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Analysis of Laminated Composite Based Deep-water Pressure Tank

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Author’s contribution

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

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ABSTRACT

Large submersible deep-water vehicles have become the key equipment for global exploration of the ocean. As one of the core components of underwater equipment, underwater pressure tanks protect internal devices from huge water pressure on the one hand, and are also the main supplier of underwater buoyancy on the other hand. Compared with metal materials, the designability of composite materials can provide researchers with a variety of structural methods. In this paper, a new type of double-layer pressure tank is proposed, the influence of structural size on the critical load of the pressure tank is explored, and a grid structure is designed to optimize the stability of the large-size pressure tank. The feasibility is proved by finite element analysis experiments.

Keywords: Underwater pressure tanks; composite material; critical load; grid structure.

1. INTRODUCTION

As a new frontier of development, how to make full and reasonable use of rich mineral and biological resources is a necessary condition for sustainable development. However, in terms of understanding and developing Marine resources, the high pressure and extreme environment of the seabed make it impossible for human beings to effectively explore and exploit deep-sea resources with existing underwater equipment [1]. Therefore, the rapid development of

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underwater intelligent vehicles is particularly important. As key equipment for ocean development and ocean research, it can not only obtain underwater intelligence information, but also complete tasks such as environmental detection and target identification, which has broad development prospects [2]. With the increasing of the design depth of underwater intelligent equipment, the compressive performance of the structure of the submersible is an important consideration. As the main pressure component of underwater intelligent equipment, the pressure tank is used to protect the internal devices from huge water pressure and seawater erosion to ensure the normal operation of precision instruments. At the same time, the weight of the pressure tank itself occupies a part of the underwater intelligent equipment, which is between one-fourth and one-half of the total weight, and also acts as the main supplier of underwater buoyancy [3].

With the deepening of human exploration in the deep-sea field, the research of pressure tank is becoming more and more advanced, and many researchers are committed to the in-depth analysis and discussion on its performance optimization. Hafiz et al. [4] took wood as the core material of the composite sandwich submersible and optimized the pressure shell based on finite element analysis (FEA). Taheri-Behrooz et al. [5] studied the effect of initial geometric defects on the buckling behavior of perfect and perforated composite cylinders, and BinLi et al. [6] Proposed a collaborative optimization method for ring-reinforced composite pressure hull used in underwater vehicles. Zuo Xinlong et al. [7] made spiral wound carbon fiber composite shells with different length-to-diameter ratios, and found that the length-to-diameter ratio had a certain influence on the strength and stiffness of the shells. Yoon et al. [8] derived an empirical formula for predicting the collapse strength of composite cylindrical shells based on the function of structural geometry and layup Angle of pressure tanks subjected to external hydrostatic pressure loads. Narayan Sharma et al. [9] conducted dynamic and aeroelastic analysis of variable fiber spacing composite (VFSC) laminates. P Chandrakar et al. [10] investigated the reason why the thermal buckling performance of VATL deteriorates due to the presence of damage (internal defects) under the condition of uncertainty of various composites and damage properties.

In this paper, based on the application status of composite materials in Marine equipment, the advantages of their application in underwater pressure tanks are analyzed, and a new structural pressure tank is proposed for optimization study.

2. APPLICATION AND DEVELOPMENT OF COMPOSITE MATERIALS IN UNDERWATER EQUIPMENT

In recent years, non-metallic materials have become more and more widely used in the field of ships and underwater vehicles, thanks to their lightweight characteristics and excellent performance. From early military ships to all kinds of Marine ships today, and even the key parts of large ships, the application of composite materials continues to expand. In the Marine energy sector, composites such as carbon fiber are favored for their light weight, high strength and corrosion resistance. In particular, the preparation of underwater pressure tanks, non-metallic materials such as carbon fiber resin matrix composite materials play an important role, providing strong support for deep-sea exploration and Marine resources development.

2.1 Underwater Application of Composite Materials

As early as 1946, the U.S. Navy pioneered composite ships and successfully built the first ships of this type using fiberglass. In the 1960s, the United States further in-depth research, set up a composite pressure shell project, through a series of comparative tests with metal pressure shells, confirmed the significant advantages of composite pressure shells in strength and weight. In 1996, the United States made another breakthrough, using glass fiber reinforced resin composite materials to develop DeeP Flight 1 observation manned submersible, to achieve a depth of 1000 meters underwater operation. In the 21st century, the pace of technological innovation in the United States has not stopped, and the M80 Dagger stealth ship put into use in 2006 is a masterpiece of carbon fiber composite materials, and its integrated molding process avoids cumbersome steps such as welding, greatly reducing the weight of the hull, and improving the operation efficiency and stability. In the 10th century, the United States launched Cyclops Ⅰ and Cyclops Ⅱ, the main section of the cabin using carbon fiber automatic wire laying technology, to further improve the reliability of the cabin. These milestones not only demonstrate the technological strength of the United States in the field of composite materials, but also inject new vitality into the development of deep-sea exploration and ship construction.

European countries have also made remarkable achievements in the research of composite underwater equipment. Talisman multi-functional autonomous unmanned underwater vehicle developed by the United Kingdom is an advanced technology and multi-functional Marine equipment, it includes two parts of the vehicle and remote control console, can perform a variety of tasks. The vehicle consists of a shell made of a carbon fiber composite material, which houses a carbon fiber composite pressure vessel containing the electronic system and payload. This design not only ensures the structural strength of the vehicle, but also ensures the stable operation of its internal systems. In addition, the housing is equipped with a commercial booster fairing, giving the vehicle better maneuverability and the ability to rotate 360 degrees to adapt to a variety of complex Marine environments. Norway's Hugin 3000 fuselage, made of carbon fiber laminate and composite foam, is strong enough to ensure maximum payload, but also means that it can carry sufficiently accurate navigation sensors, as an autonomous vehicle, the Hugin 3000 is highly autonomous and intelligent. It can make autonomous decisions and operate according to a preset task plan, or it can be remotely operated by an operator in remote control mode.

2.2 Molding Process of Composite Materials

2.2.1 Traditional composite molding process

Composite molding process is the basis and condition for the development of composite technology. At present, there are more than 20 kinds of molding methods for composite materials, and different molding processes can be developed according to different types of composite materials. Common industrial production methods include resin transfer molding technology (RTM), pultrusion molding process, winding molding process, etc. Resin transfer molding technology is a kind of resin material through the pipeline into the mold molding technology, suitable for the manufacture of composite materials, as shown in Fig. 1. In this process, a reactive liquid resin is injected under pressure into a closed mold in which the fiber preform is laid. Under the condition of maintaining a certain pressure, the curing reaction of the resin is triggered by heating the mold. At the same time, through the interface effect, the resin is combined with the reinforcement to form an integrated composite structure with excellent physical, chemical and specific functions [11]. The technology is mainly suitable for the production of large and complex products, such as automobile shells, electrical shell, etc., with the advantages of fast molding speed, high precision of finished products and high production efficiency. Pultrusion is a process in which materials are extruded through an extruder as shown in Fig. 2. That is, the thermoplastic resin and continuous fiber reinforced material are pre-impregnated or mixed evenly, and then the mixed composite material is sent to the pultrusion machine, which is heated and extruded to form the required shape, and finally cooled and cured [12]. Composites prepared by pultrusion usually have excellent mechanical properties and surface quality, and are widely used in various fields. The composite pressure tank studied in this paper adopts the winding molding process. The working flow is to combine the fiber material with resin or other adhesive, and then wrap it along a specific axis to form the composite product with axial fiber layer. The winding molding process has the characteristics of automation, which can effectively control the winding Angle and interlayer arrangement of the fiber, and prepare lightweight composite materials.

2.2.2 New composite molding process

The development trend of composite molding process is moving towards a more diversified, efficient, environmentally friendly and intelligent comprehensive process. With the continuous progress of science and technology, the composite molding process has achieved significant improvement in production efficiency and product performance. In order to improve production efficiency and reduce energy consumption, the preparation process of composite materials is gradually introducing more advanced equipment and processes to achieve efficient production. At the same time, fine treatment of raw materials and regulation of process parameters can ensure the quality and stability of composite materials, meet the growing market demand, promote the application of composite materials in Marine equipment and other fields, and promote the sustainable development of the entire industrial chain. The British developed the two-ring braiding machine, consisting of 288 and 192 spool, which is more than twice as flexible as the single-ring braiding machine, and can weave complex circles in the widest range of equivalent diameters from 50mm to 8000mm. As shown in Fig. 3, the two-ring knitting machine is engaged in weaving work, which can be finely crafted according to the needs of the project.

Developed countries such as the United States have developed an automated industrial technology - robot winding molding, which uses different fiber textiles, such as carbon fiber, glass fiber, etc., to be manufactured under tension to produce extremely strong or flexible parts specifically for the desired application. The advantage over traditional technologies is their ability to orientate stiffness according to the required function and load conditions, and with the latest computing power, it is possible to create ultra-light structural components that can reduce weight by up to 70%. As shown in Fig. 4, the robot is processing components.

Fig. 1. RTM

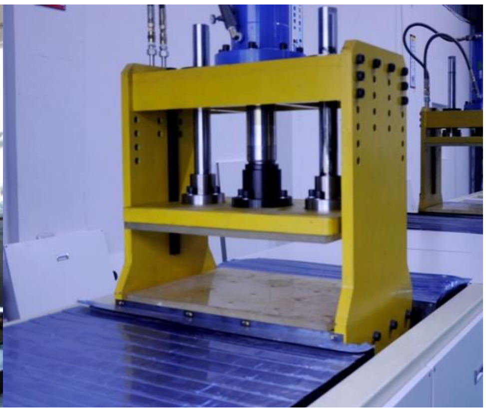

Fig. 2. Pultrusion

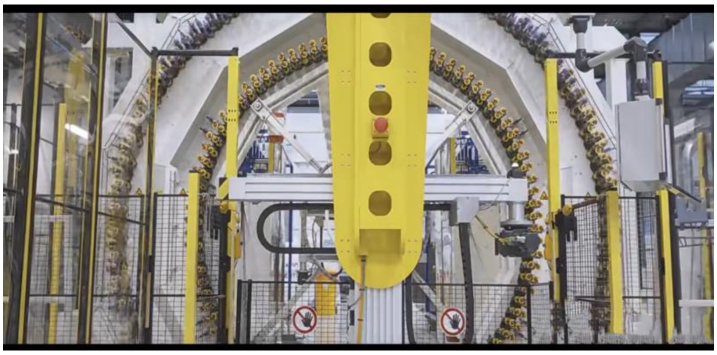

Fig. 3. British two-ring knitting machine

Fig. 4. Robot winding

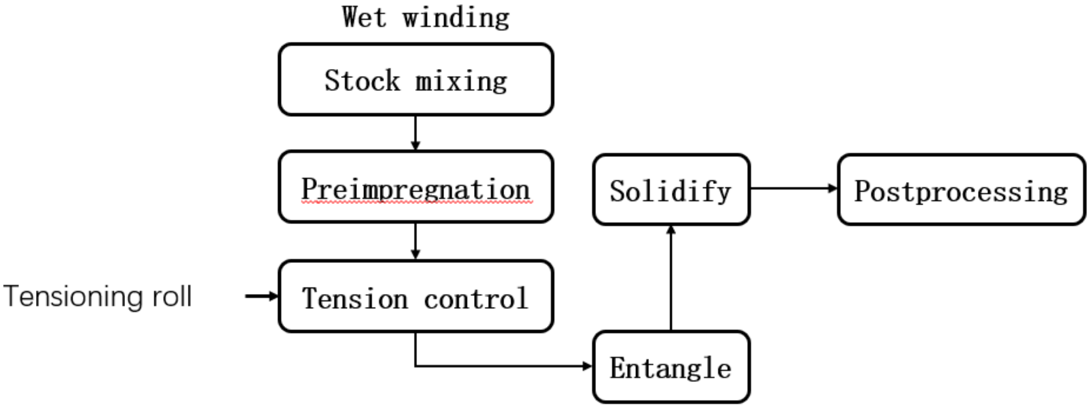

Fig. 5. Winding diagram

2.2.3 In this paper, the composite material molding process

The underwater pressure tank designed in this paper is a cylindrical structure, which can be prepared by fiber wet winding process. Wet winding specifically refers to the method of impregnating continuous fiber or fiber cloth in resin through a storage tank, and then winding directly on the mold under the guidance of the silk nozzle, and finally curing. In the wet winding process, the fibers are pre-immersed in a resin paste by an impregnating agent and then wrapped around a mold or blue plate. This method usually requires a long curing time so that the resin can cure sufficiently and obtain the desired properties, and the production process is shown in Fig. 5.

Wound molded products stand out for their outstanding high strength and stiffness properties, thanks to the continuity and pretension of the fibers, so that the fibers are tightly arranged inside the product, thus significantly improving the overall mechanical properties. At the same time, its excellent fatigue resistance ensures the stability of the product under long-term repeated loads, extending the service life. In addition, the winding design is flexible and changeable, and by adjusting the fiber winding parameters, it can meet various complex shapes and performance requirements, so it is widely used in many fields. More importantly, the winding molding realizes automated continuous production, improves production efficiency, while reducing manufacturing costs, showing its efficient and economical advantages.

3. PRESSURE STRUCTURE DESIGN

The design of pressure structure is the key to ensure the safe and stable operation of deep-sea equipment. In the design, factors such as material selection, structural layout, strength calculation, sealing performance and safety redundancy should be considered comprehensive to achieve the stability and durability of the cabin under extreme water pressure environment. At the same time, it is also necessary to pay attention to lightweight design to improve the overall performance of the equipment. Through accurate calculation and simulation analysis, the pressure structure is ensured to withstand deep sea high pressure, providing a solid guarantee for deep sea exploration and scientific research. According to the requirement of underwater application, a cylindrical pressure tank with carbon fiber composite material as shell and alloy material as inner liner is proposed in this paper.

3.1 Design of Composite Pressure Parameters

The cylindrical body segment composed of fiber composite materials and alloys can bear both pressure and lightweight, and its structural strength is affected by structural parameters such as thickness and length. In this section, the relationship between the winding Angle of the fiber layer, the length of the main segment and the thickness of the main segment is studied based on Abaqus finite element software. The performance parameters of the fiber layer and alloy are shown in Table 1 and Table 2.

Table 1. 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

Table 2. Titanium alloy material parameters

Material	ρl （g/cm^3）	Modulus of elasticity/*MPa*	μ
Titanium alloy	4.5	107800	0.34

Table 3. Diameter thickness ratio design parameter

Radius-thickness ratio	Winding Angle (θ°)	Length-diameter ratio
22	$\theta°_i$	3, 5, 7, 10
30	$\theta°_i$	3, 5, 7, 10

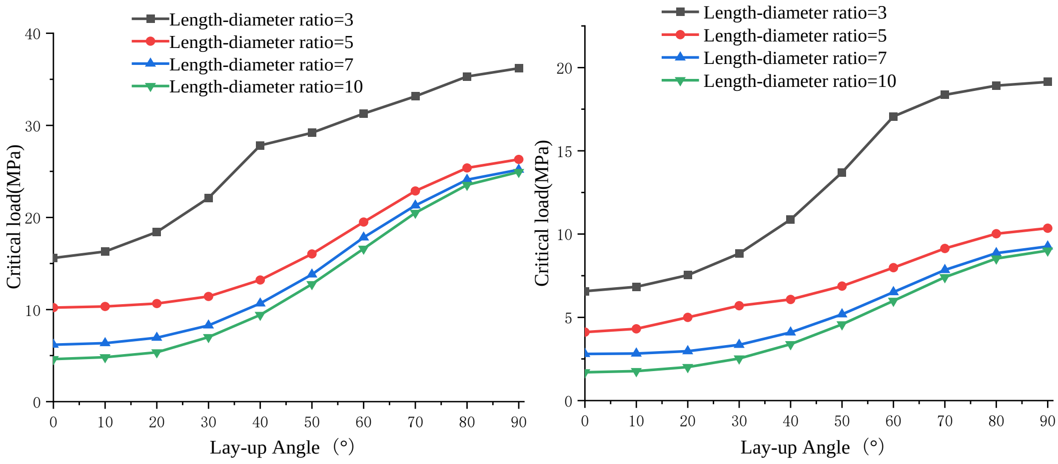

Fig. 6. Relation of winding Angle of cylinder with different length and critical load under different diameter thickness ratio

Assume that the outer diameter of the cylinder D=110m, and analyze the double-layer cylinder with different diameter thickness ratios. The design parameters are shown in Table 3. The thickness of the alloy inner layer is temporarily taken as 1mm, and the winding Angle is $\theta°_i$ (i= 10,20,30,40,50,60,70,80,90).

After analyzing the data in the table, Fig. 5 shows the relationship between the winding Angle of the cylinder of different lengths and the critical load under different diameter thickness ratio.

As can be seen from Fig. 6 when the diameter to thickness ratio is constant, the critical load of cylindrical shells of different lengths increases with the increase of the winding Angle, except for the fluctuation of some angles. When the winding Angle range is near 45°, the growth range of the critical load becomes larger, and after 70°, the growth range tends to be gentle, because the hydrostatic pressure under the cylinder mainly acts on the circumference of the cylinder. When the winding Angle is larger, the pressure resistance of the cylinder is better.

Using the same outer diameter of the cylinder, the double-layer cylinder with different length-diameter ratio is analyzed. The design parameters are shown in the Table 4.

Fig. 7 shows the relationship between the winding Angle of the cylinder of different thickness and the critical load under different length-diameter ratio. It can be seen from the figure that when the length-diameter ratio is constant, the thicker the cylinder is, the more obvious the critical load changes with the winding Angle; the thinner the cylinder is, the less the winding Angle influences the critical load.

Table 4. Diameter thickness ratio design parameter

Length-diameter ratio	Winding Angle (θ°)	Radius-thickness ratio
3	$\theta^{\circ}{}_{i}$	22, 30, 40, 55
5	$\theta^{\circ}{}_{i}$	22, 30, 40, 55

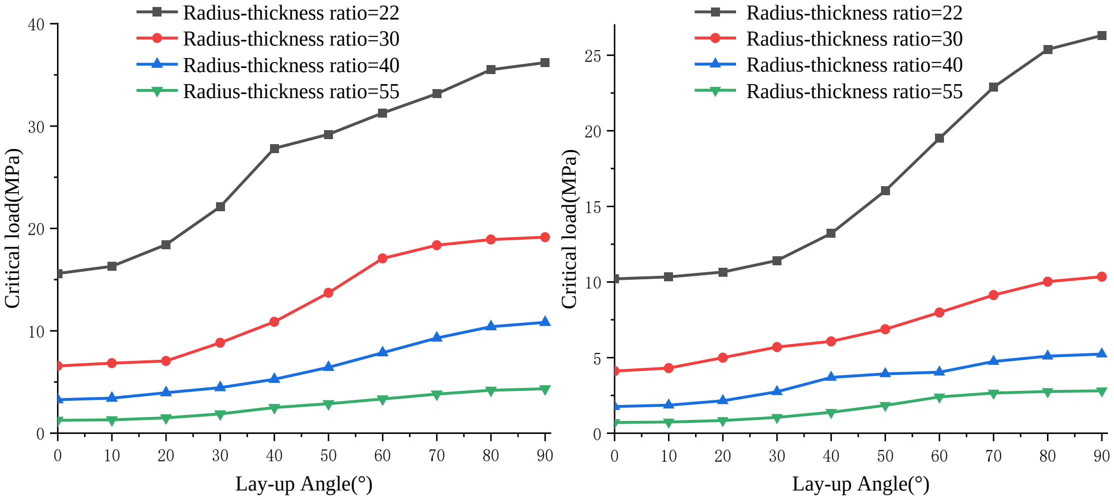

Fig. 7. Relation of winding Angle of cylinder with different length and critical load under different aspect ratio

In the design of underwater pressure tank, performance optimization is a continuous process, which requires continuous optimization of the parameters of the length and thickness of the pressure tank through simulation analysis and experimental verification, so as to improve its structural strength, stiffness and shock absorption performance, etc. At the same time, the internal space of the pressure tank should be considered, and the diameter of the main section cylinder should be considered to maximize its structural role. And meet the characteristics of lightweight.

3.2 Lining Parameter Design

In order to achieve the lightweight goal of the pressure tank, we proposed the concept of using an ultra-thin metal liner to prepare a composite pressure vessel, where the thickness of the metal liner is strictly controlled within 1mm. After further research, we found that for every 0.1mm reduction in the thickness of the metal lining, the mass of the main section of the pressure tank can be reduced by 3% to 6%, which provides a strong support for lightweight. Under the constraint of the composite shell, the buckling of the metal lining can only develop inward but cannot spread outward. This limited buckling mode is caused by the local structural defects of the lining. According to the buckling theory, the local buckling of the inner lining needs to meet certain conditions, in which the external pressure is an indispensable factor. Taking titanium alloy as an example, the relationship between the liner thickness and the critical load is deeply investigated. As shown in Fig. 8, through the analysis of titanium alloy liners with different thicknesses (0.8mm, 1mm, 1.2mm, 1.4mm, 1.6mm, 1.8mm, 2mm, 3mm), we found that the critical load reached its peak when the thicknesses were 1.6mm and 1.2mm. This result clearly shows that the critical load of the pressure tank is significantly affected by the thickness of the titanium alloy liner, and this effect is not a simple linear relationship. Therefore, when designing and analyzing the lining layer of pressure tank, we should give priority to the structural design of the lining layer, and deeply study its forming method. By optimizing the design and improving the process, we can avoid the loss of pressure stability due to design and process problems, thus ensuring that the pressure can maintain stable performance under high pressure.

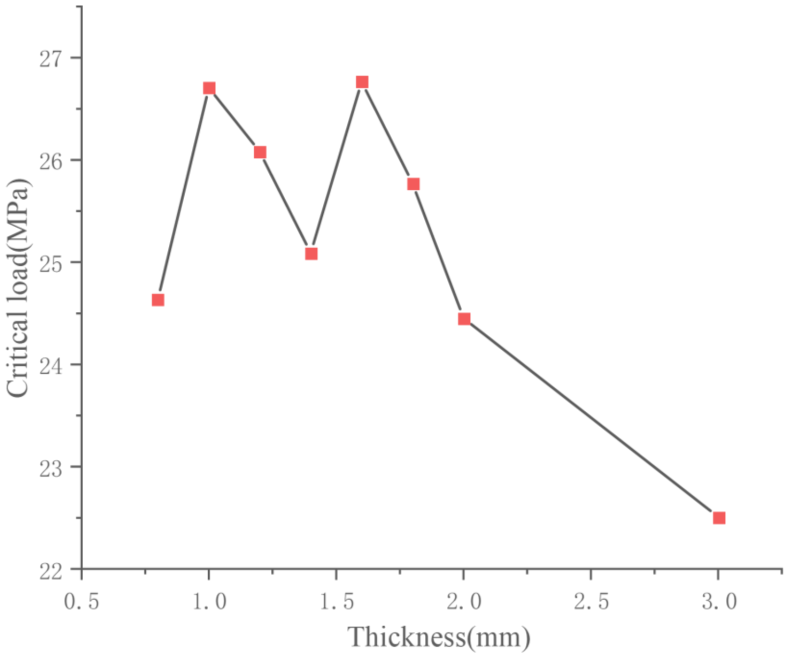

Fig. 8. Relationship between critical load and thickness of titanium alloy layer

4. LARGE SIZE COMPOSITE MATERIAL PRESSURE STRUCTURE OPTIMIZATION

4.1 Buckling Simulation Analysis

The stability of the pressure tank is closely related to the structural design of the main section cylinder, but the rigidity of the pressure tank with different lengths is quite different. In order to explore the structural stability of the large-size pressure tank, the 8000mm double-layer pressure cylinder is analyzed. It is expected that the submersible depth of large-size pressure tank is 200 meters. According to the national pressure vessel design code, the experimental pressure is 1.25 times of the actual pressure, that is, 2.5MPa is applied in the simulation process, and the first six modes are extracted. Each mode and its characteristic value can be extracted from the analysis and post-processing, as shown in Table 5.

It can be concluded from the above analysis that when the large-sized cylinder is subjected to external pressure in static water, the ultimate load of stiffness failure is 0.195MPa, which cannot meet the working requirements under 200m water. Therefore, it is necessary to optimize the cylinder structure and improve the stability of the cylinder within the controllable range.

4.2 Stability Optimization

The common stability optimization method is to thicken the pressure cylinder and add reinforcement, because the design goal is to achieve a lighter pressure cylinder under the condition of meeting the strength and stiffness. Therefore, this design only thickens the carbon fiber composite shell. Fig. 9 shows the change of the characteristic value of the pressure tank after the thickening of the shell.

Table 5. Buckling characteristic values and instability waves

Modal phase	Eigenvalue	Destabilizing wave	Ultimate load (MPa)
Rank 1	0.078	2	0.195
Rank 2	0.093	3	0.232
Rank 3	0.093	3	0.232
Rank 4	0.096	4	0.240
Rank 5	0.124	8	0.310
Rank 6	0.125	8	0.313

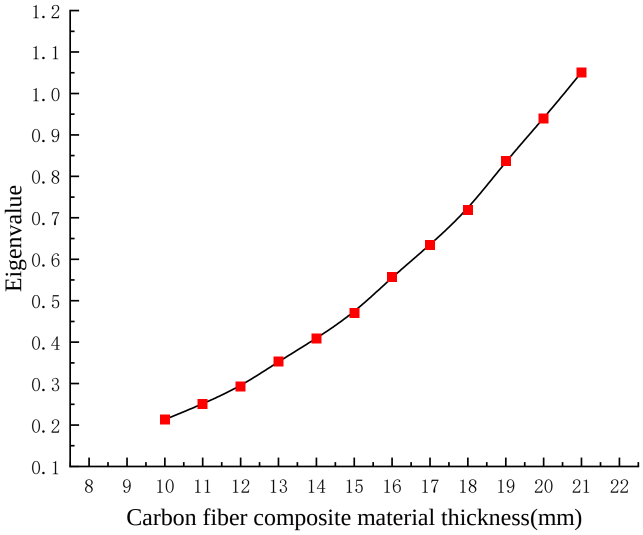

Fig. 9. The relationship between thickened tank body and characteristic value

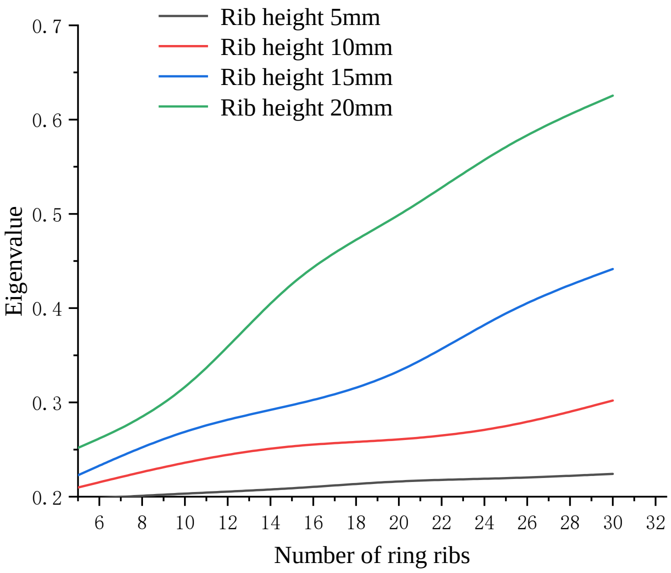

Fig. 10. Optimization results of large size pressure stability

With the thickening of the carbon fiber shell, the characteristic value continues to increase. When the thickness reaches 22mm, the characteristic value exceeds 1, that is, the pressure tank meets the working environment of 200m underwater at this time. However, just by thickening the hull, the overall weight of the underwater vehicle will be greatly increased, so the next research is conducted by adding ring ribs to the outer surface of the pressure tank.

As can be seen from Fig. 10 when the shell thickness of the carbon fiber composite material is constant, the smaller the rib height of the ring rib, the more gentle the change of buckling characteristic value, indicating that the size design of the ring rib has a certain influence on the critical buckling load, and the number of ring ribs laid is one of the main factors for raising the stiffened cylinder pressure tank. The presence of ring ribs not only effectively improves the stability of the pressure tank, but also reduces the strength-to-weight ratio compared to the solution using the thickened carbon fiber shell.

4.3 Grid Structure Optimization

The design of the optimal scheme of pressure tank is the key and difficult point affecting its stability. The above annular rib design does not increase the critical load of pressure tank linearly. The reason may be that stress concentration is prone to occur at the joint of pressure tank and annular rib after the placement of the ring rib, resulting in premature strength fatigue of the cylinder. Generate unwanted responses. Therefore, a grid structure is proposed in this section on the basis of the optimization scheme of ring ribs, as shown in Fig. 11 and the overall stability of the cylinder is enhanced by adding longitudinal and transverse ribs to the external surface.

According to the simulation analysis of the cylinder, the number and size of the circumferential ribs and longitudinal ribs are optimized. The mesh structure material is titanium alloy, the thickness of the structure is 5mm, and the working environment of 200m underwater is simulated. The buckling analysis of the optimized pressure structure is carried out by Abaqus. Now, three schemes are designed to analyze the influence of ring ribs of different widths on the strength and stability of the structure under the condition of the same number of longitudinal ribs.

It can be seen from Table 6 that the stress value generated by the carbon fiber composite shell can be reduced by laying the grid structure on the outer surface of the cabin body, thus improving the bearing capacity of the composite pressure shell. With the increase of the width of the ring rib, the stress value and displacement of the whole pressure tank do not change greatly. At this time, there is a phenomenon of stress concentration in the composite pressure shell, especially when the width of the ring rib reaches 200mm, the stress and displacement are mainly concentrated in the part not covered by the grid structure, which is mainly due to the loading of external pressure, resulting in the internal extrusion of the grid structure. It has a certain impact on the non-covered part, but the impact is small, and does not make the material and structure fail.

The structure design of the grid part effectively improves the stability of the cylinder in the main section. As shown in Table 4, the characteristic value of buckling analysis increases with the increase of ring rib width, and when the ring rib width reaches 300mm, the characteristic reaches 0.950. In the following optimization, it is proposed to increase the number of ring classes in four pairs of grid structures with ring rib width less than 300mm, increasing the number of ring ribs from 17 to 19. The curve characteristic value is 1.0021, that is, the large-size pressure tank can meet the hydrostatic pressure of 200m underwater environment at this time, and maintain a certain safety margin.

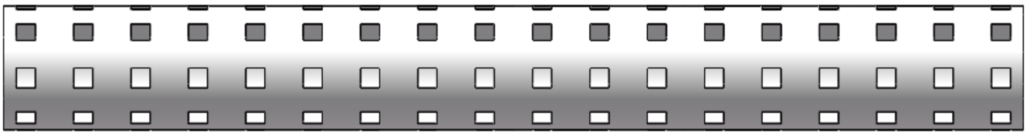

Fig. 11. Grid structure diagram

Table 6. Ring rib laying scheme

Option	Breadth /mm	Quantity	Stress /MPa	Displacement /mm	Eigenvalue
1	100	27	361.1	0.993	0.532
2	200	20	271.5	0.946	0.824
3	300	17	362.9	0.975	0.950

5. CONCLUSION

With the increase in human demand for deep-sea resources exploration, the research of large submersible deep-water vehicle and its core component, pressure tank, has become very important. The pressure tank not only bears great water pressure, but also acts as a buoyancy force for the vehicle. Compared with traditional metal materials, the application of composite materials in pressure design shows unique advantages, such as strong designability and light weight. In this paper, a new type of two-layer pressure tank is proposed, and the influence of the size of the structure on the critical load is investigated by finite element analysis. At the same time, in order to enhance the stability of the large size pressure tank, the grid structure is designed to optimize. These studies not only help to improve the compression performance of the pressure tank, but also effectively reduce its weight, thereby increasing the buoyancy of the vehicle. Through the analysis of the application status of composite materials in Marine equipment, this paper emphasizes the advantages of composite materials in pressure tank design. In the future, with the continuous progress of technology, composite materials will play a greater role in the field of Marine equipment, and promote the development of deep sea exploration to deeper and wider areas.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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