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Seismic reinforcement analysis and measurement research of reinforced concrete frame structure

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Abstract. In China, there are many reinforced concrete frame buildings that have reached the end of their design life, or have not been designed with seismic requirements in mind and need to be reinforced. In this paper, a reinforced concrete frame structure which needs to be reinforced is taken as an example. Two common reinforcement methods are used to reinforce the reinforced concrete frame structure by adding shear wall and increasing column section. BIM-GSSAP software is used to analyze maximum inter-storey drift angle and the member response under frequent earthquakes, and the whole structure of the weak layer under rare earthquakes is checked. The results show that both methods can significantly improve the seismic performance of buildings. At the same time, combined with the project example, the advantages and disadvantages of the construction process are analyzed, which can provide a useful case reference for this kind of reinforced concrete frame structure projects.

Keywords: reinforced concrete frame structure, shear wall, column section, earthquakes.

1. Introduction

According to researches, a large number of buildings built in the last century have reached their design life. The load-bearing capacity of some elements in the original buildings cannot meet the requirements of the existing codes due to long-term use and the changes in the bearing layer of the foundations. There are also structures that have not been designed for seismic resistance at the design stage [1]. As a result, many existing buildings need maintenance and strengthening design.

Reinforced concrete frame structures are one of the most significant structural forms in building construction, where beams, columns and walls are the main load-bearing elements of the structure [2]. Their seismic performance directly affects the seismic performance of the overall structure. Reinforcement methods such as strengthening or bracing have become mainstream reinforcement techniques to improve structure’s seismic performance [3]. The choice of different methods has crucial research implications for the extension of a building's service life [4].

In the essay, the seismic strengthening of a reinforced concrete frame residential building is taken as an example. Its seismic effects are analyzed under multiple and rare earthquakes by two strengthening methods, including the addition of shear walls and the enlargement of column sections [3].

2. Project background

2.1. Project overview

The apartment is a 15-storey partially prefabricated monolithic frame structure with a floor area of 460.17 (for level 1) and 429.81 square metres. The building plan is approximate rectangle, with a length of 40.4 m and a width of 11.1 m. Each floor height is 2.8 m.

The cross-sectional dimensions of the frame columns on each floor are 220*220 mm. The transverse distance of the frame column is 2.8 m, 4.4 m, 2.3 m, 1.5 m and 2 m, and the longitudinal distance is 1.1 m, 2.4 m, 1.3 m, 1.4 m and 2.5 m. The longitudinal and transverse frame beams are cast-in-place rectangular section beams, the transverse beam section is 200*400 m, 200*500 m and 200*600 m. Longitudinal beam section is 200*400 m, 200*500 m and 200*100 m. The specific place is shown in Figure 1. The foundations are reinforced concrete independent foundations. The strength of all concrete beams and columns is C30. The seismic fortification intensity of structure is 8 degrees.

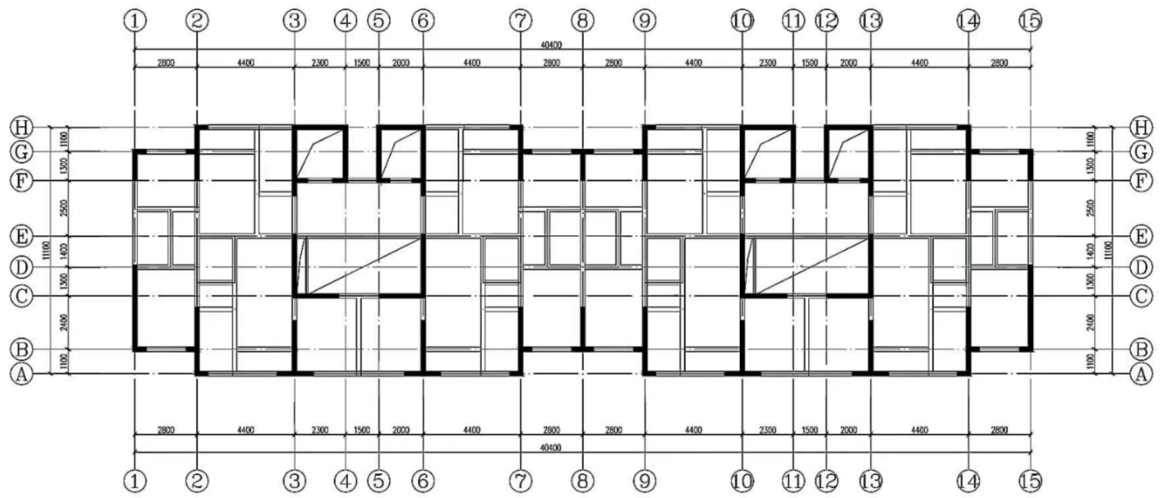

Figure 1. 2-15 layer beam structure plane dimensions 1:100.

2.2. Structural status assessment

The structure has been tested and found to be basically symmetrical in its arrangement of transverse and longitudinal structural construction, with a relatively even distribution of stiffness. The overall frame structure is complete. The infill wall arrangement is primarily uniform and symmetrical, and its stiffness is considered by increasing the seismic action through period reduction. The diameters and reinforcement rates of structural beams and columns meet the requirements of the code and have good current condition. Some of the floor slabs, internal walls, balcony slabs, laminated slabs and staircases are made of prefabricated components. At the same time, there is no obvious settlement of the foundation at the site.

2.3. Seismic information

The seismic intensity of the structure is 8 degrees. The design seismic grouping is Group two and the building site category II. The direction of seismic action is 0 degrees and 90 degrees. The characteristic period is 0.36 seconds. The structural damping ratio of seismic action is 0.05. The maximum horizontal seismic influence coefficient is 0.16. The period reduction factor is 0.90. The seismic rating of the frame and shear wall are both level 2.

2.4. Layout of reinforcement

According to analysis and calculation, some of the story-drift of the initial building under frequent earthquakes was greater than the limit of 1/550 for reinforced concrete frame structures [5]. It was also found that the bearing capacity of some existing beams and columns in the structure are unable to meet the standards. Therefore, it is indispensable to carry out an overall reinforcement to reduce the horizontal displacement of the structure under normal use and to ensure its stiffness and overall stability [2].

Based on the prevailing strengthening methods for reinforced concrete frame, this paper intends to choose shear walls and column cross-section expansion to compare, which aims to obtain the optimal solution for this project.

2.4.1. Shear wall addition. Shear walls are supposed to be provided at appropriate locations in the structure. The arrangement needs to satisfy the standards about the limitation of elastic displacement angle for the structure. Moreover, the reinforcement is coincident to the relevant strengthening areas. Longer shear walls require openings to divide the wall into uniform sections so that both the wall and the connecting beam have sufficient bending deformation capacity [4].

2.4.2. Column cross-section expansion. Similar to shear wall, the distensible columns need to be limited by elastic displacement up to standard. Under the conditions of the code, the cross-section of the columns on each floor was redesigned: the cross-section of the columns on the 1st floor was increased to 300*300 mm and the remaining floors was increased to 265*265 mm. The strength of the concrete used was C30 [5].

3. Seismic capacity assessment

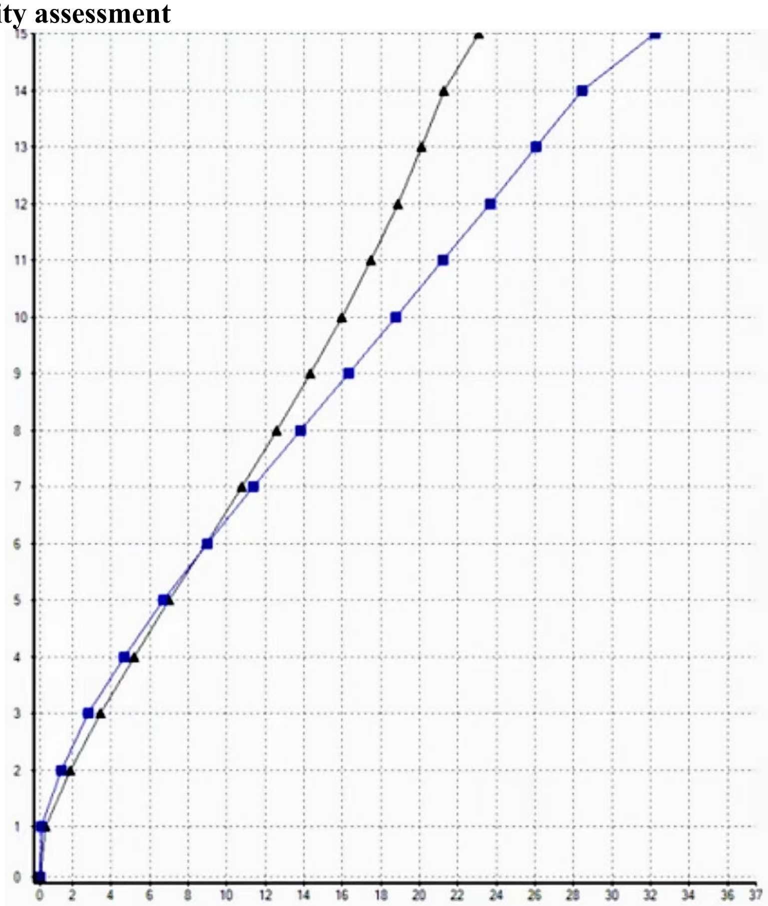

Figure 2. Inter-storey drift curve under horizontal earthquake action (Shear wall addition method).

3.1. Calculation of inter-storey drift angle

According to the seismic design code GB50011-2010 and technical specification for concrete structures of tall building JGJ3-2010 [5, 6], when the building height is not greater than 150 m, the maximum displacement between floors and the ratio of floor height is limited to 1/550 for frame structures and 1/800 for frame shear wall structures [5].

After analysis and calculation by BIM-GSSAP, the maximum inter-storey drift angle of the structure after the addition of shear walls is 1/1468 at 0 degrees in the seismic direction (floor number 6) and 1/1011 at 90 degrees (floor number 15). The maximum inter-storey drift angle of the structure after reinforcement with expanded column sections is 1/1274 at 0 degrees (floor number 1) in the seismic direction and 1/943 at 90 degrees (floor number 15). And show the inter-storey drift curve under horizontal earthquake action in Figure 2 and the value for shear wall additions in Table 1. Both methods meet the code requirements for (concrete) frame structures.

Table 1. Maximum inter-storey drift angle for shear wall addition method.

level	Maximum inter-storey drift for method of shear wall additions	
	0-degree	90-degree
1	0.64	0.4
2	1.88	1.4
3	3.44	2.85
4	5.19	4.66
5	7.04	6.73
6	8.92	8.99
7	10.79	11.37
8	12.61	13.82
9	14.35	16.31
10	15.99	18.79
11	17.51	21.26
12	18.9	23.69
13	20.15	26.09
14	21.28	28.44
15	23.1	32.23

3.2. Response analysis of structural elements in frequent earthquake

According to the design code, the structural elements of the original building, the additional shear wall and the increased column cross-section were analysed [5]. The results of the analysis are shown in Table 2. The new shear walls could take up most of the horizontal seismic forces, resulting in a significant reduction in the bending moment of the structure [7]. And by increasing the column cross-section, the column overturning moment is significantly reduced and the internal forces of the whole structure change due to changes in system stiffness and mass.

3.3. Checking of weak layer under rare earthquake action

According to the seismic design code for buildings [5], the elastic-plastic inter-storey drift angle of reinforced concrete frame is limited to 0.02, and that of reinforced concrete frame-shear wall structure is limited to 0.01. Due to the limitation of space in this paper, only the inter-storey drift angle table in the direction of 0-degree seismic action are given in Table 3. It could be seen that the maximum values of the inter-storey drift angles for both strengthening solutions under rare earthquakes meet the standards. Both the addition of shear walls and the enlargement of column sections actually improve the deformation resistance of the structure under rare earthquakes. In the case of this project, the deformation resistance of the building with the addition of shear walls is higher than that of the building with enlarged column sections.

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Table 2. Response of the structural elements in frequent earthquake.

Level	No.	Wall overturning moment (Shear wall addition)	Wall overturning moment (Initial building)	Column overturning moment (Cross-section increase)	Column overturning moment (Initial building)
1	1	122593.26	224286.52	14.8	28.3
2	1	109570.57	199841.14	14.06	23.12
3	1	96819.86	174639.72	12.59	18.93
4	1	84525.91	154832.82	10.95	19.88
5	1	73189.86	124872.72	9.3	16.5
6	1	62511.01	95261.02	7.72	14.23
7	1	52512.81	81264.62	6.23	13.85
8	1	43195.73	73155.46	4.87	9.66
9	1	34550.00	56146	3.65	6.45
10	1	26589.68	42654.55	2.59	5.28
11	1	19374.15	29744.17	1.69	3.34
12	1	13014.36	18553.2	0.98	2.1
13	1	7690.07	13549.25	0.45	1.85
14	1	3632.60	6165.6	0.13	0.86
15	1	1347.79	1953.02	0	0

Table 3. Comparison of elastic-plastic displacement angles of each layer under different methods.

Level	Addition of shear wall		Enlargement of cross-section		Initial building		Limits	
	Elastic inter-storey drift angle	Plasticity inter-storey drift angle	Elastic inter-storey drift angle	Plasticity inter-storey drift angle	Elastic inter-storey drift angle	Plasticity inter-storey drift angle	Elastic inter-storey drift angle	Plasticity inter-storey drift angle
1	0.00129	0.00174	0.00184	0.00236	0.00221	0.00379	0.01000	0.02000
2	0.00249	0.00338	0.00251	0.00417	0.00331	0.00806	0.01000	0.02000
3	0.00315	0.00435	0.00309	0.00505	0.00461	0.00885	0.01000	0.02000
4	0.00353	0.00483	0.00413	0.00562	0.00813	0.00775	0.01000	0.02000
5	0.00375	0.00592	0.00424	0.00649	0.00962	0.01136	0.01000	0.02000
6	0.00383	0.00599	0.00437	0.00676	0.01031	0.01351	0.01000	0.02000
7	0.00383	0.00588	0.00441	0.00690	0.01053	0.02174	0.01000	0.02000
8	0.00376	0.00680	0.00408	0.00769	0.00980	0.02326	0.01000	0.02000
9	0.00364	0.00654	0.00385	0.00781	0.00571	0.02222	0.01000	0.02000
10	0.00345	0.00621	0.00336	0.00806	0.00526	0.01266	0.01000	0.02000
11	0.00323	0.00581	0.00330	0.00758	0.00476	0.01163	0.01000	0.02000
12	0.00296	0.00535	0.00308	0.00625	0.00420	0.01075	0.01000	0.02000
13	0.00267	0.00481	0.00294	0.00559	0.00364	0.00952	0.01000	0.02000
14	0.00240	0.00433	0.00260	0.00490	0.00326	0.01020	0.01000	0.02000
15	0.00361	0.00649	0.00429	0.00980	0.00690	0.01351	0.01000	0.02000

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4. Method evaluation

The two methods of building strengthening mentioned earlier: the addition of shear walls and the increase in column cross-sections, have their strengths and weaknesses in different respects. The effectiveness of these two methods will be evaluated based on the case of this project.

With the addition of shear walls, the original structure turns into a frame-shear wall structure. The strength and stiffness of the original frame structure have changed [8]. It may be requisite to modify the size of the columns and beams to accommodate the new load transfer path. Shear walls could effectively absorb and disperse the horizontal forces caused by earthquakes, improving the seismic performance of the building and reducing the need for columns and beams in the frame structure [9]. Thus, it increases the space utilization. At the same time, shear walls can be constructed as integral prefabricated elements, allowing better control of construction quality. However, as shear walls usually need to be set in the core area of the building, the construction process of strengthening the building requires some demolition and modification of the structure, which may have some impacts on the serviceability of the building and the construction schedule [10]. Furthermore, once the shear wall is in place, structural adjustments and modifications may become difficult and limit the functionality of the building.

The construction process of the cross-section increase method is more mature and relatively simple compared to that of frame-shear walls, but it may still require some demolition and modification of the existing structure. This method demands on-site work such as reinforcement erection and concrete pouring, which generates more construction waste, while the increased section may reduce the building space [11]. Reinforcement measures such as fiber-reinforced composites may be considered when using this method.

5. Conclusion

Both strengthening methods (shear wall addition and cross-section increase) are capable of significantly increasing the lateral stiffness of the structure and reducing the inter-storey drift angle of the structure. For this project, the additional shear wall method is recommended. This method is observably more effective than the section increase method in both frequent and rare earthquakes, improving the overall seismic performance of the structure while ensuring that the building space occupancy is not reduced. It will provide a viable solution for the strengthening of such reinforced concrete frame structures.

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