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Application of Energy Dissipation Technology in High-Rise Buildings

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Abstract

The principle of energy dissipation technology is to dissipate or absorb the seismic energy input through the deformation or velocity change of dampers installed in the main structure of high-rise buildings, so as to reduce the seismic response of the buildings. With the development of energy dissipation technology, recognized as an effective and new measurement for reducing seismic effects, its application in high-rise buildings has become more and more popular. The appropriate energy dissipation devices suitable for high-rise buildings are introduced in this paper. The effectiveness of energy-dissipation technology for reducing the seismic response of high-rise buildings with various structural forms is demonstrated with a number of actual examples of high-rise buildings equipped with various energy dissipation devices.

Key words: Energy dissipation technology, Dampers, Practical application, High-rise buildings

1. Introduction

In recent years, energy dissipation technology has been used more and more popular in practical applications. The main principle of itself is to set dampers in some parts of the structure. Under earthquakes, the dampers are capable of dissipating or absorbing the seismic energy by means of friction, bending, shear, torsion or other deformations, as wells as velocity changes. So far, there are three widely-used methods of energy dissipation technology as shown in Fig. 1 to Fig. 3, which include reducing seismic actions by increasing damping ratio, extending structural period, and changing structural stiffness distribution.

Commonly-used dampers can be divided into velocity-related type and displacement-related type, as shown in

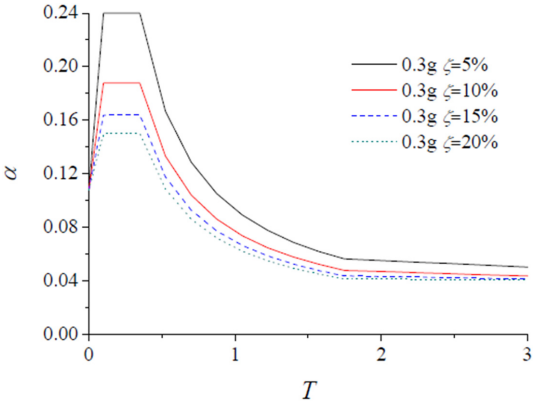


Figure 1. Decrease in design spectrum for increase in damping ratio(2010).

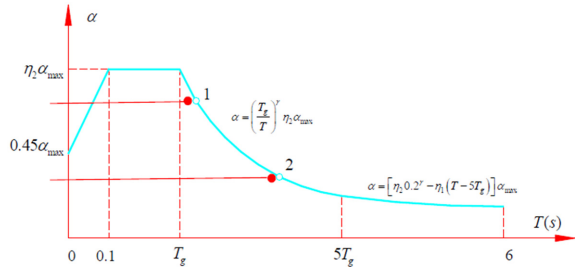


Figure 2. Decrease in spectral acceleration for increase in natural period(2010).

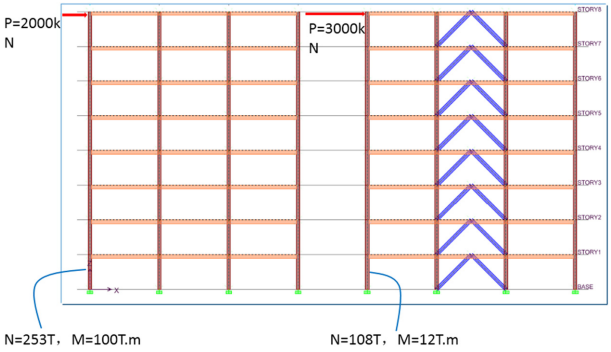
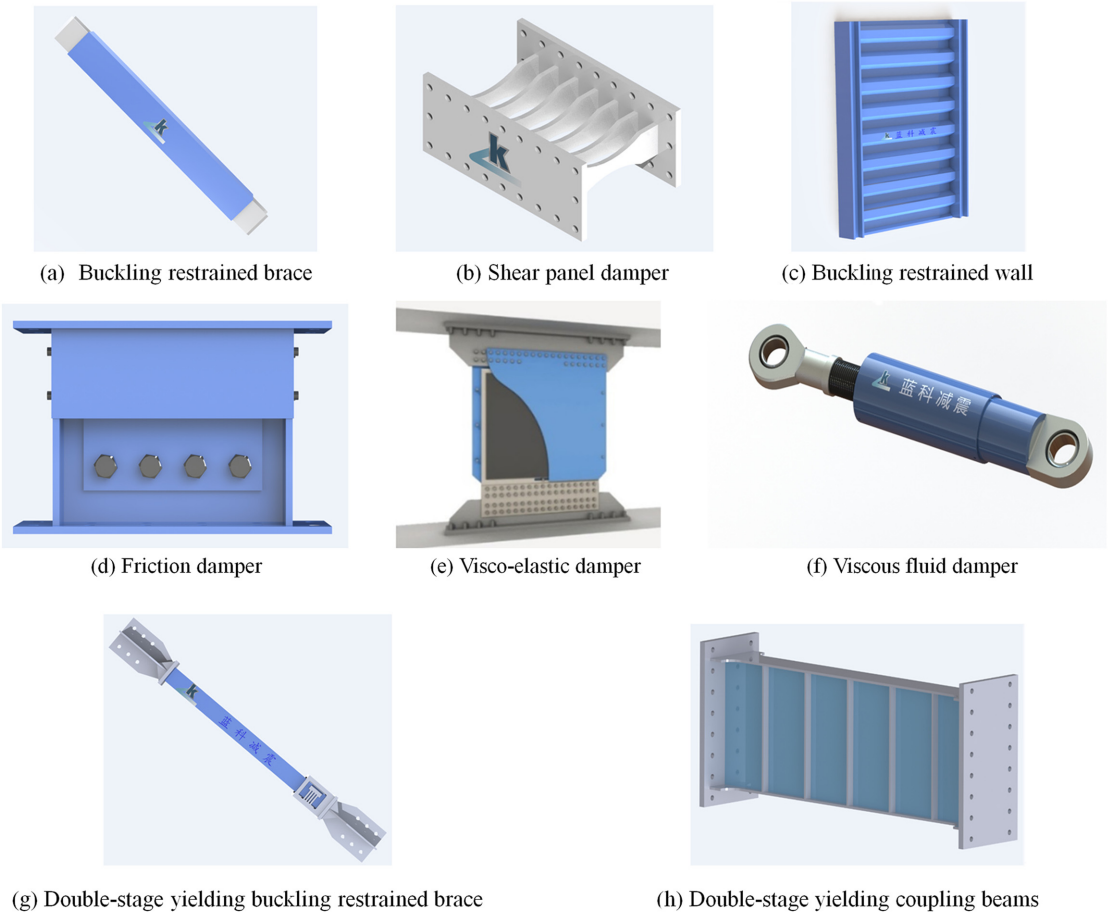


Figure 3. Changing the structural stifffness distribution.

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(a) Buckling restrained brace (b) Shear panel damper (c) Buckling restrained wall

(d) Friction damper (e) Visco-elastic damper (f) Viscous fluid damper

(g) Double-stage yielding buckling restrained brace (h) Double-stage yielding coupling beams

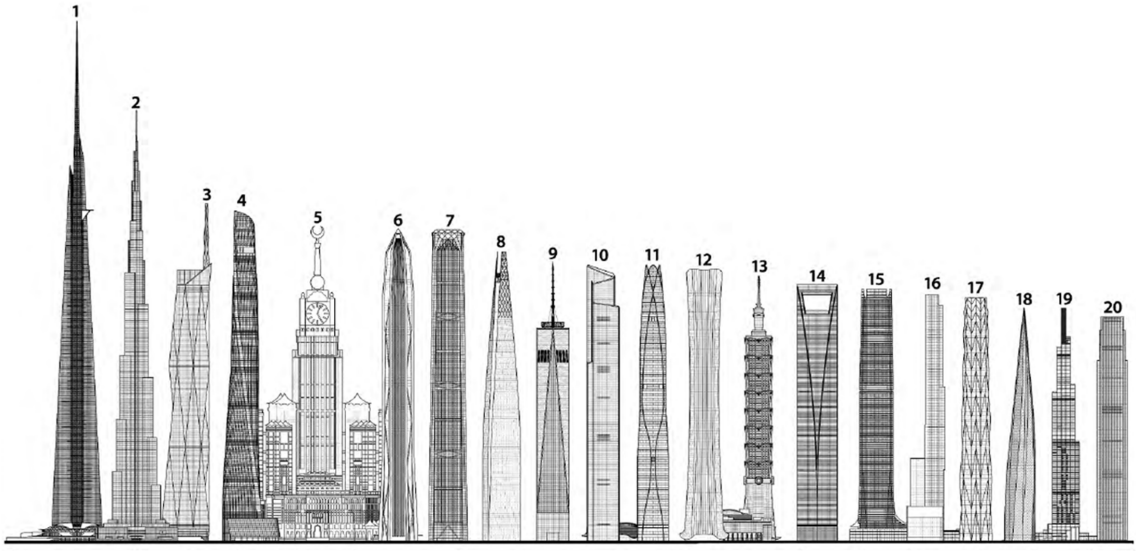
Figure 4. Commonly used dampers in engineering.

Fig. 4. The velocity-related type is mainly about viscous fluid dampers, while the main displacement-related type damper is the metal damper, such as buckling restrained braces, shear panel dampers, friction dampers, and so on. Besides, viscoelastic damper is a combination of velocity-related and displacement-related type. In addition, in order to achieve the goal to dissipate energy in different levels of earthquake, researchers have proposed double-stage yielding dampers such as double-stage yielding buckling restrained braces, double-stage yielding energy dissipation coupling beams, and so on, which are capable of providing additional damping ratio by the first-stage yielding under frequent earthquake, as well as protecting the main structure by the second-stage yielding under intermediate and rare earthquakes.

Based on the different characteristics of dampers, components are selectively made to achieve yielding under different levels earthquakes. By actively adjusting the layout and mechanical parameters of energy dissipation dampers, the energy consumption efficiency of the dampers for the structure can be optimized.

With the rapid development of economy, numbers of super high-rise buildings have been built up since the beginning of this century in China, including Shanghai Tower, Shenzhen PingAn Financial Center and CITIC Tower, etc, as shown in Fig 5. As the critical parts of structural design and construction, the structural system not only improves and develops the functions of buildings but also determines the safety and economy of the buildings. The analysis, calculation method and the design principle of the structural system are facing new challenges(Ding *et al.*, 2014).

As for high-rise buildings, horizontal loads such as wind force or seismic actions, are the most important fundamental factors for the structural design. The lateral-force-resisting systems of high-rise buildings are the key to the rationality and economy of the structures(Wang et al., 2019, Kim, 2017, R, 2007). With the development of the height and function of buildings, it has developed and changed from frame structures, shear wall structures and other basic systems to frame-shear wall systems, frame-core tube systems and so on. At present, the most commonly used is the frame-core tube system, as shown in Fig. 6. However, in order to improve the lateral stiffness of buildings, more and more high-rise buildings use outriggers to connect the frame and core tubes. Thus, the moments of the core tubes can be transferred to the outer frame, which improves the anti-overturning moment capacity of



1	2	3	4	5	6	7	8	9	10
Jeddah Tower 1,000+ m / 3,281+ ft *Jeddah*	Burj Khalifa 828 m / 2,717 ft *Dubai*	Merdeka PNB118 644 m / 2,113 ft *Kuala Lumpur*	Shanghai Tower 632 m / 2,073 ft *Shanghai*	Makkah Royal Clock Tower Hotel 601 m / 1,972 ft *Mecca*	Ping An Finance Center 599 m / 1,965 ft *Shenzhen*	Goldin Finance 117 597 m / 1,957 ft *Tianjin*	Lotte World Tower 555 m / 1,819 ft *Seoul*	One World Trade Center 541 m / 1,776 ft *New York City*	Guangzhou CTF Finance Centre 530 m / 1,739 ft *Guangzhou*
11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Tianjin CTF Finance Centre 530 m / 1,739 ft *Tianjin*	CITIC Tower 528 m / 1,732 ft *Beijing*	TAIPEI 101 508 m / 1,667 ft *Taipei*	Shanghai World Financial Center 492 m / 1,614 ft *Shanghai*	International Commerce Centre 484 m / 1,588 ft *Hong Kong*	Central Park Tower 472 m / 1,550 ft *New York City*	Chengdu Greenland Tower 468 m / 1,535 ft *Chengdu*	Lakhta Center 462 m / 1,516 ft *St. Petersburg*	Vincom Landmark 81 461 m / 1,513 ft *Ho Chi Minh City*	Changsha IFS Tower T1 452 m / 1,483 ft *Changsha*

Figure 5. The world's top 20 super high-rise buildings in 2020(Wang Dasui et al, 2019).

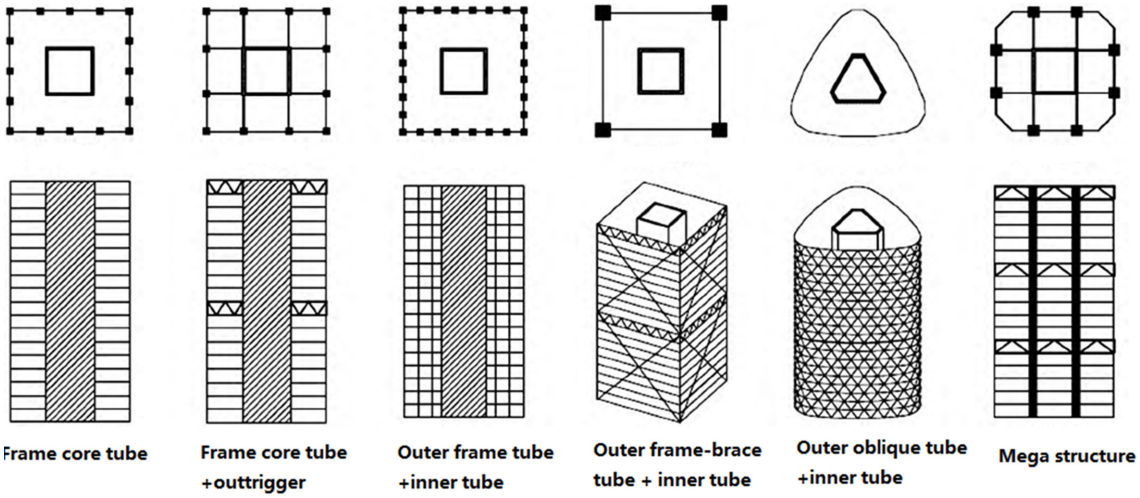


Figure 6. Common structural system and layout of super high-rise buildings (Ding et al., 2014).

the whole structure, and enhances the lateral stiffness under wind forces or seismic actions (J, 2015).

As for super high-rise buildings, the traditional design method is to resist the seismic actions through enough stiffness and strength of the components. As a result, the stiffness of structure will become larger and larger, and in turn it induces greater seismic actions. In recent years, with the development of energy dissipation technology, adopting energy dissipation technology has become a new seismic design method in the design of super high-rise structures(Nanduri and Hussain, 2013). The location of seismic dampers can be divided into frame parts, core tube parts, belt trusses, and outrigger trusses. The types of damper used include buckling restrained braces, viscous fluid dampers, shear metal dampers, energy dissipation coupling beams, and so on. Through the seismic-energy consumption of damping devices, the seismic effect of the main structure can be reduced, and the safety of building can be effectively improved(Burton, 2017).

2. Application of Dampers in Frame Part

In the frame-core tube structure for high-rise buildings, there are some disadvantages, such as insufficient lateral

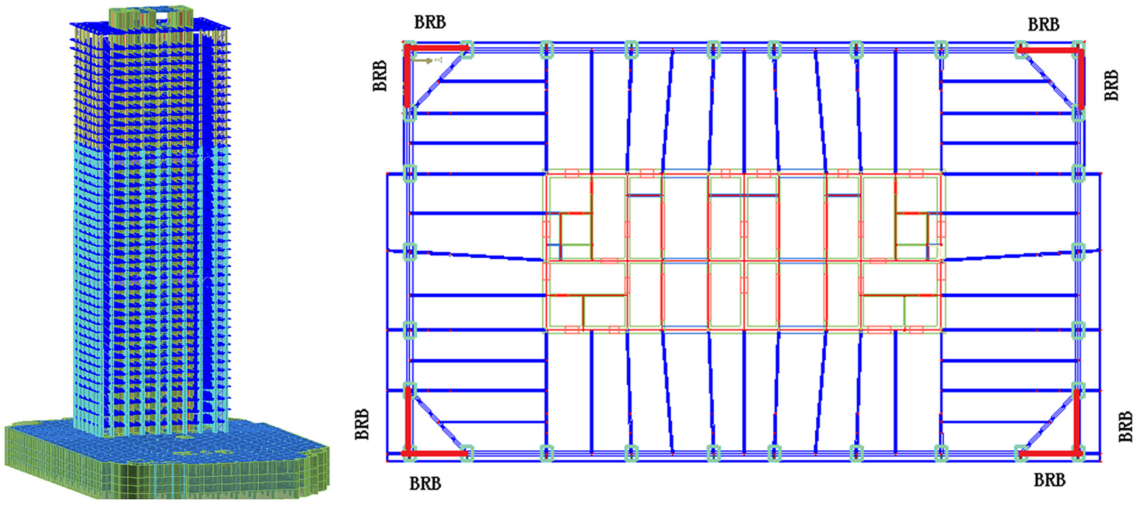


Figure 7. Three dimensional structural drawing and standard floor plan.

stiffness of the frame, large deformation, and large internal forces of the core tube, which lead to the failure of the outer frame to resist the lateral force. By setting dampers in the frame parts, the problem of insufficient stiffness of the frame part can be solved and the seismic performance is improved. Viscous fluid dampers are used to provide the additional damping ratio under frequent earthquake, and buckling restrained braces are used to consume seismic energy and improve the overall seismic performance of the structure under intermediate and rare earthquakes(Ding et al., 2021).

Hainan Building project, located in Haikou, has a seismic intensity of 8 degrees (0.3 g). The main building has 46 floors with a height of 198.6 m. The steel frame-concrete core tube system was adopted as the structural system, with the structural strengthening layers located at the 17th and 31st floor. The strengthening layers adopt the entire truss mode of the whole layer, and the outrigger trusses are set between the frame columns and the tubes. Between them, the waist trusses adopt buckling restrained braces, while the standard floors are set with buckling restrained braces in four corners from the first floor above the ground to the 45th floor above the ground. The plane layout is shown in the Fig. 7.

It can be calculated that the overturning moments of the frame part with buckling restrained braces are relatively bigger than that when buckling restrained braces are not used, as shown in Figure 8, which indicates that buckling restrained braces can effectively improve the stiffness of the frame part, as well as the seismic performance of the whole structure.

Xujiahui Center project is located in Shanghai with a seismic intensity of 7 degrees (0.1g). The height of the building is 370m with 70 stories above the ground. The lateral force resisting system is composed of a peripheral frame with belt trusses and a reinforced concrete core

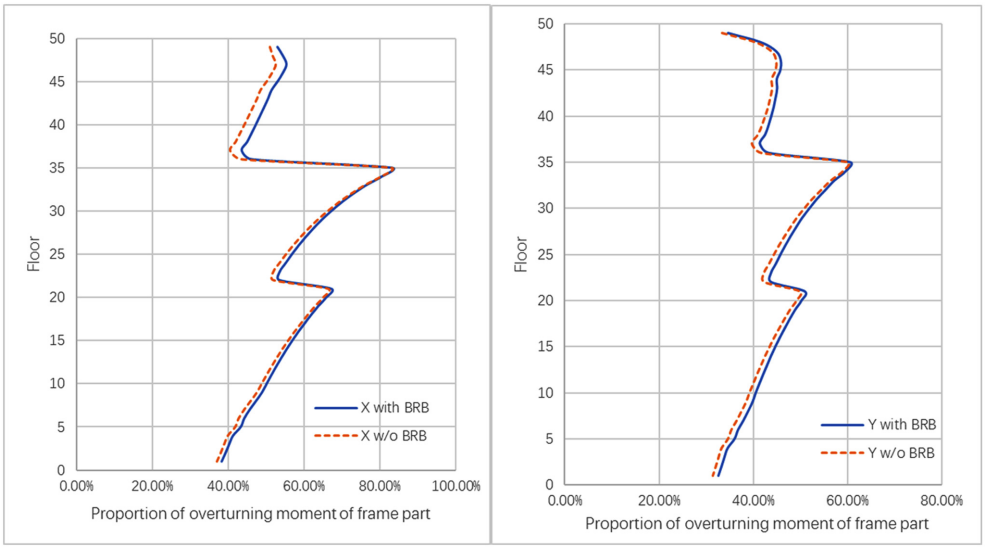


Figure 8. Overturning moment results.

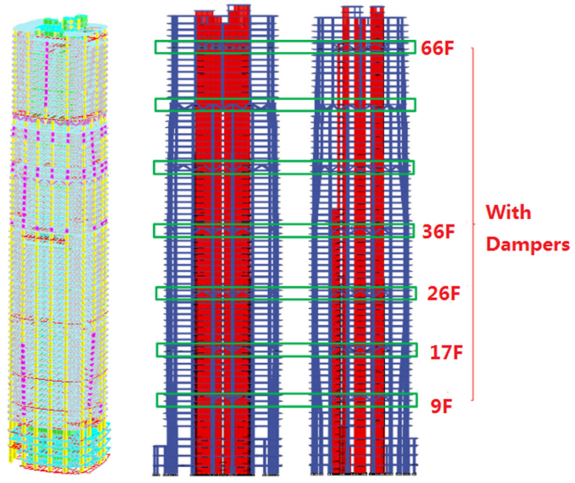


Figure 9. Three dimensional structural model and damper location.

Table 1 Layout plan of the dampers

Item	Floor	X Direction	Y Direction	Total
Viscous fluid Damper	9F	8	12	20
	17F	8	16	24
	26F	12	10	22
	36F	12	12	24
	66F	12	10	22
Total			112	

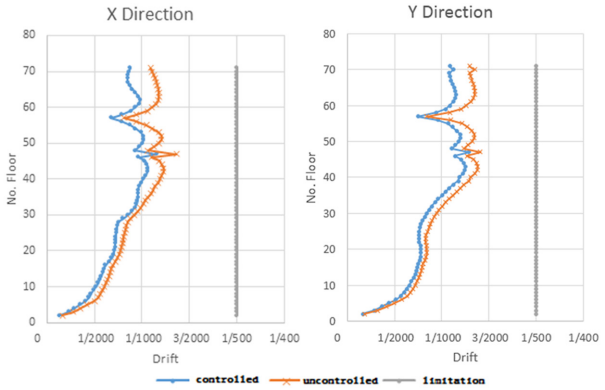
tube. In order to minimize the influence on the space of the building (especially the mechanical and electrical layout), viscous fluid dampers are used at the belt trusses of the refuge floors, and herringbone and W-shaped layout are adopted. There are 7 refuge floors in the tower, of which the 46th and 56th floors are used as structural strengthening layers, and belt trusses are set around them. Therefore, the 9th, 17th, 26th, 36th, and 66th floors are selected as damper-layout floors, as shown in Figure 9, and the number of dampers is shown in Table 1.

The design target is to provide 0.02 the additional damping ratio under frequent earthquake, and reduce the inter-story drift ratio and base shear by about 10% compared to the original structure.

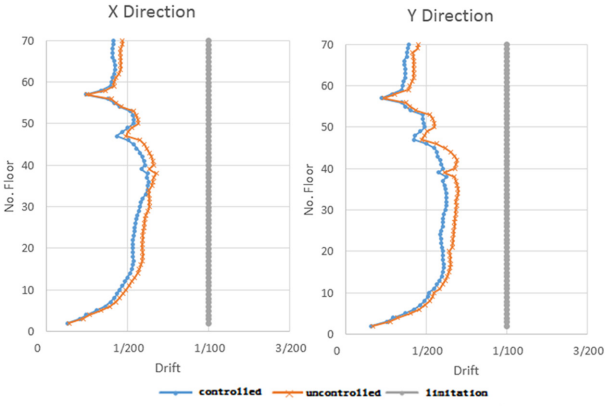
The results of nonlinear time history analysis show that the maximum inter-story drift ratio of uncontrolled and controlled structures under frequent earthquakes are 1/724 and 1/802, respectively, which indicates that the maximum drift ratio of the structure decreases by about 10% after applying dampers. The results show that the maximum story drift ratio under rare earthquake of uncontrolled and controlled structures are 1/143 and 1/158, respectively, which indicates that the maximum story drift ratio of the structure also decreases by about 10%.

3. Application of Dampers in Core Tube Part

Shear wall and frame-core tube structural systems are



(a) Inter-story drift ratio under frequent earthquake



(b) Inter-story drift ratio under rare earthquake

Figure 10. Results of drift ratioes under frequent and rare earthquakes.

widely used in high-rise buildings. The coupling beams connecting wall limbs and the beams connecting columns and wall limbs often have the characteristics of small span and large section height. If reinforced concrete is used to design this type of beam, the coupling beams will be seriously damaged and difficult to repair after earthquake.

In areas of high seismic intensities, concrete coupling beams are often seriously damaged under seismic actions. Thus, engineers have tried to replace the concrete coupling beams with the steel ones. At present, there are two practical ways to use steel coupling beams as the energy dissipation components, which are directly replacing the reinforced concrete coupling beams with steel coupling beams or replacing the reinforced concrete coupling beams with the shear panel dampers.

The headquarter building project, as shown in Fig. 11 (Sun *et al.*, 2012) of a bank in Uzbekistan is located in a high -intensity area, with a seismic intensity of 9 degrees and the building height of is 135.1 m. In order to ensure the safety and reliability of the structure, and taking the construction materials and other factors into consideration, the system of concrete frame-core tube structural system equipped with dampers was adopted. Viscous fluid dampers are set on the 10th and 21st floors of the equipment floors combined with outrigger trusses, and coupling beam

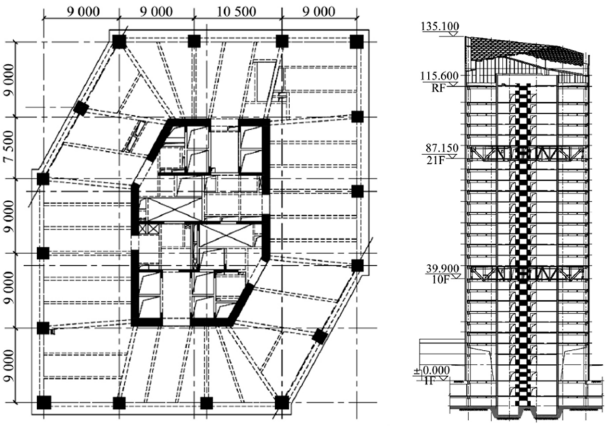


Figure 11. Structural plan and schematic diagram of standard floor(Sun et al., 2012).

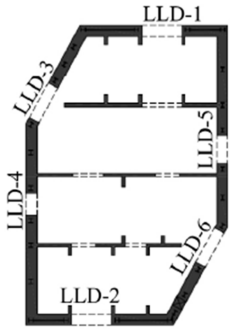


Figure 12. Location of coupling beam dampers(Yan et al., 2020).

dampers are set at some floors, as shown in Fig. 12.

Through the nonlinear time history analysis of the structure, the maximum inter-story drift ratio in X and Y directions are 1/190 and 1/207, respectively, which meet the requirements of 1/100 by the code, and the overall damage of the core tube is slight (Fig. 13). Parts of the walls in the non-bottom strengthening area were moderately damaged under rare earthquake, the concrete coupling beams have cracked obviously, the steel and steel bars in the coupling beams were slightly damaged, and the degree of damage of the entire structure was controllable.

People's Daily Office Building, as shown in Fig. 14, (Sun et al., 2012) is located in Beijing. The main structure has 32 floors above the ground with a standard floor height of 4.5 m and the maximum height of 180 m. This

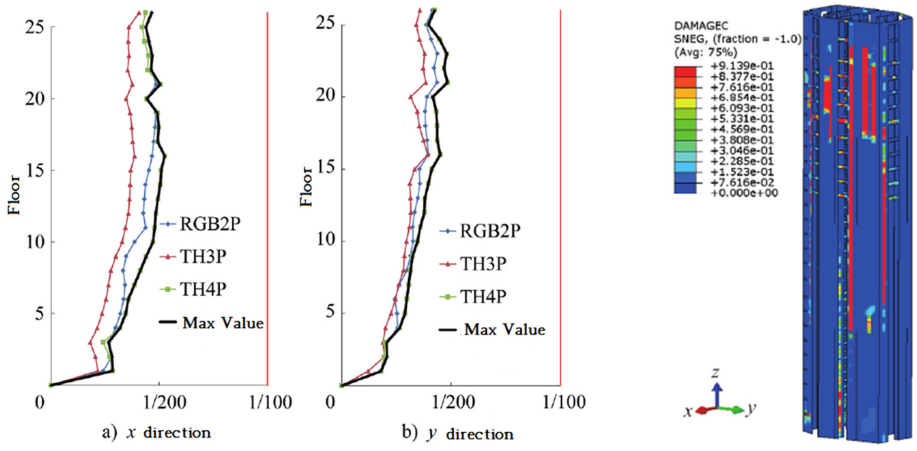


Figure 13. Inter-story drift ratio and damage of core tube under rare earthquake(Sun et al., 2012).

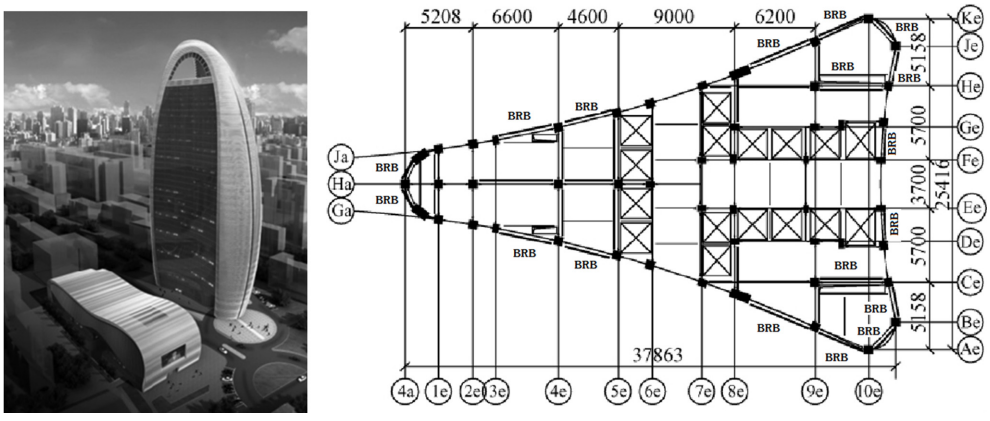


Figure 14. Architectural effect drawing and BRB layout plan of core tube area(Sun et al., 2012).

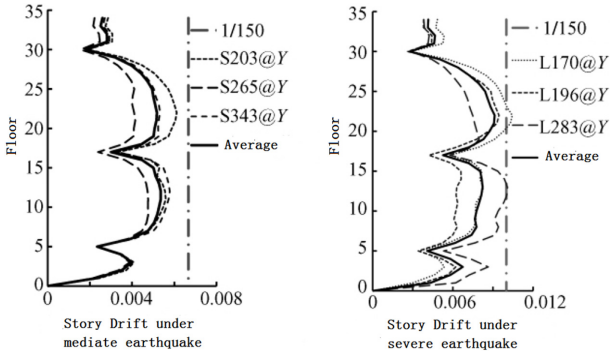


Figure 15. Results of inter-story drift ratio under intermediate and rare earthquakes(Xun et al., 2012).

project adopts steel frame with braces as structural system, and the buckling restrained braces are fully used in the core tube part. Through the energy dissipation of buckling restrained braces, the seismic performance of the structure is improved. At the same time, the braces system is easy to adjust the structural stiffness, so as to reduce the eccentricity of the stiffness center and the mass center.

According to the nonlinear time history analysis of the entire structure, the maximum inter-story drift ratio is about 1/147, and all drift ratios are less than 1/150 under intermediate earthquake, while under rare earthquake, the maximum inter-story drift-ratio is 1/89, and the average drift ratio is 1/120, as shown in Fig. 15. Thus, the structure still has a significant reserve of strength and deformation capacity under rare earthquake.

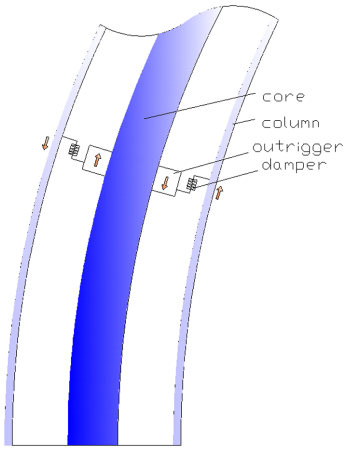


Figure 16. Novel damped outrigger systems.

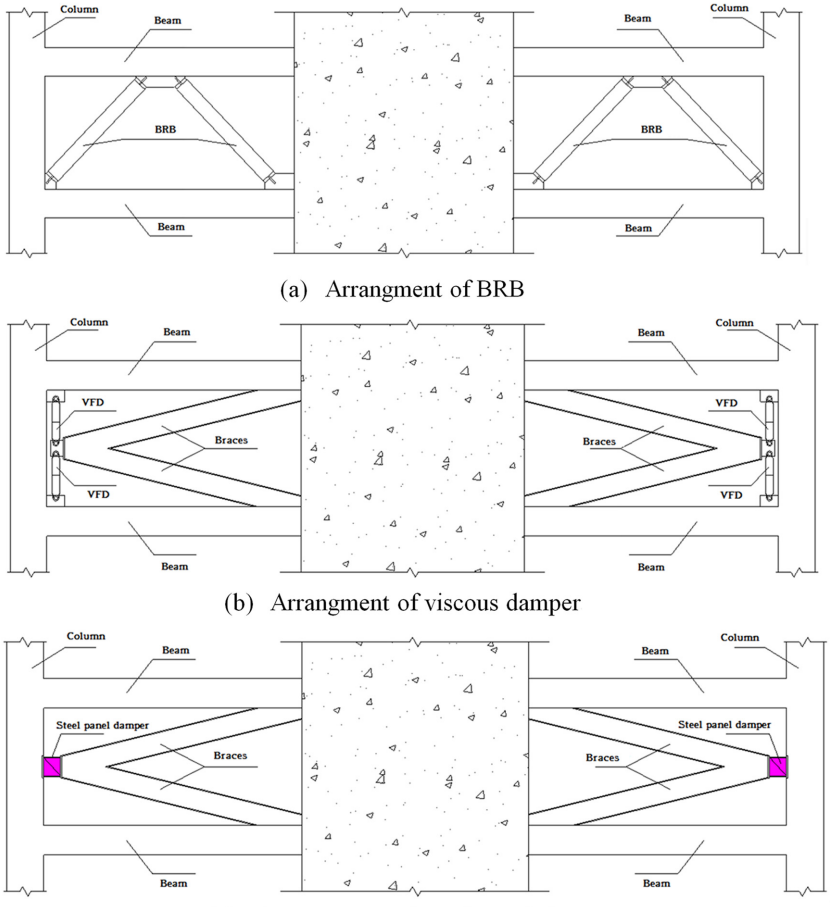


Figure 17. Damper layout.

4. Application of Dampers in Outtrigger Part

As the key components of super high-rise buildings, outrigger trusses work together by connecting columns and core tubes to achieve the overall bending resistance of the structures. However, due to the large stiffness of the ordinary outrigger trusses, the force-flow of the outrigger truss floors change, as well as the stiffness and internal forces of the outer frame and core tubes, which leads to weak floors. At the same time, when displacement at the end of the truss reaches a certain extent, the truss members will buckle before yielding, which leads to the rapid degradation of the bearing capacity and insufficient deformation capacity of the outrigger trusses, and finally low energy consumption capacity, insufficient ductility, and poor post-earthquake recovery capacity of the ordinary outrigger trusses. In order to solve above problems, researches have also proposed energy dissipation outrigger trusses(Xun et al., 2012), in which energy dissipation devices are set to reduce the corresponding energy consumption of the main structure under wind loads and earthquakes, as shown in Fig. 16.

At present, the common application methods of energy dissipation outrigger trusses include energy dissipation outrigger trusses using buckling restrained braces, viscous damper or steel panel dampers at the end of outrigger trusses, which are shown in Fig. 17.

Baoji Guojin Center project has a seismic intensity of 8 degrees (0.2 g). Two strengthening layers are set at the 24th and 39th floor of the structure, and buckling restrained braces are used in the belt trusses and outrigger trusses respectively. Under this condition, the yielding capacity of the buckling restrained braces of the belt truss are 15000 kN, while those at the outrigger trusses are 30000 kN.

Chongqing Raffles Plaza project consists of 8 super high-rise towers, 6-storey commercial building, and 3-storey basements(Zhu *et al.*, 2015). Among them, T3N and T4N are collectively referred to as the North Tower, and T1 / T2 / T3 / T4 / T5 / T6 are collectively referred to the South Tower. The four towers of T2 / T3 / T4 / T5 are connected through a 300 m-long bridge on the roof. The heights of T3N and T4N are 356 m, and the lateral resistance system is composed of a mega frame with belt trusses plus an outrigger system plus reinforced concrete core tube plus external secondary frame tube, as shown in Fig. 19.

The stiffness and ductility of the outrigger system is of great significance to the integrity of super high-rise towers. The system, as shown in Fig. 20 consists of a steel panel damper connected to the outer frame column, a reinforced concrete cantilever wall extending from the corner of the core tube, a steel brace connecting the shear damper and the concrete wall, and a reinforced concrete beam surrounding the core tube. The system takes the advantage of the large stiffness of concrete cantilever walls to improve the overall stiffness of the structure. Through the design of a reasonable yielding sequence of system components, the shear panel dampers can yield under rare earthquake and play a role as a fuse for the entire structure. The ductility and energy dissipation capacity after yielding of the steel panel dampers are used to protect the concrete cantilever walls and core tube.

A super high-rise building in Lanzhou(Wu *et al.*, 2014), Gansu Province, with a seismic intensity of 8 degrees (0.20 g), structural height of 250 m, four floors underground and 51 floors above ground, adopts the structural system of the composite outer frame plus reinforced concrete core tube plus outrigger belt trusses, as shown in Fig. 21. Along the vertical, the belt trusses are set on the 23rd, 36th, and 52nd floors, and the outrigger trusses are set on the 23rd and 36th floors.

In the outrigger trusses of the structure, viscous fluid dampers are arranged as shown in Fig. 22. Through the analysis, it can be concluded that the outrigger trusses with dampers can effectively reduce the seismic response

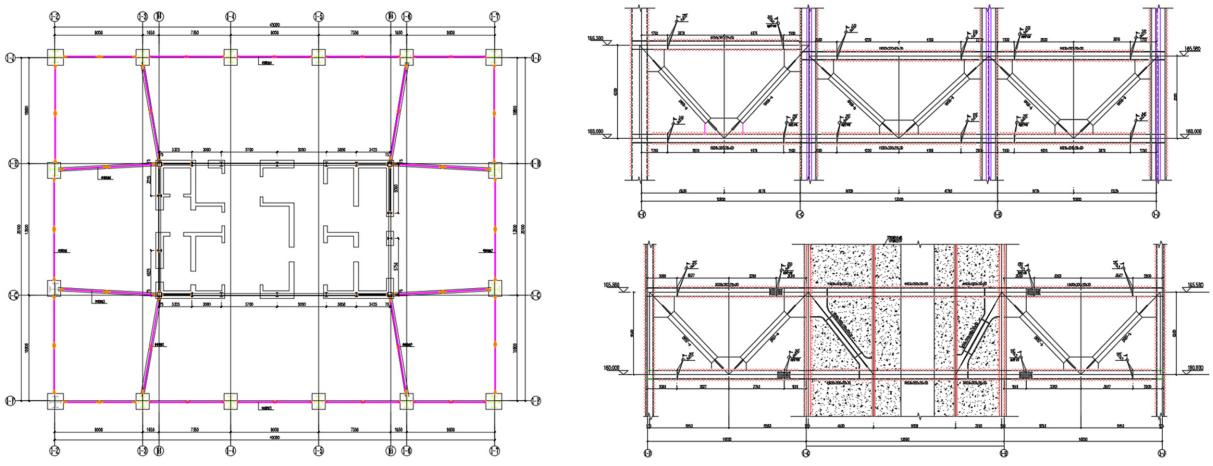


Figure 18. Layout and elevation plan of strengthening floors.

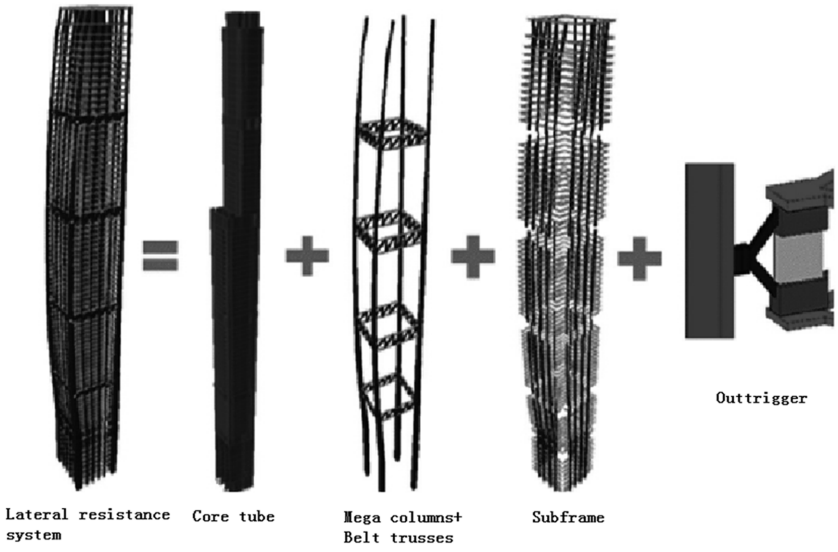


Figure 19. Lateral resistance system(Zhu et al., 2015).

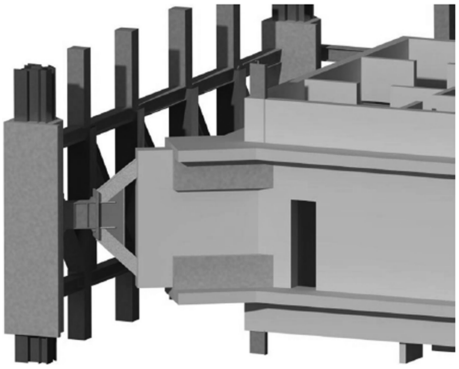


Figure 20. Schematic diagram of outtrigger system(Zhu et al., 2015)

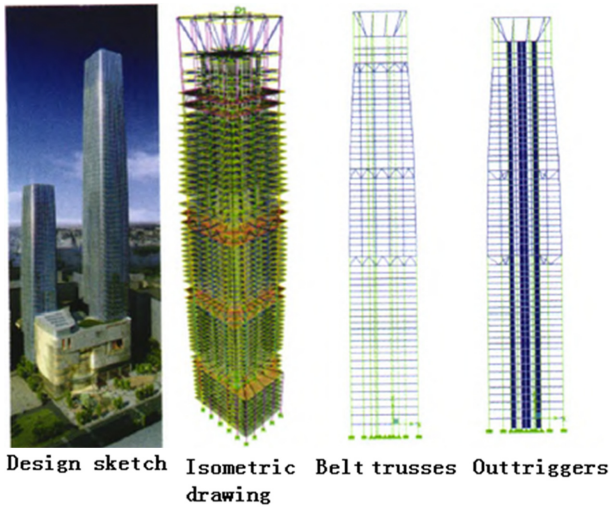


Figure 21. Structure diagram(Wu et al., 2014).

and the local plastic damage of the shear wall caused by outrigger trusses. Therefore, the combination scheme of

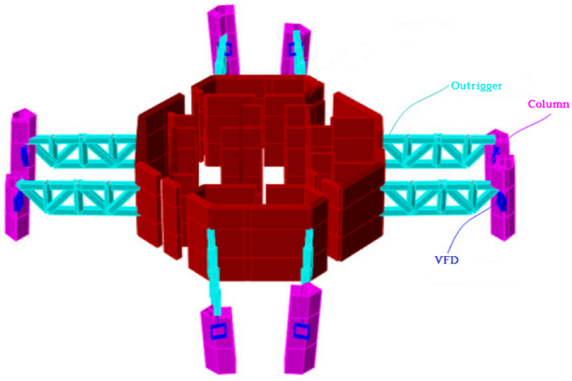


Figure 22. Damper layout.

viscous fluid dampers and outrigger truss is feasible.

5. Hybrid Damping Structures

At present, the form of hybrid damping is also widely used in practical applications. Under frequent earthquakes, only the velocity-related dampers dissipate energy, while the displacement-related dampers maintain elastic, and only provide the lateral stiffness for the structure. However, under intermediate and rare earthquakes, the metal dampers gradually enter into the yielding states to realize the optimization of energy consumption efficiency.

The seismic intensity of Dianchi Convention and Exhibition Center project (Wu et al., 2020) is 8 degrees (0.20 g). It has a height of 330m and 65 floors above ground. As the project is located at a high seismic intensity area, in order to ensure the safety and reliability of the structure, a double lateral force resistant structural system of "composite outer frame structure and reinforced concrete core tube" is applied, as shown in Fig. 23.

Due to its high importance and high seismic intensity, the energy dissipation technology is adopted to improve

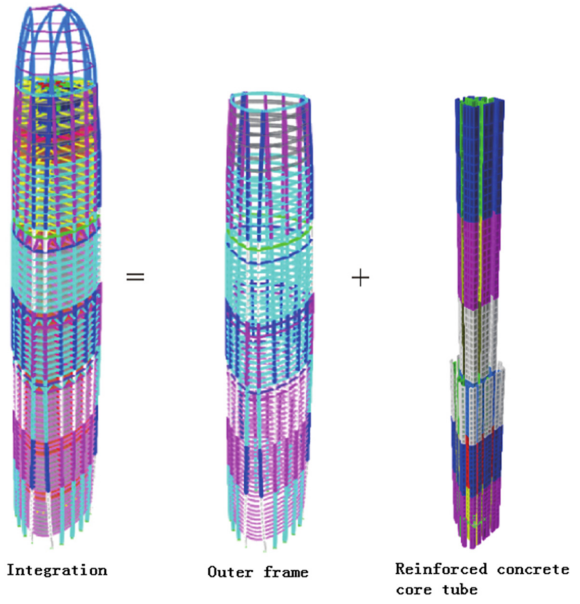


Figure 23. Structural system composition(Wu et al., 2020).

the energy dissipation capacity and the safety of the structure. In order to improve the energy dissipation capacity of the structure under earthquake, viscous fluid dampers are arranged at the 31st, 41st, and 51st floors of the structure. In order to improve the energy dissipation capacity of the structure under intermediate and rare earthquakes, buckling restrained braces are also arranged in the same equipment floor by considering the characteristics of structural deformation. Meanwhile, energy dissipation coupling beams are used in the core tube position of the

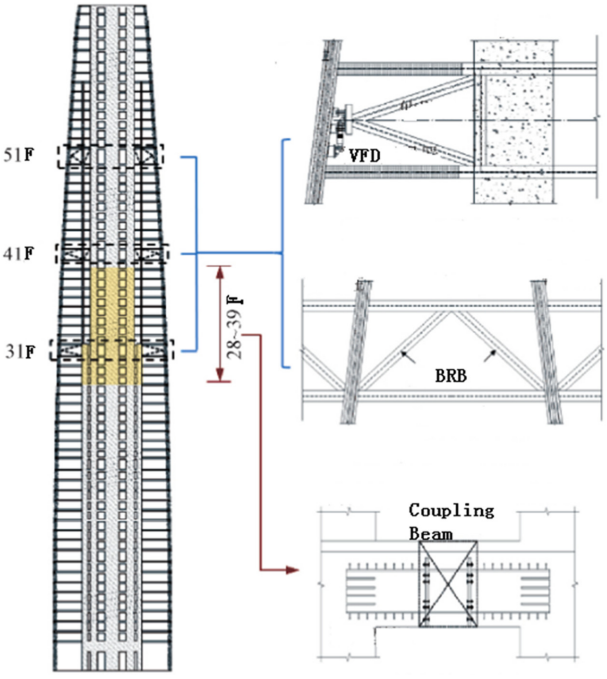


Figure 24. Dampers Placement(Wu et al., 2020).

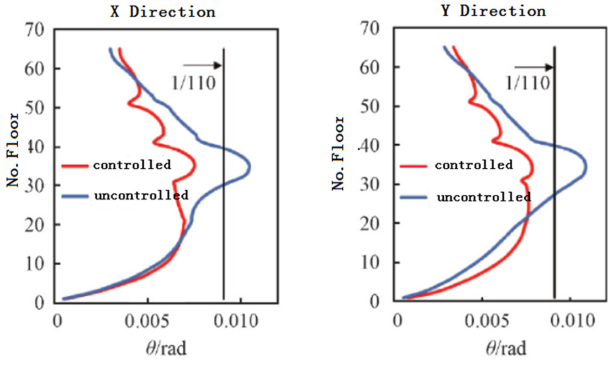


Figure 25. Results of inter-story drift ratios (Wu et al., 2020).

28th to 39th floors, as shown in Fig. 24.

Under rare earthquake, the maximum inter-story drift ratio in X and Y directions are 1/133 and 1/128 respectively, while that of the original structures in X and Y directions are 1/95 and 1/92 which exceeds the target value of 1/110, as shown in Fig. 25.

6. Summary

(1) In high-rise buildings located at high seismic intensity areas, the application of energy dissipation technology can effectively reduce the seismic effects.

(2) The belt trusses with energy dissipation dampers can effectively reduce the seismic response and the damage caused by earthquakes, so the applications of dampers in frames are reliable.

(3) Using the energy dissipation coupling beams instead of the original concrete beams in the core tubes, it can obviously reduce the damage of the main structures under earthquakes and improve the seismic performance of the structures.

(4) The results show that the cantilever trusses with dampers can reduce the local damage of the shear wall effectively.

(5) Energy dissipation technology can effectively reduce the seismic response of the structure and improve its seismic performance, which is a promising direction for the seismic design of high-rise structures in the future.

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