*Structural Engineering and Mechanics, Vol. 44, No. 5 (2012) 611-631*
DOI: http://dx.doi.org/10.12989/sem.2012.44.5.611


# A simplified design procedure for seismic retrofit of earthquake-damaged RC frames with viscous dampers

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*(Received July 3, 2011, Revised September 30, 2012, Accepted October 27, 2012)*

**Abstract.** The passive energy dissipation technology has been proven to be reliable and robust for recent practical applications. Various dampers or energy dissipation devices have been widely used in building structures for enhancing their performances during earthquakes, windstorm and other severe loading scenarios. This paper presents a simplified seismic design procedure for retrofitting earthquake-damaged frames with viscous dampers. With the scheme of designing the main frame and the supplemental viscous dampers respectively, the seismic analysis model of damped structure with viscous dampers and braces was studied. The specific analysis process was described and approach to parameter design of energy dissipation components was also proposed. The expected damping forces for damped frame were first obtained based on storey shear forces; and then they were optimized to meet different storey drift requirements. A retrofit project of a RC frame school building damaged in the 2008 Wenchuan earthquake was introduced as a case study. This building was retrofitted by using viscous dampers designed through the simplified design procedure proposed in this paper. Based on the case study, it is concluded that this simplified design procedure can be effectively used to make seismic retrofit design of earthquake-damaged RC frames with viscous dampers, so as to achieve structural performance objectives under different earthquake risk levels.

**Keywords:** simplified seismic design procedure; viscous damper; RC frame; energy dissipation; equivalent damping ratio

## 1. Introduction

In the past several decades, a variety of energy dissipation devices have been developed, such as oil dampers, viscous dampers, visco-elastic dampers, metallic dampers, and friction dampers, etc. Among them, the viscous damper, which has an out-of-phase relationship between the column restoring force and damper force (Symans and Constantinou 1998), may be the best option to control stress and deflection simultaneously for a structure subjected to an impulse loading. The

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fluid viscous damper, which is initially used in the military and aerospace industry, typically consists of a piston head with orifices contained in a cylinder filled with a highly viscous fluid. It dissipates the external energy by transferring it into heat (Housner *et al.* 1997, Hanson and Soong 2001). Due to its unique characteristics, the viscous damper is regarded as one of effective approaches for structural vibration control and has been widely applied for seismic design of new buildings and retrofit of existing structures. Based on a statistics from Taylor Devices Inc. (http://www.taylordevices.com/) and Shanghai Research Institute of Material (http://www.srim.com.cn/), some typical projects that viscous dampers are used in the design or retrofit include: Hydra Waves (Mazatlan/Mexico 2009), T. F. Green Airport Parking Garage (Providence/USA 2009), Uni-President B8 Project (Taipei/Taiwan 2009), Meguro Gajoen Extension Project (Tokyo/Japan 2010), Shanghai World Expo 2010 Theme Hall (Shanghai/China 2010), and Kimpo Airport Phase (Seoul/South Korea 2009), ASE I - Mihai Eminescu Project (Bucharest/Romania 2009), 865 Market Street - San Francisco Centre (San Francisco/USA 2009), Nagoya - Port Government Office Main Building (Nagoya/Japan 2009), Dujiangyan Gas Company Building (Sichuan/China 2009), Dujiangyan Middle School (Sichuan/China 2010).

With the extensive application of passive energy dissipation technologies in the industry and the civil construction field, reasonable design methods and rational analytical models have been studied by many researchers recently (Tsai *et al.* 2000, Kasai and Kibayashi 2004, Lavan and Levy 2004, Dargush and Sant 2005, Hwang *et al.* 2007, Li and Liang 2007, Lin *et al.* 2008, Sorace and Terenzi 2008, Weng *et al.* 2009, Taylor 2010, Lavan and Levy 2010, Kakaletsis *et al.* 2011, Silvestri *et al.* 2011). Many guideline documents have been published in different countries, such as ATC-33 (Applied Technology Council 1997), FEMA-273/274 (Federal Emergency Management Agency, 1997), NEHRP 2000 Provision (National Earthquake Hazards Reduction Program 2000), FEMA-368, NEHRP 2003: Chapter 15 – Structures with Damping Systems, EC 8: Design of Structures for Earthquake Resistance – Part 1 (Eurocode 8 2003), ASCE 7-05: Seismic Provisions (American Society of Civil Engineering 2005), JSSI Manual: Design and Construction Manual for Passively Controlled Buildings (Japan Society of Seismic Isolation 2003/2005/2007), Technical Specification for Building with Energy Dissipation Devices (People's Republic of China Profession standard 2011), etc.

Although the design procedures vary in different standards, they are almost all based on the response spectrum modal analysis method. Among above guidelines, only the JSSI Manual provides relatively more specific instructions for distributing viscous dampers along the height of a structure. The main design process is described as follows (Kasai and Kibayashi 2004): Firstly, for a given earthquake input of a smooth response spectrum, the peak displacement and the base shear of a frame prior to damper installment is predicted from the response spectrum. Then, the target reduction ratios of displacement and base shear is estimated based on the required performance. Finally, with the target reduction ratios and the performance curve, the necessary stiffness of viscous dampers and braces are determined; An optimum design solution to control both displacement and force is obtained from the performance curve. However, it is noted that the performance curves are given based on the SDOF system and therefore, the design of viscous dampers in a multi-storey case needs to be conducted by modeling the MDOF frame using an equivalent SDOF system,. The distribution principle of total viscous dampers to every storey is that that the damper's loss stiffness, defined as the force at zero displacement divided by the peak deformation in steady-state responses of the viscous damper (JSSI Manual 2007), shall be proportional to the corresponding storey stiffness of the MDOF system.

The effectiveness of the JSSI Manual to guide the seismic design of framed structures with viscous dampers in Japan has been demonstrated through a large number of engineering practice, which is virtually conducted based on the time-history analysis with appropriately-selected ground motions. However, design of damped structures in the JSSI Manual is implemented based on performance curves, which are drawn according to the statistic regression of numerous Japanese earthquake waves. Therefore, it is difficult to directly apply the JSSI Manual design method in other countries. To promote the application of viscous dampers for seismic design of buildings in China, it is inevitable to explore a new simplified design procedure based on Chinese seismic design codes, which is just the objective of the work presented in this paper.

## 2. Viscous damping principle

When viscous dampers (usually with required braces) are used to retrofit existing (or earthquake-damaged) frames, the later-added viscous dampers-braces can be regarded as a supplemental system to the main frame. In this way, the viscous dampers-braces system and the main frame can be analyzed separately. Based on this philosophy, the analytical model of the damped frame can be equivalently divided into the main frame model and the viscous dampers-braces (VDB) system model, as shown in Fig. 1.

It is assumed that the actual structural damping in buildings can be idealized as a linear viscous dashpot; and the equation of motion for the bare frame structure without dampers can be given by Eq. (1)

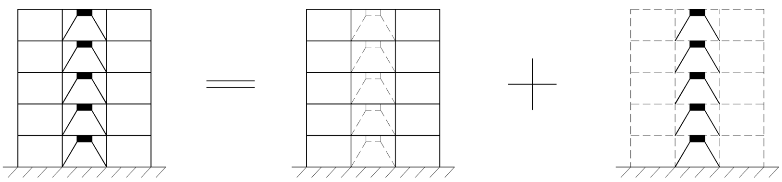
$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\} = -[M]\{\ddot{u}_g(t)\} \tag{1}$$

Where $[M]$, $[C]$, $[K]$ are the mass matrix, the damping matrix, the stiffness matrix of the frame structure, respectively; and $u(t), \dot{u}(t), \ddot{u}(t)$ are its displacement vector, velocity vector, acceleration vector relative to the ground respectively; while $\ddot{u}_g(t)$ is the ground acceleration vector.

For a structure with the viscous damping system, the dampers and braces can be represented by a generic integro-differential operator, $\Gamma$, which is a comprehensive force provided by the additional mass, additional damping, and the additional stiffness. The equations of motion for the damped structure are then given as follows

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}+\Gamma = -([M]+[M_a])\{\ddot{u}_g(t)\} \tag{2}$$

$$\Gamma = [M_a]\{\ddot{u}(t)\}+[C_a]\{\dot{u}(t)\}+[K_a]\{u(t)\} \tag{3}$$



(a) Damped Structure Model (b) Main Frame Model (c) VDB Model

Fig. 1 Analytical model of a damped structure with viscous dampers and braces

Where $[M_a]$, $[C_a]$, $[K_a]$ are the additional mass matrix, the additional damping matrix, the additional stiffness matrix provided by the viscous damper and brace system, respectively.

In the practical design and analysis, the added mass of viscous damper-brace system is usually far less than the total mass of a building. The added stiffness, associated with the brace stiffness, damping constant and load frequency (Fu and Kasai 1998), is also rather small compared to the structural stiffness. Therefore, to simplify the calculation process in preliminary design phase, it is assumed that $[M_a] = 0$ and $[K_a] = 0$ (the stiffness of damping-brace system will be considered in the modified design phase). The $\Gamma$ operator can be consequently expressed by the pure viscous damping force, as given in Eq. (4)

$$\Gamma = \{F_d(\dot{v}(t))\} = \{C_d \cdot Sgn(\dot{v}(t) \cdot |\dot{v}(t)|^{\alpha})\} \tag{4}$$

Where $F_d(\dot{v}(t))$ is the viscous damping force, which directly depends on the relative velocity of the damper, $(\dot{v}(t))$; *Sgn* denotes the symbolic function; $C_d$ is the damping coefficient; $\alpha$ is the velocity exponent ($0 \le \alpha \le 1$).

Approximately, the damping force can be re-written as Eq. (5) with equal dissipated energy.

$$\Gamma = \{F_d(\dot{v}(t))\} \approx [C_a]\{\dot{u}(t)\} \tag{5}$$

where $[C_a]$ is obtained by equivalent linearization associated with the velocity vector relative to ground, $(\dot{u}(t))$.

Substituting Eqs. (3), (4) and (5) into Eq. (2) gives

$$[M]\{\ddot{u}(t)\} + ([C] + [C_a])\{\dot{u}(t)\} + [K]\{u(t)\} = -[M]\{\ddot{u}_g(t)\} \tag{6}$$

Eq. (6) can be solved by the Implicit Newmark Iterative method or the Discrete Fourier Transform method (Soong and Dargush 1997). The viscous dampers can then be preliminarily designed based on the added equivalent damping ratio to the main frame structure.

## 3. Simplified design process

A simplified design procedure for seismic retrofit of earthquake-damaged frames using the viscous damper-brace system proposed in this paper is shown in Fig. 2.

Step 1: Setting precautionary goal. According to certain seismic precautionary grade and seismic protection classification of the structure, a seismic precautionary goal, given by *Code for Seismic Design of Buildings* (GB 50011-2010, PRC Code) and *Standard for Classification of Seismic Protection of Building Constructions* (GB 50023-2008, PRC Code), needs to be determined under a given earthquake.

Step 2: Finite element analysis (FEA) of the bare frame. Prior to seismic retrofit of earthquake-damaged buildings, seismic evaluation needs to be conducted firstly. Any repair work should be included in assessment. A finite element model of the bare frame is established to estimate its current seismic performance. Sometimes, a simplified lumped-mass model is used for a quick design.

Step 3: Setting structural performance level. For damped frames, their target performances should be set to meet both the owner's requirements and the seismic precautionary goal determined in Step 1.

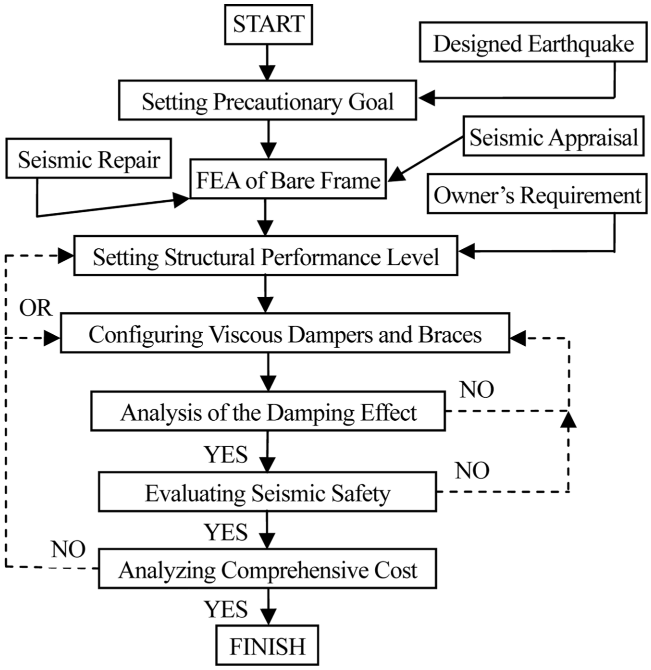



Fig. 2 Process of the simplified design procedure

The seismic precautionary goal of a structure is associated with the design code. In practice, the storey drift is usually used to represent the structural performances, and their limit values vary in different design codes issued by different countries.

Step 4: Configuring the viscous damper-brace system. As presented by Weng *et al.* (2011), the damping forces provided by the viscous damper-brace system can be calculated according to the required additional damping ratio, which can be obtained by a specific structural performance requirement set in Step 3. The configuration of the added viscous damper-brace (e.g., diagonal brace and chevron brace) system can be preliminarily determined in the light of the architectural function and structural arrangement of a building. With the required additional damping force being calculated, the viscous damper distribution and related parameters of the damper-brace system, including the damping coefficient, the velocity exponent, and the brace stiffness, are designed. It is usually assumed that the brace keeps in elasticity under the maximum damping force.

Step 5: Analysis of the damping effect. Since most current viscous dampers have nonlinear characteristics, the time-history analysis should be implemented for the frame structure with additional dampers in a practical design. A approach is proposed in this step to verify whether the damping effect provided by the viscous damper-brace system meet the seismic behavior demands for the damped frame under the frequently occurred earthquake, the precautionary earthquake and the rarely occurred earthquake, which are defined as "earthquakes with a 10% probability of exceedance in 50-year service period", "earthquakes with 63% probability of exceedance in 50-year service period", "earthquakes with 2~3% probability of exceedance in 50-year service period", respectively, in the GB 50011-2010 (PRC Code). It is noted that the structural stiffness decreases when the structure goes into the inelastic stage under rare earthquakes. This is considered in the proposed method by reducing the lateral stiffness of frame columns with a discount coefficient, $1/\mu_\Delta$, where $\mu_\Delta$, as the so-called displacement ductility factor, equals to the maximum displacement divided by yield displacement of the framed structure. Three sub-tasks need to be completed in this step: (1) calculating the additional equivalent damping ratio, (2) comparing storey shear forces and storey drifts (or storey drift rotation) between bare frame and damped frame, and (3) checking the structural performances of the building with the damper-brace system (Weng *et al.* 2011). If the damping effect is unsatisfactory, the designer shall return to Step 4 to adjust the configuration of viscous dampers and braces for desirable damping results.

Step 6: Evaluating seismic safety. After satisfactory damping effects are achieved in Step 5, seismic safety assessment of the entire structure should be conducted subsequently, which mainly includes the elastoplastic deformation check, the safety evaluation of added system, and the verification of seismic design details. If the evaluation results are unsatisfactory, the designer shall go back to Step 4.

Step 7: Analyzing comprehensive cost. Since viscous dampers used in the retrofit design are relatively expensive currently, the cost analysis should be performed to compare the total cost between different strategies. Various economical factors involved in adding the damper-brace system, including the construction cost of supplemental system, the maintenance money for its operation, and the reduced losses of damped frame under new seismic hazard, need to be considered. It is a task for designers is to seek the optimal safety-cost ratio in seismic design of the structure through an iterative process. Besides, the final cost should also be approved by the owner.

## 4. Damper parameter design

Two types of viscous damper-brace system are commonly used in civil engineering in China, the diagonal brace-damper (Fig. 3), and the chevron brace-damper (Fig. 4). Additional rubber bearings are usually required for the chevron brace-damper system. The beam-column joints that are connected with viscous damper-brace system need to be specially strengthened, especially for earthquake-damaged buildings. In this paper, the steel-enveloped approach is adopted to reinforce these beam-column joints (Weng *et al.* 2012). The steel plates are added throughout the floor slab around the joint.

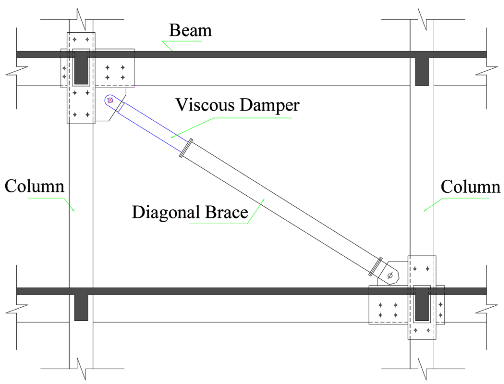



Fig. 3 Diagonal brace-damper

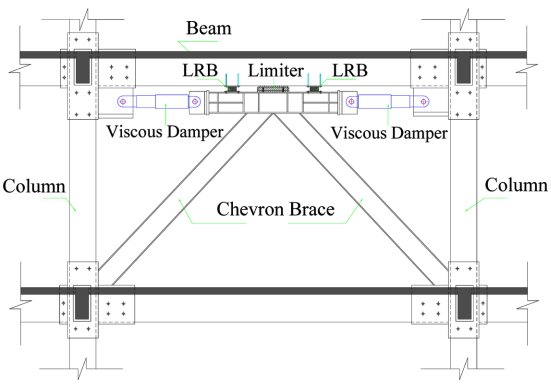



Fig. 4 Chevron brace-damper

### 4.1 Estimate of required equivalent damping ratio

As discussed above, the added stiffness to the frame provided by the viscous damper-brace system is neglected in the preliminary design phase and viscous dampers are designed according to the required equivalent damping ratio. Therefore, a rational estimation of the required damping ratio is crucial for the entire design. In reality, the required damping ratios of the structure along $X$ direction and $Y$ direction are different for the different damping target at these two directions. For RC frame with shearing deformation, the required damping ratio can be estimated based on the energy concept (Uang and Bertero 1988). That is to say, the number of assembling viscous dampers-braces and their design parameters are determined by how much seismic energy need to be absorbed by these additional damper-brace system. Another way to estimate the required equivalent damping ratio is based on the Code Response Spectrum (e.g., GB 50011-2010, PRC Code), as given in Eq. (7)

$$\Delta_{max}/\Delta_T = \alpha_{0.05}/\alpha_{(\zeta_r+0.05)} \tag{7}$$

Where $\Delta_{max}$ is the maximum value of storey drift in the structure obtained under precautionary earthquakes; $\Delta_T$ is the corresponding target value of storey drift; $\zeta_r$ is the required equivalent damping ratio; $\alpha_{0.05}$ is the seismic influence coefficient for the damping ratio of 5%; and $\alpha_{(\zeta_r+0.05)}$ is the seismic influence coefficient for the damping ratio of ($\zeta_r$ + 0.05).

The horizontal seismic influence coefficient $\alpha$, as defined in China's Code for Seismic Design of Buildings (GB 50011-2010, PRC Code), equals to the absolute maximum acceleration of single oscillator $S_a$ divided by the acceleration of gravity $g$, which can be determined by Eq. (8) and shown in Fig. 5.

$$\alpha = \begin{cases} (10T\eta_2 - 4.5T + 0.45)\alpha_{max}, & 0 \le T \le 0.1s \\ \eta_2\alpha_{max}, & 0.1s \le T \le T_g \\ (T_g/T)^{\gamma}\eta_2\alpha_{max}, & T_g \le T \le 5T_g \\ [\eta_2 0.2^{\gamma} - \eta_1(T - 5T_g)]\alpha_{max}, & 5T_g \le T \le 6s \end{cases} \tag{8}$$

where $\alpha_{max}$ is the maximum of seismic influence coefficient; $T$ is the structural natural period; $T_g$ is the design characteristic period of ground motion; $\gamma$ is the attenuation index in the curvilinear decrease section of curve; $\eta_1$ is the modified coefficient of descent slope in the linear decrease section (≥0), $\eta_2$ is the modified coefficient of damping (≥0.55).

$\gamma$, $\eta_1$ and $\eta_2$ are three parameters that can be calculated based on the damping ratio of structure $\zeta$ by following Eq. (9)

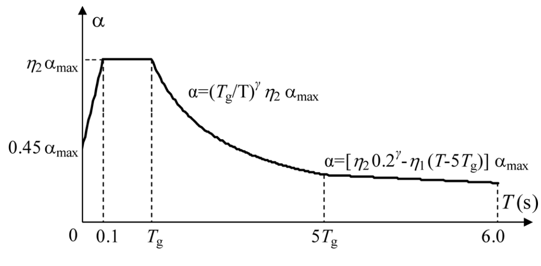



Fig. 5 Seismic influence coefficient curve

$$\gamma = 0.9 + (0.05 - \zeta)/(0.3 + 6\zeta) \tag{9a}$$

$$\eta_1 = 0.02 + (0.05 - \zeta)/(4 + 32\zeta) \tag{9b}$$

$$\eta_2 = 1 + (0.05 - \zeta)/(0.08 + 1.6\zeta) \tag{9c}$$

It should be noted that the final required damping ratio should not exceed 25% in general. If the additional damping ratio requirement goes beyond 25%, it usually means that the bare frame is too weak to be retrofitted to a certain precautionary target. Therefore, the building frame itself needs some additional strengthening.

### 4.2 Calculation of expected damping force

The required damping ratio mentioned in Subsection 4.1 is obtained based on the equivalent Single Degree Of Freedom system analysis. For a multi-storey model, the storey damping force is assumed to be proportionate to the storey shear force and the force is also associated with the required damping ratio. The required storey damping force can then be expressed by Eq. (10)

$$F_{di} = \zeta_r \cdot \beta \cdot Q_{0i} \tag{10}$$

where $F_{di}$ is the required damping force on the $i$th floor; $\beta$ is a scale coefficient, which is a constant and represents the relation between storey damping force and shear force; $Q_{0i}$ is the storey shear force on the $i$th floor of the bare frame, which can be obtained under the designed precautionary intensity.

For Eq. (10), $\beta$ needs be determined firstly for the calculation of the expected damping force. An analytical approach that can be used to estimate the real equivalent viscous damping ratio, $\zeta_a$, for an energy dissipation structures is Eq. (11) (Clough and Penzien 1993)

$$\zeta_a = W_c/(4\pi \cdot W_s) \tag{11}$$

where $W_c$ is the energy dissipated by all added viscous dampers in one cycle at the expected displacement of the structure; $W_s$ is the total strain energy of the energy dissipated structure at the expected displacement.

A preliminary design can then be implemented based on a simplified multi-storey model, where only one equivalent viscous damper is supposed to be installed for each storey. Therefore, energy dissipated by the $i$th viscous damper (i.e., on the $i$th floor) approximately equals to a parallelogram, as shown in Fig. 6; and therefore Eq. (11) can be further expressed as

$$\zeta_a = \frac{W_c}{4\pi \cdot W_s} \approx \frac{4\sum_{i=1}^{N}[F_{di} \cdot (\Delta_{1i} - \Delta_{adi})]}{4\pi\sum_{j=1}^{N}[(Q_{1j} \cdot \Delta_{1j})/2]} = \frac{2\sum_{i=1}^{N}[F_{di} \cdot \Delta_{0i} \cdot (\Delta_{1i}/\Delta_{0i}) \cdot (1 - \Delta_{adi}/\Delta_{1i})]}{\pi\sum_{j=1}^{N}[Q_{0j} \cdot \Delta_{0j} \cdot (Q_{1j}/Q_{0j}) \cdot (\Delta_{1j}/\Delta_{0j})]} \tag{12}$$

where $F_{di}$ is the required damping force on the $i$th floor; $\Delta_{adi}$ is the displacement corresponding to

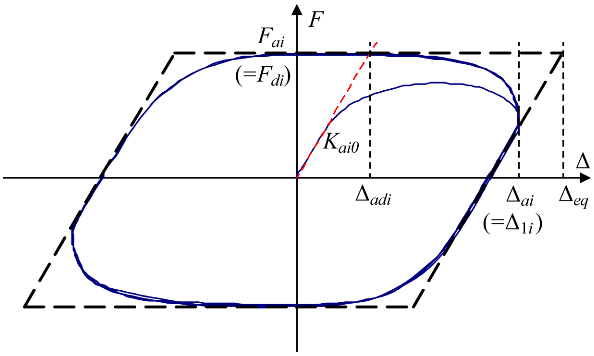



Fig. 6 Hysteretic loops of VDB

$F_{di}$ with the initial composited stiffness of VDB, $K_{aio}$, on the $i$th floor; $\Delta_{1i}$ is the storey drift on the $i$th floor of the damped frame, which equals to the maximum displacement of hysteretic loops of VDB (i.e., $\Delta_{ai}$); $Q_{1j}$ and $Q_{0j}$ are the storey shear force on the $j$th floor of the damped frame and bare frame under the designed precautionary intensity, respectively. $K_{aio}$, as shown in Fig. 6, can be determined for the viscous damper and brace system based on the hysteretic loop.

Substituting Eq. (10) into Eq. (12) gives

$$\zeta_a = \frac{2\zeta_r\beta\sum_{i=1}^{N}[Q_{0i}\cdot\Delta_{0i}\cdot(\Delta_{1i}/\Delta_{0i})\cdot(1-\Delta_{adi}/\Delta_{1i})]}{\pi\sum_{j=1}^{N}[Q_{0j}\cdot\Delta_{0j}\cdot(Q_{1j}/Q_{0j})\cdot(\Delta_{1i}/\Delta_{0i})]} \tag{13}$$

Setting $\phi = \zeta_a/\zeta_r$, $\mu_i = \Delta_{adi}/\Delta_{1i}$, $\lambda_j = Q_{1j}/Q_{0j} \approx \Delta_{1j}/\Delta_{0j}$ in Eq. (13) give

$$\beta = \left[\phi\cdot\pi\sum_{j=1}^{N}\Delta_{0j}\cdot Q_{0j}\cdot\lambda_j^2\right]\Big/\left[2\left(\sum_{i=j_1}^{N_1}\Delta_{0i}\cdot Q_{0i}\cdot(1-\mu_i)\cdot\lambda_i\right)\right] \tag{14}$$

$$\lambda = \begin{cases}(0.6\zeta_r+0.16)/(1.6\zeta_r+0.16), & 0.1s\le T\le T_g\\ (T_g/T)^{[-\zeta_r/(0.6+6\zeta_r)]}\cdot(0.6\zeta_r+0.16)/(1.6\zeta_r+0.16), & T_g\le T\le 5T_g\end{cases} \tag{15}$$

where $\phi$ is the damping safety factor, which is the value to indicate the real equivalent damping ratio versus the required estimated value and is usually set ≥1; $N$ is the total number of floors for calculation; $N_1$ is the total number of floors equipped with viscous dampers; $j_1$ is the initial number of floor equipped with viscous dampers; $\lambda_j$ is the control ratio, which is the ratio of storey drift or storey shear force between the damped structure and the bare structure; $\mu_i$ is a ductility ratio of the damper, reflecting the slope of the equivalent parallelogram, which is the ratio of $\Delta_{adi}$ and $\Delta_{eq}$. In a simplified design, $\lambda$ is assumed to be same for different floors, as expressed in Eq. (15); $\Delta_{eq}$ is replaced by $\Delta_{1i}$, as shown in Fig. 6.

When viscous dampers are installed on every floor of the frame, then $j_1 = 1$, $N_1 = N$, and $\lambda_i = \lambda$, which are substituted into Eq. (14), therefore

$$\beta = \frac{\pi \cdot \phi \cdot \lambda}{2(1-\mu)} \tag{16}$$

When viscous dampers are used to retrofit frames damaged during the 2008 Wenchuan earthquake to increase one seismic precautionary intensity level, $\zeta_r = 0.2$ and $\mu = 0.2$ are usually assumed for the low-period frame (i.e., $0.1 \le T \le T_g$); therefore $\beta \approx 1.15\phi \approx 1.2$ are obtained from Eq. (16), where viscous dampers are installed on every floor of the earthquake-damaged frame.

To achieve a better damping effect, an optimizing coefficient is introduced to modify the designed damping forces of Eq. (10), which can be expressed as

$$F_{(di)m} = \Omega_i \cdot F_{di} \tag{17a}$$

$$\Omega_i = \Delta_{0i} \Bigg/ \left( \sum_{k=j_1}^{N_1} \Delta_{0k} / N_1 \right) \tag{17b}$$

where $F_{(di)m}$ is the modified damping force on the $i$th floor; $\Omega_i$ is the optimizing coefficient on the $i$th floor.

It should be noted that the optimization process of designing damping forces is advisory but not compulsory and the final damping force is usually within the range between the value obtained by Eq. (10) and the one calculated from Eq. (17a) by considering the allowable storey drift. Moreover, a controlling variable $r$ is defined as the final damping force divided by the yield shear force in a certain storey, and the interval of which is recommended as $r \le 0.6$ by Weng and Lu (2004). In summary, the final designed damping forces for the retrofitting frame are virtually determined based on storey shear forces and then optimized based on storey drifts.

### *4.3 Design of brace stiffness and RB*

As to the integrated system, the brace stiffness affects the energy-dissipated capability of viscous dampers (Weng and Lu 2004). In practical damping design, the brace stiffness for each story is usually recommended as

$$K_{bi} \ge (6\pi/T_1) \cdot C_{vi} \quad \text{(Linear VD)} \tag{18a}$$

$$K_{bi} \ge 3K_{ci} = 3F_{(di)m,\max}/u_{(di)m,\max} \quad \text{(Nonlinear VD)} \tag{18b}$$

where $K_{bi}$ is the equivalent horizontal stiffness of the brace used to support the viscous damper on the $i$th floor of the frame structure; $T_1$ is the fundamental vibration period of the damped frame; $C_{vi}$ is the linear damping factor of the linear viscous damper (VD) on the $i$th floor; $K_{ci}$ is the loss stiffness of the nonlinear VD on the $i$th floor; $F_{(di)m,\max}$, $u_{(di)m,\max}$ are the maximum designed damping force and the maximum stroke of the nonlinear VD on the $i$th floor under precautionary earthquake, respectively.

When the chevron brace is used, the rubber bearing (RB) is installed to prevent the out-of-plane instability of the damper-brace system and to improve the seismic performance of damped frame, especially for the structures with inadequate lateral stiffness. The RB is analyzed by using Bouc-Wen plastic model or bilinear model in the design.

### 4.4 Examination of equivalent damping ratio

Since the added viscous dampers are designed based on the estimate of required damping ratio (section 4.1), the real equivalent damping ratio should be examined by comparing it to the pre-estimated damping ratio. For the damped frame structure, when the torsion effect is neglected, the total strain energy and energy dissipated by viscous dampers can be estimated by Eq. (11) and Eq. (12), which can also be further calculated by Eq. (19)

$$W_c = \sum_{i=1}^{N_1} W_{ci} \tag{19a}$$

$$W_{ci} = \sum_{j=1}^{N_{di}} E_{d(ij),\max} = 4\sum_{j=1}^{N_{di}} \psi_{ij} \cdot |F_{d(ij)}(t)|_{\max} \cdot (|\Delta_{a(ij)}(t)|_{\max} - |F_{d(ij)}(t)|_{\max}/K_{a(ij)0}) \tag{19b}$$

$$W_s = \frac{1}{2}\sum_{i=1}^{N} (|Q_{1i}|_{\max} \cdot |\Delta_{1i}|_{\max}), \text{ or } W_s = \frac{1}{2}\sum_{i=1}^{N} (M_i \cdot |\ddot{u}_i(t) + \ddot{u}_g(t)|_{\max} \cdot |u_i(t)|_{\max}) \tag{19c}$$

where $W_{ci}$ is the energy dissipated by viscous dampers on the $i$th floor in one cycle at the expected displacement of the structure; $N_{di}$ is the total number of viscous dampers installed on the $i$th floor; $E_{d(ij),\max}$ is the peak energy dissipated by the $j$th damper on the $i$th floor when moving back and forth in one cycle, like the area of equivalent parallelogram in Fig. 6; $\psi_{ij}$ is an equivalent reduction factor and it is set to embody the error between the parallelogram and the real hysteresis hoops of the $j$th damper on the $i$th floor, which is neglected in Eq. (12); $F_{d(ij)}(t)$, $\Delta_{a(ij)}(t)$ are the damping force and the stroke of the $j$th damper on the $i$th floor at the fixed time $t$, respectively; $K_{a(ij)0}$ is the initial composited stiffness of the $j$th damper on the $i$th floor, similar to $K_{ai0}$ in Fig. 6; $M_i$ is the lumped mass of the $i$th floor; $u_i(t)$ is the displacement of the center of mass on the $i$th floor at the time $t$; $\ddot{u}_i(t)$ is the acceleration of the lumped mass on the $i$th floor at the time $t$; while $\ddot{u}_g(t)$ is the ground acceleration at the time $t$.

## 5. Case study

The engineering case used for this paper is an existing 4-storey RC frame school building in Dujiangyan, China, which was constructed in 2006. As shown in Fig. 7, some beams, columns, beam-column joints, infill walls and staircase of this frame suffered various degrees of damages in the 2008 Wenchuan earthquake. The frame was originally designed based on seismic precautionary intensity 7, which corresponds to the basic ground acceleration of 0.1 $g$ ($g$ is the gravitational acceleration) with the response spectra characteristic period $T_g = 0.35$ s. $T_g$ is the design characteristic period of ground motion determined by the site-class and the design seismic group provided by the Chinese code (reference). However, after Wenchuan earthquake, the local seismic precautionary intensity is increased from intensity 7 to intensity 8 with the corresponding design basic ground acceleration of 0.2 $g$. Moreover, the seismic precautionary classification of the school buildings is improved from the standard precautionary category to the major precautionary category after the Wenchuan earthquake. These means that the new seismic measures should be taken to enhance seismic performances of the local school buildings to meet the intensity 9 requirement set

Table 1 Details of seismic design under intensity 7~9 earthquake

| Structural details \ Precautionary intensity | 7 | 8 | 9 |
|---|---|---|---|
| Grade of frame structures with height not more than 24 *m* | 3-rd | 2-nd | 1-st |
| Length of the densified regions of hoops in the beam end (the greater value /*mm*) | $1.5h_b$, 500 | $1.5h_b$, 500 | $2h_b$, 500 |
| Maximum spacing of hoops in the beam (the smallest value /*mm*) | $h_b/4$, $8d_b$, 150 | $h_b/4$, $8d_b$, 100 | $h_b/4$, $6d_b$, 100 |
| Minimum diameter of hoops in the beam (*mm*) | 8 | 8 | 10 |
| Maximum distance between the crossties in the densified region of hoop at beam end (the greater value) (*mm*) | 250, $20d$ | 250, $20d$ | 200, $20d$ |
| Limit value for the axial-force-ratio of column | 0.9 | 0.85 | 0.75 |
| Minimum total reinforcement ratios of longitudinal bars in columns (%) | 0.7 (Corner 0.8) | 0.8 (Corner 0.9) | 1.0 (Corner 1.1) |
| Maximum spacing of hoops in the column hoop densified regions (the smaller value) (*mm*) | $8d_c$,150 (Bottom 100) | $8d_c$,100 | $6d_c$,100 |
| Minimum diameter of hoops in the column hoop densified regions (*mm*) | 8 | 8 | 10 |
| Maximum distance between the crossties densified region of hoop at the column end (the greater value) (*mm*) | 250, $20d$ | 250, $20d$ | 200 |
| The regions of densified hoops of corner columns | Partial height | Overall height | Overall height |
| Volumetric ratio of spiral reinforcement in the column hoop densified regions (no less than) | 0.4% | 0.6% | 0.8% |
| The hoop characteristic values at the node of the frame (no less than) | 0.08 | 0.10 | 0.12 |
| The hoop volumetric ratio at the node of the frame (no less than) | 0.4% | 0.5% | 0.6% |

Note: $h_b$ is the depth of the beam; $d_b$ is the diameter of longitudinal bars in the beam; $d_c$ is the minimum diameter of the longitudinal bar in the column; $d$ is the corresponding hoop diameter in the beam or column.

by the Chinese code. It is two grades higher than the original precautionary intensity 7 for which the buildings were designed. In this case study, with $T_g$ = 0.4 s, design parameters and seismic performance requirements to meet the new seismic precautionary target are listed in Table 1.

According to the field investigation results, although a few nonstructural components, corner beam column joints, and staircases have suffered serious damages, as plotted in Fig. 7, most structural components only have slight damages. A finite elemental analysis model for the primary frame was established to further investigate structural seismic responses and structural properties as well as the analytical results are listed in Table 2 and Table 3, respectively. It is found that that the existing structure is insufficient to resist the designed precautionary earthquake with the intensity 8. Especially for the ground floor, the storey drifts under frequently-occurred earthquake are greater than the limit value of 1/550 set in Chinese code. Therefore, it is necessary to retrofit this damaged frame for its consequent service.

(a) South elevation of the building (b) Damages on the ground floor (c) Damages of beam-column joint

(d) Damages of stringer and staircase (e) Cracks on the stairway plate (f) Cracks on the infilled wall

Fig. 7 Damages of a framed structure in the Wenchuan earthquake

Table 2 Structural period properties

| Period | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ |
|---|---|---|---|---|---|---|
| (s) | 1.2668 | 1.2580 | 1.1355 | 0.3696 | 0.3548 | 0.3391 |

Table 3 Model information under frequently occurred earthquake of intensity 8 (PGA = 0.2$g$)

| Floor | Height (m) | *X*-direction | | | | *Y*-direction | | |
|---|---|---|---|---|---|---|---|---|
| | | Storey mass (t) | Stiffness (kN/mm) | Shear force (kN) | Rotation (rad) | Stiffness (kN/mm) | Shear force (kN) | Rotation (rad) |
| 4 | 3.6 | 968 | 397 | 1354 | 1/1055 | 333 | 1317 | 1/911 |
| 3 | 3.6 | 969 | 403 | 2148 | 1/676 | 331 | 2061 | 1/578 |
| 2 | 3.6 | 939 | 415 | 2732 | 1/547 | 380 | 2594 | 1/527 |
| 1 | 4.5 | 1219 | 244 | 3307 | 1/487 | 234 | 3126 | 1/444 |

Noted: The ground floor height here is the effective height calculated from the top of ground beam.

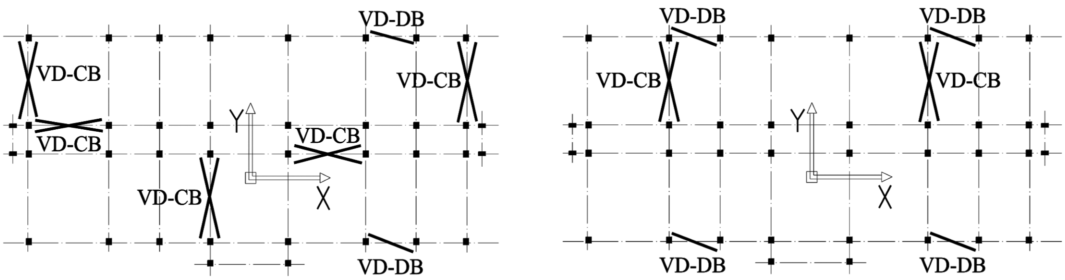
A comprehensive strengthening strategy was adopted for the retrofit of the school building: (1) the damaged beam-column joints were repaired with enveloped steel plates throughout the floor slab around the core area and epoxy resin was injected into cracks (Fig. 8(a)); (2) the damaged staircase (i.e., stairway beams and plates) was repaired by enclosing steel sheet (Fig. 8(b) and Fig. 8(c); (3) the framed structure was strengthened by using supplemental viscous dampers and braces (Fig. 9). This project is used to demonstrate the feasibility and reliability of the aforementioned simplified design procedure for seismic retrofit of earthquake-damaged frame with viscous dampers. Here the

(a) Strengthening beam column joint (b) Strengthening stairway beam (c) Strengthening stairway plate

Fig. 8 Seismic repair of the damaged structural components


(a) Viscous dampers with chevron brace (b) Connecting part of diagonal brace (c) Reinforced joint related to brace

Fig. 9 Seismic retrofit by using viscous dampers and braces




(a) Location of viscous damper-brace on the 1st floor (b) Location of viscous damper-brace on the 2nd floor

Fig. 10 Location of viscous dampers with different braces categories

required additional damping ratio was first estimated to be approximately 20% according to Eq. (7) and Table 2. With seismic response requirements listed in Table 3, the added viscous dampers were installed only on the first and second floor. The expected damping forces were determined by Eq. (10) and Eq. (17), and 20 viscous dampers with diagonal brace or chevron brace were installed based on the architectural function. The layout of installed damper-brace systems are shown in Fig. 10 and Table 4, where "VD-DB" is the viscous damper with diagonal brace and "VD-CB" is the viscous damper with chevron brace.

Table 4 shows the final horizontal damping forces provided by viscous dampers-braces (VDB) in the first and second floor. With above designed damping forces, three different VDB categories ($\boldsymbol{A}$, $\boldsymbol{B}_1$, $\boldsymbol{B}_2$) are used in this engineering case, they are of different brace type, but with the same design

Table 4 Information of supplemental viscous dampers-braces (VDB)

| Floor | H | *X*-direction | | | | *Y*-direction | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Expected horizontal force (kN) | | | VDB | Expected horizontal force (kN) | | | VDB |
| | ($m$) | Calculated value | Optimal value | Actual value | (N×Category) | Calculated value | Optimal value | Actual value | (N×Category) |
| 2 | 3.6 | 1782 | 1166 | 1200 | 4×$\boldsymbol{B_2}$ | 2302 | 1449 | 2000 | 4×$\boldsymbol{A}$ |
| 1 | 4.5 | 2158 | 2904 | 2500 | 4×$\boldsymbol{A}$+2×$\boldsymbol{B_1}$ | 2774 | 3801 | 3000 | 6×$\boldsymbol{A}$ |

Noted: 1. VDB category $\boldsymbol{A}$ is VD-CB, VDB category $\boldsymbol{B_1}$ and $\boldsymbol{B_2}$ are VD-DB with installed angle of 45° on the 1st floor and with installed angle of 39° on the 2nd floor, respectively.

Table 5 Examination of the controlling variable under rarely occurred earthquake

| Floor | *X*-direction | | | *Y*-direction | | |
|---|---|---|---|---|---|---|
| 1 | $F_{di,\max}$ (kN) | $Q_{yi}$ (kN) | $r_i$ | $F_{di,\max}$ (kN) | $Q_{yi}$ (kN) | $r_i$ |
| 1 | 1680 | 6858 | 0.245 | 2800 | 6549 | 0.428 |
| 2 | 3500 | 8421 | 0.416 | 4200 | 8270 | 0.508 |

Noted: $F_{di,\max}$, $Q_{yi}$ and $r_i$ is the maximum damping force, the yield shearing force of the main frame and the controlling variable on the *i*th floor, respectively; where $r_i$ is defined as $r_i = F_{di,\max} / Q_{yi}$.

mechanics properties of the viscous dampers, which is $\alpha = 0.2$, and $C_v = 250$ kN/(mm/s)$^\alpha$, where $\alpha$ is the velocity exponent and $C_v$ is the damping coefficient. This kind of viscous damper is designed to provide approximately 500 kN damping force according to retrofit demand under precautionary earthquake. However, once the main frame goes into inelastic state in rarely occurred earthquake, the maximum damping force of each viscous damper will reach 700 *kN*. Thus the controlling variables mentioned in Section 4.2 should be examined in this case, all of which are verified to be smaller than the limit of 0.6, as shown in Table 5.

To improve the preliminary design of the viscous damper-brace system, the time-history analysis method was implemented with three earthquake records (Fig. 11), including the N21E components of the Taft accelerogram (Taft N21E), the earthquake records from the 1979 Imperial Valley-06 earthquake event (IMPVALL), and the 1989 Loma Prieta earthquake event (LOMAP). Different PGA values under the earthquake of intensity 8, 70 cm/s$^2$ for the frequently occurred earthquake, 200 cm/s$^2$ for the precautionary earthquake, and 400 cm/s$^2$ for the rarely occurred earthquake, were designed for the excitation inputs during the time-history analysis. Considering the extra stiffness provided by non-structural components, the PGAs of the frequently occurred earthquake and the precautionary earthquake were multiplied by a coefficient of 1.22.

Structural responses of the bare frame (ST0) and the damped frame (ST1) were obtained and compared. The storey drift and shear force results of ST0 and ST1 under frequently occurred earthquake, precautionary earthquake, and rarely occurred earthquake are shown in Fig. 12 and Fig. 13. Please note that the storey shear forces were obtained from section cut forces of frame columns without the viscous damper-brace system.

From Fig. 12 and Fig. 13, it is obvious that ST1 has excellent structural performances by showing a nearly uniform distribution of storey drift rotations and storey shear forces. Compared to ST0,

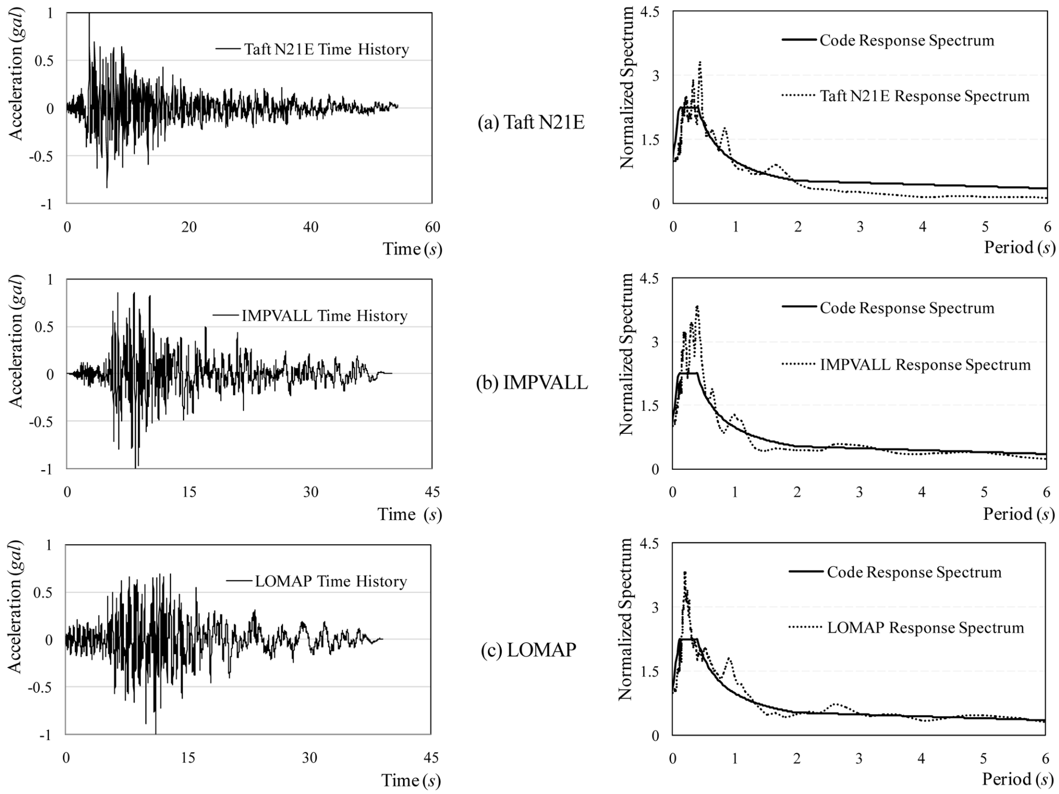



Fig. 11 Normalized time-history curves and response spectra

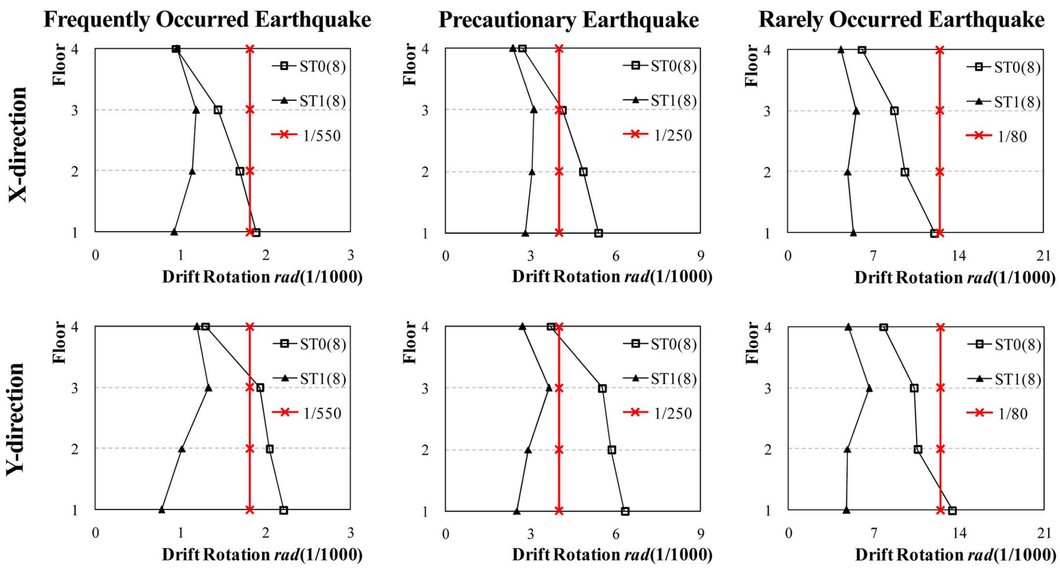



Fig. 12 Comparison of the control storey drifts

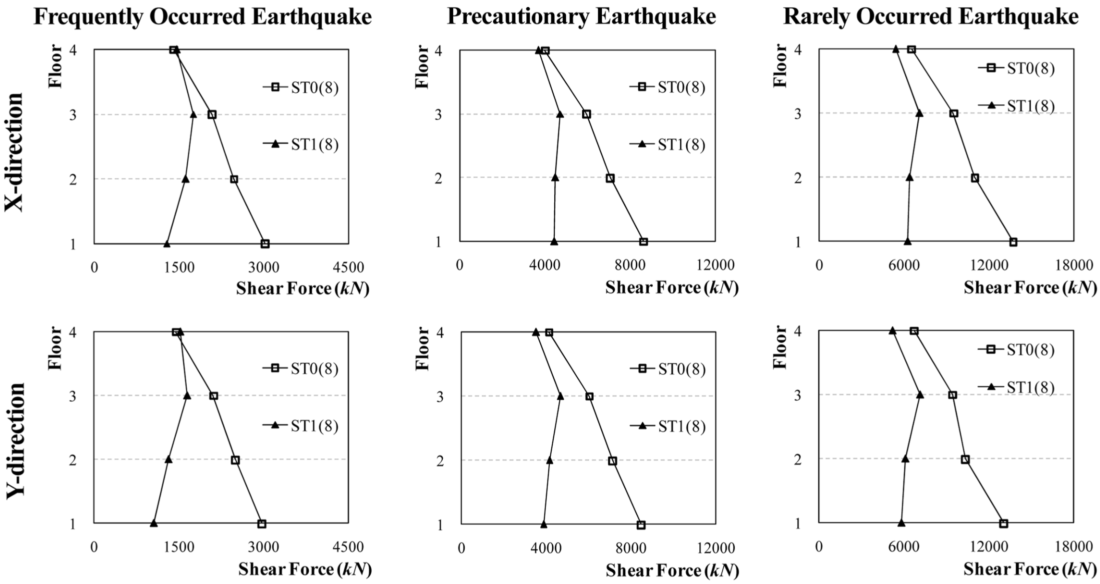



Fig. 13 Comparison of the control storey shear forces

Table 6 Result comparison of the push-over analysis of ST0 and ST1 under the intensity 8 earthquake

| Seismic action direction | ST0 | | | ST1 | | | Comparison | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base shear $Q_0$ (kN) | Drift rotation $\theta_0$ (rad) | Vertex displacement $\Delta_0$ (mm) | Base shear $Q_1$ (kN) | Drift rotation $\theta_1$ (rad) | Vertex displacement $\Delta_1$ (mm) | $\frac{Q_1-Q_0}{Q_0}$ | $\frac{\theta_1-\theta_0}{\theta_0}$ | $\frac{\Delta_1-\Delta_0}{\Delta_0}$ |
| *X*-dir. | 9725 | 1/83 | 153.6 | 8609 | 1/110 | 122.6 | -11.48% | -24.55% | -20.18% |
| *Y*-dir. | 9762 | 1/88 | 161.2 | 8566 | 1/117 | 127.9 | -12.25% | -24.79% | -20.66% |

Noted: The elastic-plastic analysis was conducted based on the Chinese design response spectrum (GB 50011-2010, PRC Code)

ST1 shows a remarkable improvement for seismic performances of the weak ground floor, which means that the viscous dampers were well designed to enhance seismic behaviors of a non-ductile structure. The viscous dampers were only installed on the first and second floors in this project for fast construction and reducing cost. Therefore, the seismic responses of the upper two floors are of little change, which, however, remains within their seismic capacities.

Based on Eq. (11) and Eq. (19), the average equivalent damping ratios of the damped frame (ST1) under the frequently occurred earthquake, the precautionary earthquake, and the rarely occurred earthquake were calculated to be about 32%, 23% and 17%, respectively, which are close to the initial estimated value of required equivalent damping ratio under precautionary earthquake.

To further verify the simplified design procedure, the elastoplastic push-over analysis of the damped frame (ST1) and the bare frame (ST0) were performed and the comparative results are listed in Table 6. It can be seen that: (1) the base shear force of ST1 is reduced by about 11% than that of ST0; (2) the storey drift rotation of ST1 is about 24% smaller than that of ST0; and (3) the

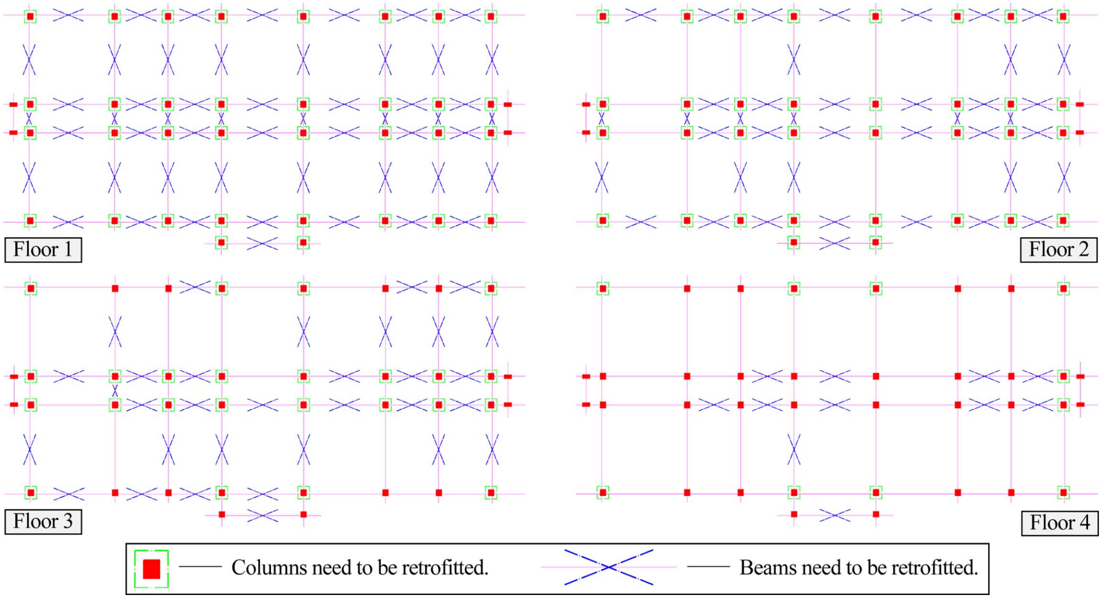



Fig. 14 Columns and beams need to be retrofitted in ECS strategy

vertex displacement is reduced by about 20%. Seismic design details of the damped frame are also verified according to the Chinese code (GB 50011-2010, PRC Code).

A comprehensive cost analysis was conducted by comparing the costs of three retrofit strategies: enlarging concrete section (ECS), installing buckling-restrained braces (BRB), or using the viscous damper-brace system (VDB). For the ECS method, under the new precautionary earthquake, the intensity 8 earthquake, almost all beams and columns need to be strengthened (Fig. 14), which leads to an extensive destruction of existing structural decorations and probably a retrofitting of foundations. For the BRB strategy, since the added stiffness from the BRB is relatively large, the adjacent columns and foundation need to be additionally reinforced. For the VDB strategy, as mentioned before, the storey drifts and shear forces can be simultaneously reduced; and therefore less reinforcement measures are required. The constructing cost of ECS, BRB, and VDB strategies are about 1.45 million RMB, 1.1 million RMB, and 1.25 million RMB, respectively. However, if demolishment cost for structural decorations is considered, the comprehensive cost of ECS, BRB, and VDB strategies are about 2.4 million RMB, 1.55 million RMB, 1.6 million RMB, respectively, based on the price level in China in 2009 (Zeng 2010). Besides, considering the limitation of construction period for school buildings, VDB strategy is more preferable and was finally adopted by the school administration.

## 6. Conclusions

In this paper, a simplified design procedure is proposed for seismic retrofit of earthquake-damaged frames with viscous dampers. Several key design steps were elaborated, including the estimation of the required equivalent damping ratio, the calculation of the expected damping force, the design modification the damping effect analysis, structural safety evaluation, and a comprehensive cost analysis. Following this simplified design procedure, viscous damping forces are first determined by storey shear forces and they are consequently optimized by storey drifts.

A case study was presented to demonstrate the effectiveness of the simplified design procedure. The results show that this simplified design procedure increase the design efficiency by reducing complex iterative computational analysis and yet with an enough accuracy for a practical design. Since the required damping ratio can be flexibly adjusted in a large range (i.e., 0~25%), though designing configuring viscous dampers, this simplified design method can not only meet current Chinese design codes but also satisfy different demands proposed by owners.

The simplified method proposed in this paper is not only developed for the retrofit design of earthquake-damaged frame structures with viscous dampers, but also for the damping design of new building or existing buildings. To be specific, it can be used to improve structural dynamic behaviors of a building structure by modifying its damping.

## Acknowledgements

The authors wish to gratefully acknowledge the generous support of this work by the National Key Technology R&D Program of China under Grant No. 2009BAJ28B02, the Key Consulting & Research Project of Chinese of Academy Engineering under Grant No. 2010-ZD-4, and the fund from Science and Technology Commission of Shanghai Municipality under Grant No. 10DZ2252000.

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