Strength study of a large suspended tower based on numerical simulations

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Abstract. Regarding the structure and loadings undertaken, suspended tower is a specially vessel in engineering. In this paper, finite element models for a large suspended tower were established. Stress analyses and the static as well as fatigue strength assessment under some load cases with different combination of loadings were performed. It is found that the large suspended tower subjected to the normal working conditions is satisfied to strength requirement according to the JB4732-1995 Steel Pressure Vessels—Design by Analysis.

1. Introduction

Pressure vessels are closed containers to hold gases or liquids at a pressure substantially different from the ambient pressure. They are widely used in thermal and nuclear power plants, chemical industries, oil refineries etc. As working under pressures, pressure vessels need to be more stringent in their design, manufacture, and operation because of the huge property and life risk that would result from an explosion. Consequently, pressure vessel design, manufacture, and operation are regulated by engineering authorities backed by legislation[1].

For the design of pressure vessels, there exist two methods, namely design by rules and design by analysis. J G Li et al.[2] compared design by rules and design by analysis and stated their advantages and disadvantages. For two design methods, the designer should choose a more reasonable design method according to practical experience and calculation. M W Lu et al.[3] take ASME VIII-2 2007 edition as the main line to introduce the latest development of stress classification, discuss and comment on the JB4732 standard of China and EN13445 2002 of EU standard. B Gao et al.[4] proposed a convenient method to decompose the overall stress field to derive the primary bending stress based on the principle of superposition. The proposed method also allows us to obtain the primary membrane plus primary bending equivalent stress ($P_m+P_b$), which was often mixed with secondary bending stress leading to over conservation. From validation in different structural pressure vessels, this method is generalized for applications in a wide range of structures such as flange, nozzle at the small end of the conical shell, and nozzle of the spherical shell.

For tall vertical pressure vessel, apart from the column design, the wind and seismic loading calculation is one of the major requirements. A M S Anbalazahan et al.[5] studied how tall column has to be designed for withstanding heavy wind and seismic conditions and what are all the design steps fabricator needed to be considered during their design for preventing failures. The calculation is generated with respect to the requirement of international codes and standards. F Zhao[6] numerically
analyzed the strength of the combined structure of a tower and chimney by using the finite element software ANSYS, and the stress analysis of the model under loadings including wind load and earthquake load is carried out according to the standard, and the strength of the structure is checked by the stress classification method. In addition, a two-dimensional simulation analysis of the Karman vortex problem caused by wind induced vibration of tower equipment using computational fluid software fluent, and the Vortex-street variation under the action of wind loads in different directions of the composite structure is studied. It is found that the Reynolds number is in a certain range, the single tower device will appear the phenomenon of the Boltzmann vortex, causing the induced vibration, the composite structure is more difficult to induce vibration, and the flow field distribution of the composite structure is related to the wind direction.

In this paper, finite element models for a large suspended tower were established. Stress analyses and the static as well as fatigue strength assessment under some load cases with different combination of loadings were performed.

2. Establishment of the finite element model

2.1. Geometrical and grid model

In structure, the suspended tower is mainly composed of a cylindrical vessel, a ring bracket support with four lifting lugs, and two sets of bolted plate structures. The ring bracket support is welded to the outside surface of the cylindrical vessel and is used to suspend the vessel by hinging to four lifting rods with the four lifting lugs. The two sets of bolted plate structures are also welded to the cylindrical vessel but can slide axially and radially to the surrounding steel frame and in this way, swing movement of the suspended tower can be prevented but the axial and radial thermal expansions are not limited. The inside diameter of cylindrical vessel is 2600mm and the height of vessel is 15000mm. The top and bottom heads are standard elliptical heads. Many openings with tubes are set up on the vessel especially on the top head. Table 1 lists some parameters of the suspended tower.

| Item                      | content            |
|---------------------------|--------------------|
| Medium                    | Melt salt          |
| Main materials            | Q345R/16MnIII      |
| Volume (m³)               | 85                 |
| Working temperature (°C)  | 290                |
| Design temperature (°C)   | 320                |
| Working pressure (MPa)    | 2.5                |
| Design pressure (MPa)     | 2.9                |
| Corrosion allowance (mm)  | 3                  |
| Design life (y)           | 30                 |
| Working cycle number      | 11000              |

Figure 1 and Figure 2 show the whole geometrical model of the suspended tower. Solid elements (Solid186) with the large commercial finite element software ANSYS are used to mesh the structure and perform stress analysis. Figure 3 shows the grid model of the upper part of the suspended tower and Figure 4 shows the grid model of the top head with tube connections of the suspended tower.
Figure 1. The whole geometrical model of the suspended tower (front view).

Figure 2. The whole geometrical model of the suspended tower (top view).

Figure 3. The grid model of the upper part of the suspended tower.

Figure 4. The grid model of the top head with tube connections of the suspended tower.

Figure 5. The grid model of the ring bracket support of the suspended tower.

Figure 6. Application of hydrostatic pressure.
2.2. Loadings and boundary conditions

Usually, the suspended tower undertakes loadings including the internal pressure, hydrostatic test pressure, thermal load, and hydrostatic test pressure. As the tower is housed and hinged on a steel frame in service, the wind load and earthquake load can be neglected and thus, the following load cases are considered:

Load case 1: D+P+L (dead load + internal pressure + hydrostatic pressure)
Load case 2: D+P+L+T (dead load + internal pressure + hydrostatic pressure + thermal load)
Load case 3 (hydrostatic test case): D+P (dead load + hydrostatic test pressure)
Load case 4 (fatigue): D+P+L+T (dead load + internal pressure + hydrostatic pressure + thermal load)

For constraints, all nodes on the four lugs contacting with the lifting rods are fixed in axial and circumferential directions as shown in Figure 7.

3. Results and discussions of the finite element analysis

3.1. Stress analysis and static strength assessment

For the design of 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. In addition, for the solid element meshed shell, in order to classify membrane stress and bending stress, stress linearization along the shell thickness at critical points should be performed. Therefore, paths on the tower at critical points should be defined as shown in Figure 8 for the paths on the bottom head and the connected tube.

Figure 9 shows stress intensity distribution at the whole tower under load case 1. Figure 10 shows stress intensity distribution at the bottom head and the connected tube of the tower under load case 1.
In addition, according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*, stress intensity at the shell must 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 $S_{III}$, primary plus second stress intensity $S_{IV}$ 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 without wind load and seismic load, $k=1.0$.

The material for the cylindrical vessel is low alloy carbon steel Q345R and 16MnIII. Based on *JB4732-1995 Steel Pressure Vessels—Design by Analysis*, the design stress intensity $S_m$ of Q345R at the design temperature of 320°C is 129MPa for the plate thickness greater than 36mm and less than or equal to 60mm. The design stress intensity $S_m$ of 16MnIII at the design temperature is 129MPa. The design stress intensity $S_m$ of the two materials at room temperature are respectively 181MPa and 178MPa.

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

| Steel brand | Q345R (16mm-36mm) | Q345R(36mm-60mm) | 16MnIII |
|-------------|-------------------|-----------------|----------|
| 1.0kS_m     | 139               | 129             | 129      |
| 1.5kS_m     | 208.5             | 193.5           | 193.5    |
| 3.0 S_m     | 417               | 387             | 387      |

Note: $k$ is the factor for load combinations and in this study $k = 1.0$.

As an example, Table 3 lists results of the stress intensity calculation and assessment at the bottom head and the connected tube under load case 1. By checking all stress intensities at all parts of the
vessel under all load cases, it is found that the suspended tower meets the strength requirements according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*.

**Table 3.** Results of the stress intensity calculation and assessment at the bottom head and the connected tube.

| Locations                                                                 | Stress intensity categories | Values (MPa) | Allowable values (MPa) | Results |
|---------------------------------------------------------------------------|----------------------------|--------------|------------------------|---------|
| Along thickness of the bottom head at the transition area (Path 7 in Figure 8) | $S_{II}$                    | 131.02       | 193.5                  | satisfied |
|                                                                           | $S_{IV}$                    | 191.64       | 387                    | satisfied |
| Along thickness of the bottom head at the middle area (Path 8 in Figure 8) | $S_{I}$                     | 104.77       | 129                    | satisfied |
|                                                                           | $S_{III}$                   | 108.92       | 193.5                  | satisfied |
| Along thickness of the bottom head at the connection area between the bottom head and the medium input tube (Path 9 in Figure 8) | $S_{II}$                    | 165.74       | 193.5                  | satisfied |
|                                                                           | $S_{IV}$                    | 201.24       | 387                    | satisfied |
| Along diagonal line at the connection area between the bottom head and the medium input tube (Path 10 in Figure 8) | $S_{II}$                    | 178.23       | 193.5                  | satisfied |
|                                                                           | $S_{IV}$                    | 207.69       | 387                    | satisfied |
| Along thickness of the tube at the connection area between the bottom head and the medium input tube (Path 11 in Figure 8) | $S_{II}$                    | 161.63       | 193.5                  | satisfied |
|                                                                           | $S_{IV}$                    | 174.24       | 387                    | satisfied |
| Along thickness of the bottom head at the middle area (Path 8 in Figure 8) | $S_{I}$                     | 104.77       | 129                    | satisfied |
|                                                                           | $S_{III}$                   | 108.92       | 193.5                  | satisfied |

3.2. *Fatigue strength assessment*

From the numerical simulation, the maximum peak stress intensity at the structure under the load case 4 can be calculated and based on *JB4732-1995 Steel Pressure Vessels—Design by Analysis*, the allowable cycle number can be obtained and thus, the fatigue strength of the suspended tower can be assessed. Results are listed in Table 4. The factor of usage is smaller than 1, meaning that the fatigue failure of the suspended cylindrical vessel will not happen under the fatigue load case 4.

**Table 4.** Fatigue strength assessment.

| Item                        | content |
|-----------------------------|---------|
| Load case                   | 4       |
| Internal pressure (MPa)     | 2.5     |
| Peak stress intensity $S_t$ (MPa) | 240.62  |
| Alternating stress intensity $S_{alt}$ (MPa) | 120.31  |
| Allowable cycle number $N$  | 173708  |
| Working cycle number $n$    | 11000   |
| Factor of usage $U=n/N$     | 0.0633  |

4. **Conclusions**

Based on above numerical simulation results, it is concluded that the suspended tower subjected to normal working conditions meets the strength requirement according to the *JB4732-1995 Steel Pressure Vessels—Design by Analysis*. 
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