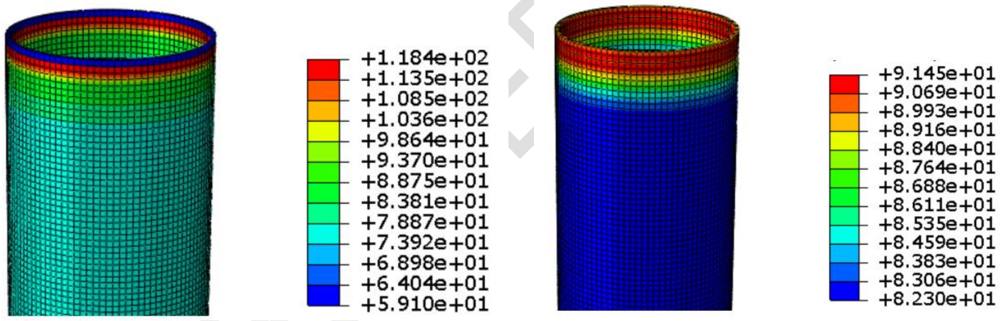
Table 3.Material parameters of carbon fiber composites

| $E_x$ | $E_y$ | $E_z$ | $V_{xy}$ | $V_{yz}$ | $V_{xz}$ | $G_{xy}$ | $G_{yz}$ | $G_{xz}$ |
|---|---|---|---|---|---|---|---|---|
| 115000 | 6200 | 6200 | 0.28 | 0.34 | 0.28 | 6100 | 4500 | 6100 |

Different from the structural design of metal materials, the design of composite materials usually requires layering, which makes the composite materials have a certain designability. Different layering methods will have different effects on the prepared cylindrical shell of ballast tank, and the performance will be greatly different. The layering design generally adopts 90° layer to bear axial load, 0° layer to bear radial load and 45° layer to bear shear load. In order to facilitate subsequent physical tests, the layup design of [90°/90°/0°] was selected for simulation analysis in ABAQUS.

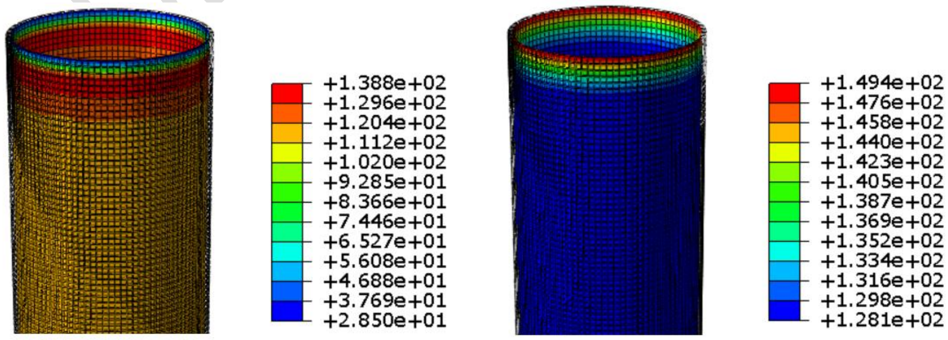
## 3.2.STRENGTH ANALYSIS

The depth of ballast tank is estimated to be 500m. ABAQUS is used to simulate the deep-sea environment of 500m. Hydrostatic pressure is applied outside the ballast tank to analyze the strength. The water pressure of 100m of ordinary still water is about 1MPa, and 500m is 5MPa. According to the pressure vessel design standard, the water pressure applied by the ballast tank shell should be 1.25 times the actual pressure, that is, the uniform external pressure of 7.5MPa is applied in the simulation process.Titanium alloy adopts 3D stress-C3D8R unit in the simulation process, carbon fiber adopts continuous shell -SC8R unit. Fig. 2, 3, 4 and 5 are stress analysis diagrams.



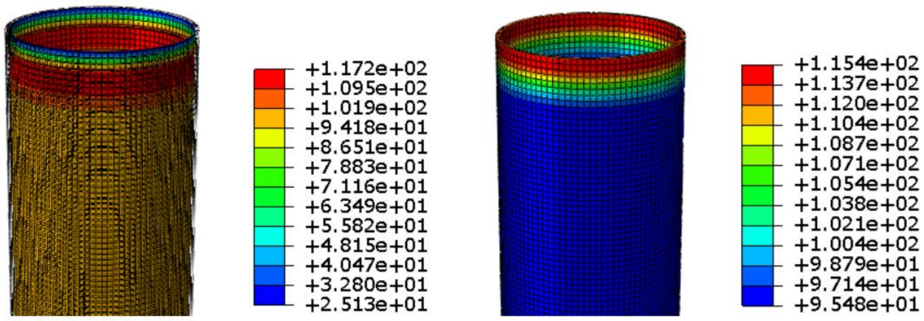

a.Titanium enclosure　　　b. Titanium alloy lining

Fig 2.Stress diagram of double titanium alloy ballast tank




a. Carbon fiber shell　　　b. Carbon fiber lining

Fig3. Double carbon fiber ballast diagram




a. Carbon fiber shell b. Titanium alloy lining

Fig 4.Carbon fiber/titanium alloy pressure withstand cabin stress diagram

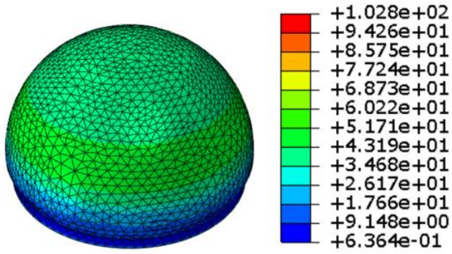



Fig 5.Stress diagram of ballast ball head

It can be seen from the above stress diagram that the three types of ballast tanks can meet the strength requirements. The double-layer titanium alloy ballast chamber produces the least stress, and the carbon fiber/titanium alloy ballast chamber has a medium performance, indicating that in the static water environment of 500m underwater, the strength of titanium alloy is better, and the probability of strength damage of the shell is small. However, the stress value of the double-layer carbon fiber composite ballast is also less than the upper limit of strength, and it can be seen from Table 1 that its strength limit is higher than that of titanium alloy, and the mass drainage ratio is also better than that of titanium alloy ballast.

## 3.3.STABILITY ANALYSIS

When the ballast tank is working underwater, the external needs to withstand the effect of hydrostatic pressure, and the weakening of its stress stiffness matrix will lead to the reduction of the structure's resistance to lateral load, and when the stress hardening effect exceeds the inherent stiffness, the cabin body will suffer buckling instability {13}. The instability of cabin body is usually manifested as lateral instability, axial instability and local instability. The theoretical way to calculate whether the cabin is unstable is to judge the Pcr size, that is, the critical load size. The two methods of Pcr calculation are as follows.

Calculation method of critical load of long tank body

$$P_{cr}=\frac{2E^t}{1-\mu^2}\left(\frac{\delta_e}{D_0}\right)^3$$ （**Error! Bookmark not defined.**）

Formula 2：$P_{cr}$-Critical load，MPa；

$E^t$-Modulus of elasticity，MPa；

$\mu$-Poisson's ratio；

$\delta_e$-Effective thickness of cylindrical shell，mm；

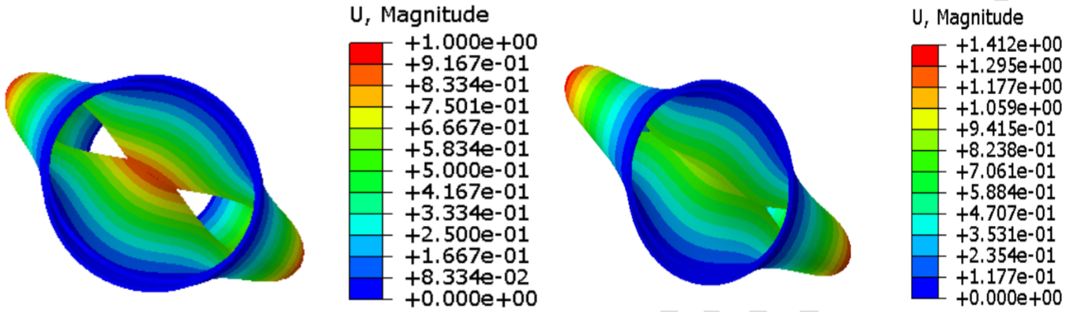
$D_0$-Cylindrical shell outer diameter，mm。

Calculation method of critical load on short hull

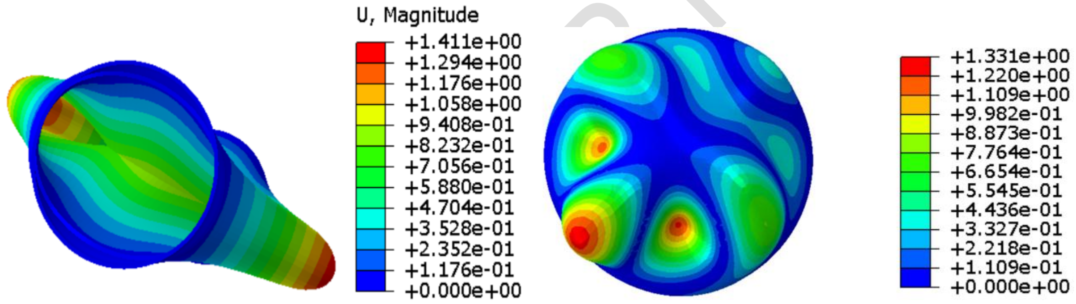
$$P_{cr}=2.59E^{t}\frac{(\delta_e/D_0)^{2.5}}{(L/D_0)} \quad \textbf{（Error! Bookmark not defined.）}$$

The long tank body or short tank body is determined by Lcr (critical length). If the true length of the cylinder shell of the ballast tank is greater than Lcr, it is the long tank body, and otherwise it is the short tank body.

The above is a theoretical calculation method for stability analysis. The ABAQUS finite element software is used to calculate the critical load and the form of instability of the cylindrical shell of the ballast tank by obtaining the characteristic value through buckling analysis. In the buckling analysis, the boundary conditions of the ballast tank were consistent with the static analysis, and the hydrostatic pressure was loaded at 7.5MPa.




a.Double titanium alloy ballast tankb.Double carbon fiber ballast tank




c.Carbon fiber/titanium alloy ballast tankd.ball head

Fig 6.Comparison of buckling modes of double deck ballast tank

According to the modal diagram, we can see that the modulus of the first-order buckling modes of various ballast tanks is the same, but it does not mean that their critical loads are the same. The following table shows the characteristic values and critical loads of the first-order modes.

Table4. Characteristic values and critical loads

| | Double titanium alloy ballast tank | Double carbon fiber ballast tank | Carbon fiber/titanium alloy ballast tank |
|---|---|---|---|
| First-order modal eigenvalues | 2.5643 | 1.9211 | 1.9623 |
| Critical load /MPa | 19.23 | 14.41 | 14.72 |

The critical load size is calculated as follows:

$$p_{cr} = \lambda p \quad \textbf{（Error! Bookmark not defined.）}$$

Formula4：$\lambda$-Value

According to the analysis and obtained data, the double-layer titanium alloy ballast tank has the maximum critical load of 19.23MPa under the underwater environment of 500m, and the performance of other ballast tanks is also extremely excellent, reaching 14.41MPa and 14.72MPa. The critical load of the three ballast tanks exceeds the loaded 7.5MPa hydrostatic external pressure, that is, they can meet the needs of underwater vehicles.

# 4.BALLAST FILLING TEST

Due to the special needs of the environment, it is necessary to ensure that the ballast tank has enough water tightness and air tightness. In order to verify whether the structural design ballast can meet the requirements, the carbon fiber/titanium alloy ballast material was prepared, and the material was subjected to 2MPa and held for 24h.

fig7.Pressure test of ballast tank

As shown in Figure 7, the prepared ballast tank is placed in a cylindrical holding tank and pressurized internally by pressurizing equipment.Then hold the pressure for 24 hours.During the whole experiment, the structure of the cabin remains intact, with good strength and stability, and there is no leakage of water and gas, which proves that the structural design and simulation analysis are feasible.

# 5.Conclusion

In this paper, a small double-deck ballast tank with a length of 500mm and a diameter of 100mm is designed, which is suitable for underwater vehicles.Titanium alloy and carbon fiber composite materials were selected to prepare the underwater double-layer ballast tank, and the strength and stability of the cylindrical shell and the ball head of the three ballast tanks were checked and compared, and finally the carbon fiber/titanium alloy ballast tank was developed to complete the pressurization experiment.

（1）In the choice of metal materials, titanium alloy has obvious advantages compared with aluminum alloy and alloy steel. The higher yield strength can guarantee the higher stability of the cabin body, and the specific strength is stronger than other metal materials, which is the high-quality choice of metal base ballast. Compared with metal materials, carbon fiber composite materials have lower density, higher specific strength and specific modulus, which can prepare lightweight ballast tanks while ensuring strength and stability.

（2）The finite element model is established to evaluate the strength and stability of the double-layer ballast tank. The results show that the three kinds of ballast tanks meet the requirements of strength and stiffness, and are far from reaching the yield limits of fiber and metal. Among them, the double-layer titanium alloy ballast chamber has the smallest stress and the largest critical load, reaching 14.72MPa.

（3）The pressure retention test for 12h with 2MPa internal pressure is carried out, and the results show that the cabin body has no damage to strength and stiffness, and has reliable sealing property

The selection of materials is necessary for the preparation of underwater double-deck ballast tanks. The cabin body developed by different materials is suitable for different scenarios, and the carbon fiber cabin body is obviously lighter, which is suitable for the pursuit of lightweight underwater vehicle; Titanium alloy hull can provide excellent stiffness performance on the applicable submersible, but the upper limit of strength is weaker than that of carbon fiber composite. With carbon fiber composite material as the outer shell and titanium alloy as the inner liner, the cabin body has moderate performance, which can not only reduce weight, but also provide reliable performance and have more diversified functions.

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