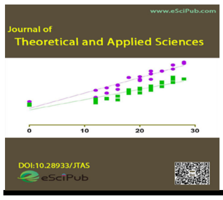
Research Article JTAS (2020), 3:15



Journal of Theoretical and Applied Sciences
(ISSN:2637-692X)

The Ultimate Strength of Ring Stiffened Cylindrical Shell and Its Influence Factors

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ABSTRACT

Calculating the modes of cylindrical shell, then embed them into ideal perfect cylindrical pressure-resistant shell as the initial geometric imperfections to form the modal. According to the characteristics of each mode, the first 30 modes can be classified into four types, and it is found that the mode of the first type is the worst defect form. By calculation, the cylinder shell has the minimum ultimate strength when the 23rd mode happened. The sensitivity analysis of cylindrical shells with initial geometric defects shows that the critical buckling load has approximate linear relationship with different thickness radius ratio and defect amplitude. Six cylindrical shells of different materials are selected for research, and it is found that although the modal orders of the worst geometric defects of various materials are not the same, they all belong to the first type of mode. The comparison showed that the 921 steel and 909 steel materials are economic.

Keywords: Ring-stiffened cylinder; Ultimate strength; Initial imperfection; Mode

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How to cite this article:
XIONG Zhixin, HUI Hanju, HUANG Zhiquan. The Ultimate Strength of Ring Stiffened Cylindrical Shell and Its Influence Factors. Journal of Theoretical and Applied Sciences, 2020; 3:15

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Introduction

In China, with the in-depth exploration in the ocean as an important part of various underwater equipment, the research about the safety of pressure shell structure is more and more important[1]. The stress of deep-sea cylindrical pressure shell is dominated by external hydrostatic pressure, and the most typical failure mode is buckling, that is, when the load is started, the deflection increases with the increase of the load, but when passing a certain extreme point, even if the load is not increased, the deflection still increase, and finally caused structural failure[2]. During the production of shell plate, the defects such as small pits on the shell surface caused by the processing methods, such as welding defects, non-roundness of cross section surface and rust removal, can be collectively referred to as initial defects[3]. The stiffened cylindrical shell can increase its critical buckling load under the same weight and reduce its sensitivity to initial defects[4]. Do[5] applied failure load to four cylindrical shells and two perfect cylindrical shells under hydrostatic pressure to obtain their ultimate strength, and verified the results of numerical simulation with it. Finally, the design formula of ring stiffened cylindrical shells under dangerous conditions was derived. Korucuk[6] through 14 groups of experiments with different groove depth and number of longitudinal grooves, it is concluded that the ultimate bearing capacity of the cylindrical shell will be improved after reaching the initial buckling, and the carbon fiber material can improve the initial buckling load of the cylindrical shell, so as to achieve the function of repairing the bearing capacity. Muttaqie[7] used eight groups of typical cylindrical shell experimental models, considered the initial geometric defects and the residual stress generated during welding and forming to simulate and calculate, and obtained that the numerical simulation is very consistent with the experiment data, and all the failure patterns are also corresponding. Cho[8] has carried on the experiment and the numerical simulation to the ring stiffened cylindrical shell in the underwater residual strength, finally has carried on the analysis to the different destruction form to the residual strength influence. Wan[9] used three numerical simulation methods, arc length method, nonlinear stability algorithm and display dynamic method, compared with the experimental data of three thin-walled cylindrical shells, obtained that arc length method and nonlinear stability method are more accurate to simulate the real situation. Zhang[10] found that for shells with similar discrete eigenvalues, the high-order buckling mode may be more likely to lead structural failure, but only the first few buckling modes may not be able to reflect the real situation.

This paper has calculated the finite element simulation of the first 30 modes of the cylindrical shell is carried out, and the arc length method in ABAQUS software is used to calculate the ultimate strength. Because of the different linear modal shape of the cylindrical shell, it is classified into four types, and the minimum ultimate strength obtained is compared with the experimental data to verify the reliability of the numerical simulation. The influence of radius thickness ratio, defect amplitude and manufacturing materials on the ultimate strength of ring stiffened cylindrical shell with initial defects is analyzed, which provides reference for engineering design.

1. Modal defect

According to the data of test model in reference [11], Elastic modulus of cylindrical shell is 218800 MPa, Poisson's ratio v = 0.3, yield strength is

288.3 MPa; the Elastic modulus of ring stiffened material is 205300 MPa, Poisson's ratio v = 0.3, Yield strength is 297.5 MPa. The boundary condition is the bottom is completely fixed, i.e. T1 = T2 = T3 = R1 = R2 = R3 = 0; the top is free. The cylindrical shell and the chassis are covered by uniform water pressure, as shown in Figure 1. A total of 28087 nodes, 27900 S4R cells and 186 S3R cells are generated by sweeping method.

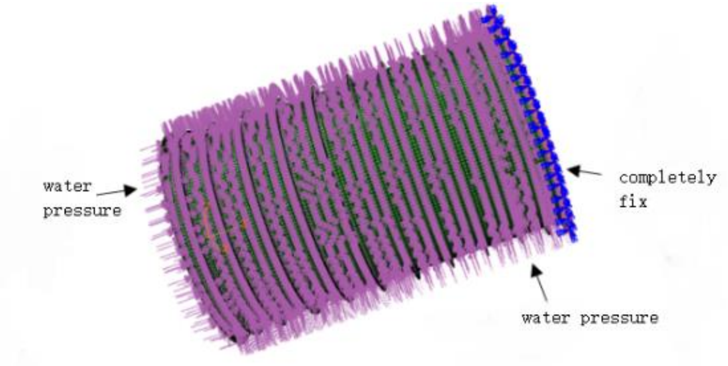
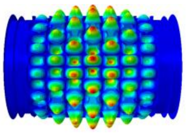
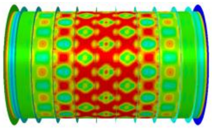
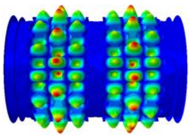
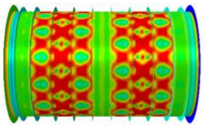
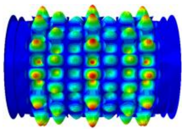
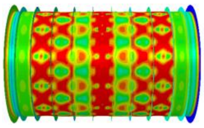
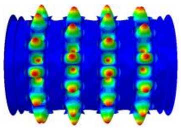
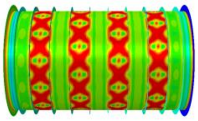


Figure 1. Force condition and constraint condition of cylindrical shell

There are three steps to simulate modal defects by finite element software: Firstly, calculating the model by linear eigenvalue buckling then obtained the first 30 modes. Secondly, through the submarine specification[12], the defect assignment is determined and embedded in the defect free model. Finally, the arc length method in ABAQUS software is used to track the nonlinear post buckling. Through the analysis of the first 30 modes, it is found that the change of the modal shape of cylindrical shell is related to the frequency of its peak value, and divided into four types. The order contained in each type is not completely continuous, as shown in Table 1. By ABAQUS calculation, the minimum ultimate strength of each type is obtained and compared. It is found that the ultimate strength increases with the number of modal peaks. When the first type of modal changes, the cylindrical shell has the minimum ultimate strength, that is, the first type of modal peak only appears once is the worst initial geometric defect shape of the cylindrical shell. In reference [11], the experiment of T-shaped ring stiffened cylindrical shell model under uniform water pressure is carried out, and the ultimate strength of experimental data of this cylindrical shell is cited as Pexp = 1.844MPa. Compared the experimental data with the limit strength of the first 30 modal defect cylindrical shells, as shown in Figure 2, the error between the 3rd modal defect and the experimental data is only 0.4%; the minimum limit strength of the 23rd modal defect cylindrical shell is 1.79MPa, and the error between the 23rd modal defect cylindrical shell and the experimental value is -2.7%; the maximum limit strength of the 27th modal defect cylindrical shell is 1.963MPa, and the error of experimental value is 6.7%. It can be seen from Figure 2 that the overall trend of the ratio of experimental data to numerical simulation is gradually decreasing, that is to say, with the increase of modal order, the overall trend of ultimate strength is also gradually increasing.

Table 1: Classification and ultimate strength of the first 30 modes

Type	Mode	Cylinder shape of mode	Stress nephogram

Type 1	1,2,3,4,9,10,17，18,23,24		 P_{cr}=1.794
Type 2	5,6,7,8, 11,12,19,20		 P_{cr}=1.861
Type 3	13,14,15,16,21,22,29,30		 P_{cr}=1.901
Type 4	25,26,27,28		 P_{cr}=1.930

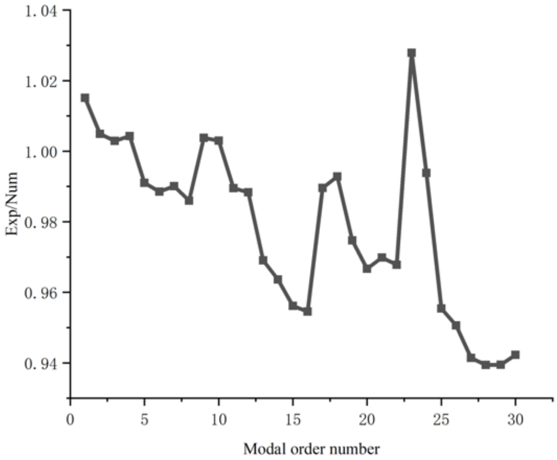


Figure 2. the ratio of experiment and numerical calculation

2. Sensitivity analysis of modal defects

For the analysis of nonlinear buckling model with initial geometric imperfections, there are many factors affected the calculation results. In the actual engineering manufacturing, there may be various sizes of defect amplitudes. By assigning a wider range of defects to the model and calculating then made comparison; the diameter thickness ratio has a great influence on the cylindrical shell, and by changing the thickness, the influence of different diameter thickness ratio on the modal defects can be obtained; in the end of this section, different manufacturing materials are used to study the influence of different materials on the cylindrical shell The lowest mode is used to analyze the influencing factors of the ultimate strength of the cylindrical shell.

2.1 Effect of defect amplitude on critical buckling load

For the cylindrical shell with the same thickness, the interval from 1mm to 8mm is 0.5mm, and 16 kinds of defect amplitudes are set for nonlinear buckling analysis. The calculation results are as shown in Figure 3, where t is the thickness of cylindrical shell. Then 10 kinds of thickness with equal spacing of 2mm from 4mm to 22mm are selected respectively, so that the calculation results can be compared from the longitudinal and transverse directions.

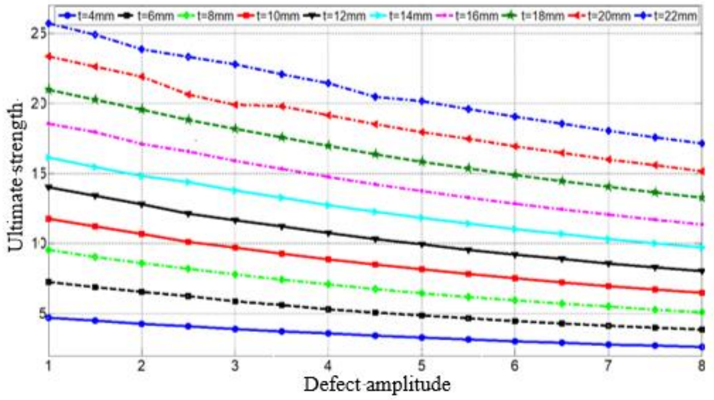


Figure 3. Relationship between defect amplitude and critical buckling load with different thickness

It can be seen from Fig. 3 that the critical buckling load of the same thickness decreases with the increase of defect amplitude; the critical buckling load increases with the increase of thickness for same defect amplitude. It can be seen from the figure that the critical buckling load obtained by the maximum thickness and the minimum defect assignment is the maximum. The larger the thickness is, the faster the critical buckling load decreases with the defect assignment. For example, for the curve of t = 25mm in the figure, when the defect assignment is 1-8mm, the critical buckling load decreases by 8.94MPa, while when t = 5mm, the defect assignment is 1-8mm, and the critical buckling load decreases by 2.28MPa, 3.92 times. Under the condition of manufacturing technology and cost, the thicker the submersible is, the less sensitive it is to the initial geometric defects.

2.2 Influence of thickness radius ratio on critical buckling load

The t/R value and critical buckling load of cylindrical shell can reflect the sensitivity of different sizes of cylindrical shell to defects, which has certain reference value for structural design. For the 10 different t/R cylindrical shells mentioned in the previous section, 16 defect amplitudes are applied from 1mm to 8mm, and the curve of critical buckling load to thickness radius ratio is obtained. As shown in Figure 4

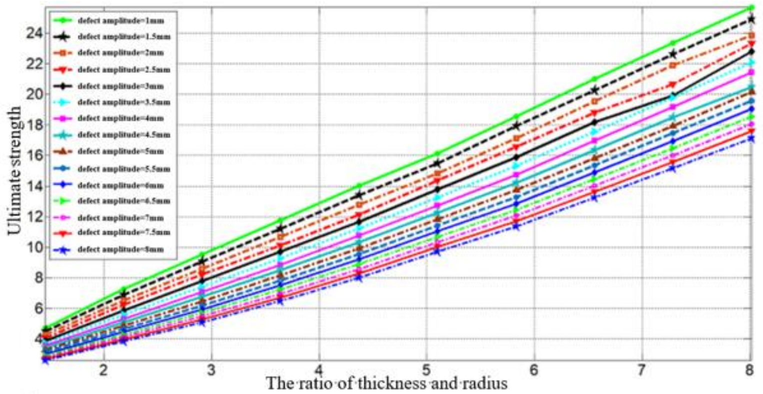


Figure 4. Relationship between ultimate strength and the ratio of thickness and radius

For the same defect assignment, with the increase of t/R value, the critical buckling load of cylindrical shell increases linearly, except for the defect amplitude of 3mm and the fluctuation of t/R between 7-8mm

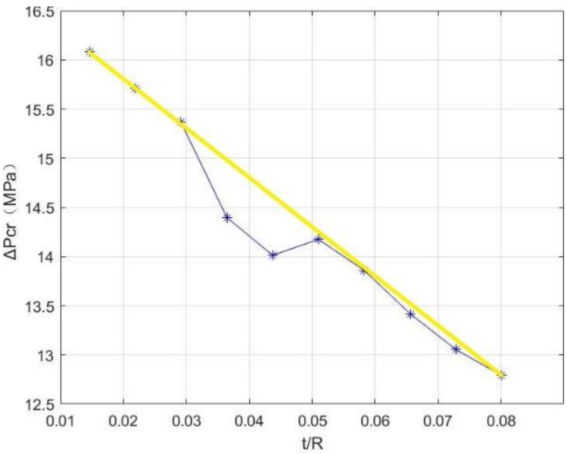


Fig. 5 t/R value corresponding to the critical buckling pressure difference ΔPcr

In order to better study the influence of diameter thickness ratio, the difference of critical buckling pressure between two curves with defect amplitude δ = 6mm and δ = 20mm is selected as the representative, and figure 5 is the difference of critical buckling pressure ΔPcr fluctuation curve. As shown in the figure, it can be seen that there is a downward trend between 0.01-0.043 and 0.051-0.08, that is, under the same defect amplitude, the change amplitude of critical buckling pressure decreases with the increase of thickness; while between 0.043-0.051, the change amplitude of critical buckling pressure increases with the increase of thickness, and the curve shows an upward trend. When the head and tail are connected into a yellow line, it can be found that the values of t/R between 0.043 and 0.051 are all below the yellow line, that is to say, there is a lower difference of ultimate strength, and the sensitivity to defect amplitude is reduced in this area.

2.3 Effect of material characteristics on modal defects

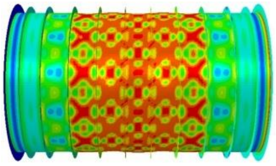
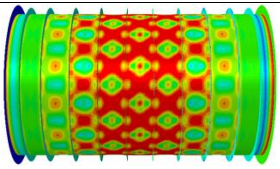
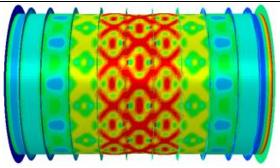
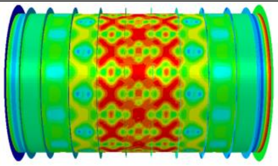
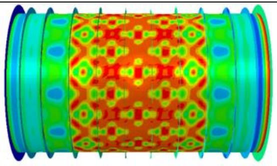
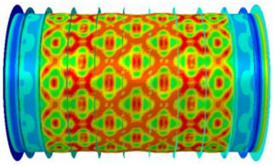
Six kinds of commonly used ship and offshore engineering materials[13-14] are selected from the references and introduced into the model parameters for numerical simulation, as shown in Table 2:

Table 2. Material property

Material	Yield str（MPa）	Young modulus（MPa）
6061-T6 Aluminium alloy	276	70000
AH32	315	205800
921 steel	588	213858
909 steel	641	221706
980 steel	784	200000
TC4	943	115000

Refer to the numerical simulation calculation method in Section 2.1, and calculate these six methods separately. The specific results are shown in Table 3 below

Table 3. The ultimate strength of different materials

Material	Ultimate strength（MPa）	Mode	Stress nephogram
6061-T6 Aluminium alloy	1.137	7	
AH32	1.921	2	
921 steel	2.792	17	
909 steel	2.824	18	
980 steel	2.988	18	
TC4	2.685	25	

It can be seen from the table that the modal order corresponding to the lowest ultimate load of different materials is not the same, but according to the classification method based on the above peak occurrence times, the six lowest modes still belong to the first type. Although the stress nephogram of each different material is different, all the failure trends are the same, showing that the middle part of the cylindrical shell is earlier than other places. When the yield load is reached, the cylindrical shell will be destroyed. Therefore, it can be determined that the mode with only one wave crest is the most suitable form for the initial geometric defect of cylindrical shell. Due to the different materials, the ultimate strength is not the same. Among the six materials, the Aluminum alloy with the minimum yield stress and elastic modulus has the minimum ultimate strength. TC4 is a titanium alloy, so it has a high yield stress, but its elastic modulus is not high, and its ultimate strength is moderate among the six materials. The other four are all steel. It can be found that 980 steel is the most suitable material for the construction of deep submersibles, and 921 steel and 909 steel with high cost performance ratio are selected. In this paper, only six kinds of materials are selected, and many kinds of materials can be used to simulate the actual manufacturing, found that the most suitable construction materials.

3. Conclusion

(1) In the different modes with only one wave crest, there exists the worst geometrical defect distribution of the pressure cylinder shell. In the process of nonlinear finite element analysis, it is necessary to carry out multi-modal calculation and find out the lowest ultimate strength as the reference value in actual construction.

(2) For the pressure cylindrical shell with initial geometric defects, the influence trend of defect assignment and the ratio of diameter to thickness is linear. The smaller the defect assignment is, the greater the ratio of diameter to thickness is, the greater the ultimate strength of the pressure cylindrical shell is. In this paper, taking δ = 6mm and δ = 20mm as examples, it is found that the ratio of diameter to thickness will correspondingly reduce the sensitivity of defect amplitude to ultimate strength in a region.

(3) The lowest modes of different materials are different, but the lowest modes are all the first modes.

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