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Case Study On The Seismic Design Strategy For Post-Quake Functional Buildings In China

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Abstract In response to China's "Regulations on the Management of Earthquake Resistance of Building Constructions" on the provision of eight types of important buildings to maintain functional after fortified earthquakes occur, "Guidelines for Seismic Design of post-quake functional buildings (Draft for Review)" distinguishes Class I and Class II buildings, and gives the performance objectives and seismic verification requirements for design earthquakes and severe earthquakes respectively. In this paper, a hospital and a school building are selected as examples to design according to the requirements of fortification of Intensity 8 and 7 respectively. Two design strategies, the seismic isolation scheme and energy dissipation scheme, are considered which are evaluated through elastic-plastic dynamic time-history analysis to meet the requirement of post-quake functional buildings. The results show that the seismic isolation design can meet the requirements in the above cases, and the energy dissipation scheme is difficult to meet the requirements of the "Guidelines" on floor acceleration in some cases, for which the scheme shall be made valid through the seismic resilience assessment. The research in this paper can provide a reference for designers to choose schemes for post-quake functional buildings.

Keywords Post-quake functional, Base isolation, Energy dissipation, Hospital design, School design

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1. Introduction

Resilience refers to the ability of a system to recover function and adapt better to its environment when subjected to sudden shocks or long-term stress. Resilience-based urban planning and building design concepts have gradually been known and applied in various aspects. Due to the uncertainty and huge destructive power of earthquakes, resilience-based seismic design concept has already got great attention in building industry. Systematic evaluation system and design methods have emerged. The building repair time and cost after an earthquake and the level of casualties are calculated to assess building's seismic resilience performance, and the seismic resilience design of new or retrofitted buildings according to prescriptive performance levels is proposed. The relevant international design guidelines include the REDi standard compiled by Arup et al (Li X. et al. 2018).

With the continuous development of economy and society and the increasing level of urbanization, China has also put forward higher requirements for the resilience and recoverability of specific building types in the event of natural disasters such as earthquakes. In 2020, the "Standard for seismic resilience assessment of buildings" (GB/T38591-2020) compiled by Tsinghua University, Arup and other organizations was released. "Regulations on the Management of Earthquake Resistance of Building Constructions" (hereinafter referred to as the "Regulations"), officially enforced on September 1, 2021, clearly stipulates in Article 16 that "newly built schools, kindergartens, hospitals, elderly care institutions, buildings such as child-care institutions, emergency command centers, emergency shelters, and radio/television facilities shall adopt seismic isolation and energy dissipation technologies in accordance with relevant state regulations to ensure that they can remain functional after fortified earthquakes occur in the area."

In order to implement the requirement on these eight types of post-quake functional buildings, the Institute of Standards and Quotas of the Ministry of Housing and Urban-Rural Development organized the compilation of the "Guidelines for Seismic Design of post-quake functional buildings (Draft for Review)" (hereinafter referred to as the "Guidelines"). The "Guidelines" divides post-quake functional buildings into Class I and Class II buildings with different seismic performance objectives and seismic verification requirements. Class I buildings include emergency command centers, main hospital buildings, emergency

shelter buildings, and radio/television facilities. The damage of such buildings in an earthquake will cause serious secondary disasters or seriously affect earthquake relief. Class II buildings include school buildings, kindergartens, ancillary hospital buildings, elderly care institution buildings, and child-care institution buildings, which accommodate vulnerable people or crowded habitants. Based on the above-mentioned differences in the degree of post-earthquake impacts, the "Guidelines" put forward more stringent seismic performance requirements for Class I buildings.

The "Guidelines" set corresponding inter-story drift ratio and floor acceleration limit requirements for Class I and Class II buildings respectively. If the floor acceleration limit cannot be met, the validity of the design should be justified by seismic resilience assessment according to GB/T 38591-2020, in which Class I buildings should achieve three-star rating, and Class II buildings achieve two-star rating or above. The assessment of seismic resilience is carried out by obtaining engineering demand parameters such as interstory drift ratio and floor acceleration under design and severe earthquakes to determine the damage state of structural components, non-structural components, and electromechanical equipment, etc., and then calculate the corresponding repair costs, repair time and casualties, so as to comprehensively evaluate the seismic resilience level of the building according to the above three indicators.

With the implementation of the "Regulations" and the compilation of "Guidelines", the implementation of seismic isolation and energy dissipation devices, and performance analysis of post-quake functional buildings such as hospitals and schools have gradually attracted the attention of scholars and designers. Pan P. et al. (2022) introduced and sorted out the current research progress and engineering applications of seismic isolation technology, and put forward relevant suggestions for the problems of existing researches. Qu Z. et al. (2022) introduced the main earthquake damages of isolated buildings in the Sichuan Luding M6.8 earthquake, and studied the damage causes of isolated buildings with nonlinear seismic response analysis. Xie L.L. et al. (2022) took the reinforced concrete frame-shear wall structure in the 8-degree zone as a research example, and compared the seismic responses and seismic resilience of seismic resistant scheme and based isolation scheme. Wang Y.X. et al. (2023) conducted a nonlinear time-history analysis on the base isolated structure based on the prescriptive design method, and studied the influence of different parameters on the functionality of the structure under multi-level earthquakes. Zeng D.M. et al. (2023) designed a hospital outpatient building using base-isolation and energy dissipation technologies respectively, and compared and analyzed its seismic response. Zhang J. et al. (2023) designed and compared different energy dissipation schemes for a nursing home. Ye L.Y. et al. (2023) conducted an earthquake response analysis on the energy dissipation scheme of a hospital's ancillary buildings. Zhang J. et al. (2023) adopted a three-dimensional seismic isolation technology for the history museum of a secondary school and analyzed its control effect on the structural response. To sum up, there are still relatively few studies on the structural design strategies of post-earthquake functional buildings. More research and case studies are necessary to understand the proper design strategies for post-quake functional buildings in different scenarios.

In this study, a hospital building and a school building are selected as typical examples of Class I and Class II post-quake functional buildings. They are assumed to be located in design fortification degree 8 (PGA = 0.2 g) and degree 7 (PGA = 0.1 g) zone respectively. Structure systems with base isolation or different energy dissipation devices are adopted. Based on the elastic-plastic dynamic time-history analysis, the seismic responses of different schemes under design earthquake (475-yr return period) and severe earthquake (around 2000-yr return period), such as inter-story drift ratio and floor acceleration, are obtained, so as to evaluate whether different structural design schemes can meet the requirements of post-quake functional buildings. According to the above analysis results, seismic design strategies are given for Class I and Class II buildings in 8-degree and 7-degree zones, which serve as a reference for the structural design of post-quake functional buildings in high seismic intensity zones.

2. The Hospital Building: Structural Design

2.1. Project information

The outpatient building of a hospital is taken as the example. There are 11 floors above the ground, and the total height of the structure is 57m. The structural design reference period and design service life are 50 years, the safety level of the building structure is Class I, the seismic fortification category is Class B, the site category is Class II, and the (earthquake distance) design earthquake grouping is the second group. The seismic fortification intensity is taken as 8-degree (0.2g) and 7-degree (0.1g) respectively. According to the "Guidelines", for the 7-degree (0.1g) zone, the maximum value of the horizontal seismic influence coefficient used by the response spectrum analysis and the maximum acceleration value used by the time-history analysis method should be increased by 50%.

Two schemes, base isolation and energy dissipation with fluid viscous damper (FVD) are considered. For the base isolation scheme, the response spectrum function and the parameters in the "Standard for seismic isolation design of buildings" (GB/T 51048-2021) is used; for the energy dissipation scheme, the response spectrum function and parameters in "Code for seismic design of buildings (GB 50011-2010 (2016 revision)) is adopted.

2.2. The base isolation scheme

For the seismic isolation scheme, a dual system composed

of composite steel frame and reinforced concrete core is adopted. The frame is composed of concrete-filled steel tube (CFT) columns and steel beams. The seismic isolation layer is placed between the ground floor and the B1 floor, and the seismic isolation bearings are natural rubber bearings (NRB) and lead rubber bearings (LRB). The structural system is shown in Figure 1.

For the 8-degree (0.2g) zone, the diameter of the typical perimeter frame columns from bottom to top is 900 mm~650 mm, the height of typical perimeter frame beams is 900 mm, and the thickness of the core wall is 600 mm~350 mm from bottom to top. The effective diameter of NRB and LRB is 1100 mm~1500 mm. The overall structural analysis model is established in the structural design software, and the dynamic analysis and RSA are carried out on the structure with-and-without seismic isolation. The main results listed in Table 1 shows the base isolation effectively elongates the period and reduce the base shear.

For the 7-degree (0.1g) zone, the diameter of the typical perimeter frame column is 600 mm, the height of the typical perimeter frame beam is 700 mm, and the thickness of the core wall is 600 mm~300 mm from bottom to top. The effective diameter of NRB and LRB is 1100 mm~1500 mm. The period and base shear of the scheme with-and-without base isolation under design earthquake are shown in Table 2.

Table 1. Dynamic period and base shear of the structure with-and-without base isolation (8-degree zone)

Item		Without base isolation	With base isolation
Period(s)	T_1	1.85	4.46
	T_2	1.81	4.40
	T_3	1.66	4.11
Design earthquake base shear (MN)	X-dir	77.03	34.77
	Y-dir	82.37	34.83

Table 2 Dynamic period and base shear of the structure with-and-without base isolation (7-degree zone)

Item		Without base isolation	With base isolation
Period(s)	T_1	2.11	4.17
	T_2	1.97	4.11
	T_3	1.80	3.81
Design earthquake base shear (MN)	X-dir	54.05	26.47
	Y-dir	57.58	26.46

2.3. The energy dissipation scheme with FVDs (the FVD scheme)

For the FVD scheme of the hospital building, the structure adopts a dual system with steel moment frame and steel braced frame. All columns are CFT sections, beams are I-shaped sections, and braces are box-shaped sections. Viscous dampers are used on each floor of the whole building. The structural system is shown in Figure 2.

For the 8-degree (0.2g) zone, the diameter of the typical frame column from bottom to top is 900 mm ~650 mm, the height of the typical moment frame beam is 900 mm, the typical brace section is 600 × 600 mm, and the damping coefficient of the viscous damper is

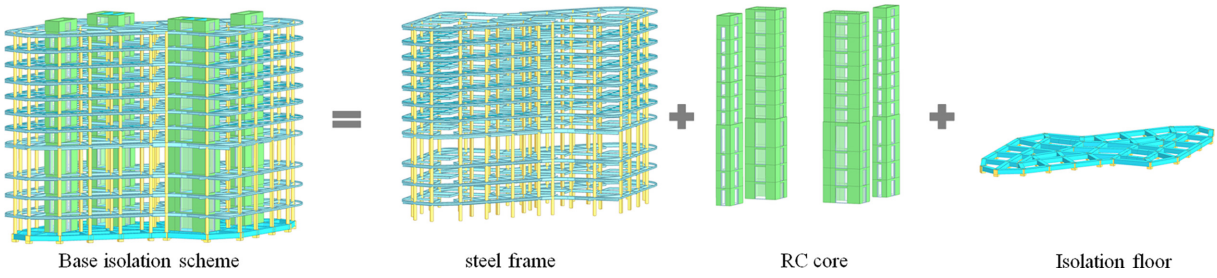


Figure 1. Hospital building: structural diagram of base isolation scheme.

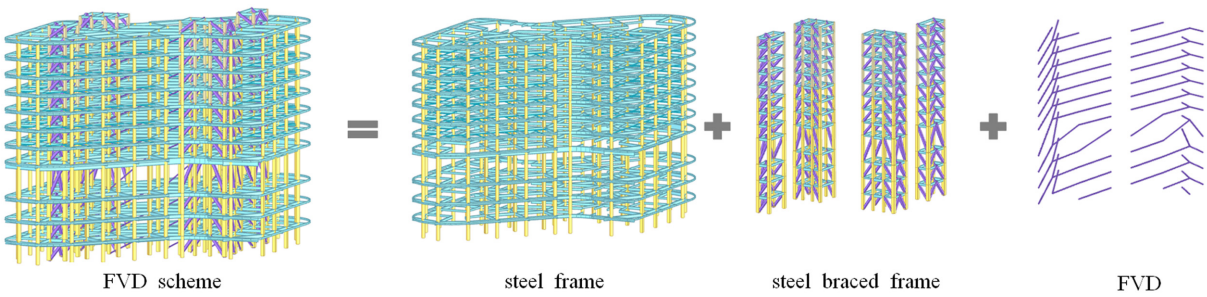


Figure 2. Hospital building: structural diagram of energy dissipation scheme.

Table 3. Dynamic period and base shear of the structure with-and-without energy dissipation device (8-degree zone)

Item		Without FVDs	With FVDs
Period(s)	T_1	1.77	1.77
	T_2	1.62	1.62
	T_3	1.56	1.56
Design earthquake base shear (MN)	X-dir	76.96	61.55
	Y-dir	84.46	66.50

Table 4. Dynamic period and base shear of the structure with-and-without energy dissipation device (7-degree zone)

Item		Without FVDs	With FVDs
Period(s)	T_1	1.94	1.94
	T_2	1.87	1.87
	T_3	1.83	1.83
Design earthquake base shear (MN)	X-dir	54.38	45.81
	Y-dir	56.50	46.41

5000 kN/(m/s). The overall structural analysis model is established in the structural design software, and the dynamic analysis and RSA are carried out on the structure with-and-without energy dissipation. The results in Table 3 shows the base shear under design earthquake is reduced by about 20% by adding the dampers.

For the 7-degree (0.1g) zone, the diameter of the typical frame column from bottom to top is 900 mm ~650 mm, the height of the typical moment frame beam is 700 mm, the typical brace section is 500 × 500 mm, and the damping coefficient of the viscous damper is 3000 kN/(m/s). It can be seen from Table 4 that with the dampers installed, the shear force of the structure base decreases by about 16%.

3. The Hospital Building: Evaluation For Post-quake Functional Building Requirements

3.1. The base isolation scheme

The general nonlinear dynamic finite element analysis software LS-DYNA is used to carry out three-dimensional refined finite element analysis for the base isolation scheme of the hospital building. The LS-DYNA finite element analysis model is shown in Figure 3, in which beams and columns are simulated by fiber beam elements, floors and shear walls are simulated by shell elements, and isolation bearings are simulated by discrete beam elements with the material type *MAT_SEISMIC_ISOLATOR.

Five groups of natural seismic time history records and two groups of artificial records are chosen to carry out the elastic-plastic dynamic time history analysis for the structure under design earthquake and severe earthquake. It can be seen from Figure 4 that the averaged spectrum of the records matches the code spectrum well at the main periods.

For the base isolation scheme of the hospital structure in 8-degree (0.2 g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 5. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/520 and 1/632 respectively, which meets the required 1/500 limit in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration in X-dir and Y-dir is 0.14g and 0.14 g respectively, which meets the 0.25 g requirement in the "Guidelines" for Class I buildings. Under severe earthquakes, the inter-story drift ratios in X-dir and Y-dir are 1/222 and 1/263 respectively, meeting the required 1/200 in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration in X-dir and Y-dir is 0.21g and 0.22 g respectively, which meets the 0.45 g requirement in the "Guidelines" for Class I buildings.

For the base isolation scheme of the hospital structure in 7-degree (0.1 g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 6. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/595 and 1/689

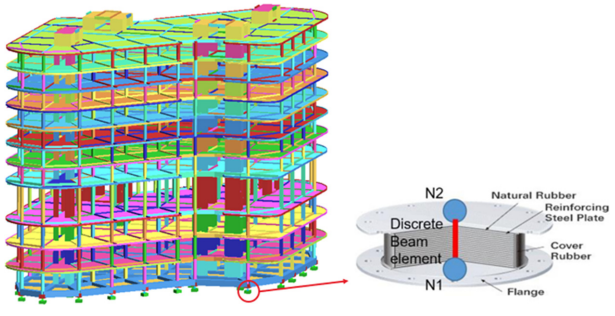


Figure 3. LS-DYNA model of the base isolation scheme of the hospital building.

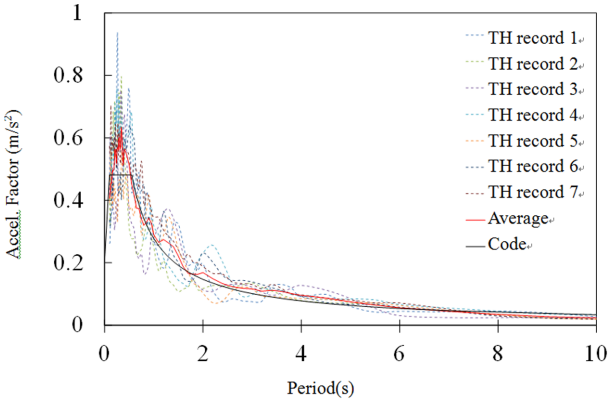


Figure 4. Response spectra of TH records compared with code spectrum.

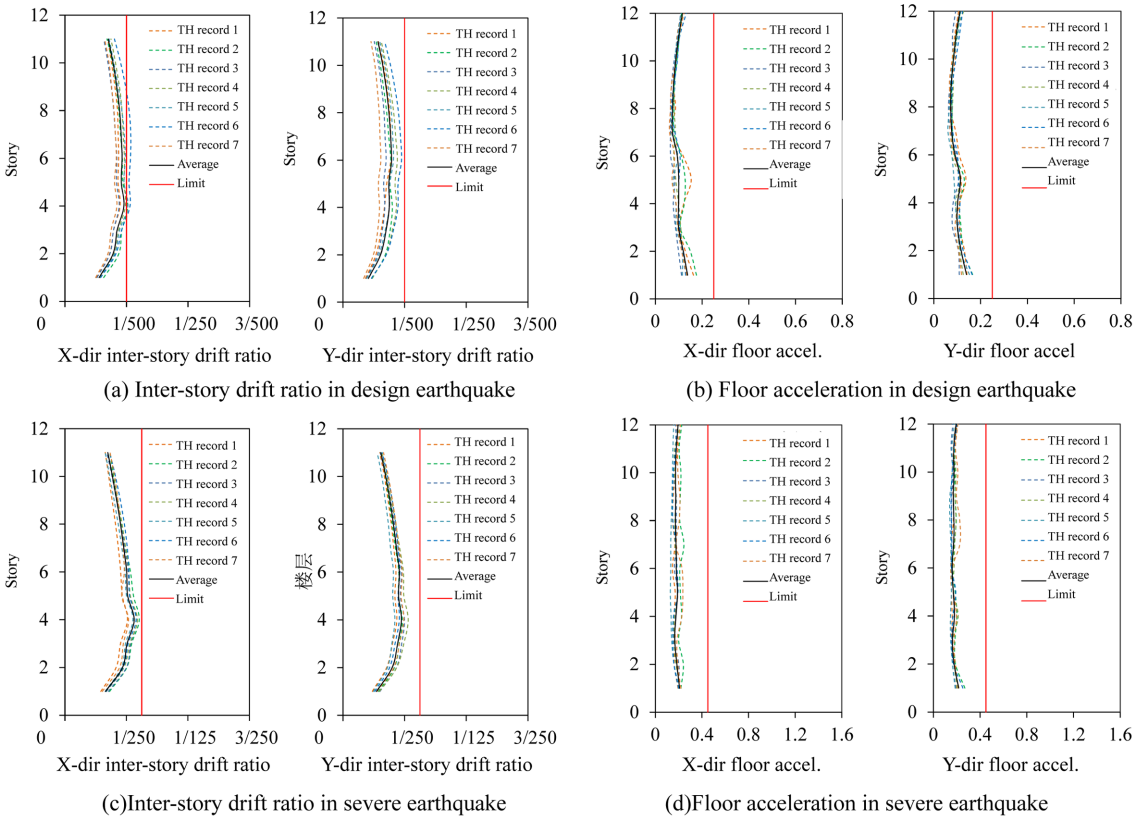


Figure 5. Seismic responses of base isolation scheme of the hospital building in 8-degree zone.

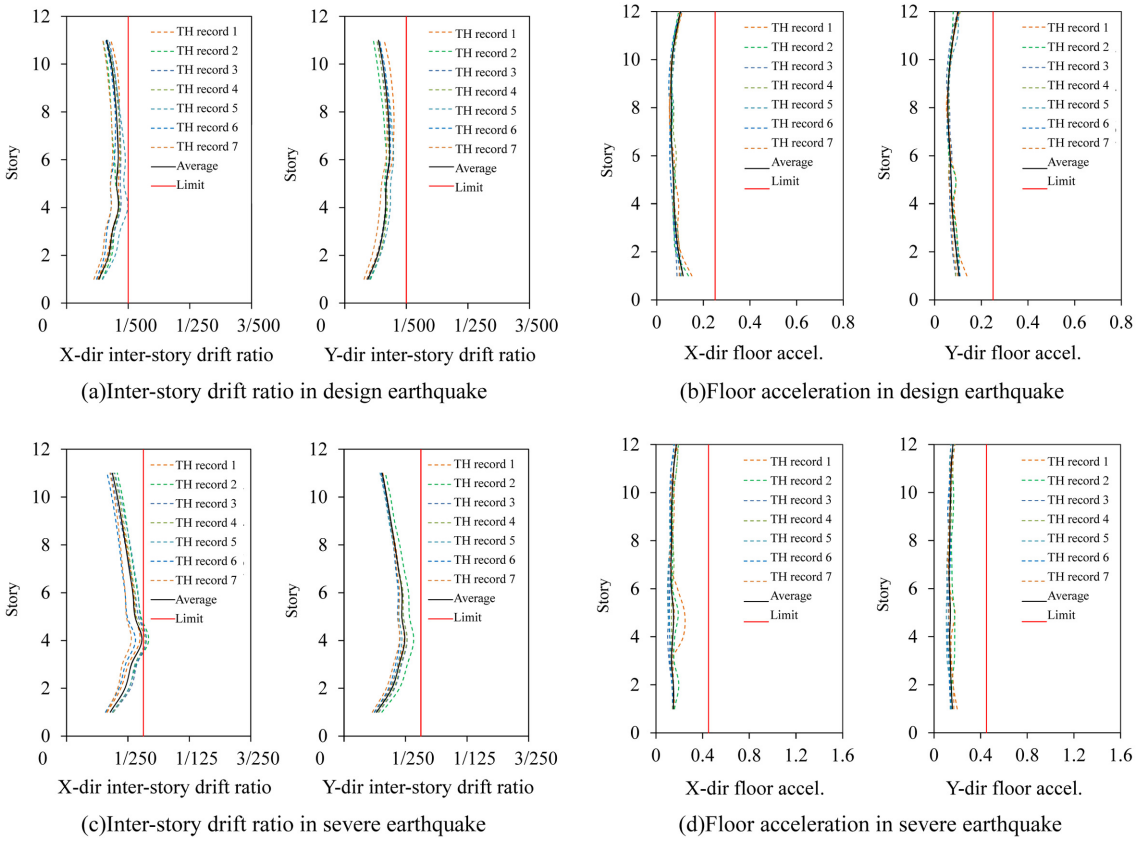


Figure 6. Seismic responses of base isolation scheme of the hospital building in 7-degree zone.

respectively, which meets the required 1/500 limit in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration is 0.11 g and 0.11g respectively, which meets the 0.25 g requirement in the "Guidelines" for Class I buildings. Under severe earthquakes, the inter-story drift ratios in X-dir and Y-dir are 1/203 and 1/253 respectively, meeting the required 1/200 in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration in X-dir and Y-dir is 0.17 g and 0.16 g respectively, which meets the 0.45 g requirement in the "Guidelines" for Class I buildings.

3.2. FVD scheme

Similarly the software LS-DYNA is used to carry out three-dimensional refined finite element analysis for the FVD scheme of the hospital building The LS-DYNA finite element analysis model is shown in Figure 7, in which beams and columns are simulated by fiber beam elements, floors and shear walls are simulated by shell elements, and viscous dampers are simulated by discrete beam elements with the material type *MAT_DAMPER_NONLINEAR_VISCOUS.

Five groups of natural seismic time history records and two groups of artificial records are chosen to carry out the elastic-plastic dynamic time history analysis for the structure under design earthquake and severe earthquake. It can be seen from Figure 8 that the averaged spectrum

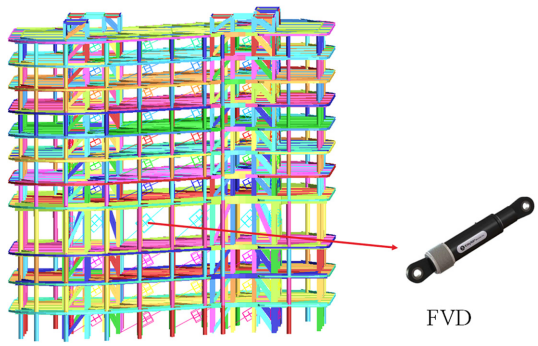


Figure 7. LS-DYNA model of the energy dissipation scheme of the hospital building

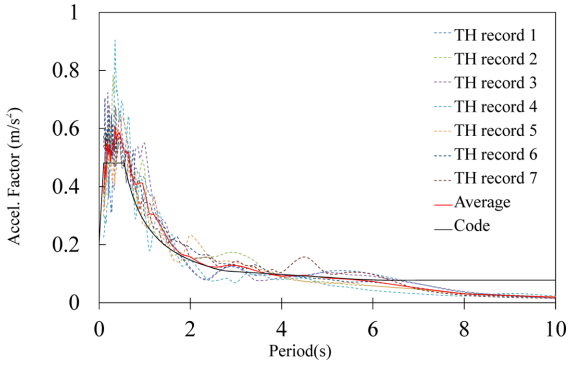
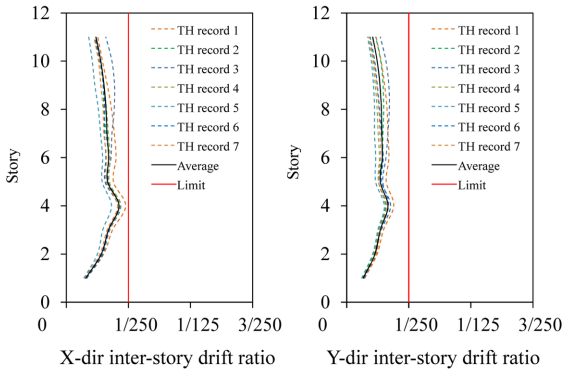
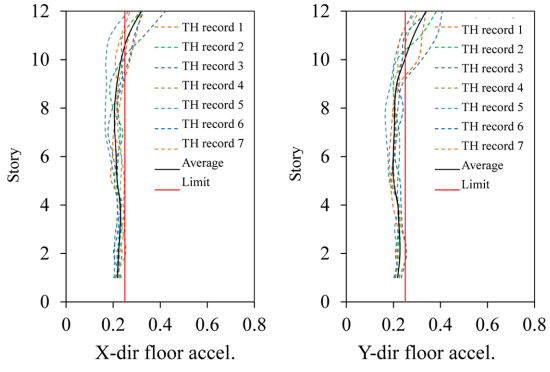


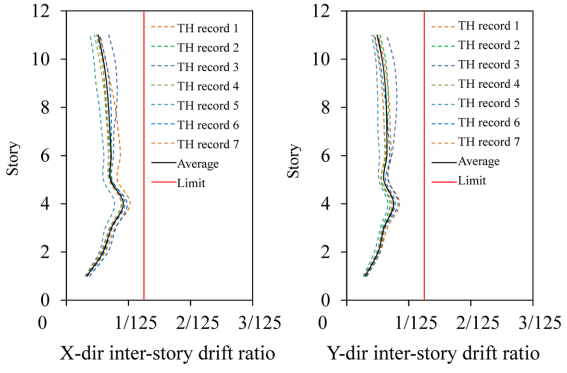
Figure 8. spectra of TH records compared with code spectrum.



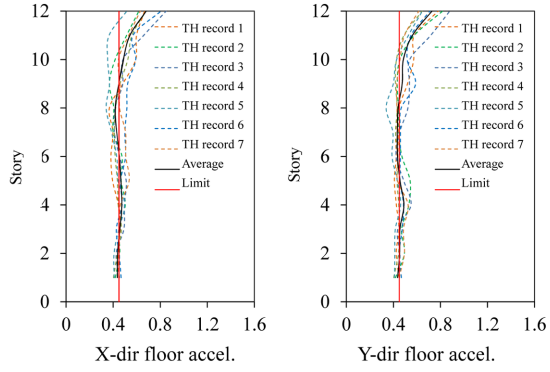
(a)Inter-story drift ratio in design earthquake



(b)Floor acceleration in design earthquake



(c)Inter-story drift ratio in severe earthquake



(d)Floor acceleration in severe earthquake

Figure 9. Seismic responses of energy dissipation scheme of the hospital building in 8-degree zone.

of the records matches the code spectrum well at the main periods.

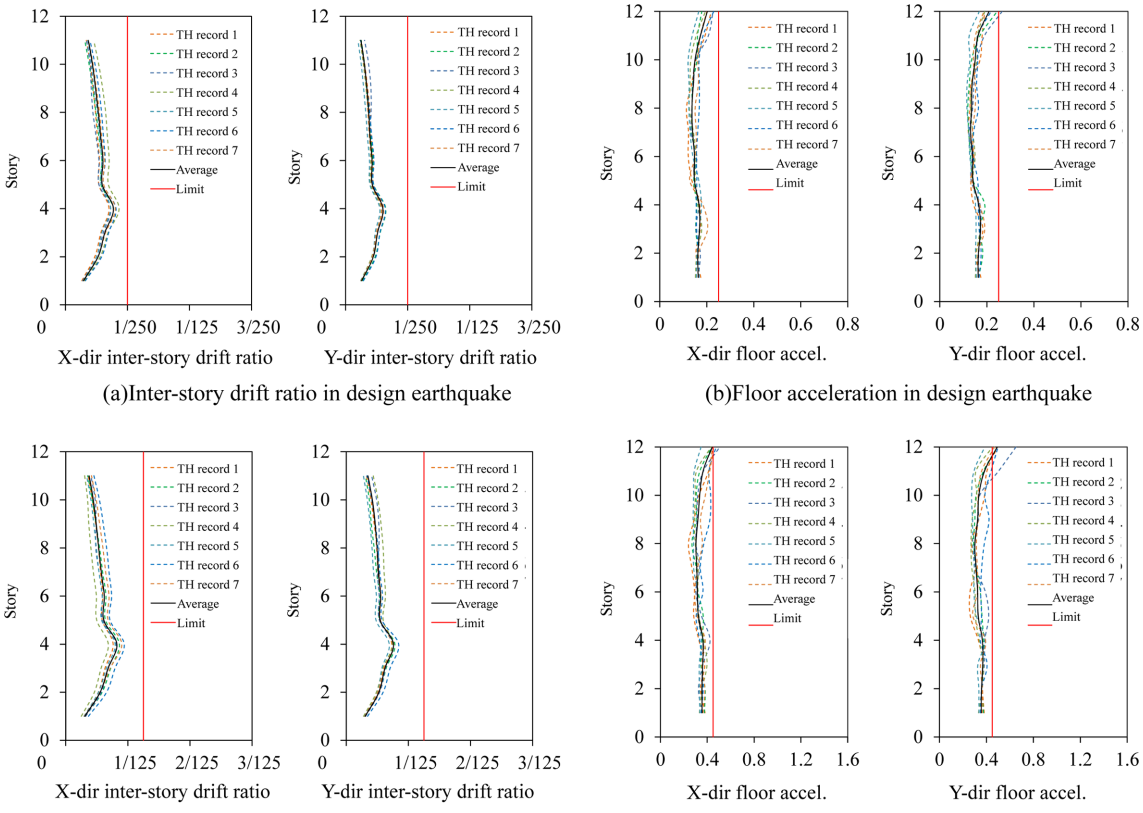
For the FVD scheme of the hospital structure in 8-degree (0.2 g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 9. Under design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/294 and 1/375 respectively, which meets the required 1/250 limit in the "Guidelines" for the steel structure of Class I buildings. The maximum floor acceleration is 0.32 g and 0.34 g respectively, which meets the 0.25g requirement in the "Guidelines" for Class I buildings. Under severe earthquakes, the inter-story drift ratios in X-dir and Y-dir are 1/135 and 1/165 respectively, meeting the required 1/100 in the "Guidelines" for the steel structure of Class I buildings. The maximum floor acceleration in X-dir and Y-dir is 0.68 g and 0.73 g respectively, and most floors do not meet the 0.45 g requirement in the "Guidelines" for Class I buildings.

For the FVD scheme of the hospital structure in 7-degree (0.1 g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 10. Under design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/323 and 1/416 respectively, which meets the required 1/250 limit in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration is 0.20 g and 0.21g respectively, which meets the 0.25 g requirement in the "Guidelines" for Class I buildings. Under severe earthquake, the inter-story drift ratios in X-dir and Y-dir are 1/151 and 1/164 respectively, meeting the required 1/100 in the "Guidelines" for the frame-core dual system structure of Class I buildings. The maximum floor acceleration in X-dir and Y-dir is 0.44 g and 0.49 g respectively. All but the Y-dir acceleration of the top floor meets the 0.45 g requirement in the "Guidelines" for Class I buildings.

4. The School Building: Structural Design

4.1. Project information

A school building is taken as the example. There are 8 floors above the ground, and the total height of the structure is 29.6 m, floor-to-floor height being 3.7 m. The structural design reference period and design service life are 50 years, the safety level of the building structure is Class I, the seismic fortification category is Class B, the site category is Class II, and the (earthquake distance) design earthquake grouping is the second group. The seismic fortification intensity is taken as 8-degree (0.2 g) and 7-degree (0.1 g) respectively. According to the "Guidelines", for the 7-degree (0.1g) zone, the maximum



(a)Inter-story drift ratio in design earthquake

(b)Floor acceleration in design earthquake

(c)Inter-story drift ratio in severe earthquake

(d)Floor acceleration in severe earthquake

Figure 10. Seismic responses of energy dissipation scheme of the hospital building in 7-degree zone

value of the horizontal seismic influence coefficient used by the response spectrum analysis and the maximum acceleration value used by the time-history analysis method should be increased by 50%.

Two energy dissipation devices, buckling restrained brace (BRB) and fluid viscous damper (FVD) are considered separately. The response spectrum function and parameters in "Code for seismic design of buildings (GB 50011-2010 (2016 revision)) is adopted.

4.2. BRB scheme

The structural system is a dual system composed of steel moment frame and steel braced frame, with BRB placed in several spans at story 1~7. The structure is shown in Figure 11.

For the 8-degree (0.2g) zone, the typical frame column is square hollow section (SHS) of 450 × 450 mm, the typical moment frame beam is I-shaped of 900 mm high, the BRB yield capacity is taken as 700 kN. The overall structural analysis model is established in the structural design software, and the dynamic analysis and RSA are carried out on the structure with-and-without BRBs. The results in Table 5 shows the base shear under design earthquake is reduced by about 15% by adding the BRBs.

Table 5. Dynamic period and base shear of the structure with-and-without BRBs (8-degree zone)

Item		Without BRBs	With BRBs
Period(s)	T_1	1.10	1.14
	T_2	1.09	1.13
	T_3	0.77	0.81
Design earthquake base shear (MN)	X-dir	15.07	12.88
	Y-dir	15.12	12.95

Table 6. Dynamic period and base shear of the structure with-and-without BRBs (7-degree zone)

Item		Without BRBs	With BRBs
Period(s)	T_1	1.45	1.51
	T_2	1.41	1.47
	T_3	1.03	1.09
Design earthquake base shear (MN)	X-dir	9.30	8.04
	Y-dir	9.12	7.74

For the 7-degree (0.1g) zone, the typical frame column is square hollow section (SHS) of 400 × 400 mm, the typical moment frame beam is I-shaped of 650mm high, the BRB yield capacity is taken as 290 kN. The results in Table 6 shows the base shear under design earthquake is reduced by about 15% by adding the BRBs.

4.3. FVD scheme

The FVD scheme for the school building adopts steel moment frame structure with FVD placed in story 1~7, as shown in Figure 12.

For the 8-degree (0.2g) zone, the typical frame column is square hollow section (SHS) of 450 × 450 mm, the typical moment frame beam is I-shaped of 700 mm high, the damping coefficient of the FVD is 500 kN/(m/s). The overall structural analysis model is established in the structural design software, and the dynamic analysis and RSA are carried out on the structure with-and-without dampers. The results in Table 7 shows the base shear under design earthquake is reduced by about 25% by

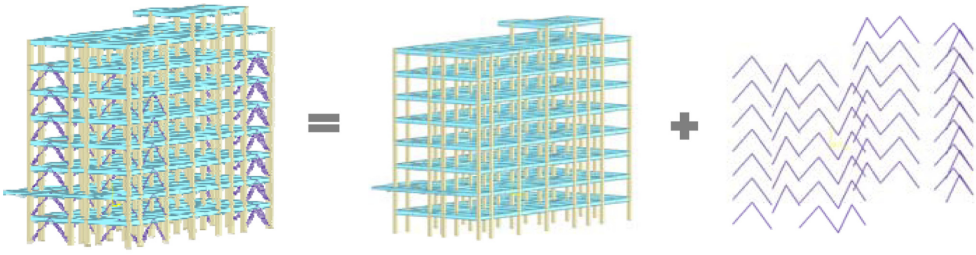


Figure 11. The school building: structural diagram of BRB scheme.

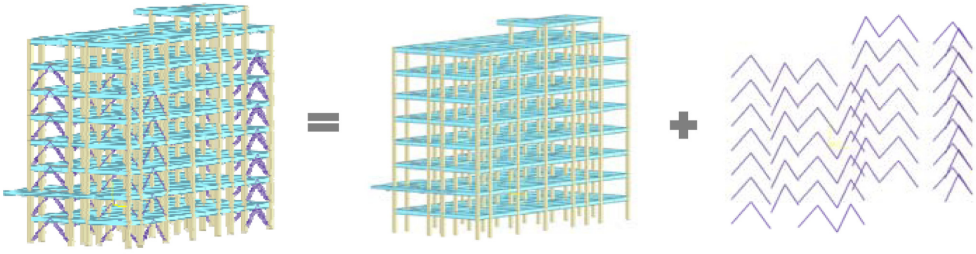


Figure 12. The school building: structural diagram of FVD scheme.

Table 7. Dynamic period and base shear of the structure with-and-without FVDs (8-degree zone)

Item		Without FVDs	With FVDs
Period(s)	T_1	1.42	1.42
	T_2	1.40	1.40
	T_3	1.15	1.15
Design earthquake base shear (MN)	X-dir	12.09	9.08
	Y-dir	12.28	9.25

Table 8. Dynamic period and base shear of the structure with-and-without FVDs (7-degree zone)

Item		Without FVDs	With FVDs
Period(s)	T_1	1.69	1.69
	T_2	1.67	1.67
	T_3	1.37	1.37
Design earthquake base shear (MN)	X-dir	8.13	6.64
	Y-dir	8.09	6.62

adding the dampers.

For the 7-degree (0.1g) zone, the typical frame column is square hollow section (SHS) of 400 × 400 mm, the typical moment frame beam is I-shaped of 650 mm high, the damping coefficient of the FVD is 300 kN/(m/s). The results in Table 7 shows the base shear under design earthquake is reduced by about 18% by adding the dampers.

5. The School Building: Evaluation For Post-quake Functional Building Requirements

5.1. BRB scheme

Still the software LS-DYNA is used to carry out three-dimensional refined finite element analysis for the BRB scheme of the school building. The LS-DYNA finite element analysis model is shown in Figure 13, in which beams and columns are simulated by fiber beam elements, floors and shear walls are simulated by shell elements,

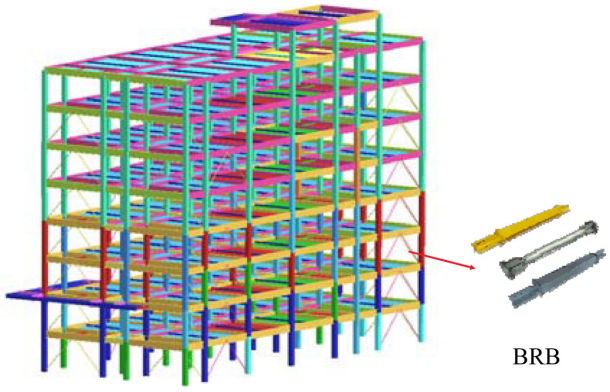


Figure 13. LS-DYNA model of the BRB scheme of the school building.

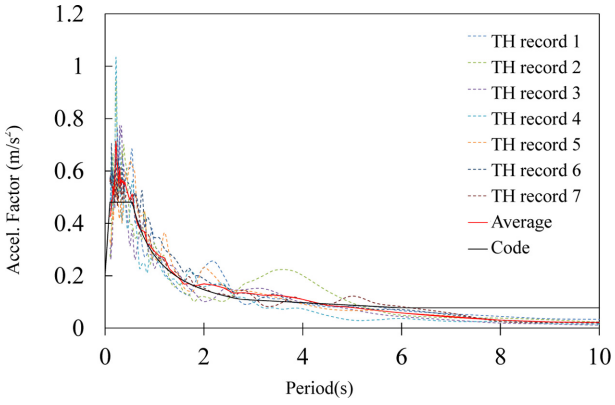
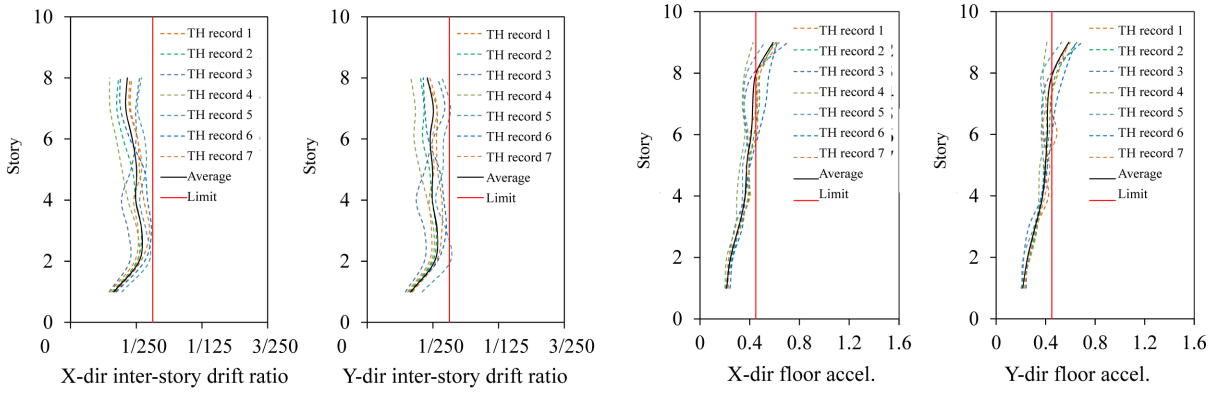


Figure 14. Spectra of TH records compared with code spectrum.

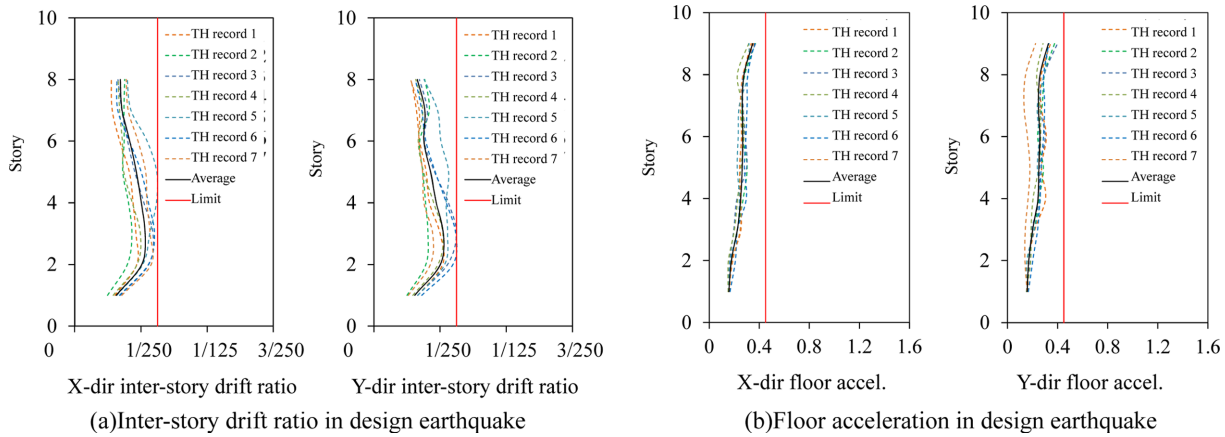
and BRBs are simulated with the material type *MAT_HYSTERETIC_BEAM.

Five groups of natural seismic time history records and two groups of artificial records are chosen to carry out the elastic-plastic dynamic time history analysis for the structure under design earthquake and severe earthquake. It can be seen from Figure 14 that the averaged spectrum



(a)Inter-story drift ratio in design earthquake (b)Floor acceleration in design earthquake

Figure 15. Seismic responses of BRB scheme of the school building in 8-degree zone.



(a)Inter-story drift ratio in design earthquake (b)Floor acceleration in design earthquake

Figure 16. Seismic responses of BRB scheme of the school building in 7-degree zone.

of the records matches the code spectrum well at the main periods.

For the BRB scheme of the school structure in 8-degree (0.2g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 15. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/230 and 1/234 respectively, which meets the required 1/200 limit in the "Guidelines" for the steel structure of Class II buildings. The maximum floor acceleration is 0.59 g and 0.59 g respectively, some high-level floors do not meet the 0.45g requirement in the "Guidelines" for Class II buildings.

For the BRB scheme of the school structure in 7-degree (0.1g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 16. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/235 and 1/238 respectively, which meets the required 1/200 limit in the "Guidelines" for the steel structure of Class II buildings. The maximum floor acceleration is 0.35g and 0.33g respectively, some high-level floors do not meet the 0.45g requirement in the "Guidelines" for Class II buildings.

5.2. FVD scheme

Similarly LS-DYNA is used to carry out three-dimensional refined finite element analysis for the BRB scheme of the school building. The LS-DYNA finite element analysis model is shown in Figure 17, in which beams and columns are simulated by fiber beam elements, floors and shear walls are simulated by shell elements, and FVDs are simulated by discrete beam elements with the material type *MAT_DAMPER_NONLINEAR_VISCOUS.

Five groups of natural seismic time history records and two groups of artificial records are chosen to carry out the elastic-plastic dynamic time history analysis for the

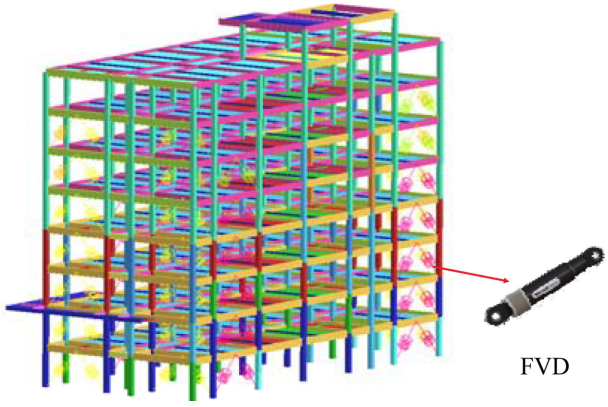


Figure 17. LS-DYNA model of the FVD scheme of the school building.

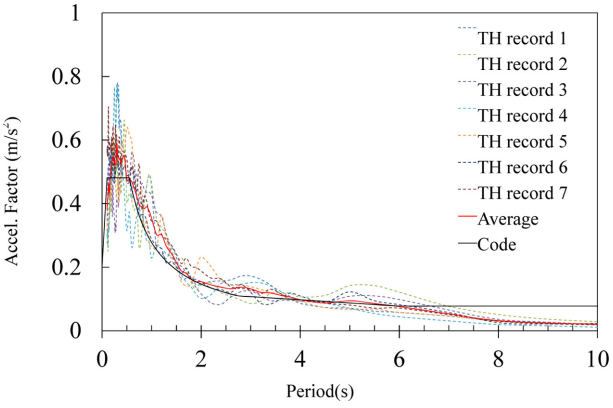
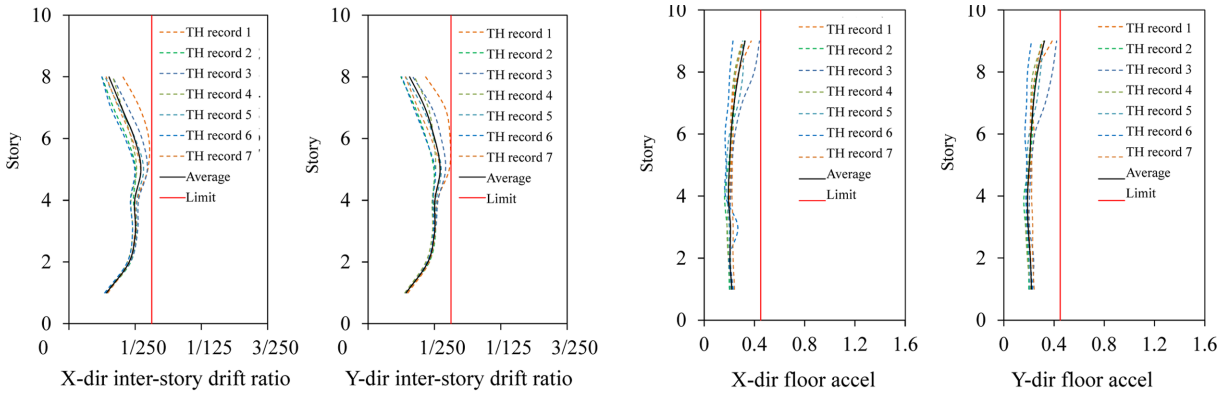


Figure 18. spectra of TH records compared with code spectrum.

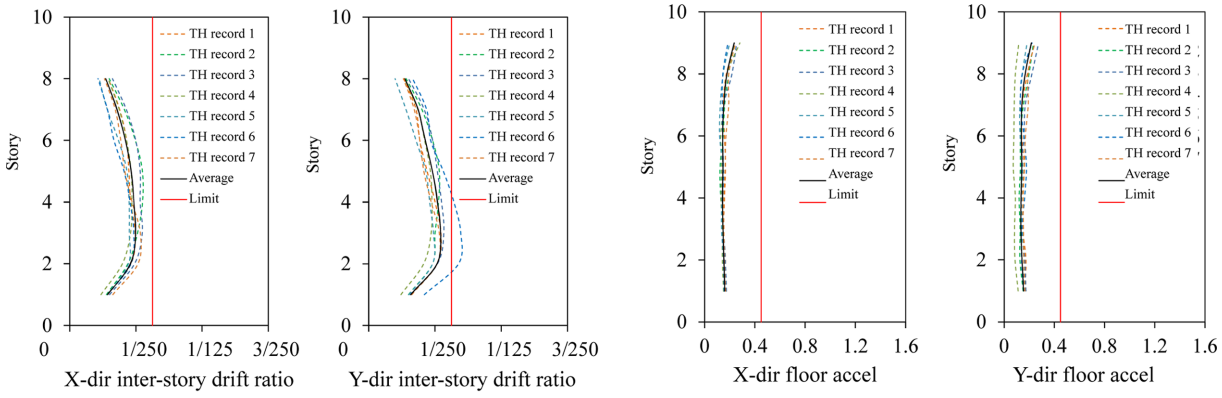
structure under design earthquake and severe earthquake. It can be seen from Figure 18 that the averaged spectrum of the records matches the code spectrum well at the main periods.

For the FVD scheme of the school structure in 8-degree (0.2 g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe



(a)Inter-story drift ratio in design earthquake (b)Floor acceleration in design earthquake

Figure 19. Seismic responses of FVD scheme of the school building in 8-degree zone.



(a)Inter-story drift ratio in design earthquake (b)Floor acceleration in design earthquake

Figure 20. Seismic responses of FVD scheme of the school building in 7-degree zone.

earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 19. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/229 and 1/230 respectively, which meets the required 1/200 limit in the "Guidelines" for the steel structure of Class II buildings. The maximum floor acceleration is 0.33 g and 0.32 g respectively, meeting the 0.45g requirement in the "Guidelines" for Class II buildings.

For the FVD scheme of the school structure in 7-degree (0.1g) zone, the distribution of inter-story drift ratio and floor acceleration under design earthquake and severe earthquake obtained through elastic-plastic dynamic analysis is shown in Figure 20. It can be seen that under the design earthquake, the maximum inter-story drift ratios of X-dir and Y-dir are 1/251 and 1/230 respectively, which meets the required 1/200 limit in the "Guidelines" for the steel structure of Class II buildings. The maximum floor acceleration is 0.24g and 0.22g respectively, meeting the 0.45 g requirement in the "Guidelines" for Class II buildings.

6. Conclusion

This study is based on the classification of post-quake functional buildings proposed in the "Guidelines" and its corresponding seismic performance objectives and seismic evaluation requirements. One hospital building and one school building are taken as the example of Class I and Class II building, and are designed according to seismic forces in 8-degree and 7-degree zones. The schemes with base isolation, energy dissipation with BRBs, energy dissipation with FVDs are considered and evaluated using the elasto-plastic time-history analysis. The main findings are as follows:

(1) For hospital buildings in the 8-degree zone, the base isolation scheme is able to meet the requirements of the "Guidelines" for Class I post-quake functional building; for the energy dissipation with FVDs, the floor acceleration of many floors is difficult to meet the limit given in the "Guidelines". Therefore, for Class I buildings such as hospitals in the 8-degree area, it is recommended to use base isolation technology to achieve post-quake functional.

(2) For the hospital buildings in the 7-degree zone, the

base isolation scheme can also achieve the post-quake functional; For energy dissipation scheme with FVDs, most floors can meet the floor acceleration limit requirements, while the top few floors exceed the limit. Therefore, for Class I buildings such as hospitals in the 7th degree area, it is recommended to adopt either seismic isolation technology, or further fine-tune the parameters of dampers if FVD scheme is adopted to meet the requirements of floor acceleration. If it is difficult to meet the floor acceleration requirements, the seismic resilience assessment can be carried out, according to the "Guidelines", and proper design provisions in structural and non-structural components are made to meet the three-star resilience rating in "Standard for seismic resilience assessment of buildings" (GB/T 38591-2021).

(3) For school buildings in the 8-degree zone, the energy dissipation scheme with FVDs is able to meet the requirements for Class II post-quake functional building. For energy dissipation scheme with BRBs, the floor acceleration of some floors in the high level is difficult to meet the "Guidelines" requirement for Class II buildings. Therefore, for Class II buildings such as schools in the 8-degree zone, it is recommended to adopt either base isolation scheme, or energy dissipation scheme with FVDs. If energy dissipation scheme with BRBs is to be adopted and the floor acceleration does not satisfy, the seismic resilience assessment may be carried out, and proper design provisions in structural and non-structural components are made to meet the two-star resilience rating.

(4) For school buildings in the 7-degree zone, the energy dissipation schemes with either FVDs or BRBs are able to satisfy the requirement for post-quake functional building. Therefore, for Class II buildings such as schools in the 7-degree zone, either base isolation scheme, energy dissipation scheme with FVDs, or energy dissipation scheme with BRBs can be chosen for the post-quake functional buildings.

The above results are preliminary findings based on two examples. Different building forms, heights, and layouts vary widely, thus this article only serves as reference for designers and engineers. More relevant researches are necessary to develop design rule-of-thumbs and design strategies.

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