External pressure buckling analysis of large pressure vessels

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Abstract. In the external buckling analysis, it is significant to determine the magnitude of the critical buckling load value. This paper introduces a method based on ANSYS finite element method for external pressure buckling analysis of pressure vessels and determination the critical loads. Eigenvalue buckling analysis and nonlinear buckling analysis are introduced. After the initial selection of structural parameters and reasonable structural design, ANSYS software was used to establish a reasonable and valid 3D solid model. Check the design and hydraulic condition is necessary after establishing the 3D solid model. It is the precondition of buckling analysis. After passing the internal pressure strength test, external buckling analysis will be start. In this paper, the buckling critical load of a 1500m³ spherical tank is obtained by comparing the eigenvalue buckling analysis with the nonlinear buckling. And the value of nonlinear buckling is lower. Because nonlinear buckling analysis considers the flaws of the actual structure. Therefore, nonlinear buckling analysis is more suitable for practical engineering analysis.

1. Introduction

With the development of science and technology, large pressure vessels have become widely used in the world, especially in chemical and petroleum, city gas, aerospace [1] and other enterprises. For these companies, safe operation is the greatest economics. The strength of large pressure vessels and the stability of external pressures are particularly important, and failures in these areas are the greatest threat to the economy. Therefore, the study of internal pressure strength and external pressure buckling of large pressure vessels have obvious economic and social benefits. It is necessary to analyze the stability of these structures. On the other hand, as the volume of the pressure vessels increase, its weight will be multiplied. And this kind of situation will lead to a sharp increase in cost. Reasonable structural design and lightweight design of large pressure vessels will reduce the cost of such vessels and enhance structural stability.

At present, the manufacturing level of large pressure vessels in foreign countries is much higher than that in China. According to statistics, the proportion of pressure vessels under 1000m³ is about 93.3% in our country before the 1980s. However, 55.4% percent pressure vessels’ volume are larger than 1000m³, in Japan. With the continuous development of materials and welding, manufacturing and construction technology, the pressure vessel container is developing towards high parameters (the volume, temperature, pressure, and so on).

As a result of mechanical and/or thermal load, pressure vessels tend to produce overall or partial pressure stress. When the pressure stress is too large, the whole or part of the structure will be bucking [2]. In order to improve the performance of large pressure vessels and reduce the possibility of fracture,
instability and buckling of pressure vessels, taking the 1500m³ spherical tank as an example to conduct simulation analysis. The finite element simulation analysis of 1500m³ spherical tanks under design conditions, internal pressure conditions and external pressure conditions was carried out. Firstly, according to the given process conditions and relevant criteria, the thickness of the spherical tank is preliminarily selected, and then the ANSYS software is used to establish a reasonable and effective spherical tank model, and the strength under design conditions and hydraulic test conditions are analyzed. Then, consider the buckling under external pressure. Through the analysis of this model, we have a deeper understanding of the external pressure buckling concept of pressure vessels.

2. Principle
This part mainly introduces the finite element method and the theory of buckling analysis used in this paper.

2.1. Finite element method
The finite element method (FEM) is an efficient and commonly used numerical calculation method that can be used to solve various mechanical and physical problems. The finite element method is a simulation method based on elastic mechanics. It uses the variational principle to establish a finite element equation of a mathematical model through the process of discrete processes, unit analysis, and overall analysis. It is usually a set of algebraic equations that are easily solved by numerical methods, and so on [3]. The basic idea of the finite element method is mainly to discrete a continuous whole with an infinite number of degrees of freedom into a unit with a finite number of degrees of freedom connected in a certain way,. That is to say, replace the original continuum with a collection of discrete units.

In general, the main steps of the finite element method to solve the problem are divided into the following aspects:

1: Discretization of the structure
2: Selection of displacement mode
3: Analysis of the mechanical properties of the unit--establishing the element stiffness matrix
4: Calculate the equivalent nodal force
5: Establish an overall stiffness matrix
6: Apply boundary conditions and mechanical conditions
7: Solve

2.2. Buckling analysis theory
Research on the bucking of pressure vessels has been continuous. According to the research of several scholars, the basic theories of shell buckling mainly include small deflection buckling theory, pre-buckling consistency theory, nonlinear large deflection buckling theory, initial post-buckling theory and boundary layer theory [4].

The form of buckling is various, and it is related to various factors such as the size of the structure, the mechanical properties of the material, the load conditions, and the boundary conditions. When the load on the structure reaches a certain value, the equilibrium state of the structure will change greatly if a small increment is added. This condition is called structural buckling [5]. The load at which such buckling occurs is called the ultimate load, also known as the buckling load. The corresponding point is called the buckling point or the critical point. The equilibrium state of the structure before reaching the critical point is called pre-buckling, and the equilibrium state after exceeding the critical state is post-buckling [6].

There are two main ways of buckling analysis: eigenvalue buckling analysis and the nonlinear buckling analysis. The nonlinear buckling analysis method only considers the elastic case. Nonlinear buckling analysis can truly consider the actual structure and track the instability process. In the following, the two buckling analysis methods are introduced respectively.
2.2.1. Eigenvalue buckling analysis. Eigenvalue buckling analysis only considers linear behavior, and any linearity (such as plasticity, gap cells, etc.) will be ignored. For contact units, they will be calculated in their initial state and will not change in subsequent calculations. The material considered is also linear, isotropic. The analysis process is as follows:

1. First enter the static analysis. And set the stress stiffness matrix.
2. Apply a load. The calculated eigenvalue multiplied by the pre-applied load is the critical load.
3. The eigenvalues obtained in the buckling analysis will be multiplied for all loads to obtain the ultimate load.

2.2.2. Buckling analysis based on geometric nonlinearity. Nonlinear buckling analysis is a static analysis process considering large displacements. The ultimate load or the maximum load that the structure can reach is regarded as critical load in nonlinear buckling analysis. The plasticity effect can be considered in the analysis. The basic method of the analysis is to apply incremental loads until the results diverge. When approaching a critical load, the step size of the load should be chosen to be very small in order to obtain a more accurate threshold. This is very important. And it can be achieved by using an automatic time step. There is a problem in nonlinear buckling analysis needs attention. The direction remains invariable during the deformation for the applied force or displacement. However, the surface load applied will be duly based on the geometry of the structure changed during the deformation process. In other words, it is going to change with the deformation. Therefore, the properties of the loads to be applied should be correctly selected.

Convergence is sometimes affected by numerical stability issues in the calculation process. It can be improved by adjusting the calculation model for the un-convergenced structure. The arc-length method can be used to make a preliminary prediction of the critical buckling load. Comparing the result with the value that obtained by using the automatic time step. Then it can be judged whether the carrying capacity of the structure truly reaches the maximum load. In general, the steps of nonlinear buckling analysis are as Figure 1:

**Figure1.** Steps of nonlinear buckling analysis.
3. External pressure buckling analysis

The buckling analysis is divided into eigenvalue buckling analysis and nonlinear buckling analysis. Eigenvalue buckling analysis is a method of external pressure buckling analysis by ANSYS finite element software, which is relatively simple in analyzing buckling problems. It does not take into account the equipment’s defects in its manufacture. The equipment or structure considered in this method is the ideal structure. The nonlinear buckling analysis is more accurate than the eigenvalue buckling analysis method described above. Because the nonlinear buckling analysis method considers the structure under actual conditions, these structures have some defects, such as the out-of-roundness of the structure, the pre-stress in a certain part, and the influence on the structure after each step of loading [7]. This paper first performs eigenvalue buckling analysis and nonlinear buckling analysis, and then compares the results.

3.1. Structural model

Under normal circumstances, the design conditions, operating conditions, and operating environment of the equipment will be obtained from the manufacturer before designing a pressure vessel. Such as the maximum (minimum) size of the equipment, design pressure, design temperature, test pressure, wind pressure, filling factor, etc. Generally, the conditions given will be presented in the form of a task book. According to the conditions given in the task book, according to the relevant chapters of JB/T4732-1995 "Steel Pressure Vessel - Analysis Design Standards", the material selection and thickness calculation and selection are carried out [8]. Among them, the local high-stress areas such as the take-up and pillar are adopted ANSYS software. Model and perform detailed strength checks.

In this paper, the external pressure buckling analysis of large pressure vessel structures is carried out with 1500m³ spherical tanks as an example. The material used in this spherical tank is Q345R, etc. The material strength at different temperatures is shown in Table 1.

| Material     | Temperature/°C | Strength of design stress/ (σn/MPa) |
|--------------|----------------|-----------------------------------|
| Q345R        | 50             | 181                               |
| 20 steel     | 50             | 147                               |

In this paper, the external pressure buckling analysis of large pressure vessel structures is carried out with 1500m³ spherical tanks as an example. It is necessary to ensure that the pressure vessel can meet the internal pressure strength before buckling analysis under external pressure. Therefore, the internal pressure strength is checked first. The internal pressure strength condition is satisfied in this paper, and it is not detailed here. And the external load conditions are as follows:

External pressure working conditions: external pressure 0.1 MPa, working temperature 50 °C.

3.2. External pressure buckling analysis

The 1500m³ spherical tank is a thin-walled pressure vessel with an inner diameter that is several hundred times the wall thickness. In this case, if the model is built using 3D solid elements, the calculation result is the most accurate. However, its nodes are large in scale, and the calculation time is quite long due to the efficiency lower. In contrast, the three-dimensional shell element has better convergence, plasticity, large deformation and large strain characteristics. And the size of the three-dimensional shell element is also moderate, which can improve the analysis efficiency while ensuring the calculation accuracy. Therefore, the model unit type is finally selected as the shell unit (SHELL63), in the buckling analysis. The model built is shown in Figure 2. And the external pressure applied to the model is 0.1 MPa. The finite element displacement boundary condition is to add fixed constraint on the bottom of the pillar. The boundary conditions and load conditions are shown in Figure 3.
3.2.1. Eigenvalue buckling analysis. First, the eigenvalue buckling of the structure is analyzed. Eigenvalue buckling analysis is simple and convenient, which can improve the efficiency of buckling analysis. But there are also some drawbacks. For example, this analysis method will be inaccurate, generally only used as an early step of another analysis method, and the results are generally not used in actual engineering. The solution steps of the method are roughly as follows: establishing a model → obtaining a static solution → obtaining a characteristic instability solution → expanding solution → observation result.

Observe the buckling load factor and critical load in ANSYS as shown in Figure 3. It can be seen from Figure 4 that the critical buckling load under external pressure conditions is $-0.1 \text{MPa} \times 92.402 = -9.24 \text{MPa}$.

![Figure 2. Spherical shell unit model.](image1)

![Figure 3. External pressure load and displacement constraint.](image2)

![Figure 4. Eigenvalue buckling load factor.](image3)
3.2.2. Nonlinear buckling analysis. The nonlinear buckling analysis is more accurate than the eigenvalue buckling analysis method described above. Because the nonlinear buckling analysis method considers the structure under actual conditions. These structures have some defects, such as the out-of-roundness of the structure, the pre-stress in a certain part, and the influence on the structure after each step of loading. The external pressure load and the constraint are applied to the model, and the external buckling nonlinear buckling analysis is performed.

The displacement is extracted in ANSYS - the load diagram is shown in Figure 5.

![Figure 5. Load sub-steps and displacement curves under external pressure conditions.](image)

It can be seen that the spherical tank is flexed at the position marked by the red line. At this time, TIME=0.69 can be read, so the critical load obtained by the nonlinear buckling analysis is 0.69×(-9.24)=-6.37MPa. The nonlinear buckling instability mode under this condition is shown in Figure 6.

![Figure 6. Nonlinear buckling instability mode of spherical tank.](image)

4. Contrast and Conclusion

4.1. Comparison between eigenvalue buckling and nonlinear buckling

Comparison of the eigenvalue buckling analysis results and the nonlinear buckling analysis results under external pressure conditions is shown in Table 2.
Table 2. Comparison of critical load between eigenvalue buckling and nonlinear buckling analysis under external pressure.

| Working condition | Eigenvalue buckling analysis | Nonlinear buckling analysis | Critical load relative error |
|-------------------|-----------------------------|----------------------------|-----------------------------|
| External pressure condition | -9.24MPa | -6.37MPa | 31.1% |

It can be seen from the table that the critical load of the nonlinear buckling analysis is smaller than the critical load of the eigenvalue buckling analysis. The critical load value of the nonlinear buckling analysis is about 70% of the critical value of the eigenvalue buckling analysis.

5. Conclusions

The external pressure of the spherical tank is -0.1MPa, and the external buckling critical load calculated by the nonlinear buckling analysis method is greater than 0.1MPa. From the criterion of buckling failure (failure due to sudden transition of equilibrium configuration), the 1500m³ spherical tank does not undergo buckling under the additional pressure conditions.

In conclusion, the results of nonlinear buckling analysis are smaller than those of eigenvalue buckling analysis. The results of nonlinear buckling analysis are more reliable because it takes into account some defects of actual structures. Namely, nonlinear buckling analysis considers nonlinear factors are more suitable for practical engineering analysis.

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