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Study on Optimization Design of Reinforced Concrete Special-shaped Column Frame Structure

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In order to make the design of reinforced concrete (RC) special-shaped column frame structure safe and economical, the optimization design of the structure based on the general design is put forward. In the general structural design, there are problems of mismatch in structural arrangement, overall performance parameter and basic component parameter. By optimizing the period ratio, stiffness ratio and displacement ratio of special-shaped column, rectangular column and framed girder, the structure can be improved. Through increasing the strength grade of concrete and the size of the column section, the axial compression ratio of column can be optimized in proportion. The shear pressure ratio of beam-column node area can be improved by increasing the strength grade of concrete, haunching the beam and raising the beam height. According to the engineering practice, the overall performance parameter control reference value of RC special-shaped column frame structure is put forward. The design process of special-shaped column frame structure is introduced with the examples of engineering design and the optimization design result is ideal. Optimization design goal and optimization means of special-shaped column frame structure provide a new design concept for the design of special-shaped column frame structure.

1. Introduction

With the development of the fabricated structure, the standard composite floor slabs have been widely used. The multi-floor high-quality large-scale houses have become the mainstream of residential construction, and the special-shaped column structure that has been silent for many years has returned to people's vision. The column whose geometry of section is L-shaped, T-shaped, cruciform and Z-shaped, and height and thickness ratio of section limbs is not more than 4 is special-shaped column. Special-shaped columns used in building structures include RC special-shaped columns, fiber RC special-shaped columns, and fashioned iron RC special-shaped columns. Structures of special-shaped columns include special-shaped column frame structure and special-shaped column frame—shear wall structure (Zhou and Zhu, 2015). The width of the special-shaped column limbs can be the same as the thickness of the building maintenance wall to avoid lobe inside the room, and the layout column grid is flexible, which well achieves the use functions (Wang, 2015).

Studies on force analysis of special-shaped columns and beam-column node area of different materials configuration have got some achievements. Special-shaped column is subject to complicated forces and its construction is difficult. At present, the design of RC special-shaped column frame based on the design idea that basically meets the basic requirements of "standard" results in high cost of structural design and construction, especially in earthquake fortification areas. The special-shaped column frame with reasonable design has good ductility, strong deformation capacity and energy dissipation capacity (Wang and Wang, 2008). The realistic goal of structural design is structural safety and reasonable construction cost. To achieve this goal, optimization design of special-shaped column frame should be carried out based on the general structural design. Thus, the study on optimization design is of more practical significance.

To achieve the goal of optimization, this paper will elaborate from special-shaped column frame structure, the existing problems in the design of RC special-shaped column frame structure, the countermeasures, means and control indexes of structural optimization design, and the optimization process through engineering practice.

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2. Scope of Application of Special-shaped Column Frame Structure

The special-shaped column frame structure is mainly suitable for residential buildings with non-aseismic design and earthquake fortification intensity of 6 degrees, 7 degrees (0.10g, 0.15g) and 8 degrees (0.20g) (Huo, 2001). At present, no attempt for design has been carried out in high earthquake fortification intensity area, so special-shaped column frame structure should not be adopted in areas of 8 degrees (0.30g) and degrees (Rong and Zhang, 2016). The maximum height and maximum aspect ratio of special column frame structure housing are in Table 1. Housing height refers to the height of the outdoor ground to the main roof, excluding the height of the elevator machine room, water tank, framework that protrude from the roof. The aspect ratio is the ratio of the height above the ground (excluding the partially protruding roof section) to the minimum projected width of the building direction.

Table 1 Maximum height and maximum aspect ratio of special column frame structure housing

Earthquake fortification intensity	Non-aseismic design	Aseismic design			
		6 degrees	7 degrees		8 degrees
		0.05g	0.10g	0.15g	0.20g
Maximum height(m)	28	24	21	18	12
Maximum aspect ratio	4.5	4.0	3.5	3.0	2.5

The structural arrangement, the direction of special-shaped columns and limbs, the section forms of special-shaped columns and the number of special-shaped columns all have different degrees of influence on the overall performance parameter, the bearing capacity of components, the amount of concrete and reinforcing steel materials, further affecting safety of structure and project cost. Therefore, it is very necessary to optimize RC special-shaped columns frame structure.

3. Problems in Structural Design

3.1 Structural arrangement

Generally, structural arrangement is conducted by following the requirements of “standard”, building plan foundation and design habits. At present, computer-aided design has been basically used, so little consideration is given to the complexity of the self-imposed force of the special-shaped columns and the particularity of the structural system in the beam-column arrangement stage, which leads to the unsatisfactory overall performance parameter. In the structure arrangement, such phenomena exist, such as there is small spacing of special-shaped columns; the L-shaped columns or T-shaped columns are arranged randomly at the intersection of the three beams; the cruciform columns are directly arranged at the intersections of the four beams; the influence of the beam span around the columns is ignored.

3.2 Overall performance parameter

The overall performance parameters mainly include period ratio, displacement ratio, lateral stiffness ratio, elastic displacement angle between floors, and the ratio of bearing capacity between floors.

The period ratio should not be greater than 0.9. It is not appropriate when the period ratio is close to 0.9 without processing. When the period ratio is close to 0.9, the first natural period of torsional vibration is close to the first natural period of translational motion. At this time, the torsional effect of the structure is obvious and the data meets the requirements, but the work performance of structure is not ideal. When the period ratio is greater than 0.9, it is sometimes not possible to reduce the period ratio by increasing the height of the end frame beam. If the frame beam is too high, it is contrary to the seismic conceptual design of the “wall column weakening beam”.

The displacement ratio should not be greater than 1.2 and shall not be greater than 1.45 (Li and Liu, 2001). The displacement ratio between 1.2 and 1.45 meets the requirements, but the torsional effect of the structure is obvious and the structure is averse to earthquake fortification.

The lateral stiffness ratio of the floor to the adjacent upper floor shall not be smaller than 0.7 or the lateral stiffness ratio of the floor to the mean stiffness ratio of adjacent three upper floors shall not be smaller than 0.8 (Guo, 2014). It is also not appropriate if the stiffness of the structure is not processed when the ratio is satisfactory but very close or equal to 0.7 or 0.8. The stiffness ratio is close to or equal to the limit, indicating that this floor basically forms or is about to form a “weak floor”, where the structure works at a critical stiffness state, which is extremely averse to earthquake fortification. When the stiffness ratio is less than 0.7 or 0.8, this floor is “weak floor”, and the seismic sheer force of each floor should be magnified by 1.25 times to calculate other design contents, then the material consumption will be significantly increased.

The elastic displacement angle between floors shall not be greater than 1/550. When the calculated displacement ratio of the structure is far less than 1/550, it shows that the structural stiffness is excessive too much, which will cause a lot of material waste (Wang and Wang, 2010).
The ratio of bearing capacity between floors should not be smaller than 0.8 and shall not be smaller than 0.65. When the ratio of bearing capacity between floors is between 0.8 and 0.65, it meets the requirements. The seismic sheer force of each floor should be magnified by 1.25 times to calculate other design contents, and then the material consumption will be significantly increased.

3.3 Basic component parameter

The main parameters of component include the sectional dimension of beam and column, the axial compression ratio of column, the shear pressure ratio of core beam-column node area, the reinforcement of the beam-column components, and the strength grade of concrete.
The sectional dimension of beam and column has a significant impact on the overall performance parameter. In order to adjust the performance parameter, the sectional dimension of beam and column is greatly increased without making clear where problems appear, which is crude and wasteful.
For "safety", the amount of steel and strength grade of concrete are improved, which are not good design concepts.
The above structural arrangement, overall performance parameter, design and adjustment of component parameter are not wrong but are in conflict with our design concept. Our structural design aims at finding the joint point of structural safety and reasonable cost under the premise of achieving the building functions, that is, the structure is safe and economical.

4. Optimization of Structural Design

According to the study and analysis of engineering practice, it is concluded that the matching relationship of the overall parameters has a great impact on the number of reinforcement of components. The overall parameter control reference values of RC special-shaped column frame structure are in Table 2, which is the main technical objective of the optimization design.

Table 2: Overall parameter control reference values of RC special-shaped column frame structure

Parameter name	Structural period ratio	Displacement ratio		Lateral stiffness ratio		Ratio of bearing capacity between floors	Elastic displacement angle between floors (earthquake conditions)
		Most conditions	A few conditions (≤2)	The floor to the adjacent upper floor	Mean value of adjacent three upper floors		
Control reference values	≤0.84 (The maximum torsional period is the third period)	≤1.2	≤1.3	≥0.75	≥0.82	≥0.82	1/600~1/900

4.1 Layout of frame column

Sectional limb thickness of special-shaped column and width of wall should take 200 mm and limb length shall be500-600 mm. Rectangular frame columns should be arranged in elevator shafts and stairwell sections, as well as structures subject to complicated forces. Besides, rectangular frame columns should be arranged in where the frame beams intersect, especially where the three beams intersect without hindering the use of functions. Column spacing should not be small and 4.0m-6.0m is appropriate. It is concluded that the overall performance parameters of the frame structure combined with the rectangular columns and the special-shaped columns are better than those of frame structure totally composed by special-shaped columns.

4.2 Layout of frame beam

The sectional width of the frame beam around the structure is the same as lime thickness of special-shaped column, and the height of the beam section is 1/10-1/12 of beam span. Inside the structure, the width of the frame beam is the same as lime thickness of special-shaped column, and the height of the beam section is 1/12-1/18 of beam span. The liner stiffness ratio of beams and columns shall be controlled in the range of 1-4, otherwise, it will run counter to the structural conceptual design. At the same time, that anti-point position offset is too large can also cause that the shear span ratio of columns is too small.

4.3 Axial compression ratio of column

Axial compression ratio is an important index affecting the ductility of concrete special-shaped columns. Ductility is an important index that reflects the seismic performance of the structure. There are many factors affecting the ductility, such as the strength grade of concrete, the sectional dimension of column, and the shear span ratio of column. The optimization of axial compression ratio is more difficult. The axial compression ratio limit of column shall be subject to the current "Technical Regulations of Concrete Special-shaped Column Structure" JGJ 149 (hereinafter referred to as "Regulations"). The means to optimize the axial compression ratio include: when over 20% (including 20%) of the axial compression ratio of columns does not meet the requirements, the strength grade of concrete can be improved; otherwise, the sectional dimension shall be gradually increased one by one until it meets the requirements (Li and Peng ,2015).

4.4 Shear pressure ratio of beam-column node area

A large number of calculations have found that the shear pressure ratio of beam-column node area often does not meet the requirements. The optimization of shear pressure ratio is in Table 3. In addition, according to the experimental study on the bearing capacity of nodes, the actual bearing capacity is 1.1-1.2 times of the calculated bearing capacity of the "Regulations". The calculation of the "Regulation" is too conservative. Under the premise of meeting the conceptual design, the calculated bearing capacity can be increased by 1.1 times (Long,2000).

Table 3: Optimization of shear pressure ratio of beam-column node area

Proportion of nodes that don't meet the requirements of the total number of nodes in this floor %	≥20	＜20
Optimization means	Improving the strength grade of concrete	Optimization means and order: (1) Increasing the height of girder cross-section; (2) Haunching in the vertical direction of girder; (3) special-shaped columns are transferred into rectangular columns Note: The height of girder cross-section can't be increased infinitely and shall not exceed the 1/4 of span of girder.

The various optimization processes are mutually interactional and we can't simply pursue a goal while neglecting changes in other parameters.

5. Project Examples

A residential building is 25.4 meters lone and 11.5 meters wide with 6 floors above ground. The total height of the ground structure is 18m and the first underground floor is for garage. Its earthquake fortification intensity is 7 degrees (0.1g). The second group is design seismic group and venue category is II. Structural system uses special-shaped column frame structure with shaped column limb thickness of 200mm and frame beam width of 200mm. 200-mm thick coal gangue hollow bricks are used to fill the wall. The class of seismic measure is third-level.

5.1 Structural arrangement

The structural arrangement is shown in Figure 1, and the shadow of the figure is frame column. Rectangular columns are arranged around the hoist way. The rectangular columns on the A-axis are arranged according to the architectural shape. Rectangular columns are arranged in point 1 and 2 to connect the larger axis to stagger away from the large-spacing beam, that is, rectangular columns are arranged in where forces are complex. Special-shaped columns are arranged in point 3 and 4 originally. After calculating, the shear pressure ratio hasn't met the requirements, thus special-shaped columns are replaced by rectangular columns.

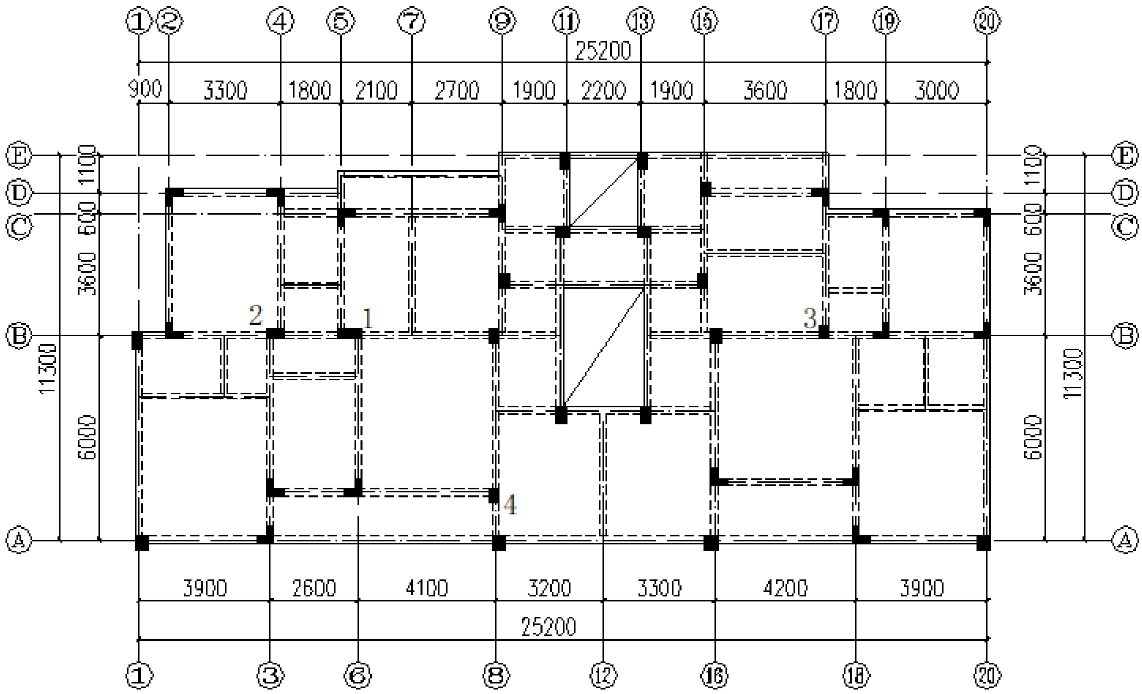

Figure 1: Structural arrangement diagram (standard floor)

5.2 Calculation analysis and main results

Optimization design is calculated according to the above-mentioned way. The 2010 PKPM series software SATWE compiled by China Academy of Building Research is used for overall structural calculation and the main results of performance parameters are shown in Table 4.
According to the calculation of structural analysis, the displacement ratio in Y direction of the structural system is more than 1.2 but not more than 1.3, which belongs to the general irregularity of torsion. Other major indexes are within the ideal range. Besides, the amount of reinforcing steel bars used on the ground is ideal. The average consumption of reinforcing steel bars based on the area of structure is 54.6 kg per square meter.

Table 4: Calculation results of the main performance parameters

Considering the overall parameters of earthquake action		Considering accidental eccentricity and two-way earthquake
Period ratio	Tt/T1	0.78
	Tt/T2	0.85
	Tt is 3rd period	
Maximum displacement ratio	X direction	1.15
	Y direction	1.23
Lateral stiffness ratio (stiffness of 1st floor above the ground is weak)	1 floor/2 floor	0.76
	1 floor / mean value of adjacent three upper floors	0.82
Ratio of bearing capacity between floors (3rd floor is weak)	3 floor /4 floors	0.92
Maximum elastic displacement angle between floors	X direction	1/875
	Y direction	1/756

6. Conclusions

Special-shaped column frame structure in has broad application prospects in multi-floor residential buildings, especially in non-aseismic areas and middle and low intensity areas. The special-shaped column frame structure provides a structural system for the structural design of multi-floor high residential buildings. Due to the special natures of special column section, the difference and complexity of forces and the uncertainty of earthquake action, special-shaped column frame structure design should be strictly controlled and structural design should take bearing capacity, stiffness, stability, ductility into consideration to carry out optimization design to make the structure safe, reliable and economical.

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