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Strength and stability analysis of a cryogenic storage tank

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Abstract. Cryogenic liquefied-gas storage tanks are more and more widely used in engineering. As a typical pressure vessel with a complicated structure and working at a low temperature, it is critical to ensure the safety under all possible loadings. In this paper, a finite element model for a cryogenic liquefied-gas storage tank was established. Stress analysis and the strength as well as stability assessment under two load cases with different combination of loadings were performed. It is found that the cryogenic liquefied-gas tank subjected to the normal design pressure, wind and seismic loads is satisfied to strength requirement according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*.

1. Introduction

With more and more applications of pressure vessels under extreme conditions such as high pressure, low temperature etc., concepts of safety, economy and resource saving have become increasingly important in the development of pressure vessels[1]. Vertical cylindrical storage tank is a typical pressure vessel composed of an inner vessel working at low temperature and an outer shell under external pressure. As both the structure and the loads are complex, the present design for the vertical cylindrical storage tank based on relevant codes is not so rational. However, the optimal design based on the finite element analysis is more and more used in the design of large storage tanks.

By applying three design methods of the one-foot method, the variable-design-point method and the finite element analysis, F Bu designed and compared two large storage tanks. Results indicate that the optimal design based on the finite element analysis is very effective and rational[2]. S J Li's study is based on the structure and bearing behavior of CST, the global and local stress distributions are obtained by the finite element method for different working conditions in the practical use. By this method the structure rationality of the CST was proved[3]. X D Mao *et al.* built 3-D solid models for a low temperature liquid tank. The weakest part of the structure was selected as the object for analysis. Two models for the analysis were presented based on finite element software, which is used for the contrastive analysis on the stress and displacement of the structure with full loading. The strength of the material was checked according to *JB4732-1995 Steel Pressure Vessels-Design by Analysis*, which confirmed that the finite element structure analysis based on the solid model is feasible and simple[4]. X Y Lu *et al.* used finite element software ANSYS to carry out the finite element simulation of the cryogenic LNG horizontal storage tank, focusing on the rationality of the structures of axial and radial connecting strips between outer and inner vessels. The result indicates that with enough radial strips, the axial connecting strips are not necessary because they could induce large local stresses and even lead to the failure based on the strength requirement of the tank. In addition, the axial connecting strips



will cause more heat conductivity between outer and inner vessels, increasing the evaporation of the liquefied medium stored in the tank[5]. R Duan *et al.* used finite element software ANSYS Workbench to carry out the analysis of the cryogenic storage tank. In order to enhance the anti-instability ability of outer vessel under external pressure load, reinforcement ribs were arranged on the vessel. Multi-objective driven optimization was conducted to optimize the reinforcement ribs under the given requirements for the critical buckling pressure[6].

In this paper, a finite element model for a cryogenic liquefied-gas storage tank was established. Stress analysis and the strength as well as stability assessment under two load cases with different combination of loadings were performed. The study provides a certain reference for the design of the tank.

2. Establishment of the finite element model

2.1. Geometrical and grid model

The cryogenic storage tank mainly composed of the inner vessel with the internal diameter of 2500mm and the height of 12620mm and outer vessel with the internal diameter of 3000mm and the height of 14040mm. The inner vessel is supported by three tubes with insulation blocks on the lower head of the outer vessel. The whole structure are supported on the lower head of the outer vessel by three prop supports .

Cryogenic medium with the temperature of -196°C is filled inside the inner vessel. The space between the inner vessel and outer vessel is vacuumed to stop the heat transfer. Table 1 lists some parameters of the cryogenic storage tank. Fig. 1 shows the whole geometrical model of the cryogenic storage tank. Fig. 2 shows the geometrical model of the bottom heads and supports of the cryogenic storage tank. Solid elements (Solid185) with the large commercial finite element software ANSYS are used to mesh the structure and perform stress analysis. Fig. 3 shows the grid model of the bottom heads and supports of the cryogenic storage tank.

Table 1. Some parameters of the cryogenic storage tank.

Item	Value	Item	Value
Vacuum weight (kg)	25700	Material of the outer shell shell	Q345R
Max. weight (kg)	51200	Material of the inner shell shell	S30408
Medium	LNG	Material of the supports	Q235B
Design pressure	1.44MPa	Corrosion allowance	0
Design Temperature	-196°C		

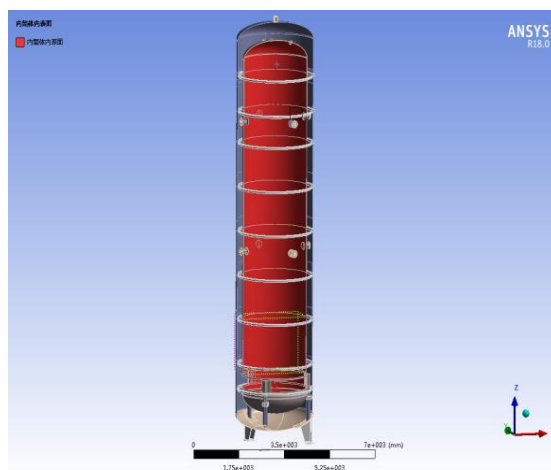


Figure 1. Geometrical model of the cryogenic storage tank(half sectional view).

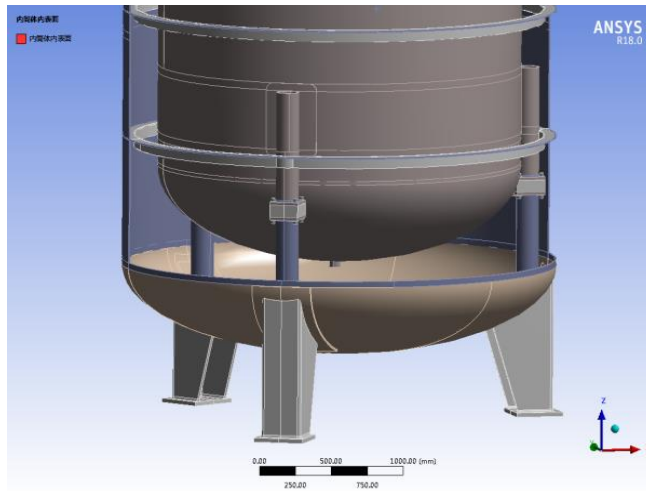


Figure 2. Geometrical model of the bottom heads and supports of the cryogenic storage tank.

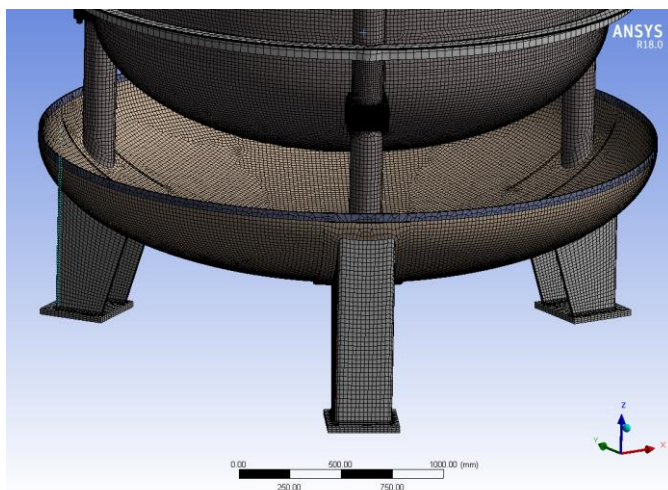


Figure 3. The grid model of the bottom heads and supports of the cryogenic storage tank.

2.2. Loadings and boundary conditions

Under the normal operation, the inner vessel contains the liquefied gas with a saturated vapour pressure at -196°C . The outer vessel is a vacuum vessel. In addition, the tank may undertake wind load and earthquake load. Thus, the following load cases on the tank are considered:

Load cases 1: $D+P+E+0.25W$ (dead load + Pressure + seismic load + $0.25W$)

Load cases 2 (hydraulic test case): $D+P+0.3W$ (dead load + Pressure + $0.3W$)

Fig. 4 shows the application of the dead weight, internal pressure and external pressure.

For constraints, all nodes on the bottom of the four supports are fixed as shown in Fig. 5.

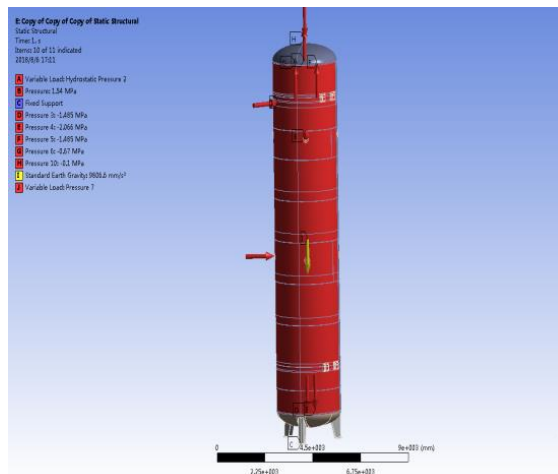


Figure 4. Application of the dead weight, internal pressure and external pressure.

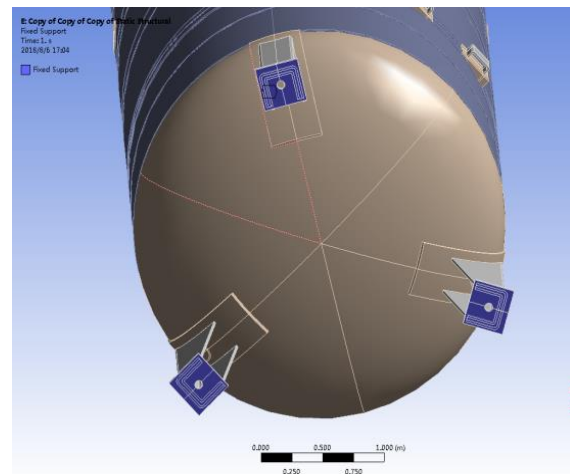


Figure 5. Constrains applied on the bottom of the three supports.

3. Results and discussions of the finite element analysis

3.1. Strength analysis and assessment

For the design pressure vessels, there exist two methods, namely design by rules and design by analysis. In this study, the method of design by analysis is employed which should conform to the Chinese standard of *JB4732-1995 Steel Pressure Vessels—Design by Analysis*. Based on this standard, stress intensity which is defined as the two times of the maximum shear stress, is taken as the parameter to perform strength assessment. Fig. 6 shows stress intensity distribution at the whole storage tank under load case 1. Fig. 7 shows stress intensity distribution at the bottom heads and supports of the cryogenic storage tank under load case 1.

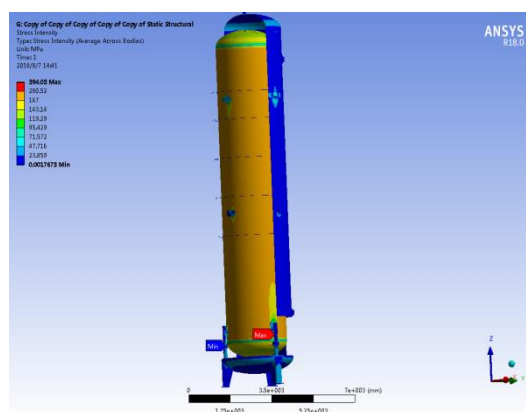


Figure 6. Stress intensity distribution at the whole storage tank under load case 1.

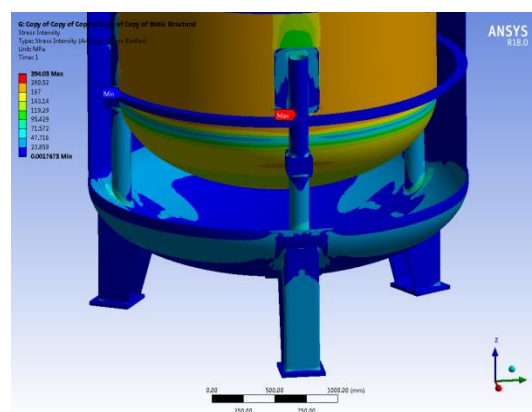


Figure 7. Stress intensity distribution at the bottom heads and supports of the cryogenic storage tank under load case 1.

In addition, according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*, stress intensity at the shell should be classified as five categories according to their effects on the strength failure of the equipment, namely general primary membrane stress intensity S_I , local membrane stress intensity S_{II} , primary membrane plus primary bending stress intensity $S_I, S_{II}, S_{III}, S_{IV}, S_V$, primary plus second stress intensity S_{II} and peak stress intensity S_V . For strength assessment, the allowable stress

intensity values of $S_I, S_{II}, S_{III}, S_{IV}$, and S_V , are respectively $kS_m, 1.5kS_m, 1.5kS_m, 3S_m$ and S_a where S_m is the design stress intensity of materials, S_a is determined from suitable fatigue design curves according to the specified load cycle numbers and k is the factor for load combinations. For loadings with wind load and seismic load, $k=1.2$.

The material for the inner vessel is stainless steel S30408 with the design stress intensity S_m at room temperature being 167MPa. The material for the outer vessel is Q345R with the design stress intensity S_m at room temperature being 189MPa. The material for supports is Q235B with the design stress intensity S_m at room temperature being 116MPa.

The allowable material stress intensity values for different stress intensity categories are listed in the Table 2.

Table 2. Allowable material stress intensity values for different stress intensity categories.

Steel brand	S30408	Q235B	Q345R
1.0KS	200.4	139.2	226.8
1.5KS	300.6	208.8	340.2
3.0KS	601.2	417.6	680.4

By categorizing the strength intensity and comparing with different limits for different stress categories it is found that the cryogenic storage tank meets the strength requirements according to the *JB4732-1995 Steel Pressure Vessels-Design by Analysis*.

3.2. Stability assessment

Under the action of external pressure, the stability of the outer vessel must be checked. To do so, eigenvalue buckling analysis was carried out using numerical simulations. By applying external pressure of 0.1MPa on the outer vessel, it is obtained that the load factor for the first order instability is 0.441, meaning that the safety factor for the stability of the outer vessel is 4.41 which is larger than 3 for the usually accepted value assessing stability of cylindrical vessels or in other words, the outer vessel is stable under the action of the normal external pressure. Fig. 8 is the first order instability modal. Clearly, if instability happened, it would be circumferential and the reinforce rings on the vessel did play an important role in resisting the instability of the vessel.

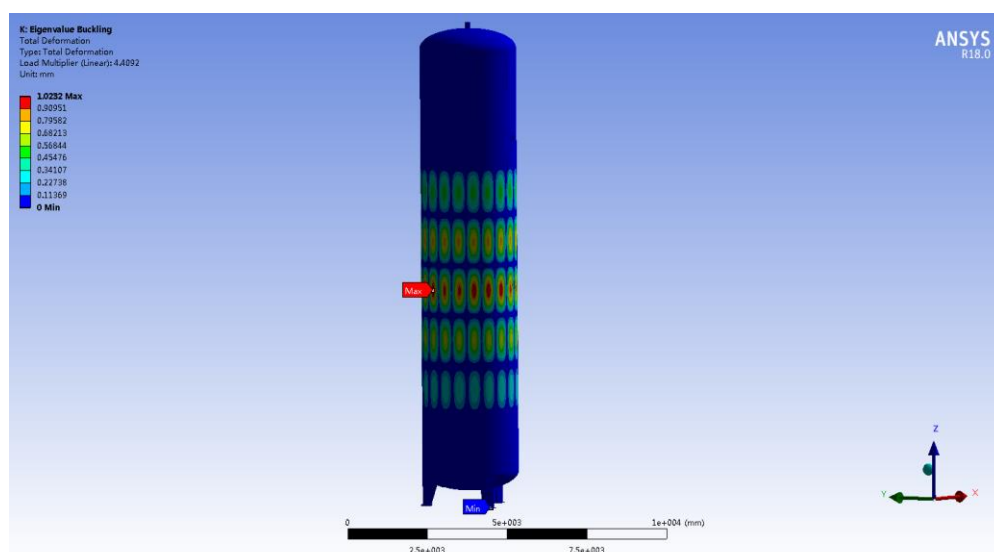


Figure 8. The first order of the instability modal.

4. Summary

Based on above numerical simulation results, it is concluded that the cryogenic liquefied-gas storage tank subjected to normal design pressure, wind and seismic loads is satisfied to strength requirement according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*. Also, the outer vessel is stable under the action of the normal external pressure.

Acknowledgement

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