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Application research of combined energy dissipation technology in a super high-rise building in high seismic intensity region

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Abstract

Seismic loading of super high-rise buildings located in high seismic intensity region is quite large, so enhancing seismic performance of super high-rise building and realizing seismic performance design is a crucial problem. Combined energy dissipation technology is a creative application of energy dissipation technology, which refers to the technology using velocity-dependent and deformation-dependent devices simultaneously, offering a new feasible idea for seismic design of super high-rise buildings in region of high seismic intensity. Velocity-dependent dampers are designed to dissipate energy under frequent, basic and rare earthquakes. Deformation-dependent devices are designed to remain elastic to provide lateral stiffness under frequent earthquakes, and designed to be yielded to dissipate energy under basic and rare earthquakes. A 230m super high-rise office building located in China was selected as an example to examine the efficiency of the proposed combination method. Three kinds of energy-dissipation devices, i.e. viscous wall dampers(VWDs), buckling restrained braces(BRBs) and mild steel coupling beams(MSCBs), were applied to this building to achieve expected performance levels. The optimum layout and damping parameters of VWDs were analyzed. The superiority of the combined energy dissipation scheme was illustrated by comparing the overall structural response, seismic performance and costs to the traditional seismic resistant scheme. Finally, the elastic-plastic analysis of the case building under rare earthquakes was carried out to prove the effectiveness of the combined energy dissipation technology. The combined energy dissipation method of this project provide a valuable reference for similar engineering design.

Keywords: performance-based seismic design; combined energy dissipation technology; viscous wall dampers; mild steel coupling beams; buckling restrained braces

1. Introduction

With the rapid development of economy and construction technology, more and more super high-rise buildings are under construction across the world. Lateral loading, such as seismic loading and wind loading, have more obvious influence on super high-rise buildings, threatening its structural safety and serviceability. Therefore, it is essential to control the performance of super high-rise buildings under horizontal loads. In recent years, passive supplemental damping system strategies for high rise buildings, including viscous dampers, viscoelastic dampers, metallic dampers, are widely used as effective means to mitigate the effects of lateral loading [1-3].

In this paper, a new kind of combined energy dissipation technology is introduced. It was demonstrated by the design of a 230m super high-rise building located in Lanzhou City, Gansu Province, China. Under frequent earthquakes, additional damping is provided by velocity-dependent dampers, and deformation-dependent dampers remain elastic to provide lateral stiffness. Under basic and rare earthquakes, deformation-dependent dampers yield gradually, which compensate the shortcoming of the reduced energy dissipation capacity of the velocity-dependent dampers. Nonlinear time history analyses were conducted to verify the expected performance object of the case structure. Performance-based design method will be taken to evaluate the seismic performance. Finally, advice on practical engineering were put forward to guide the application of combined energy dissipation technology.

2. Combined energy dissipation technoloy

There are two kinds of energy dissipation devices wildly used in practice according to energy-dissipation way, which is velocity-dependent dampers and deformation-dependent damper. The velocity-dependent damper is mainly refer to viscous dampers, and deformation-dependent damper is mainly refer to metallic dampers.

Combined energy dissipation technology is a new design concept stem from the traditional performance-based design concept. This method use velocity-dependent and deformation-dependent devices simultaneously. The energy dissipation effect of the velocity-dependent damper under large deformation is worse than that of the small deformation, while deformation-dependent damper has better energy dissipation effect with deformation increasing. By adjusting the location and mechanical parameters of the different type of dampers, it is convenient to ensure that they play the corresponding role under different level of earthquakes, satisfying the requirements of structural stress and deformation, and improve the seismic performance of the structure at the same time.

3. Prototype Design

3.1 Preliminary design

The proposed combined energy dissipation technoloty is demonstrated by the design of a 47-story office building in Lanzhou city, Gansu Province, China. The building is located in the Category II site with a site characteristic period of 0.45s. According to the intensity 8 (0.2g) of the local region, the PGA is 70gal for frequent earthquakes, 200gal for basic earthquakes, and 400gal for rare earthquakes. The local basic wind pressure is 0.30kN/m^2 with a return period of 50 years.

Fig. 2 and Fig. 3 shows the typical floor plan and elevation view of the building. Overall dimension is 53.2m in *x* direction and 52.2m in *y* direction. The total construction height is 230m, and its ratio of height to width is 4.4. The lateral force is mainly resisted by frame-outrigger-core wall system, which is commonly used in super high-rise building across the world. The main structural members include SRC columns, core tube shear walls, belt trusses, steel beams. Three belt trusses are arranged at story 9, story 19 and story 29, respectively.The belt trusses work with perimeter frames, forming strenthened stories. Main design parameters for superstructure members is shown in Table 1.

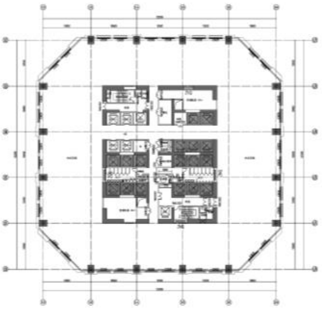


Fig. 1 – Plan view of the typical story

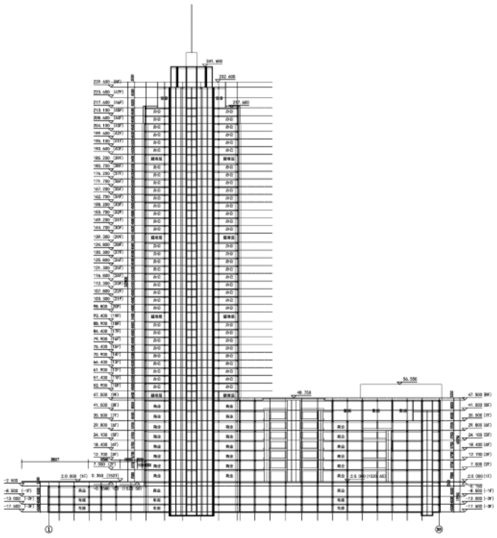
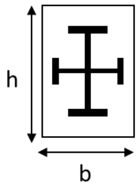
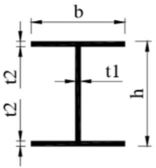


Fig. 2 – Elevation view of the building


Fig. 3 – Rendering of the building

Table 1 – Main design parameters for superstructure members (mm)

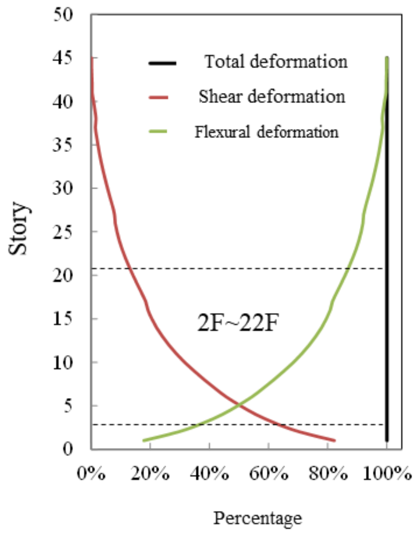
Story	Shear wall thickness (exterior/interior)	Column		Beam		Slab thickness
		hxb	Steel ratio	Peripheral beam	Central beam	
				hxbxt_1xt_2 		
F40~F45	500 / 300	1300x1000	4.1%	H900x450x16x36	H550x300x16x28	120
F30~F39	600 / 400	1400x1000	4.0%			
F20~F29	800 / 500	1600x1200	4.2%			
F10~F19	1000 / 600	1800x1400	4.2%			
F1~F9	1200 / 600	2000x1600	4.0%			

3.2 Lay out and parameters of energy dissipation devices

1) Velocity-dependent dampers

In order to improve the energy dissipation capacity of the structure under frequent earthquakes, VWDs were adopted. VWDs is a kind of velocity-dependent damper dissipate energy by shear deformation [4-5]. Lateral deformation distribution is shown in Fig. 4. Due to the high proportion of shear deformation in the lowers stories of the building, VWDs were placed in lower stories, i.e. 2nd floor to 22nd floor excluding strengthened stories, as shown in Fig. 5. A total number of 80 VWDs were used in this case.

The constitutive relationship for this model is $F=CV^{\alpha}$, where C means damping coefficient, V stands for relative velocity between two ends of VWDs, α denotes velocity exponent, and F is damping force in VWDs. In this case, α is equal to 0.45, and C is equal to 4000 kN/(m/s)$^{0.45}$, and maximum axial bearing force equals to 2000 kN, as shown in Table 2.



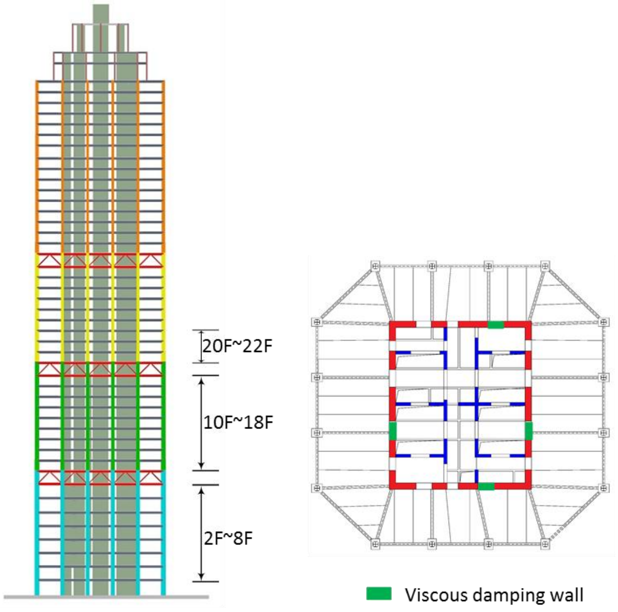


Fig. 4 – Lateral deformation distribution

Fig. 5 – Lay out of VWDs

Table 2 – Parameter of VWDs

Damping coefficient /kN/(m/s)$^{0.45}$	Velocity exponent	Maximum axial bearing force /kN	Maximum stroke /mm
4000	0.45	2000	50

2) Deformation-dependent dampers

In order to enhance the energy dissipation capacity under basic and rare earthquakes, combined with the structural deformation characteristics, deformation-dependent dampers are arranged at appropriate positions of the structure. By comparing the position and mechanical characteristic parameters of the energy dissipation devices. Different types of energy dissipation devices will be activated under different levels of earthquakes, optimizing the energy dissipation as a result.

According to the characteristics of the structure, stricter requirements are imposed on the deformation of the building, so controlling lateral deformation is essential to structural design. The MSCB is composed of non-yielding segments and yielding segments, as displayed in Fig. 6. The MSCB is an innovative structural component designed to increase the seismic resilience of reinforced concrete shear wall structures, with advantages of replaceable and easily repaired after severe earthquakes. Considerable experimental and analytical investigations [6-8] indicate that MSCBs can improve structural performance significantly. According to research work by WU [9], MSCBs is reasonable to be placed at stories with larger inter-story drifts. In this case, MSCBs were placed at 15F~27F, as shown in Fig. 7. Parameters of MSCs used in this case are shown in Table 3. A total number of 78 MSCBs were used in this case.

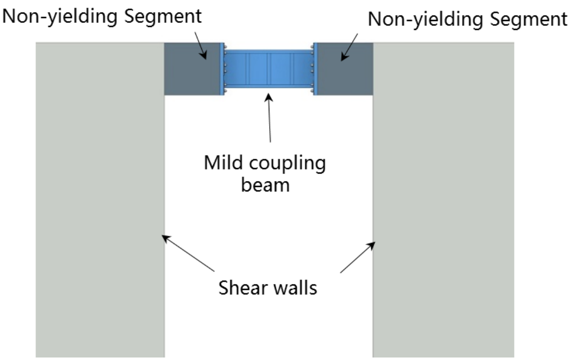


Fig. 6 – Details of MSCBs

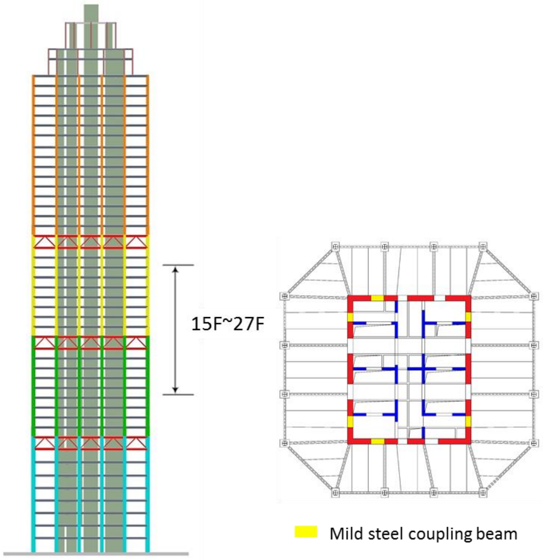


Fig. 7 – Lay out of MSCBs

Table 3 – Parameter of MSCBs

Story	**Shear stiffness /kN/m**	**Yielding displacement /mm**	**Yielding force /kN**
15F~27F	2.22E+6	1.2	2700

Lateral rigidity of super high-rise structure can be enhanced by setting strengthened stories, causing a sudden change in structural rigidity and forming weak stories under seismic loading. To solve this problem, web of the belt truss of the original structural strengthened stories were replaced with BRBs, making structural stiffness distributed more evenly along altitude. The seismic response of the structure will be mitigated and the energy dissipation capacity of the structure will be enhanced at the same time. Parameters of BRBs are listed in Table 4. A total number of 96 BRBs were used. Energy dissipation object of both velocity-dependent dampers and deformation-dependent dampers under different level of earthquakes is shown in Table 5.

Table 4 – Parameter of BRBs

Story	**Materials**	**Yielding Force /kN**	**Equivalent area /mm^2**
29F	Q235	8000	42553
9F；19F	Q235	10000	42553

Table 5 – Energy dissipation object under different level of earthquakes

Energy dissipation device	**Frequent earthquake**	**Basic earthquake**	**Rare earthquake**
VWDs	√	√	√
BRBs	--	√ （Partially yielded）	√ （Totally yielded）
MSCBs	--	√	√

3.3 Modelling method

The finite element analysis software SAP2000 and Perform-3D was used to simulate the elastic and elastoplastic time history response of structure under different level of earthquakes. The maxwell model, with damper and spring connected in series, is employed to model the viscious damping walls and the Plastic Wen model is employed to model metallic dampers.

The prevailing uniaxial Mander constitutive relationship is adopted to model concrete, ignoring tensile strength of concrete. For Q345 steel, elastic perfectly plastic relationship is adopted, where the elastic modulus is 2.06x10^{5}MPa. For HRB400 rebar, its constitutive relationship allows for strain hardening, and the curve does not fall once it reaches the ultimate strength of the material, where the hardening factor is 0.01, and the elastic modulus is 2.0x10^{5}MPa.

3.4 Selection of ground motion records

5 strong ground motion records were selected from the seismic records database and 2 artificial ground motions were generated by SIMQKE_GR code. All the records were selected to match the target spectrum given by *Code for Seismic Design of Buildings (GB50011-2010)* [10] for the minor earthquake level (Intensity 8, PGA=70gal), and scaled to the rare earthquake level (PGA=400gal) in the nonlinear time history analysis. The basic information of these seven records is listed in Table 6. The mean spectrum and the target spectrum is plotted in Fig. 8.

Table 6 – Basic information of selected ground motions

Name	**Type**	**Interval time /s**	**Duration /s**	**Name**	**Type**	**Interval time /s**	**Duration /s**
S0202	Natural	0.02	36.96	S0721	Natural	0.02	41.94
S0523	Natural	0.02	45.24	TRB1	Artificial	0.02	30.0
S0640	Natural	0.02	44.90	TRB2	Artificial	0.02	30.0
S0646	Natural	0.02	49.36				

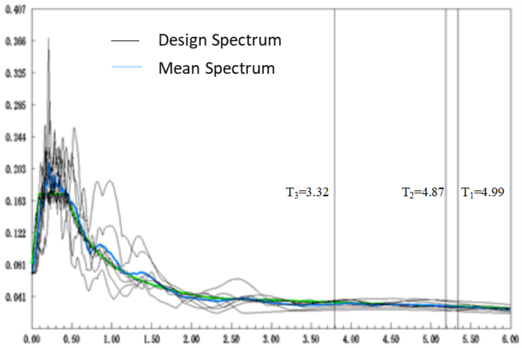


Fig. 8 – Acceleration response spectra

4. Performance Analysis

To demonstrate the energy dissipation effect of this combined energy dissipation technology, another traditional undamped structure without energy dissipation devices was established for comparison. This structure has the same layout and structure height of the damped structure, and outrigger trusses and belt trusses were arranged at 9F, 19F and 29F. Comparison result of inter-story drift, base shear and overturning moment, additional damping ratio, maximum ration of demand to capacity and other indexes are discussed in this section.

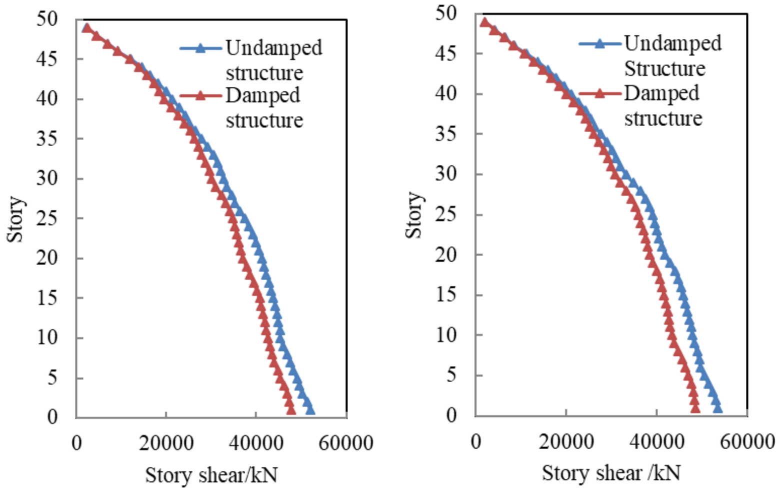
4.1 Structural response

The first 60 modes were calculated and the corresponding sum of the modal participating mass ratio exceeds 90%, which meet the requirement of *Technical Specification for Concrete Structures of Tall Building* (Ministry of Housing and Urban Rural Development. 2010).

The maximum mean inter-story drifts and story shear under 7 seismic waves are shown in Table 7. The structural inter-story drifts of damped structures are satisfactorily controlled. Compared with the damped structure, under frequent earthquakes the maximum inter-story drifts are reduced by 10% and the base shear are reduced by 8%~10%. The VWDs can provide about 1.0% additional damping ratio under frequent earthquakes.

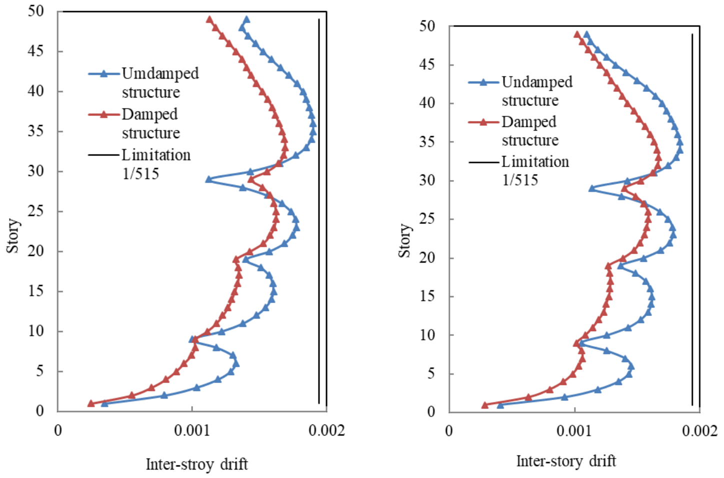
Table 7 – Comparison of the damped and undamped structure under frequent earthquakes

Comparion item		**Damped structure**	**Undamped structure**	**Undamped/Damped**
Period /s	1	4.75	4.99	105%
	2	4.73	4.87	103%
	3	3.22	3.32	103%
	4	1.62	1.64	101%
	5	1.57	1.60	102%
	6	1.35	1.34	99%
Mean base shear	X Direction	51921	47806	92%
	Y Direction	54619	49252	90%
Mean inter-story drift	X Direction	1/532	1/589	90%
	Y Direction	1/543	1/605	89%
Damping ratio		4%	X: 5.0% (Additional damping ratio 1.0%) Y: 5.1% (Additional damping ratio 1.1%)	



(a) X Direction (b) Y Direction

Fig. 9 – Comparison of story shear under frequent earthquake



(a) X Direction (b) Y Direction

Fig. 10 – Comparison of inter-story drift under frequent earthquake

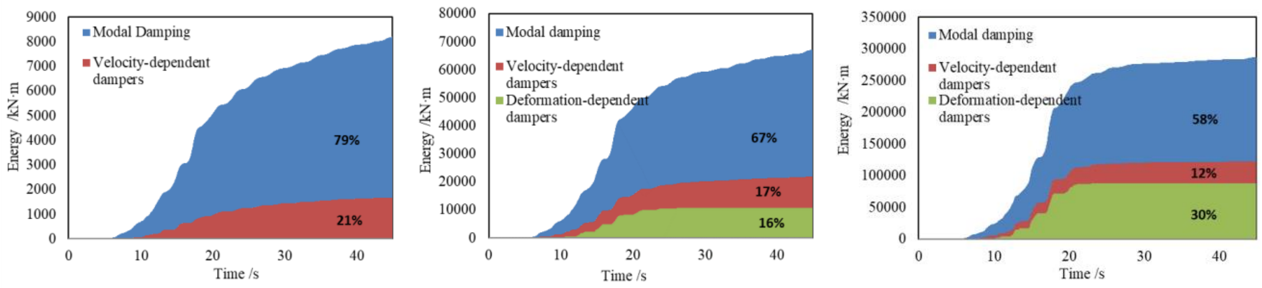
4.2 Energy dissipation

Figure 11~14 shows the energy dissipation accumulation curves of the damped structure and hysteretic loops of different type of energy dissipation devices under S0202 seismic records at frequent, basic and rare earthquakes.

The VWDs provide additional damping for the damped structure at all level of earthquakes. With the increase of earthquake excitation, the energy dissipation ratio of the viscous damper gradually decreases.

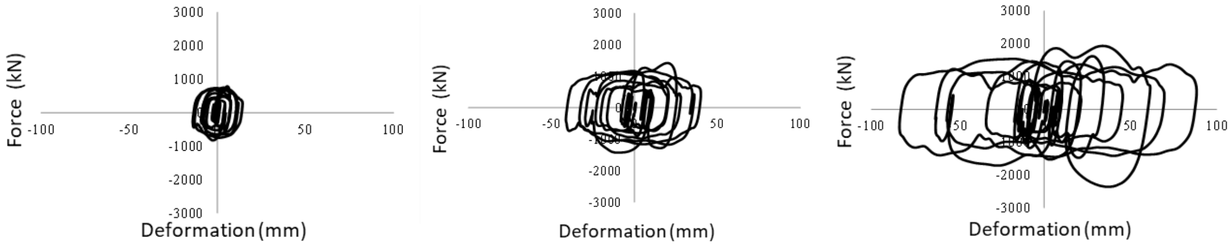
MSCBs and BRBs remain elastic under frequent earthquake, and offer sufficient stiffness to the damped structure without yielding. With the increase of earthquake excitation, all of the MSCBs and part of the BRBs yield under basic earthquakes. The maximum forces and deformations of MSCBs and BRBs increases significantly as seismic intensity increases.

With the increase of earthquake excitation, the velocity-dependent damper and the deformation-dependent damper dissipate energy simultaneously, leading to the reduction of the base shear and the inter-story drift, as shown in Table 8. The calculated energy dissipation mechanism is consistent with the expected design target.



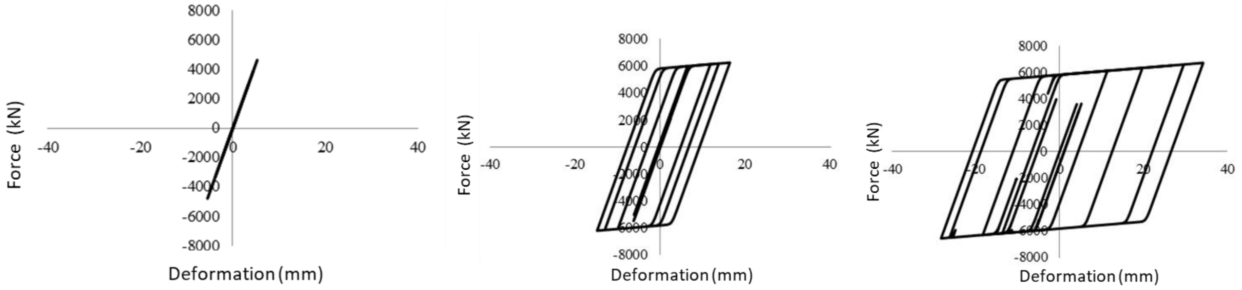
(a) Frequent earthquake (b) Basic earthquake (c) Rare earthquake

Fig. 11 – Comparison of energy dissipation under different earthquake levels



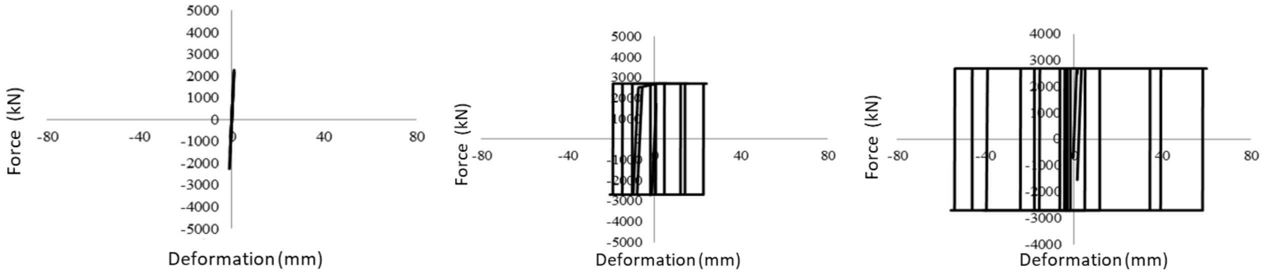
(a) Frequent earthquake (b) Basic earthquake (c) Rare earthquake

Fig. 12 – Hysteretic loops of VWDs under different earthquake levels



(a) Frequent earthquake (b) Basic earthquake (c) Rare earthquake

Fig. 13 – Hysteretic loops of BRBs under different earthquake levels



(a) Frequent earthquake (b) Basic earthquake (c) Rare earthquake

Fig. 14 – Hysteretic loops of MSCBs under different earthquake levels

Table 8 – Damping effect under frequent, basic and rare earthquakes

Level of earthquakes	**Undamped Structure**		**Damped Structure**			
	Base shear (kN)		**Base shear(kN)（Damped/Undamped）**		**Additional damping ratio**	
	X Direction	**Y Direction**	**X Direction**	**Y Direction**	**X Direction**	**Y Direction**
Frequent	51921	54619	47806(92%)	49252（90%）	1.0%	1.1%
Basic	148345	156054	127023(86%)	132325（85%）	1.8%	1.9%
Rare	228205	235641	187128(82%)	190869（81%）	2.8%	2.9%

4.3 Structural damage assessment

According to the the design code provided by Tall Buildings Structural Design Council [11], the damage of structural members under earthquake exciatations include three different limit states, namely the immediate occupation limit state (IO), the life safety limit state (LS), and the collapse prevention limit state (collapse prevention, CP). Damage of the main components (SRC columns, core tube shear walls, coupling beams and frame beams) is analyzed in this section.

4.3.1 Core tube shear walls

Stress of concrete and rebars of core tube shear walls under S0202 rare earthquake are shown in Fig. 15~16. Base story core tube shear walls suffer more severe damages than those at other stories. Maximum strain of concrete is 1200με, which is less than ultimate strain. In the design progress, shape steel will be set in the core tube shear walls to enhance ductility.

4.3.2 Coupling beams

The plastic hinge diustribution of coupling beams under S0202 rare earthquake is shown in Figure 17. Usually, coupling beams are allowed to damage under basic and rare earthquakes to protect main conponents of the structure. Therefore, it is acceptable to let the plastic hinge of coupling beams be at CP limit state. In this case, all of the plastic hinge of coupling beams are under LS limit state, which shows satisfactory seismic performance.

4.3.3 SRC columns and frame beams

Plastic hinge distribution of SRC columns and frame beams are shown in Figure 18~19. The analysis result shows that all of the SRC columns and frame beams are below IO limt state.

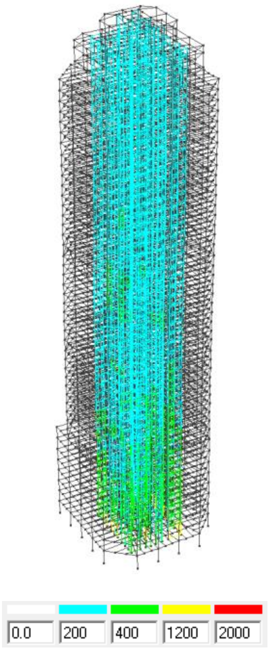


Fig. 15 – Concrete stress of core tube shear walls under rare earthquake

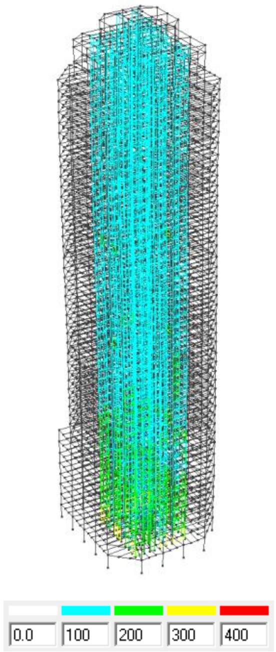


Fig. 16 – Rebars stress of core tube shear walls under rare earthquake

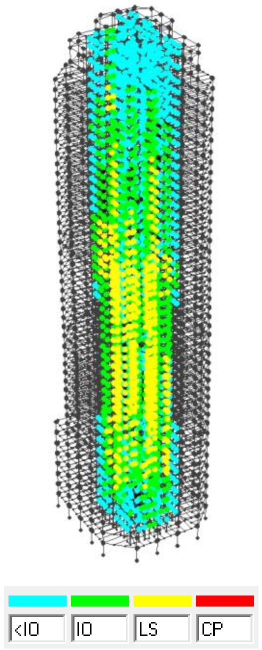


Fig. 17 – Plastic hinge distribution of coupling beams under rare earthquake

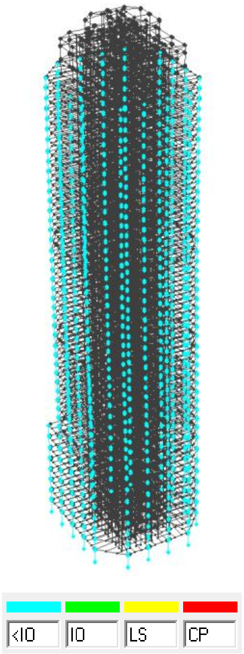


Fig. 18 – Plastic hinge distribution of SRC columns under rare earthquake

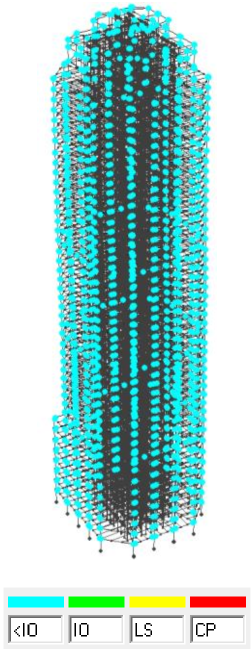


Fig. 19 – Plastic hinge distribution of frame beams under rare earthquake

5. Conclusions

This paper proposes a kind of combined energy dissipation technology for high-rise buildings to resist seismic loads. After a series of analysis, several conclusions are drawn as follows:

1) Compared with traditional outrigger structures, under different level of earthquake excitations, the maximum base shear of the damped structure can be reduced by about 10%, and the maximum story drift can be reduced by about 10%, which effectively reduces the seismic response of the structure.

2) Through the application of combined energy dissipation technology, various types of energy dissipation devices are activated under the frequent, basic and rare earthquakes. Energy dissipation is divided into stages, and the energy dissipated by the energy dissipation device accounts for 21%, 33% and 42% of the total energy under frequent, basic and rare earthquakes, respectively, showing a satisfactory energy dissipation mechanism.

3) Under the frequent, basic and rare earthquakes, all kinds of damping devices can fully participate in the energy dissipation for the structure. Compared with the traditional seismic resisting structure, the seismic response and structural damage can be effectively controlled, achieving the performance-based combined energy dissipation and energy dissipation expectations.

6. Acknowledgements

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7. Copyrights

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