Seismic Behavior Analysis and Isolation Story Optimum Design of Mid-Story Isolation Building

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SUMMARY:
Studies on seismic behavior and isolation story optimum design of mid-story isolation building are analyzed. In this paper, a twenty-story mid-story isolation building which is composed of a large podium and two towers is investigated. Rubber bearings and viscous dampers are used in the seismic isolation story. And the finite element model of the building is established. In the design process, the arrangement of rubber bearings and viscous dampers of the isolation story are optimized based on the eccentric ratio. The seismic responses of mid-story isolation building and non-isolated building are calculated using the nonlinear dynamic time-history analysis method, which results indicate that the seismic responses of mid-story isolation building such as story shears and story displacements are smaller than those of non-isolated building. It is concluded that seismic responses of mid-story isolation building are decreased not only in superstructure but also in substructure.

Keywords: mid-story isolation building, optimum design, seismic response, rubber bearing,

1. INTRODUCTION

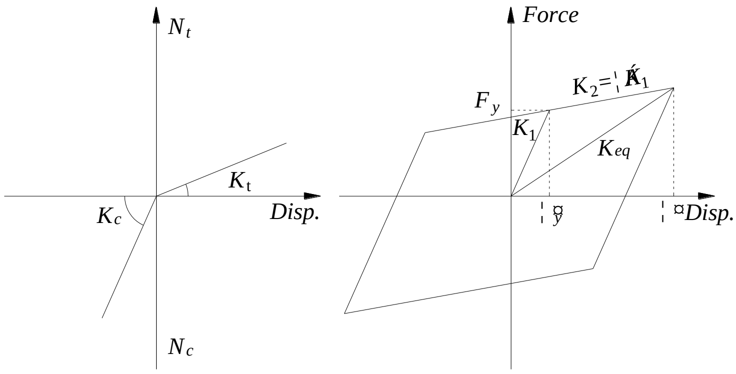
The seismic isolation technology is extensively used in structural vibration control since 1994 Northridge earthquake and 1995 Kobe earthquake. According to different locations of the isolation story, the seismic isolation building can be divided into base isolation building and mid-story isolation building. The mid-story isolation building in which the isolation story is designated at the top of the first or other stories has many advantages. It can practically satisfy architectural concerns, potentially facilitate constructions in site and effectively utilize the limited available space (Chang, 2010). Numerical analysis and shaking table test of mid-story isolation building are taken by many researchers (Li 2002, Xu 2005 and Qi 2006). Based on the studies, the mid-story isolation technology can be used to design the building with large podium and several towers.

In this paper, the mid-story isolation technology is used in a twenty-story building with a large podium and two towers in China. The design principles for isolation story are introduced. The arrangement of the isolation story and seismic responses of the whole building are studied. It is showed that the seismic responses of towers and podium are both reduced significantly.

2. DESIGN PRINCIPLES FOR ISOLATION STORY

A mid-story isolation building is taken to illustrate design principles for seismic isolation. The building is a complex structure which composed of a two-story basement, a four-story large podium and two sixteen-story L-type towers. The building is a frame shear wall structure and its total height is 73.7 m. The building is located in a high intensity zone in Jiangsu province China, whose design basic acceleration of ground motion is 0.3g. The site characteristic period is 0.35s. As a result, the mid-story isolation technology is used in this project with comprehensive consideration of seismic precautionary and economy. The isolation story whose height is 1.8m is set between the podium roof and the bottom of two towers. The elevation view of the mid-story isolation building is shown in Figure 1.

Figure 1. Elevation view of the mid-story isolation building



(a) vertical characteristic (b) lateral characteristic

Figure 2. Mechanical models of rubber bearings

The key aspect of seismic isolation design is the simulation of rubber bearings. Figure 2 (a) gives the vertical stiffness model of rubber bearings. As shown in the figure, the tensile stiffness is much smaller than the compressive stiffness. The lateral characteristic of natural rubber bearing is assumed to be linear because of its lateral stiffness and damping is smaller. Figure 2 (b) gives the lateral characteristic of lead rubber bearing which is simplified to be a bilinear system.

Eccentric ratio of the isolation story is an important factor for seismic isolation design. Japan norm and Taiwan norm clearly defined that eccentric ratio of isolation floor cannot exceed 3% in X and Y directions. As a result, eccentric ratio of the isolation story is calculated in the mid-story isolation building design. Eccentric ratios of the isolation story in two directions ρ_x, ρ_y are calculated by the following equations:

$$\rho_x = \frac{e_y}{R_x},\ \rho_y = \frac{e_x}{R_y} \tag{2.1}$$

$$e_x = \left|Y_g - Y_k\right|,\ e_y = \left|X_g - X_k\right| \tag{2.2}$$

$$R_x = \sqrt{\frac{K_t}{\sum K_{ex,i}}},\ R_y = \sqrt{\frac{K_t}{\sum K_{ey,i}}} \tag{2.3}$$

$$X_g = \frac{\sum N_{l,i} \cdot X_i}{\sum N_{l,i}},\ Y_g = \frac{\sum N_{l,i} \cdot Y_i}{\sum N_{l,i}} \tag{2.4}$$

$$X_k = \frac{\sum K_{ey,i} \cdot X_i}{\sum K_{ey,i}},\ Y_k = \frac{\sum K_{ex,i} \cdot Y_i}{\sum K_{ex,i}} \tag{2.5}$$

$$K_t = \sum\left[K_{ex,i}\left(Y_i - Y_k\right)^2 + K_{ey,i}\left(X_i - X_k\right)^2 \right] \tag{2.6}$$

where $N_{l,\,i}$ is long-term axial compression load taken by the i^{th} bearing; X_i and Y_i are the coordinates of X and Y direction of the i^{th} bearing; $K_{ex,\,i}$ and $K_{ey,\,i}$ are the equivalent stiffness of X and Y direction, respectively, when the i^{th} bearing produce a specified displacement Δ.

3. SEISMIC ISOLATION STORY DESIGN

In order to get a good seismic isolation effect, the isolation story should have four basic characteristics: (1) It should have a large vertical load capacity, which can support the superstructure safely; (2) It should have a variable lateral stiffness. Bigger initial shear stiffness can make the isolation story not yield under wind load and micro-vibration. Smaller post-yielding stiffness can turn the isolation floor into a flexible system which separate earthquake ground motions effectively when major earthquakes happens; (3) It should have a elastic restoring force, which makes isolation story reset its position quickly under earthquakes; (4) It should have sufficient damping. So the structure can have a greater energy dissipation capacity.

In order to achieve the above requirements, rational distribution of lead rubber bearings, natural rubber bearings and viscous dampers is essential. Lead rubber bearing should be arranged in the isolation story peripheral to control the torsion. The arrangement of natural rubber bearing can coordinate with the eccentric ratio. Viscous dampers can provide large damping force under major earthquakes, so the dampers can be arranged around the structure to control the torsion.

Based on the layout principles, the arrangement of isolation floor of the mid-story isolated building is shown in Figure 3 and Figure 4. LRB900 denotes lead rubber bearing with a diameter of 900mm. RB1000 denotes natural rubber bearing with a diameter of 1000mm. The parameters of the rubber bearings used in this project are shown in Table 3.1.

Table 3.1. Parameters of rubber bearings used in the project

Type	LRB900	LRB1000	LRB1100	LRB1300	RB1000	RB1200
Area (cm^2)	6107	7540	9157	12821	7815	11271
Diameter of lead (mm)	180	200	210	240	/	/
Diameter of center hole (mm)	/	/	/	/	70	70
Number of rubber layers	30	33	32	37	29	29
Total thickness of rubber (mm)	180	198	224	259	203	203
Thickness of steel plate (mm)	4.4	4.4	4.4	4.4	4.3	4.3
The first shape factor	37.5	41.7	39.3	46.4	33.2	40.4
The second shape factor	5.0	5.1	4.9	5.0	4.9	5.9
Vertical stiffness (kN/mm)	4415	5321	5476	7325	4003	6803
Lateral stiffness (kN/mm)	2.52	2.83	2.90	3.41	1.49	2.15
Initial stiffness (kN/mm)	18.12	20.34	21.72	26.20	/	/
Post-yield stiffness (kN/mm)	1.394	1.565	1.671	2.016	/	/
Yield force (kN)	202.9	250.4	276.1	360.6	/	/
Number used in the building	24	21	8	3	8	5

Rubber shear elasticity modulus is $0.392N/mm^2$

Figure 3 shows the isolation story arrangement of tower A. Fifteen LRB900, five LRB1000 and eight LRB1100 arrange along the structure of peripheral. Five RB1000 and two RB1200 arrange along the structure of internal. Figure 4 shows the isolation story arrangement of tower B. Nine LRB900, sixteen LRB1000 and three LRB1300 arrange along the structure of peripheral. Three RB1000 and three RB1200 arrange along the structure of internal. Both two towers arrange eight viscous dampers along the structure of peripheral to control torsion effect.

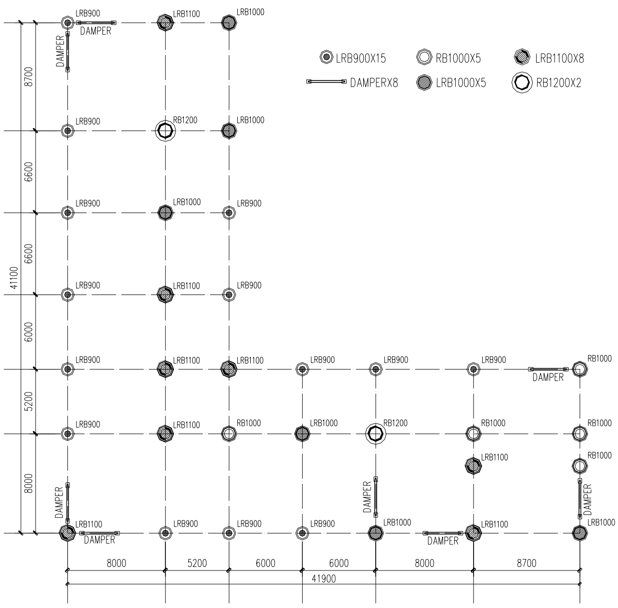


Figure 3. Isolation story arrangement of tower A

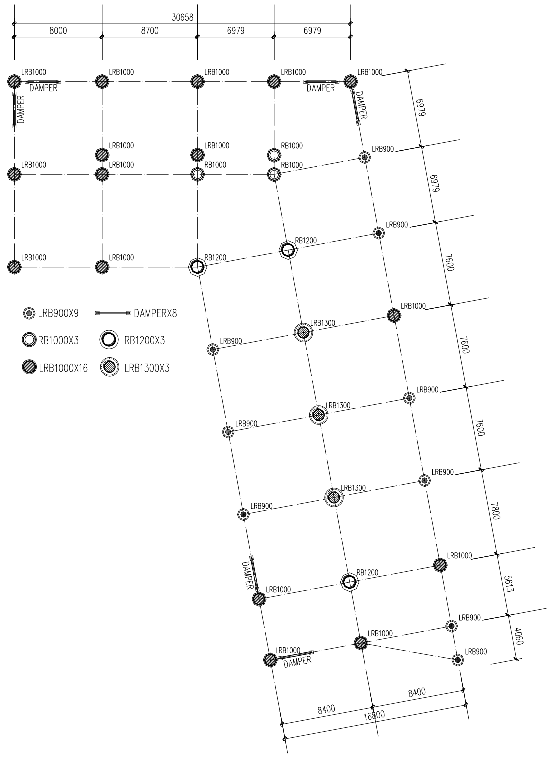


Figure 4. Isolation story arrangement of tower B

Figure 5 and Figure 6 give the restoring force of two towers. As shown in the figures, the isolation story has a large yield force to sustain the wind load. The smaller post-yield stiffness ensures the building a good isolation effect.

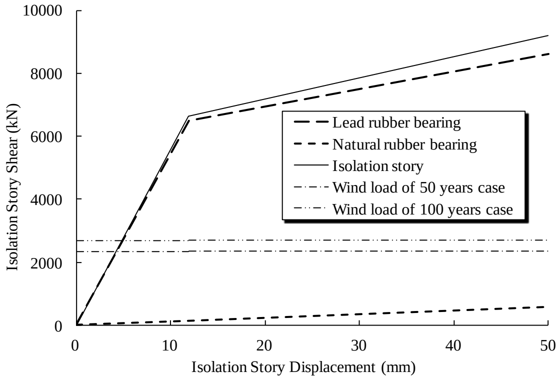


Figure 5. Isolation restoring force of tower A

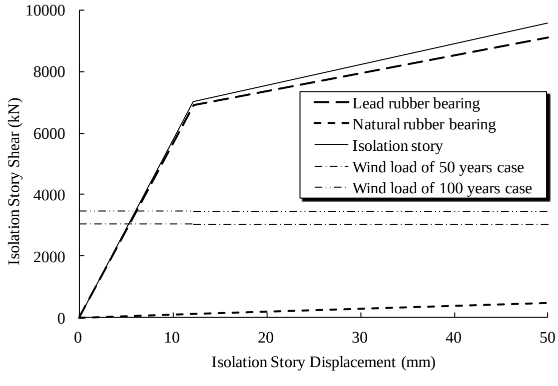


Figure 6. Isolation restoring force of tower B

According to equation (2.1) ~ (2.6), Table 3.2 gives eccentric ratios of tower A and tower B. Figure 7 and Figure 8 give the schematic diagrams of eccentric ratio of two towers.

Table 3.2. Eccentric ratio of the isolation story

	Layout direction	Tower A	Tower B
Center of gravity (m)	X =	24.628	73.576
	Y =	19.769	34.698
Center of rigidity (m)	X =	24.624	73.428
	Y =	19.895	34.679
Eccentric distance (m)	X =	0.004	0.149
	Y =	-0.127	0.019
Torsion stiffness (kN/m)	K_t =	2.88E+11	3.96E+11
Gyration radius (m)	R_x =	18.201	21.075
	R_y =	18.201	21.075
Eccentric ratio	ρ_x =	-0.007	0.001
	ρ_y =	0.000	0.007

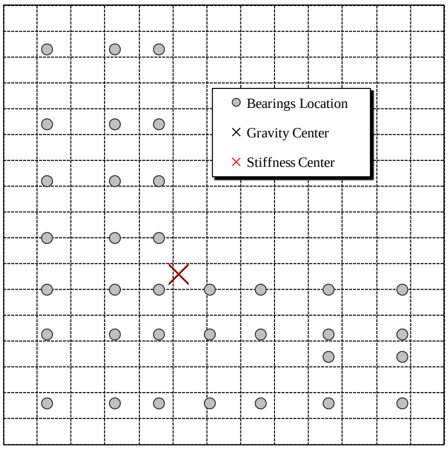


Figure 7. Eccentric ratio of isolation story of tower A

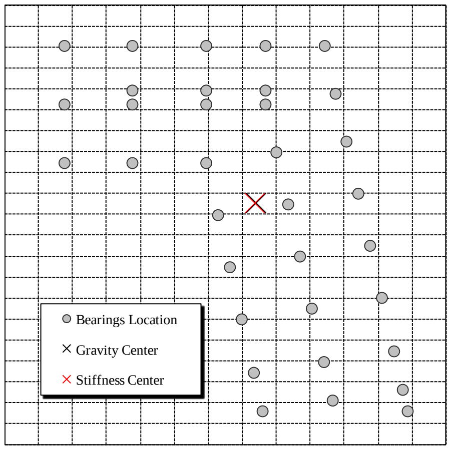


Figure 8. Eccentric ratio of isolation story of tower B

The results show that eccentric ratios of two towers are both smaller than 3% in X and Y directions. It is indicate that isolation story is arranged regularly. Gravity center and stiffness center are nearly in the same position. And the towers are in a parallel motion state. So the rubber bearings have sufficient stability and safety to keep the towers in a parallel motion state under earthquakes.

4. SEISMIC REPONSE ANALYSIS OF MID-STORY ISOLATION BUILDING

In order to study the seismic behavior of mid-story isolation building, four earthquake ground motions (EGM) were selected to start nonlinear time history analysis. The load cases are bidirectional ground motion input. And primary and secondary direction of ground motion intensity ratio is 1:0.85. In this paper, the seismic responses of isolated and non-isolated building under intensity earthquakes and major earthquakes are investigated. Figure 9 gives the acceleration spectrum of four major earthquake ground motions used in this project.

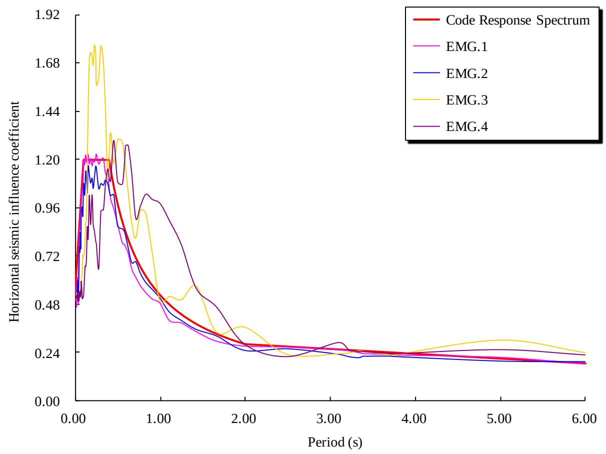


Figure 9. Acceleration spectrum of major earthquake ground motion

Figure 10 give the story shears of towers under precautionary intensity earthquake between isolated and non-isolated building. As shown in the figure, the story shears of towers of mid-story isolation building is one third of the non-isolated building.

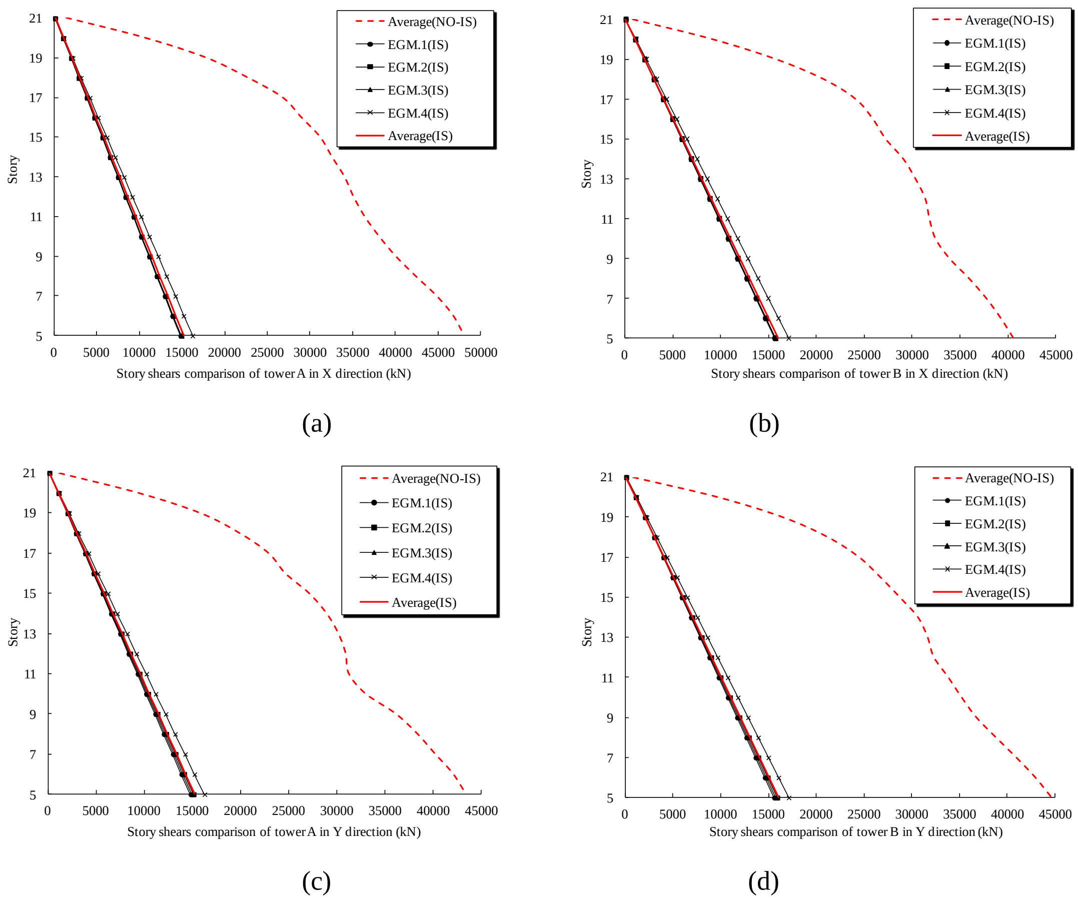


Figure 10. Story shears of towers under precautionary intensity earthquake

Figure 11 (a) and Figure 11 (b) give the story shears of podium under precautionary intensity earthquake between isolated and non-isolated building. The figure shows the story shears of podium of mid-story isolation building is half of the non-isolated structure. Figure 11 (c) and Figure 11 (d) give the story displacements of podium of mid-story isolation building under precautionary intensity earthquake. The figures show that story drifts of podium are less than 1/1000 in two directions.

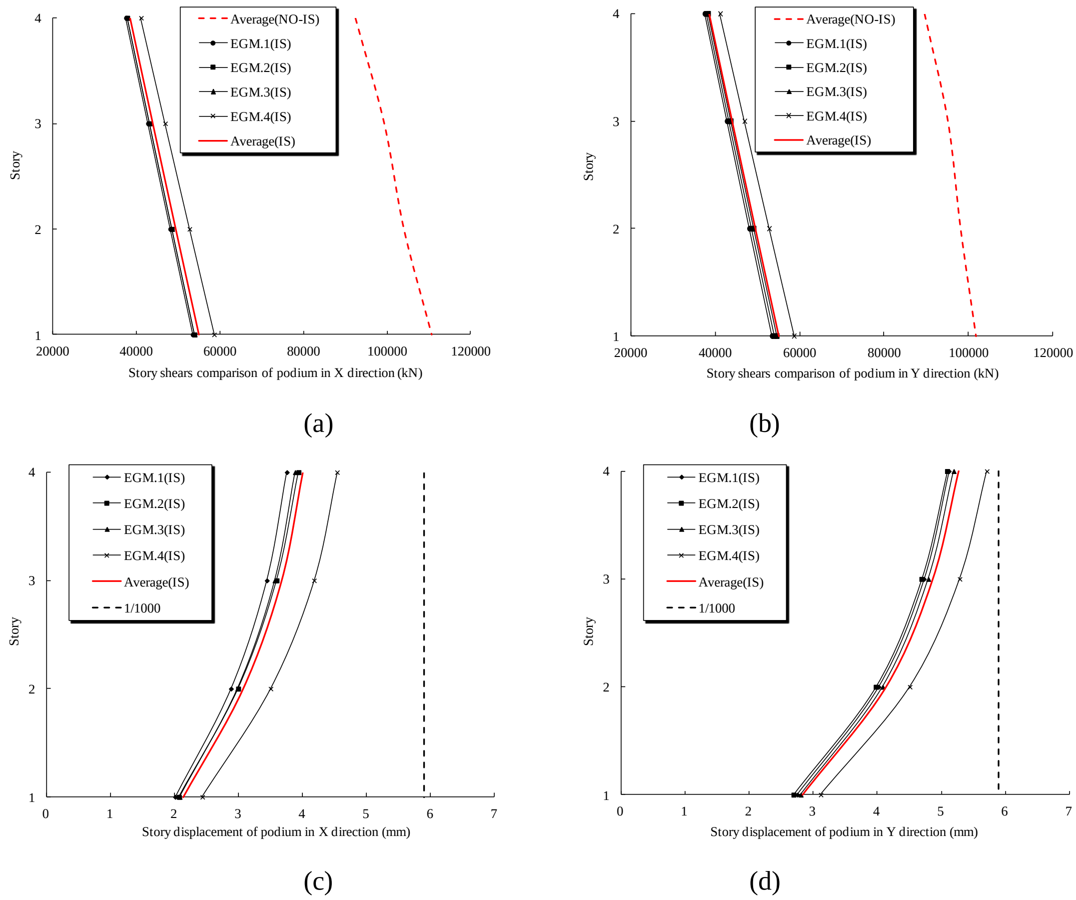


Figure 11. Seismic responses of podium under precautionary intensity earthquake

Figure 12 (a) ~ Figure 12 (d) give the story displacements of mid-story isolation building towers under precautionary intensity earthquake. The figures show that story drifts of towers are less than 1/500 in two directions.

Figure 13 and Figure 14 give the story displacements of mid-story isolation building under rare earthquake. As shown in Figure 13, the story drifts of towers are less than 1/200 in two directions under rare earthquake. Figure 14 shows the story drifts of podium are less than 1/500 in two directions under rare earthquake.

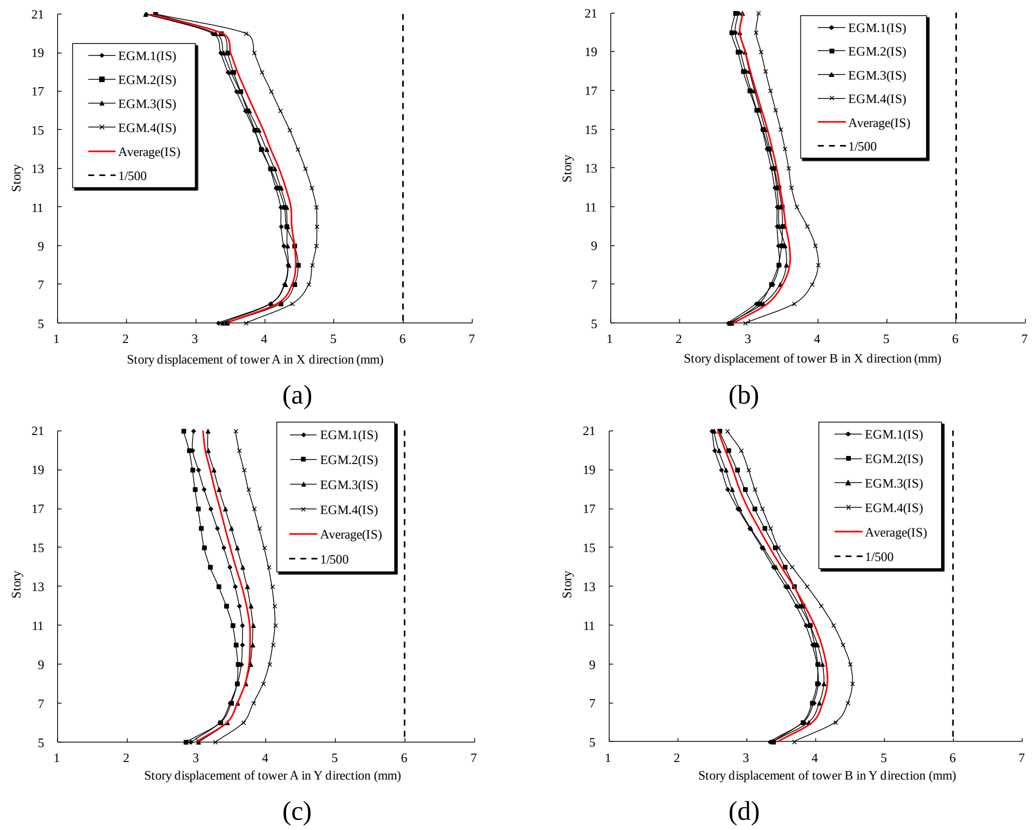


Figure 12. Story displacements of towers under precautionary intensity earthquake

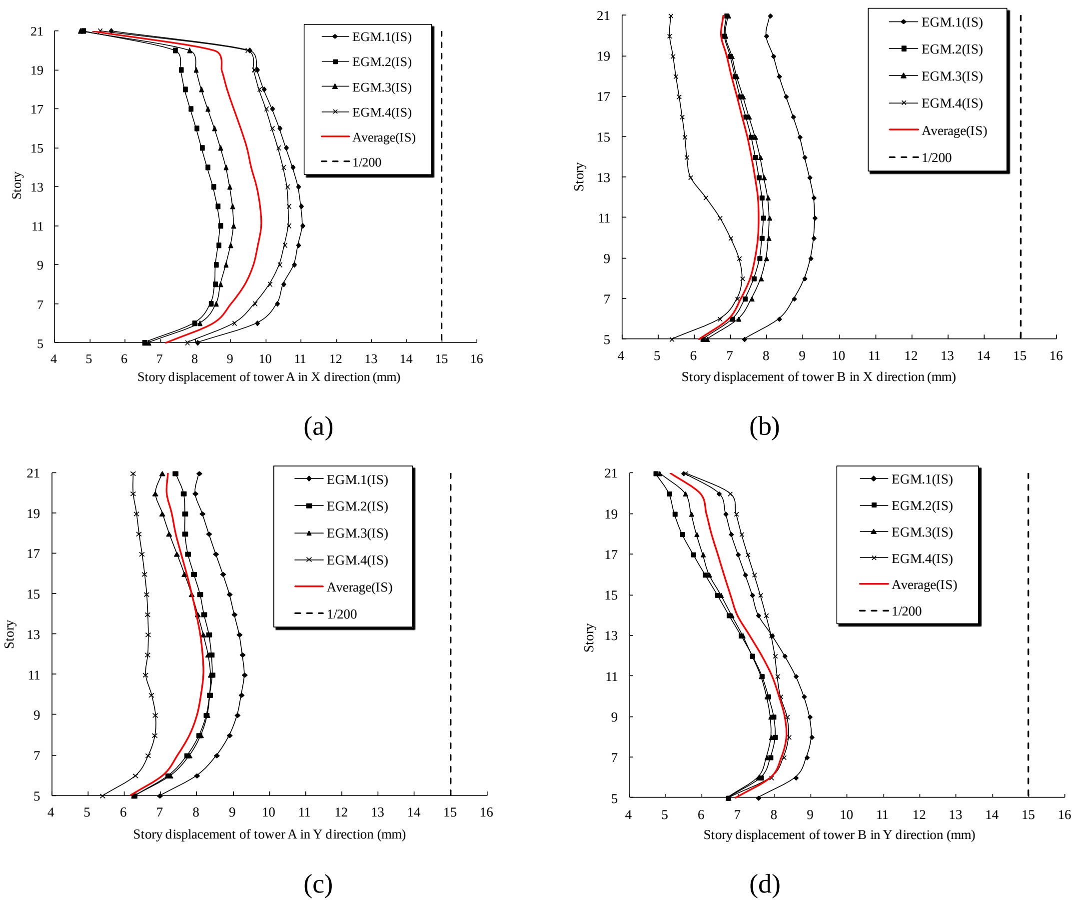
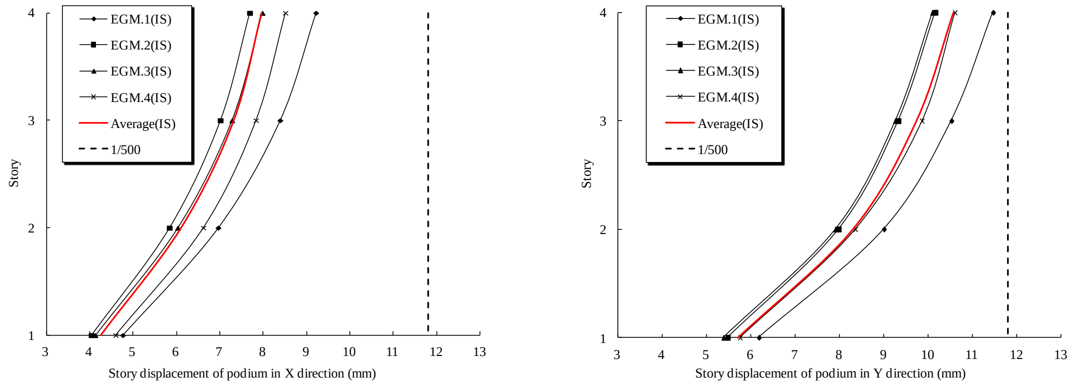


Figure 13. Story displacements of towers under rare earthquake



(a) (b)

Figure 14. Story displacements of podium under rare earthquake

The seismic responses comparison of mid-story isolation and non-isolated buildings are shown in Fig.7(a-d). Compared with non-isolated structure, story displacements of isolated structure are very small, and the deformations are mainly concentrated in the isolation layer. So the two towers are in a parallel motion under earthquake. Story shears of isolated structure are smaller than non-isolated structure. The story shears of two towers are significantly reduced, while the shears of the podium also decrease.

5. CONCLUSIONS

In this paper, the isolation story design of mid-story isolation building with large podium and two towers is analyzed. And the seismic responses of isolated and non-isolated structures are studied by nonlinear time history method. The conclusions are as follows: (1) Using the bilinear system to simulate the lateral characteristic of isolation story is reasonable. Variable lateral stiffness ensures the isolation story not yield under wind loads or micro-vibration. And when earthquakes come, the isolation story has a good isolation effect. In the design process, the eccentric ratio of isolation story is an important factor which cannot exceed 3% in X and Y directions. As a consequence, the towers can move in a parallel motion. (2) Analysis showed that story shears of mid-story isolation building are smaller than the non-isolated building under precautionary intensity earthquake. Story displacements of mid-story isolation building are also within the limit. (3) Story displacement of mid-story isolation building is smaller than interstory drift limit of China code under major earthquakes. The mid-story isolation technology can reduce the seismic responses of the whole structure, when it is used in the structure of two towers and large podium in high-intensity zone. The technology makes the structure in a flexible state and protects the building effectively.

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