Research on Seismic Performance Index of Existing Frame structure

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Abstract

The seismic design methods based on performance and seismic appraisal methods of existing buildings at home and abroad are summarized. The seismic performance of existing buildings is divided into six levels. According to the difference of the following service-life, the exceeding probability which is equal to 50 years are given. Based on the pseudo-static test of the frame column, the limits of the inter-layer displacement angles of the existing frame structures with different performance targets and following service-life are given. The methods of seismic appraisal and strengthening of existing buildings are given. The seismic appraisal and strengthening of slab-column seismic wall structure shows that the seismic response of the structure can be reduced effectively by increasing the energy dissipation device.

Keywords: existing buildings, seismic performance level, interlayer displacement angle, seismic appraisal and strengthening

1. Introduction

The occurrence of destructive earthquakes, often accompanied by various secondary disasters, and cause enormous casualties and property losses. Seismic damage investigation shows that RC frame structure damage modes include collapse, weak layer yield, beam and column damage, joint damage, no-structure failure and so on. Some kinds of damage modes are shown in Figure 1. According to the investigation and statistics, the damage degree of the existing RC frame building through earthquake action is related to the construction age. Therefore, it is particularly important to evaluate the seismic performance of existing structures. With the progress of society, structure design should not only ensure the safety of human being but also need to avoid the economic loss exceeding the bear ability of the owner and society. Therefore, performance-based seismic design arises at the historic moment. The author aims to study the limits of the inter-layer displacement angles of existing RC frame structures with different performance targets and following service-life based on quasi-static test of frame column. In the meanwhile, the author aims to study current seismic appraisal and strengthening methods of existing buildings by analyzing some typical cases. The research results should be helpful for engineering designers.

a. Collapse b. second layer yield c. damage of column top

Fig. 1– Typical failure modes of common frame structures

2.Performance-based seismic design

2.1 Performance-based seismic design theory

With the development of the seismic theory, seismic fortification goals have evolved from a single level of life safety to multi-levels, furthermore to dynamic goals based on performance requirements. [1]ATC-40[2], FEMA273[3], SEAOC[4], CECS160:2004[5], (GB50011-2010)[6], (JGJ3-2010)[7] have provided references for multiple performance targets in the evaluation and reinforcement of existing buildings. At present, the seismic design theories in various countries mostly adopt two-level or three-level design thought. It said that when it comes to small earthquake ,the building will not be affected, it can used by people normally; when medium earthquake happens, buildings allowed to be damaged in an extent which buildings can be repaired; what's more ,when facing an big earthquake, it forbidden buildings to collapse. The performance-based design theory is different from the current design method. It is a kind of design idea that pays more attention to the actual demands of owner under the premise of meeting the requirements of current specification. This theory is applicable to both new and existing buildings. There are three kinds of performance-based seismic design methods: bearing capacity-based design, displacement-based design and energy-based design. During these days, displacement-based design method is the main design method. For example, the direct displacement-based design method was proposed by Priestley and Cavil [8], and seismic code of Japan in 2000 and FEMA proposed pushover analysis method which also based on displacement method.

2.2 seismic appraisal method of the existing building

Seismic appraisal methods of existing buildings vary from country to country. Chinese code GB50023-2009[9] divides the RC frame structure seismic appraisal into two levels. The first level is to conduct a comprehensive evaluation mainly based on macro-control and seismic structural measures. The second level

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is mainly based on seismic calculation. Japanese code JBDPA2001[10] divides the RC frame structures' seismic appraisal into three levels. The first level is to determine the basic seismic bearing capacity index of the floor without considering the ductility calculation of the structure. The second level is to use the layer model to calculate the shear bearing capacity and plastic deformation capacity of each vertical member. The third level is that the appraisal result is determined by strength index C and ductility index F according to the failure mode of the structure. American code ASEC31-03[11] divides the RC frame structures' seismic appraisal into three levels. The first level(Screening Phase) is to quickly check the strength of the component according to the requirements after the performance goal is selected. The second level(Evaluation Phase) is to adopt the linear static or dynamic method to control the maximum deformation of the structural member, prevent the maximum deformation of the component from exceeding its ductility ability, and avoid the force control member yielding before deformation control member. The third level is to check the seismic performance of components and overall structure by means of nonlinear static or dynamic methods. It can be seen that the Chinese code GB50023-2009 [9] pays more attention to the macro control of structural system for the seismic appraisal of RC frame buildings, which is different from the other countries.

2.3 seismic performance levels of the existing building

The division of performance levels varies from country to country. Chinese code JGJ3-2010[7] divides the seismic performance of structures into five levels, while American code ASCE41-13[15] divides the seismic performance of structures into four levels, namely, normal operation, immediate occupancy, life safety and collapse prevention. According to the codes of two countries, the seismic performance of existing buildings can be divided into 6 levels. Level 1, basically intact – The stressed members and the main non-structural members are not damaged, some non-structural members are occasionally and slightly damaged. The structure is basically at elastic state. Level 2, slightly damaged – The structural members are good, some non-structural members have repairable damage, but it has no obvious influence on the bearing capacity and normal operation. Level 3, moderate damage – moderate damage to structure, 10% ~ 30% of the structural members can be used after repair or reinforcement. Level 4, larger damage – If the structure is damaged in a big extent, 30% ~ 50% of the structural members need to be repaired or reinforced before reusing. Level 5, severe damage – The bearing capacity of the main part of the structure is insufficient, and the repair is not feasible technically or economically. Although the deformation is large, it is not collapsed. Level 6, collapse – Partial or total collapse of structure.

According to GB50023-2009 [9], the existing buildings are divided into three categories: A, B and C, with corresponding subsequent service life of 30, 40 and 50 years respectively. Performance goals of structures with different subsequent service life and seismic fortification categories are shown in Table 1. According to GB50023-2009 [9], the subsequent service life of buildings built in 1990s should not less than 40 years. Therefore, the performance goals of existing buildings with subsequent service life of 40 and 50 years can keep consistent. In Table 1, the subsequent service life of targets in brackets is 30 years. Referring to the methods of appraisal and reinforcement at home and abroad, as well as the performance goals of existing buildings, the process of appraisal and reinforcement of existing frame structures can be carried out according to Figure 2.

2.4 Ground motion levels of different following service life

Referring to the codes and standards of different countries, the ground motion levels of existing buildings can be adopted in accordance with GB50011-2010 [6]. The ground motion levels are divided into multiple earthquakes (small earthquakes) -- 63.2% exceeding probability within 50 years, fortification intensity earthquakes (moderate earthquakes) -- 10% exceeding probability within 50 years, and estimated rare earthquakes (major earthquakes) -- 2%~3% exceeding probability within 50 years. According to the difference of the subsequent service life of existing buildings, the exceeding probability and peak acceleration corresponding to 50 years can be converted according to formula (1) and (2), as shown in Table

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2. For example, 63.2% exceeding probability of subsequent service life 30 years is equivalent to 81.10% exceeding probability in 50 years. [14]

Table 1–Performance targets of different fortification structures

Seismic fortification / Earthquake levels / Performance levels	Special fortifications	Key fortifications	Standard fortifications	Appropriate fortifications
Multiple earthquakes	1	1（1）	1（1）	2（2）
Fortification intensity earthquakes	1	2（2）	3（4）	4（5）
Estimated rare earthquakes	2	3（4）	5（5）	5（6）

$$S = 1 - \left(1 - S'\right)^{50/t} \tag{1}$$

$$\lg\left\{-\ln\left[1 - S\left(I \geq i\right)\right]\right\} + 0.9773 = k\lg\left(\frac{1.5 - lg\,A_{max}}{1.5 - lg\,A_{max}^{10}}\right) \tag{2}$$

Where t is subsequent service life, S' is the exceeding probability which is equal to 63.2%(small earthquakes), 10%(moderate earthquakes), 2%~3%(major earthquakes), respectively, with the subsequent service life t. S is the exceeding probability with subsequent service life 50 years. Amax10 is the peak acceleration of moderate earthquakes.

Table 2–Peak acceleration A_{max}(gal)/ adjustment coefficient of each ground motion level with different subsequent service life (t)

Subsequent service life	Ground motion level	Exceeding probability	Seismic fortification intensity			
			6	7 (0.15g)	8 (0.3g)	9
30	small earthquake	81.1%	13	26（38）	51（76）	101
	moderate earthquake	16.1%	40	80（121）	16（244）	326
	major earthquake	3.3%～4.9%	93	181（258）	33（428）	519
40	small earthquake	71.3%	15	30（45）	60（90）	120
	moderate earthquake	12.3%	45	91（137）	18（275）	367
	major earthquake	2.5%～3.7%	103	200（284）	36（469）	570
50	small earthquake	63.2%	18	35（55）	70（110）	140
	moderate earthquake	10%	50	100（150）	20（300）	400
	major earthquake	2%～3%	125	220（310）	40（510）	620

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3. Ground motion levels of different following service life

In accordance with GB50011-2010 [6], corresponding to the above levels 1 ~ 6, the of interlayer displacement angle limits of newly built reinforced concrete frame structures can be set as 1/550, 1/550 ~ 1/450, 1/450 ~ 1/300, 1/300 ~ 1/150, 1/150 ~ 1/50 and >1/50, respectively. However, there are great differences in seismic measures of existing RC frame structures, the limits of interlayer displacement angles based on performance of existing RC frame structures needs to be studied in depth. Therefore, quasi-static test of the 15 scale frame columns with stirrups at different intervals were carried out, and the interlayer displacement angle limits of existing building frame structures were obtained. [12] The different stirrup spacing corresponds to subsequent service life of existing structures in china. Parameters and failure modes of the frame columns are shown in Table 3 and Figure 3.

Table 3 –Specimen parameters and failure forms

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
A0	A01	267×267	1700	4Φ12	φ6@200	0.4	F1	1/325	1/98	1/39	8.6
	A02					0.6	F1	1/274	1/115	1/55	5
	A03					0.8	F2	1/347	1/156	1/100	3.5
	A04			4Φ14		0.6	F2	1/232	1/125	1/83	2.9
	A05					0.8	F2	1/340	1/158	1/115	3
A	A1	267×267	1700	4Φ12	φ6@133/200	0.4	F1	1/346	1/91	1/36	9.6
	A2					0.6	F1	1/348	1/101	1/49	7.1
	A3					0.8	F2	1/301	1/126	1/79	3.8
	A4			4Φ14		0.6	F1	1/307	1/133	1/55	5.6
	A5					0.8	F2	1/317	1/183	1/88	3.7
B	B1	267×267	1700	4Φ12	φ6@66/133	0.4	F3	1/401	1/104	1/37	10.8
	B2					0.6	F3	1/297	1/121	1/41	7.2
	B3					0.8	F3	1/371	1/144	1/61	6.2
	B4			4Φ14		0.6	F3	1/326	1/111	1/51	6.4
	B5					0.8	F3	1/275	1/109	1/60	4.6

Annotations: Q1 –Specimen category, Q2 –Specimen Number, Q3 –Section size, Q4 –Clear height, Q5 –Longitudinal reinforcement, Q6 –Stirrup, Q7 –Axial compression ratio, Q8 –Failure forms, Q9 – $\overline{\theta}_y$, Q10 – $\overline{\theta}_{Fu}$,Q11 – $\overline{\theta}_u$, Q12 –Ductility coefficient μ, $\overline{\theta}_y$ –yield displacement angles, $\overline{\theta}_{Fu}$ –peak displacement angles, $\overline{\theta}_{Fu}$ –ultimate displacement angle. F1 –Bending failure, F2 –bending shear tensile failure, F3 –bending shear compression failure

According to GB50011-2010[6], the reference value of interlayer displacement angle deformation of level 1 is (<$[\Delta Ue]$), level 2 is (1.5-2$[\Delta Ue]$), level 3 is (3-4$[\Delta Ue]$), level 5 is (<0.9$[\Delta Up]$), level 6 is (> $[\Delta Up]$). $[\Delta Ue]$ is the interlayer displacement angle limits in elastic, and $[\Delta Up]$ is the interlayer displacement limits in elastic-plastic. According to the reference value of interlayer displacement angle

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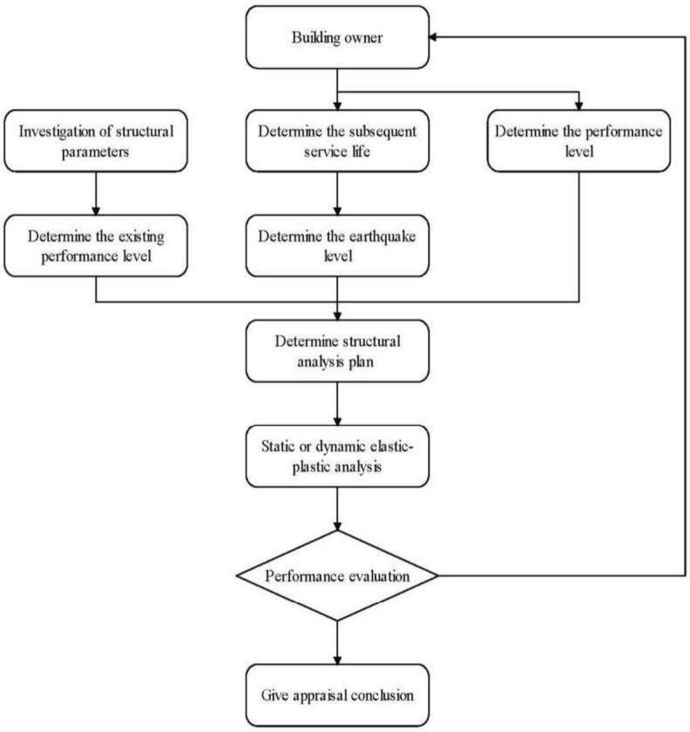
deformation and test results, the interlayer displacement angles of frame columns with different stirrup spacing and axial compression ratio are classified, as shown in Table 4 below. Thereupon, the category A and B frame buildings conforming to GB50023-2009[9] can be classified. The interlayer displacement angle limits of existing RC frame buildings to achieve different performance goals are shown in Table 5 and Table 6.



a.bending failure

a.bending failure

Fig.2 – The performance-based seismic appraisal process

Fig.3–The forms of failure

Table 4– Performance index of inter-story displacement angle with different stirrup spacing under different axial compression ratio

SS	U	P-Level 1	P-Level 2	P-Level 3	P-Level 4	P-Level 5	P-Level 6
300mm	0.4	1/550	1/400	1/100	1/60	1/40	>1/35
	0.6			1/130	1/100	1/85	>1/80
	0.8			1/180	1/140	1/120	>1/110
200mm	0.4	1/550	1/400	1/100	1/60	1/40	>1/35
	0.6			1/130	1/80	1/60	>1/50
	0.8			1/180	1/120	1/90	>1/85
100mm	0.4	1/550	1/400	1/100	1/60	1/40	>1/35
	0.6			1/130	1/70	1/55	>1/45
	0.8			1/180	1/100	1/70	>1/55

Notations: U –Axial compression ratio, SS –Stirrup spacing, P-Level –Performance levels

Table 5– Displacement angles of existing RC frame buildings to achieve different performance goals （Class B）

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Axial compression ratio	Ground motion level	Seismic fortifications			
		Special fortifications	Key fortifications	Standard fortifications	Appropriate fortifications
0.8	small earthquake	1/550	1/550	1/550	1/400
	moderate earthquake	1/550	1/400	1/180	1/100
	major earthquake	1/400	1/180	1/70	1/70
0.6	small earthquake	1/550	1/550	1/550	1/400
	moderate earthquake	1/550	1/400	1/130	1/70
	major earthquake	1/400	1/130	1/55	1/55
0.4	small earthquake	1/550	1/550	1/550	1/400
	moderate earthquake	1/550	1/400	1/100	1/60
	major earthquake	1/400	1/100	1/40	1/40

Table 6– Displacement angles of existing RC frame buildings to achieve different performance goals （Class A）

Axial compression ratio	Ground motion level	Seismic fortifications	
		Standard fortifications	Appropriate fortifications
0.8	small earthquake	1/550	1/400
	moderate earthquake	1/120	1/90
	major earthquake	1/90	>1/85
0.6	small earthquake	1/550	1/400
	moderate earthquake	1/80	1/60
	major earthquake	1/60	>1/50
0.4	small earthquake	1/550	1/400
	moderate earthquake	1/60	1/40
	major earthquake	1/40	>1/35

4. Frame quasi-static test

The Five floor-two span RC frame structure is designed.First of all, the transverse and longitudinal column spacing is 6 m and 3.6 m respectively.While the section size of frame column is 400 × 400 as well4.Secondly, the section size both transverse and longitudinal frame beam is 250 × 500 and 250 × 450 respectively.Thirdly,the layer height is 3.0 m, fortification intensity is 8 degrees. According to the earthquake action of subsequent service life 30 years (category A) and 40 years (category B), the reinforcement design was carried out, respectively. One of the horizontal frame of bottom three layers were designed to models of 1:1.5. Model A and B is the reinforcement drawing of category A and B structure respectively, as shown in Figure 4. The test device is shown in Figure 5. Frame quasi-static test was carried on model A and B. Loading position is in the middle of the third layer beam cross-section. The loading mode is displacement control. Column axial compression ratio is equal to 0.65.

When the top displacement reach 99mm, the upper end pressure zone concrete of the third layer middle column of model A was crushed, while longitudinal reinforcement yield. However, it is just protective layer shedding at the same place of model B. When the top displacement reaches 176mm, the longitudinal reinforcement at the bottom of the beam end at the edge joints of the first and second floors buckles, and the concrete protective layer peels off in model A and B. The maximum displacement at the top is 176mm. Figure 6 shows the max interlayer displacement angle of model A and B at each floor. The model B maximum interlayer displacement angles are less than model A at second and third floor, which means the displacement capacity of model B better than model A.

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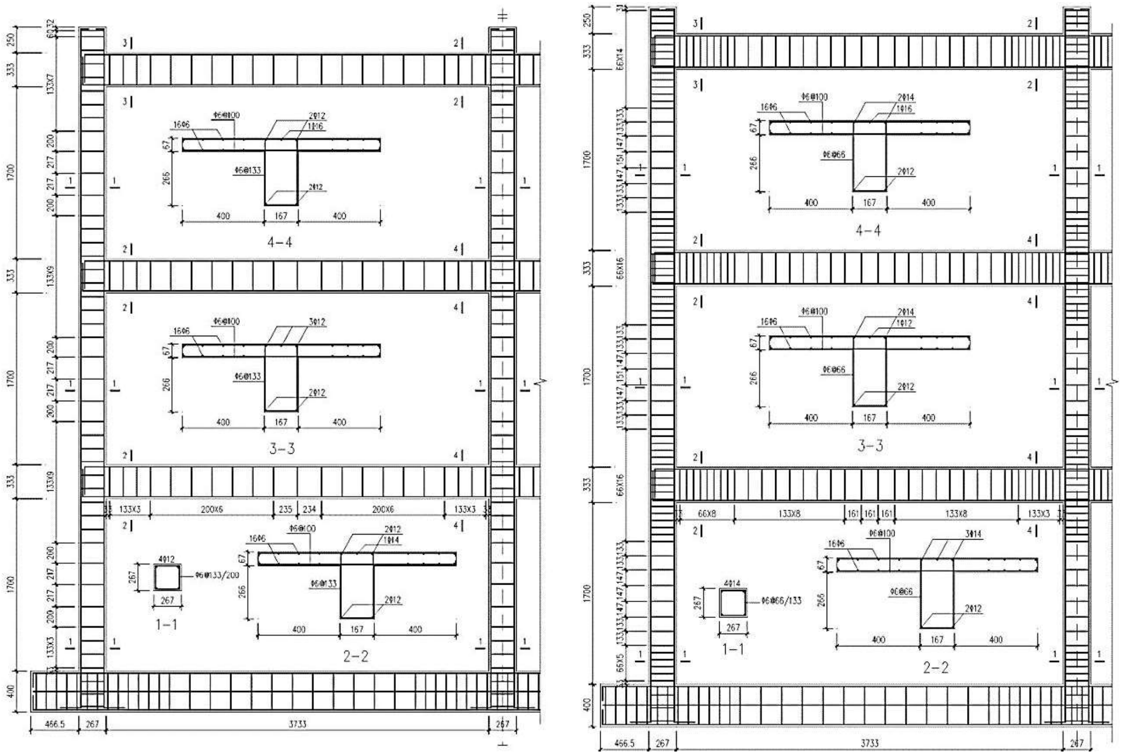
Table 5 shows that the displacement angle limit is 1/40 to keep structure from collapsing, while the max displacement angles of model A is 1/23. It means that if the axial compression ratio is not more than 0.6, the category A structure would not collapse, when a major earthquake happens.



Model A Model B

Fig.4–The reinforcement drawing of category A and B structure

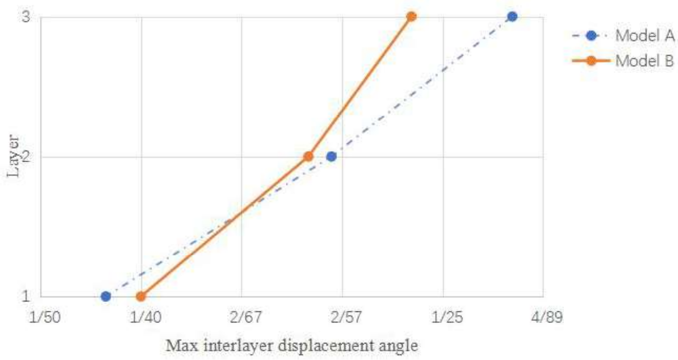


Fig.5–Test device Fig.6 – Max interlayer displacement angle of model A and B

5. Appraisal and reinforcement of the lab-column shear wall structure

5.1 Project summary

The teaching building was built in 1991 with one floor underground, nine floors above ground and eleven floors locally. The building height is 34m while the total building area is 7848m^2. The structural system is reinforced concrete slab-column seismic wall structure, the foundation form is box foundation. The middle part of the ground floor from the first floor to the eighth floor is beam-slab floor, and the rest of the floor is beam-slab floor. The three-dimensional integral model of the structure is shown in Figure 7.

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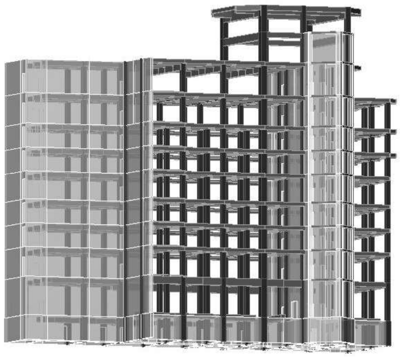

Fig.7– Structure model

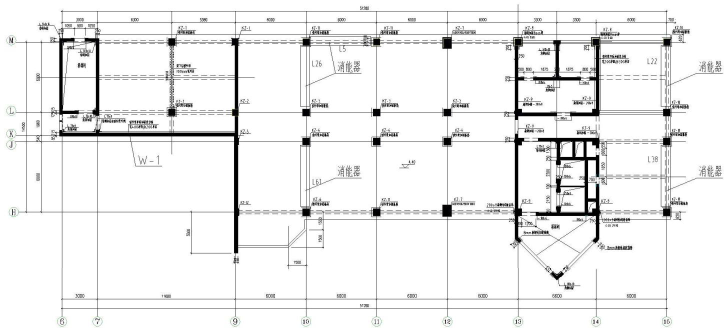

Fig.8– The plane reinforcement plan of the first floor

5.2 Seismic appraisal

According to the field test and calculation review, the main problems of the original structure are as follows:

1) The layout and the lateral stiffness of seismic wall is uneven.

2) When an small earthquake happens, many frame beam longitudinal and stirrup bars of the original structure fail to meet the requirements of seismic bearing capacity. The longitudinal reinforcement of the frame beam is insufficient, and the diameter and spacing of the stirrups do not meet the requirement that the diameter of the stirrups should be no less than 10mm and the spacing should be no more than 100mm within the stirrups encryption area of the beam end stipulated by GB50023-2009[9].

3) The volume stirrup ratio in the dense area of frame column and the diameter and spacing of stirrup does not meet the requirements of GB50023-2009[9].

4) There are no edge members at ends of the seismic wall and at sides of the hole. The shear bearing capacity of seismic walls is insufficient. The reinforced structure needs to meet the relevant requirements of GB50023-2009 on Class B buildings.

5.3 Performance goals

The teaching building was built in 1991. According to GB50223-2008[13], seismic reinforcement should be carried out according to key fortified buildings, with the following service life should be considered as 40 years.

5.4 Strengthening plan

According to the reinforcement process shown in Figure 2, the reinforcement plan is as follows. The plane reinforcement plan of the first floor is shown in Figure 8.

1)The structure was unloaded, and the clay brick retaining wall and partition walls in the original building were removed and replaced with light weight walls, so as to reduce the earthquake action.

2)The structure is changed into an energy dissipation - seismic structure by adding an energy dissipation device.

3)For the frame beams with insufficient flexural capacity, the top of the beam and the bottom of the beam are bonded with steel plate and carbon fiber cloth for reinforcement, respectively.

4)The method of sticking carbon fiber cloth was used to reinforce the frame columns in case of insufficient stirrup in the dense area.

5.5 Seismic performance analysis before and after reinforcement

5.5.1 The lateral deformation

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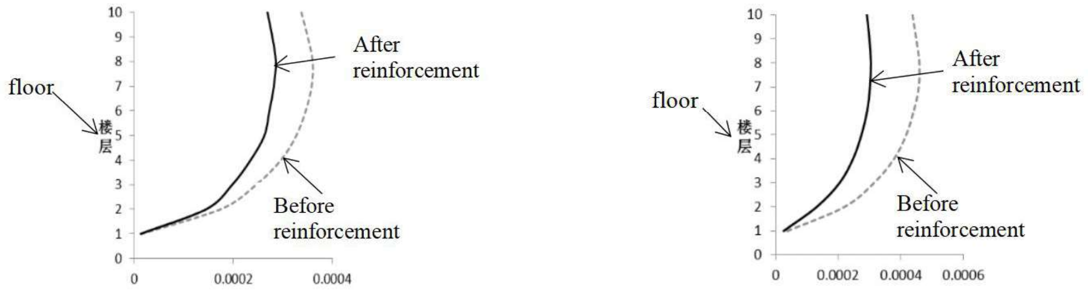
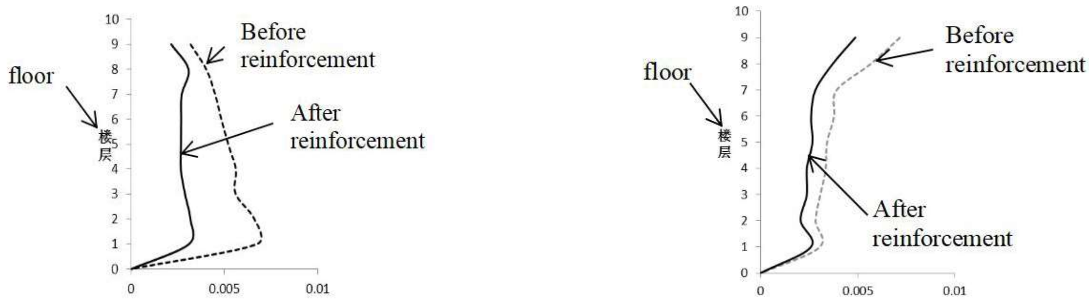
The comparison of inter-story displacement angles before and after reinforcement in small earthquake is shown in Figure 9. As can be seen from Figure 9, the interlayer displacement angle curve is gentle and no abrupt transitions occur, indicating that the vertical layout of the damper is reasonable and there is no obvious weak layer effect. After reinforcement, the x-directional displacement Angle decreases from 1/1886 to 1/2380 with a decrease of 20%, and the Y-directional displacement Angle decreases from 1/2075 to 1/3448 with a decrease of 33%. It shows that the addition of damper can effectively reduce the seismic action on the main structure while improve the overall seismic performance of the structure as well.



(a) The inter-story displacement angles of X-direction (b) The inter-story displacement angles of Y-direction

Fig.9– The inter-story displacement angles before and after reinforcement (small earthquake)



(a) The inter-story displacement angles of X-direction (b) The inter-story displacement angles of Y-direction

Fig.10– The inter-story displacement angles before and after reinforcement (rare earthquake)

The comparison of interlayer displacement angles before and after reinforcement in rare(big) earthquake is shown in Figure 10. As can be seen from Figure 10, the maximum x-direction displacement angle both occurred at the first floor, and the specific value decreased from 1/149 to 1/322, with a decrease of 53% after reinforcement. When the structure enters the elastic-plastic stage, the first layer of X-direction becomes a weak layer, at the same time, concentration of plastic deformation is more obvious. The maximum y-direction interlayer displacement angle both occurred at the top floor of the original and reinforced structure. However, after reinforcement the specific value decreased from 1/139 to 1/314, with a decrease of 41%. The reason why the specific value decrease so fast is that in order to meet the need of large space on the top, two rows of frame columns were removed from the top two floors, resulting in the formation of a weak floor on the top floor. The effect of the weak floor was significantly alleviated after the addition of energy dissipation devices.

In general, after the reinforcement, the stress concentration of the floors is greatly alleviated, the vertical inter-story displacement angle curve becomes relatively gentle without sudden change. It shows that the vertical layout of damper is reasonable and the effect of weak layer is greatly reduced.

5.5.2 Seismic analysis of key components

For the seismic wall W-1, the bearing capacity with the action of small earthquakes, moderate earthquakes and major(rare) earthquakes are calculated respectively, and the calculation results are shown in Table 7~ 8.

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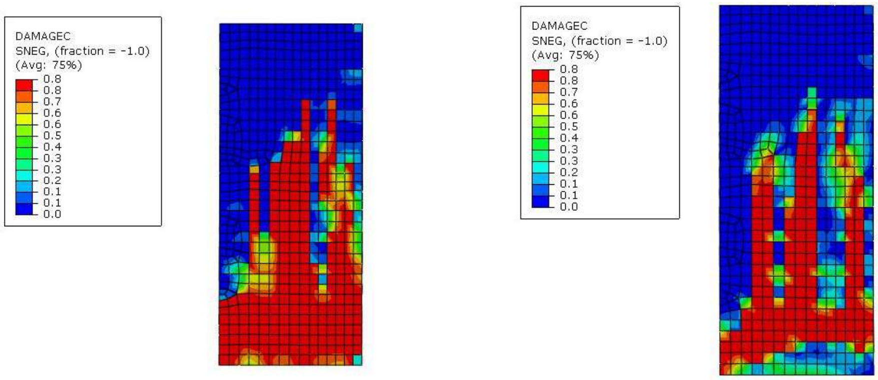
It can be seen from Table 7 that under the action of small earthquakes, the wall limb of W-1 is a tensile bending member, which is prone to brittle failure. Under moderate earthquake, the amount of reinforcement of the w-1's concealed column increased significantly. It can be seen from Table 8 that the wall cannot meet the requirements of shear section checking under major earthquakes. However, the wall can meet the requirements by setting a reasonable number of energy dissipation devices and increasing the shear bearing capacity of the wall. As shown in Figure 11, after the reinforcement, the damage parts of the seismic wall are reduced and more evenly distributed, and the damage degree is also reduced to some extent. The failure mechanism and location are reasonable, which avoids the problem of centralized failure of vertical key components, indicating that the technical measures adopted have achieved the purpose of reinforcement

Table 7- Calculation of W-1 section in small and moderate earthquakes (compression is negative)

	wall limb	Internal force of X-direction (KN)			internal force combination (KN)			Reinforcement checking	
		N	M	V	N	M	V	As	Ash
Small earthquake	W-1	5415	44665	4354	587	64419	6060	6473	316
Moderate earthquake	W-1	15231	25620	12246	13797	171192	16296	47827	737

Table 8- Calculation of W-1 section in major earthquakes (compression is negative)

Direction	Wall limb	Shear (KN)	0.15*fc*B*Ho
x	W-1	23636	12707



(a)before reinforcement (b)after reinforcement

Fig.11– Damage cloud of before and after reinforcement

Through the analysis of this case, it can be seen that it is reasonable to follow the identification reinforcement process as shown in Figure 2. The vertical unevenness of the lateral force system can be effectively improved by adding energy dissipation devices. Meanwhile, the use of energy dissipation devices can avoid the occurrence of the weak layer effect, and reduce the degree of floor damage under the earthquake.

6. Conclusion

(1) The seismic design methods based on performance and seismic appraisal methods of existing buildings at home and abroad are summarized.

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(2) According to the difference of the following service-life, the seismic index of existing building RC frame structure which is equal to 50 years are given.

(3) Based on the pseudo-static test of the frame column, the limits of the inter-layer displacement angles of the existing frame structures with different performance targets and following service-life are given.

(4) Through the seismic appraisal and reinforcement of a reinforced concrete slab - column - seismic wall structure building, the rationality of the seismic appraisal and reinforcement process based on the performance of existing buildings are verified. The seismic performance of existing buildings can be effectively increased by adding energy dissipation devices.

7. Acknowledgements

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