Comparative Study on Seismic Behavior of RC Frame Structure Using Viscous Dampers, Steel Dampers and Viscoelastic Dampers

X.L. Lu, K. Ding & D.G. Weng
Tongji University, China

K. Kasai & A. Wada
Tokyo Instituion of Technology, Japan

SUMMARY:
Viscous dampers (VD), steel dampers (SD) and viscoelastic dampers (VED) are prevalent energy dissipation devices for seismic applications in China, especially after Wenchuan earthquake. For the purpose of investigating the seismic effect of these three types of dampers, an 8-story reinforced-concrete (RC) frame structure is established based on a damaged RC building suffering from Wenchuan earthquake. The building retrofitting design procedure with dampers is introduced in brief. The parameters of the three types of dampers are selected on the condition that these dampers have equivalent maximum damping forces under moderate earthquake. Then, the seismic performance of the 8-story RC frame added with viscous dampers, viscoelastic dampers and steel dampers are investigated respectively. The shear forces and the inter-story drifts of the frame structure with the three types of dampers are compared. At last, the seismic effects of viscous dampers, viscoelastic dampers and steel dampers under different levels of earthquakes are discussed in detail.

Keywords: passive control; viscous dampers; steel dampers; viscoelastic dampers; reinforced-concrete frame

1. INTRODUCTION

1.1. General

As a part of Strategic China-Japan Cooperative Program on Science and Technology organized by the National Nature Science Foundation of China (NSFC) and Japan Science and Technology Agency (JST), the joint research on the seismic evaluation and mitigation technologies is being conducted by the researchers at Tongji University and Dalian University of Technology, China and at Tokyo Institute of Technology (Tokyo Tech.) and Hokkaido University, Japan. The first stage of the research focuses on the use of energy dissipation devices, hereby called as “dampers”, for seismic repair or upgrade of existing reinforced concrete (RC) buildings.

1.2. Scope and Objectives

Accordingly, the present paper and the companion paper (Kasai et al, 2012) discuss key issues related to seismic retrofit of tall RC frames using viscous dampers (VD), steel dampers (SD) and viscoelastic dampers (VED). The present paper describes an 8-story tall building based on a damaged RC fame suffering from Wenchuan earthquake, the seismic design method for repair with dampers, and the comparative seismic responses of the 8-story RC frames retrofitted using the three types of dampers.

2. DESCRIPTION OF 8-STORY RC FRAME BUILDING

The 8-story RC frame building designed based on a damaged RC frame suffering from Wenchuan Earthquake. It is an office building in Dujiangyan, Sichuan Province. The structure was originally designed based on a seismic intensity of 7 in 1997. The plan layout and elevation are shown in Fig. 2.1

and Fig. 2.2. The structure has a plan dimension of 50.4 m by 17.4 m. Story 1-2 have a height of 4.2m and story 3-8 have a height of 3.6m. The total height of the structure is 30 m. RC frame structural system is applied to undertake the gravity loads and lateral forces. The cross sections of frame beams are 350 mm by 600 mm and those of columns changed along the structural height from 800 mm by 800 mm to 500 mm by 500 mm. The thickness of the slab is 100 mm. The strength classes of concrete are C30 that has a designed compressive strength of 14.3 MPa. The total mass of the building is about 7,800 tons. After the Wenchuan earthquake, the seismic design intensity in Dujiangyan is increased from 7 with peak ground acceleration (PGA) of 0.1 g to 8 with PGA of 0.2 g.

In order to investigate the seismic responses, the analytical model of the structure is built up by ETABS. Five sets of time histories, including three earthquake records and two artificial accelerograms, are applied to study the dynamic responses of the building. The PGA in the time-history analysis is scaled to 70 cm/s^2 to accommodate the minor earthquake of seismic intensity 8. The maximum inter-story drifts under five ground motions and Chinese code response spectrum are shown in Fig. 2.3.

We can easily find that the inter-story drifts of the frame in both directions are beyond the Chinese code limitation of 1/550 under minor earthquake of seismic intensity 8. So strengthening of the building is required by the building regulation and codes to control the structural responses and to meet the code provisions.

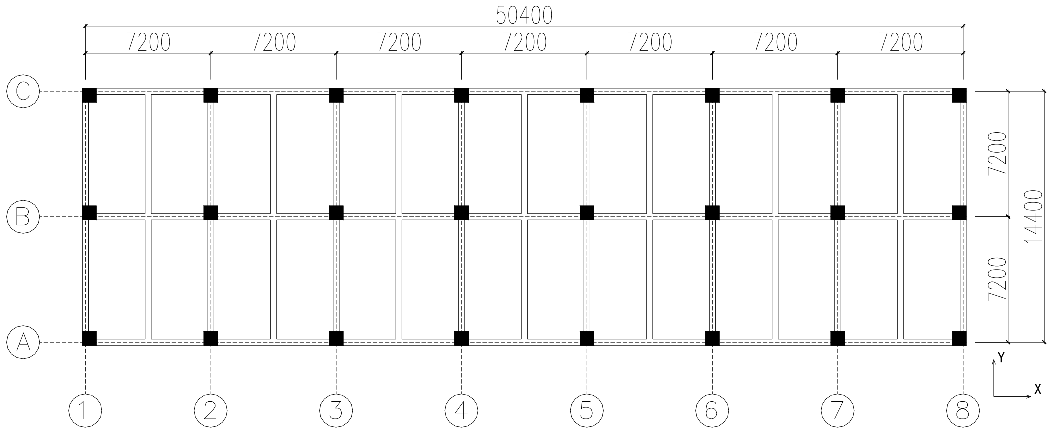


Figure 2.1. Plan layout of the building

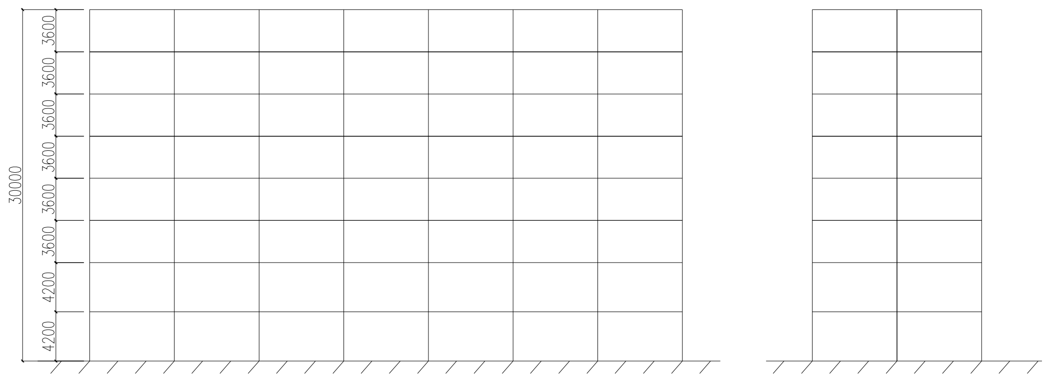


Figure 2.2. Elevation of the building (X- and Y- direction)

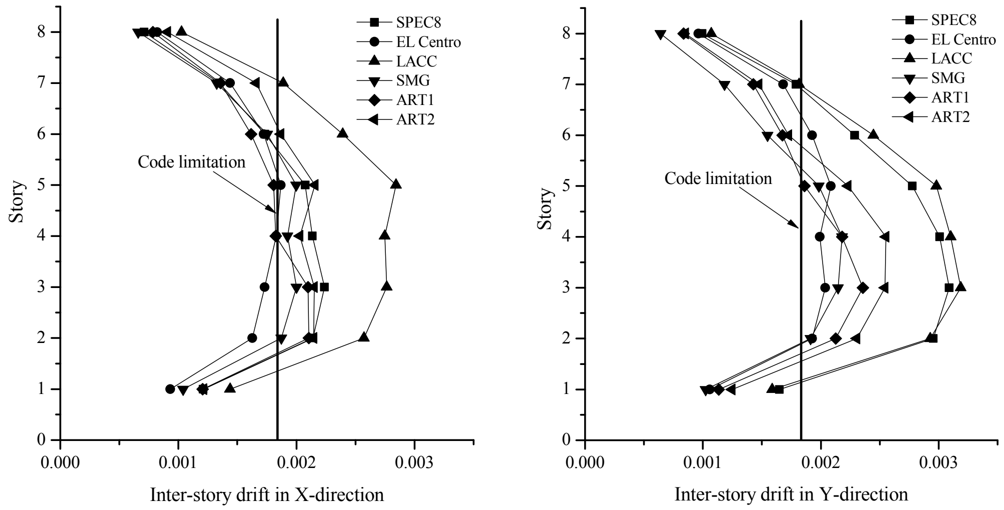
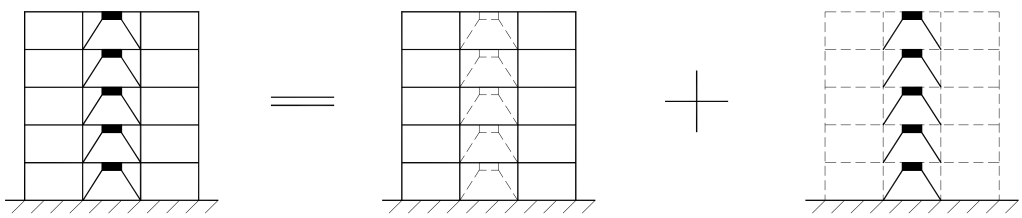


Figure 2.3. Inter-story drift in X- and Y- direction

3. BUILDING RETROFITTING DESIGN PROCEDURE WITH DAMPERS

The common practice to strengthen earthquake damaged buildings in China is to strengthen damaged members and joints with concrete or steel jacketing and to increase the size of most structural members so as to meet the new design requirements. However, it needs to demolish all the decorations of undamaged members, which is a time-consuming process, and the site construction may pollute the environment. Considering the above disadvantages, damper retrofitting procedure with less labor work was selected.

Energy dissipation retrofit procedure is to add energy dissipation devices to the damaged structure for absorbing the earthquake energy and reducing the seismic responses. The common practice in China is to strengthen the damaged joints with steel jacketing and to inject epoxy resin into the cracks firstly, and then, to use dampers and steel bracing to increase the overall stiffness or damping of the structure while to reduce the seismic responses to the structure. Fig. 3.1 shows the analytical model of retrofitting structure with dampers.



(a) Damped model (b) Model of frame (c) Model of dampers

Figure 3.1. Analytical model of retrofitting structure with dampers

On the selection of dampers in preliminary design phase, the required added equivalent damping ratio of the structure need to be estimated. However, the Chinese code for seismic design of buildings (GB50011-2010) stipulates that the added equivalent damping ratio shall not exceed 25% in general, whereas it should be counted to 25% once exceeds, which also means that the frame shall be further strengthened in this case. According to the calculated required damping ratio, the expected designed damping force can be obtained by the following equations:

$$F_{di} = \xi_r \cdot \beta \cdot Q_i \tag{3.1}$$

$$\beta = \left[\pi \sum_{j=1}^{N} \Delta_j Q_j \right] \Big/ \left[2 \sum_{i=j_1}^{N_1} \Delta_i Q_i (1-\mu_i) \right] \tag{3.2}$$

$$\mu_i = \Delta_{di} / \Delta_i \tag{3.3}$$

Where F_{di} is the expected damping force on the i-th floor, ξ_r is the required added equivalent damping ratio, β is the design coefficient related to story damping force and shear force, Q_i is the story shear force on the i-th floor under moderate earthquake, N is the total number of floors for calculation, N_1 is the total number of floors equipped with dampers, j_1 is the initial number of floor equipped with dampers, μ_i is the ratio of yield displacement of damper and peak value of story drift on the i-th floor, Δ_{di} is the yield displacement of damper on the i-th floor, Δ_i is the story displacement of the i-th floor.

Specially, to achieve the best damping effect of the added dampers, an optimizing coefficient is introduced to modify the designed damping forces given by Eqn. 3.1. The modified damping force is given as follows:

$$F_{(di)m} = \Omega_i \cdot F_{di} \tag{3.4}$$

$$\Omega_i = \Delta_i \Big/ \left(\sum_{j=1}^{N} \Delta_j / N \right) \tag{3.5}$$

Where $F_{(di)m}$ is the modified designed damping force on the i-th floor, Ω_i is the optimizing coefficient on the i-th floor. However, it needs to explain that the optimizing process of designed damping forces here is an advisory step but not an compulsory step, and therefore the final designed damping forces are usually interpolated in the value range between the designed damping forces given by Eqn. 3.1 and the modified damping forces given by Eqn. 3.4 with the combination of the allowable inter-story drift for buildings in Chinese seismic design code.

Based on above steps of design and distribution of expected damping force on the specified floor, it is concluded that the expected added damping forces of existing frame are designed on the basis of story shear forces and optimized according to story drifts.

For the purpose of investigating the seismic responses of the structure retrofitted by viscous dampers, steel dampers and viscoelastic dampers, the 8-story frames added with the three different dampers are analyzed respectively on the premise that the three different dampers have the approximately equal maximum damping force under moderate earthquake. Properties and parameters of the three different dampers will be given in next section.

4. DESIGN AND SEISMIC ANALYSIS

For comparative study on the seismic performance of the damped frame, viscous dampers (VD), steel dampers (SD), and viscoelastic dampers (VED) are considered. The structures added with viscous dampers, steel dampers, and viscoelastic dampers are analytically used to achieve the aforementioned retrofitting objective on the premise that the three dampers have the same distribution and have approximately equal maximum damping force under moderate earthquake. Thus, four structural model (ND, VD, SD, and VED) are established in the comparative analysis, here ND is the frame without dampers, VD is the frame added with viscous dampers, SD is the frame added with steel dampers, VED is the frame added with viscoelastic dampers.

4.1. Structural Property

The finite element modeling and analysis are performed by ETABS programs, and the structural properties of frame without dampers under seismic intensity 8 are shown in Table 4.1. And, the first nine periods of the frames added with different dampers are shown in Table 4.2. After a series of basic analysis, 5 sets of earthquake records and 2 sets of artificial accelerograms are adopted to the later time history analysis.

Table 4.1. Structural Properties of the Frame Under Seismic Intensity 8

Floor	Height (m)	Story mass (t)	X-direction			Y-direction		
			Stiffness (kN/mm)	Shear force (kN)	Drift angle (rad)	Stiffness (kN/mm)	Shear force (kN)	Drift angle (rad)
8	3.6	603	292	2084	1/500	224	2051	1/358
7	3.6	1000	326	4409	1/264	259	4255	1/199
6	3.6	999	345	5994	1/205	275	5720	1/155
5	3.6	1002	344	7145	1/171	272	6788	1/128
4	3.6	1007	381	8108	1/167	287	7690	1/118
3	3.6	1019	407	9090	1/159	315	8611	1/115
2	4.2	1046	402	10015	1/166	313	9499	1/120
1	4.2	1067	748	10529	1/294	581	9999	1/216

Note: The shear forces and story drift of the frame are obtained under moderate earthquake of response spectrum.

Table 4.2. The First Nine Periods of the Frames Added with Different Dampers

Mode	Period (s)				Mode shape
	ND	VD	SD	VED	
1	1.661	1.590	0.930	1.391	Y translation
2	1.565	1.503	0.923	1.326	X translation
3	1.528	1.456	0.802	1.262	Z torsion

4.2. Damper Parameters

Based on the simplified retrofitting design procedure introduced in Section 3, design and distribution of expected damping forces of the frames are conducted. Four of the same dampers were employed in each story in X- and Y- direction. Therefore, 64 dampers with different maximum damping force are installed on the 1st to 8th floor, as listed in Table 4.3. Here it is noteworthy that the total numbers of viscous dampers, steel dampers and viscoelastic dampers and their locations are exactly the same, while the only difference is their mechanical properties. The square steel tubes with cross-section of 450×450×30 are selected for the damper-braces.

Table 4.3. Distribution of the Added Dampers

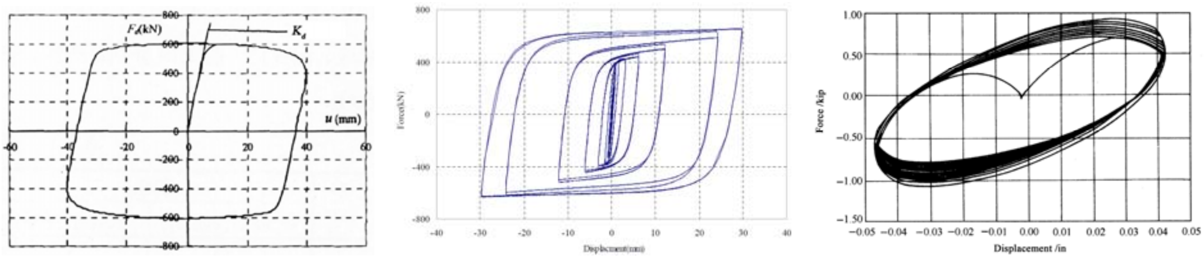
Floor	VD, SD, VED	
	X-direction	Y-direction
8	4×200kN	4×200kN
7	4×400kN	4×400kN
6	4×400kN	4×400kN
5	4×600kN	4×600kN
4	4×600kN	4×600kN
3	4×600kN	4×600kN
2	4×800kN	4×800kN
1	4×800kN	4×800kN

Note: 200kN, 400kN, 600kN, 800kN means the maximum damping force of different dampers.

According to the structural property and the objective performance, analysis parameters of different dampers are preliminary designed, as shown in Table 4.4. As to viscous damper, where C_d is the damping coefficient, α is the velocity exponent, and K_d is the stiffness of viscous damper that assigned to 70% of C_d according to the previous experiments. As to steel damper, where K is the stiffness, F is the yield strength, r is post yield stiffness ratio, exp is the yielding exponent. As to viscoelastic dampers, K_d is the storage stiffness, C_d is the damping coefficient, η is the loss factor of the viscoelastic material. The typical force-displacement hysteresis curves of the three types of dampers are shown in Fig. 4.1.

Table 4.4. Mechanic Properties of Different Dampers

Damping Force (kN)	Viscous Dampers			Steel Dampers				Viscoelastic Damper		
	C_d (kN/(mm/s)α)	α	K_d (kN/mm)	K (kN/mm)	F (kN)	r	exp	K_d (kN/mm)	C_d (kN/(mm/s))	η
200	80	0.2	56	200	200	0.01	2	31	6	0.8
400	160	0.2	112	400	400	0.01	2	31	6	0.8
600	240	0.2	168	600	600	0.01	2	36	7	0.8
800	320	0.2	224	800	800	0.01	2	57	12	0.8

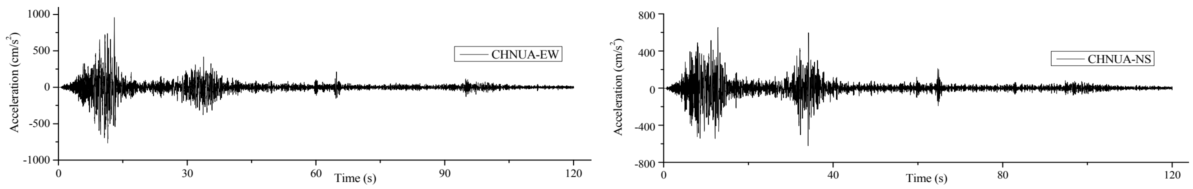


(a) Viscous dampers (b) Steel dampers (c) Viscoelastic dampers

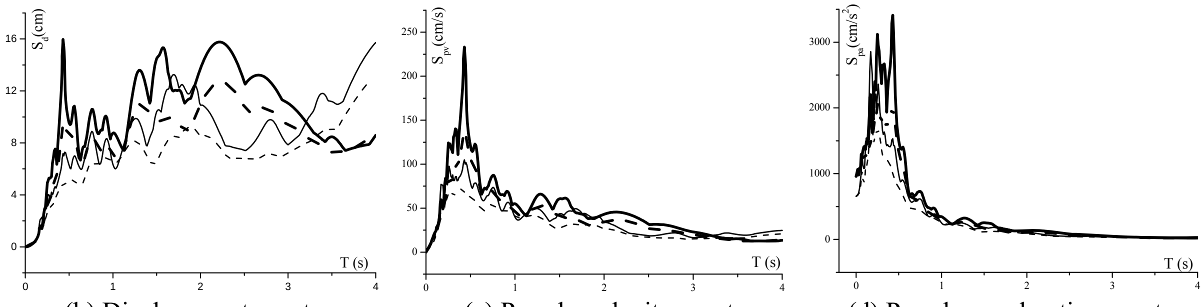
Figure 4.1. Typical force-displacement hysteresis curves of different dampers

4.3. Input Time History Records

Seven sets of ground acceleration time histories are used to examine the structural performance, of which two are artificial accelerograms and five are recorded ones. In the five earthquake records, two of them are Wenchuan earthquake records at Wolong station, named as CHNUA-EW and CHNUA-NS. The peak ground acceleration (PGA) of the two records is 957.7 cm/s^2 and 652.85 cm/s^2, respectively. Fig. 4.2 shows the two acceleration histories and corresponding response spectra with 5% and 10% damping ratio. According to the China seismic design code, the PGA for seismic intensity 8 should be 70, 200, and 400 cm/s^2 for minor, moderate, and major earthquake, respectively. In order to consider the contribution of infilled wall to the stiffness of the structure under minor and moderate earthquake, the PGA is amplified by 22%, the values of 85.4 and 244 cm/s^2 will be used, respectively. Fig. 4.3 shows the corresponding normalized pseudo-acceleration spectra with 5% damping ratio.



(a) Time histories of Wenchuan earthquake records



(b) Displacement spectra (c) Pseudo-velocity spectra (d) Pseudo-acceleration spectra

Figure 4.2. Time histories of Wenchuan earthquake records and their response spectra
(Solid line = 5% damping ratio, dash line = 10% damping ratio)

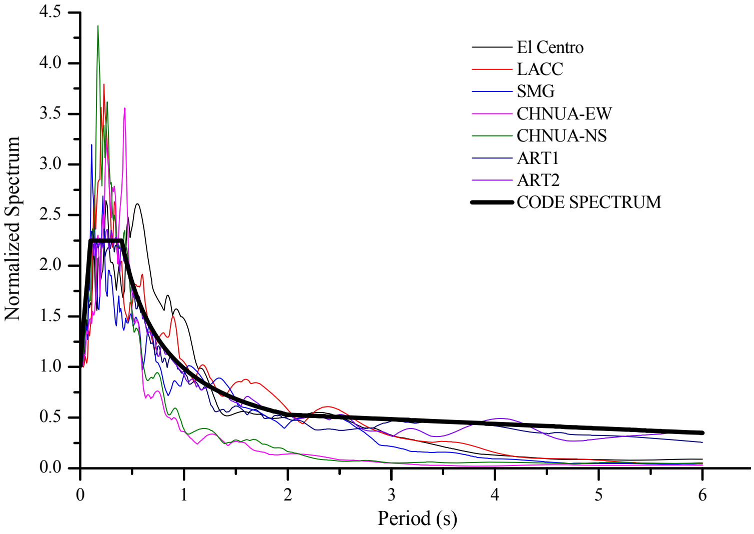


Figure 4.3. Normalized response spectrum curves under different earthquake waves

4.4. Seismic Responses of the Frames Added with Different Dampers

Comparative analysis of ND, VD, SD and VED are performed through time-history analysis method with the aforementioned ground accelerations. The comparison of the averages of the inter-story drift and story shear forces under minor earthquake, moderate earthquake and major earthquake are shown in Fig. 4.4 and Fig. 4.5, respectively. It is noted that the story shear forces are obtained from section forces of columns (without damper-braces) and frames (columns and damper-braces). Moreover, for the analysis cases under major earthquake, the elastic modulus of concrete will decrease with the structural members yield, therefore the lateral stiffness of story is approximately reduced 40% for simplified calculation based on experience.

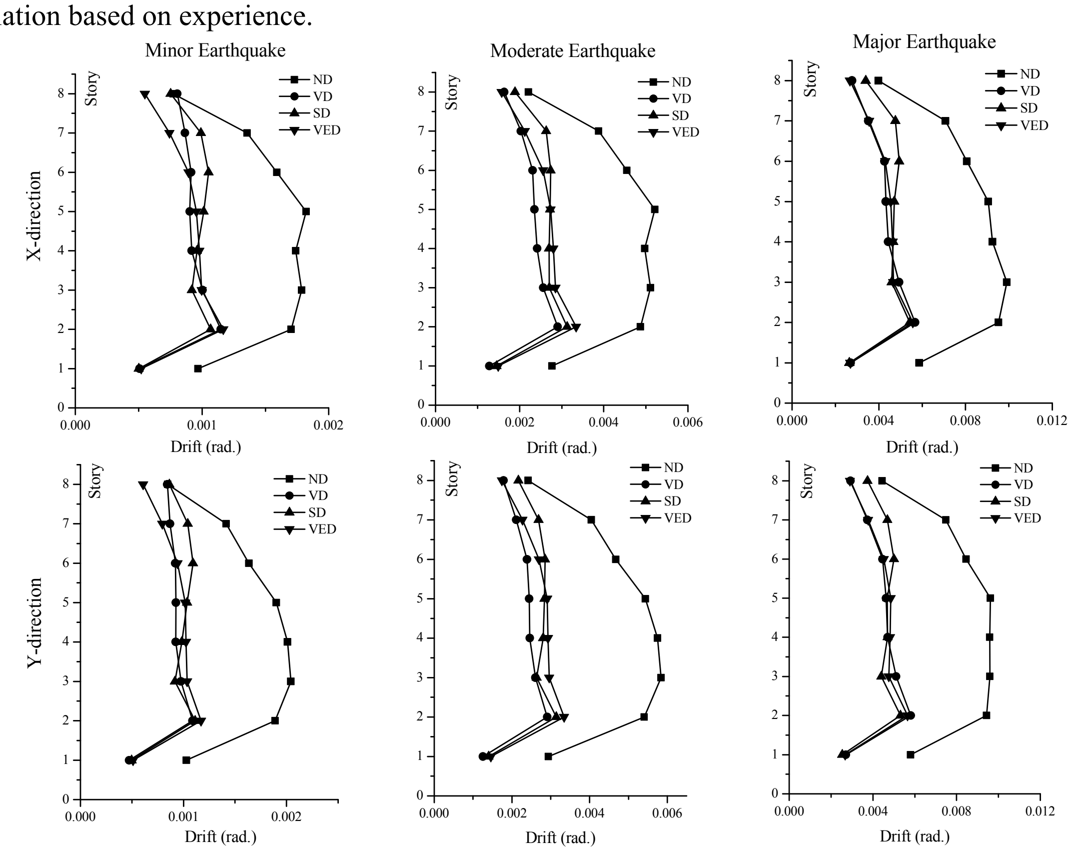


Figure 4.4. Inter-story drift of RC frame with and without dampers

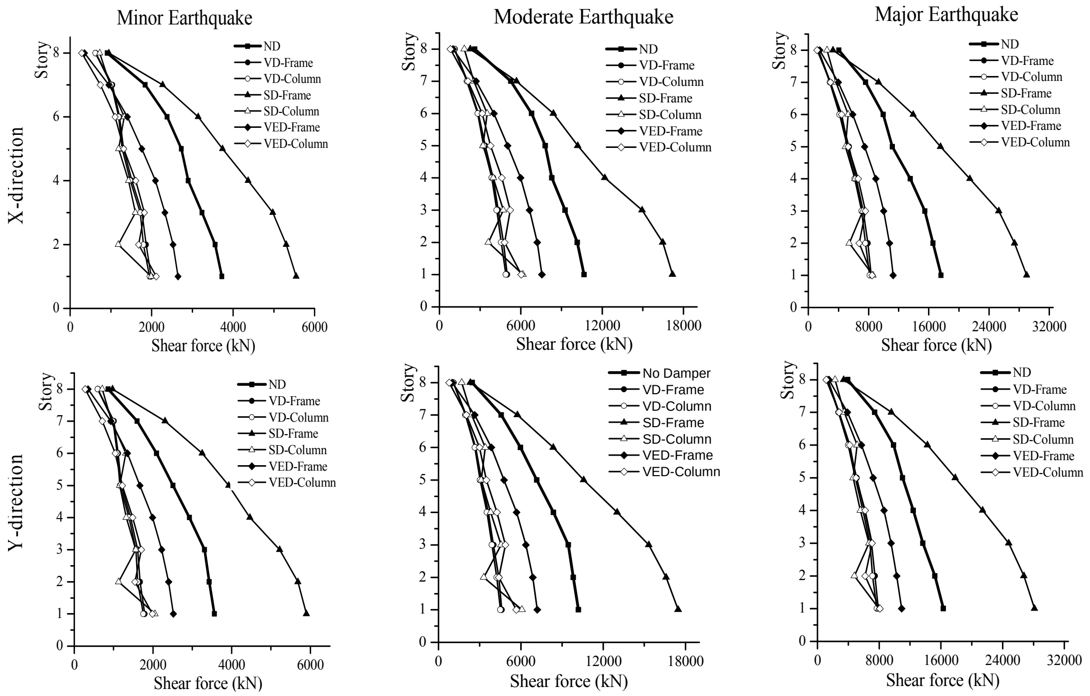


Figure 4.5. Shear forces of RC frame with and without dampers

From above figures, it is easily seen that all three frames of VD, SD and VED have excellent structural performances and remarkable control effect compared to frame without dampers. So, the viscous dampers, steel dampers and viscoelastic dampers can be appropriately designed to control seismic behavior of non-ductile concrete frame.

The average inter-story drift of VD, SD and VED reduced about one-half and less than code limitation compared to the frame without dampers, as shown in Fig. 4.4. The displacement control of VD is apparently superior to that of SD and VED, especially under moderate earthquake and major earthquake. But under the minor earthquake, SD has better control effect in the lower story, while VED has better control effect in the upper story.

As shown in Fig. 4.5, the story shear forces of columns (without damper-braces) are decreased nearly one-half also. VD, SD and VED have similar control effect under moderate earthquake and major earthquake. But under minor earthquake, SD has better control effect in the lower story, while VED has better control effect in the upper story. On the other hand, the total shear forces of frames (columns and damper-braces) are different. The shear forces of SD frame are larger than those of ND frame, but most of them are taken by damper-braces. The shear forces of VED frame are less than those of ND frame, and the damper-braces take part of shear forces also. The shear forces of VD frame are much less than those of ND frame, and the damper-braces hardly take the shear forces.

4.5. Damper Energy Dissipation and Damping Force

The force-displacement curves of viscous damper, steel damper and viscoelastic damper located on the third floor in X-direction under the major earthquake of El Centro records are shown in Fig. 4.6. The full shapes of the hysteresis curves indicate that a large mount of energy input by the earthquake wave is dissipated by dampers. Therefore, the dampers protect the frames free from the severe damage.

In order to check the reasonableness of damper parameter design, the ratio of actual maximum damping force to design damping force under different levels of earthquake is shown in Fig. 4.7. Under the moderate earthquake, the average ratios of actual maximum damping force to design damping force are 0.88 for viscous dampers, 1.01 for steel dampers and 0.84 for viscoelastic dampers, respectively.

Therefore, the maximum damping forces basically meet the initial parameter design. It is noteworthy that the damping force of viscoelastic dampers are increased quickly than that of viscous dampers and steel dampers under major earthquake, while the damping force of viscoelastic dampers are much smaller than that of viscous dampers and steel dampers under the minor earthquake.

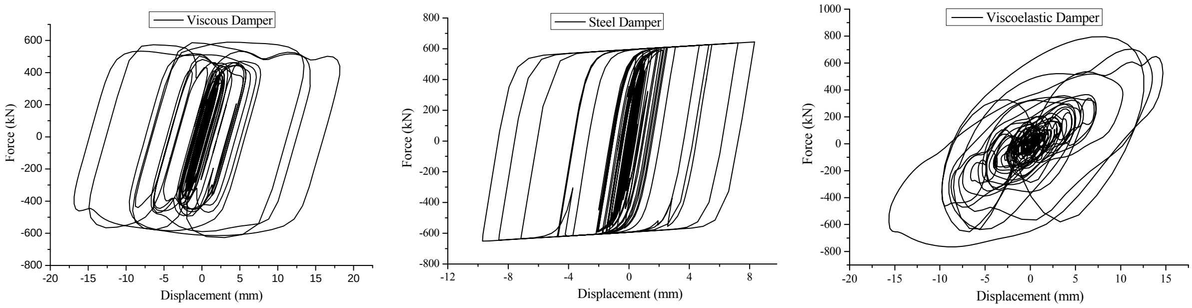
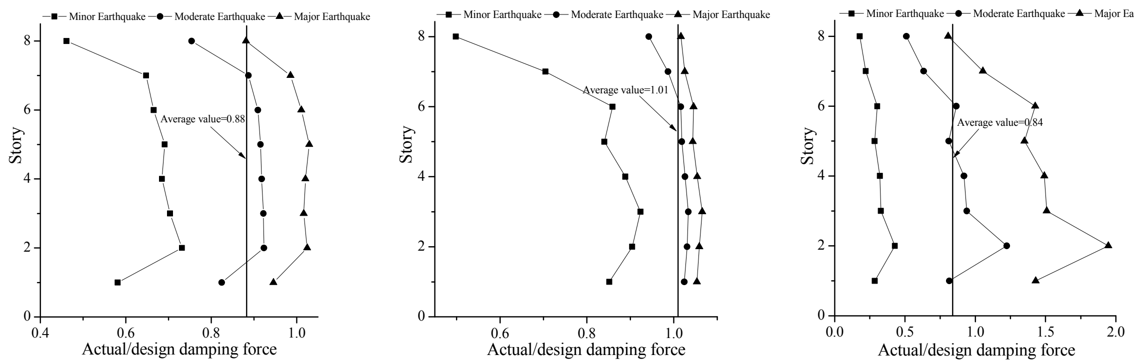


Figure 4.6. Force-displacement curves of different dampers on the 3rd floor



(a) Viscous dampers (b) Steel dampers (c) Viscoelastic dampers

Figure 4.7. The ratio of actual damping force to design damping force

5. CONCLUSIONS

An 8-story building based on a damaged RC frame suffering from Wenchuan earthquake was introduced, and the seismic design method for repair by dampers was proposed, and finally, the seismic responses of the 8-story RC frames retrofitted using viscous dampers, steel dampers and viscoelastic dampers were investigated and compared.

Although there are some differences in energy dissipation principle and mechanical properties, all the three types of dampers show excellent damping effect and evidently can be used to achieve the expected retrofitting objective if designed and distributed properly.

As to the retrofitted frame added with viscous dampers, steel dampers and viscoelastic dampers, the average inter-story drift and shear forces of columns can be reduced nearly one-half compared to the frame without dampers. When three types of dampers are designed with the equal maximum damping force under moderate earthquake, it is apparent that viscous dampers have better control effect of displacement, especially under moderate earthquake and major earthquake. The dampers can dissipate a large mount of energy and the force-displacement curves of dampers are very full. The ratio of actual damping forces to the expected damping force under moderate earthquake indicates that the initial damper parameter design is proper.

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