Aseismic Design of an Out-of-Code High-Rise Building in Shanghai

Hongmei Ren, Jianping Zhu, Yanyan Lv, and Weiwei Qin

Abstract Proper structural system and performance-based seismic design are the key issues in designing high-rise building structures. This project has unique building facade shape and complex plane function layout, and the structural plane and vertical layout are irregular. The superstructure adopts assembled integral concrete frame-shear wall structure, which is judged as out-of-code high-rise building by seismic review. Firstly, the site conditions, foundation design and structural form selection are introduced. Then, YJK software is used to calculate and analyze the seismic force of the superstructure, and the seismic performance indexes of the structure can meet the requirements of the code. Finally, the regularity of each structural unit of the superstructure is judged, and the corresponding main seismic strengthening measures are put forward.

Keywords Assembled integral frame-shear wall structure · Structural regularity · Seismic fortification measures · Out-of-code high-rise building

1 Introduction

AN out-of-code high-rise building in Shanghai is located in Pudong New District, Shanghai. It is a high-rise building with 1 basement and 3 8-story towers (including 3 podium floors). The total construction area is 45,570 m^2, including 38,990 m^2 above the ground and 6580 m^2 underground (Fig. 1). The superstructure is divided into three structural units by setting aseismic joints: unit A, B and C of 8 floors (Fig. 2). Integrated concrete frame-shear wall structure is adopted in the ground building and cast-in-place concrete frame structure is adopted in the basement.

The design service life of the building structure is 50 years, and the structural safety grade is grade II. The seismic fortification intensity of Pudong New District is

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Fig. 1 Architectural renderings

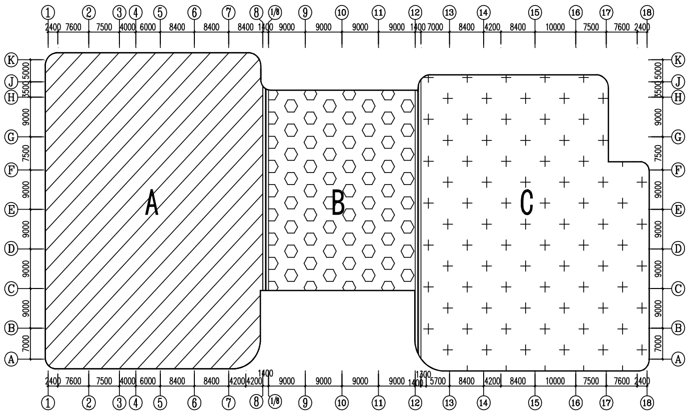

Fig. 2 Schematic diagram of building layout (Unit A, B and C)

7° and the design basic seismic acceleration is 0.10 g. The design earthquake group is group II, the site category is class IV, the design characteristic period is 0.9 s, and the seismic fortification category of the building is class C. The seismic grade of the shear wall is grade two, the seismic grade of the frame is grade three, and the seismic grade of basement frame is grade three. The maximum horizontal seismic influence coefficient under the action of frequent earthquakes is 0.08. The maximum horizontal seismic influence coefficient under the action of rare earthquakes is 0.45, the basic wind pressure is 0.55 kN/m^2 (return period of 50 years), and the ground roughness is class A [1–4]. The basement roof is used as the embedded part of the superstructure, and the lateral stiffness of the basement floor is 1.5 times higher than that of the first floor. The first floor adopts cast-in-situ concrete beam slab structure. The floor thickness of the superstructure is 250 mm, and double-layer bi-directional connection configuration of the rebar is adopted, which meets the requirements of embedding [5].

2 Foundation and Basement Structure Design

The design grade of the project foundation is grade B, and the waterproof grade of the basement is grade one [6]. According to the geotechnical engineering investigation report of the project, the proposed site is an unfavorable seismic site. According to the characteristics of the project and the actual distribution of the foundation soil layer on the site, the foundation adopts the pile foundation of bearing platform under column (wall) + raft. The thickness of raft is 600 mm and the strength grade of raft concrete is C35. The Φ 500 mm PHC prestressed concrete pipe pile is selected and the pile length is 28 m. The load bearing layer was not less than 4.2 m. The design value of vertical compressive bearing capacity of single pile is 1680 kN. The total number of piles is 266 and the load bearing layer of pile tip is ⑦-1 layer sandy silt.

The plane outsourcing size of the basement is about 148 m × 69.2 m, which belongs to super-long basement structure (Fig. 3). In order to reduce harmful cracks caused by concrete shrinkage cracks and temperature cracks, the following measures are taken in the design: (1) Set post-construction pouring belt (width: 0.8 m ~ 1 m) or expansion reinforcing belt (width: 2 m), and use micro- expansion concrete to compensate for concrete shrinkage. (2) The reinforcement ratio of the basement roof is not less than 0.25%. The spacing between the basement roof reinforcement and the horizontal reinforcement of the basement exterior wall is well controlled so as to enhance the shrinkage resistance of the basement concrete. (3) Cement with low shrinkage heat of hydration is used to avoid using high grade concrete. (4) Maintenance is strengthened during construction.

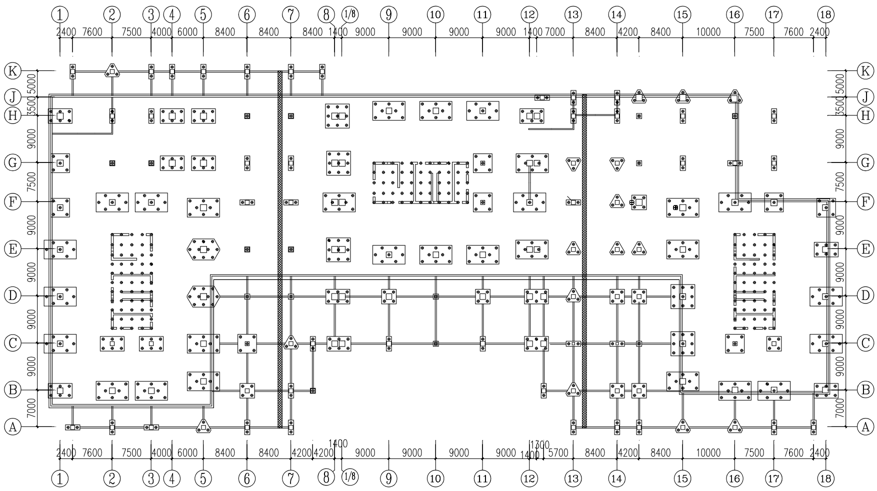

Fig. 3 Basement foundation layout plan

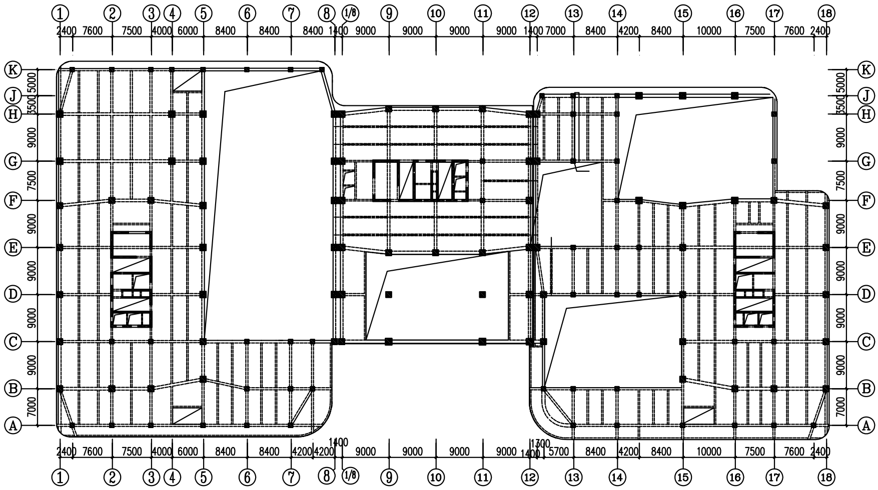

Fig. 4 Structural plan of the 2nd floor

3 Superstructure Design

3.1 Lateral Force Resistant Structural System

The main column spacing of the superstructure is 9.0 m. After setting seismic joints at axis 3 and axis 12, the superstructure is divided into three structural units, namely unit A (①~⑧ axis/A axis ~ K axis), unit B (⑧ axis ~ ⑫ axis/C axis ~ H axis) and unit C (⑫ axis ~ ⑱ axis/A axis ~ K axis). Each layer height: the first layer is 8.0 m, the second layer is 5.4 m, the third layer is 7.2 m, 4 ~ 8 layer is 4.8 m. The indoor and outdoor height difference is 0.30 m and the main roof height is 44.9 m, which is a class A high-rise building [7]. The main structure adopts assembled integral frame shear wall structure and composite floor slab.

Based on the principle of seismic conceptual design, combined with the characteristics of structural plane and the demand of the building use function, the shear wall is arranged symmetrically in two directions in stairwell, elevator, end compartment and partition wall. The stiffness shall be evenly distributed in the plane layout to reduce the torsional effect under the earthquake. Typical floor plans are shown in Figs. 4, 5, 6 and 7.

3.2 Structural Calculation and Analysis

Considering the torsional coupling effect, the YJK software is used for structural analysis and seismic internal force calculation of the building. The floor stiffness

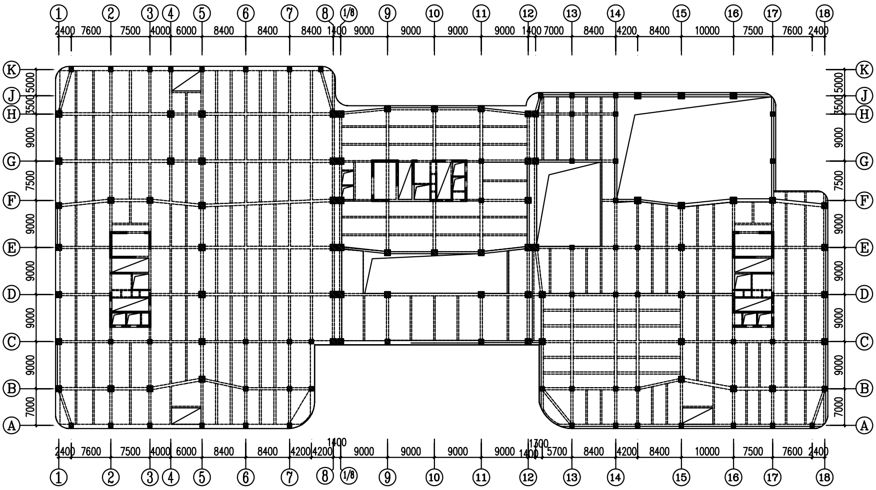

Fig. 5 Structural plan of the 3rd floor

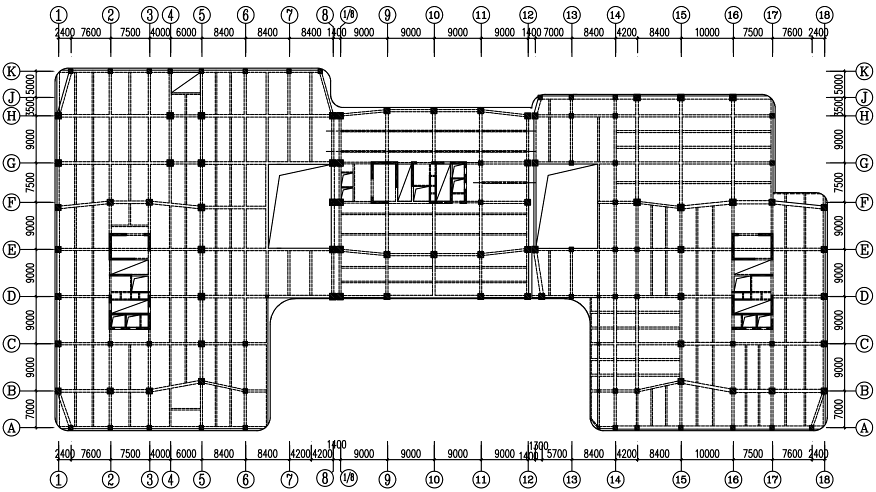

Fig. 6 Structural plan of the 4th floor

adopts the shear stiffness algorithm and 21 vibration modes are calculated. The calculation results of structural vibration characteristics of unit A, B and C are shown in Table 1 respectively. The ratio of the first natural vibration period T3 dominated by torsion to the first natural vibration period T1 dominated by translation is less than 0.90, which meets the specification requirements [7].

Other main calculation results such as inter story displacement angle, torsional displacement ratio, shear weight ratio and other indicators meet the specification requirements, as shown in Table 2. Stiffness ratio refers to the ratio of the lateral

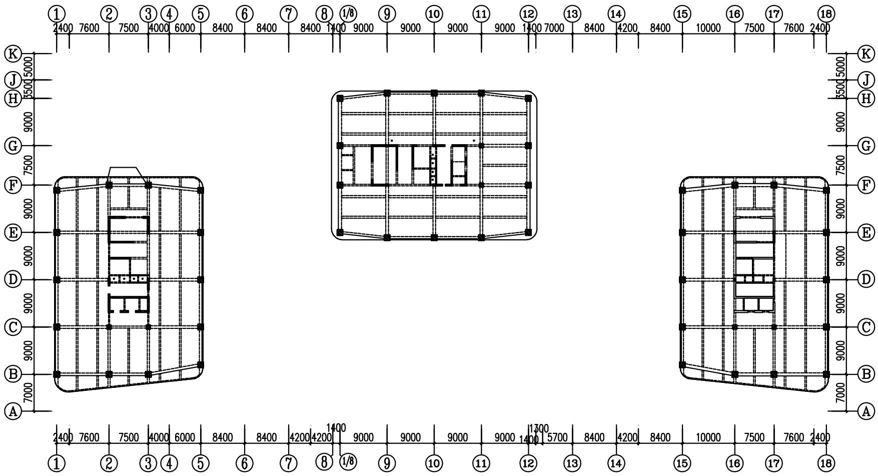

Fig. 7 Structural plan of the 5th floor ~ roof

Table 1 Vibration characteristic index

Structural element	Vibration model No.	Natural vibration period (s)	Translation coefficient	Torsion coefficient
Unit A	1	1.0415	0.07(X) + 0.85(Y)	0.08
	2	0.9892	0.90(X) + 0.09(Y)	0.01
	3	0.8736	0.07(X) + 0.10(Y)	0.83
	T3/T1 = 0.8736/1.0415 = 0.84 ≤ 0.90			
Unit B	1	1.0534	0.93(X) + 0.01(Y)	0.07
	2	1.0356	0.01(X) + 0.99(Y)	0.00
	3	0.9166	0.07(X) + 0.00(Y)	0.93
	T3/T1 = 0.9166/1.0534 = 0.87 ≤ 0.90			
Unit C	1	1.0121	0.67(X) + 0.25(Y)	0.07
	2	0.9703	0.32(X) + 0.63(Y)	0.05
	3	0.8174	0.02 (X) + 0.15(Y)	0.82
	T3/T1 = 0.8174 /1.0121 = 0.81 ≤ 0.90			

stiffness of this floor to 70% of the lateral stiffness of the adjacent upper floor or 80% of the average lateral stiffness of the three adjacent floors above it. The calculation results show that there is no soft layer in the superstructure.

Table 2 Main calculation indexes of structure

Calculation results	Structural element					
	Unit A		Unit B		Unit C	
	X direction	Y direction	X direction	Y direction	X direction	Y direction
Floor minimum shear weight ratio	4.89%	4.62%	5.08%	5.45%	5.08%	4.61%
Effective mass coefficient	98.72%	99.52%	97.62%	97.81%	92.10%	91.88%
The maximum ratio of the maximum horizontal displacement to the average value of the floor under earthquake	1.38 (3rd floor)	1.25 (3rd floor)	1.38 (1st floor)	1.27 (1st floor)	1.37 (1st floor)	1.36 (3rd floor)
Seismic base shear (kN)	16,610.40	15,685.00	11,673.70	12,513.72	15,925.72	14,467.11
Minimum shear capacity ratio of floor	0.83 (1st floor)	0.86 (1st floor)	0.94 (3rd floor)	0.94 (3rd floor)	0.87 (2nd floor)	0.91 (2nd floor)
Lateral stiffness of bottom embedded layer (>1.5)	6.7320	6.4724	9.8043	3.4956	7.2437	6.8209
Maximum axial compression ratio of frame column/shear wall limb	0.86/0.31		0.87/0.31		0.71/0.25	
Stiffness weight ratio of structural overall stability calculation (≥1.4)	9.44	8.55	10.18	10.78	10.00	10.52

4 Determination of Structural Regularity and Main Seismic Strengthening Measures

The structural height of the project is 44.9 m < 120 m and the height width ratio is 1.75 < 6, which meet the requirements of the code. According to the technical regulations of the Ministry of construction and Shanghai Municipality on the regularity judgment of out-of-code high-rise buildings [8, 9], the regularity judgment of structural unit A, B and C is conducted respectively.

4.1 Rule Judgment of Unit A and Unit C

(1) Torsional irregularity: when considering the specified horizontal force of accidental eccentricity, the maximum elastic horizontal displacement of the floor is greater than 1.2 times the average value of horizontal displacement at both ends of the floor.
(2) Eccentric arrangement: the eccentricity between the mass center and the stiffness center of floors 1~3 is greater than 0.15.
(3) Local discontinuity of floor slab: the effective width of floor slab after opening is less than 50% of the typical width of floor slab in the Y direction of ⑤ axis ~ ⑧ axis on the second floor of unit A, the X direction of ⑭ axis/F axis ~ J axis on the second floor, the Y direction of ⑫ axis ~ ⑭ axis on the second floor, and the X direction of ⑫ axis ~⑰ axis/F axis ~ G axis on the third floor of unit C.
(4) Irregular lateral stiffness: the local retraction size of the fourth floor is greater than 25% of the adjacent lower floor.

Among them, (1) and (2) do not double calculate the irregular items, so there are three irregularities in unit A and unit C, which belong to out-of-code high-rise buildings.

4.2 Main Seismic Strengthening Measures of Unit A and Unit C

(1) Torsional irregular and eccentric arrangement: the spatial calculation model is adopted, the torsional coupling effect is included and the accidental eccentricity and two-way seismic effect are considered. The structural quality participation coefficient is controlled to be no less than 90%. Adjust the structural stiffness to make the torsional period ratio within 0.9 and control the structural torsional displacement ratio within 1.4. Properly increase the structural stiffness and reduce the inter story displacement angle of the structure under earthquake.

(2) Local discontinuity of floor slab: the slab thickness around the opening is not less than 140 mm, and two-way and double-layer reinforcement is provided. And the reinforcement ratio is not less than 0.25%. At the same time, the calculation model in line with the actual stiffness change in the plane is adopted. During YJK calculation, the floor slab type is set as elastic membrane, the floor slab stress analysis is carried out for 2~4 floor, and the reinforcement design is checked according to the results.
(3) Irregular lateral stiffness: The 4-storey floor slab at the sudden change of vertical shape is thickened to 150 mm. The floor slab thickness of adjacent 3 and 5 floors is not less than 130 mm, 3~5 double-layer two-way reinforcement, and the reinforcement ratio is not less than 0.25%. The calculation model for reviewing the actual stiffness change in the plane is adopted. During YJK calculation, the floor type is set as elastic membrane, the floor stress of 3~5 floors is analyzed, and the reinforcement design is verified according to the results.

Measures are taken to reduce the change of structural stiffness at the body retraction. The displacement angle between 4 layers of the bottom floor of the upper retraction structure is not greater than 1.15 times of the maximum displacement angle between layers of adjacent lower sections.

The seismic level of the vertical components around the tower of 2–5 stories is increased by one level, that is, the seismic level of the column is increased to two levels, and the seismic level of the shear wall is increased to one level.

4.3 Rule Judgment of Unit B

(1) Torsional irregularity: when considering the specified horizontal force of accidental eccentricity, the maximum elastic horizontal displacement of the floor is greater than 1.2 times the average value of horizontal displacement at both ends of the floor.
(2) Eccentric arrangement: the eccentricity between the mass center and the stiffness center of floors 1~3 is greater than 0.15.
(3) Local discontinuity of floor slab: the effective width in X direction after opening of 2-story C-axis ~ E-axis and 3-story D-axis ~ E-axis floor slab is less than 50% of the typical width of floor slab.

Among them, (1) and (2) do not double calculate the irregular items, so there are two irregularities in unit B, which does not belong to out-of-code high-rise building.

4.4 Main Seismic Strengthening Measures of Unit B

(1) Torsional irregular and eccentric arrangement: the spatial calculation model is adopted, the torsional coupling effect is included and the accidental eccentricity

and two-way seismic effect are considered. The structural quality participation coefficient is controlled to be no less than 90%. Adjust the structural stiffness so that the torsional period ratio is within 0.9, and control the structural torsional displacement ratio within 1.4 to ensure that the torsional stiffness of the structure is large enough.

(2) Local discontinuity of floor slab: the slab thickness around the opening is not less than 140 mm, and two-way and double-layer reinforcement is provided. The reinforcement ratio is not less than 0.25% to strengthen the integrity of the floor slab. At the same time, the calculation model in line with the actual stiffness change in the plane is adopted. During YJK calculation, the floor slab type is set as elastic membrane and the floor slab stress is analyzed. The reinforcement design is checked according to the results to avoid shear failure of weak floor under large earthquake.

5 Conclusion

Based on the principle of seismic conceptual design and on the premise of meeting the building use function, the structural plane and facade layout of the structure are optimized. The reasonable structural system and calculation assumptions are adopted. The seismic strengthening measures for the weak parts of the structure are taken to ensure the bearing capacity and deformation capacity of the structure and meet the design requirements of safety, applicability and economy.

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