Failure Analysis of the Top Reticulated Shell Structure of a 20,000 Cubic Meter Floating Roof Storage Tank

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Abstract — The single-layer spherical reticulated shell structure is used as the fixed roof of a 20000 m³ internal floating roof tank. In the process of inspection and maintenance, the reticulated shell collapsed. In this paper, the strength, stiffness and stability of the design structure of the tank roof reticulated shell are calculated based on the finite element model, and the weak points of the shell structure are revealed, and the failure causes of the shell structure are comprehensively analyzed.

1. Introduction
Hub node single-layer spherical reticulated shell is widely used in large-span tank roof structure for its good economy and construction convenience[1]. With the development of large-scale storage tank, the large-scale reticulated shell structure of fixed roof storage tank becomes the difficulty and focus of tank construction[2]. At present, schweidler type, united square type, kewitt type and short-range linear structure are often used in the roof latticed shell structures of large and medium-sized storage tanks in China. Considering the convenience of construction, the hub joint is often used in the connection of reticulated shells[3,4].

The single-layer reticulated shell structure with embedded hub node is adopted on the top of four 20,000 m³ storage tanks in the tank farm of a petrochemical enterprise. The structural form is kewitt type plus united square type which is shown in figure 1. The whole spherical reticulated shell is supported on the top ring beam of the tank wall through bolt connection, and the thickness of the tank steel plate is 10 mm. In May 2019, during the construction process of replacing the tank roof skin, the reticulated shell structure collapsed as a whole. In order to determine the failure cause of the reticulated shell structure, the strength, stiffness and stability of the reticulated shell structure on the top of the tank are comprehensively analyzed and evaluated in this paper.
2. Overview of storage tanks
The failure tank is an internal floating roof tank with a volume of 20000 cubic meters and the storage medium is gasoline. The height of the storage tank wall is 17,820mm and its inner diameter of storage tank is 38,000mm. Table 1 gives the basic parameters of the tank structure. During the annual inspection process, the equipment personnel found that the roof of the tank was seriously eroded and thinned. Subsequently, measures were taken to replace the tank roof after cleaning the tank. During the hoisting of spare parts on the roof of the tank, the tank roof collapsed as a whole. Site investigation found that the reticulated shell structure on the top of the tank presents the overall crushing collapse, brittle fracture occurs at the joint between the rod end piece and the hub joint shown in figure 2, and some members show lateral buckling instability characteristics.

Table 1 Basic parameters of tank top reticulated shell structure

| Project                      | Value         |
|------------------------------|---------------|
| **Wall parameters**          |               |
| Diameter(mm)                 | 38,000        |
| Thickness(mm)                | 17/16/14/12/11/9/8/8/8/8 |
| Story height(mm)             | 17,820        |
| Material                     | 16MnR         |
| **Shell parameters**         |               |
| Reticulated sphere radius (mm) | 37,797       |
| Yataka (mm)                  | 4,998.4       |
| Component material           | Q235-B        |
| Rod end material             | ZG275-485H    |
| Node size (mm)               | φ130          |
| Span (mm)                    | 37,640        |
| Weight (kg)                  | 26,957        |
| Section type                 | H14           |
| Node form                    | Hub node      |
| Design code                  | JGJ 7-2010 Technical specification of space grid structure |
3. Calculation model

3.1. Finite Element Model

Combined with the completion data of storage tank, ANSYS is used to establish the finite element model of tank structure including tank top\(^5\), as shown in Figure 3. In the finite element model, the tank top lattice structure uses beam 188 unit. The gravity acceleration is 9.8\(\text{m/s}^2\), and the equivalent density is used for the density of the reticulated shell, which makes the weight of the structure reach 26,957\(\text{kg}\).

Considering the structural characteristics of hub joints, the rod end members are connected to the hub nodes through pin shaft structure. According to the code for design of reticulated shell structures, the in-plane effective length coefficient of hub joints is 1.0, that is, the in-plane member support form is hinged at both ends. Therefore, in the finite element modeling of reticulated shell structure, the rotational degree of freedom of the beam element node around the Z axis of the element coordinate system should be set to 0, that is, the node does not bear the bending moment in the tank roof plane, which conforms to the actual stress characteristics of the structure.

Figure 3. Finite element model of storage tank
3.2. **Load Condition**
In this part, the actual condition that the collapse happened was considered for the analysis. Actual conditions takes the actual load before structural failure as the analysis condition, which is: $D_L + P_T$, where $P_T$ is the local stacking load, which is 7,000kg. Since the plane size of the stacked object is 1600mm×300mm, combined with the size of each node of the reticulated shell, loading position took two nodes for calculation. Element 1 and 33 near the center of the tank top were choose for loading.

4. **Analysis results**

4.1. **Overall Rigidity Checking of the Structure**
Figure 5 shows the structural deformation cloud diagram of actual condition when the stacking load is applied at the center of the tank top. The maximum deformation of the structure is 15.54mm, the maximum deformation position is shown in the figure which shows that the maximum deflection does not exceed the allowable deflection 94.1mm (0.0025 times the inner diameter, that is 1/400 of the span), the overall rigidity of the structure meets the requirements of code GB/T 50341.

4.2. **Component Strength Check**
Figure 6 and figure 7 shows the axial stress and bending stress cloud diagram of the rod when loading at two points near the tank top. As can be seen from the data in the figure 5 and figure 6, the maximum composite compressive stress of the axial force and a bending moment of the dangerous member reaches 72.77MPa (47.27MPa+25.50MPa), the allowable strength stress given by the storage tank design code is not exceeded.
4.3. Strength Checking of the End Piece of the Hub Node (necked part)

According to the double-point loading condition under the actual condition of the tank roof, the strength of the casting part at the rod end is checked. The minimum size section of the end, i.e. the rectangular section of 12mm × 80mm, is selected. After calculation, the maximum stress of cast steel at the rod end of element 1, 36 and 37 (as shown in Fig. 3) reaches 433.7MPa, when the allowable stress of the joint casting is exceeded (ZG230-450H strength design value is 215MPa, the end face pressure is 315MPa), the strength of the joint embedded parts is damaged.

4.4. Stability Check of Single Component

GB/T50341 Point out that when considering the instability of the lateral compression rod of the single-limb component, the allowable stress should be calculated separately. Table 2 gives the allowable stress values determined according to the slenderness ratio of the component when considering the lateral instability of the component. From the data in the table, for instability in the plane of the component (outside the bending plane), its allowable stress is relatively lower than that of 145MPa under the strength control condition. The main reason is that the structure of the hub node makes the members hingedly supported in the plane of the lattice shell. And the section of the member belongs to the weak axis in this direction; therefore, the ability of the component to resist instability in this direction is weak. By comparing the equivalent stress of each member with the allowable stress value given in Table 2, no components were found that did not meet the stability of single limb.
As another constraint condition for characterizing single limb instability, it can be seen from table 2 that many members with slenderness ratios (unsupported length / minimum radius of gyration) exceeding 150, accounting for 50% of the total number of purchased members, do not meet the requirements of JGJ 7-2010. It is also shown that the buckling resistance of this type of latticed shell members is weak outside the bending moment plane (in the shell plane).

Table 2 Allowable stress considering lateral instability of single limb

| Element type number | Allowable stress | Slenderness ratio | Element type number | Allowable stress | Slenderness ratio |
|---------------------|------------------|-------------------|---------------------|------------------|-------------------|
| 1                   | 94.02            | 128.68            | 14                  | 51.95            | 156.47            |
| 2                   | 94.12            | 128.61            | 15                  | 84.98            | 141.72            |
| 3                   | 50.98            | 159.39            | 16                  | 89.31            | 132.17            |
| 4                   | 88.35            | 132.87            | 17                  | 46.61            | 176.12            |
| 5                   | 48.32            | 168.63            | 18                  | 91.02            | 130.92            |
| 6                   | 87.15            | 139.83            | 19                  | 50.56            | 160.69            |
| 7                   | 94.21            | 128.54            | 20                  | 89.82            | 137.40            |
| 8                   | 47.32            | 172.82            | 21                  | 55.40            | 147.56            |
| 9                   | 86.32            | 134.33            | 22                  | 90.63            | 131.20            |
| 10                  | 54.39            | 149.98            | 23                  | 55.74            | 146.77            |
| 11                  | 88.34            | 132.88            | 24                  | 60.64            | 151.66            |
| 12                  | 46.84            | 174.99            | 25                  | 53.63            | 151.90            |
| 13                  | 89.45            | 132.07            | 26                  | 27.48            | 171.46            |

4.5. Overall Stability Check
Figure 8 shows the load-displacement response curve of the lattice structure considering geometric nonlinearity. As can be seen from the curve data, the absolute value of displacement increases linearly during the design load loading process. There is no tremendous increase in displacement. It can be seen that the structure did not undergo overall buckling instability under the ultimate load.

Figure 8. Load-displacement curve under the action of two-point limit load
5. Failure cause analysis
Through the finite element analysis of the reticulated shell structure on the top of the tank under the design conditions and the ultimate operating conditions, and according to the relevant standards and specifications, the overall stiffness, local strength and stability, and overall stability are checked. The check conclusion is shown in Table 3.

| Item               | Design Condition                                      | Actual Condition                                      |
|--------------------|--------------------------------------------------------|-------------------------------------------------------|
| Overall stiffness  | Meet the requirements of evaluation standards          | Meet the requirements of evaluation standards          |
| Component strength | Meet the requirements of evaluation standards          | Meet the requirements of evaluation standards          |
| Single limb stability | Meets the requirements of G50341 standard, but does not meet the requirements of JGJ 7 standard | Meets the requirements of G50341 standard, but does not meet the requirements of JGJ 7 standard |
| Rod end piece strength | The actual stress value of the material is close to the design value of the material's tensile strength, and the safety margin is low | The actual stress of the material exceeds the design value of the material's tensile strength |
| Overall stability  | Meet the requirements of evaluation standards          | Meet the requirements of evaluation standards          |

6. Conclusions
Under actual condition, the overall stiffness of the structure and the overall stability under the conditions of nonlinear analysis meet the requirements of relevant design codes. The material strength of the component is also lower than the allowable strength of the material. However, when verifying the lateral stability of a single component, the equivalent stress of the component (axial stress plus bending stress) has exceeded the critical allowable stress value of instability, the rod will undergo local instability of single limb. At the same time, because of the necking of the end member, the stress value of the section exceeds the allowable strength of the material, which shows the failure of the material strength.

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