Stress analysis and strength assessment of ammonia water storage tank

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Abstract. In this paper, a large vertical cylindrical steel ammonia storage tank was numerical simulated. Strength and stability assessment under earthquake load, wind load, internal pressure and dead weight were performed. It is found the strength of the tank meets the strength requirements according to JB4732-1995 Steel Pressure Vessels-Design by Analysis. The tank is in stability even under the compressive stress at the leeward side of cylindrical vessel under the combined wind load and earthquake load.

1. Introduction
In petroleum engineering, large storage tanks are widely used to store various petrochemical materials because of the advantages of saving steel, reducing floor space, facilitating operation management, reducing storage tank attachments and pipeline length [1]. The destruction of large storage tanks often causes huge economic loss and environmental damage. The damage forms of large storage tanks mainly involve of the crack at shell-to-bottom fillet weld of the base zone and the storage tank wall caused by hydrostatic pressure, tank wall buckling caused by wind load, elephant-foot buckling (EFB) at the tank wall caused by earthquake load and so on.

F Bu et al. [2] studied mechanical property and structural design of large storage tanks from aspects of intensity and stability of storage tanks. The paper analyzes basic deformation forms and stress distribution characteristics of 2×10⁵m³ large storage tanks. There is abrupt structure change and high stress level at the shell-to-bottom fillet weld area. The highest stress appears at the lower edge of the inner side of the shell-to-bottom fillet weld which is the connecting position between weld and base zone. In order to improve the accuracy of stress calculation of large non-anchored crude oil storage tanks, Z P Chen et al.[3] proposed a new stress calculation method based on long and short combined cylindrical shell theory by comparing the difference between existing theoretical analysis and finite element numerical calculation solution and measured stress data. The new method replace the long cylindrical shell theoretical analysis method which is currently used. The experimental result shows that the calculation accuracy of the new method is much higher than the original method. W J Dou et al. [4] take advantage of MIDAS GEN software to simulate and analyze the deformation and stress situation of the vault of large storage tank under five different load combinations involving of constant load, movable load, wind load, snow load and earthquake load. In order to improve the stability and safety coefficient of whole structure, buckling analysis was carried out to check whether the strength and stability of the tank met the requirements. The simulation analysis result shows that...
the strength and stability of storage tank meet the requirements. J M Li et al. [5] used ANSYS Workbench finite element analysis software to carry out static analysis of static tank. By extracting the path at the vault, pressure ring and tank wall, the author extracted and analyzed stress characteristics curve of the set path position. It is found that from the welding position between the vault and pressure ring to the distance of 0.8R from center of the vault, the vault deforms rapidly and the deformation reaches the maximum at 0.8R while the stress variation of the vault is opposite. The stress of pressure ring top plate almost remains constant from the foremost end of the top plate and the stress is abruptly reached the maximum until the position which is welded to the support plate. The total deformation trend of the tank wall is same with the stress distribution of the tank wall basically which gradually grows from bottom to the top. It reaches the maximum at the bottom of the tank wall and reaches the minimum at the bottom of the tank wall where tends to zero. J Liu et al.[6] determined the dangerous section of the vault reticulated shell by comparing theoretical calculation result and numerical simulation result of the stress of the vault under the uniform load and concentrated load. The result shows that under the uniform load and concentrated load, the stress of the circular beam of outermost of vault and the radial beam near the arch springing are higher which is the dangerous section of the vault. A Zingoni et al. [7] proposed a linear elastic theory formulation for the stress state of large thin-walled liquid-filled containers. The formulation assumes that the transfer of membrane stress between adjacent shell layers only requires stress balance in the vertical direction. Through the finite element simulation analysis of the storage tank, the theoretical calculation result of the formulation is similar to the simulation analysis result which shows that the formulation fits correctly. Z P Chen et al. [8] proposed a calculation method for the stress distribution of large tank walls based on the theory of combined cylindrical shell for the circular stress distribution characteristics of cylindrical shell sections with different wall thicknesses. The bottom wall is regarded as short cylindrical shell and the other walls are regarded as long cylindrical shells. The result of the example analysis shows that the result obtained by the stress calculation method of the combined cylindrical shell theory are consistent with the measured result basically which can provide technical reference for the large vertical cylindrical steel welded storage tank.

In this paper, stress analysis and strength assessment on a large vertical cylindrical ammonia storage tank under various loads will be performed. Instability of the tank will also be investigated. The study provides a certain reference for the design of the tank.

2. Establishment of finite element model

2.1. Geometrical and grid model

The ammonia water storage tank is mainly composed of three parts: vault, cylindrical vessel and bottom floor. 25% ammonia water with the density of 907kg/m$^3$ is stored under the normal operation. The vault and cylindrical vessel are connected by the angle steel ring.

This analysis is aimed to perform stress analysis and strength assessment for the storage tank under the combined loadings including hydrostatic load, inner pressure, earthquake load, wind load, platform load, stairway load and rainshed load. To establish the finite element model of the tank, based on technological requirements and structural characteristics of the ammonia water storage tank, shell181 element is employed for meshing the vault, cylindrical vessel, bottom floor and other connection structures while solid186 element is employed for the extension of manhole and beam188 is for support frames of stairway. Bond contacts are employed for the connections between stairway support and welding plate, and between cylindrical vessel and the manhole extension. The finite element model of the whole structure is shown in Figure 1-2.
2.2. **Loadings and boundary conditions**

According to engineering application requirements, the following loads on the tank are considered:

- **Inner pressure**: The design inner pressure of the cylindrical vessel is 5kPa.
- **Hydrostatic pressure**: The tank contains 25% ammonia water with the density of 907kg/m³. The height of media is 12000mm.
- **Dead weight of the tank**: Applying a 9.8m/s² gravity acceleration on all bodies.
- **Platform loads**: Applying a 68600N force on the platform. The direction is downward and perpendicular to the platform.
- **Rainshed loads**: Applying 14700N forces on each of the six upper panels of rainshed supports.
- **Stairway loads**: Applying 8575N forces on each stairway support frame. The direction is downward and perpendicular to the stairway support frame.
- **Wind loads**: Regarding the most dangerous surface (the side having stairway welding plate) as windward side. Applying $2.5046e-003 \cos (y+90^\circ)$ MPa wind pressure on the windward side wall.
- **Earthquake loads**: Applying 1351mm/s² horizontal earthquake acceleration on the windward side. The direction is windward.
- **Equivalent tube pressure**: Applying approximately 0.1MPa equivalent tube pressure on the manhole end.

The following constraints on the tank are applied:

- Z direction displacement constraint on the bottom floor and XYZ direction displacement constraints on the surfaces for assembling the 24 bolts.

Loads and constraints are shown in Figure 3-4.
3. Results of FEA and strength assessment

3.1. Design stress intensity of the material

The material for main components is S30400 (ASME SA-240M). The design stress intensity for S30400 is 137MPa.

Allowable stress intensity values for the material are listed in the Table 1.

| Steel brand       | S30400 (ASME SA-240M) |
|-------------------|------------------------|
| $1.0k_Sm$         | 164.4 MPa              |
| $1.5k_Sm$         | 246.6 MPa              |
| $3.0k_Sm$         | 493.2 MPa              |

3.2. Strength assessment

To ensure the safety of the tank, strength assessment should be performed and stress intensity is usually taken as the parameter to make the strength check. Figure 5-9 show the stress intensity distributions at the whole or local structures. By categorizing the strength intensity and giving different limits for different stress categories, it is found that the ammonia water storage tank meets the strength requirements according to the JB4732-1995 Steel Pressure Vessels—Design by Analysis.

Because of the horizontal action of the wind load and earthquake load, compressive stress may present at the tank wall which may induce instability failure of the tank. Figure 10 shows the axial compressive stress distributions at the leeward side of cylindrical vessel under the wind load and earthquake load. It is seen that the axial compressive stress is no more than 10MPa which is found to
be less than the critical value for axial instability of the tank, indicating that the cylindrical vessel is 
stability under the combined wind load and earthquake load.

Figure 11 shows the force reactions of ground to bottom floor. It is found that under the normal 
operation condition, even on the windward side, the reaction force of ground to the bottom floor is 
upward, meaning the ankle bolts are not in tensile state. However, the ankle bolts are needed for 
positioning of the tank.

![Stress intensity distribution on whole tank](image1)

**Figure 5.** Stress intensity distribution on whole tank

![Stress intensity distribution at the center board](image2)

**Figure 6.** Stress intensity distribution at the center board.

![Stress intensity distribution at the vault](image3)

**Figure 7.** Stress intensity distribution at the vault.
Figure 8. Stress intensity distribution at the cylindrical vessel.

Figure 9. Stress intensity distribution at the bottom floor.

Figure 10. Axial compressive stress distribution at the leeward side.

Figure 11. The force reaction of ground to the bottom floor.

4. Conclusions

(1) Under the normal operation condition, the ammonia water storage tank meets the strength requirements according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*.

(2) The compressive stress caused by wind load and earthquake load at the leeward side of cylindrical vessel is less than the critical value for axial instability of the tank, indicating that the cylindrical vessel is stability under the combined wind load and earthquake load.

(3) Under the normal operation condition, the ankle bolts are not in tensile state. However, the ankle bolts are needed for positioning of the tank.
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