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Study on seismic response of a new double story isolated structure

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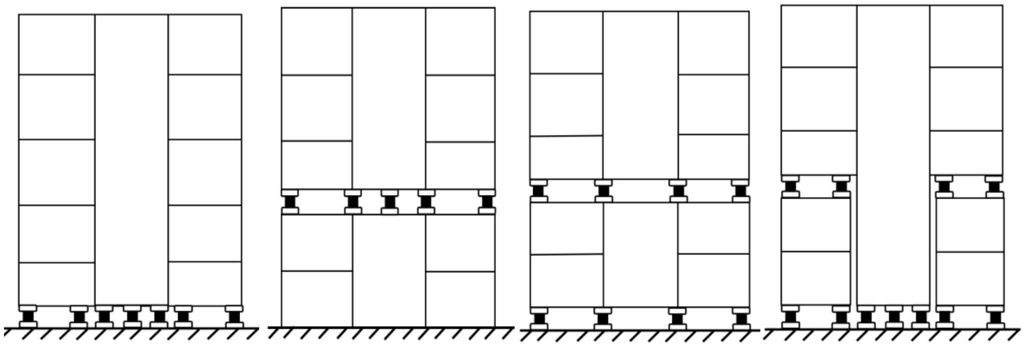
Abstract: The traditional double story isolated structure is a type of isolated structure developed from base isolated structure and inter-story isolated structure. The new double story isolated structure is a new type of isolated structure developed from traditional double story isolated structure. In order to study the seismic response of the new double story isolated structure, the model of the structure was established. At the same time, models of basic fixed, base isolated, inter-story isolated and traditional double story isolated structures were established. The nonlinear dynamic time history response of the new double story isolated structure under rare earthquakes was analyzed. The study shows that compared to basic fixed, the new double story isolated structure has superior performance in all aspects. Compared with base isolated and inter-story isolated, the new double story isolated structure can significantly reduce the inter-story shear force, top acceleration, and inter-frame displacement of the structure. The horizontal displacement of the new double story isolated structure is concentrated on the two isolated layers of the structure, dissipating most of the input seismic energy. Compared with the traditional double story isolated structure, the new one reduces the displacement of the inter-isolation layer in the middle of the frame, ensuring the integrity of the core tube and avoiding collapse and damage of the structure.

1. Introduction

The new double story isolated structure is a new type of isolation system developed on the basis of traditional double story isolated structures. The characteristic of the base isolated structure is the isolated layer lies at the bottom of the structure, as shown in Figure 1a. The characteristic of the inter-story isolated structure is the isolated layer lies in the middle of the structure, as shown in Figure 1b. The characteristic of the traditional double story isolated structure is isolated layers lie at the bottom and middle parts of the structure, as shown in Figure 1c. The seismic isolated layer of the new double story isolated structure is divided into two parts, the isolated layer at the bottom of the core tube and the frame, which forms a similar base isolated structure, and the isolated layer in the middle of the frame, which forms a similar inter-story isolated structure, as shown in Figure 1d. The new double story isolated structure removes the isolated bearing in the middle of the core tube based on the traditional double story isolated structure, avoiding stress concentration and damage at the connection between the core tube and the isolated bearing, ensuring the integrity of the core tube.



(a) Base isolated structure (b) Inter-story isolated structure (c) Traditional double story isolated structure (d) New double story isolated structure

Figure 1: Schematic diagram of four types of seismic isolated structures

The research on base isolated by Zhou Fulin[1], Nakai Arisa[2], Gupta P K[3] and others has brought the base isolated to a more mature stage. The research on inter-story isolated structure at home and abroad began later than that on base isolated structure, and the research on inter-story isolated has increased year by year due to the study efforts of Zhou Fulin[4], Ishizawa Yuji[5], Park H S[6], and others. Compared with base isolated structures that are not suitable for structures with large height-to-width ratios, and inter-story isolated structures, which have poor damping effects on the lower part of the structure and cannot guarantee the integrity of the core tube, the new double story isolated structure can effectively compensate for the shortcomings of these two structures. Ou Jinping[7] studied the large-displacement friction pendulum base and multi-layer isolated to provide a new structural system and key development direction for the development of ductility structures. Zhang Ying[8] proposed a method for selecting the stiffness and damping parameters of each isolated layer in a segmented isolated structure, and performed a simulation analysis of the seismic performance of the segmented isolated structure. Gao Jianping and Pan Yueyue[9,10] conducted parameter and energy analyses to obtain optimal parameter combinations for segmented isolated structure, as well as energy response laws, and established an energy-based passive control parameter optimization method for segmented isolated structure. Qiao Liwei[11] studied the impact of changes in stiffness and damping of isolated layers on isolation effectiveness in segmented isolated structure. Wu Qiaoyun[12,13] analyzed the effect of seismic waves with different earthquake characteristics on short-period wave action of segmented isolated frame structure, and based on shaking table tests, determined the impact of changing the position of the intermediate isolated layer on isolated effectiveness. Hu Baoqing[14] analyzed and compared the seismic responses of segmented isolated structures under one-dimensional and two-dimensional horizontal earthquake actions. Wang Xueqing[15] conducted finite element analysis on a segmented isolated high-rise building structure using an SMA-laminated rubber bearing designed as the isolated layer.

2. Numerical model

2.1 Project Overview

An 18-story reinforced concrete frame-core structure located on a site with a characteristic period of 0.40 seconds, maximum response modification factor of 0.45, design base shear reduction factor of 0.85, and a seismic design acceleration of 0.2g. The layout of the plan is shown in Figure 2, with dimensions of 35m × 15m. The total height of the building is 68.4m, the first floor height is 4m, and the standard floor height is 3.6m. A 3D rendering of the structure can be seen in Figure 3. The concrete strength levels for the frame columns, beams, and core tube have been defined as C40, and the slab thickness is 150mm. The thickness of the protective layer for the pillars and beams is 40mm. The longitudinal reinforcement bars are HRB400, while the stirrup is HRB335. The information on the frame beams and columns is shown in Table 1, and the shear wall information for the core tube is shown in Table 2.

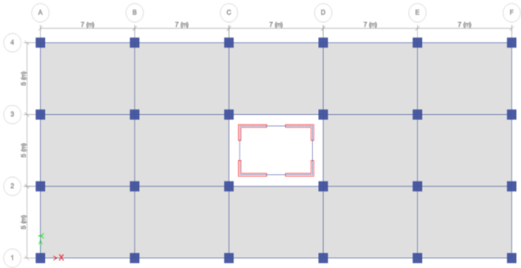


Figure 2: Floor plan

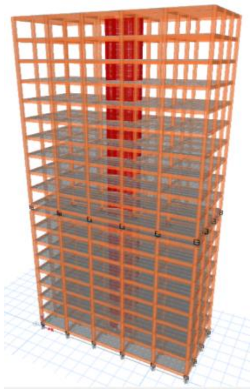


Figure 3: Three-dimensional diagram

Table 1: Information of frame section

Component type	Component position (floor)	Sectional dimension (mm)
Frame column	1~8	700×700
	9~18	600×600
Frame beam	1~8	700×350
	9~18	600×300
Connecting beam	1~18	400×200

Table 2: Information of shear wall section

Component type	Sectional name	Unit type	Concrete thickness /mm	Vertical distribution of reinforcing bars ratio
Shear wall in non-bottom strengthening zone	Wall	Thin-shell	200	--
Shear wall with constrained edge members	Wall-Edge	Multi-layer shell	200	5%
Shear wall with non-constrained edge members	Wall	Multi-layer shell	200	0.50%

2.2 Model parameter definition

When building a new double story isolated structure model using ETABS finite element software, the shear walls of constrained edge components and non-constrained edge components are simulated using layered shells to reinforce the bottom area of the core tube, which is set in two layers at the bottom of the core tube. Thin shell elements are used to simulate the shear walls for the non-reinforced bottom area. The isolated bearing uses Isolation units, which have two shear deformation components that need to consider nonlinear characteristics. Spatial beam-column elements are used for frame columns and beams, and shell elements are used for slabs. P-M2-M3 hinges are adopted for frame columns, and M3 hinges are used for both ends of the beam and the connecting beam. The concrete strength level C40 adopts Takeda hysteresis type, and the steel bars HRB335 and HRB400 adopted Kinematic hysteresis type. The structural analysis uses direct integration method to calculate the model.

The seismic isolated layer is set on the top of the 8th floor of the frame, the bottom of the frame and the bottom of the core tube, the isolated bearings are connected with the columns through consolidation, the height of each isolated layer is 1.6m. The frame isolated layer is equipped with 48 LRB800 lead-core rubber seismic isolated bearings, the core tube isolated layer is equipped with 12 LRB900 lead-core rubber seismic isolated bearings. Information on LRB800 and LRB900 lead rubber isolated bearings can be found in Table 3.

Table 3: Parameters of isolated bearings

Model	Effective diameter (mm)	Total thickness of rubber (mm)	Stiffness before yield (kN m^{-1})	250% horizontal shear deformation (kN m^{-1})	Vertical stiffness (kN mm^{-1})	Yield strength (kN)
LRB800	800	160	13808	1770	4355	167.5
LRB900	900	162	17046	2213	5233	212

2.3 Selection of seismic waves

To study the seismic reduction effect of the new double story isolated structure, five actual earthquake records were selected from the Pacific Earthquake Engineering Research Center (PEER) earthquake motion database, and two artificial waves generated by GM-Tools software were also chosen. After processing, the peak acceleration of the earthquake waves was adjusted to 400cm/s^2, which is equivalent to the peak acceleration value corresponding to the basic seismic intensity of level VIII under rare earthquakes. The earthquake wave acceleration response spectrum is shown in Figure 4.

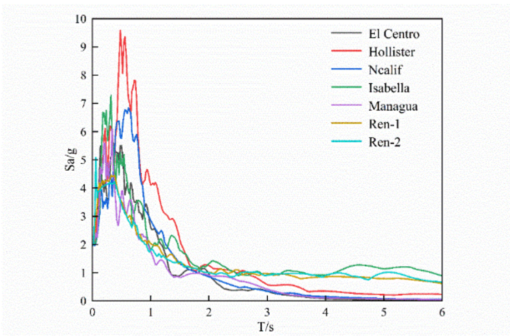


Figure 4: Acceleration spectra of selected ground motion records

3. New double story isolated structure seismic response research

3.1 Modal Analysis

Modal analysis was conducted on five structural models, including the basic fixed, base isolated, inter-story isolated, traditional double story isolated, and new double story isolated models. The first six natural vibration periods for each model are shown in Table 4.

Table 4: First six orders of self-oscillation period (s) for the five structural systems

Modal period	Basic fixed	Base isolated	Inter-story isolated	Traditional double story isolated	New double story isolated
1	1.761	3.236	2.859	3.925	3.776
2	1.544	3.117	2.646	3.789	3.761
3	1.52	3	2.632	3.695	3.428
4	0.583	0.972	0.653	1.589	1.589
5	0.542	0.853	0.634	1.556	1.555
6	0.536	0.846	0.586	1.412	1.412

As shown in Table 4, both base isolated, inter-story isolated, and double story isolated structures can effectively increase the natural vibration period of the structure. The traditional and new double story isolated structures have greater prolongation of the natural vibration period due to the additional isolated layer compared to base and inter-story isolated structures. The first natural vibration periods of the base isolated and inter-story isolated structures are 1.838 and 1.624 times that of the basic fixed structure, respectively, not meeting the general limit of a period ratio of 2[16]. The first natural vibration periods of the traditional and new double story isolated structures are 2.229 and 2.144 times that of the basic fixed structure, respectively, meeting the limit of a period ratio of 2. Compared with base and inter-story isolated structures, the fourth, fifth, and sixth higher modes of the new double story isolated structure show more significant increases, which can enhance the damping effect on higher modes and reduce damage to the upper structure under seismic actions.

3.2 Comparative analysis of seismic isolated effect

3.2.1 Comparison of base shear force

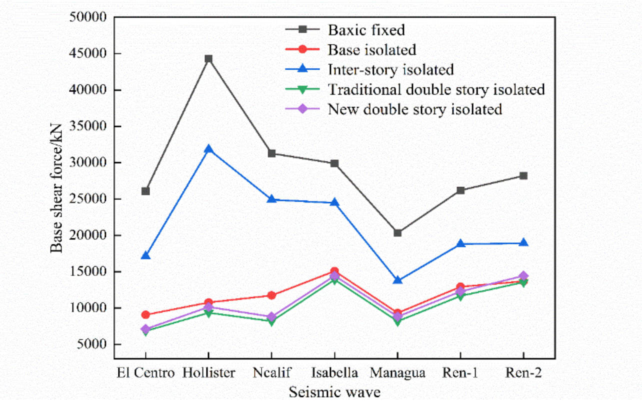


Figure 5: Base shear force

The comparison of base shear among the five isolated structures is shown in Figure 5. As depicted, under the action of seven earthquake waves, both traditional and new double story isolated structures show lower base shear values than the basic fixed, base isolated, and inter-story isolated structures. The average base shear values of the traditional and new double story isolated structures are respectively reduced by 13.2% and 7.91% compared to the base isolated structure, and by 52.16% and 49.24% compared to the inter-story isolated structure, indicating that traditional and new double story isolated structures can further weaken the energy transmitted to the upper structure.

3.2.2 Top-floor acceleration comparison

The comparison of top floor acceleration among the five isolated structures is shown in Figure 6. As illustrated, under the action of seven earthquake waves, the average top floor acceleration of both traditional and new double story isolated structures are respectively reduced by 74.13% and 73.83% compared to that of the basic fixed structure; by 38.22% and 37.51% compared to that of the base isolated structure, and by 53.8% and 53.27% compared to that of the inter-story isolated structure, indicating that traditional and new double story isolated structures can better reduce the vibration of the structure itself.

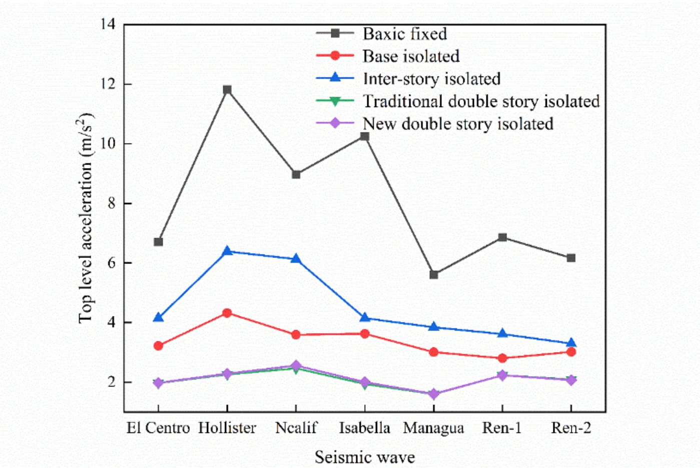


Figure 6: Top level acceleration

3.2.3 Inter-story shear force comparison

The average inter-story shear forces of five types of seismic isolated structures under the action of seven earthquake waves are shown in Figure 7. It can be seen from the figure that compared to basic fixed structure, base isolated structure, and inter-story isolated structure, the traditional and new double story isolated structures can effectively reduce the inter-story shear forces. Moreover, there is little difference in inter-story shear forces between traditional and new double story isolated structures.

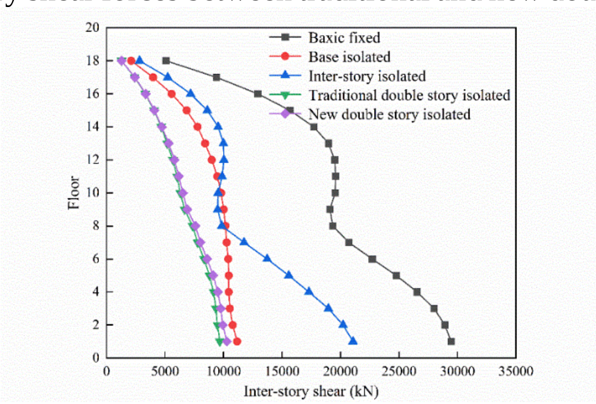


Figure 7: Average value of inter-story shear force for the action of seven seismic waves

3.2.4 Displacement of seismic isolated layer

According to the "Code for Seismic Design of Buildings" (GB 50011-2010)[17], under the rare seismic effect of level VIII, the tensile stress of the isolation bearings should not exceed 1MPa, and the compressive stress limit is 30MPa. The maximum horizontal displacement of the isolated bearings should not exceed the smaller value between 0.55 times the diameter of the bearing and 3 times the total thickness of the rubber layer. This article adopts LRB800 bearings and LRB900 bearings, so the horizontal limit of the isolated bearings is 800mm $\times$ 0.55 = 440mm and 162 $\times$ 3 = 486mm. According to Table 5, the tensile and compressive stress and the maximum displacement of the isolated layers in the framework, bottom of core tube and intermediate isolated layer of the new double story isolated structure are within the specification limits.

Table 5: Stress in vibration isolated bearing

Bearing indicators		Compressive stress (MPa)	Tensile stress (MPa)	Maximum horizontal deformation (mm)
Base isolated		12.36	0.89	170.693
Layer Isolated		8.87	0.37	168.266
Traditional double story isolated	Upper isolated layer	6.41	0	280.594
	Lower isolated layer	12.40	0.48	
New double story vibration isolated	Upper isolated layer	6.43	0	203.492
	Lower isolated layer	12.48	0.97	

3.2.5 Inter-story displacement

Inter-story displacements of five types of isolated structures, including a basic fixed structure, a base isolated structure, an inter-story isolated structure, a traditional double story isolated structure, and a new double story isolated structure, were obtained under the action of seven seismic waves. The inter-story displacement under the action of the seven seismic waves is shown in Figures 8 to 10. The frame inter-story displacement and the core tube inter-story displacement of each type of seismic isolated structural system under the El Centro, Hollister, Ren-1, waves are shown in Figures 8, 9, 10, respectively for (a) the frame inter-story displacement and (b) the core tube inter-story displacement.

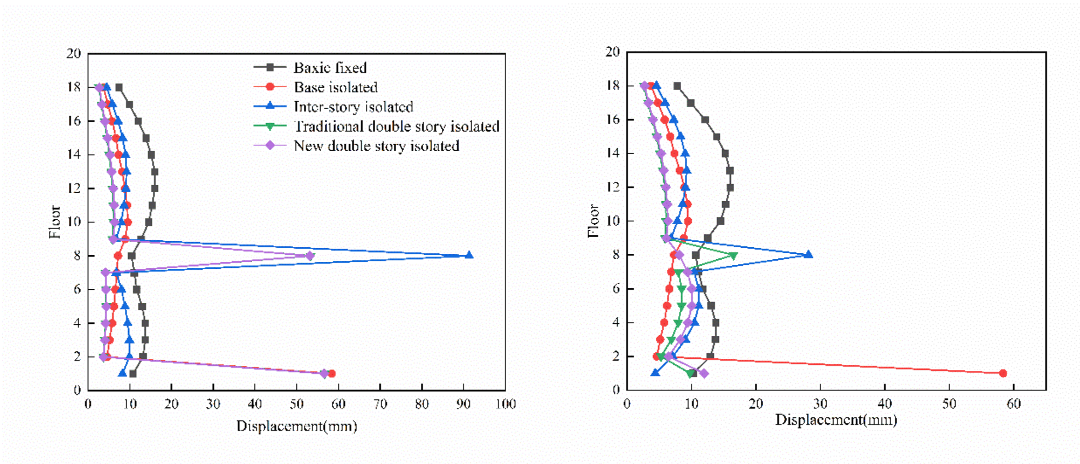
Based on Figures 8-10, it can be determined that under the excitation of seven earthquake waves, both the new and traditional double story isolated structures exhibit smaller inter-story displacement and reduced top floor displacement compared to basic fixed structure. However, the displacement of the base isolated layer of the frame is relatively larger than that of the intermediate isolated layer. The inter-story displacement of both the new and traditional double story isolated structures, as well as the base isolated structure and inter-story isolated structure, are all smaller than basic fixed structure. Furthermore, the inter-story displacement of the new and traditional double story isolated structures in the frame is superior to that of the base isolated structure and inter-story isolated structure.

The comparison between the new double story isolated structure and the base isolated structure is shown in Figures 8 to 10. It can be seen that the inter-story displacement of the new double story isolated structure is smaller than that of the base isolated structure. Although the bottom isolated layer displacement of the new double story isolated structure is slightly larger than that of the base isolated frame, the difference between them is significant compared with the bottom isolated layer displacement of the core tube. This indicates that the new double story isolated structure can effectively reduce the displacement of the bottom isolated layer of the core tube.

The comparison between the new double story isolated structure and the inter-story isolated structure based on Figures 8-10 indicates that the inter-story displacement of the new double story isolated structure is smaller than that of the inter-story isolated structure. The new double story isolated structure can effectively reduce the inter-story displacement at the intermediate isolated layer of the frame, indicating that it has a strong control ability over the lateral displacement of the anti-seismic members near the intermediate isolated layer.

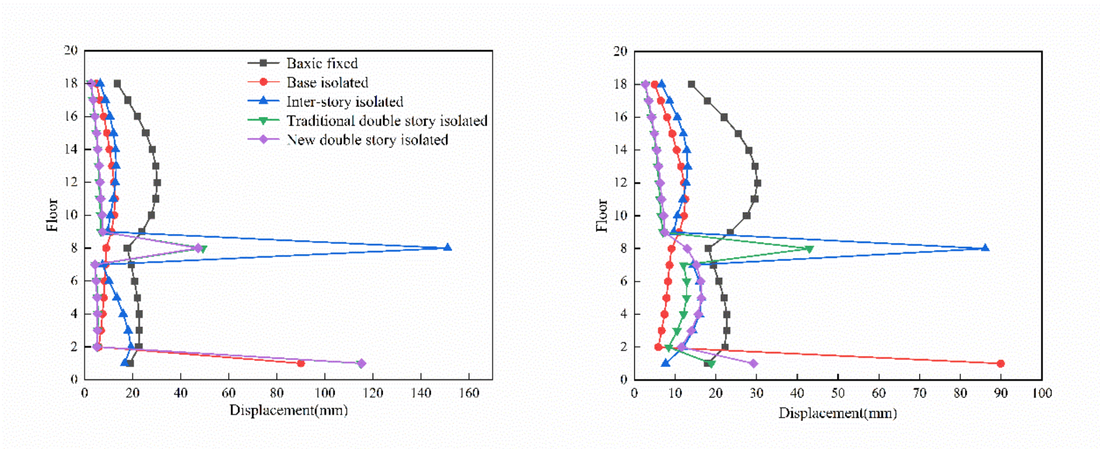
From Figures 8-10, it can be inferred that the displacement of the core tube in the new double story isolated structure is superior to that of the traditional double story isolated structure. This is because the new double story isolated structure does not have an intermediate isolated layer in the core tube, which ensures the integrity of the core tube.

Overall, the new double story isolated structure integrates the advantages of both base isolated and inter-story isolated, achieving a higher level of seismic isolation effectiveness for the building structure. Furthermore, the new double story isolated structure guarantees the integrity of the core tube.



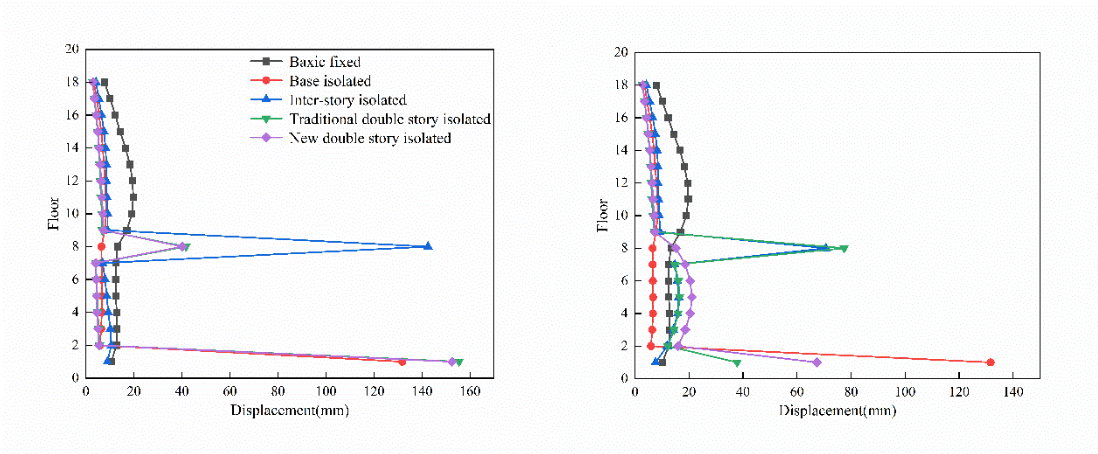
(a) Frame inter-story displacement (b) Inter-story displacement of core tube

Figure 8: Inter-story displacement under El Centro seismic wave



(a) Frame inter-story displacement (b) Inter-story displacement of core tube

Figure 9: Inter-story displacement under Hollister seismic wave

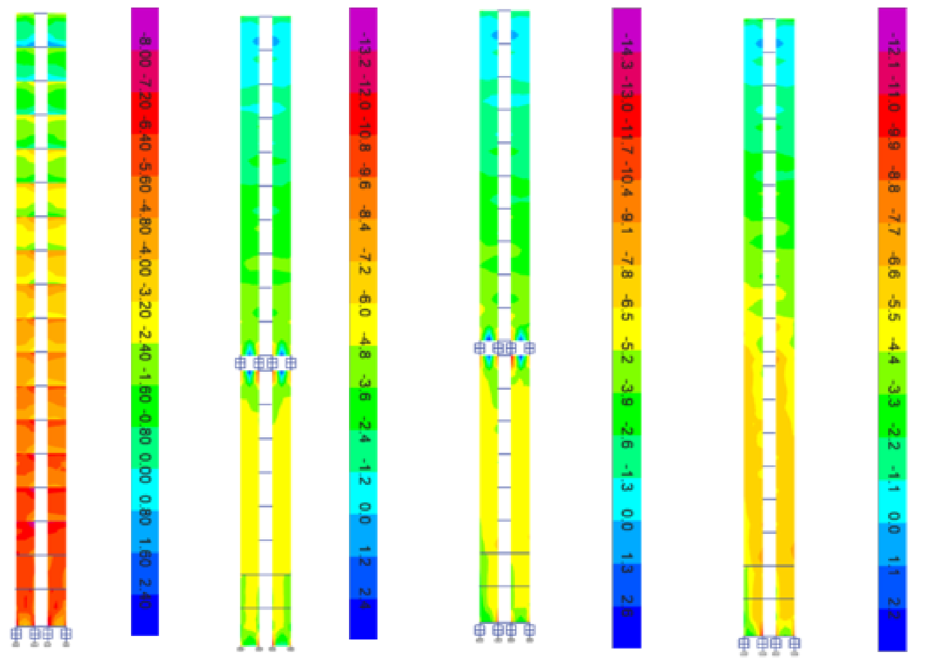


(a) Frame inter-story displacement (b) Inter-story displacement of core tube

Figure 10: Inter-story displacement under Ren-1 seismic wave

4. Comparative analysis of structural internal force damage

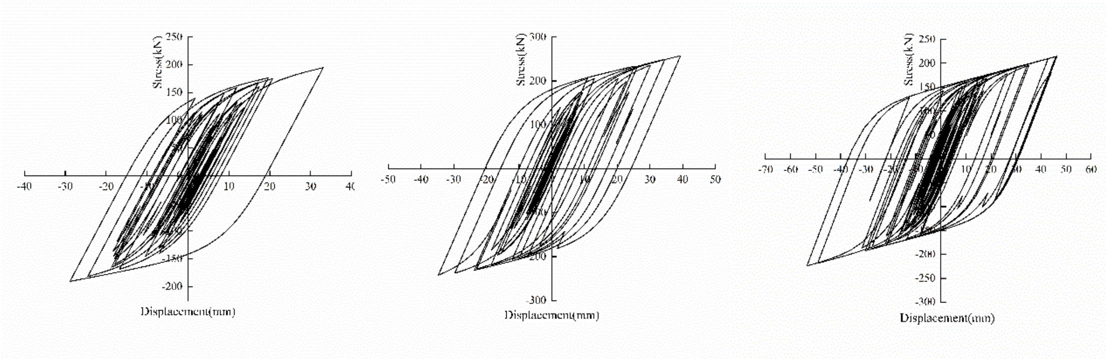
Taking the El Centro earthquake as an example, the stress damage of the structure's core tube under seismic action for base isolated, inter-story isolated, traditional double story isolated, and new double story isolated structures are shown in Figures 11(a), (b), (c), and (d), respectively. From the figures, it can be seen that the damage of the new double story isolated structure mainly concentrates between the middle isolated layer of the frame and the isolated layer of the core tube; the lower part of the core tube has more severe damage than the upper part. Compared with the traditional double story isolated structure, the new double story isolated structure guarantees the integrity of the core tube, avoiding stress concentration and damage at the connection between the middle isolated layer and the bearing in the core tube, and is therefore more economical and safe.



(a) Base isolated (b) Inter-story isolated (c) Traditional double story isolated (d) New double story isolated

Figure 11: Core tube damage under seismic action

The hysteresis curves of the isolated bearings for the middle and bottom corner columns of the frame isolated layer and the corner isolated bearings of the core tube isolated layer in the new double story isolated structure are shown in Figure 12. From the figure, it can be seen that the hysteresis curve of the isolated bearing on the corner column at the bottom of the frame isolated layer is very full, with good energy dissipation effect and excellent seismic performance and energy dissipation capacity. The fullness of the hysteresis curves for the isolated bearings on the corner column at the middle of the frame isolated layer connected to the core tube is lower than that of the corner column at the bottom of the frame isolated layer. Also, the fullness of the hysteresis curves for the isolated bearings connecting to the core tube exceeds that of the corner column at the middle of the frame isolated layer, with moderate energy dissipation effect, but it can also absorb a certain amount of seismic energy.



(a) Frame bottom seismic isolated layer (b) Seismic isolated layer at the bottom of the core (c) Seismic isolated layer in the frame

Figure 12: Hysteresis curve of seismic isolated bearing

5. Conclusion

A new double story isolated structure model was established, and the seismic response of the new double story isolated structure under rare earthquake motion was analyzed. The seismic response results of the new double story isolated structure were compared with those of basic fixed structure, base isolated structure, inter-story isolated structure, and traditional double story isolated structure. It was concluded that:

(1) The new double story isolated structure has better seismic performance than the base isolated and inter-story isolated structures, effectively reducing inter-story shear forces and top floor accelerations of the structure, and dissipating most of the earthquake energy.

(2) The horizontal displacement of both the new and traditional double story isolated structures is mainly concentrated on the upper and lower isolated layers. Compared with base isolated structure, the new double story isolated structure can effectively reduce the displacement of the bottom isolated layer of the core tube. Compared with inter-story isolated structures, the new double story isolated structure can effectively reduce the displacement of the middle isolated layer of the structure.

(3) The damage of the core tube in the new double story isolated structure is mainly concentrated between the middle isolated layer of frame and the core tube isolated layer. The stress concentration at the connection between the layered shell with edge constraint at the bottom of the core tube and the isolated bearings is significant, which increases the possibility of failure.

(4) The hysteresis curve of the corner column isolated bearing at the bottom isolated layer of the frame of the new double story isolated structure is full and has better energy dissipation than the isolated bearings at the middle of the frame and the isolated bearings at the bottom of the core.

Acknowledgments

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