Structural system selection and design of Zhangzhou Opera House Fujian Province

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Abstract: Zhangzhou Opera House adopts the complex structure system of petal shape. According to the building shape and architectural layout, the structure combines the steel truss for large-span space and the frame-shear wall structure surrounding. This article introduced its structural system, multi-line defense line arrangement and anti-seismic performance objectives, and summarized the structural characteristics of the overall structure, especially focusing on key issues such as setting the ring floor beam to resist the extroversive forces, anti-seismic performance of key components and the design of the junction between the steel truss and concrete structure. The results show that the structure has strong adaptability to the building shape with suitable seismic performance, and fulfilling both the requirements of seismic performance design and the structural safety.

1. Project Overview

Zhangzhou Opera House located in Zhangzhou city, Fujian Province, is a landmark building in the Future development center of Zhangzhou City. The shape of Zhangzhou Opera House is taken from daffodil. The architectural flower shape divides the building plane into 8 petal units, the formation of small big fancy modelling on architecture, petal modelling surround close area of central opera house large space formation, the opera house renderings as shown in figure 1.

Figure 1. Effect of Zhangzhou Opera House in Fujian Province

The total building area of the Opera House is 106,582 square meters, with a total building height of 45.0 meters. The highest point of the outer petal structure is 34.5 meters, and its top elevation is 40.5 meters. The whole building is 120 meters long and 80 meters short. The theater has 1,017 seats, with 8 floors above ground and 1 floor underground. The seismic fortification category of this project is the key
fortification category, the seismic fortification intensity is 7 degrees (0.10g), the site is class III, and the seismic design group is adjusted to the second group according to the seismic zoning map of the fifth generation.

Fig. 2 Schematic diagram of main functional zoning of the building

2. Introduction of structural System
The opera House adopts the concrete frame-shear wall structure system, and uses the vertical traffic cores around the auditorium and large stage space to arrange the concrete shear wall cylinder as the main anti-lateral force component of the overall structure. The overall calculation model is shown in Figure 3.

Fig. 3 Calculation model of Zhangzhou Opera House

1. Inclined columns; 2: Oblique frame of the stand; 3. Steel trusses for the auditorium and stage roof and their supporting structures; 4: Peripheral oblique column structure

Fig. 4 Schematic diagram of architecture and structural model with long axis section
The opera House section along the long axis is shown in Figure 4. The whole building is symmetrical along the long axis. The surrounding floors of the whole structure are composed of a frame structure supported by inclined columns. The auditorium is divided into two floors. The lower floor is supported by an inclined frame supported by the lower frame column, and the height direction spans the height difference of one floor by 6.5m. The upper floor is cantilever formed by four floors of frame beams supported on bifurcated columns, and cantilever beams extend along the direction of concrete shear wall. The floor frame system, combined with the characteristics of building floor by floor boundary expansion, sets oblique frame columns along the inclined direction, and uses frame beams perpendicular to the
outward direction to pull in the ring direction to resist the outward thrust generated by the outward direction. The layout of typical plane structure is shown in Figure 5.

![Fig. 5 Layout of typical plane structure](image)

![Fig. 6 Diagram of steel truss at the top of stage](image)

Oblique frame columns with the same inclination direction and Angle are arranged along the building plane to form an expanded floor plan layer by layer. As shown in the arrow direction in FIG. 5, the span of each layer expands outwards along the arrow direction, but the column spacing perpendicular to the arrow direction remains unchanged. The Angle between the exterior inclined frame column and the vertical direction is 23 degrees. Because the tilt of the vertical members causes the floor to have a large pull along the inclined direction, the frame beam and the inclined column are connected to the concrete shear wall cylinder in the inclined direction of the column, effectively transferring the pull force to the vertical anti-lateral force members. In the ring direction perpendicular to the inclined direction and in the ring direction perpendicular to the inclined direction, multiple ring hoops are arranged from inside to outside, and the ring hoops of the frame beam are pulled to the concrete core tube. In the inclined direction, the distance between the column span on the bottom floor and the vertical concrete wall is about 7m. As the top floor tilts outwards, the distance between the inclined column and the concrete wall extends to 11m. In the vertical inclined direction, the span between the columns is 9m.

The stage area has a high requirement for sound insulation, so it is necessary to set a heavy construction sound insulation wall above the front and back entrance of the stage and the joint of the floor, considering the convenience of connecting the proscenium beam with the outer floor structure, concrete vertical ventral columns between the beams are used instead of constructional columns to connect the proscenium beam to form an vierendeel truss system with a height of four stories, as shown in Fig. 6. This vierendeel truss also serves as a reliable support for the steel truss on the upper part of the stage. Concrete vierendeel truss vertical diagonal column 4 m, horizontal spacing along the height spacing of 2.5 m, along the direction of the beam span even set the horizontal beam, the late sound insulation partition can be directly masonry buildings sound barriers constructional column, ring beam are late without the need to set up late so as to reduce the construction difficulty, avoid the planting bar after such as constructional column construction damage in concrete main structure.

![Audience hall (left), stage (right) calculation model axonometric map](image)

![Typical steel trusses at the top of the hall](image)

Fig. 7 Steel structure of the auditorium (left) and stage (right)

The large span space of the audience hall and the top of the stage adopts steel truss structure, as shown in Figure 7. Steel truss plane position and alignment of the horizontal cylinder concrete wall body,
in the lateral wall with truss on the bottom chord and the ventral pole position setting steel embedded column, to effectively transfer truss support position of bending shear, steel truss are connected to the concrete wall limb at the same time be lower chord foot amplification, and improve the stiffness of the truss, to improve the mechanical performance of steel truss. At the top of the auditorium, the three main trusses span 26m to 28m, the mid-span structure height is 2.4m, the height of the root of the trusses is 4.3m, and the spacing of the trusses plane is 7.35m. In order to ensure the stability of the truss in the construction stage and service stage, the steel pull rod is used to connect the steel truss in the plane with the concrete structure of the floor to ensure the lateral stability of the truss.

The space on the top of the stage has a lot of mechanical loads of large weight, such as stage machinery. Meanwhile, a cooling tower equipment room is set on the top of the stage, which carries a large load. The structural system in this area adopts steel trusses, with concrete vierendeel trusses above the stage as supports. The span of steel trusses is 17.7m, the height of trusses is 2.2m, and the horizontal distance is 4.5m. The stage machinery is suspended at the lower part of the truss, which is beneficial to the lateral stability of the truss. At the same time, transverse steel beams are arranged at the joints of the truss at the lower chord of the truss perpendicular to the span. The steel beam end is connected with the concrete side wall, and all trusses are connected externally to ensure the stability of the truss length direction above the stage. The truss arrangement at the top of the auditorium is shown in Figure 8.

Fig. 8 Method of steel truss support at the junction of truss and concrete structure

As there are many large space and span areas in this project, the loads under the columns and walls are quite different. In addition, considering the soil layer at the bottom of the building, the foundation structure system of pile foundation cap under the columns and waterproof plate is adopted.

Part of the main building is prefabricated 600mm diameter pressure-resistant pipe pile. Residual cohesive soil or fully weathered granite is adopted as the bearing layer. The effective length of the pile is about 30m. For the pure basement part, the prefabricated pipe pile with a diameter of 500mm is used, and the coarse sand or gravel sand layer is used as the supporting layer. The effective pile length is about 15m. The shear wall cylinder in the center of the building uses a large area of pile foundation caps to disperse concentrated loads. Considering the eccentricity generated by additional bending moment under normal working conditions, the column bottom caps are eccentric along the inclined direction to evenly distribute the vertical pressure of each pile. The pile foundation caps under the columns and walls are 1500mm~2200mm thick, and the waterproof plate is 500mm thick, as shown in the figure 9.
3. Seismic performance design of key parts

3.1. Overview of structural performance
Due to the large shape and mass distribution of the lower part and upper part of the Zhangzhou Opera House, torsion oriented formations are easy to appear in the first few stages of the structure. Therefore, it is necessary to adjust the reasonable distribution of lateral stiffness of the vertical components in order to enhance the overall torsion stiffness of the structure. This project mainly adjusts the horizontal and torsional stiffness of the overall structure by uniformly arranging the frame column, shear wall and adjusting the width of the concrete wall door and the height of the connecting beam along the long direction. The dynamic characteristics of the adjusted structure are shown in Table 1.

Table 1 Structure period, translational and torsion ratio

| sketch map | period (X+Y) | torsional period |
|------------|--------------|-----------------|
|            | 0.7443(Y)    | 0.96(0.00+0.96) |
|            | 0.6265(X)    | 0.98(0.98+0.00) |
|            | 0.4943(T)    | 0.05(0.00+0.05) |
| The first formation |                  |                  |
| The second formation |                  |                  |
| The third mode       |                  |                  |

3.2. Check the wall tension
As the total weight of the building shape floor in this project increases with the increase of height, the whipping effect of the upper floor becomes more obvious. In seismic conditions, in addition to the large tensile stress at the bottom of the first wall, the upper wall limb is also prone to large tensile force due to the reduction of axial pressure and the large overturning moment. Fig. 10 shows the change trend of tensile stress of concrete wall limb with the increase of floor when no steel dark column is set. It can be seen that under the elastic condition of medium earthquake, the tensile stress of the wall located in the outer ring reaches more than 0.8fTk, and the stress of the first, second and 6, 7 floors 1-1, 3-1, 5-1 has more than 2 times the standard value of concrete tensile strength fTk. In combination with the steel truss at the top of the auditorium, H-beam steel extending to the foundation is set at the connection between the truss and the wall to resist the pulling force. Meanwhile, part of the longitudinal reinforcement of the dark column is reduced to reduce the construction difficulty of the embedded column.

4. Conclusion
The project is complex in shape and has many irregular construction projects beyond the limit. In the structural design, reasonable structural system and layout are adopted, corresponding performance targets are set and effective seismic measures are taken, so as to reduce the adverse effects caused by the over-limit, make the structure have better seismic performance, and the design results meet the
requirements of the current codes and regulations. At the same time, it is necessary to pay attention to the time history analysis of the adverse impact of the high vibration mode on the upper floor of the structure, which is of guiding significance for judging the weak parts of the structure and corresponding enhanced ductility design.

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