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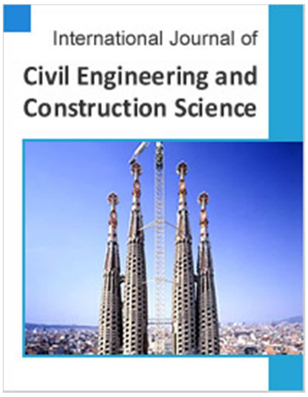

Nonlinear Dynamic Analysis of an Innovative RC Frame with Self-centering Energy Dissipative Rocking Column

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Abstract
This paper introduces a new design form for frame structure with self-centering energy dissipative rocking columns. Corner braces as key elements are installed in both sides of the rocking columns to improve the performance of the frame structure, such as the restorability and the capability in energy dissipation. Five single-span framework models of reinforced concrete are formulated by the finite element software OpenSees to simulate elastic-plastic dynamic response under different intensity ground motions, such as frequent, fortification and rare earthquake. Analysis results show that story acceleration and residual displacement of the innovative structure can be reduced significantly compared with conventional RC structures, while using self-centering energy dissipative rocking columns; in addition, under the rare earthquake, story displacements and inter-story drift ratio are slightly less than the traditional framework.

1. Introduction

Story displacement or inter-story drift ratio are taken commonly as performance index for evaluations of seismic properties of structure. Using joint enhancements, addition of shear walls, or addition of some braces, engineers increase the stiffness and strength of structure and reduce deformation in seismic behavior. The rocking and self-centering structure by loosening the constraints of specified members was proposed and implement for the same purpose. However, if story displacement and inter-story drift ratio are employed simply to evaluate the seismic performance of structure, the priorities of seismic behaviors of structure can't be reflected well. Therefore, more performance indices should be chosen to estimate the seismic performance, such as peak story acceleration, base shear force, residual displacement and residual drift ratio etc. In the present study, the rocking and self-centering structures are realized by using "rocking column" with post-tensioned tendons as a proposed practical technique to reduce residual deformations after earthquake. The addition of energy dissipation device instead of structural damage was suggested to achieve energy dissipation. The concept of connecting precast concrete frame elements with beam prestressing tendons debonded through the joint, and for some distance on either side of the column, was discussed by Priestley and Tao [1]. The behavior of two six-story unbonded post-tensioned frame is studied by EL-Sheikh [2] using nonlinear push-over static and dynamic time-history analysis. Two analytical models, the fiber model and the spring model, are developed in his research. The results show that the behavior of unbonded post-tensioned precast frame, in particular, the strength and self-centering capability, is more than adequate for severe earthquake loading. A "precast rocking column" as a type of double hinged column was proposed by Roh [3], [4], [5], [6], [7], this column resisting vertical loads with minimum without lateral strength was installed in the structure to decrease story stiffness, and the inter-story diagonal viscous damper was added to control structural deformations. The story displacement, inter-story drift, story acceleration and floor shear force response of 3-story single-span frame under white noise, which showed the precast rocking column adding viscous damper can reduce effectively structural responses. An update 'Shape-flagged' (AFS) system was proposed by Kam [8], and the corresponding designing methods of the specific performance based on displacement, inter-story drift ratio, residual drift ratio and story acceleration were analyzed. W. D. Yang [9] designed the light-weight energy dissipation rocking rack based on stiffness requirements, considered structural inter-story displacement focused coefficient (DFC) as controlled target to analyze the earthquake mitigation performance of the system; DFC [10] can reflect whether energy dissipation of the global structural system is raised and there emerge vulnerable layers or not, which can assess the effect that the rocking rack controls inter-story deformation modes of the global structure.

According to slight energy dissipation of the rocking column proposed by Roh and the character that additional diagonal damper may influence structural serving properties. A rocking column with small corner braces installed in the both side of column end are presented, combining self-centering and energy dissipation, which constitutes a self-centering energy dissipation rocking column applied in the traditional structures as a new-style self-centering energy dissipation framework. The concept of designing a new-style RC frame with self-centering energy dissipation rocking column based on the displacement is presented and some performance indices such as the acceleration, inter-story drift ratio, story displacement and residual deformation are discussed, respectively.

2. Elasto-Plastic Dynamic Time-History Analysis

2.1. Brief Introduction of Method

Elasto-plastic dynamic time-history analysis as a direct dynamic analysis method is an effective method to study the dynamic response of the structure under different earthquake levels. Compared with the static elasto-plastic method, the external loads applied to the structure in elasto-plastic dynamic time-history analysis are time-varying. In addition, the response of structure not only related to the time variation, but related to the structure's dynamic characteristics and external loads characteristics. At each moment, acceleration, velocity, displacement of structure and deformation, internal force of members can be calculated by the dynamic calculation, which can clearly and completely reflect the response of the structure under the whole seismic process. Conceptually, dynamic nonlinear time-history analysis can reflect the weak-story position, yield mechanism and failure mode under earthquake. Therefore, in practical engineering projects, it would be more beneficial to use the dynamic time-history analysis method to check the stiffness and bearing capacity of the weak-part of the structure, in order to avoid the collapse and severe damage of the structure under the major earthquake.

Elastic-plastic dynamic time-history analysis is employed to analysis seismic performance of structure by considering the type of site, seismic fortification objectives and other factors. Firstly, according to the type of site and structure characteristics and other conditions, the suitable seismic waves were selected and input; and then, the finite element dynamic model is used to establish the vibration equation under earthquake and solve it. In general, acceleration, velocity and displacement response of structure at each moment under earthquake, the relationship between internal force and deformation from elastic to plastic stage, the progressive failure process of the components can be obtained by using the step-by-step method. Finally, extracting the calculate data and selecting the data that can reflect the index of seismic performance to judge the performance of the structure.

2.2. The Selection of Seismic Wave

The rationality and accuracy of the analysis calculation results are heavily dependent on the selected ground motion records as seismic excitation. So, the characteristic of the seismic wave is one of the main factors affecting the results of structure elastic-plastic time-history analysis. Three elements of ground motion: amplitude, frequency spectrum and duration. The different combination of these parameters are tied to the seismic source characteristics, earthquake size, distance, etc. The results are more reasonable when seismic wave that can reflect accurately characteristics of the structure and the site category were chosen in the time history analysis.

At present, there are three common methods for the selection of ground motion records: (1) Based on the most unfavorable earthquake ground motion; (2) Based on the method of choosing stations and the earthquake information; (3) Based on the method of choosing the design response spectrum. When studying on the seismic performance of different dynamic characteristics or different types of structures, the second method are often chosen to collect earthquake waves. Because this method to select the ground motion without considering the dynamic characteristics of structure. Normally, ground motion records that are similar to the building site were selected, according to the inputting of required ground motion level and the selecting of ground motion records, doing different levels of amplitude modulation in order to meet the requirements when doing elastic-plastic time history analysis.

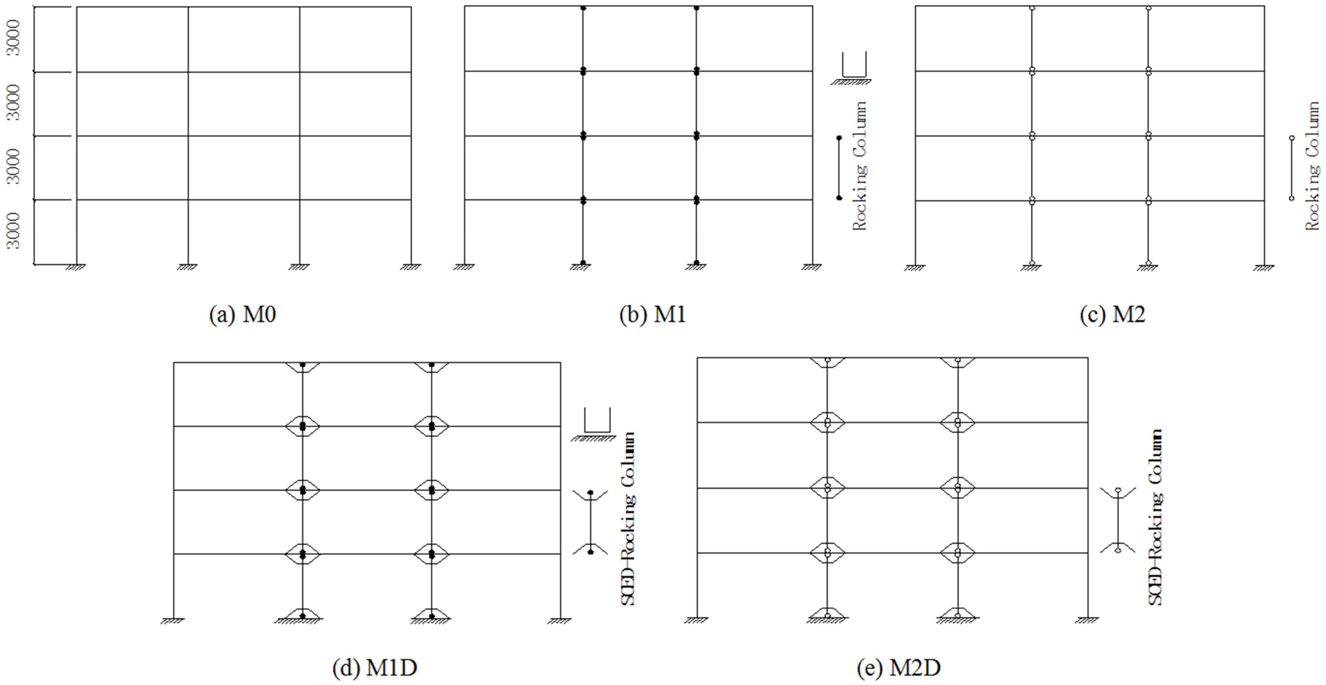
3. Establish Dynamic Analysis Model Based on OpenSees Calculative Platform and Results Analysis

3.1. Descriptions of Model

Based on the current code, a four-layer RC frame, which longitudinal length is 8×4200mm, horizontal length is 3×4800mm, floor height is 3000mm, was designed by the finite element software PKPM. The fortification intensity is 8 degrees (0.2g), site class is II, characteristic period is 0.45s. The Beam-column's concrete strength grade is C35, longitudinal reinforcement strength grade is HRB335, stirrups strength grade is HPB300. Floor information of framework shown in Table 1. Due to the layout of structure elevation and plane are rules, the middle span of framework was selected for analysis and calculation. The floor's dead load is 4.5kN/m^2, live load is 2.0kN/m^2.

In this paper, five different finite element models were established by the finite element program OpenSees. Those models were named as M0, M1, M2, M1D and M2D. The schematic diagram of structure models shown in Figure 1.

Model M0 is an interior plane frame as shown in Figure 1a, which is removed from the original structure. M1 is the model that using precast rocking column, the top and bottom ends of that column has square angle as transformation of the two columns in the middle of the model M0 as shown in Figure 1b. In order to compare with the M1 and verify that the precast-column with square angle has certain lateral resistance, M2 model as a contrastive example is showed in Figure 1c. It is assumed that the lateral stiffness of precast rocking column in M2 model is zero while the vertical bearing capacity is same as frame column. The "rocking column" is a type of double hinged column which is used to simulate releasing moment as shown in Figure 1c. Model M1D, which constitute the RC frame with the self-centering energy dissipation rocking columns as shown in Figure 1d, are compared with the model M1 (Figure 1b). Similarly, M2D showed in Figure 1e is a modified model as a contract to M2. Figure 1e shows that the small self-centering energy dissipative brace were installed in the both sides of the hinged column on the basis of the M2. The distance from self-centering energy dissipative brace of model M1D and M2D to the end of the column is 600mm.



(a) M0 (b) M1 (c) M2

(d) M1D (e) M2D

Figure 1. *Structure models.*

Table 1. *Story parameters of structure.*

Story	Story height (mm)	Column section (mm×mm)	Beam section (mm×mm)	strength grade of concrete	Plate thickness (mm)	longitudinal reinforcement	stirrups
4	3000	400×400	300×500	C35	120	HRB335	HPB300

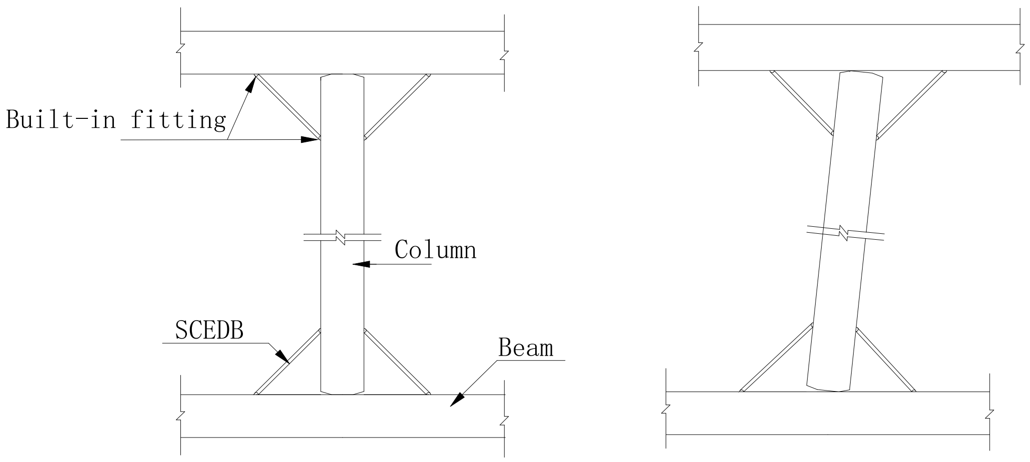


Figure 2. *Self-centering energy dissipation rocking column.*

Table 2. *Nature period of structures.*

Structure model	M0	M1	M2	M1D	M2D
Nature period	0.49844	0.55035	0.90427	0.43371	0.44687

Based on the working principle of SCED, Q235 steel tube was used to make the small self-centering energy dissipative brace. The outer tube size of SCED is 90mm×90mm×3mm, the cross section area is 1044mm^2, and the inner tube size of SCED is 70mm×70mm×4mm, the cross section area is 1056mm^2. The prestressed tendon was composed of two Technora cables, which diameter is 10mm. The initial prestress of SCED is 31.5kN and the friction force is 28.5kN. By calculation: K_1=364.485kN/mm, K_2=13.508kN/mm, the parameter β is taken as 0.95 in this paper. Natural period of five structure models shown in Table 2. From the Table 2, we can know that the period of M1D and M2D becomes smaller, which is due to the additional stiffness of the brace were considered.

In this paper, seismic waves were selected by means of stations and seismic information. 15 seismic waves were selected from the 22 far-field seismic records, which were proposed in American ATC-63, to do dynamic elastic-plastic time history analysis of the structure. The peak ground acceleration (PGA) was used as indicators of ground motion intensity (IM) in analysis. According to the current seismic design code, the seismic waves were modulated to frequent earthquake, fortification earthquake and rare earthquake with the 8 degree, respectively. The 15 ground motion records and station names shown in Table 3.

Table 3. *Ground motion recorder.*

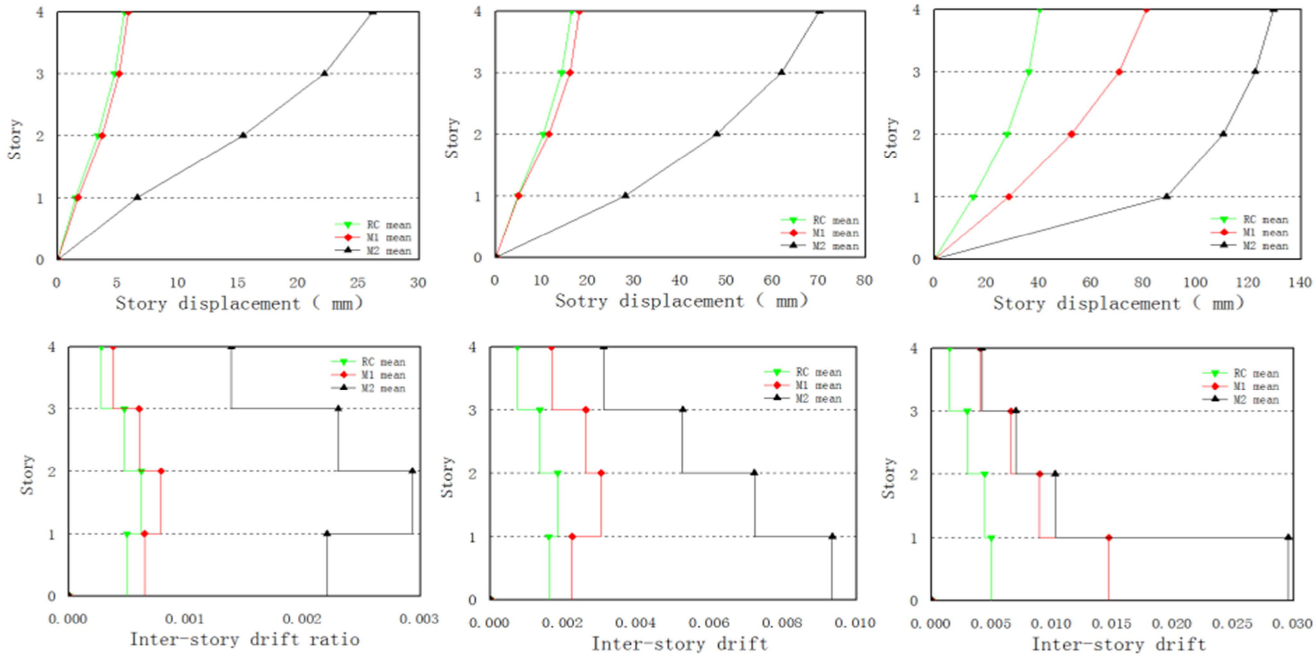
Number	Name	Magnitude	Year	Station	Vibrate Weight
1	Northridge, USA	6.7	1994	Beverly Hills-Mulhol	NORTHR/MUL279
2	Northridge, USA	6.7	1994	Canyon Country	NORTHR/LOS270
3	Duzce, Turkey	7.1	1999	Bolu	DUZCE/BOL090
4	Imperial Valley, USA	6.5	1979	EI Centro Array #11	IMPVALL/H-E11230
5	Kobe, Japan	6.9	1995	Nishi-Akashi	KOBE/NIS090
6	Kobe, Japan	6.9	1995	Shin-Osaka	KOBE/SHI090
7	Kocaeli, Turkey	7.5	1999	Arcelik	KOCAELI/ARC090
8	Loma Prieta, USA	6.9	1989	Gilroy Array #3	LOMAP/GO3009
9	Superstition Hills, USA	6.5	1987	EI Centro Imp. Co	SUPERST/B-ICC090
10	Superstition Hills, USA	6.5	1987	Poe Road (temp)	SUPERST/B-POE360
11	Cape Mendocino, USA	7	1992	Rio Dell Overpass	CAPEMEND/RIO360
12	Loma Prieta, USA	6.9	1989	Capitola	LOMAP/CAP090
13	Hector Mine	7.1	1999	Hector	HECTOR/HEC090
14	San Fernando	6.6	1971	LA-Hollywood Stor	SPERN/PEL180
15	Friuli, Italy	6.5	1976	Tolmezzo	FRIULI/A-TMZ270

3.2. Results Analysis

In order to evaluate the self-centering effect and seismic performance of the RC frame with self-centering energy dissipative rocking columns, five parameters: peak story displacement, peak inter-story drift ratio, peak story acceleration, residual displacement and residual drift ratio were employed to analysis the structure seismic performance in this paper. Peak story displacement and peak inter-story drift ratio can be used as the composite indicator to evaluate the damage of the structure. Residual displacement and residual drift ratio can be used as the indicator to evaluate the self-centering capacity of the structure. Peak acceleration can be used as the indicator to evaluate the seismic performance of structure in earthquake. In order to consider the discrete property of the calculation results under the seismic wave conditions, the mean and mean plus standard deviation methods were adopted to analyzing seismic performance of

RC frame with the self-centering energy dissipative rocking columns.

The curves of story displacement and inter-story drift ratio of the model M0, M1 and M2 under the frequent earthquake, fortification earthquake, rare earthquake, as shown in Figure 3, were obtained by amplitude modulation the ground motion based on Table 3. Through the analysis we can know that the structure with precast rocking column has a certain lateral resistance force, can withstand a certain intensity of earthquake, but the response of story displacement and inter-story drift ratio are too large to meet the specification. In order to modify its energy dissipation capacity, small self-centering energy dissipative braces were installed in the top and the bottom of the precast rocking column.



(a) Frequent earthquake (b) Fortification earthquake (c) Rare earthquake

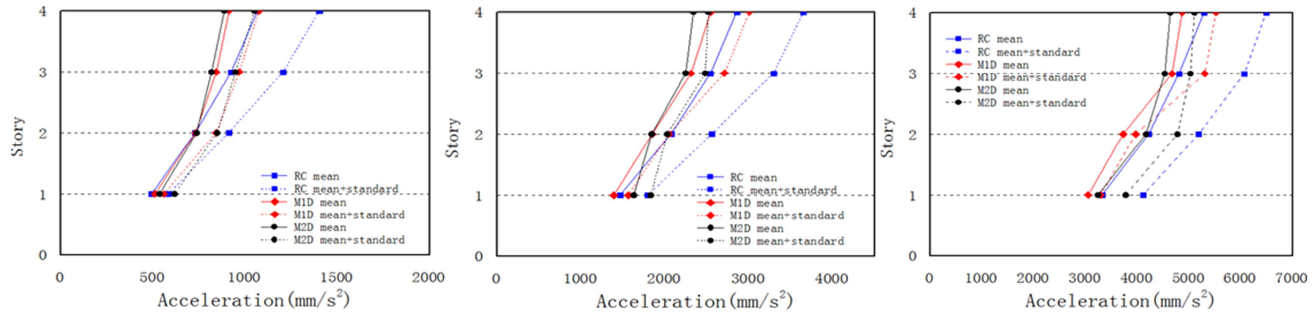
Figure 3. *Story displacement and story drift ratio curves under earthquake.*

The curves of peak acceleration response of model M0, model M1D and model M2D under different earthquake as shown in Figure 4 and in Table 4. Analysis results show that structure with self-centering energy dissipative rocking column has a good damping effect and can reduce peak story acceleration no matter how fortification earthquake or rare earthquake. When the discreteness of ground motion in the calculation were considered, the damping effect of the structure are more obvious.

Table 4. *Peak acceleration and seismic-reduction rate of structure under earthquake.*

		M0		M1D				M2D			
		Mean	**Mean+ Standard**	**Mean**	**Reductio n Rate**	**Mean+ Standard**	**Reduction Rate**	**Mean**	**Reduction Rate**	**Mean+ Standard**	**Reduction Rate**
Frequent earthquake	1	491.5	582.3	509.1	-3.591	558.0	4.177	534.6	-8.771	616.3	-5.835
	2	728.4	909.4	730.0	-0.223	842.0	7.418	735.7	-0.998	847.1	6.859
	3	922.6	1203	842.7	8.666	966.4	19.69	816.5	11.51	946.3	21.36
	4	1066	1400	912.0	14.45	1074	23.33	886.3	16.86	1049	25.11
Designed earthquake	1	1460	1793	1389	4.924	1560	12.99	1627	-11.39	1828	-1.950
	2	2071	2556	1846	10.85	2045	19.88	1840	11.17	2025	20.81
	3	2540	3289	2308	9.116	2706	17.72	2245	11.61	2478	24.68
	4	2852	3649	2544	10.81	3003	17.68	2338	18.06	2515	31.08
Rare earthquake	1	3314	4105	3049	8.001	3288	19.90	3236	2.381	3238	21.12
	2	4212	5181	3721	11.66	3962	23.53	4165	1.128	4166	19.59
	3	4798	6062	4668	2.706	5300	12.56	4526	5.669	4532	25.25
	4	5284	6485	4860	8.025	5512	14.99	4633	12.33	4645	28.37

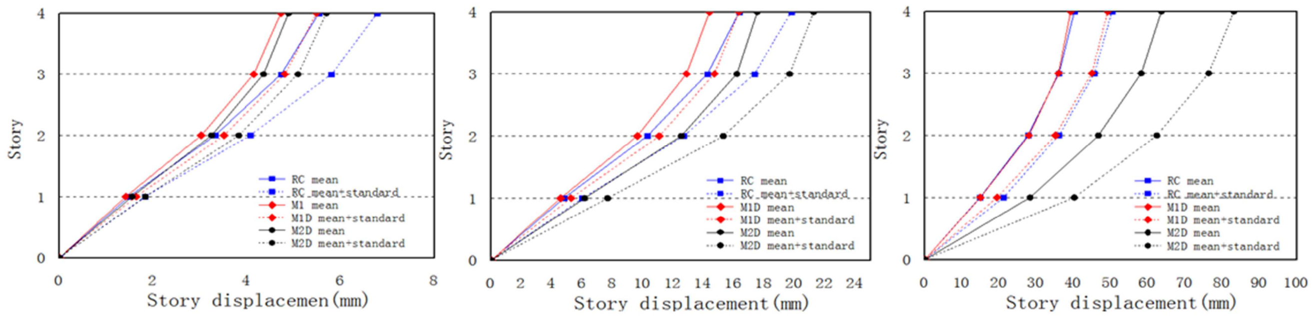
Note: The units of the mean of story acceleration and the mean plus standard deviation of story acceleration are also mm/s^2. Seismic-reduction rate = $(a_1-a_2)\div a_1\times 100\%$, a_1 is the mean of peak story acceleration or the mean plus standard deviation of peak story acceleration of M0, a_2 is the mean of peak story acceleration or the mean plus standard deviation of peak story acceleration of M1D or M2D.



(a) Frequent earthquake (b) Fortification earthquake (c) Rare earthquake

Figure 4. *Story acceleration curves under earthquake.*

The response curves of peak story displacement of model M0, model M1D, model M2D as shown in Figure 5 and in Table 5. In Figure 5(a), under the frequent earthquake, the mean seismic-reduction rate of top-story displacement of model M1D and M2D are 14.66% and 21.38%, respectively. The mean plus standard deviation seismic-reduction rate of the top story displacement are 19.1% and 25%, respectively. In Figure 5(b) and Figure 5(c), under the fortification and rare earthquake, the mean seismic-reduction rate of the top-story displacement are 12.04% and 2.47%. The mean plus standard deviation seismic-reduction rate of the top-story displacement are 17.4% and 2.3%, respectively. The top-story displacement of M2D framework is enlarged, which demonstrate that the M2D framework's function of displacement control is weaker under fortification and rare earthquake. By comparing the story displacement curves between Figure 5 and Figure 3(c), it is found that the mean displacement of each story in model M1D and M2D has decreased in varying degrees and the top-story's mean displacements are reduced by 44.9% and 50.9%, respectively. The results show that the self-centering energy dissipative brace on the rocking column can effectively reduce the story displacement of the rocking structure.

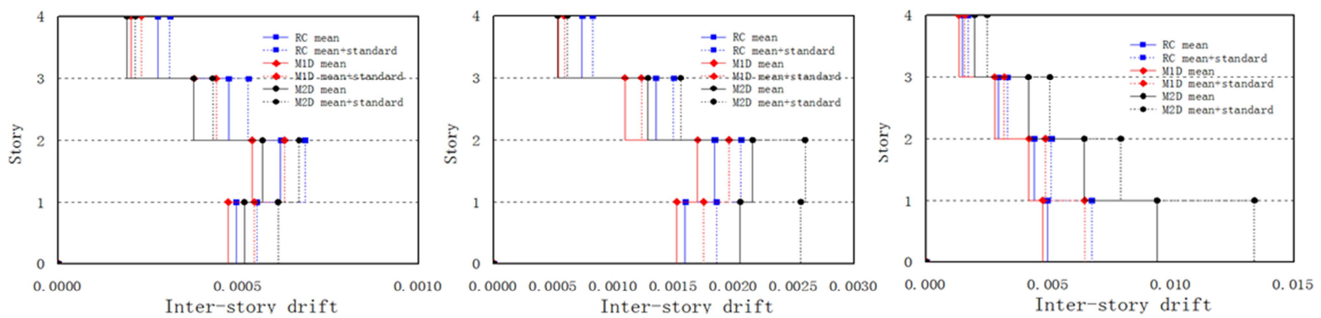


(a) Frequent earthquake (b) Fortification earthquake (c) Rare earthquake

Figure 5. *Story displacement curves under earthquake.*

Table 5. *Peak displacement and seismic-reduction rate of structure under earthquake.*

	M0		M1D				M2D			
	Mean	Mean+ Standard	Mean	Reduction rate	Mean+ Standard	Reduction rate	Mean	Reduction rate	Mean+ Standard	Reduction rate
Frequent earthquake	5.533	6.776	4.721	14.67	5.481	19.10	4.349	21.38	5.085	25.00
Designed earthquake	16.33	19.75	14.37	12.04	16.31	17.40	17.53	-7.260	21.25	-7.500
Rare earthquake	40.15	50.25	39.16	2.468	49.08	2.300	63.54	-58.25	83.04	-65.20

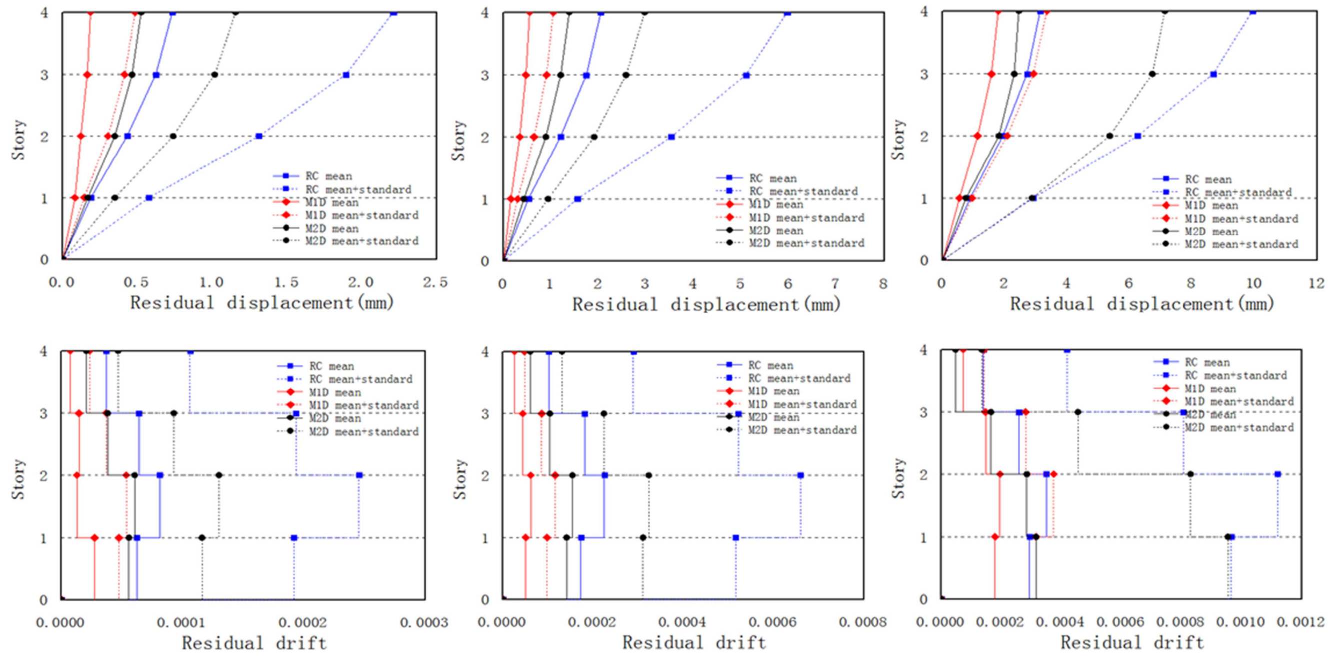


(a) Frequent earthquake (b) Fortification earthquake (c) Rare earthquake

Figure 6. *Story drift ratio curves under earthquake.*

The seismic damage of each model is evaluated according to the damage state and deformation reference, which has been given in the current seismic code. Maximum inter-story drift corresponding to intact, slight destructive, secondary devastating, less serious destroyed components are 1/550, 1/250, 1/120 and 1/60, respectively. The mean value and the mean value plus standard deviation of inter-story drift ratio of the M0, M1D and M2D frame as shown in Figure 6 are less than the Norm (1/550), the structure gets in good conditions and the weakening-story of the structure emerges in the second floor. Under the fortification earthquake, mean value of inter-story drift ratio on the story of the original structure M0 is 0.001838(1/544), which turns out to be between slight devastation and intact conditions. Similarly, M1D's is 0.001695(1/590) that decreases by less 7.76% than the original M0, therefore M1D is in intact states, M2D's is 0.002155(1/464) in slight destructive conditions. Under rare earthquake, the mean values of inter-story drift ratio on the original M0 and M1D are 0.004936(1/202.6) and 0.004916(1/203.4), respectively, which is between slight state and secondary destruction state, but M2D's is 0.009412(1/106.2) between secondary state and less serious damage state.

Above analysis shows that M1D's inter-story drift damping ratio is not significant under the earthquake, but it is better than the original structure. Under the fortification and rare earthquakes, the inter-story drift of M2D is larger than the original structure, but there was no collapse under the rare earthquakes and the acceleration response can be reduced.



(a) Frequent earthquake (b) Fortification earthquake (c) Rare earthquake

Figure 7. *Residual displacement and residual drift ratio curves under earthquake.*

Table 6. *Residual displacement and seismic-reduction rate of structure under earthquake.*

		M0		M1D				M2D			
		Mean	**Mean + Standard**	**Mean**	**Reduction rate**	**Mean + Standard**	**Reduction rate**	**Mean**	**Reduction rate**	**Mean + Standard**	**Reduction rate**
Frequent earthquake	1	0.186	0.575	0.082	56.09	0.142	75.30	0.167	10.51	0.348	39.58
	2	0.430	1.310	0.120	72.03	0.303	76.91	0.348	19.01	0.737	43.73
	3	0.621	1.891	0.164	73.66	0.413	78.13	0.462	25.58	1.015	46.31
	4	0.732	2.209	0.185	74.70	0.483	79.44	0.524	28.43	1.155	47.72
Designed earthquake	1	0.518	1.545	0.151	70.76	0.293	81.03	0.424	18.12	0.931	39.76
	2	1.192	3.521	0.336	71.79	0.640	81.82	0.886	25.66	1.900	46.05
	3	1.736	5.087	0.467	73.07	0.898	82.35	1.197	31.00	2.571	49.46
	4	2.041	5.954	0.543	73.40	1.041	82.51	1.378	32.44	2.962	50.25
Rare earthquake	1	0.878	2.893	0.535	39.09	0.943	67.40	0.946	-7.674	2.862	1.073
	2	1.925	6.250	1.120	41.84	2.064	66.97	1.799	6.551	5.350	14.40
	3	2.700	8.666	1.561	42.17	2.906	66.47	2.293	15.064	6.713	22.53
	4	3.121	9.921	1.779	42.98	3.333	66.41	2.435	21.961	7.115	28.28

The residual displacement and residual drift ratio of each calculation model under the earthquake, as shown in Figure 7 and Table 6. Under the fortification earthquakes, residual displacement's mean damping ratio and the residual drift's mean damping ratio of frame M1D and M2D are 73.4%, 32.4%, 72.6% and 31.4%, respectively. Under the rare earthquakes, mean damping rate of the residual displacements and the residual drift ratio of frame M1D and M2D are 43%, 21%, 44.1% and 18.5%, respectively. Analysis results shows that frame M1D and M2D with self-centering energy dissipative rocking-columns, which the residual displacement and residual drift ratio can be reduced greatly compared with the original structure, and the discreteness of the calculation results is smaller. That is more beneficial to control the residual displacement and can ensure the function of the structure after earthquake. Therefore, the structure can continue to play the important role after the earthquake.

4. Conclusion

Through the dynamic response analysis of five reinforced concrete framework under different level earthquake, we can obtain the following conclusions:

1. The structure with precast rocking column has a certain resistance to lateral force, and that can withstand a certain intensity of earthquake, while the response of story displacement and inter-drift ratio are too large to meet the specification.
2. M1D and M2D can effectively reduce the story acceleration of the structure. Compared with the original frame M0, story displacement and drift control of the frame M1D is not obvious, but there is a certain reduction in the displacement response. In further research, the inter-story displacement and drift can be improved by optimizing the parameters and reasonable arrangement of the brace.
3. M1D and M2D can effectively reduce residual displacement and residual drift ratio of the structure under the earthquake. It is proved that the self-centering energy dissipation rocking column with small SECD can provide a certain amount of self-centering abilities and maintain some building function of structure after earthquake. In this paper, the self-centering energy-dissipation rocking columns are used to perfect the original structure and reinforce the structure of minor damage after earthquake. At the same time, a new method is provided for the assembly of the prefabricated structure in the future.

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