Analysis of ultimate bearing capacity of pressure spherical shell with openings

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Abstract. As the main pressure bearing structure of the deep submerger, it is inevitable to open manholes and observation holes on the pressure spherical shell, and the openings will affect the ultimate bearing capacity of the pressure spherical shell. In this paper, 7000m pressure spherical shell is taken as the research object, the finite element model of the spherical shell is established based on ANSYS, and the influence of the opening size on the ultimate bearing capacity of the spherical shell is calculated. At the same time, the trunk bulkhead strengthening method is adopted, and the thickness and height are taken as variables to calculate the change of the ultimate bearing capacity under different working conditions. The results show that the wall strengthening can significantly reduce the influence of opening on the pressure spherical shell, and the appropriate increase of thickness or decrease of height can increase the ultimate bearing capacity of the structure.

1. Introduction

The ocean accounts for 71% of the earth's surface area, and ocean resources are thousands of times that of land resources. With the development of science and technology and the improvement of human cognition of ocean resources, human beings are accelerating the process of developing ocean resources. Deep submergence vehicle is an important tool for human to explore the ocean. As the core part of deep submergence vehicle, pressure hull has an important influence on its structural performance. Its main task is to withstand deep water pressure and protect internal electronic components, equipment and personnel from water pressure and corrosion. Therefore, the pressure-resistant shell needs to have sufficient strength and sealing performance.

Through the comparison of submergence depth and pressure shell shape of deep submersibles in various countries, it is found that the deep submersibles with large depth adopt spherical pressure shell [1]. Because of the occupational requirement, it is inevitable to open holes on it, such as manholes, observation holes and construction of through holes, which will weaken the ultimate bearing capacity of the structure. In order to meet the requirements of diving, the opening area must be strengthened. On the premise of Kirchhoff hypothesis, Love put forward the hypothesis of deformation related to the thin shell [2], which provides the basis for the nonlinear theory of the shell. Wang Zili [3] studied the influence of spherical shell defects and out of roundness on the ultimate bearing capacity, and obtained the transformation curve of the ultimate bearing capacity with the initial defects. These methods are mainly for the analysis of the complete spherical shell, without considering the influence of the opening, but at present,
there is no empirical formula to directly calculate the ultimate bearing capacity of the opening reinforced structure.

In this paper, ANSYS is used to calculate the ultimate bearing capacity of the spherical shell with openings. Considering material nonlinearity and geometric nonlinearity, the trunk bulkhead is used to strengthen the spherical shell with openings, and the better reinforcement size is determined by changing the parameters.

2. Ultimate Bearing Capacity of Complete Spherical Shell

In this paper, 7000m pressure spherical shell is taken as the research object [4], the inner diameter of the spherical shell is 2100mm, the thickness is 78mm, the material is titanium alloy Ti-6Al-4V, the elastic modulus is $1.08 \times 10^5$ MPa, Poisson's ratio is 0.3, and the yield strength is 830 MPa. Because the pressure shell belongs to the range of moderately thick shell, solid186 high-precision volume element is adopted, dividing two grid layers in the direction of spherical shell thickness and the whole spherical shell is divided into 26410 node and 4800 units. In the process of modeling, the spherical shell is constrained by three points and six displacement components. The model is as shown in figure 1.

![Fig. 1.Pressure hull model](image)

Unit load is applied on the surface of pressure spherical shell, the critical load of the structure is 664.09 MPa. However, the critical load is the upper limit value of the ultimate bearing capacity, which is usually several times of the actual situation. In order to get the result close to the actual situation, it is necessary to consider material nonlinearity and geometric nonlinearity, and uniformly apply more than 664.09 MPa on the outer surface of pressure spherical shell. According to the results of linear buckling analysis, the first-order buckling mode is extracted, and the initial defect of the structure is set to 1mm by adjusting the displacement multiplier (if there is no special description below, the initial defects are set to 1mm). According to the nonlinear buckling analysis, the load displacement curve is shown in Figure 2, and the ultimate bearing capacity is 119.27 MPa. The calculated results of the finite element method are in good agreement with the results of the Russian empirical formula given in reference [6], and the error is only 1.84%.
3. Influence of Opening on Spherical Shell

In order to study the influence of opening on the pressure spherical shell, the opening is made on the above pressure spherical shell and the radius of opening is changed. The analysis method is consistent with that of the complete spherical shell [3]. According to the linear buckling analysis, the first-order buckling modal nephogram of the structure is obtained. The first-order modal nephogram of each size is basically the same as shown in Figure 3. The maximum deformation area is located at the opening of the pressure spherical shell, which indicates that the opening does have an impact on the structure.

The change of ultimate bearing capacity with opening size is shown in Table 1, and the conclusion is drawn in Figure 4. According to figure 4, the ultimate bearing capacity of the pressure spherical shell decreases with the increase of the opening radius. When the opening radius is 50 mm-150 mm, the decrease is relatively gentle. When it exceeds 150 mm, the decrease is rapid. When it reaches 350 mm, it tends to be gentle again.
Table 1: Change of ultimate bearing capacity with opening radius

| Opening Radius (mm) | 50  | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Bearing Capacity (MPa) | 119.| 119.| 116.| 87.3| 57.7| 40.0| 29.3| 22.4| 21.9| 21.3|

Table 2: Change of ultimate bearing capacity with thickness

| Thickness (mm) | 78  | 90  | 100 | 110 | 120 | 130 | 140 |
|----------------|-----|-----|-----|-----|-----|-----|-----|
| Bearing Capacity (MPa) | 101.91| 106.53| 110.8| 113.19| 115.97| 118.05| 118.66|

4. Reinforcement Analysis of Opening Wall

4.1. Influence of Thickness on Ultimate Bearing Capacity of Spherical Shell with Openings

Due to the huge influence of opening on the ultimate bearing capacity of pressure spherical shell, in order to make the pressure shell still be able to dive, the wall reinforcement method as shown in Figure 5 is adopted for the opening area.

Fig. 5. Schematic Diagram of Wall Reinforcement

In order to explore the influence of wall thickness on the ultimate bearing capacity of pressure spherical shell, ensure that the height of the wall structure is 150 mm, a model with a radius of 300 mm is selected to change the thickness of the trunk bulkhead to calculate the ultimate bearing capacity.

Fig. 6. Curve of ultimate bearing capacity versus wall thickness

Table 2 shows the calculation results, draw the curve as shown in Figure 6, it can be seen that the trunk bulkhead reinforcement at the opening has a significant improvement on the overall ultimate bearing capacity of the pressure shell. When the thickness of the wall is 78 mm, the ultimate bearing capacity of the whole structure increases by 154.2% compared with that of the
whole structure, and the ultimate bearing capacity increases with the thickness of the wall. When the thickness of the wall is 140mm, the ultimate bearing capacity of the pressure spherical shell is only 0.51% less than that of the whole spherical shell.

At the same time, comparing the first-order buckling mode nephogram under different wall thickness, it can be found that when the structure reaches the critical load, the deformation area is located at the joint between the wall reinforcement and the shell, and moves slowly up the shell with the increase of the wall thickness. When the wall thickness reaches 140mm, the deformation at the joint is very small. The main deformation is located on the shell, and the ultimate bearing capacity obtained by nonlinear analysis is closer to the calculated value of the complete spherical shell.

![Fig. 7. Trunk bulkhead thickness 90mm](image1)

![Fig. 8. Trunk bulkhead thickness 120mm](image2)

![Fig. 9. Trunk bulkhead thickness 140mm](image3)

### Table 3 Change of ultimate bearing capacity with height

| height (mm) | 150  | 200  | 250  | 300  | 350  | 400  | 150  |
|-------------|------|------|------|------|------|------|------|
| bearing capacity (MPa) | 118.66 | 118.59 | 118.45 | 118.23 | 117.98 | 117.55 | 118.66 |

4.2. Influence of height on ultimate bearing capacity of spherical shell with openings

According to the above calculation, it can be found that after the thickness of the trunk bulkhead increases to 140mm, the ultimate bearing capacity of the whole structure is almost the same as
that of the complete spherical shell. Therefore, the influence of the enclosure height on the ultimate bearing capacity of the structure is discussed under the condition that the thickness of the trunk bulkhead is 140mm.

Table 3 shows the calculation results, draw the curve as shown in Figure 10. It can be seen in Figure 10 that the ultimate bearing capacity decreases with the increase of the trunk bulkhead height, and the larger the reduction is with the increase of the height, so the height should not be too large when the trunk bulkhead is strengthened.

![Fig. 10. Change curve of ultimate bearing capacity with wall height](image)

The results of nonlinear analysis are shown in Fig. 11 and Fig. 12, when the opening radius is 300 mm, the wall thickness is 140 mm and the height is 150 mm. According to the deformation nephogram, it can be seen that the area with the largest deformation is close to the junction of the opening reinforcement structure and the spherical shell, which may be because the opening reinforcement structure weakens the strength of the surrounding structure. According to the failure stress nephogram, the maximum stress is 853mpa, which exceeds the yield strength of the material by 830mpa, indicating that the material has entered the non-linear stage.

![Fig. 11. Deformation nephogram](image)

![Fig. 12. Failure stress nephogram](image)
5. Conclusion
In this paper, the analysis and calculation of pressure spherical shell with openings are carried out, and the ultimate bearing capacity of the spherical shell with different openings and different reinforced structures are calculated respectively. The conclusions are as follows:

(1) For the pressure spherical shell with no reinforcement at the opening, the ultimate bearing capacity of the shell decreases with the increase of the opening size, and the decreasing trend is gentle first, then sharp and then gentle, among which the small opening has little effect on the ultimate bearing capacity of the pressure spherical shell.

(2) The ultimate bearing capacity of the pressure spherical shell strengthened by the trunk bulkhead increases rapidly, which shows that the effect of the strengthening at the opening is good. For the opening area, the method of appropriately increasing the thickness of the trunk bulkhead or reducing the height of the trunk bulkhead can be used to improve the ultimate bearing capacity of the structure.

(3) For the calculated pressure spherical shell with a hole radius of 300 mm, the reinforced structure with a wall thickness of 140 mm and a height of 150 mm can meet the reinforcement requirements at the hole.

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