Stability and Strength Analysis of Internal Floating Roof Atmospheric Tank

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Abstract. The 101 vacuum residue tank of a company has been exploded by high temperature liquid vapor expansion due to improper operation. In this paper, the finite element analysis of the overpressure condition of the tank was carried out, the stress distribution of the tank under the pressure was given, the damage location of the tank was analyzed, and the strength of the tank under the condition of water pressure test was checked for the tank structure after the wall plate is replaced.

1. Introduction
Vertical vaulted tank is an important equipment in the process of crude oil storage and transportation [1]. The causes of overpressure, calculation of destructive pressure and determination of destructive conditions and weak roof design have been key technical problems in tank design and safe operation [2-4]. In all liquefied petroleum gas accidents, the proportion of steam cloud physical explosion accidents is about 25%. Boiling liquid extended vapor explosion is a typical form of vapor cloud explosion. This kind of explosion model is mainly based on the explosion rupture of liquid storage tank and the strength yield of tank material, also based on the leakage and evaporation of liquid inside the tank. However, the above indexes can only be entered in a conservative way at present which is hard to assess [5-7]. At present, the overpressure condition under the action of destructive pressure is commonly used to simplify the treatment of the influence of boiling liquid expanding steam explosion on the storage tank. Based on the stress analysis results, a reasonable maintenance strategy is formulated [8-10].

In this paper, one 15000m³ in-use oil tank which suffered a physical explode is modeled by ANSYS. the stress intensity under rupture pressure is given. Three typical stress intensity evaluation is obtained based on JB4732-1995[11]. The stress intensity check after repaired is issued which shows that the strength also meet the requirement.

2. Storage tank survey
Tank 101 is used to hold vacuum residue. The schematic diagram of the tank structure is shown in Figure 1. Tank 101 was put into use in 2012. The basic technical parameters of the tank are shown in Table 1. In order to determine the influence of damage load on the key parts of tank such as large fillet weld, we issued the finite element static analysis to evaluate the stress intensity of the key structure of tank based on the third strength theory. Reasonable maintenance strategy and after maintenance evaluation were formulated.
Table 1. Table of basic technical parameters

| NO. | Type of roof | Design temperature (°C) | Design pressure (kPa) | Vault |
|-----|--------------|--------------------------|-----------------------|-------|
| 101 | Vault        | 170                      | 1.961                 |       |

Material:
- Panel: Q345R
- Bottom: Q234B
- Panel Thickness (mm): Nominal 20/18/16/14/12/12/10/8/8
- Bottom edge plate: 18
- Bottom middle plate: 10
- Roof: 6

Corrosion allowance (mm): 2.0
Nominal diameter (mm): Φ34,000

Effective Section Area of Compression Ring (mm²): 7,583.3
Panel height (mm): 17,800 (10×1780)

Nominal volume (m³): 15,000
Maximum local deformation of tank wall (mm): 30

3. Model of FEM
Based on the axisymmetric characteristics of the geometric structure, constraint and mechanical boundary conditions of tank body and foundation, an axisymmetric model is established. Axisymmetric shell element SHELL61 and structural entity element SOLID182 with axisymmetric option are used to simulate tank structure and concrete foundation respectively. Both tank body and foundation are made of isotropic elastic materials. Specific parameters are shown in Table 2. When simulating the interaction between tank and foundation, 2-D TARGE169 and CONTA171 elements are used to establish contact pairs. The finite element model is shown in Figs. 2. Because of the axisymmetric and contact analysis model, only the displacement of the bottom layer node of the foundation and the degree of freedom of the radius direction of the node on the symmetrical axis of the tank body are constrained, the acceleration of gravity is 9.8m/s².

Table 2. Tank body and foundation parameters

|                      | Modulus of elasticity | Poisson ratio | Density   |
|----------------------|-----------------------|---------------|-----------|
| Tank body            | 201.0GPa              | 0.3           | 7850kg/m³ |
| Foundation           | 3.0GPa                | 0.2           | 2500 kg/m³|

4. Overpressure condition
4.1. Load calculation
GB50341\cite{11} gives the calculation method of maximum design pressure and failure pressure of micro-
internal pressure tank with design pressure not more than 18 kPa. According to the formula for
calculating the maximum design pressure:

\[
P_i = \frac{A R'_L \tan \theta}{200D^2} + \frac{0.00127D_{LR}}{D^2}
\]

(1)

Formula for calculating failure pressure:

\[
P_f = 1.6P_i - \frac{0.000746D_{LR}}{D^2}
\]

(2)

Formula for calculating hydrostatic pressure \(p\) (varying with distance \(h\) from liquid level):

\[
p = \rho y gh
\]

(3)

Where: \(P_i\)—Maximum design pressure for micro internal pressure tanks, kPa. \(A\)—Effective section
area of the compression ring at the connection of the tank roof and the tank wall, mm\(^2\). \(D\)—Oil tank
inner diameter, m. \(D_{LR}\)—The weight of tank roof and its accessories, N. \(R'_L\)—Lower limit of standard
yield strength of compression ring materials at design temperature, take as 175 MPa. \(\theta\)—The angle
between the tank roof and the horizontal plane at the connection between the tank roof the tank wall,
take as 30. \(P_f\)—Calculated failure pressure, kPa. \(P_i\)—Maximum design pressure, kPa. \(p\)—Hydrostatic
pressure, Pa. \(\rho\)—Liquid density, kg/m\(^3\). \(G\)—Gravity acceleration, m/s\(^2\). \(H\)—Calculate the height from
the position to the designed liquid level, m. Results from formula 2 and formula 3 were applied to the
finite element model of the tank to carry out the non-linear static analysis.

4.2. Stress analysis results

Figure. 3—Figure. 8 shows the distribution of circumferential and radial stresses of tank wall and tank
bottom under overpressure conditions. It can be seen from Figure. 3 that: (1) Because of bending
moment on the side wall, the vertical tensile stress at the bottom inner wall of the first ring of the tank
wall is generated, the maximum value is 172 MPa. (2) Axial compressive stress is generated at the
bottom outer wall of the first ring tank wall, the minimum value is -169.2 MPa. (3) After the height of
0.6 meters from the bottom of the tank, the axial stress of the tank wall is very small.

It can be seen from Figure. 5 that: (1) With the increase of the height of the tank wall, the
circumferential stress of the outer wall of the first ring tank increases gradually, the maximum value is
about 90 MPa. (2) With the increase of height, the circumferential stress line of the second ring tank
wall increases slightly at first and then decreases. (3) With the increase of height, the circumferential
stress of other wall tanks continues to decrease slowly. (4) The maximum circumferential stress of the
tank wall appears at the joint of the tank wall and the tank roof at the top of the tank wall, the
maximum value is 215.6 MPa.

Figure 3. Axial stress inside wall
Figure 4. Axial stress outside wall
4.3. Stress strength assessment

Based on the relevant requirements of standard [12,13], the stress intensity of primary film, primary local film plus primary bending strength and primary plus secondary stress strength of tank wall and bottom are calculated and evaluated. Figure 7 and Figure 8 are the curves of the stress intensity of the tank wall and bottom plate with the height and radius direction of the tank under the failure pressure load. Maximum and permissible values of stress intensity of tank wall and bottom plate are shown in Table 3 and Table 4, where $K$ takes as 1.25, $S_{III}$ of Q345R takes as 168MPa, and $S_{III}$ of Q235B takes as 130MPa. It can be seen from Table 3 and Figure 8 that the stress intensity $S_I$ and $S_{IV}$ at the joint of tank wall and tank roof exceeds the allowable value, the structure is destroyed here, which is consistent with the actual failure situation. The stress components and stress intensity values of the remaining parts of the tank still meet the strength requirements under the action of failure pressure.

| Stress intensity | Calculated value | Allowable value | Position | Result |
|------------------|------------------|-----------------|----------|--------|
| $S_I$            | 215.624          | $KS_m$          | Connection between wall and roof | Broken |
| $S_{III}$        | 196.4            | 1.5$KS_m$       | Connection between wall and bottom | Safe   |
| $S_{IV}$         | 392.8            | 3$S_m$          | Wall top outside | Broken |

| Stress intensity | Calculated value | Allowable value | Position | Result |
|------------------|------------------|-----------------|----------|--------|
| $S_I$            | 62.9             | $KS_m$          | Connection between wall and bottom | Safe   |
| $S_{III}$        | 209.0            | 1.5$KS_m$       |          | Safe   |
| $S_{IV}$         | 381.2            | $3S_m$          |          | Safe   |
According to the result of stress intensity evaluation, the construction unit replaced the failure parts of the upper five-layer wall and roof of the tank wall.

5. Hydraulic test conditions
The calculation under overpressure condition shows that the strength of the other wall panels and tank bottom panels can meet the requirements of service strength, except for the obvious structural damage on the top of tank roof and tank wall. In this paper, the strength of the tank repaired from the top of the tank and the tank wall is checked under the condition of hydraulic test. Figure. 9 and 10 show the curves of stress intensity $S_{IV}$ of tank wall and tank bottom with the height and radius direction of tank wall under this condition. It can be seen that the main stress intensity of repaired tank wall and tank bottom meet the allowable requirements.

![Figure 9. Curve of wall $S_{IV}$ with height](image)

![Figure 10. Curve of bottom $S_{IV}$ with radial distance](image)

6. Calibration of stability
In engineering applications, external pressure stability of storage tanks is usually transformed into strength problems. Due to improper technology, the circumferential weld zone of the wall plate is partly deformed beyond the standard. The maximum measured imperfect roundness is 30mm. This section mainly checks the strength of the tank wall under external pressure. The formula for calculating the total stress of the non-circular shell subjected to external pressure is as follows[14,15]:

$$
\sigma_{total} = \frac{3P_0D_0}{r^2(1-1/m)} + \frac{P_0D_0}{2r} \leq [\sigma] 
$$

(4)

Where, $\sigma_{total}$ — The total stress of an imperfect shell subjected to external pressure, MPa. $D_0$ — The diameter of the tank, takes as 34 000mm. $t$ — Wall thickness, the conservative value is 6 mm. $[\sigma]$ — Allowable stress of tank material, MPa. $a_0$ — The radial displacement at the maximum local deformation of the tank wall measured at a value $a_0=30$mm. $m$ — The stability factor, the ratio of theoretical critical pressure to allowable design external pressure, which is 3.0 for steel pressure vessels in China. Considering the local deformation of storage tanks, 6.0 for conservative consideration. $P_0$ — Design external pressure of tank barrel, which $P_0=1.24$ kPa.

Formula (4) On the one hand, the local stress increase caused by tank deformation is considered, the influence of tank deformation on tank stability is introduced through the selection of safety factor $m$. The values of each parameter are substituted into the formulas above and $\sigma_{total} = 129.96\text{MPa} \leq [\sigma] = 168\text{MPa}$. Considering that the actual total stress of the tank with local deformation is less than the allowable stress of the wall material, the local strength of the tank with local deformation under external pressure meets the requirements.
7. Conclusion
The 15,000 m³ crude oil atmospheric storage tank was analyzed by finite element method under overpressure condition. Stress assessment was carried out by pressure vessel analysis and design criteria. The evaluation results show that:
- The stress intensity of the primary film and the secondary stress intensity at the joint of the top tank wall plate and the tank roof under the failure load are both greater than the allowable value, which can be used to determine the yield failure of the material.
- The stress intensity indexes of the remaining tank wall plate and the bottom plate still meet the strength requirements.
- Under the strong hydraulic test condition, the tank after maintenance works safely at the highest designed liquid level.
- Under the condition of non-roundness deformation, the external pressure strength of storage tank meets the material allowable requirements.

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