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Seismic performance evaluation of typical dampers designed by Chinese Code subjected to the main shock-aftershocks

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ABSTRACT

A practical design method in the current Chinese code is introduced and used to design various dampers, which assumes that dampers provide building structures with the effective stiffness and effective damping ratio. Aftershocks followed by the main shock are likely to cause further structural damage. However, the influence of aftershocks is not considered in this design method. It is not clear for the seismic performance of code-designed dampers under the main shock-aftershock sequences. This paper concentrates on the seismic performance of dampers designed by the Chinese code by considering the effect of aftershocks. Five types of dampers, namely buckling-restrained braces (BRBs), viscoelastic(VE) dampers, viscous dampers(VDs), friction dampers(FDs), and self-centring(S–C) dampers that are installed on a high-rise building structure are designed by the Chinese code. Using the incremental dynamic analysis and fragility analysis, the seismic performance of five types of dampers under the main shock-aftershock sequences are compared from the respective of structural collapse, damage and the equipment's acceleration failure. The results show that the design method of dampers in the Chinese code are applicable even without considering the influence of aftershocks. The seismic responses of structure-damper systems are mainly caused by the main shock. Different dampers with different effective stiffness and effective damping ratio have their own distinctive advantages of enhancing the building structural safety. FDs and S–C dampers are superior to other dampers in controlling the structural collapse. VDs perform best in reducing the structural damage and equipment's acceleration failure probabilities.

1. Introduction

Seismic loads pose a potential threat to the building structures located at the seismic active area of China. It is evident that a large number of buildings have suffered severe damage and even collapse under the recent devastating earthquakes such as Ms 8.0 Wenchuanearthquake [1] in 2008, Ms 7.1 Yushu earthquake [2] in 2010 and Ms 7.0 Lushan earthquake [3] in 2013. Apart from that, the aftershocks, usually followed by the main shock may cause further damage on the building structures [4-6]. This can be seen from what happened during the Wenchuan earthquake in 2008. The aftershock larger than 5.0 magnitude happened 64 times after the main shock with 8.0 magnitude, causing lots of structures damaged and even collapsed, inflicted direct economic loss of more than 110 billion dollars and tens of thousands of people death [7–10].

To effectively protect the building structures from being subjected to seismic loads, the passive energy dissipation device is quite promising, especially for dampers, which have been a strong tendency for the newly designed buildings and existing buildings in China [11–13]. The installation of dampers on the building structures is cost-effective as they can be easily replaceable in the post-earthquake reconstruction. Besides, dampers are effective in absorbing the earthquake energy and mitigating the structural seismic responses and thereby protect the building structures again earthquakes [14,15]. The typical dampers such as mild steel dampers [16], viscous dampers [17–19], friction dampers [20–23] have exhibited excellent seismic energy dissipation ability in mitigating the vibration of structures.

The effectiveness of various dampers in mitigating the seismic responses of structures has been investigated in some recent studies. Viscous dampers (VDs) exhibit better seismic performance than viscoelastic (VE) dampers in reducing the seismic displacement of adjacent connected buildings [24]. Compared with tuned mass damper (TMD),

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friction dampers (FDs) are superior in mitigating the seismic responses of a fifteen-story building structure [25]. Both BRBs and viscous dampers (VDs) have similar seismic performance in controlling the drift damage of a five-storey office building, but the latter perform better in the reduction of structural acceleration [26]. For the FDs, VE dampers and combined FDs-VE damping devices located within shear walls, the hybrid damping system always perform the best than other two dampers in reducing the peak accelerations and deflections of the structure [27]. It can be concluded that different dampers display different seismic performance from each other. However, these studies compared the effectiveness of dampers under specific seismic loads without considering uncertainties in seismic hazards and structural capacity. From a probabilistic perspective, the seismic performance evaluation of existing bridges retrofitted with different dampers were discussed by using the fragility analysis [28]. The shape memory alloy cables (SMAs) are the most effective in mitigating the seismic fragility of an existing bridge at all the damage states, then FDs, VDs and yielding steel cables. Using the fragility analysis, BRBs and VE dampers that are incorporated in a nine-storey steel building can effectively reduce the acceleration responses, and VDs provides the best drift control [11–13,29]. However, these studies investigated the seismic performance of dampers from a probabilistic perspective only considering the main shock without involving the influence of aftershocks. Thus, it is a necessity to investigate the seismic performance of various damper under the main shock-aftershocks, especially for the high-rise building structures that face high potentially seismic risks.

To discuss the seismic performance of dampers, the design method in the Chinese code [30] is introduced. The supplemental dampers incorporated within structures are designed to provide structures with the effective stiffness and effective damping ratio. This code-designed method is very practical as it greatly simplifies the design of dampers. However, each design method of dampers has its own limitations. A new performance-based design method of dampers proposed recently, which can satisfy multiply response targets of the low-rise to medium-rise frame structures, is also effective and practical in obtaining the supplemental damping properties of dampers. It is found to accurately predict the displacement and base shear of damping systems. However, the prediction for the acceleration is less accurate due to the influence of higher model [31]. Similarly, in the design method provided by the Chinese code (JGJ297-2013), only the single seismic load is considered without involving the effect of aftershocks.

To figure these issues out, five typical dampers including BRBs, viscoelastic (VE) dampers, viscous dampers (VDs), friction dampers (FDs) and self-centering (S–C) dampers were designed according to the Chinese code (JGJ297-2013) with a same design target. Using the incremental dynamical analysis(IDA) and fragility analysis, the influence of aftershocks on the seismic performance of code-designed dampers are discussed. The seismic performance of dampers was well-investigated under the main shock-aftershock sequences. This paper is helpful to gain a better understanding of the effectiveness of code-designed dampers in mitigating the responses of the building structure under the main shock-aftershocks.

2. Design of typical dampers based on Chinese code

2.1. the design method of dampers

The design method of various dampers in the Chinese Code [30] is given in Fig. 1. The basic design principle is to assume that dampers provide building structures with the effective stiffness K_{eff} and effective damping ratio ζ_{eff} to reduce structural seismic responses. K_{eff} and ζ_{eff} are two critical parameters for designing dampers to concern, which are calculated by the equations [30]:

$$W_c = A_j \quad W_s = \sum_{i=0}^{i=n} F_i u_i/2, \tag{1}$$

$$K_{eff} = \frac{|F^+| + |F^+|}{|x^+| + |x^-|}, \zeta_{eff} = \sum_{j=0}^{j=n} W_c/(4\pi W_s) \tag{2}$$

in which, W_c is the seismic energy absorbed by the jth damper in a cycle with the target interstory displacement; A_j is the hysteretic loop area of the jth damper at the interstory displacement. W_s is the total strain energy under the horizontal earthquake excitation; F_i is the horizontal shear force of building structures at the ith floor (KN/m); u_i is the horizontal displacement of building structures at the ith floor (m); x is the horizontal displacement of dampers (m); F is the horizontal damping force of dampers (KN) (+ and – are the positive and negative direction, respectively).

In the design flow chart of dampers, the response spectrum analysis is firstly adopted to calculate the seismic responses of building structures without dampers. Then the seismic vibration mitigation target D_{ob} is determined, and the structure-damper systems are established. Two-round iterations are employed to obtain the design parameters of dampers. The first round is achieved when the K_{effi} and ζ_{effi} provided by dampers obtained from the ith iteration are equal to the $K_{eff\,(i+1)}$ and $\zeta_{eff\,(i+1)}$ calculated by the response spectrum analysis and equations (1) and (2). As shown in Fig. 1, in the response spectrum analysis, the total stiffness K is the sum of the main structural stiffness K_s and the effective stiffness of dampers K_{eff}. Similarly, the total damping ratio ζ is the sum of the main structural damping ratio ζ_s and the effective damping ratio of dampers ζ_{eff}. In the second round iteration, if the vibration mitigation target D_{ob} is achieved, the design parameters of dampers will be input. If not, the design will return to step 4 for the next round trial.

2.2. benchmark building structure model

Benchmark models [32] are steel structures established by the American Society of Civil Engineering Committee (ASCE), which are available common platforms for the performance evaluation of the different control techniques. They include 3-storey, 9-storey and 20-storey steel structure models. In this paper, the 20-storey steel building structure model is adopted and established by Opensees, as shown in Fig. 2. The beam-column element is simulated with the fiber section and dispBeamColumn element. The mass of each floor is evenly assigned to the corresponding nodes. The rigid floor is established by setting a master node and slave nodes so as to make the uniform vibration. To establish the structure-damper system, five types of dampers including bucking-restrained braces (BRBs), friction dampers(FDs), self-centering(S–C) dampers, viscoelastic(VE) dampers and viscous dampers(VDs) are selected to be installed on each story of the 20-storey building structure, respectively.

The maximum interstory drift of the 20-storey building structure model is obtained by the response spectrum analysis. To enhance the safety of the building structure under seismic loads, five types of dampers are incorporated in the twenty-storey building structure. All dampers are designed by the Chinese code [30] by achieving a same vibration mitigation target that is specified to reduce 78% of the original maximum interstory drift of the building structure. This is beneficial to evaluate the effectiveness of various code-designed dampers in mitigating the seismic responses of the building structure.

2.3. the design of typical dampers

In the design method of dampers provided by the Chinese code [30], the mechanical models of dampers that describes the force-displacement relationship, as shown in Table 1, are needed to determine the effective stiffness K_{eff} and effective damping ratio ζ_{eff}.There are some critical parameters in the mechanical models which determine the mechanical properties of dampers. For example, the Bouc-Wen model

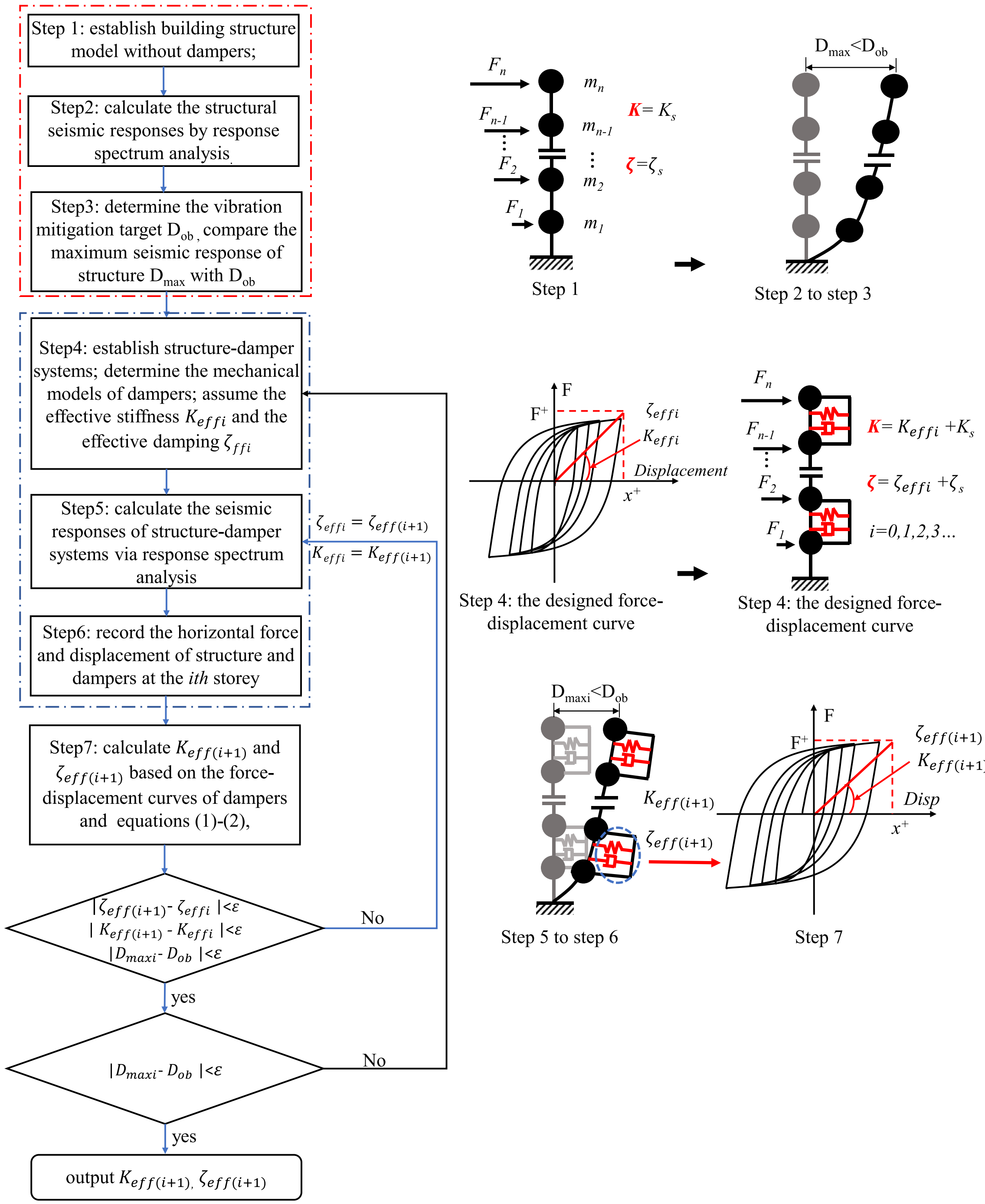
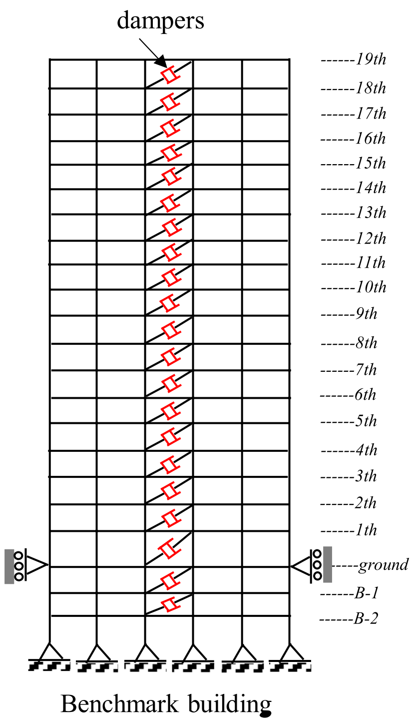


Fig. 1. Design flow chart of various dampers by Chinese code.

[33,34] in Table 1(a) have parameters such as A controlling the tangent stiffness; γ, β controlling the shape of curves. To ensure the accuracy of the numerical model of dampers, the experimental data from previous research work is adopted to calibrate the mechanical models of BRBs, FDs and S–C dampers.

In wich, $\dot{x}$ is the relative velocity of dampers at the vibration direction(m/s); α is the ratio of post-yield stiffness to the initial elastic stiffens ($0 < \alpha < 1$); K is the initial elastic stiffness (kN/m); A is the parameter controlling the tangent stiffness; γ, β, z are the parameters that control the shape of the hysterical cureves; n is the parameter representing the transition from linear to nonlinear range; x_y is the yield displacement of dampers at the vibration direction (m); x_{max} is the maximum displacement of dampers at the vibration direction (m); K_1, K_2 are the tangent stiffness of oa, ab, bc, cd (kN/m); x_a, x_b are the displacement of dampers (m); sign(x) represents the sign function; C is the damping coefficient of dampers;

BRBs used in the experiment in Fig. 3 were made of steel material with the yield strength of 210 MPa. The experimental curve of BRBs in Fig. 4(a) was obtained by the uniaxial tension-compression test based on the displacement control [35]. FDs were made of the aluminum plate, which were tested by the cyclic loading experiment based on the displacement control [36], which is shown in Fig. 4(b). The material of S–C dampers is the shape memory alloy with the characteristics of the self-centering ability and superelasticity. S–C dampers were tested by the triangular wave with the frequency equal to 0.05Hz [37], as shown in Fig. 4(c). All these dampers in the experiment have exhibited good

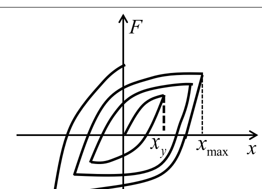
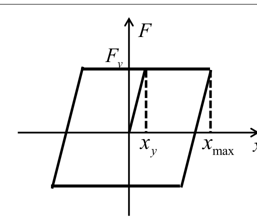
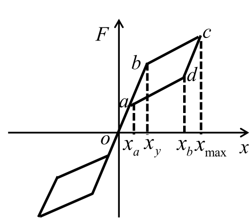
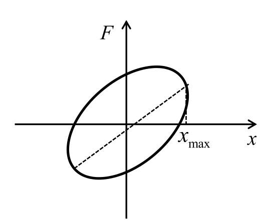
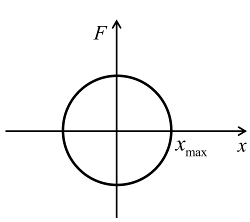


Columns(345Mpa)			
Corner columns		interior columns	
A 0.38m square box columns			
B-2-4th W24x335			
B-2-1th	5.08cm(t)	5th-10th	W24x229
2th-4th	3.18cm(t)	11th-13th	W24x192
5th-13th	2.54cm(t)	14th-16th	W24x131
14th-18th	1.91cm(t)	17th-18th	W24x117
19th-20th	1.27cm(t)	19th-20th	W24x84
Beams(345Mpa)			
B-2-4th	W30x99	5th-10th	W30x108
11th-16th	W30x99	17th-18th	W27x84
19th	W24x62	20th	W21x50

Weights		Heights		Periods
Ground	5.32×10^5kg	Basement level	3.65m	T_1=3.96s
1st level	5.63×10^5kg	Ground level	5.49m	T_2=1.36s
2nd-19th level	5.52×10^5kg	1st-19 th level	3.96m	T_3=0.79s
20th level	5.84×10^5kg	Bay wilds	6.10m	

Fig. 2. Twenty-storey benchmark building structure with dampers.

Table 1
Mechanical models of typical dampers.

Dampers	Mechanical models	Dampers	Mechanical models
 (a) BRBs	$F = \alpha K x_y + (1-\alpha) K z$; $\dot{z} = A\dot{x} - \gamma \lvert\dot{x}\rvert z \lvert z\rvert^{n-1} - \beta\dot{x}\lvert z\rvert^n$ Bouc-wen model (Bouc,1967;Wen, 1976)	 (b) Friction dampers	$F = Kx_y$ Elastic-plastic model (Ohmata et al.,1995)
 (c) Self-centering dampers	$F = \begin{cases} K_1 x_a \\ (K_1 - K_2) x_b sign(x) + K_1 x \\ (K_1 - K_2)(x_b - x_c) sign(x) + K_1 x \\ (K_1 - K_2) x_a sign(x) + K_2 x \end{cases}$ SMA constitutive model (Graesser and Cozzarelli, 1991)	 (d) Viscoelastic dampers	$F = Kx + C\dot{x}$ Kelvin model (Xu et al.,2013)
 (e) Viscous dampers	$F = C\lvert\dot{x}\rvert^a$ Linear model (Kit et al.,2010; Lee D et al., 2010)		

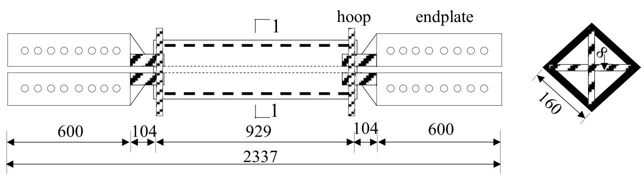


Fig. 3. Dimension of BRBs in the experiment.

energy dissipation abilities.

To describe the force displacement curves, all dampers are simulated with twoNodeLink element in OpenSees. BWBN material is used to simulate the Bowc-Wen model for BRBs and the elastic-perfectively plastic model for FDs [38,39]; Self-centeirng material is adopted to simulate the self-centering ability of S–C dampers [40,41]. It can be observed from Fig. 4 that the numerical curves of dampers are agreeable well with the experimental curves.

By the calibration, the critical parameters in the Equations of Table 1 are determined, then the unknow initial stiffness K is obtained by iterative trials in the process of designing dampers, as it is associated with the effective stiffness K_{eff} and effective damping ratio ξ_{eff}. Once the K is calculated, the cross-section size of dampers can be easily designed.

All design parameters of five types of dampers are calculated according to the code-designed method, as shown in Fig. 5. It can be seen that different dampers have provided the twenty-storey building structure with the K_{eff} and ζ_{eff} even based on the same vibration mitigation target. S–C dampers have the largest K_{eff} of 60.5 kN/mm while VDs are designed with the largest ζ_{eff} of 0.148; FDs have the smallest K_{eff} of 29.0 kN/mm and the second largest ζ_{eff} of 0.0634. The K_{eff} and ζ_{eff} provided by BRBs are 53.4 kN/mm and 0.034, respectively. As both provide structures with the K_{eff} and ζ_{eff}, the design parameters of VE dampers are set to be same with these of BRBs, which is expected to discuss applicability of the code-designed method considering the influence of aftershocks by comparing their seismic performance.

3. Seismic record selection and construction of main shock-aftershocks

The selection of seismic records is important for the seismic response analysis of structures. In general, the uncertainty of seismic records such as spectral characteristics and numbers have some effect on the seismic response of structures [42]. To reduce the uncertainty, the real seismic records are allowed for the seismic analysis of building structures in most seismic codes worldwide such as Eurocode 8 [43–45]. The basic principle is to make the average elastic spectrum match the design spectrum within a 10% tolerance in a broad range of periods depending on the structural dynamic properties [44,46]. Similarly, this seismic record selection method is also recommended in the Chinese seismic code for building [47], which is beneficial to find enough real seismic records for the seismic analysis of structures, especially ones located at regions with the scarcity of the recorded seismic records. In the Chinese seismic code for building [47], the factors that may affect the seismic responses of building structures, such as the intensity, frequency spectrum and effective time duration, are also involved for the seismic record selection. By scaling each seismic record is to the design earthquake intensity level, the average response spectrum value of selected seismic records should match the design spectrum value within a 20% tolerance in the range of critical periods; the effective duration of the seismic records should be 5 to 10 times the natural period of the building structures.

In the Chinese seismic code for building [47], at least seven seismic records are required for the time history analysis of building structures. Previous study has shown that ten-twenty seismic records are enough to provide accuracy for the seismic analysis of building structures [48]. Seven to ten seismic earthquake records are also widely used for the seismic analysis of the structure with dampers [11–13,29,49,50]. In this paper, under the case of meeting the code's requirement, ten seismic records are selected from the ground motion database of Pacific Earthquake Engineering Research Center (PEER) [51], as shown in Table 2. It can be observed that the mean response spectrum of selected seismic records is agreeable well with the design spectrum in Fig. 6 (a)-(b).

To investigate the seismic responses of the 20-story building structure incorporated with five types of dampers, the main shock-aftershock sequences are artificially constructed due to a lacking of the actual aftershock records. The magnitude of aftershock is determined by Bath's law [52] based on the assumption that the largest aftershock has the same spectral characteristics with the main shock. The relationship of the main shock and aftershock [52] is defined by:

$$\Delta M = M_{ms} - M_{as}^{\max} \approx 1.2 \tag{3}$$

in which, M_{ms} is the magnitude of main shock; M_{as}^{max} is the magnitude of the largest aftershock; the derivation ΔM between main shock and the largest aftershock is 1.2.

Accordingly, the peak acceleration of the aftershock is calculated by the attenuation formula proposed by [53,54]. The acceleration attenuation equation [53,54] is expressed as:

$$\log(PGA) = 0.49 + 0.23(M-6) - \log(\sqrt{R^2+8^2}) - 0.0027\sqrt{R^2+8^2} \tag{4}$$

in which, PGA denotes the peak ground acceleration, and the unit of PGA is gravity acceleration (g); M is the magnitude of earthquake, and R is the epicentral distance.

Introducing Equation (3) into (4) yields:

$$\frac{(PGA)_{as}}{(PGA)_{ms}} = \frac{10^{0.49+0.23(M_{as}^{\max}-6)-\log\left(\sqrt{R^2+8^2}\right)-0.0027\sqrt{R^2+8^2}}}{10^{0.49+0.23(M_{as}-6)-\log\left(\sqrt{R^2+8^2}\right)-0.0027\sqrt{R^2+8^2}}} = 0.529 \tag{5}$$

According to Equation (5), a series of main shock-aftershocks are constructed. For example, when the PGA of the main shock is 0.1 g, the

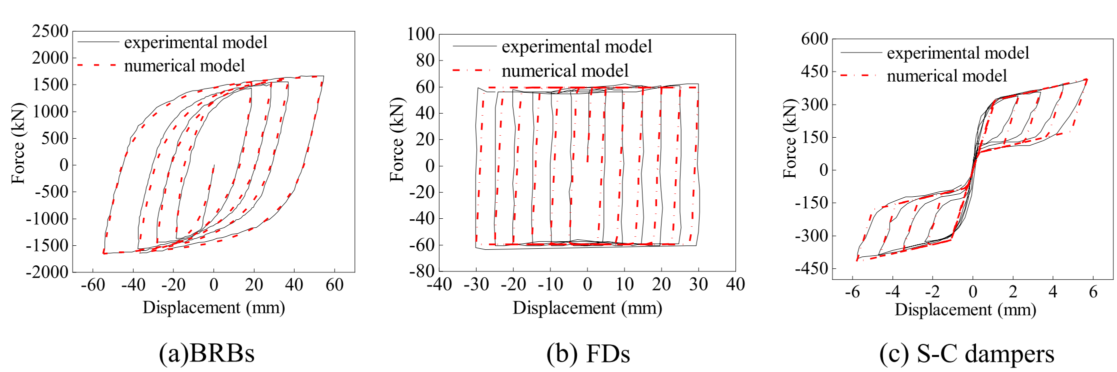


Fig. 4. Experimental and numerical curves of dampers.

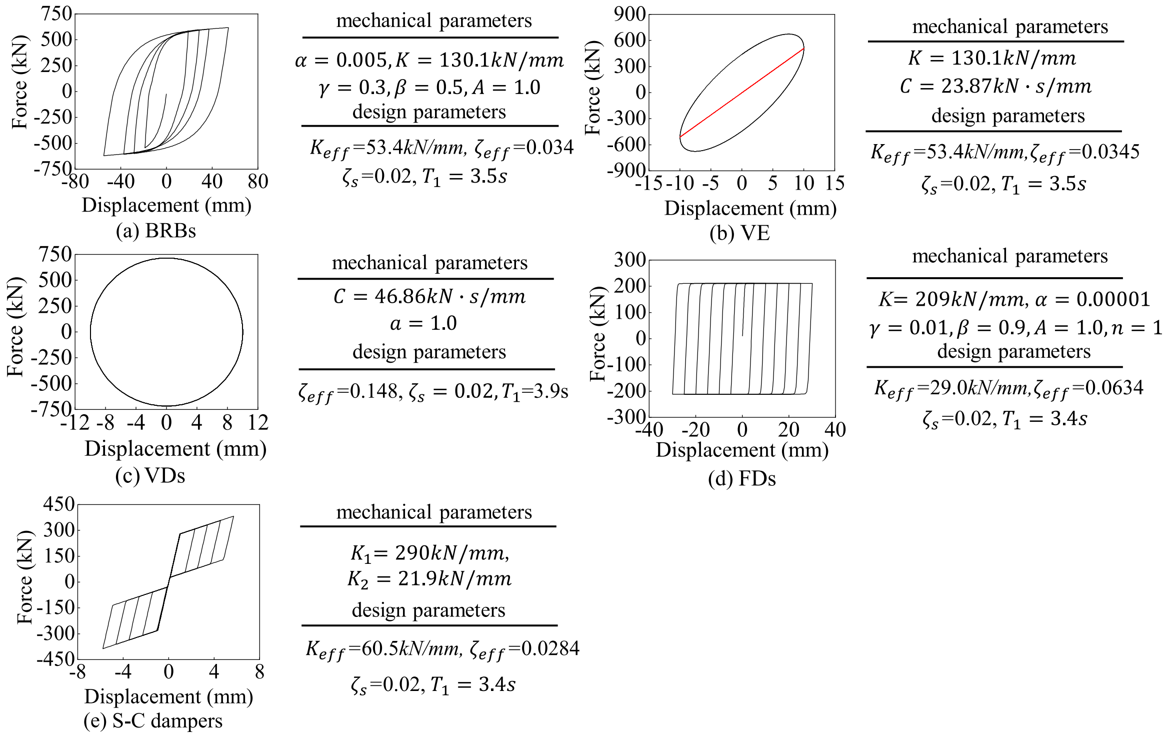


Fig. 5. Mechanical and design parameters of various dampers.

Table 2
Selected earthquake records from the ground motion database.

Seismic records	Name	Year	Station	Magnitude
1	Whittier Narrows-01	1987	Huntington Beach - Lake St	5.99
2	Landers	1992	Barstow	7.28
3	Landers	1992	Mission Creek Fault	7.28
4	Duzce_ Turkey	1999	Lamont 362	7.14
5	Iwate_ Japan	2008	YMT017	6.9
6	Manjil Iran	1990	Abbar, L	7
7	Chuetsu-oki_ Japan	2007	NGN004	6.8
8	Chuetsu-oki_ Japan	2007	NIGH01	6.8
9	Chuetsu-oki_ Japan	2007	NIGH06	6.8
10	Darfield_ New Zealand	2010	MAYC	7

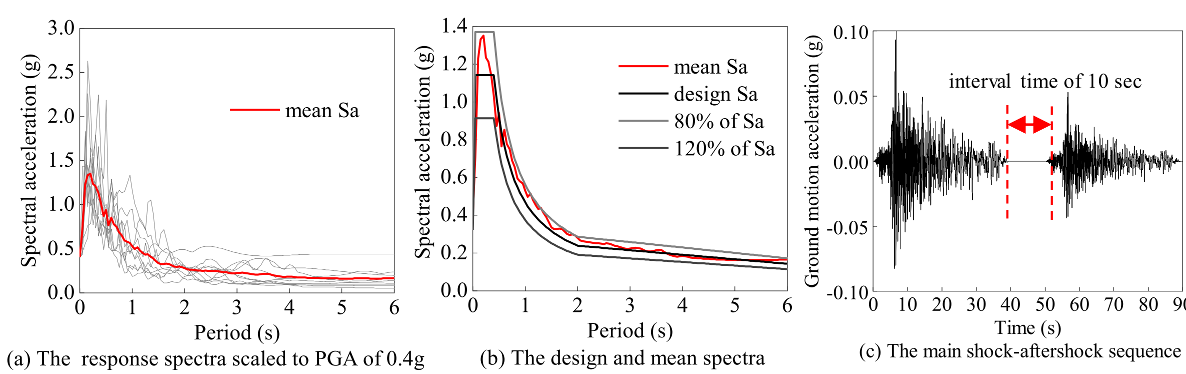


Fig. 6. Response spectra and the main shock-aftershock sequence.

corresponding largest aftershock is 0.0529 g, as shown in Fig. 6(c). The interval time of the main shock and the aftershock is set as 10 s, which is considered to eliminate the influence of the structural free vibration.

4. Seismic performance evaluation of dampers

4.1. the seismic performance evaluation method

The fragility analysis [55] is adopted to evaluate the seismic performance of structure-damper systems. Fragility curves can quantitatively define the relationship of the structural damage and the seismic intensity and reflect the probabilities beyond a certain limit status of structures at a given intensity level of the earthquake. Seismic fragility probabilities can be calculated based on the lognormal distribution function [56], which is defined as:

$$P[\mu \geq C|S_a = x] = F\left\{\frac{\ln(\bar{u}) - \ln(\bar{C})}{\sqrt{\beta_u^2 + \beta_c^2}}\right\} \tag{6}$$

in which, $\bar{u}$ and $\bar{c}$ are the average values of structural capacity $_C$ and demands μ, respectively, and β_c , β_u are the logarithmic standard deviations of C and μ, respectively.

To obtain the fragility curves, the incremental dynamic analysis (IDA) is adopted to calculate the seismic responses of structure-damper systems by employing a series of nonlinear dynamic analysis [57]. Each IDA involves two scalers. One is the intensity measure (IM) that describes the scaling of the ground motion records [58], such as peak ground acceleration (PGA), peak ground velocity (PGV), pseudo-spectral acceleration Sa(T_1) at the fundamental period of structures. PGA and PGV are single-valued parameters, they can be easily obtained. However, such parameters are insensitive to the frequency content and the duration of the ground motion record. This may result in larger dispersion of structural seismic responses [59]. By contrast, Sa (T_1) is more effective parameter and is commonly adopted in evaluating the seismic performance of the structure with various dampers [60–62], because it can involve the seismic characteristics and structural properties [59,63]. The other scaler is the engineering demand parameter (EDP) that is used to measure the structural capacity. The maximum interstory drift θ_{max} is generally used to describe the seismic responses of building structures [57]. In this paper, Sa (T_1) and θ_{max} are selected as two scalers in the seismic fragility analysis.

The seismic performance evaluation procedure of structure-damper systems is schematically shown in Fig. 7. Seismic responses of building structure and structure-damper systems are calculated by the IDA. By considering the effect of aftershocks, the seismic performance of code-designed dampers is investigated from the perspective of structural collapse, damage and equipment's failure.

To compare the seismic performance of five types of dampers, the performance indices are defined firstly. For the structural collapse analysis, the collapse limit is defined as 20% of the initial tangent stiffness of the fragility curves [64], as shown in Fig. 8. For the damage analysis, the interstory drift limit that describes the different damage state of the twenty-storey building structure is defined in the Chinese code [30], as shown in Table 3. It should be noted that the definition of collapse in Table 3 is determined based on the structural safety and reliability, which is distinguished from that related with the degraded tangent stiffness in Fig. 8. In the equipment's failure analysis, the acceleration limit of hospital equipment is regarded as performance index, which is discussed later. All these performance indices depend on the seismic responses of building structures. Dampers are designed as the supplemental components that provide the building structure with the effective stiffness and effective damping ratio. The failure of code-designed dampers is not identified in the Chinese code [30]. The seismic performance of dampers incorporated with the 20-story building structure is evaluated by comparing how much they have reduced the structural seismic responses. As this paper mainly focuses on the effectiveness of code-designed dampers by the Chinese code [30] in mitigating the structural seismic responses, it has to be noted that the failure of code-designed dampers is not considered in the fragility analysis.

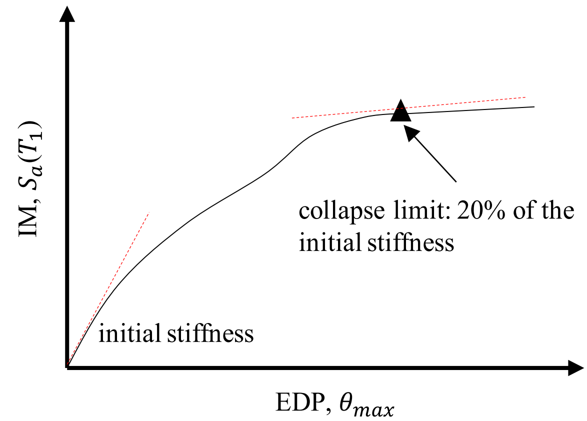


Fig. 8. Collapse limit of building structure.

Table 3
Damage limits of steel building structures defined by Chinese code.

No damage	Slight damage	Moderate damage	Severe damage	collapse
< **1/250**	< 2/250	< 4/250	< 9/500	> [1/50]

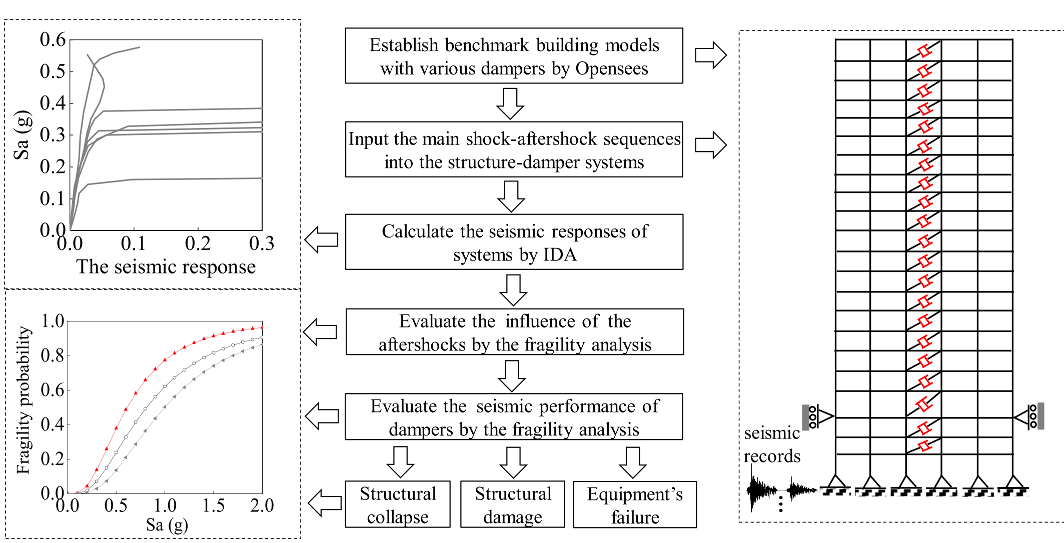


Fig. 7. Seismic performance evaluation procedure of dampers.

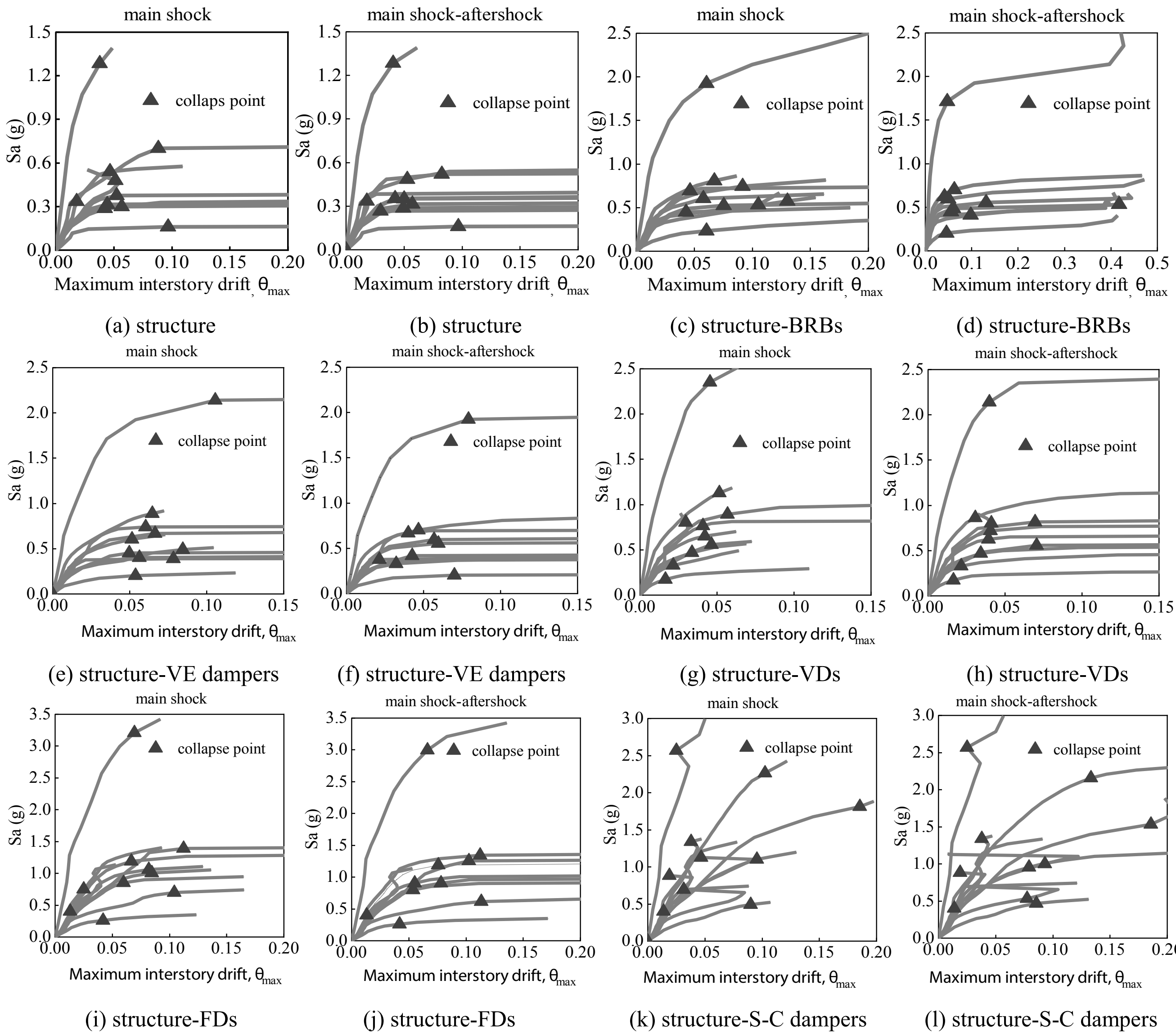


Fig. 9. IDA curves of structure-damper systems under the main shock and the main shock-aftershocks.

4.2. the influence of aftershocks

To investigate the influence of aftershocks on the seismic performance of code-designed dampers, the seismic responses of structure-damper systems are calculated by the IDA under the main shock and the main shock-aftershock sequences. The collapse limits are marked as the collapse points, as shown in Fig. 9.

The distribution of collapse points is described by Equation (6), and the collapse fragility curves of structure-damper systems can be calculated by these collapse points, as shown in Fig. 10 (a). To discuss the influence of aftershock on the seismic performance of five types of dampers, the collapse fragility curves of structure and structure-damper systems are demonstrated in Fig. 10(b)–(h).

Fig. 10(b) demonstrates that aftershocks will increase the collapse risk of the building structures. However, aftershocks have similar influence on the structure-damper systems, as shown in Fig. 10 (c)–(g).The comparisons of collapse probabilities in Fig. 10(h) show that the effect of aftershocks on the collapse probabilities of dampers are not obvious. When Sa is less than 1.0 g, FDs and S–C dampers are the least affected by aftershocks compared to BRBs and VE dampers. Overall, the increased collapse probabilities of structure-damper systems caused by aftershocks are less than 10%. This suggests that the collapse of structure-damper systems is mainly caused by the main shock. It can be concluded that the code-designed method without consideration of the influence of aftershocks is still applicable for designing various dampers.

4.3. the collapse analysis

To compare the seismic performance of dampers under the main shock and the shock-aftershock sequences, the collapse probability curves are shown in Fig. 11.

Fig. 11 shows that all dampers can greatly reduce the collapse probability of the twenty-storey building structure, and the seismic performance of five types of dampers are different in enhancing the structural safety under the main shock and the main shock-aftershocks. S–C dampers perform best in reducing the structural collapse probability, followed by FDs. BRBs and VE dampers have the similar collapse probability. VE dampers and VDs exhibit a similar capacity in the structural collapse control when Sa is less than 0.5 g, and VDs are superior to VE dampers with Sa increasing. For a specific illustration, the collapse probabilities of structure-damper systems under the high-level earthquakes for 8-degree (Sa = 0.9 g) are shown in Table 4. The rate of vibration mitigation is defined as the ratio of the collapse probability of

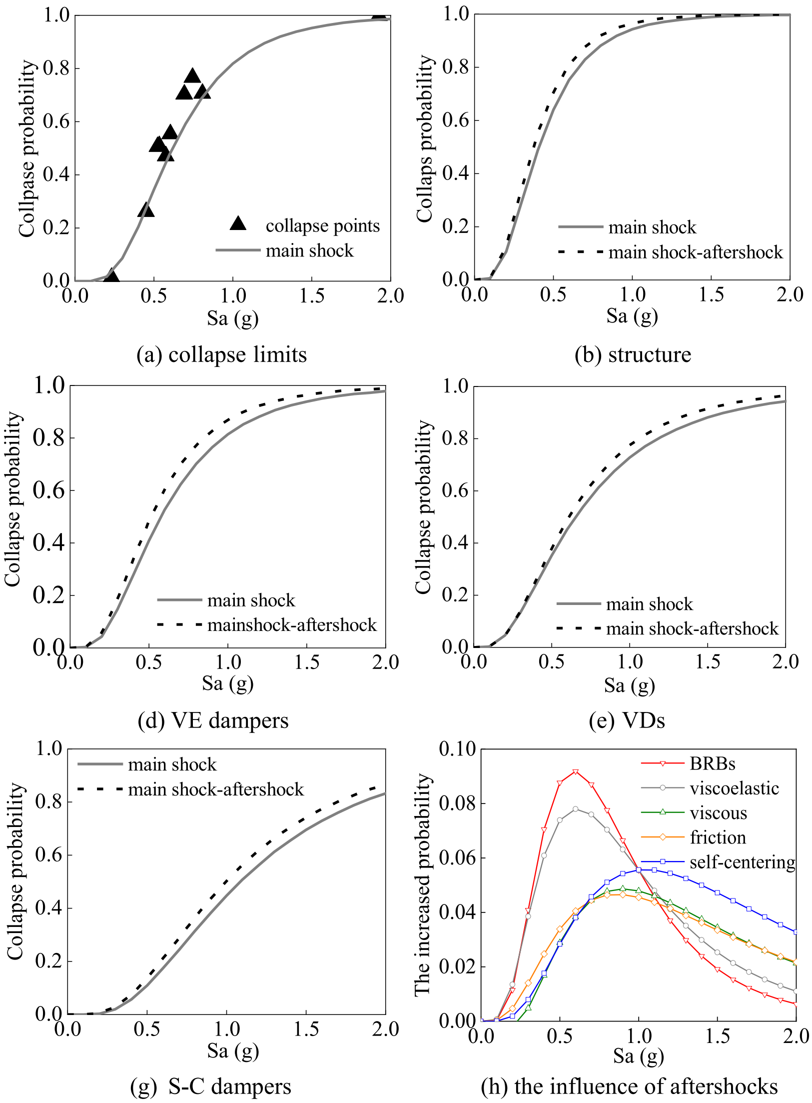


Fig. 10. Collapse fragility curves of structure-damper systems under the main shock and main shock- aftershocks.

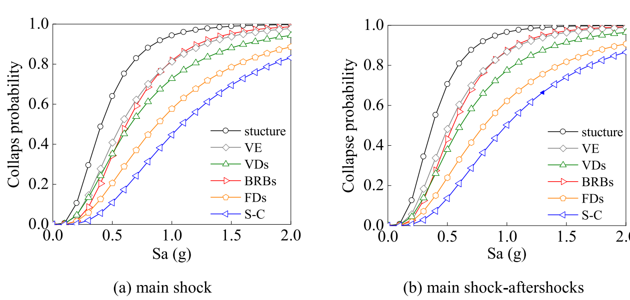


Fig. 11. Collapse fragility curves of structure-damper systems.

Table 4
Collapse probabilities of structure-damper systems.

Dampers	Collapse probability			
	Main shock	Rate of vibration mitigation	Main shock-aftershock sequences	Rate of vibration mitigation
Building structure	91.8%	-	94.8%	-
BRBs	76.1%	82.9%	82.7%	87.2%
VE dampers	76.4%	83.2%	82.7%	87.2%
VDs	67.5%	73.4%	72.4%	76.4%
FDs	51.6%	56.2%	56.2%	59.5%
S–C dampers	38.2%	41.6%	43.7%	46.1%

structure-damper systems to that of the building structure without dampers.

Under the high-level earthquake with 0.9 g Sa, different dampers designed by the same vibration mitigation target have different rates of vibration mitigation under the main shock and the main shock-aftershocks. S–C dampers and FDs are more effective in the structural collapse control. Despite the different mechanical models of BRBs and VE dampers, the rates of vibration mitigation of these two dampers are almost same. This is evident from their collapse fragility curves in Fig. 11. The same scenario is also occurred in the following damage fragility analysis. It is because BRBs and VE dampers are both designed with the same effective stiffness and effective damping ratio provided for the twenty-storey building structure. This means that the effective stiffness and effective damping ratio are two critical parameters to determine the seismic performance of dampers. In other words, the design method in the Chines code is effective for designing dampers.

4.4. *the damage fragility analysis*

High-rise building structures may have different damage state when

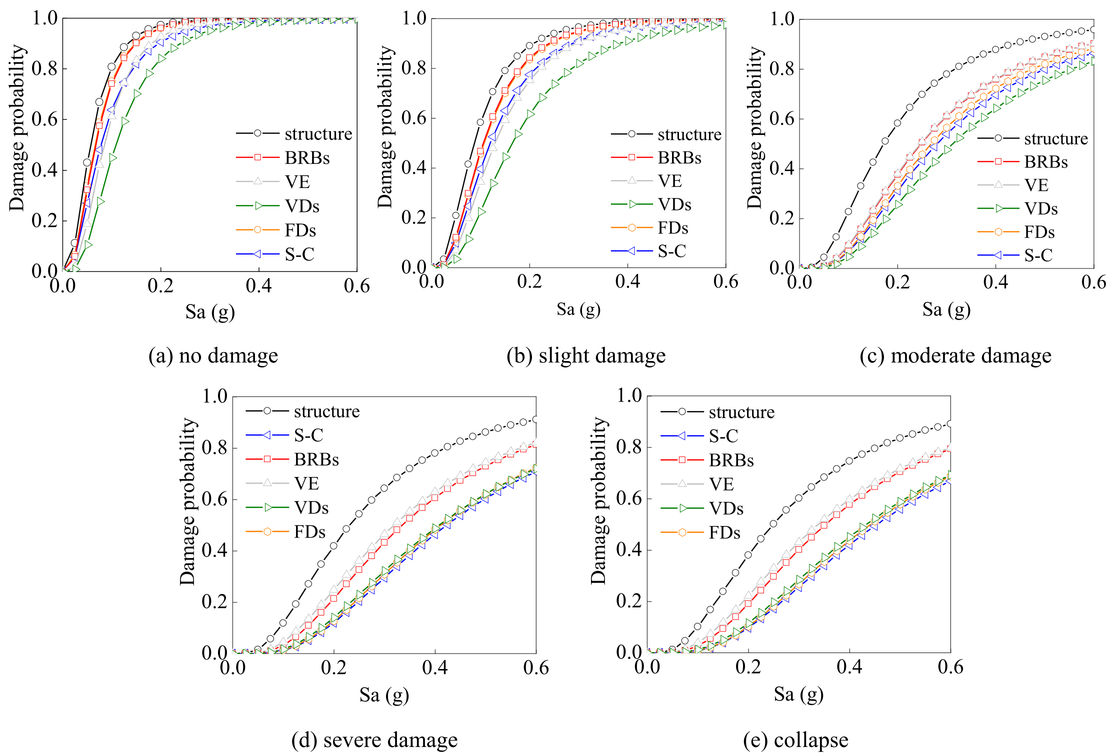


Fig. 12. Damage fragility curves of structure-damper systems.

subjected to the main shock-aftershocks. In this case, the damage fragility analysis of structure-damper systems is necessary to focus on. According to the interstory drift limit defined in the Chinese code [30], the damage fragility curves of five types of structure-damper systems under the main shock-aftershock sequences are shown in Fig. 12.

Fig. 12 demonstrates that all dampers can mitigate the interstory drift of the twenty-storey building structure as the structure-damper systems have the lower damage probabilities than the structure without dampers under the main shock-aftershocks. VDs are the most effective in reducing the damage probability of the building structure at all the damage states. BRBs and VE dampers, S–C dampers and FDs perform similar seismic energy dissipation abilities in controlling the no damage, slight damage and moderate probability of structures, as shown in Fig. 12 (a–c). FDs, VDs and S–C dampers have similar seismic performance in the severe damage and collapse states control, which have lower damage probabilities than BRBs and VE dampers in Fig. 12 (d–e). For all damage state, it can be observed that BRBs and VE dampers with the same effective stiffness and effective damping ratio have similar damage probability.

4.5. *the acceleration fragility analysis*

The acceleration fragility is used to analyze the failure of the equipment that is sensitive to the acceleration and may be failed under the strong acceleration. In this paper, the acceleration failure limit is 0.15 g PGA for the hospital equipment [65]. To discuss the comparative seismic performance of dampers in controlling the acceleration responses of different floors, the 4th, 7th, 13th and 19th floors are selected to represent the bottom, middle, high and top of the building structure, respectively. With the assumption that the equipment is rigidly connected to the floor slab, the acceleration fragility curves of structure-damper systems under the main shock-aftershock sequences are shown in Fig. 13.

It can be observed that the seismic performance of BRBs, FDs and S–C dampers are not obviously affected by different floors of the high-rise building structure almost, in terms of controlling the acceleration failure probability, as shown in Fig. 13(a), (d) and (e). By contrast, VDs and VE dampers are superior in the acceleration failure control at the 13th floor but are relatively inferior at 4th floor, as shown in Fig. 13(b)–(c). It can be concluded that the velocity type dampers including VDs and VE dampers are more sensitive to the acceleration compared with the displacement-dependent dampers such as BRBs, FDs and S–C dampers.

To compare the seismic performance of dampers in controlling the acceleration response of the high-rise building structure, the acceleration fragility curves of structure-damper systems are given in Fig. 14.

Fig. 14 has demostrated that velocity type dampers are more effective in reducing the acceleration response of the twenty-storey building structure than displacement-independent dampers. VDs are the most effective in mitigating the acceleration failure probability of equipment at different floors under the main shock-aftershocks, followed by VE dampers. BRBs, FDs and S–C dampers are less effective in controlling the equipment's acceleration failure. With the same designed effective stiffness K_{eff} and effective damping ratio ζ_{eff}, VE dampers are superior than BRBs in term of the acceleration failure control. This reveals that the K_{eff} and ζ_{eff} are not effective to determine the seismic performance of dampers in mitigating the structural acceleration response. The method provided by the Chinese code [30] is non-applicable to design dampers that are used for controlling acceleration responses of building structures.

5. Discussion

Based on above discussions, all dampers designed by the Chinese code [30] are effective in protecting building structures against the main shock-aftershocks. However, different dampers exhibit their own distinctive advantages in mitigating the seismic responses of the twenty-storey building structure, as shown in Table 5. The number of sign + is used to evaluate the seismic performance of dampers. The more the number of sign + is, the better the effectiveness of dampers in mitigating the structural seismic responses is.

From Table 5, it can be seen that design parameters K_{eff} and ξ_{eff} are

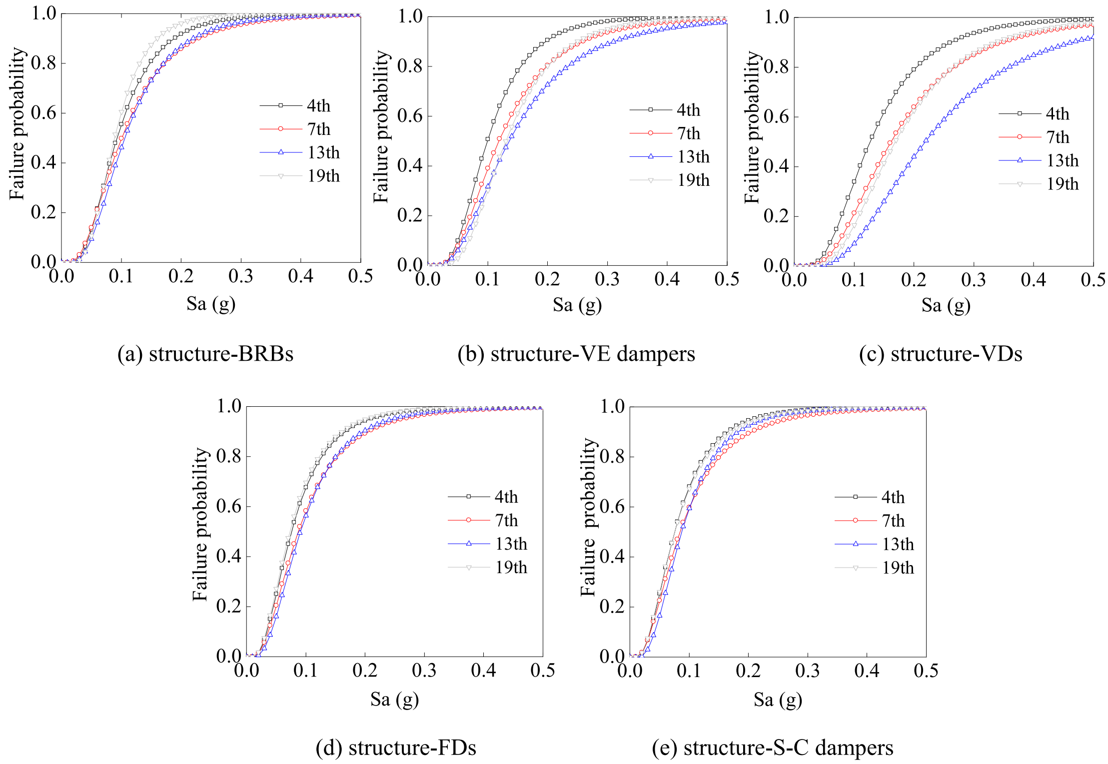


Fig. 13. Aceleration fragility curves of structure-damper systems.

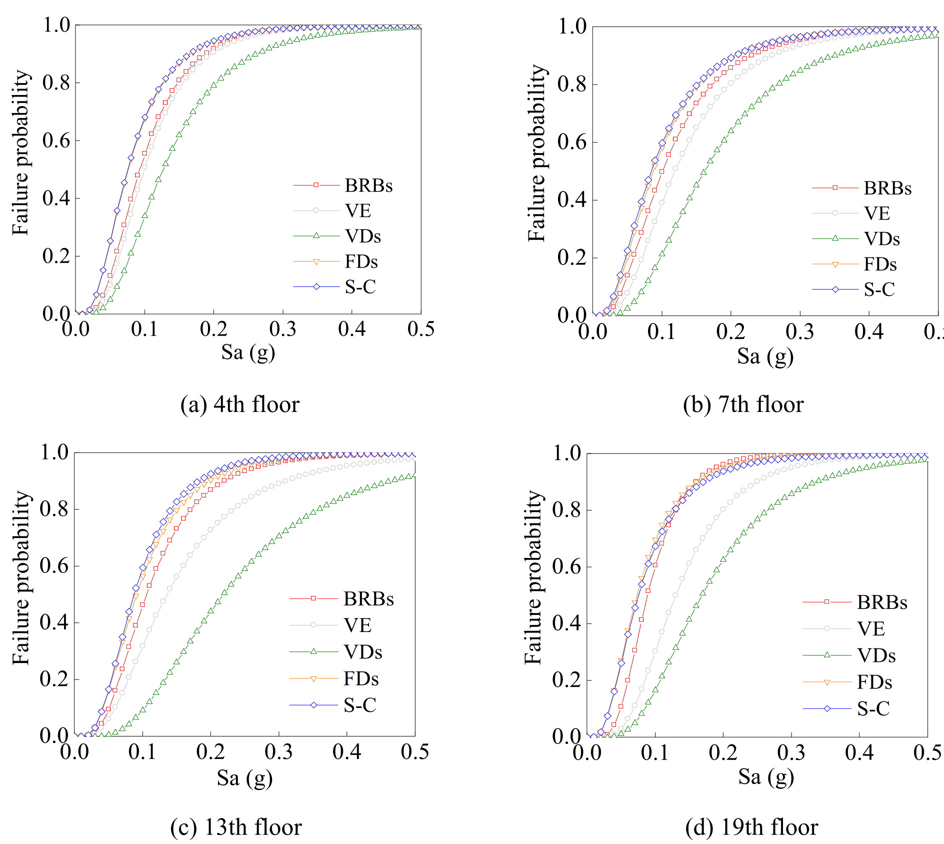


Fig. 14. Acceleration failure curves of structure-damper systems.

Table 5
Seismic performance evaluation of 5 types of dampers.

Dampers	ξ_{eff}	K_{eff} (kN/mm)	Collapse control	Damage control	Scceleration control
BRBs	0.0340	53.4	+	+	+ +
VE dampers	0.0340	53.4	+	+	+ + + +
VDs	0.1480	—	+ +	+ + + + +	+ + + + +
FDs	0.0634	29.0	+ + + +	+ + +	+
S–C dampers	0.0284	60.5	+ + + + +	+ + + +	+

related with the effectiveness of dampers in reducing the seismic responses of the twenty-storey building structure. With the similar effective stiffness K_{eff} and effective damping ratio ξ_{eff}, BRBs and VE dampers have demonstrated similar effectiveness in the controlling the structural seismic responses. VDs that have the largest ξ_{eff} perform best in the damage and the acceleration failure control. S–C dampers with the largest K_{eff} display excellent seismic energy dissipation ability in the structural collapse and damage control. FDs with the second largest ξ_{eff} and the smallest K_{eff} are also effective in minimizing the structural damage fragility. It can be concluded that five types of dampers with different design parameters designed by the Chinese code have their own distinctive advantages in mitigating the seismic responses of the building structure.

In this paper, although five dampers are designed by the same vibration mitigation target based on the code-designed method, all of them have demonstrated different seismic performance in in reducing structural seismic responses. Compared with other findings in recent studies on the effectiveness of various dampers, there are some similarities and differences for results obtained from this study. For the seismic performance analysis of VDs and VE dampers incorporated within the single-storey adjacent building structures [24], the comparative seismic response effectiveness of dampers is discussed by setting up the optimum damping parameters. The result shows that VDs are more effective than VE dampers in reducing the displacement response of the single-storey adjacent building structures. Although with the different structure system and design target, VDs also perform better than VE dampers in mitigating the seismic responses of the twenty-story building structure. In the seismic performance evaluation of BRBs, VDs, and VE dampers incorporated in a nine-storey steel building [29], dampers were designed by the same vibration mitigation target. Without considering the effect of aftershocks, VDs are most effective than BRBs and VE dampers in the reduction of damage probabilities, which is consistent in the conclusion in this study. Although VDs dampers were found to be inferior to VE dampers in terms of the control of collapse and acceleration failure, which is different from the findings in this paper. Such difference is allowed, for the seismic performance of dampers is greatly affected by the structural properties. Similarly, in the bridge system, the superelastic shape memory alloy cables (SMAs) with the superior self-centering capacity have demonstrated the best effectiveness in mitigating the seismic fragility probabilities of the existing bridge, followed by FDs and VDs [28]. In this study, S–C dampers with the self-centering capacity perform better seismic performance than FDs in mitigating the damage fragility probability but are less effective than VDs. Such different effectiveness is acceptable considering the different dynamical characteristics of the building and bridge structures. Overall, S–C dampers exhibit excellent seismic performance in mitigating the structural seismic fragility probabilities. In a frame-shear wall system, the optimal use and comparative performance of FD, VE dampers and combined FD-VE dampers is well investigated by considering the different natural frequencies of systems [27]. Results have shown that FDs and VE dampers have their own advantages in mitigating the peak accelerations and deflections of shear walls, which depend on the locations these dampers were placed. Combined FDs-VE dampers display best seismic performance. In this paper, the influence of location and configuration of FDs and VDs are not considered. Our study focuses on the comparative performance of five types of code-designed dampers incorporated within a twenty-storey steel building structure. Although these dampers are designed to achieve the same vibration mitigation target, various dampers exhibit different effectiveness in the terms of the control of the structural damage and acceleration. FDs perform effectively in the control of collapse, and VD dampers are very effectively in reducing the damage and acceleration responses of the building structure.

6. Conclusion

This paper designed five types of dampers including BRBs, VE dampers, VDs, FDs, and S–C dampers using the design method provided by the Chinese code, then compared the seismic performance of code-designed dampers under the main shock-aftershock sequences. Using the IDA and fragility analysis, the seismic fragility of a twenty-storey building structure incorporated with dampers were studied from the perspective of structural collapse, damage control and acceleration control. Some conclusions are given as follows:

Although aftershocks can increase the seismic responses of structure-damper systems, the influence of aftershocks is not obvious. The seismic responses of the building structure are mainly caused by the main shock. From this point, the design method that ignore the effect of aftershocks in the Chinese code is feasible and applicable.

S–C dampers are the most effective in minimizing the collapse probability of the building structure then FDs. VDs dampers perform best in controlling the structural damage, followed by S–C dampers and FDs. In the reduction of structural acceleration responses, velocity type dampers (VDs and VE dampers) always perform better than displacement-dependent dampers (FDs, BRBs and S–C dampers), especially VDs.

In terms of the design parameters of dampers, VDs with largest effective damping ratio are effective in reducing the structural damage and equipment's acceleration failure probabilities. S–C dampers which have the largest effective stiffness perform well in controlling the structural collapse and damage. With the same effective stiffness and effective damping ratio designed by the Chinese code, both BRBs and VE dampers exhibit similar seismic performance in reducing the collapse and damage probabilities of the building structure, while VE dampers perform better than BRBs in controlling the acceleration responses. It is suggested that the two design parameters are effective in determining the seismic performance of dampers in mitigating the structural damage and collapse while not applicable to reflect the reduction of structural acceleration responses.

This paper evaluated the seismic performance of dampers designed by the Chinese code based on the performance indices of the twenty-storey building structure. Dampers are all designed by the same vibration mitigation target based on the Chinese code, however, the actual performance of various dampers differs under the main shock-aftershocks. Such conclusions depend on not only code-designed method but also the properties of the building structure and damper itself. However, from the perspective of engineering, the effectiveness of code-designed dampers was well investigated, thus providing a better understanding of the application of dampers in the practical engineering. For the failure mechanism analysis of dampers under the seismic loads, further investigations need to be carried out.

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Appendix A. Supplementary data

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