Structural selection and design analysis of a super high-rise office building

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Abstract. A super high-rise building, with a height of 238 meters, 4 floors underground and 50 floors above the ground, exceeds the Class B height limit of the specification, and belongs to an ultra-high over-limit structure. Through the selection of different structural systems, its structural system is determined as the frame core tube structure. This structure uses YJK, SATWE, PKPM- SAUSAGE for structural analysis, uses performance-based methods for seismic design, and the weak parts of the structure are strengthened accordingly. Structural analysis mainly includes elasticity analysis of small earthquakes, elastic time history analysis of small earthquakes, elastic and inflexion analysis of moderate earthquakes, inflexibility analysis of large earthquakes and elastoplastic time history analysis of large earthquakes.

1. Project Overview
The project are 2 office towers in the south area, which are D tower and E tower. The D\E towers communicate with each other to form the G commercial building, which is a 7-story commercial complex. This article analyzes the design of the E tower office building. The E tower office building has four underground floors and 50 floors above the ground, with a total height of 238.3 meters, a structural height of 222.4 meters, and a building area of 99561m². Among them, 2-6 floors are commercial complex skirt rooms, the basement floor is the commercial and main tower office lobby, supporting equipment room, and a mezzanine floor is partly located for the bicycle garage and equipment room. Two underground floors-four underground floors are garages, civil air defense facilities, and supporting equipment rooms. The plane size is approximately 46mX46m. The architectural renderings are shown in Figure 1 and the sectional views are shown in Figure 2.

The service life of the project is 50 years, the safety level of the building structure is Grade 2, the fire rating of the building structure is Grade 1, and the design level of the foundation is Grade A. According to the "Code for Seismic Design of Buildings" (GB50011-2010) (2016 edition)¹¹, the design earthquakes in the project area are grouped into the third group, the site category is type III, and the earthquake resistance rating is 6 degrees 0.05g. And the relevant documents of Shandong Province require unified design according to 7 degrees 0.10g, the corresponding characteristic period is 0.65s. The seismic fortification of the connection between the ground floor and the podium is classified as the key fortification class (type B), and the upper office area is for general fortification (type C).
2. Structural design

2.1. Structural system selection and scheme comparison

The structure belongs to reinforced concrete high-rise buildings exceeding the standard B-level\(^1\) Frame-core tube structure system is selected.

Core tube part: The core tube is located in the center of the tower, and the elevator, elevator hall, evacuation stairs, bathroom and equipment room are arranged inside. For buildings that reach the maximum use height limit for high-rise buildings of Class B height, it is necessary to adopt more measures to ensure structural safety, while reducing the self-weight of the structure, reducing the earthquake action and reducing the foundation reaction force. Therefore, for the reinforced area at the bottom of the core tube wall of the tower, the use of profiled steel walls can improve the seismic performance of the core tube shear wall, reduce the wall thickness and structural self-weight, and enhance the safety of the structure. The use of section steel walls can also solve the problems of excessive reinforcement of the wall under elastic shock and the tension of the bottom wall. The layout of the core tube's outer wall and inner wall is regularly symmetrical. The coupling beam layout can avoid the adverse effects of opening holes in the wall at the later stage of the equipment specialty, which is conducive to the consistency of the calculation model assumptions and actual conditions.

Peripheral frame columns: For buildings that reach the maximum use height limit for high-rise buildings of Class B height, reinforced concrete columns with section steel are used in the bottom reinforcement area. Compared with ordinary reinforced concrete members, in addition to increasing the ductility of the structure and improving the safety of the B-level height structure, it can also appropriately reduce the column size, increase the use area, and have good fire resistance. On the premise of satisfying the building function, the role of the surrounding frame will be fully exerted, the requirements of the frame sharing rate will be met, and the seismic performance target of the dual lateral force-resistant structural system will be achieved.
2.2. Basic load values
In order to consider the structure main body and the reserved load in the future, the dead load value is 4.0 kN/m$^2$, and the live load value is 3.5 kN/m$^2$. The remaining live loads are taken according to the load specification\cite{2}. Live load in the public area is 2.5 kN/m$^2$, live load in the staircase is 3.5 kN/m$^2$, live load in the refuge floor is 4.0 kN/m$^2$, and live load in the elevator engine room is 7.0 kN/m$^2$\cite{3}.

2.3. Sections and materials of main structural members
As the structure height increases, the concrete strength grade of columns and shear walls gradually decreases \cite{4} from C60 to C40 from bottom to top, and the thickness of the outer wall of the core tube shear wall changes from 1000mm to 400mm from bottom to top, and the diameter of the concrete columns wall changes from 2000mmx1800mm to 1000mmX800mm from bottom to top. Typical beam cross section is 400mm X850mm.

3. Structural performance-based design
According to the "Technical Regulations for Concrete Structures of High-rise Buildings" (JGJ 3-2010) \cite{3}, this project exceeds the 180-meter B-level limit for 7-degree areas, and performance-based design of the structure is required. According to the degree of over-limit, the seismic performance target of the structure is set to C, and the performance of key structural members under different seismic levels is shown in Table 1\cite{5}.

| Anti-seismic level       | Frequent earthquakes | Precautionary intensity | Rare earthquake     |
|--------------------------|----------------------|-------------------------|---------------------|
| the limit value of interlayer displacement | 1/558                |                         | 1/100               |
| Analysis method          | Response spectrum, time-history response analysis | Response spectrum | Dynamic time-history response analysis |
| Frame column             | Shear resistance     | elastic                 | elastic             | Meet the shear section restrictions |
|                          | Bending resistance   | elastic                 | un-yield            | Several bottom columns yield in bending, No collapse |
| coupling beam in seismic shear walls | elastic             | Can yield, but still has a certain vertical bearing capacity | Can yield, but still has a certain vertical bearing capacity |
| coupling beam supporting frame beam | elastic             | Shear resistance in elastic stage, No bending yield | Meet the shear section restrictions, Bending yield |
| Reinforced area at the bottom of core tube | Shear resistance of wall | elastic               | elastic             | Meet the shear section restrictions |
|                          | Bending resistance of wall | elastic               | un-yield            | Local yield |
| Other seismic walls      | elastic              | un-yield                | Local yield         |

4. Calculation and analysis
4.1. Calculation and analysis of frequent earthquakes
In the design process, according to the above different performance objectives, the elastic analysis of small earthquakes, elastic time history analysis of small earthquakes, elastic and nonyielding analysis of medium earthquakes, elastic-plastic time history analysis of large earthquakes are carried out. This project’s elasticity analysis in the event of frequent earthquakes uses YJK as the main design calculation software for the structure and SATWE to check and compare the main indicators. The torsional coupling effect, accidental eccentricity and two-way seismic effect are considered in the analysis of frequent earthquakes.

Through the comparison of the main indexes of the two software calculation results, it can be seen that the results of the two software are similar, which shows that the mechanical model is correct. According to the results of main calculation software yjk, the first and second periods are translation periods, and the third period is torsion period. The stiffness difference between the two directions of the structure is small, and the ratio of the first torsion cycle to the first translation cycle of the structure is less than 0.85, which meets the requirements of the code. The shear weight ratio of the two directions at the bottom of the structure also meets the requirements of the code not less than 1.2%. The maximum inter story displacement angle of the structure is 1 / 724 in X direction and 1 / 904 in Y direction, both of which are less than the specification limit of 1 / 558. In the case of accidental eccentricity, yjk results show that the maximum floor displacement to average displacement ratio (the ratio of the maximum floor displacement to average floor displacement) is 1.20, which meets the requirement that the code should not be greater than 1.4.

Table 2. Comparison of main calculation results.

|                           | YJK                  | PKPM                 |
|---------------------------|----------------------|----------------------|
| Mode of vibration(s)      |                      |                      |
| T1                        | 6.1398               | 6.2289               |
| T2                        | 5.3825               | 5.2766               |
| T3                        | 4.4649               | 4.4056               |
| T3/T1                     | 0.727                | 0.707                |
| Maximum displacement of vertex (mm) |                      |                      |
| X direction wind          | 154.01               | 146.8                |
| Y direction wind          | 105.05               | 95.3                 |
| X-direction earthquake    | 258.31               | 264.2                |
| Y-direction earthquake    | 204.19               | 197.5                |
| Maximum inter story displacement angle |                |                      |
| X-direction earthquake    | 1/724                | 1/687                |
| Y-direction earthquake    | 1/904                | 1/880                |
| Ratio of maximum displacement to average displacement | 1.12              | 1.11                 |
| Y-direction earthquake    | 1.2                  | 1.13                 |
| Basal shear (kN)          |                      |                      |
| X-direction unidirectional earthquake | 31493.09 (1.322%) | 30765.2              |
| (Shear weight ratio)      |                      |                      |
| Y-direction unidirectional earthquake | 31922.68 (1.340%) | 31950.9              |
| Axial pressure ratio      |                      |                      |
| Frame column              | 0.61                 | 0.58                 |
| Shear wall                | 0.48                 | 0.45                 |
| Total seismic mass (t)    | 226867               | 219526               |

4.2. Calculation and analysis of frequent earthquakes
Horizontal two-way seismic action is considered in the project, in which the ratio of peak acceleration of main direction and secondary direction seismic wave is 1:0.85. In order to check the calculation results of CQC method, yjk software is used to select 2 artificial seismic waves and 5 natural seismic waves for small earthquake elastic time history analysis of the structure. The elastic time history analysis results are compared with the calculation results of mode response decomposition spectrum method, and
the comparison results are shown in the Figure 4 and Figure 5 below. According to the figure, the base shear under the action of seismic wave is less than the floor base shear value of CQC method, and the inter floor displacement angle under the action of seismic wave is less than CQC calculation result. There is no abrupt change in the inter floor displacement angle curve, and the lateral stiffness of the structure changes uniformly along the height without obvious abrupt change. Therefore, CQC method can be used to design the structure.

4.3. Analysis on the elasticity of moderate earthquake and the unyielding of large earthquake

According to the requirements of the seismic performance of the structure, the vertical members need to be checked for the shear elasticity and flexural inflexibility of the vertical members, and the vertical members must be checked for the large-scale earthquakes under the earthquake. The maximum value of the earthquake influence coefficient is adjusted to 2.8 times that of the small earthquake, the structural damping ratio is adjusted to 0.06, and the coupling beam stiffness reduction coefficient is adjusted to 0.5. The wind load is not involved in the combination, the material strength is taken as the standard value, the load partial coefficient is adjusted to 1.0, and the seismic rating of the component is fourth grade. In the analysis of unsteady earthquakes, the material coefficient and the load partial coefficient need to be adjusted to 1.0.

According to the calculation results of the shear pressure ratio and horizontal reinforcement under moderate earthquakes, the shear sections of the shear wall meet the requirements of the code. Some of the horizontal steel bars in the outer wall of the core tube have calculated reinforcement, and the horizontal steel bars in the other shear walls are structural reinforcement. Under the analysis of unsteady earthquake, most of the longitudinal reinforcement ratios of the edge members of the shear wall are structural reinforcements, and only some wall limbs have calculated reinforcement. The vertical members under moderate earthquakes all meet the goals of bending, non-yield and shear elasticity.

5. Conclusion

Measures taken in this structural design for overruns:

1. We improve the role of the frame part as the second line of defense, and appropriately increase the reinforcement of the frame column;
2. Steel bones were added to the frame columns at the base of the tower to improve the ductility of the structure;
3. At the bottom reinforcement part, when the shear wall axial compression ratio is greater than 0.10, restraint edge members are set. In other parts, restraint edge members are set when the axial pressure ratio of the shear wall is greater than 0.25;

4. Optimize the section of the component as much as possible to reduce the weight of the structure;

5. The reinforced area at the bottom of the core tube and its upper layer are configured with several sections to achieve bending without yielding under moderate earthquakes;

6. Determine the minimum reinforcement requirements for various structural components, which is slightly higher than the specifications.

In summary, the structural indicators meet the requirements of the relevant national standards and the special review points for seismic fortification, and the structure can achieve the expected seismic performance target requirements. Through the introduction of this article, it can provide reliable guidance for similar projects.

References
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