Study on the Design of Super High-rise Shear Wall

Hu Du

Henan Zhidi Construction Engineering Group Co., Ltd., Zhumadian, Henan, China, 463000.

*Corresponding author e-mail: 1315948757@qq.com

Abstract: A 160m height of residential building with shear wall structure was a super high-rise building which was plane torsion irregular, height overrun and plane concave irregular. In the paper, the seismic design of this structure was demonstrated. To calculate the project, this paper established a mechanical model containing three different spatial analysis programs, and the results showed that the structure could be damaged in micro-earthquakes and would not collapse in strong earthquakes.

1. General situation of the project

The project was a super high-rise dwelling construction, classified by the functionality of architecture, which was a shear-wall structure of reinforced concrete cast-in-situ completely. This building, which was 160.8m high, had a total of 53 storeys above ground and 2 storeys underground. Each layer underground and the first layer on the ground had a height of 4.8m, while all other storeys on the ground were 3.0m high. The design service life of structure was 50 years, the foundation was designed with grade A level and the seismic fortification category was typical fortification type. According to the Technical Specification for Concrete Structures of Tall Building [1, 2, 3], the structure was a B-class super high-rise building. The seismic fortification intensity was 6 degree. But according to earthquake safety evaluation report the horizontal influence coefficient was 0.079, close to 7 degree fortification intensity. The roughness of ground lay in class C. Moreover, the basic wind pressure was 0.35, and while designing load-bearing member, the amplification parameter of 1.1 wind load effect must be considered. From the above, the high-rise building was height overrun, plane torsion irregular and plane concave irregular. It was shown in Fig. 1 and Fig. 2.
2. Structure
The project was a super high-rise structure, which was a shear wall structure of reinforced concrete cast-in-situ completely. The standard plane layout of the structure was shown in figure 3. In order to meet the building function standards and the demands in structure lateral stiffness [4, 5], shear wall was evenly arranged in the periphery and the corner of the building. The main structural shear wall had an initial thickness of 500mm, and then the thickness was adjusted to 200mm. Concrete strength grade was decreased from C60 to C40, and the beam and slab had a concrete strength grade categorized to C35. When designing preliminary structure, only the load of the curved balcony and the secondary beam in the construction periphery were considered, but when designing the construction drawing, all of the secondary beam members were taken into account [6, 7]. The elevator shaft connected to the vertical member had a floor with the thickness of 150mm.
compressive bearing capacity was set to 7800 KN vertically. The pile end had to be set into the bearing stratum for at least 10.5m and the bearing stratum at the end of the pile was medium weathered mudstone. Moreover, the bearing stratum at the pile end was shale powder sandstone. The effective pile must be set to more than 30m long, and the concrete strength level of pile must adopted C40.

3. Design method of structural anti-seismic performance

(1) The paper designed the structure in accordance with the elastic calculation results at the condition of frequent earthquakes as well as wind load.

(2) Under the seismic fortification intensity, criterion of yielding [9] was employed to carry out the yield check for structural members, and it was also adopted to investigate the structure damage.

(3) Static elastic-plastic method was employed to check if the storey displacement angle can meet the specifications [10, 11, 12], and the degree of structure damage was examined. As a result, the weak part structures could be determined and the measures for enhancing the structure seismic property could be put forward.

4. Elastic analysis considering frequent earthquake

According to the Design Code for High-rise Civilian Construction, in order to determine the displacement of the whole internal force, three kinds of space analysis software were adopted to calculate the structure. In addition, the comparative analysis was also carried out [12], and the torsional effect of the bidirectional horizontal earthquake was analyzed. The calculated results of comparative analysis were showed in Table 1. The results obtained from SATWE, PMSAP and MIDAS/Building showed that in the direction of the principal axis, the structure was like the vibration. Furthermore, the three kinds of program had basically the same structure vibration mode and displacement quantity, even the cycle and displacement shape. Synthesis analysis indicated that in the direction of the height, the structural earthquake action owned a reasonable distribution. Therefore, the results from the program were reliable.

Finally, all of the indicators such floor shear weight ratio, displacement angle met the requirements.

| Table 1. Comparison of elastic calculations |
|---------------------------------------------|
| Items                                      |
| Cycle                                      |
| Cycle                                      |
| T1  | 3.95 | 4.10 | 4.13 |
| T2  | 3.84 | 3.94 | 4.04 |
| T3  | 3.11 | 3.27 | 3.41 |
| Tt/T1 | 0.78 | 0.81 | 0.82 |
| Limit | ≤0.85 |
| Maximum storey drift angle                 |
| seism in x direction                       |
| 1/1211 | 1/1194 | 1/1171 |
| seism in y direction                       |
| 1/1303 | 1/1241 | 1/1194 |
| wind in x direction                        |
| 1/2442 | 1/2526 | 1/2391 |
| wind in x direction                        |
| 1/2519 | 1/2633 | 1/2375 |
| Displacement ratio                         |
| seism in x direction                       |
| 1.37  | 1.35  | 1.34  |
| seism in y direction                       |
| 1.20  | 1.19  | 1.15  |
| Limit | ≤1.4 |
| Effective mass coefficient                 |
| seism in x direction                       |
| 98.1  | 98.4  | 98.3  |
| seism in y direction                       |
| 98.3  | 98.0  | 98.3  |
| Limit | ≥90% |
| Floor shear weight ratio (%)               |
| seism in x direction                       |
| 1.63  | 1.67  | 1.53  |
| seism in y direction                       |
| 1.57  | 1.58  | 1.58  |
| Limit | ≥1.51% |
| Integral stability checking                |
| x direction                                |
| 3.56  | 3.28  | 3.10  |
5. Elasticity and seismic non-yield calculation under medium earthquake

With objectives of engineering characteristics and performance showed in figure 4, Middle earthquake elasticity and seismic non-yield calculation was undertaken in this project, and the equivalent elastic algorithm was adopted [12, 13]. The damping ratio of the structure was 0.07 and the reduction coefficient of beam stiffness was 0.04. In normal sections, influenced by the fortification intensity earthquake, the vertical members had a bearing capacity which was in accordance with the rules in the key components, so did the shear bearing capacity. The structure had a maximum drift angle between storeys of 1/475 in X direction, and it was 1/491 in Y direction. Frame and coupling beams with a smaller bending yield had some floors in yield stage, but the shear-bearing capacity did not degrade greatly, which was local ductile damage. It could be continued to use with the general repair. The displacement between storeys had a deformation no more than double the limit of elastic displacement (1/458). Under the fortification intensity earthquake, the structure could satisfy the performance purposes in expectation. The analysis result was shown in figure 5.

![Figure 4. Performance evaluation objectives](image)

![Figure 5. Displacement angle of the plastic layer in strong earthquake](image)

6. Elastic-plastic analysis in strong earthquake

In strong earthquakes, MIDAS/Gen was employed to carry out the static analysis. In order to assess the seismic performance of the building in MIDAS/Gen, the paper adopted the capacity spectrum method in ATC-40 (1996) and FEMA-273 (1997). Because the structure is asymmetric and the load distribution is non-symmetric, each load was acted by main directions of X and Y, respectively. The structure of the weak positions, after the completion of pushover analysis, was determined by means of the plastic hinge distribution which refers to the plastic hinge state. And then it was checked if the structural member could meet the demand of the performance level under the influence of strong earthquakes. The analysis results were shown in figures 6-9.

The characteristics of capacity spectrum curve in each working condition are stated as following:

1. The vertical stiffness of the structure was ultimately unified, and the displacement angle curve was consistent. Besides, no mutation showed up.

2. Under each load condition, the obtained capacity curves were all smooth within the target range, and steep drop as well as abrupt segment did not appear. There were intersection points of each capacity spectrum of the great earthquake spectrum. In addition, in the X and Y directions, stiffness
was more corresponding strength.

(3) In elastic plastic layers, the displacement angle was below 1/120, and this value could satisfy the corresponding requirements. At 24~30 layers, the maximum drift angle in X direction showed up, and from 25 to 36 layers, the maximum layer displacement angle in Y direction appeared.

![Figure 6. Elevator shaft in strong earthquake and its surrounding shear wall](image)

![Figure 7. External shear wall affected by strong earthquake](image)

![Figure 8. Coupling beams](image)

![Figure 9. Frame beams](image)
4) The following is the order of plastic hinge development after the structure entering in the plastic stage. Firstly, plastic hinge moment appeared in the coupling beams. Secondly, it showed up in the frame beam as the push deepening.

5) In compare with the loading mode with a constant acceleration, the distributed loading mode was more unfavorable. Because the thrust analysis result was highly based on the mode of horizontal load distribution, the practice of selecting various loading modes and checking with each other was more advisable.

7. Measures for strengthening
In the design of the structure, the following strengthening measures were employed:

1) At the reinforced region bottom, axial compression ratio must be set below 0.5 so as to enhance the ductility.

2) On the basis of 1.4%, the minimum longitudinal reinforcement ratio for the restrained edge member was determined. Moreover, the characteristic value of hoop reinforcement increased greatly, reaching up to 20%, and for the structural edge members, the longitudinal reinforcement ratio must be greater than 1.2%.

3) The result of the static elastic-plastic analysis showed that the frame beam with deep plastic state was recommended to increase the section and the reinforcement ratio appropriately, so the bearing ability was improved and the occurrence of large damage could be avoided.

8. Summary
Three kinds of calculating program were employed for analysis, in which indicators of the structure were compared. The results verify the reliability of the calculation model. The envelope results obtained by three programs could be used in the construction drawing design of structural components.

The calculation showed that all member of the structure could maintain flexibility under frequent earthquake. All vertical members did not yield, while part of the frame beams entered the yield stage. The whole structure was in the elastic and plastic state the maximum storey displacement angle of the floor was less than the norm under rare earthquake. However, in rare earthquakes, the vertical members exhibited a great performance, and the damage level as a whole was not very serious.

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