An energy dissipation and seismic reduction design of a hospital inpatient building using viscous fluid dampers

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ABSTRACT

Viscous fluid damper is commonly used in China to reduce building seismic response. This paper introduces the design methodology and key-points of viscous fluid damper in China using an energy dissipation design of an hospital inpatient building. The inpatient building is a 4-story reinforced concrete frame structure, the seismic precautionary intensity is 7 degree(0.10g) according to Chinese code, the dampers are connected with beam by concrete wall to dissipate energy. The performance objective of the energy dissipation structure is set according to the Chinese codes and structural characteristics. The main frame is designed with Chinese spectrum under medium seismic action, the calculation method of the damping ratio is FNA time-history analysis, the analysis software is ETABS. The additional damping ratio of the spectrum is 5%, taken as the minimum value of the cumulative energy method and the standard algorithm. The energy-dissipation substructure and the dampers are designed with time history of rare seismic action, the analysis software is SAUSG, the calculation method is the modified central difference method. The result indicate that under 7 degree seismic action, the viscous fluid damper has good energy dissipation effect, the average value of maximum story drifts and the average value of floor shear in both X and Y direction of the energy dissipation structure is reduced compared to the original structure, the plastic development under rare seismic action meets the performance objective requirement. The comparative analysis shows that the design scheme of energy dissipation and seismic reduction has good effect and unique advantages.

1 INTRODUCTION

Both the existing research and the results of earthquake damage investigation show that energy dissipation technology can significantly improve the seismic performance of buildings, not only ensure the basic integrity of the structure and non-structural components of the building, but also ensure the normal operation of the attached mechanical and electrical equipment and functional instruments, so as to provide an effective guarantee for the hospital building to continue to serve as a disaster prevention and relief site after the earthquake. As an important part of energy dissipation technology, viscous fluid damper has the advantages of mature technology and good energy dissipation effect, so it has been widely used in building energy dissipation design in China.

2 BRIEF BUILDING DESIGN

2.1 Brief Building Design

The hospital project is located in Sichuan Province, China. The 1# inpatient unit analyzed in this paper is 36.2m long, 21.2m wide, 14.85m high, with 4 floors on the ground, the structure form is reinforced concrete frame structure. The design service life of this building is 50 years, and the safety level of the structure is Grade 1. According to GB50223-2008 "Standard for classification of seismic protection of building construction", the seismic fortification category of 1# unit is the key fortification category (Category B). According to RISN-TG046-2023 "Technical guideline for maintaining normal functionality of buildings in earthquakes", the 1# unit belongs to the Class I building that maintains the normal function during earthquake. The seismic fortification intensity is 7 degrees, the design basic seismic acceleration of ground motion is 0.10g, the design earthquake group is group Ⅱ, the building site if of class I, and the site characteristic period is 0.30s.

2.2 Arrangement of viscous fluid dampers

The structure uses viscous fluid dampers as energy dissipation component, and the dampers are connected with beam by cantilever concrete wall to dissipate energy, as shown in Figure 2.2-1. The plane layout follows the principles of symmetry, perimeter, uniformity and dispersion. A total of 15 sets of viscous fluid dampers (VFDS) are arranged in this building, which are distributed in 1 ~ 3 floors. The location of the dampers in a typical floor (2nd floors) and the model of the whole building are shown in Figure 2.2.

The viscous fluid damper was simulated with Maxwell unit, and the modeling parameters were detailed in Table 2.2

Damping Coefficient kN/(mm/s)$^{0.3}$	70
Design Displacement (mm)	24.3
Design Force (kN)	312
Design Speed (mm/s)	146
Damping Exponent	0.3
Sets	15

Table2.2:Damper modeling parameters

Figure 2.2-1: Cantilever concrete wall connection

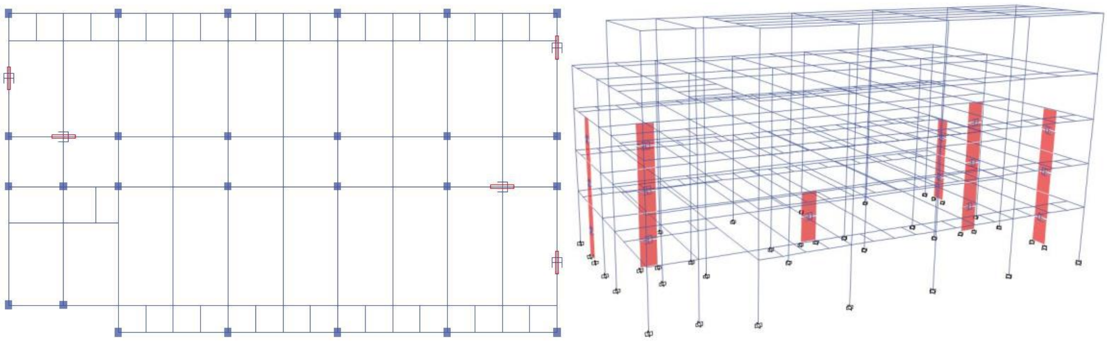


Figure 2.2-2: Typical floor damper layout and model of the whole building

3 PERFORMANCE OBJECTIVE AND CODE REFERENCE

This project is a newly built hospital building located in high seismic precautionary intensity area and key area for earthquake surveillance and protection. It follows the requirements of RISN-TG046-2023 "Technical Guidelines for Maintaining Normal Functionality of Buildings in Earthquake". The seismic performance objectives of this project are as follows: It can meet the normal operation requirements when it is affected by the earthquake with the fortification intensity of the region, ensure the basic integrity of the structure and non-structural components of the building, and the normal operation of the auxiliary mechanical and electrical equipment and functional instruments of the building; Under the action of a rare earthquake, its energy-dissipate damping system can still function normally, and the components connected with the damper still maintain in elastic or not yielding. The expected performance objectives of this project are shown in Table 3.

Table 3 Expected performance objectives under earthquake ground motion

Earthquake		**Frequent earthquake**		**Precautionary earthquake(medium earthquake)**		**Rare earthquake**	
Probability of exceedance in 50-years design reference period		63%		10%		2%	
Recurrence period(year)		50		475		2475	
Maximum value of accelerogram used for time-history anslysis a_{max}(cm/s^2)		70		230		400	
Site characteristic period(s)		0.300		0.300		0.305	
Expected performance objectives		Normal section	Oblique section	Normal section	Oblique section	Normal section	Oblique section
Bearing capacity	Key components	elastic	elastic	elastic	elastic	Not yielding	Not yielding
	Ordinary component	elastic	elastic	Not yielding	Not yielding	/	/
	dampers	Working properly		Working properly		Working properly	
Story drift		＜1/550(with total damping ratio of 5%)		＜1/400(with total damping ratio of 10%)		＜1/150	
floor acceleration		/		0.25g		0.45g	

Note: Key components -- energy dissipation sub-frame, cantilever wall. Ordinary members -- ordinary vertical components and ordinary horizontal components.

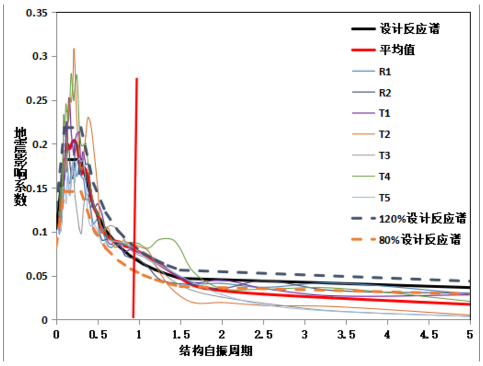
4 SEISMIC TIME-HISTORY SELECTION

According to the relevant provisions of GB50011-2010 “Code for Seismic Design of Buildings”, 7 seismic time-history records (5 natural waves and 2 artificial waves) were selected for time history analysis. The average seismic influence coefficient curve of multiple time histories are statistically consistent with the response spectrum used in the mode decomposition response spectrum method, as shown in Figure 4. The difference between the mean value of the base shear calculated by elastic time histories and that calculated by the mode decomposition response spectrum method is less than 20%, and the data are shown in Table 4.

Table 4 Comparison of base shear of elastic time histories and mode decomposition response spectrum

Items		R1	R2	T1	T2	T3	T4	T5	Spectrum	Average
Base Shear	X	3723	3309	3351	4308	-3437	-4314	3473	4266	3702
	Y	3414	3164	3216	4189	-3248	-4324	3249	3938	3543
Ratio	X	87%	78%	79%	101%	-81%	-101%	81%	100%	87%
	Y	87%	80%	82%	106%	-82%	-110%	82%	100%	90%

16:0, artificial wave 2 (R1); 11:53, artificial wave 5 (R2); Sichuan wave acc_051YBY080512142804_H2 -- horizontal matching toward 1-Acc (T1); Chi-Chi, Taiwan-05_NO_2950,Tg(0.31)(main direction)(T2); Coalinga-05_NO_408,Tg(0.28)(main direction)(T3); San Fernando_NO_68,Tg(0.52)(main direction)(T4); TH3TG030,Tg(0.30)(main direction)(T5)



Order	Period	Seismic Influence Coefficient		Average/ Spectrum
		Average	Spectrum	
1	0.974	0.078	0.067	1.163
2	0.905	0.081	0.072	1.134
3	0.827	0.084	0.077	1.087

Figure 4: The average seismic influence coefficient curve of multiple time histories

5 ELASTIC ANALYSIS OF PRECAUTIONARY EARTHQUAKE

Based on the ETABS model established above, the elastic time-history analysis of the damping structure under the precautionary earthquake ground motion is carried out. The elastic time-history analysis uses the fast nonlinear analysis method(FNA), only considering the nonlinear property of the damper, and the structure itself is assumed to be linear, and several analysis iterations are carried out. The analysis result takes the average value of the 7 seismic time-history results. The analysis includes: the comparison of story shear force, story drift and floor acceleration with and without dampers, calculation of the actual equivalent additional damping ratio and hysteresis energy dissipation analysis of the damper under precautionary earthquake.

5.1 Comparison of seismic response between ST0 and ST1

Compared with the time-history analysis results of the model without dampers (ST0), the base shear, drift and floor acceleration of the model with dampers (ST1) are significantly reduced. The x-direction base shear decreases by 19%, and the Y-direction base shear decreases by 20%. With the increase of floors, the damping effect becomes weaker. The maximum story drift of ST0 is 1/432 and 1/328, and the maximum story drift of ST1 is 1/511 and 1/421, respectively, which decreases by 17% and 22% in two directions, meeting the expected objective of 1/400. ST0 floor acceleration is 1.45m/s2 and 2.49m/s2, respectively, and ST1 floor acceleration is 1.22m/s2 and 1.78m/s2, respectively, which is reduced by 16%and 28% in the two directions, and both direction meet the expected objective of 0.25g. The analysis results of each floor are shown in Figure 5.1.

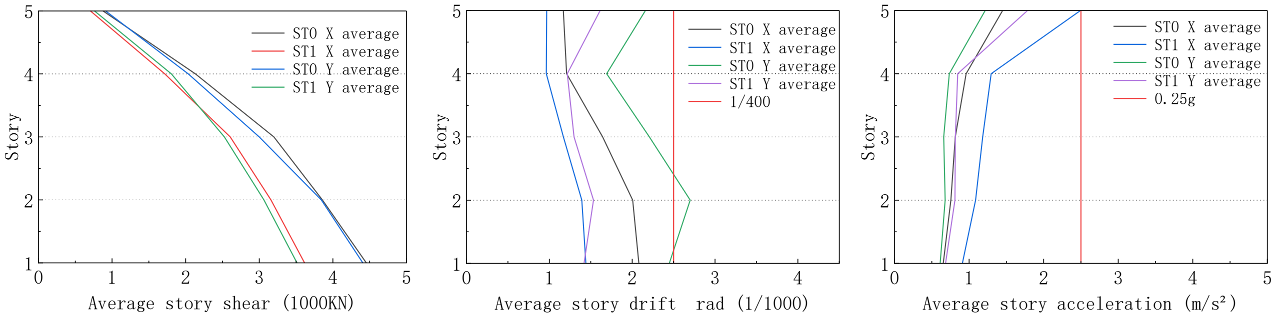


Figure 5.1: Seismic response under precautionary earthquake ground motion

5.2 Actual equivalent additional damping ratio calculation

The actual equivalent additional damping ratio calculated by standard algorithm method is 5.2% in the X direction and 5.7% in the Y direction. The actual equivalent additional damping ratio calculated by cumulative energy method is 6.0% in the X direction and 5.7% in the Y direction. The envelope values for the results are 5.2% in the X direction and 5.7% in the Y direction. The data is listed in the Table 5.2.

5.2.1 Standard algorithm method

The additional damping ratio calculated by standard algorithm method according to Article 12.3.4 of GB50011-2010 "Code for Seismic Design of Buildings", the calculation formula is as follows:

$$\zeta_a = W_c/(4\pi \cdot W_s) \quad (1) \quad W_c = \sum_{j=1}^{m} \lambda_1 . F_{\mathrm{d}\,j\max} \Delta u_j \quad (2) \quad W_s = \frac{1}{2}\sum (F_i \cdot u_i) \quad (3)$$

Where: ζ_a is the actual additional equivalent damping ratio of the damper attached to the structure; $F_{dj\max}$ is the average damping force of the J-th damper under the corresponding horizontal seismic action; Δu_j is the relative horizontal displacements at both ends of the J-th damper; λ_1 is a function of the damping index, the value is 3.66; F_i is the standard value of the horizontal seismic action of particle i; u_i is the displacement of particle i corresponding to the standard value of the horizontal seismic action.

5.2.2 Cumulative energy method

The cumulative energy method is to compare the dissipated energy of the damper with the global damping of the structure (5% of the structure) to obtain the additional damping ratio of the damper. Figure 5.2 shows the energy curves of the two directions under precautionary earthquake action of time history R1 respectively.

$$\frac{W_s}{W_c} = \frac{\xi_s}{\xi_a}$$

W_s : The energy dissipated by structure global damping; W_c : energy dissipated by dampers; ξ_s : structure global damping ratio; ξ_a : additional damping ratio of the dampers. Figure 5.2 shows the X and Y direction energy curves respectively under the action of 7 degree (0.10g) earthquake time history R1 .

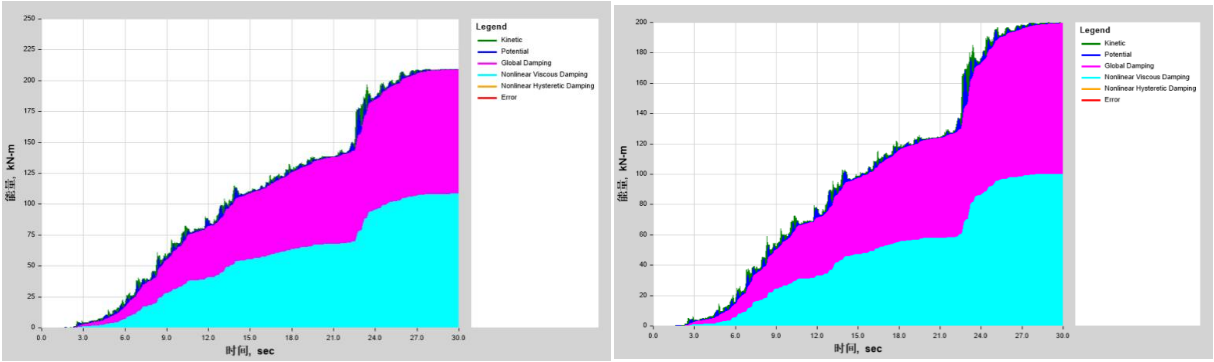


Figure 5.2: Energy curve under time history R1 action

Table 5.2 Damping ratio calculation results

Time History	Standard Algorithm Damping Ratio				Cumulative Energy Method Damping Ratio			
	X		Y		X		Y	
	damping ratio(%)	average Ratio	damping ratio(%)	average Ratio	damping ratio(%)	average Ratio	damping ratio(%)	average Ratio
T1	5.8	5.8	5.9	5.9	5.7	6	5.2	5.7
T2	5.4		5.7		6.1		5.6	
T3	5.2		5.8		6.5		6.2	
T4	4.5		5.2		7.4		7.5	
T5	5.2		5.9		5.6		4.9	
R1	5.5		5.9		5.4		5	
R2	5		5.8		5.5		5.3	

The output displacement of the damper under the action of precautionary earthquake time history R1 is extracted and the hysteresis curve is drawn, as shown in Figure 5.3. It can be seen that the hysteresis curve is relatively full, which indicates that the additional viscous fluid damper in the structure has begun to dissipate energy under the action of earthquake, showing a good damping ability.

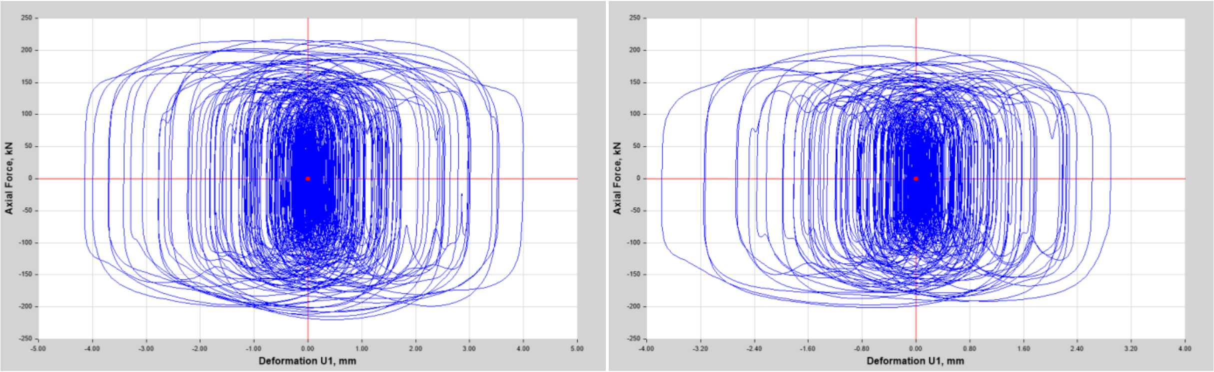


Figure 5.3: Typical X and Y damper hysteresis

6 ELASTOPLASTIC ANALYSIS OF RARE EARTHQUAKE

The structure elastoplastic analysis of rare earthquake is calculated by software SAUSAGE. The detailed step explicit dynamic direct integration method (second order central difference) is used to simulate the wave problem. The time step is controlled at 10^{-5} s order. The concrete reinforcement used in the model is designed by response spectrum under precautionary earthquake, and nonlinear fiber beam element is used for one-dimensional component, which is integrated along section and length direction respectively. The two-dimensional shell plate element adopts nonlinear layered element, which is integrated along the direction of in-plane and thickness respectively. The floor is also simulated as a two-dimensional shell unit. Three seismic time histories R1, T1, T2 with large seismic response are selected for analysis, and the envelope values of the three time histories are taken from the analysis results.

The analysis includes: the story drift and floor acceleration of the ST1 structure, the design damping force, design displacement and hysteretic energy dissipated by dampers, the elastoplastic development of the ST1 structure under the action of rare earthquakes and the stress of typical substructures.

6.1 The story drift and floor acceleration of rare earthquake

Under the action of rare earthquake duration, the maximum drift of ST1 is 1/217 and 1/191, respectively, meeting the expected objective of 1/150. The floor acceleration of ST1 is 2.53m/s^2 and 2.89m/s^2 , respectively, which both meet the expected objective of 0.45g. The seismic response of rare earthquake is shown in Figure 6.1.

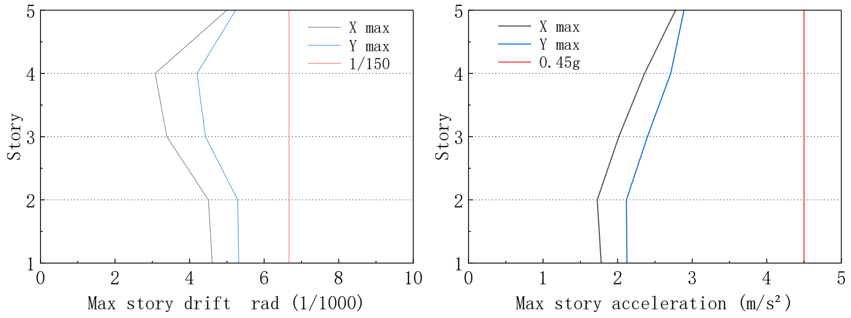


Figure 6.1: The seismic response of rare earthquake

6.2 The design damping force and design displacement

According to the statistics of three seismic time-history analysis results, the maximum output of X and Y viscous fluid dampers under rare earthquakes is 295.2kN and 311.9kN, respectively, and the maximum displacement is 19.7mm and 24.3mm, respectively. Typical X and Y damper hysteresis is shown in Figure 6.2

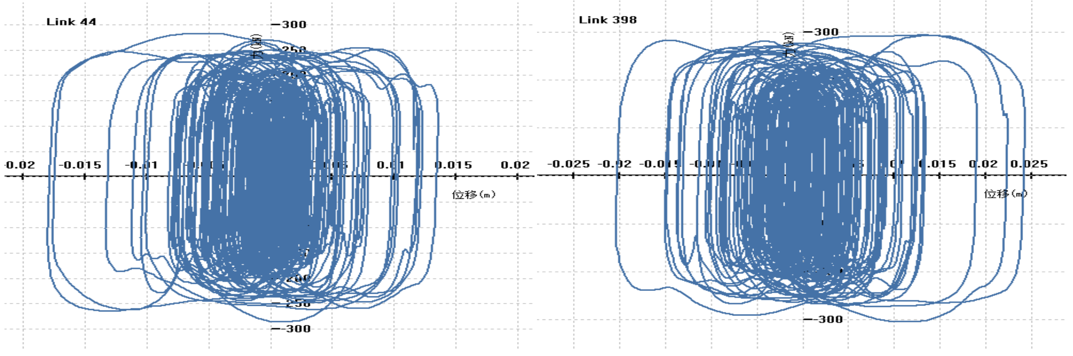
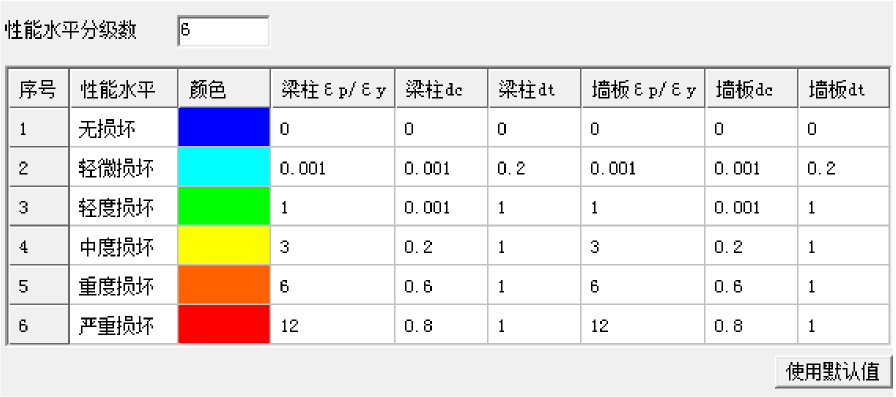


Figure 6.2: Typical X and Y damper hysteresis

6.3 Elastoplastic development of rare earthquake

The damage of the component in SAUSAGE is mainly assessed by the compressive damage factor of concrete, the tensile damage factor and the plastic strain degree of steel (rebar), as shown in Table 6.3:

Table 6.3 Elastic-plastic evaluation criteria of the structure under rare earthquake action

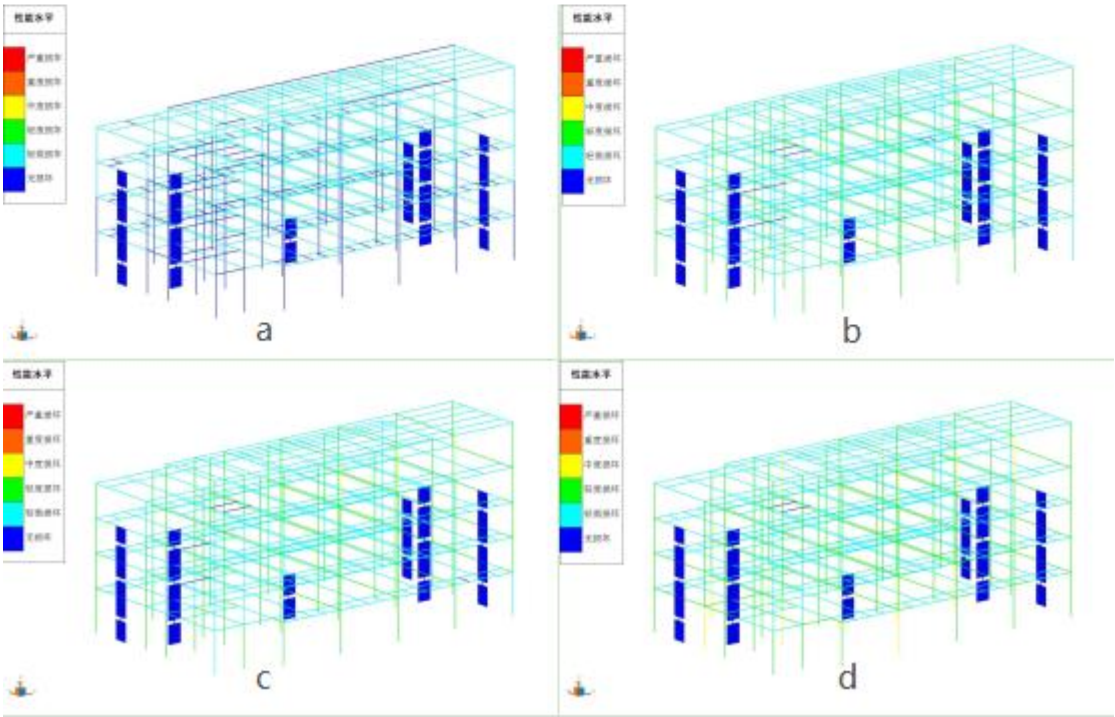


性能水平分级数 6

序号	性能水平	颜色	梁柱ε p/ε y	梁柱dc	梁柱dt	墙板ε p/ε y	墙板dc	墙板dt
1	无损坏	🟦	0	0	0	0	0	0
2	轻微损坏	🟦	0.001	0.001	0.2	0.001	0.001	0.2
3	轻度损坏	🟩	1	0.001	1	1	0.001	1
4	中度损坏	🟨	3	0.2	1	3	0.2	1
5	重度损坏	🟧	6	0.6	1	6	0.6	1
6	严重损坏	🟥	12	0.8	1	12	0.8	1

The values in the table are the upper limits of each performance level index of the unit, and each index is unfavorable. εp/εy is the plastic strain of steel bar (steel). dc is the compressive damage coefficient of concrete. dt is the tensile damage coefficient of concrete. The beam-column component performance grade is the maximum unit performance grade.

Figure. 6.3 shows the Y-direction elastoplastic development diagram of ST1 evaluated according to the above criteria under rare earthquake time history R1.



When a—1s；b—5s；c—10s；d—20s。

Figure 6.3: Time history R1 structure elastoplastic development

6.4 Stress of substructures

Each Pressure and Moment of the frame column are in its P-M curve, so the section reinforcement can be checked by this check. At the same time, the full length of the stirrup is encrypted to improve its ductility. Take the PMM curve of floor-1 1-cross-D axis substructure column as an example, as shown in Figure 6.4.

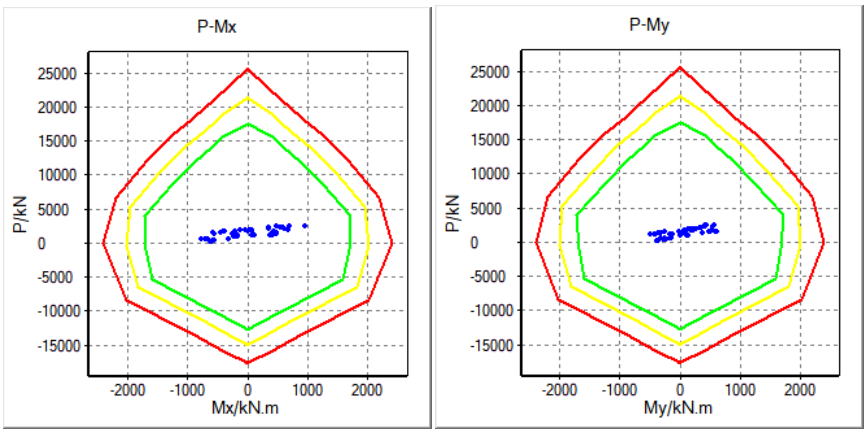


Figure 6.4: PMM curve of floor-1 1-cross-D axis substructure column

7 CONCLUSION

(1) Under the action of precautionary earthquake, the story drift of the model with dampers can meet the performance target of 1/400; The floor acceleration meets the expected performance objective of 0.25g; Compared with the model without dampers, the base shear is reduced by about 20%. The additional damping ratio meets the target of the expected additional damping ratio of 5%, which can be used in the subsequent structural design accurately. By comparative analysis, it is shown that the design scheme of energy dissipation has good effect.

(2) Under the action of rare earthquake, the drift in both X and Y directions of the model with dampers meets the performance objective of 1/150. The floor acceleration meets the expected performance objective of 0.45g; The performance level of the main structural frames is slight to mild failure, and the elastoplastic development under rare earthquakes meets the performance objective requirements, indicating that the structure is safe and reasonable.

(3) The substructural frame is still in the elastic stage under the action of rare earthquake, which can ensure that the viscous fluid dampers give full play to the energy dissipation function and achieve the expected performance target.

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