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Buckling Analysis of Pressure Vessel Based on Finite Element Method

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Abstract

Buckling collapse is one of the important failure modes of pressure vessel. But, in the past protection against collapse from bulking has not been implemented as required by codes, especially local buckling. The situation is attributed to two reasons. The first one is that pressure vessel code usually only provided design method by rules to protect against global bulking of shell under conventional loads, such as external pressure or axial compression load. However, local bulking may occur in some local discontinuity regions rather than global region and has to be evaluated using design method by analysis. The second one is that bulking analysis based on numerical method (e.g. FEA) is more sophisticated to implement compared to typical strength analysis due to non-uniqueness of result, initial imperfection, mesh generation and other reasons.

The case studied in this paper is that a heavy attaching equipment was closely connected the main equipment by triangular steel structure instead of typical shirt support for the purpose of space saving. The key point of this project case is that the 240-ton attaching equipment causes significant compress stress in the local regions such as the bottom of nozzle, shirt support of main equipment and triangular steel structure. Regarding the loads, not only weight but also wind, seismic load etc. and their load cases combinations should be considered in the bulking analysis. With this case, the paper introduced the basic principles, implementation procedures and software applications of local buckling analysis of pressure vessel.

At the end, this paper proposed some suggestion for the Chinese code of bulking analysis through this typical case study.

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Recently, with the development of pressure vessels to the direction of large-scale and light-weight, buckling often occur in such large thin-wall vessels under compressive loads. Obviously, buckling analysis for shell has become a main, even most important, part of pressure vessel design. In practice, the possibility of the global and/or local bucking failure should be evaluated by related formulas or FEA.

ASME Ⅷ-2[1] provided design method for buckling based on numerical analysis (e.g. FEA), which has caused wide public concern for engineers in China. Research and introduction for these methods has been done widely by domain experts [2-6]. Shell of pressure vessels shows complex elastic-plastic characteristic and buckling behaviors. However, ASME Ⅷ-2[1] just gave the analysis types and corresponding design factors. Few detail guidance and suggestions about how to use FEA software to finish a buckling analysis.

This paper presented a general picture of buckling design of pressure vessels from following aspects: basic fundamentals, software applications, advantages and disadvantages of each method. On this basis, the paper focused on implementation approaches and applied skills of buckling analysis for pressure vessels.

1. Introduction of buckling for shell

Buckling can be defined as a mode of failure generally resulting from structural instability due to compressive action on the structural member or element involved. From 1920s to 1970s, a lot of experiments have been done to better understand buckling behaviour of shells. The experimental evidence suggests that there is a significant differences experiment result of specimens and elastic theoretical solution of shells without imperfection. Critical load obtained from experiments is usually 70%~80% of the value from theoretic calculation, even on 30% sometimes.Some studies[7-9] also showed that such differences were caused by following reasons:

- Boundary conditions
- Pre-buckling deformation
- Geometry imperfection
- Eccentric load

Among them, initial geometrical imperfections were main factors which should not be neglected in second-order elastic analysis of buckling.

2. Buckling design methods in pressure vessel codes

In the past, because of the complexity of buckling phenomenon, pressure vessel Codes provided methods of stability design only for basic geometrical structures (e.g. cylindrical shell, conical shell, spherical shell and so on) and simple load condition (e.g. axial uniform compression, uniform external pressure, uniform torque and bending moment and their combination). Although under these simple conditions, critical load can be calculated based on elastic theory without initial imperfection, the result was overvalued compared to actual value of actual structure. In the past, condition of hardware and software were limited and it was difficult to evaluate the effects of initial imperfection through non-linear analysis. For these reasons, safety factors based on the lower limit of experimental data was adopted in pressure vessel Codes. Most Codes used such safety factors together with non-conservative Critical buckling load to perform stability checking.

3. Buckling design based on numerical analysis

A new highlight of the ASME Ⅷ-2[1] is to use numerical analysis (e.g. FEA) to perform design by analysis. The Code[1] provided three design methods for buckling based on numerical analysis (e.g. FEA) as follow.

3.1. Method 1

Method 1 is a bifurcation buckling analysis that is performed using an elastic stress analysis without geometric nonlinearities in the solution to determine the pre-stress in the component. In this analysis, the pre-stress in the component is established based on the loading combinations specified by the Code[1].

3.2. Method 2

Method 2 is a bifurcation buckling analysis that is performed using an elastic-plastic stress analysis with the effects of non-linear geometry in the solution to determine the pre-stress in the component. In this analysis, the pre-stress in the component is established based on the loading combinations specified by the Code[1].

3.3. Method 3

Method 3 is a collapse analysis in which imperfections are explicitly considered in the analysis model geometry. It should be noted that a collapse analysis can be performed using elastic or plastic material behavior. If the structure remains elastic when subject to the applied loads, the elastic-plastic material model will provide the required elastic behavior, and the collapse load will be computed based on this behavior.

4. Engineering application of buckling design

The case study focused on the process of local buckling analysis, and did not include strength calculation and calculation of global stability for cylinder. And only Design condition was considered.

4.1. Main Design Parameters

The structure consists of two parts: main equipment and accessory equipment connected by a triangle bracket, shown in Fig. 1.
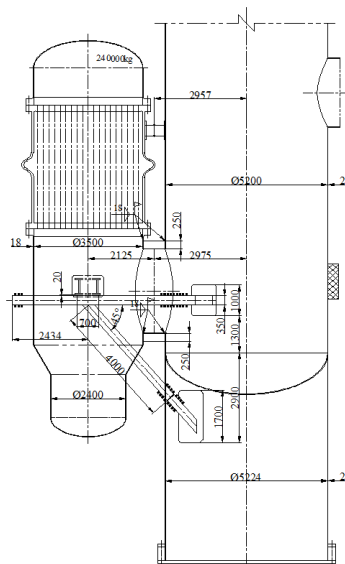

Fig. 1. Main equipment and accessory equipment connected by atriangle bracket.

Main design parameters were listed in Table 1.

Table 1.Main Design Parameters.

Main equipment	Design parameters	
Operating pressure(MPa)	-0.0992/0.36	
Design pressure(MPa)	0.4/FV	
Operating temperature(℃)	223	
Design temperature(℃)	260	
Material of cylinder	SA-240 304L	
Material of shirt support	Q345R	
Cylinder inner diameter mm	5200	
Manufacture mass (Kg)	168540	
Operating mass(Kg)	270950	
Water filling quality(Kg)	766925	
Accessory equipment	Design parameters	
	Shell side	Tube side
Operating pressure(MPa)	3.1	-0.0986/0.36
Design pressure(MPa)	5/FV	4/FV
Operating temperature(℃)	280	223
Design temperature(℃)	300	300
Material of cylinder	SA-516 Gr.70N	SA-240 304L
Material of ear supports	Q345R	
Cylinder inner diameter mm	3500	
Manufacture mass (Kg)	131630	
Operating mass(Kg)	146555	
Water filling quality(Kg)	239520	

4.2. Key points of buckling analysis

4.2.1. Load distribution between connecting nozzle and triangle bracket

In this case, main equipment and accessory equipment are connected by connecting nozzle and triangle bracket. In the other word, the weight and other loads, such as wind loads and seismic loads, were distributed on connecting nozzle and two ear supports. So before buckling analysis, Ratio of Load bearing capability between connecting nozzle and triangle bracket should be determined firstly which will be used in strength analysis.

The geometry model and meshing were established as shown in Fig.2~ Fig.4. The Solid186 element was used in the FE model. The displacement and force boundary conditions including other loads were shown in Fig.5. The analysis result showed that two ear supports bear 22% weight of accessory equipment, shown in Fig.6. This analysis is based on elastic analysis. The reason is that most area of structure remained in an elastic state during the load process. Plastic deformation of local region won't affect global elastic analysis result.
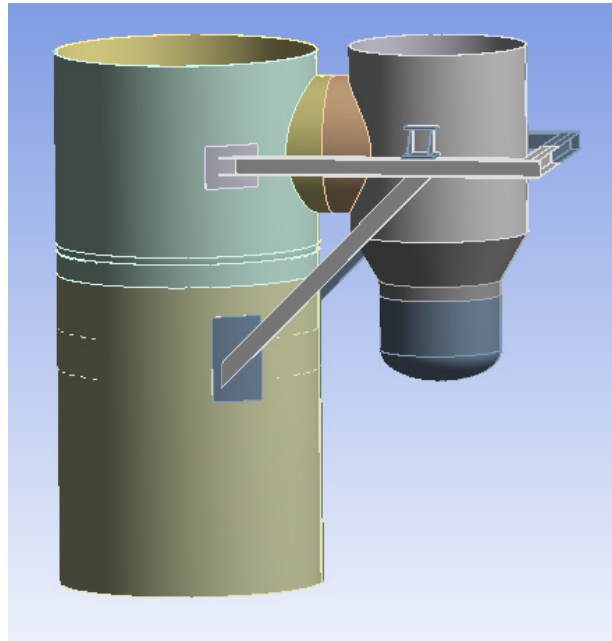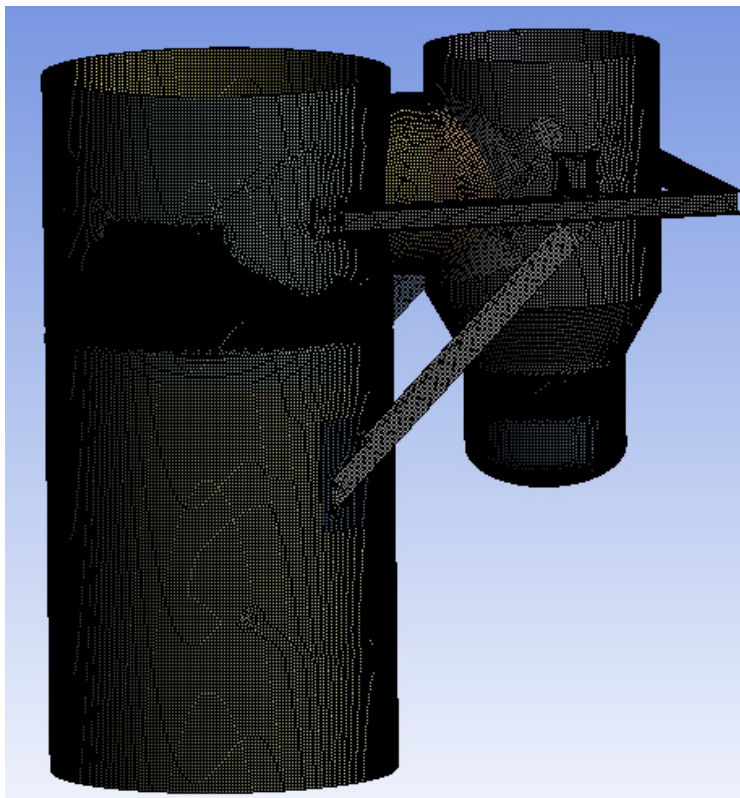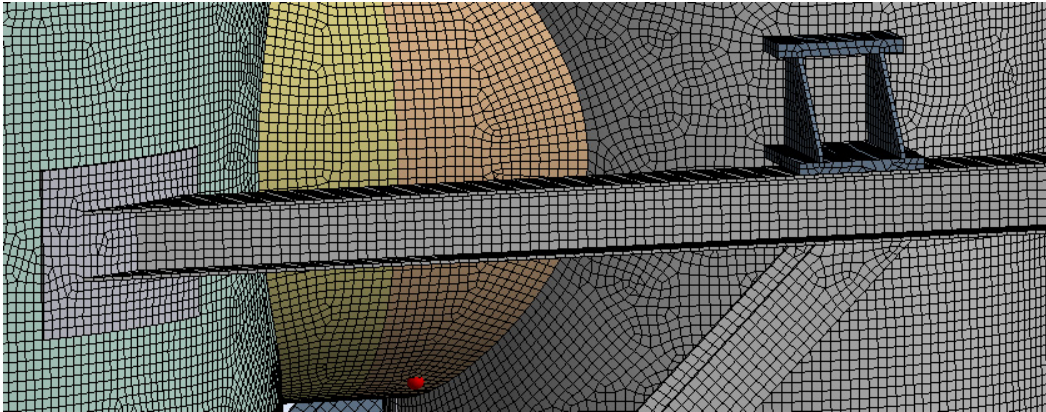
Fig.2. Geometry model.

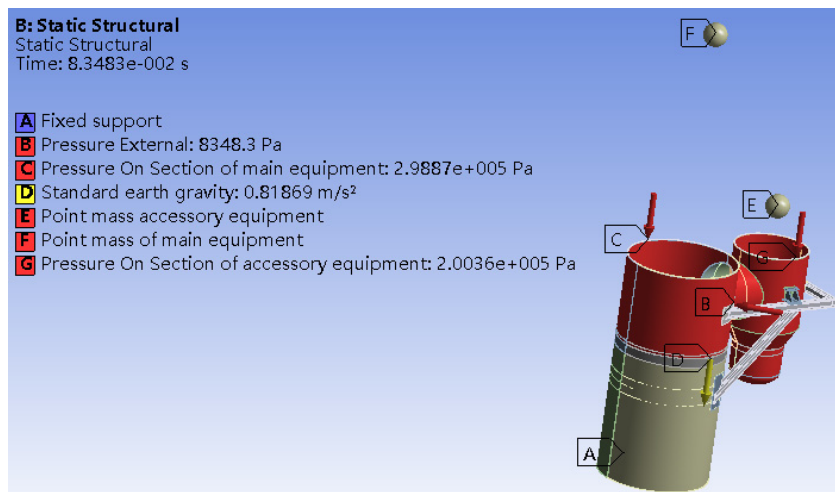Fig.3. Global meshing.

Fig.4.Detail view oflocal meshing.

Fig.5.Displacement and force boundary conditions.

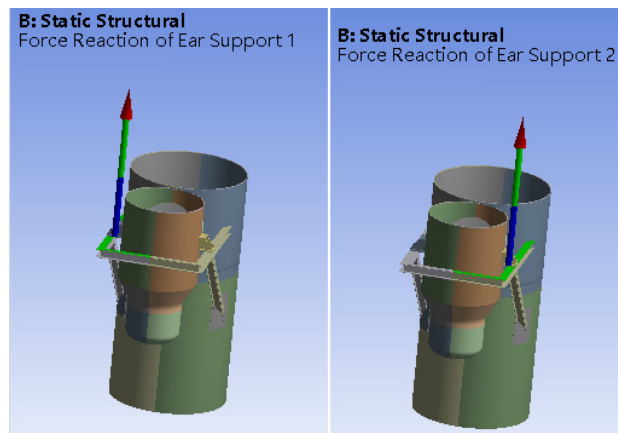Fig.6. Reaction force of ear support of accessory equipment.

4.2.2. Local area subjected to compress stress

Through mechanics analysis and finite element calculation, engineer can see local areas subjected to compress stress. Compress stress occurred at the bottom of connected region between two cylinders and nozzle, tow bracings of triangle bracket and local connecting region between tow bracings and shirt support. Buckling evaluation should be performed in these areas, shown in Fig.7.
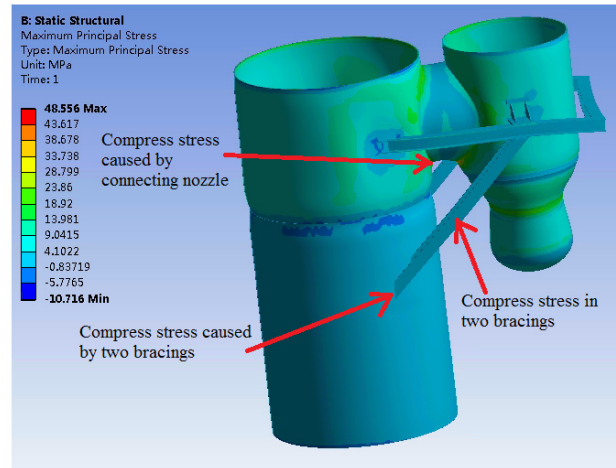

Fig.7. Maximum principal stress nephogram.

4.2.3. Evaluation of local buckling

Although the strength evaluations were fully satisfied, buckling analysis was an essential part of design. In this case study, elastic buckling analysis was used and the load multiplier is 37.491 for the first mode, shown in Fig.8.
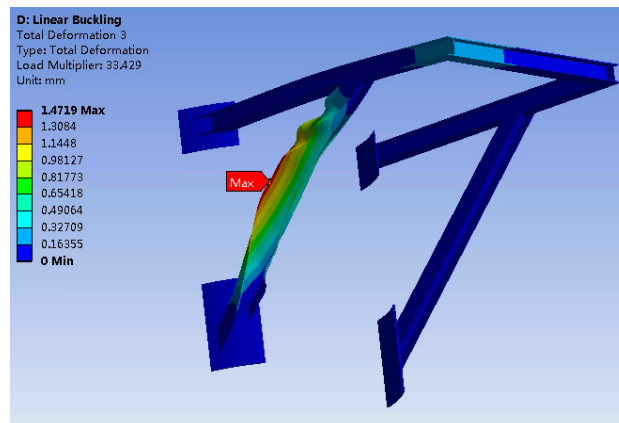

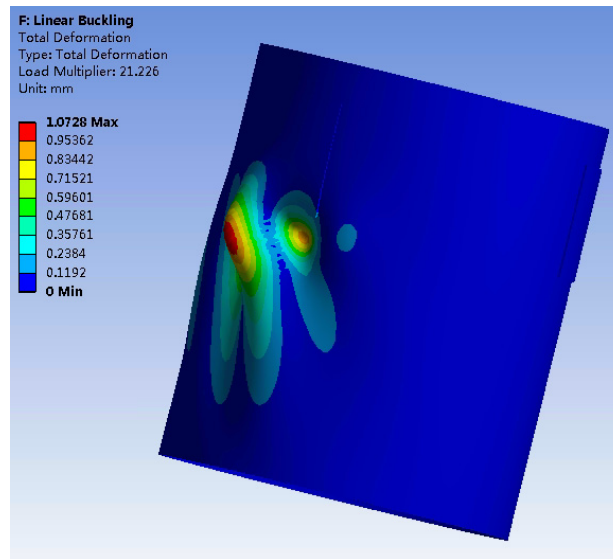Fig.8. Buckling analysis for triangle bracket.

Fig.9.Result of linear buckling analysis of shirt.

Shirt support subjected a series of loads including seismic load, wind load, eccentric load, and local loads due to triangle bracket, all of which will cause compress stress and possible buckling failure. Result of buckling analysis for shirt was shown in Fig.9.

According to corresponding design factor provided in ASME Ⅷ-2[1], Evaluation of buckling analysis was qualified.

5. Conclusions

Buckling design methods based on numerical analysis were far more advanced than classic formulation derived from elastic theory. But results obtained from numerical analysis are still too conservative compared with experimental results. Because different influence factors and their combination will lead to different buckling modes and mechanism of these influence factors are not totally understood now, the Code[1] has to adopt conservative design factors to consider the uncertainty.

For now, although pressure vessel Codes ,there still is considerable room for improvement in achieving a truly safe and economical design factors. Some direction of further study were suggested as follow:

Applying geometric defects, including shape and magnitude;

Incompatibility due to manufacture, such as alignment tolerance of welding groove;

Diversification of forms for reinforcing structures;

Considering influences of the combination of pressure load, thermal load and other mechanical loads;

Welding residual stress and Metallographic change;

Buckling behavior of new nonmetal materials, multi-layer composite materials and anisotropic materials;

In my own optimistic forecast, the next generation of buckling analysis method will be born in 10~15 years. The prominent characteristic of new methods in future is that more rational design factors are developed and more detail design guide, especially for nonlinear numerical calculation.

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