A Comparative Study on Seismic Behavior of Existing Single-span RC Frames Strengthened by Different Methods

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SUMMARY:
In this paper, four kinds of strengthening methods were used respectively to improve seismic performance of the typical single-span RC frame with cantilever walkway designed according to the previous China codes. The 3-dimensional structural models were established and the performance of the structures strengthened by different methods was compared subjected to seismic excitations. The analysis results show that although adding a row of columns can change the single-span frame into a two-span frame, it's not a reasonable method because of low efficiency and cost-effectiveness. The parameters of method using steel brace should be modified so that the seismic performance of structure can meet the requirement of code. The other two methods can greatly improve the seismic performance of the single-span frame, especially method of adding walls. In a word, the strengthening method for the typical single-span RC frame should be selected by the condition and performance objectives of building.

Keywords: single-span frame, seismic evaluation, Dynamic analysis, strengthening method

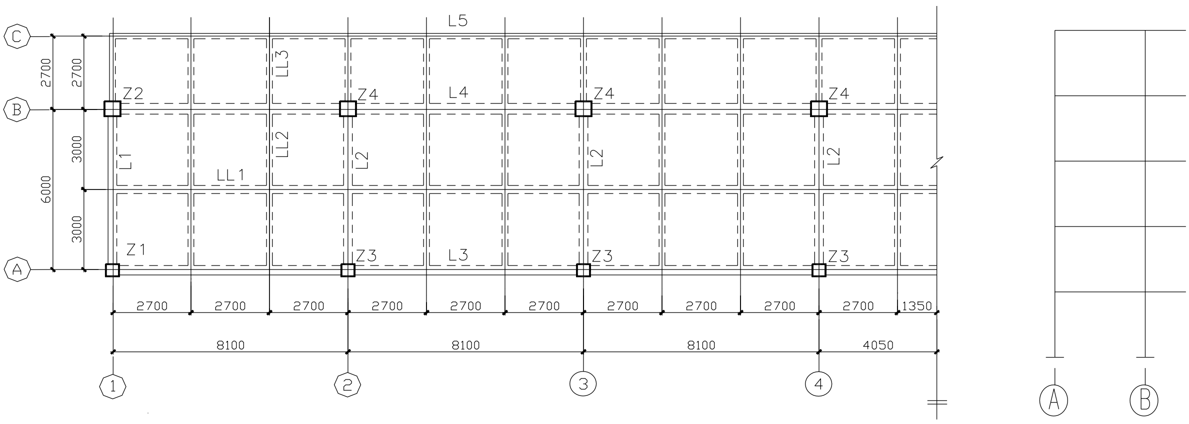
1. INTRODUCTION

Some buildings of primary and high schools had been damaged severely or even collapsed under Wenchuan earthquake on May 12 2008, and also caused death, injury and economic loss. In order to avoid similar disaster, the seismic fortification category for this type of buildings has been promoted from category C into category B by China 'Standard for Fortification Classification of Buildings GB50223-2008'. Thus it means that these buildings are not satisfied with the current code even if they are designed based on the previous code. And it was been added in 'Standard for Seismic Appraisal of Buildings GB50423-2009 that the single-span RC moment frame is forbidden for primary and high school buildings. In fact, there are many these frames still used by schools, especially in the southern of China. So it is very necessary and important to deal with these buildings which are not satisfied with the new codes, and the aim of this study is to find a reasonable, economic and efficient method to improve performance of this type of structure so as to avoid the disaster under future earthquakes.

In this paper, four kinds of strengthening methods were used respectively to improve seismic performance of the typical single-span RC frame school buildings with cantilever walkway designed according to the China Seismic Design Code. The 3-dimensional finite element structural models were established and studied using the dynamic analysis under rare earthquakes. The seismic performances of the single-span RC frame strengthened by different methods were compared.

2. GENERAL INFORMATION OF EXAMPLE AND PROPOSAL OF STRENGTHENING

In the paper, an existing RC moment frame of primary school was studied, 5 floors and single span with cantilever walkway shown as Figure 1. Its site-class is class II and design earthquake group is 1st group. And it is located in zone where fortification intensity is 8 and design basic acceleration of ground motion is 0.2g. The building, which is called STR in the paper, was originally designed according to 'China Code for Seismic Design GBJ11-89'. And its seismic fortification category was category C, seismic measure grade was 2nd. The left half of structure is shown in Figure 1a and its right one is symmetrical. Figure 1b is elevation drawing of frame in one axis and height of each floor is 3.9m. the section of column is 550x550mm.



(a) layout drawing (b) elevation drawing

Figure 1. Layout and elevation drawing of structure STR

According to current codes, the seismic fortification category of the structure STR should be improved from category C into category B as well as its seismic measure grade from 2nd into 1st grade, which means that the seismic fortification measures of each element of structure STR may not be satisfied any more with requirements of current codes. And it might be inacceptable for school to take much money and time to strength many components so as to comply with codes. Meanwhile a RC moment frame with single-span and category B should not be permitted. In order to solve these problems, four kinds of strengthening methods are used respectively, (1) a row of columns, their sizes are 400x400mm, are added in Axis C so as to change single-span moment frame into double-span one. This structure is name STR-C in the paper. (2) RC shear walls are added in Axis 1, 3, 6 and 8 along the height of structure. The length of section of wall is 1.5, 3.0, 4.5 and 6.0m respectively from Axis A. They are called STR-W1, STR-W2, STR-W3 and STR-W4 respectively shown hatched area in Figure 2. (3) Steel braces are set in Axis 1, 3, 6 and 8 shown in Figure 3. The structure is called STR-B. (4) Dampers are set in Axis 1, 3, 6 and 8 shown in Figure 4. The structure is called STR-D.

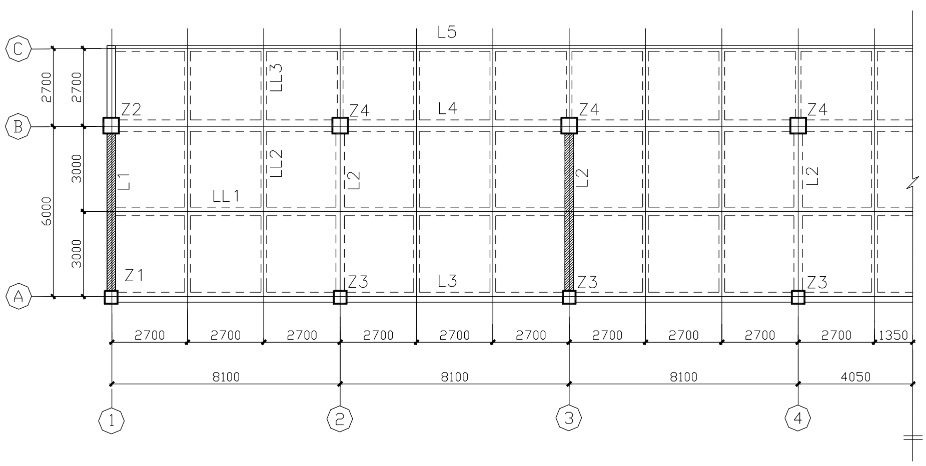


Figure 2. Plane of structure STR-W

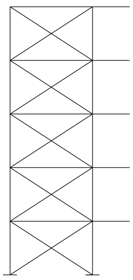


Figure 3. Elevation drawing of STR-B

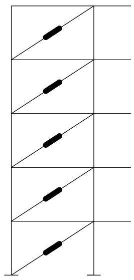


Figure 4. Elevation drawing of STR-D

3. ANALYTICAL MODEL AND CORRESPONDING PARAMETERS

The nonlinear analytical models were established using beam-column fiber element provided by OpenSees to simulate the structural behavior subjected to seismic excitations. Monegotto-Pinto model which account for strain hardening was selected to represent stress-strain relationship of steel and reinforcement fiber. The modified Kent-Part model was chosen to illustrate the relationship of stress-strain of concrete fibers in which relative slide between steel bars and concrete was not taken into account but the confinement of concrete by hoop reinforcement was considered. The RC shear wall was simulated using beam-column fiber element considering nonlinear shear effect. The truss element was selected to represent the steel brace. The strength of all material was taken as the average value.

The selected earthquake records are shown in Table 1. The actual earthquake waves were chosen using two-frequency bond-control method and an artificial earthquake wave, ACC, is obtained using ARMA method. The amplitude of earthquake waves are adjusted according to the code.

Table 1. Information of actual earthquake waves

No. of earthquake wave	PGA (m/s^2)	Time of duration (s)
USA00575	0.097	61.68
USA00676	0.196	47.06
USA001609	0.415	10.99
ACC	2.20	40.00

4. NONLINEAR RESPONSE OF STRUCTURES UNDER EARTHQUAKES

Because our research work was mainly focused on how to improve seismic performance of single-span frame, earthquake was also subjected only in direction parallel to Axis 1 during dynamic analysis. Thus the structural response was related to the direction, too.

4.1. Seismic Behavior of Structure STR

Responses of Structure STR under frequent, fortification and rare earthquake are shown in Table 2, including maximum story drift and top displacement. And maximum story drift under rare earthquake is 0.0084(1/120) occurred at the 2nd floor and maximum top displacement is up to 0.1295m.

Table 2. Maximum story drift and top displacement of Structure STR

No. of earthquake wave		ACC	USA00575	USA00676	USA01609
Frequent earthquake	Maximum story drift	0.0012	0.0012	0.0015	0.0011
	Maximum top Disp.(m)	0.0189	0.0227	0.0256	0.0184
Fortification earthquake	Maximum story drift	0.0020	0.0026	0.0027	0.0022
	Maximum top Disp.(m)	0.0433	0.0556	0.0578	0.0525
Rare earthquake	Maximum story drift	0.0081	0.0084	0.0075	0.0062
	Maximum top Disp.(m)	0.1095	0.1295	0.0959	0.0964

Figure 5 indicates distribution of plastic hinges of STR under rare earthquake, USA00575. It could be found that plastic hinges appeared at both end of columns at 1st floor of structure even thought its story drift is not exceed the limit value of story drift required by code. This means the structure would probably collapse under rare earthquake, thus structure STR should be strengthened so as to improve its seismic performance.

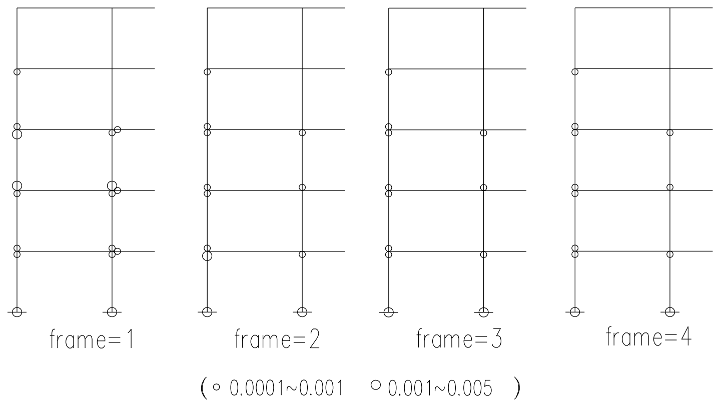


Figure 5. The distribution of plastic hinges of STR under rare earthquake
(Note: frame=1 means the frame located in the Axis 1, others are similar)

4.2. Seismic Behavior of Structures STR-C

Responses of Structure STR-C under frequent, fortification and rare earthquake are shown in Table 3. And maximum story drift under rare earthquake is 0.0084(1/120) occurred at the second floor of structure and maximum top displacement is up to 0.111m.

Table 3. Maximum story drift and top displacement of Structure STR-C

No. of earthquake wave		ACC	USA00575	USA00676	USA01609
Frequent earthquake	Maximum story drift	0.0006	0.0007	0.0007	0.0005
	Maximum top Disp.(m)	0.0100	0.0119	0.0102	0.0077
Fortification earthquake	Maximum story drift	0.0015	0.0019	0.0013	0.0009
	Maximum top Disp. (m)	0.0375	0.0453	0.0299	0.0206
Rare earthquake	Maximum story drift	0.0051	0.0084	0.0074	0.0060
	Maximum top Disp. (m)	0.0790	0.1110	0.1029	0.0880

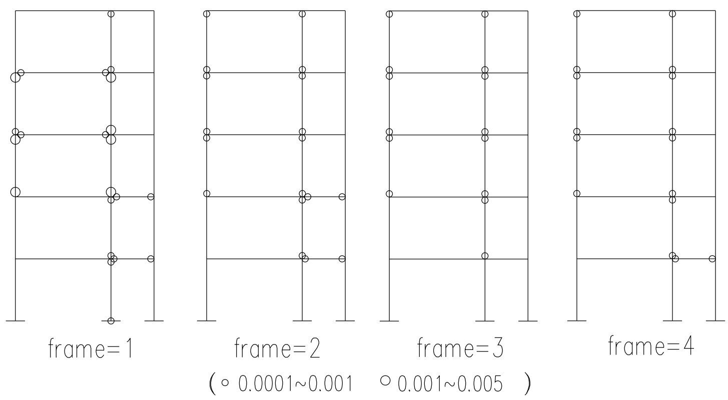


Figure 6. The distribution of plastic hinges of STR-C under rare earthquake

Figure 6 indicates distribution of plastic hinges of STR-C under rare earthquake, USA00676. It could be found that there are more plastic hinges appeared at end of columns or beams than STR except at foot of columns. And maximum story drift and top displacement didn't decrease significantly compare with structure STR. Moreover, the mechanical behavior of structure STR-C is significantly different from STR because the cantilever beam became a continuous beam. And the longitudinal reinforcement at bottom of beams might not be enough. Consequently, each beams of STR-C at walkway should be strengthened. Therefore adding a row of columns is not a perfect method for structure STR to improve its seismic performance.

4.3. Seismic Behavior of Structures STR-W*

Maximum story drift under frequent, fortification and rare earthquake is shown in Table 4, Figure 7 and Figure 8. It could be found that the more the RC shear walls used, the little maximum story drift was. And the maximum drift occurred at the top floor of structures.

Table 4. Maximum story drift of STR-W*

Earthquake level	Earthquake wave	STR-W1	STR-W2	STR-W3	STR-W4
Frequent earthquake	ACC	0.00031	0.00031	0.00028	0.00024
	USA00575	0.00029	0.00030	0.00032	0.00031
	USA00676	0.00034	0.00034	0.00029	0.00025
	USA01609	0.00035	0.00036	0.00033	0.00030
Fortification earthquake	ACC	0.00058	0.00058	0.00059	0.00051
	USA00575	0.00065	0.00075	0.00072	0.00111
	USA00676	0.00066	0.00064	0.00063	0.00054
	USA01609	0.00074	0.00074	0.00081	0.00065
Rare earthquake	ACC	0.00125	0.00117	0.00137	0.00119
	USA00575	0.00168	0.00179	0.00176	0.00180
	USA00676	0.00214	0.00165	0.00222	0.00150
	USA01609	0.00132	0.00142	0.00134	0.00140

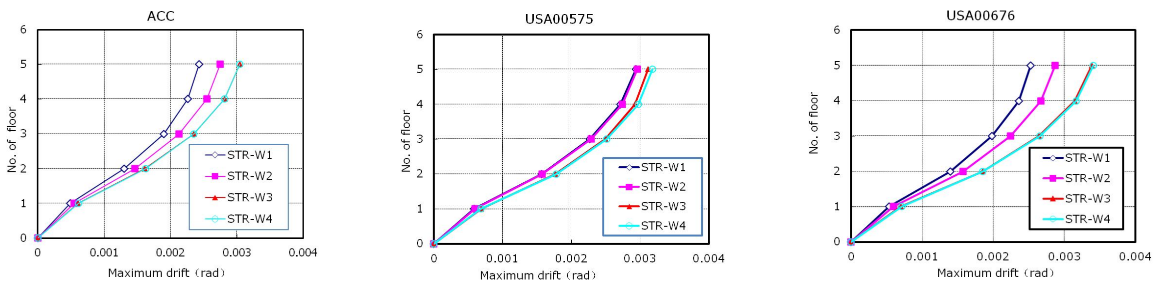


Figure 7. Maximum story drift of STR-W1~W4 under frequent earthquake

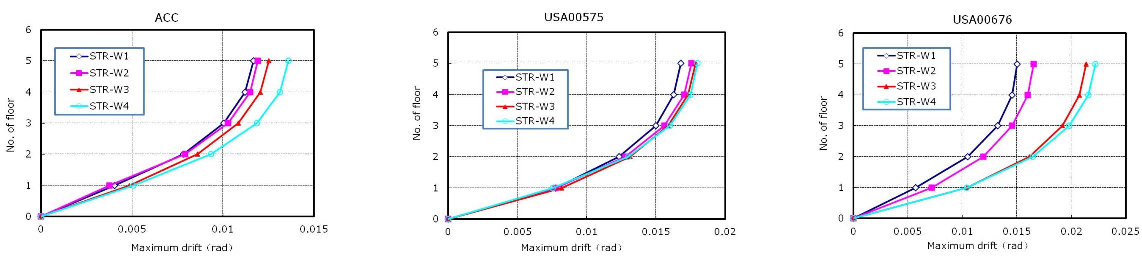


Figure 8. Maximum story drift of STR-W1~W4 under rare earthquake

From above results, it's obvious that maximum story drift and top displacement under earthquake are decreased generally and fewer plastic hinges appeared compared with behavior of structure STR. It could also found from structural response of structure STR-W1~W4 that the more walls added, the little story drift and top displacement was.

The change laws of shear force of columns influenced by adding shear walls were also investigated. In the paper, it was defined that Ratio of demand is a ratio of column's shear force of structure STR to the one of STR-C under frequent earthquake and Ratio of area is a ratio of sectional area of walls to sum of sectional area of columns at 1st floor of structure. The relationships of Ratio of shear demand versus Ratio of area in Axis 2 and 4 at 1st floor were listed in Table 5.

It could be observed that Ratio of demand would decrease while Ratio of area increase which means that many columns should not have to strength because demand of strength of columns was not strict any more if RC shear walls were added. It would save much money and time. Of course basement under walls should have to been retrofitted or other measures had to be taken to support upper walls. We chose the STR-W1 to compare with other methods considering convenience of construction and economy.

Table 5. Ratio of demand versus Ratio of area

Structural model	Ratio of area	Ratio of demand of column			
		2-A*	2-B	4-A	4-B
STR-W1	0.20	0.59	0.57	0.57	0.55
STR-W2	0.40	0.28	0.28	0.26	0.26
STR-W3	0.59	0.22	0.21	0.21	0.21
STR-W4	0.79	0.16	0.15	0.15	0.15

Note*: 2-A: column located in the axis 2 and A, the other is similar.

4.4. Seismic Behavior of Structures STR-B

Maximum story drift under frequent, fortification and rare earthquake is listed in Table 6. And maximum story drift under rare earthquake is 0.0049(1/204) occurred at the second floor of structure and maximum top displacement is up to 0.07037m.

Table 6. Maximum story drift and top displacement of Structure STR-B

No. of earthquake wave		ACC	USA00575	USA00676	USA01609
Frequent earthquake	Maximum story drift	0.00065	0.00046	0.00106	0.00054
	Maximum top Disp.(m)	0.00891	0.00610	0.01467	0.00730
Fortification earthquake	Maximum story drift	0.00222	0.00111	0.00258	0.00144
	Maximum top Disp.(m)	0.03147	0.01537	0.03652	0.02001
Rare earthquake	Maximum story drift	0.00391	0.00185	0.00490	0.00326
	Maximum top Disp.(m)	0.05566	0.02588	0.07037	0.04572

4.5. Seismic Behavior of Structures STR-D

Maximum story drift under frequent, fortification and rare earthquake is listed in Table 7. It was found that maximum story drift under rare earthquake is 0.0039(1/256) occurred at the second floor of structure and maximum top displacement is up to 0.0635m.

Table 7. Maximum story drift and top displacement of Structure STR-D

Seismic wave ID		ACC	USA00575	USA00676	USA01609
Frequent earthquake	Maximum story drift	0.00059	0.00043	0.00060	0.00055
	Maximum top Disp.(m)	0.00937	0.00429	0.00919	0.00869
Fortification earthquake	Maximum story drift	0.00149	0.00163	0.00171	0.00085
	Maximum top Disp.(m)	0.03016	0.03659	0.03472	0.01853
Rare earthquake	Maximum story drift	0.00305	0.00391	0.00371	0.00175
	Maximum top Disp.(m)	0.05126	0.06350	0.06125	0.02787

5. COMPARATIVE STUDY ON SEISMIC BEHAVIOR BY DIFFERENT METHODS

According to SEAOC Vision 2000, FEMA and China General Standard for Performance-based Design of Buildings CECS160.2004, the performance objectives are OP (Operational), IO (Immediate Occupancy), LS (Life Safety) and CP (Collapse Prevention). Table 8 indicates limited value of story drift corresponding to performance objectives for ordinary buildings. For structure which seismic fortification category is B, its performance objectives should be improved, i.e. OP subjected to frequent and fortification earthquake and LS subjected to rare earthquake.

Table 8. Acceptance criteria corresponding to performance objectives

Performance objective	OP	IO	LS	CP
Earthquake level	Frequent	fortification	Rare	Very rare
Limited value of story drift	0.2%(1/500)	1%(1/100)	2%(1/50)	4%(1/25)

Table 9 indicates maximum story drift of structures and statistics values under fortification earthquake. The results showed that the performance behaviour of structure could be evaluated by either the maximum value or $u+\sigma$ because the maximum value is almost same as $u+\sigma$, the mean plus the standard deviation. Thus the maximum value is selected to assess structural behavior in the paper. The story drift of structure STR and STR-B was not satisfied with performance objectives because its story drift was greater than OP, 0.2%, under fortification earthquake. In contrast, STR-W1 and STR-D can meet requirement of codes properly.

Table 9. Maximum story drift of structures and statistics under fortification earthquake

No. of the structure	STR	STR-C	STR-W1	STR-B	STR-D
ACC	0.0020	0.0015	0.00031	0.00222	0.00149
USA00575	0.0026	0.0019	0.00029	0.00111	0.00163
USA00676	0.0027	0.0013	0.00034	0.00258	0.00171
USA01609	0.0022	0.0009	0.00035	0.00144	0.00085
The mean / u	0.002375	0.001400	0.000323	0.001838	0.001420
The Standard deviation / σ	0.000330	0.000416	0.000028	0.000679	0.000391
$u+\sigma$	0.002705	0.001816	0.000350	0.002517	0.001811
The maximum value	0.002700	0.001900	0.000350	0.002580	0.001710

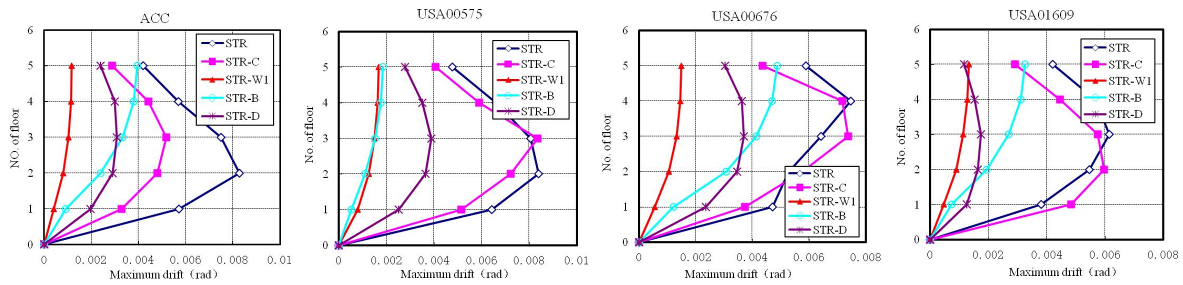


Figure 9. Maximum story drift of structures under rare earthquake

Figure 9 illustrates maximum story drifts of structures subjected to rare earthquakes. The analysis results show that seismic performance is different using four strengthening methods. Although adding a row of columns can change the single-span frame into a two-span frame, the seismic performance of the two-span frame is not improved significantly compared with the single-span frame. Furthermore, beams between Axis B and C had to be retrofitted because they were changed from cantilever beams into support beams. Therefore, this kind of strengthen method is not a reasonable one. The parameters of method using steel brace should be modified so that the seismic performance of structure can meet the requirement of code. The other two methods, especially method of adding RC shear walls, can greatly improve the seismic performance of the single-span frame buildings. The specific case is that the maximum story drift of STR-B under all earthquakes occurred at top floor compare with other cases.

6. CONCLUSION

In the paper, four kinds of strengthening methods were used respectively to improve seismic performance of the typical single-span RC frame in primary school with cantilever walkway designed according to the China Seismic Design Code. The 3-dimensional finite element structural models were established and dynamic analysis processes were carried out. The seismic performances of the single-span RC frame strengthened by different methods were compared under frequent, fortification and rare earthquakes. The conclusions were obtained from analysis results as follows, (a) Although adding a row of columns can change the single-span frame into a two-span frame, the seismic performance of the two-span frame is not improved significantly compared with the single-span frame. (b) The structure STR-B strengthened by setting braces is not satisfied with performance objectives because its story drift is greater than requirement under fortification earthquake. The parameters would be adjusted or number of braces should be added. (c) Other two methods can greatly improve the seismic performance of the single-span frame buildings, especially method of adding walls. But their efficiency and cost-effectiveness largely depends on the condition and performance objective of the building under consideration.

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