Structural calculation analysis and design of a Towering concrete building

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Abstract. This Towering building is a concrete tower with a height of 199.10m and an octagonal plane, with a complex structure. The structure is calculated as a whole through the programs of two different mechanical models, the calculation results are relatively close, and the control indicators meet the requirements of relevant specifications and regulations. This article introduces and analyzes the structural system, structural calculation and analysis methods, seismic performance objectives, and overall calculation results of the project, and details the design of the steel tower.

1. Introduction

The tower project is located in Shandong Province, with a height of 199.10m, an octagonal cross section, and a building area of about 6500m². The structure is divided into four parts: tower base, tower body, tower and mast. The tower base, tower body and part of the mast are reinforced concrete structures, and the tower and top mast are steel structures. The tower base has one floor underground and two floors above ground. The top elevation of the tower base is 10.000m. The elevation range of the tower body is 10.000m-120.000m, and the diameter of the octagonal circumscribed circle of the tower body is about 6.71m. The tower has four floors, with an elevation ranging from 120.000m to 141.600m. The mast height is 56.6m, of which the concrete mast is 44.25m and the steel mast is 12.35m. The effect diagram and structure model diagram are shown in Figure 1 and Figure 2.

The structural design service life is 50 years. The seismic fortification intensity is 6 degrees, the design basic earthquake acceleration is 0.05g; the design earthquake is divided into the third group. The building site category is I, and the site characteristic period is 0.35s. Engineering seismic fortification is classified as standard fortification, and the structural safety level is second. The basic wind pressure at the location is 0.40kN/m², and the ground roughness category is Class B. The foundation of the TV tower adopts a raft foundation, the foundation is buried at a depth of 10.30m, the foundation bearing layer is a marl layer, and the characteristic value of bearing capacity is $f_{ak}=2000$kPa.
2. Structural system and calculation

2.1. Structural system

The tower base adopts a reinforced concrete frame structure. The main structure of the tower body is a concrete cylinder with 10m as a layer. The tower is a 4-story steel frame structure attached to the main structure. The steel columns of the tower are box-shaped inclined concrete-filled steel tube columns, supported on 16 concrete walls extending from the tower body, and the bottom of the column is hinged. The floor slab of the tower is covered with reinforced concrete with closed profiled steel plates. The elevation range of the mast part is 141.600m~198.200m, of which the elevation range of the concrete mast part is 141.600m~185.850m, and the elevation range of the steel mast part is 185.850m~198.200m, the steel mast is inserted 4.0m into the concrete mast. The steel columns, beams, and masts of the tower are all made of Q345B steel.

The lateral force-resistant component of the main structure of the project is an octagonal cylindrical shear wall, which is mainly composed of the circumference of the tube, the inner floor of the tube, and the elevator car wall. The main structure is from the ground to an elevation of 141.600m.

The wall thickness around the cylinder is 600mm below 44.950m, and 500mm above 44.950m. The wall of the middle building and elevator room is 200mm. Concrete strength grade and impermeability grade: C40 for shear wall and concrete mast, and C30 for other beams and slabs. The impermeability grade of external walls and concrete masts is P6. The plan layout of the cylindrical shear wall and the layout of the tower structure are shown in Figures 3 and 4.
2.2. Structural calculation

The overall calculation uses two three-dimensional space analysis software, PMSAP and ETABS. The tower part adopts ETABS and STS for auxiliary review. The concrete wall (corbel) extending from the main structure of the tower is analyzed locally using SAP2000. Principle of calculation and analysis: Under the action of wind load, the structure maintains its elastic working state, and under the action of earthquake, the structure achieves the performance target of seismic design.

2.2.1. Wind pressure value. The basic wind pressure at the project location is 0.40 kN/ m². Considering that the towers and masts of the project are sensitive to wind loads, the wind pressure is 1.1 times the basic wind pressure, or 0.44 kN/ m², when the bearing capacity is designed. When the project is on a hillside, the modification of terrain conditions needs to be considered. The wind pressure height change coefficient should be multiplied by the correction coefficient $\eta=1.4$, and the adjusted basic wind pressure is 0.616 kN/ m² (for both bearing capacity calculation and deformation calculation).

2.2.2. Performance target of structural seismic design. All components, small shock elasticity. Tower body: elastic for moderate earthquakes and will not yield in large earthquakes. Tower steel beams and steel columns: moderate earthquake elasticity, large earthquakes allow local plasticity. Extending the wall of the tower body: no cracking in moderate earthquakes and no yielding in large earthquakes. Mast: elastic for moderate earthquakes, not to fall in large earthquakes, full consideration of the whip sheath effect. Floor: moderate earthquake elasticity.

2.2.3. Overall calculation result. In order to fully consider the influence of higher-order mode shapes on the mast, the calculated mode shapes of the two softwares are both set to 30. The calculation results of the natural vibration characteristics of the structure are shown in Table 1, and the response of the structure under wind loads and earthquakes (moderate earthquakes) is shown in Table 2. It can be seen from the data that the two software calculations can meet the requirements of the specification, and the results are very close, and the calculations are more accurate.

| Table 1. Structural natural vibration characteristics |
|-----------------------------------------------|
|                  | PMSAP                  | ETABS                  | Specification limit | PMSAP/ ETABS |
| T1 (s)           | 5.0565 (Y translation) | 5.4081 (X translation) | ______             | 0.94         |
| T2 (s)           | 4.9514 (X)            | 5.1589 (Y)            | ______             | 0.96         |
2.2.4. Wind-vibration comfort calculation on the top of the tower. When calculating the wind-vibration comfort of the tower, the standard value of wind load is taken as 0.30 kN/ m² (10-year return period), and the damping ratio is taken as 0.015. It is calculated that the maximum accelerations of the apexes of the downwind and crosswind directions in the X direction are 0.094 and 0.112 m/s², respectively, and the maximum accelerations of the apexes in the downwind and crosswind directions in the Y direction are 0.093 and 0.109 m/s², respectively, which meet the requirements of "Concrete Structure Technology of High-rise Buildings" Regulations (JGJ3-2010)” (hereinafter referred to as “High Regulations”) requirements.

2.2.5. Checking the overall stability of the structure. The stiffness-to-weight ratios in the X and Y directions of this project are respectively 2.03 and 1.96. According to 5.4.4 of the "High Regulations”, the overall stability meets the requirements. According to the "High Regulations” 5.4.1, the second-order effect of gravity should be considered Negative Effects.

3. Structural design of steel tower
The self-weight of the tower should be as light as possible, while taking into account the reliability of the technology and the convenience of construction. In view of this, the tower columns and beams of this project are made of steel, and the floor slabs are covered with closed-end profiled steel plates. For special requirements, 200-thick light steel keel gypsum board walls are used.

3.1. Steel column and column foot design
The box-shaped concrete-filled steel tube oblique column is supported on the concrete wall protruding from the main structure, and the bottom of the column is hinged, as shown in Figure 5. After calculation, the internal force at the bottom of the outer inclined column is 1300kN (standard value). When using SAP2000 to analyze the force situation of the extending wall, the internal force is input as the external load. The column foot adopts the structure shown in Figure 6.

The overhanging concrete wall and the main structure of the tower are poured at the same time. The wall reinforcement is combined according to the PMSAP overall calculation result and the SAP2000 separate analysis result. The horizontal reinforcement extends inward into the cylindrical shear wall, and the vertical reinforcement is made into a closed stirrup. And set up a structural dark column on the hypotenuse of the wall. See Figure 7.

Table 2. Structural response

| Base shear (kN) | PMSAP | ETABS | PMSAP / ETABS |
|----------------|-------|-------|---------------|
| earthquake effect | X direction | 3933 | 4125 | 0.95 |
|                     | Y direction | 3967 | 4137 | 0.96 |
| Wind load | X direction | 4333 | 4591 | 0.94 |
|                     | Y direction | 4327 | 4574 | 0.95 |
3.2. Beam-column joint design

Steel beams are made of hot-rolled H-section steel. The floor slab is covered with closed-end profiled steel plate, the model of profiled steel plate is YJ66-720. Regardless of the stiffness amplification factor of the steel beam, the control normal stress ratio of the main steel beam is 0.85, and the control normal stress ratio of the secondary steel beam is 0.9.

The beam-column nodes are rigidly connected, and bolted welding is used. The primary and secondary beams are hinged and connected by bolts. In order to ensure accurate fabrication of beam-column nodes and reduce operational errors during high-altitude construction on site, the nodes are required to be fabricated in the factory.

4. Conclusion

Through the analysis of this article, the following conclusions can be obtained:

1. This project is a high-rise structure, and the overall calculation was carried out using structural analysis software of two different mechanical models. The calculation model is accurate, the calculation results are very close, and they can meet the specification requirements.

2. By rationally arranging structural components, setting appropriate seismic performance targets, conducting a series of overall and partial calculations and analyses, and adopting reasonable
structural measures to ensure that the structural design is safe and applicable, technologically advanced, and convenient for construction.

(3) The structural response of this project under wind load is greater than that under earthquake. For the wind acceleration limit of "offices and hotels" in the reference specification, the top of the tower can meet the wind vibration comfort requirements.

(4) The steel tower is attached to the main structure, and its own weight should be as light as possible. The size of the components such as steel beams, floor slabs, and infill walls are strictly controlled. The beam-column nodes are made in the factory to ensure the quality of the nodes and speed up the construction progress.

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