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A methodology for design of metallic dampers in retrofit of earthquake-damaged frame

Chao Zhang[*1,2], Yun Zhou[2a], Da G. Weng[3b], De H. Lu[2c] and Cong X. Wu[2d]

[1]*Postdoctoral Research Station of Civil Engineering, Guangzhou University, Guangzhou, China*
[2]*College of Civil Engineering, Guangzhou University, Guangzhou, China*
[3]*State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*

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Abstract. A comprehensive methodology is proposed for design of metallic dampers in seismic retrofit of earthquake-damaged frame structures. It is assumed that the metallic dampers remain elastic and only provide stiffness during frequent earthquake (i.e., earthquake with a 63% probability of exceedance in 50-year service period), while in precautionary earthquake (i.e., earthquake with a 10% probability of exceedance in 50-year service period), the metallic dampers yield before the main frame and dissipate most of the seismic energy to either prevent or minimize structural damages. Therefore by converting multi-story frame to an equivalent single-degree-of-freedom system, the added stiffness provided by metallic dampers is designed to control elastic story drifts within code-based demand under frequent earthquake, and the added damping with the combination of added stiffness influences is obtained to control structural stress within performance-based target under precautionary earthquake. With the equivalent added damping ratio, the expected damping forces provided by metallic dampers can be calculated to carry out the configuration and design of metallic dampers along with supporting braces. Based on a detailed example for retrofit of an earthquake-damaged reinforced concrete frame by using metallic dampers, the proposed design procedure is demonstrated to be simple and practical, which can not only meet current China's design codes but also be used in retrofit design of earthquake-damaged frame with metallic damper for reaching desirable performance objective.

Keywords: metallic damper; seismic retrofit; earthquake-damaged frame; energy; equivalent damping ratio

1. Introduction

With the greater comprehension of actual poor buildings performances in recent earthquakes, the knowledge of seismic buildings behavior has been renewed, and therefore retrofit of earthquake-damaged or existing poor buildings becomes a paramount task in reducing seismic

∗Corresponding author, Ph. D., E-mail: superzh2013@163.com
[a]Professor, E-mail: zhydxs@163.com
[b]Professor, E-mail: wdg@tongji.edu.cn
[c]Ph. D. Student, E-mail: ludehui87@gmail.com
[d]Ph. D., E-mail: wu-congxiao@163.com

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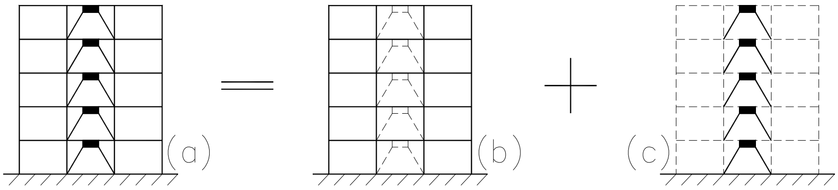
risk. Passive energy dissipation systems are now widely recognized as effective retrofit solutions to improve seismic performance of building structures by absorbing or consuming a portion of input seismic energy, and to reduce energy dissipation demand on original structural members, along with the potential of structural damages. Since Wenchuan earthquake occurred in 2008, passive energy dissipation technologies have been increasingly taken into consideration in China. Mechanisms proposed and used for energy dissipation include metal yielding, friction sliding, fluid orificing, and deformation of viscoelastic solids or liquids, etc. Among them, yielding of metals is one of the most common mechanisms. Actually, the idea of utilizing separate metallic dampers into an earthquake-resistant structure began with the conceptual and experimental work of Kelly *et al*. (1972). During the ensuing years, considerable progress has been made in researches and developments of metallic dampers (Skinner *et al*. 1975, Tyler 1983, Whittaker *et al*. 1991, Tsai *et al*. 1993, 1995, Dargush and Soong 1995, 1997, Zhou and Liu 1996, Ou and Wu 1997, Wada *et al*. 2000, Kim and Seo 2003, Curadelli and Riera 2004, Kasai and Kibayashi 2004, Li *et al*. 2007), and numerous metallic dampers with different yielding schemes have been developed, examples include shear panel dampers, flexural plate systems, torsional bar dampers, yield ring dampers, and extrusion devices, etc. Over the past few decades, metallic dampers have been increasingly used in retrofit of existing buildings for its advantages of simple construction, convenient installation, low cost and stable performance. Some typical retrofitting projects equipped with metallic dampers include: Izazaga #38-40 building and Cardiology Hospital building (Mexico), Wells Fargo Bank building and King County Courthouse building (USA), office building of Takenake Corporation (Japan), Taibei Linya Elementary School building and office building of Dujiangyan Gas Corporation (China), etc. With a lot of common practice, performance-based seismic design method is deemed as an available and generally acceptable approach to design of metallic dampers in damped structures, and varying design procedures have been proposed based on different performance indicators, such as displacement-based method (Lin *et al*. 2003, Li *et al*. 2007), capacity spectrum method (Zhang *et al*. 2006, Li and Liang 2007), hysteretic energy spectrum method (Choi and Kim 2006), linearization techniques (Parulekar *et al*. 2009), reliability-based method (Jensen and Sepulveda 2012), energy-based method (Benavent-Climent 2011, Habibi *et al*. 2013), etc. Many of these research results are included in current design codes, like FEMA 356, ASCE 7-05, JSSI Manual (i.e., Japan Society of Seismic Isolation Manual: *Design and construction manual for passively controlled buildings*), GB 50011-2010 (i.e., China's *Code for seismic design of buildings*), and JGJ 297-2013 (i.e., China's *Technical specification for seismic energy dissipation of buildings*), etc. The design specifications for energy-dissipated buildings in above design codes involve mechanical model of dampers, analysis method for structural system's dynamic response, performance requirements of dampers, and design principle for damped structures. However, there are still in need of improved rules for design of damped structure with metallic dampers, especially for damping retrofit of earthquake-damaged structures, design rules for added metallic dampers are still missing. Besides, metallic dampers can provide both added damping and added stiffness to the structure, in which added damping is designed to dissipate most of the input seismic energy, and therefore it can minimize either the structural stress or deflection simultaneously; while added stiffness to the structure reduce its natural period, which can control the maximum displacement but amplify the earthquake force on the structure. Thus, the above two variables provided by metallic dampers both have great effects on structural performances, which result in a more complex design procedure compared to the damped structures equipped with viscous dampers.

In this literature, added damping and added stiffness provided by metallic dampers have been



(a) Damped Frame Model, (b) Main Frame Model, and (c) Metallic dampers Model

Fig. 1 Analytical model of a damped frame structure with metallic dampers

analyzed based on their mechanical properties, and their effects on actual performances of energy dissipation systems have been quantified. The study has been conducted on retrofit of earthquake-damaged structures by using metallic dampers, and a comprehensive methodology, to be more conform to Chinese seismic design codes, has been proposed for common engineering practice.

2. Analytical model and design criteria

Prior to seismic retrofit of earthquake-damaged buildings, seismic appraisal needs to be conducted firstly, and any repair work shall be included in assessment. A finite element model of the pre-retrofit frame is established to estimate its current seismic performance. Moreover, metallic dampers used in seismic retrofit are actually a later-added system to the existing frame structure, thus design of supplemental metallic dampers can be conducted separately with the original frame. Based on this philosophy, analytical model of the damped frame can be equivalently divided into the modified main frame model and the metallic dampers-braces system model, as shown in Fig. 1.

Usually, seismic design of multi-storey frames is conducted under the assumptions of rigid diaphragm, lumped mass matrix and classical damping theory (Lomiento *et al*. 2010). The dynamic characteristic of frames is formulated for structure discretized with a finite number of degrees of freedom and defined in term of generalized displacements of the nodes. The equation of the motion for a generic elastic frame structure without dampers could 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, damping and stiffness matrices of the bare frame without dampers, respectively; $u(t)$, $\dot{u}(t)$, $\ddot{u}(t)$ are displacement vector, velocity vector, acceleration vector relative to the ground, respectively; and $\ddot{u}_g(t)$ is the ground acceleration vector.

Generally, supplemental metallic dampers (with supporting braces) provide an additional source of added mass, added stiffness and added damping to the original structure. However, the added mass of metallic dampers is far less than the total mass of a building and usually neglected in practical design, thereby the effects of metallic dampers on the structure can be approximately simplified to a comprehensive force provided by the added damping and the added stiffness. Pursuant to this, for such systems composed by frame and metallic dampers the equation of motion can be expressed as Eq. (2)

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

where $[C_a]$, and $[K_a]$ are the added damping and added stiffness matrices provided by supplemental metallic dampers, respectively.

According to Eq. (1) and Eq. (2), [C_a] and [K_a] are two key design variables in retrofit of existing frames equipped with metallic dampers, where the difficulty is how to determine these two variables with the consideration of their interaction, along with their influences on structural performance. Commonly, compared to traditional structures, energy dissipation structures shall be designed to acquire a better seismic performance with the higher design objective. For instance, structures incorporate buckling restrain braces (BRBs) are deemed to possess the earthquake design criteria as follows (Gao *et al* 2010): (a) the structure and BRBs are all in elastic range under minor but frequent shaking, (b) the main structure remains elastic while BRBs yield to dissipate seismic energy under moderate but occasional shaking, and (c) collapse prevention is at least strictly necessary under strong but rare shaking. In this case, BRBs are expected to provide added stiffness only during their initial elastic response under frequent earthquake (i.e., earthquakes with 63% probability of exceedance in 50-year service period), and subsequently, as BRBs yield under precautionary earthquake or rare earthquake (i.e., earthquakes with a 10% probability of exceedance in 50-year service period, or earthquakes with 2%~3% probability of exceedance in 50-year service period), the stiffness reduces and energy dissipation occurs due to their inelastic hysteretic responses. Metallic damper, especially for that with relatively large yield displacement, performs similarly with BRB in the earthquake. Thus design of structure incorporate such metallic dampers can be conducted based on similar design criteria; that is, metallic dampers, added in the existing structure, can be designed to behave linearly or to have very limited nonlinear behavior under frequent earthquake, and yield before the main structural members to dissipate most of seismic energy under precautionary earthquake.

3. Simplified design process

Based on the aforementioned design criteria, it is supposed that metallic damper only provides added stiffness (i.e., neglecting its added damping and added mass) under frequent earthquake and then contributes added damping and added stiffness under precautionary earthquake. Pursuant to this, a simplified design methodology is proposed for design of metallic dampers in retrofit of earthquake-damaged structures, as shown in Fig. 2.

The main steps for this simplified methodology and design process include: (a) setting precautionary target for retrofit of post-earthquake structure, (b) finite element analysis of the pre-retrofit frame structure, (c) assessing its reparability in light of design codes and owner's requirements, (d) setting structural performance level for damping retrofit, (e) configuration and design of metallic dampers, (f) verifying the damping effect of post-retrofit frame structure, (g) evaluating seismic safety of the main frame and supplemental dampers, and (h) conducting comprehensive cost analysis towards this retrofit strategy. Among above design steps, configuration and design of metallic dampers is the most important part in this simplified design methodology.

As different with viscous dampers, metallic dampers can not only provide added damping, but also add relatively large stiffness to the main structure. Thus design of metallic dampers in retrofitting structures is much more complicated, and needs repeated iterations. To simplify this design process, a philosophy of "added stiffness-based design under frequent earthquake and added damping-based design under precautionary earthquake" is proposed for configuration and design of metallic dampers in retrofitted frame. The specific design approach is concluded as

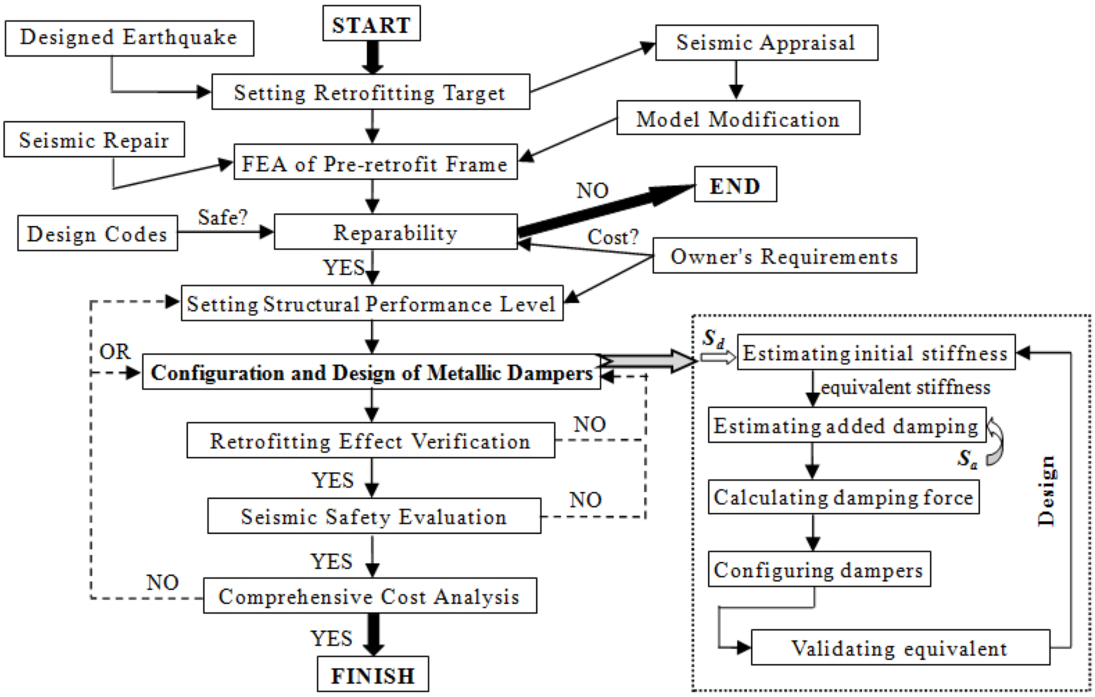


Fig. 2 Process of the simplified design methodology

follows: firstly, with certain displacement demand under frequent earthquake, the required initial stiffness of supplemental metallic dampers can be estimated through displacement response spectrum, and its equivalent stiffness under precautionary earthquake can also be calculated based on preset displacement ductility and post yield stiffness ratio; likewise, with certain shear force demand under precautionary earthquake, the required damping ratio provided by added metallic dampers can be also estimated in light of the equivalent stiffness through acceleration response spectrum; and then the designed damping forces along different storey can be calculated according to aforementioned required damping ratio, while the displacement ductility is also checked or adjusted by preset value; with designed damping force, the amount of installed metallic damper and its design parameters including initial stiffness, post yield stiffness ratio, yield deformation, and brace stiffness, etc, can be determined; in the end, the practical equivalent damping ratio provided by installed metallic dampers shall be checked by comparing with the estimated value, and if it is unsatisfactory, back to reset the added damping ratio and make design iteration.

4. Formulation of the methodology

In practice, metallic dampers are usually incorporated into a building through chevron braces, as shown in Fig. 3(a). Herein the braces are expected to keep in elastic phase, so that structural deformations are mainly concentrated on metallic dampers. The commonly-used hysteretic models, employed to describe the relationship between force and deformation of metallic damper, include idealized elastic-plastic model, bilinear hysteretic model, Ramberg-Osgood model, Bouc-

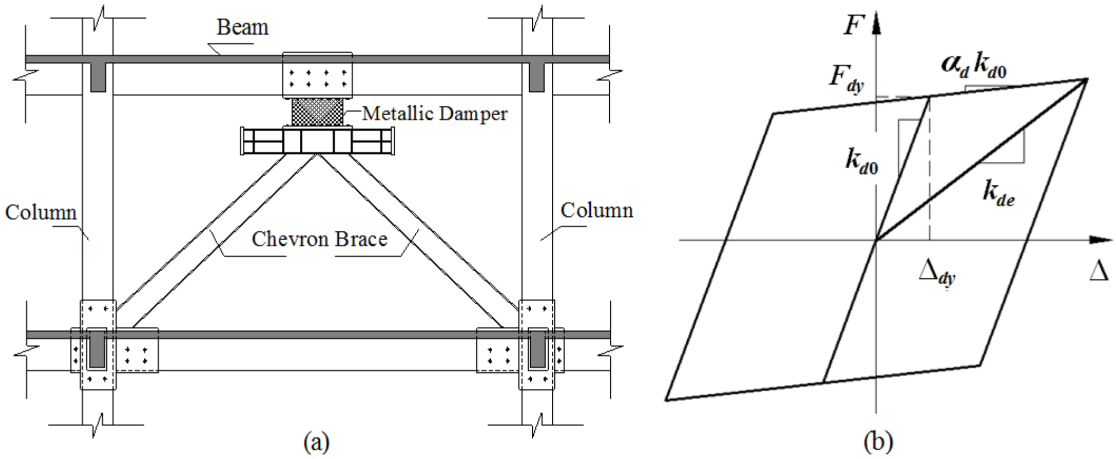


Fig. 3 Metallic damper with chevron brace, (a) typical configuration, (b) bilinear hysteretic model

Wen model, etc. For instance, the bilinear hysteretic model that can be used to identify the parameters involved in design of metallic damper is shown in Fig. 3(b), where k_{d0}, F_{dy}, α_d, and Δ_{dy}, are the initial stiffness, yield strength, post yield stiffness ratio, and yield deformation of the metallic damper, respectively. Thus, for damper i in one cycle of reciprocating movement, its dissipated energy E_{di}, equivalent stiffness k_{dei}, and equivalent damping ratio ξ_{ddi}, can be expressed as

$$E_{di} = 4k_{d0i} \cdot \Delta_{dyi}^2 \cdot (1-\alpha_{di})(\mu_{di}-1) \tag{3a}$$

$$k_{dei} = k_{d0i}\left(1+\alpha_{di} \cdot \mu_{di} - \alpha_{di}\right)/\mu_{di} \tag{3b}$$

$$\xi_{ddi} = \frac{E_{di}}{4\pi \cdot E_{pdi}} = \frac{E_{di}}{2\pi \cdot k_{dei} \cdot \Delta_{di}^2} = \frac{2(1-\alpha_{di})(\mu_{di}-1)}{\pi \cdot \mu_{di} \cdot (1+\alpha_{di}\mu_{di}-\alpha_{di})} \tag{3c}$$

where k_{d0i}, Δ_{dyi}, Δ_{di}, α_{di}, μ_{di}, and E_{pdi}, are the initial stiffness, yield deformation, maximum deformation, post yield stiffness ratio, displacement ductility, and strain energy of damper i, respectively.

From Eqs. (3a), (3b), (3c), it can be concluded that with certain initial stiffness, the equivalent stiffness and damping ratio of metallic damper closely depend on its post yield stiffness ratio and displacement ductility. However, the post yield stiffness ratio varies from different metal materials, but usually it is set to a very small value (e.g., α_{di}=0.02 for mild steel). Thus the equivalent stiffness and damping ratio of damper itself only rest with its displacement ductility μ_{di} (i.e., $\mu_{di}=\Delta_{di}/\Delta_{dyi}$).

4.1 Estimate of required initial stiffness

For a multi-storey frame, firstly it shall be transformed into an equivalent single-degree-of-freedom (SDOF) system based on equal fundamental period and elastic damping ratio, and then the equivalent displacement u_{eff}, equivalent mass M_{eff}, and equivalent stiffness K_{eff} of SDOF system can be derived. Supposed that metallic dampers only provide added stiffness under frequent earthquake, the period of retrofitted structure with giving elastic displacement demand can be determined by Eq. (4a), and subsequently the required initial stiffness K_{d0} for retrofit can be obtained, as expressed in Eq. (4b)

$$\lambda_u = u_t / u_{eff} = S_d\left(T, \zeta_0\right) / S_d\left(T_0, \zeta_0\right) \tag{4a}$$

$$K_{d0} = \left[\left(T_0/T\right)^2 - 1\right] \cdot K_{eff} \tag{4b}$$

where λ_u is the target displacement ratio; S_d is displacement response spectrum; T_0 and ζ_0 are the fundamental period and elastic damping ratio of pre-retrofit structure, respectively; T and u_t are the period and target displacement of retrofitted structure with metallic dampers (i.e., under frequent earthquake), respectively.

4.2 Estimate of required added damping ratio

As the installed metallic dampers yield under precautionary earthquake, their added stiffness to the structure reduce and can be represented by an equivalent stiffness K_{de}, which can be obtained from Eq. (3b) with giving K_{d0}, α_d, and μ_d. Substituting K_{de} into Eq. (4b) get the effective period T_1 of the retrofitted structure with metallic dampers under precautionary earthquake. Likewise, based on target storey shear force ratio λ_Q, acceleration response spectrum S_a, and aforementioned T_1, the required added damping ratio ζ_r for the retrofitted structure can be estimated by Eq. (5)

$$\lambda_Q = Q_1 / Q_0 = S_a\left(T_1, \zeta_0 + \zeta_r\right) / S_a\left(T_0, \zeta_0\right) = \alpha\left(T_1, \zeta_0 + \zeta_r\right) / \alpha\left(T_0, \zeta_0\right) \tag{5}$$

where Q_0 and Q_1 are storey shear force of pre-retrofit structure and target storey shear force of retrofitted structure under precautionary earthquake, respectively; α is the horizontal seismic influence coefficient.

As defined in GB 50011-2010, the horizontal seismic influence coefficient α equals to the absolute maximum acceleration of single oscillator S_a divided by the acceleration of gravity g, which can be determined by Eq. (6) and shown in Fig. 4.

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

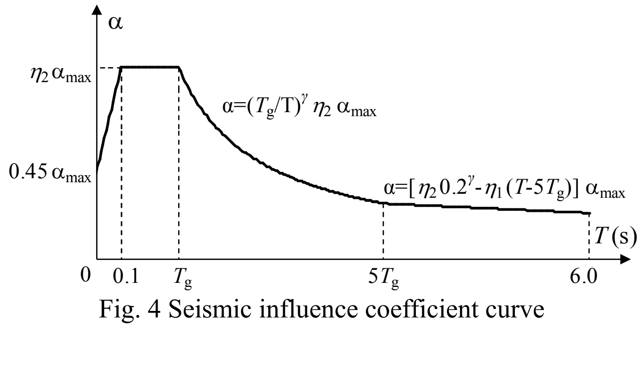


Fig. 4 Seismic influence coefficient curve

where $\alpha_{\max}$ is the maximum value of seismic influence coefficient; T is the structural natural period; T_g is the design characteristic period of ground motion; γ is the attenuation index in the curvilinear decrease section of curve; η_1 is the modified coefficient of descent slope in the linear decrease section ($\eta_1 \geq 0$), η_2 is the modified coefficient of damping ($\eta_2 \geq 0.55$).

γ, η_1 and η_2 are three parameters that can be calculated based on the damping ratio of structure ζ by following Eq. (7),

$$\gamma = 0.9 + (0.05 - \zeta)/(0.3 + 6\zeta) \tag{7a}$$

$$\eta_1 = 0.02 + (0.05 - \zeta)/(4 + 32\zeta) \tag{7b}$$

$$\eta_2 = 1 + (0.05 - \zeta)/(0.08 + 1.6\zeta) \tag{7c}$$

It is also noted that the final required damping ratio shall not exceed 25% in general. If the additional damping ratio requirement goes beyond 25%, it means that the bare frame is too weak to be retrofitted to new precautionary target, and in this case the building frame itself usually needs some additional strengthening.

4.3 Calculation of designed damping force

According to JSSI Manual and JGJ 297-2013, a rational design for structure equipped with displacement-dependent dampers is trying to make the equivalent stiffness of added dampers (and necessary supporting braces) proportionate to structural stiffness along vertical storey, and the added damping force of each storey is also designed in proportion to structural yield shearing force. Pursuant to this, the designed damping force associated with storey shear force and yield damping force can be expressed as

$$F_{di} = \zeta_r \cdot \beta \cdot Q_{0i} \tag{8a}$$

$$F_{dyi} = F_{di} / (1 + \mu_{di}\alpha_{di} - \alpha_{di}) \tag{8b}$$

where F_{di} and F_{dyi} are the designed damping force and yield damping force on the i^{th} floor, respectively; β is a scale coefficient, which is a constant and depicts the relation between storey damping force and shearing force; Q_{0i} is the storey shear force on the i^{th} floor of the pre-retrofit frame under precautionary earthquake.

As to damping design of multi-degree-of-freedom system, the added metallic dampers on each storey (to one direction) can be totally equaled to one damper per storey, and therefore the equivalent added damping ratio provided by all metallic dampers to the structure can be calculated as (Clough and Penzien 1993)

$$\zeta_a = \frac{W_c}{4\pi \cdot W_s} \approx \frac{4\sum_{i=j_1}^{N_1}\left[(1-\alpha_{di})(1-1/\mu_{di}) \cdot F_{dyi} \cdot \Delta_{di}\right]}{4\pi \cdot \left(\sum_{j=1}^{N}\left[(Q_{1j} \cdot \Delta_{1j})/2\right] + \sum_{i=j_1}^{N_1}\left[(F_{di} \cdot \Delta_{di})/2\right]\right)} \tag{9}$$

where W_c is the energy dissipated by all added metallic dampers in one cycle of reciprocating movement, W_s is the total strain energy of the energy-dissipated structure at the expected displacement; Q_{1j} and Δ_{1j} are the storey shear force and storey drift on the j^{th} floor of retrofitted structure under precautionary earthquake, respectively; N is the total number of floors for calculation; N_1 is the total number of floors equipped with metallic dampers; j_1 is the initial number of floor equipped with metallic dampers.

Supposed that metallic dampers are all installed in horizontal direction and lateral deformation of supporting braces is neglected, thus the storey drift concentrates on metallic damper only (i.e. $\Delta_{di}=\Delta_{1i}$). In this case, substituting Eqs. (8a, 8b) into Eq. (9), and setting $\phi=\zeta_a/\zeta_r$, $\lambda_{Qj}=Q_{1j}/Q_{0j}$, $\lambda_{uj}=\Delta_{1i}/\Delta_{0i}$ gives

$$\beta=\frac{\phi\cdot\pi\cdot\sum_{j=1}^{N}\left(Q_{0j}\cdot\Delta_{0j}\cdot\lambda_{Qj}\cdot\lambda_{uj}\right)}{2\sum_{i=j_1}^{N_1}\left[\frac{(1-\alpha_{di})(1-1/\mu_{di})}{1+\alpha_{di}\cdot\mu_{di}-\alpha_{di}}\cdot Q_{0j}\cdot\Delta_{0j}\cdot\lambda_{uj}\right]-\phi\cdot\zeta_r\cdot\pi\cdot\sum_{i=j_1}^{N_1}\left(Q_{0j}\cdot\Delta_{0j}\cdot\lambda_{uj}\right)} \tag{10}$$

where ϕ is the damping safety factor (i.e., usually set $\phi\geq1$); λ_{Qj} and λ_{uj} are target storey shear force ratio and target storey drift ratio on the j^{th} floor, respectively; Q_{0j} and Δ_{0j} are storey shear force and storey drift on the j^{th} floor of pre-retrofit structure under precautionary earthquake, respectively.

When metallic dampers are installed on every floor of the structure, getting $j_1=1$, and $N_1=N$. And simultaneously, for a more special case of structure with well-proportioned storey stiffness along its height, setting $\alpha_{di}\approx0$ (e.g., $\alpha_{di}=2$ for mild steel), $\mu_{di}=\mu_d$ and $\lambda_{Qj}=\lambda_Q$ in Eq. (10) gives

$$\beta=\frac{\phi\cdot\pi\cdot\lambda_Q}{2\left(1-1/\mu_d\right)-\phi\cdot\pi\cdot\zeta_r} \tag{11}$$

Apparently, based on Eqs. (8)~(11), the designed damping force on different floors can be preliminarily determined with giving scale coefficient β and required added damping ratio ζ_r. However, for damping retrofit of vertical irregular structure, this preliminary designed damping force shall be adjusted along different floors, so as to acquire a better damping effect and solve the problem of weak floor (Weng *et al*. 2012). Pursuant to this, an optimizing coefficient is introduced to modify the designed damping forces of Eq. (8a), which can be expressed as

$$F_{(di)m}=\Omega_i\cdot F_{di} \tag{12a}$$

$$\Omega_i=\Delta_{0i}\Big/\left(\sum_{k=j_1}^{N_1}\Delta_{0k}/N_1\right) \tag{12b}$$

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

Substituting Eq. (8a) and Eq. (12b) into Eq. (12a) gives

$$F_{(di)m}=\left[1\Big/\left(\sum_{k=j_1}^{N_1}\Delta_k/N_1\right)\right]\cdot F_{di}\cdot\Delta_i=\left[\zeta_r\cdot\beta\Big/\left(\sum_{k=j_1}^{N_1}\Delta_k/N_1\right)\right]\cdot Q_i\cdot\Delta_i \tag{13}$$

Eq. (13) reveals that optimization of designed damping force in this simplified methodology is virtually conducted based on storey strain energy of pre-retrofit structure. Besides, for using less damper sizes in one project, configuration of metallic damper in practical design needs comprehensive consideration of designed damping force, which is usually set a interpolation value between Eq. (8a) and Eq. (13).

4.4 Configuration of metallic dampers

The supplemental system of metallic dampers and supporting braces is of displacement-dependent characteristic, as regulated in GB 50011-2010 and JGJ 297-2013, the yield parameters of such supplemental system and frame shall meet the requirement of Eq. (14)

$$\Delta_{py} / \Delta_{sy} \leq 2/3 \tag{14}$$

where Δ_{py} is yield deformation of energy dissipation components along horizontal direction, Δ_{sy} is inter-storey yield displacement of the main structure.

It is also noteworthy that the final damping force added to the structure shall be limited to a rational level associated with structural seismic capacity. To comply with this philosophy, a variable r which defined as the final damping force divided by the yield shearing force on each storey is introduced to control the damping force, and the value range of which is recommended as Eq. (15) by Weng and Lu (2004)

$$r = F_{py} / F_{sy} \leq 0.6 \tag{15}$$

where F_{py} is yield strength of energy dissipation components along horizontal direction, F_{sy} is inter-storey yield strength of the main structure.

4.5 Validation of real equivalent damping ratio

For damped structures, the equivalent damping ratio provided by added energy dissipation devices can be typically calculated by using strain-energy-based method. Specially, for moment-resistant frame (MRF) equipped with metallic dampers, when taking no account of its torsion effects, the total strain energy can be obtained according to GB 50011-2010, which is actually derived from two parts including the main frame and the added metallic dampers. Pursuant to this, the real equivalent damping ratio added by metallic dampers to MRF can be examined by Eq. (16)

$$\zeta_a = \frac{W_c}{4\pi \cdot W_s} = \frac{W_c}{4\pi \cdot \left(W_{fs} + W_{ds}\right)} \tag{16a}$$

$$W_c = 4\sum_{i=1}^{N} W_{ci} = 4\sum_{i=1}^{N} \sum_{j=1}^{N_{di}} \left[\frac{\left(1-\alpha_{dij}\right)\left(1-1/\mu_{ij}\right)}{1+\mu_{ij}\alpha_{dij}-\alpha_{dij}} F_{d,ij} \cdot \Delta_{d,ij} \right] \tag{16b}$$

$$W_{fs} = \frac{1}{2}\sum_{i=1}^{N} (Q_{1i} \cdot \Delta_{1i}) \tag{16c}$$

$$W_{ds} = \frac{1}{2}\sum_{i=1}^{N} \sum_{j=1}^{N_{di}} (F_{d,ij} \cdot \Delta_{d,ij}) \qquad 16d)$$

where W_{ci} is energy dissipated by metallic dampers installed on the i^{th} floor in one cycle at the

(a) the building before earthquake (b) the building after earthquake (c) damage of infill walls

Fig. 5 Elevation of this office building before and after Wenchuan earthquake

Table 1 Structural period properties

Period	T_1 (X-M)	T_2 (Z-T)	T_3 (Y-M)	T_4 (X-M)	T_5 (Y-M)	T_6 (Z-T)
(s)	1.16	0.93	0.91	0.39	0.32	0.32

Noted: X-M, Y-M, Z-T denote movement along X-direction, movement along Y-direction, and torsion along Z-direction, respectively.

expected displacement; N_{di} is the total amount of metallic dampers installed on the i^{th} floor; α_{dij}, μ_{dij}, $F_{d,ij}$, and $\Delta_{d,ij}$, are post yield stiffness ratio, displacement ductility, maximum damping force, and maximum deformation of the j^{th} damper on the i^{th} floor, respectively; W_{fs} is strain energy of the main structure, W_{ds} is strain energy of added metallic dampers in the retrofitted structure.

5. Case study

An engineering case, which was in practice retrofitted by using viscous dampers (Zhang *et al* 2012), was used to validate the feasibility and availability of the design methodology proposed in this paper. As shown in Fig. 5, this 6-storey frame (i.e., the top floor was two separated and protruding stairwells) was an office building in Dujiangyan middle school, China, which was constructed in 2007 and performed well in 2008 Wenchuan earthquake (i.e., only with partially damages occurred in infill walls). This frame was originally designed based on seismic precautionary intensity 7, corresponding to the basic ground acceleration of 0.1 g (where g is the gravitational acceleration) and response spectra characteristic period T_g=0.35 s (where T_g is the design characteristic period of ground motion). However, after Wenchuan earthquake, the local seismic precautionary intensity for the construction site was increased from intensity 7 to intensity 8, which referred to an upgraded basic ground acceleration of 0.2 g and T_g=0.4 s. Thus retrofit design for this earthquake-damaged frame aims to improve its seismic precautionary intensity by using metallic dampers in this paper. Since the attic is two small staircase, the following case study, for simplified analysis, just focus on the main five storey of the frame.

Before retrofit design, seismic appraisal of this earthquake-damaged frame was conducted to evaluate its residual seismic performance, and some necessary repairs to damaged structural members were done to restore building function. Assessment of pre-retrofit frame were required to include seismic appraisal results and local reinforcements, and subsequently its modified finite element model was established to further investigate the structural seismic responses and assess its

Table 2 Model information under frequent earthquake of intensity 8 (PGA=0.2 g)

Floor	Height (m)	Storey mass (t)	*X*-direction			*Y*-direction		
			Stiffness (kN/mm)	Shear force (kN)	Rotation (rad)	Stiffness (kN/mm)	Shear force (kN)	Rotation (rad)
5	4.8	1449	359	2004	1/810	438	2318	1/791
4	3.6	1290	579	2884	1/686	862	3379	1/801
3	3.6	1159	582	3542	1/568	887	4192	1/664
2	3.6	1232	593	4124	1/498	906	4890	1/581
1	4.6	1260	523	4567	1/511	735	5395	1/539

reparability of employing damping strategy. The corresponding structural properties as well as analytical results were listed in Table 1 and Table 2, respectively. It is found that this earthquake-damaged frame is insufficient to resist the new precautionary earthquake of intensity 8. Especially for the bottom two floors, their storey drifts under frequent earthquake are far beyond the allowable value of 1/550 set in GB 50011-2010. Therefore, retrofit of this earthquake-damaged frame is necessary for maintaining subsequent service.

As mentioned above, design of metallic dampers in retrofitting earthquake-damaged structure is conducted based on the philosophy of "added stiffness-based design under frequent earthquake and added damping-based design under precautionary earthquake". The desirable performance of retrofitted frame was represented by allowable inter-storey drift as $[\theta_e]$=[1/550] under frequent earthquake and $[\theta]$=[1/250] under precautionary earthquake. Besides, its elastic-plastic inter-storey drift was also required within $[\theta_p]$=[1/80], and stresses of the main structural members (i.e., the retrofitted frame) under new precautionary earthquake were expected to be similar with those of pre-retrofit frame under original precautionary earthquake, so that extensive retrofit of the main structural members were avoided. With these design expectations, the comprehensive methodology proposed in this paper was used to configure and design metallic dampers in retrofit of this earthquake-damaged frame. The supplemental metallic dampers were installed on every storey, while the designed damping force and damper configurations along the 1^{th}~5^{th} floors were

Table 3 Information of supplemental metallic dampers

Floor	H (*m*)	*X*-direction				*Y*-direction			
		Horizontal damping force (*kN*)		Damper configuration		Horizontal damping force (*kN*)		Damper configuration	
		Calculated value	Optimal value	(*N*×Category)	Designed value	Calculated value	Optimal value	(*N*×Category)	Designed value
5	4.8	1775	1335	2×***A***+2×***B***	1700	1289	1126	4×***A***	1200
4	3.6	2564	2329	2×***A***+2×***C***	2400	1929	1553	2×***A***+2×***B***	1700
3	3.6	3151	3476	4×***C***	3400	2422	2363	2×***A***+2×***C***	2400
2	3.6	3662	4476	4×***D***	4400	2836	3115	2×***B***+2×***D***	3100
1	4.6	4026	4082	2×***C***+2×***D***	4000	3127	3899	2×***C***+2×***D***	3900

Noted: 1. all metallic dampers used in this frame are installed in horizontal direction with chevron brace; 2. ***A***, ***B***, ***C***, ***D*** denote different categories of metallic dampers, which associate with different designed damping force and different brace stiffness, as further elaborated in Table 4 and Table 5.

Table 4 Design parameters of metallic dampers

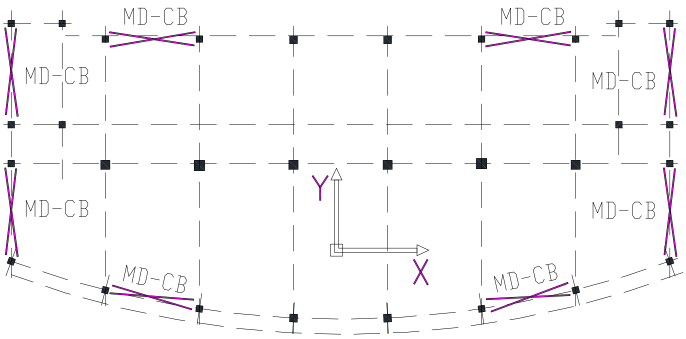
Damper type / Design parameters	***A***	***B***	***C***	***D***
Yield damping force $\boldsymbol{F_{dy}}$ (kN)	300	500	800	1000
Initial stiffness $\boldsymbol{k_{d0}}$ (kN/mm)	100	167	267	333
Post yield stiffness ratio $\boldsymbol{\alpha_d}$	0.02	0.02	0.02	0.02
Yield index $\boldsymbol{n}$	2	2	2	2

Noted: where the yield damping force F_{dy} can be derived from designed damping force F_d by Eq. 8(b).

Table 5 Comparison of stiffness of supplemental metallic dampers and main frame

Floor	Lateral stiffness along *X*-direction (kN/mm)				Lateral stiffness along *Y*-direction (kN/mm)			
	Main frame	Energy dissipation components			Main frame	Energy dissipation components		
		Brace	Metallic damper	Combination		Brace	Metallic damper	Combination
5	359	1600	534	400	438	1668	400	323
4	579	2664	734	575	862	2664	534	445
3	582	2664	1068	762	887	2664	734	575
2	593	2664	1332	888	906	2664	1000	727
1	523	1752	1200	712	735	1820	1200	723

Noted: in this engineering case, all chevron braces uses unified H-shaped steel of H440×300×11×18 (mm).



MD-CB, denote the metallic damper with chevron brace

Fig. 6 Location of metallic dampers-braces on the 1th~5th floors

shown in Table 3 and Fig 6. The corresponding design parameters and added initial stiffness of metallic dampers used in this frame were listed in Table 4 and Table 5, respectively.

Time-history analysis approach was employed to calculate responses of the retrofitted frame equipped with metallic dampers by SAP2000. Three earthquake records were selected to match in some average way the Code Response Spectrum (i.e., CRS in GB 50011-2010), as shown in Fig. 7, 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 frequent earthquake, 200 cm/s^2 for the precautionary earthquake, and 400 cm/s^2 for the rare earthquake, were designed for the excitation inputs during the time-history analysis. Considering

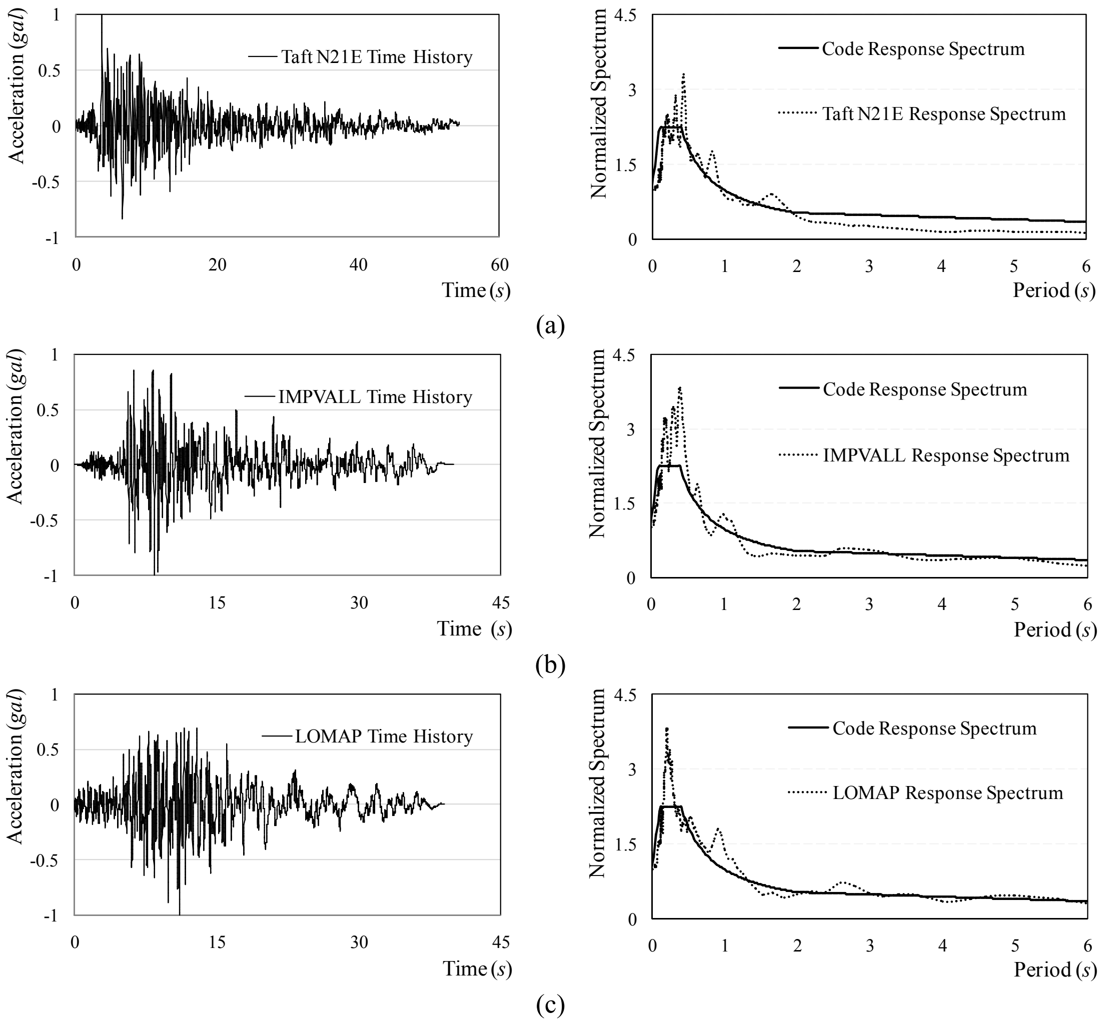


Fig. 7 Normalized time-history curves and response spectra

the extra stiffness provided by non-structural components, the PGAs of the frequent earthquake and the precautionary earthquake were multiplied by a coefficient of 1.22.

Through dynamical time-history analysis, structural response of the pre-retrofit frame (ST0) and the retrofitted frame (ST1) were obtained and compared. Figs. 8-9 show the comparisons of inter-storey drift and shear force between ST0 and ST1 under frequent earthquake and precautionary earthquake, respectively. Here the storey shear forces are obtained from section cut forces of frame columns only (i.e., without metallic dampers). The analysis results indicate that ST1 has excellent structural performances by showing a well-performed distribution of inter-storey drifts and shear forces. Compared to ST0, ST1 shows a remarkable improvement of seismic performances in weak floors. To be specific, the inter-storey drifts of ST0 are partially beyond the allowable value of [1/550] under frequent earthquake and the desirable performance of [1/250] under precautionary earthquake, however, with the retrofit solution of using metallic dampers, the inter-storey drifts of ST1 under different seismic levels are all controlled within various

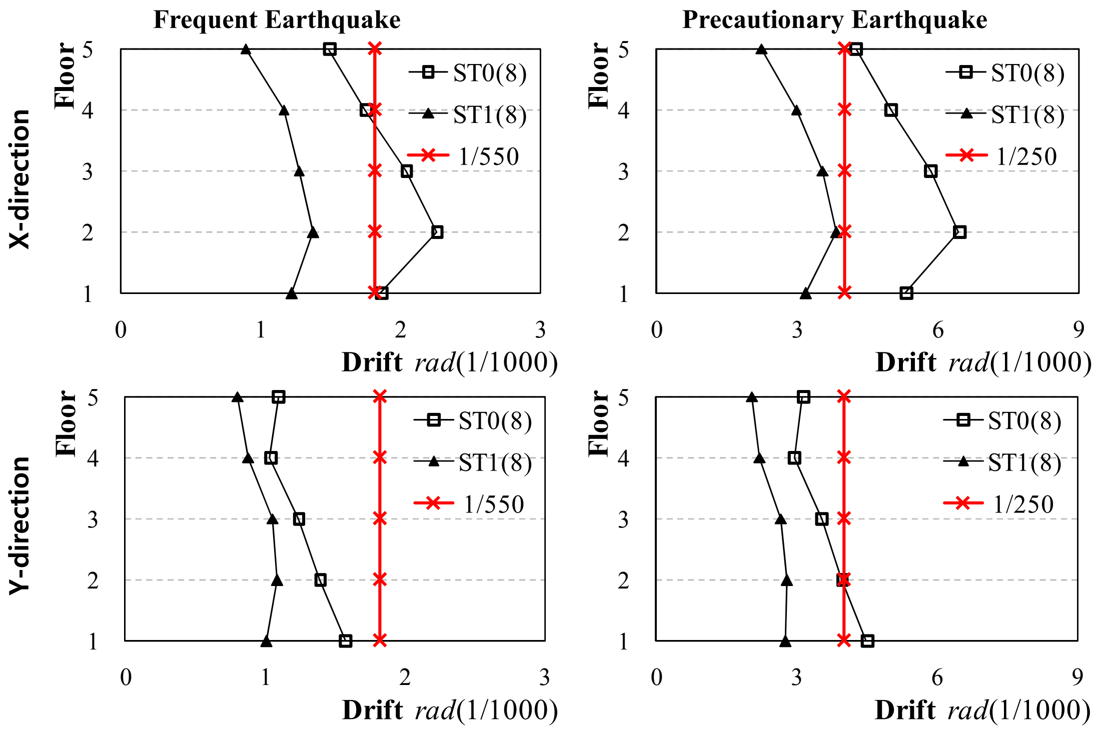


Fig. 8 Comparison of the inter-storey drifts under intensity 8

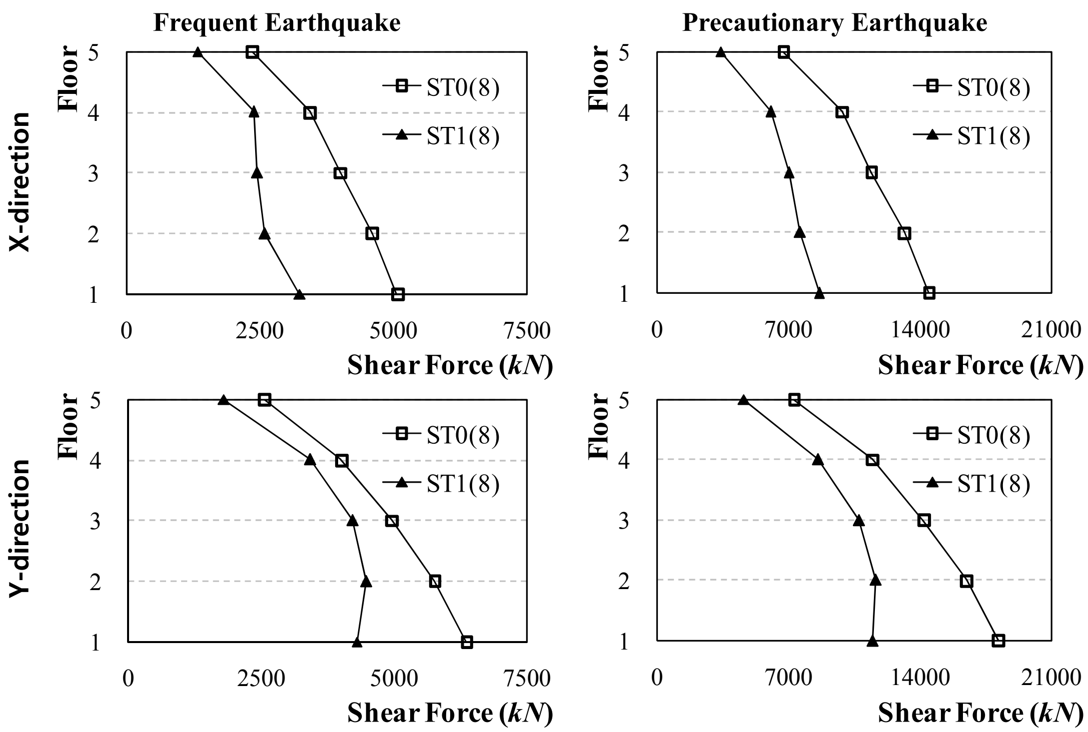


Fig. 9 Comparison of the shear forces under intensity 8

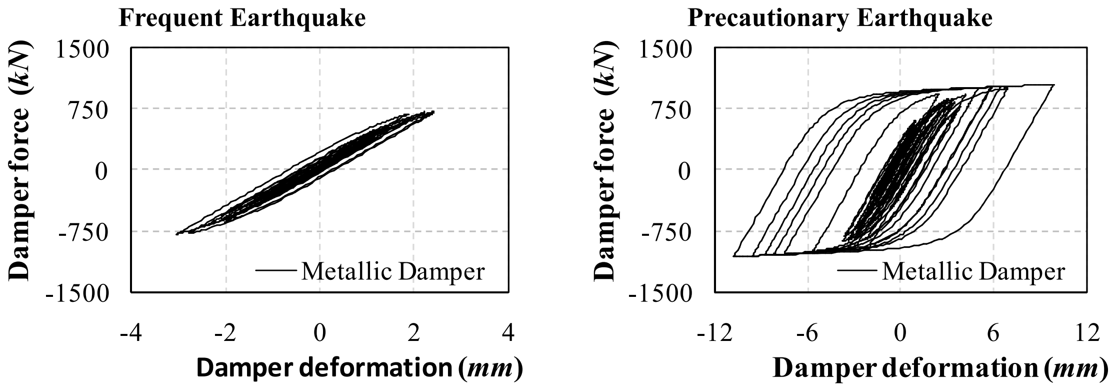


Fig. 10 Hysteretic curves of the metallic damper under intensity 8

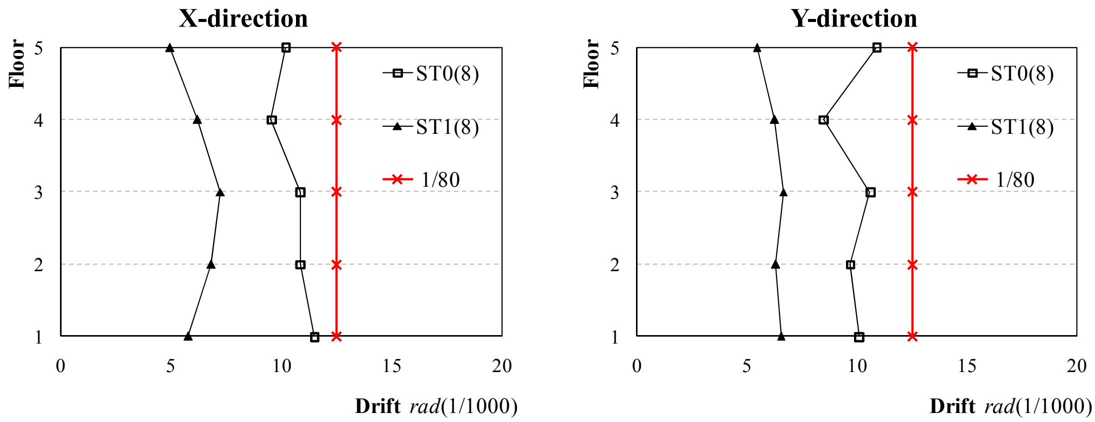


Fig. 11 Comparison of elastic-plastic inter-storey drift under rare earthquake of intensity 8

performance demands. Thus, it is concluded that metallic dampers can be well designed in non-ductile structures to enhance their seismic performances or to reach certain design objectives under different seismic hazards.

To examine the real energy-dissipated capability of metallic dampers added in the retrofitted frame (ST1), a metallic damper installed on the 2^{th} floor along *X* direction was selected to exhibit its force-deformation hysteretic curve under frequent earthquake and precautionary earthquake, respectively, as shown in Fig. 10. Force-deformation curve of this selected metallic damper is of narrow and small shape under frequent earthquake, but a full hysteresis loop under precautionary earthquake. It is also concluded that metallic damper used in this engineering case exhibits very limited nonlinear behavior under frequent earthquake, and dissipates a lot of seismic energy under precautionary earthquake. Such behaviors of the metallic damper strongly support aforementioned design philosophy of "added stiffness-based design under frequent earthquake and added damping-based design under precautionary earthquake".

The elastic-plastic models of the frame with or without metallic dampers were established based on ABAQUS software, so as to further evaluate seismic safety of the main frame and supplemental metallic dampers under rare earthquake. Herein the beams, columns and braces were simulated by the B31 element provided by ABAQUS, the floors were simulated by the S4R

ST0

ST1

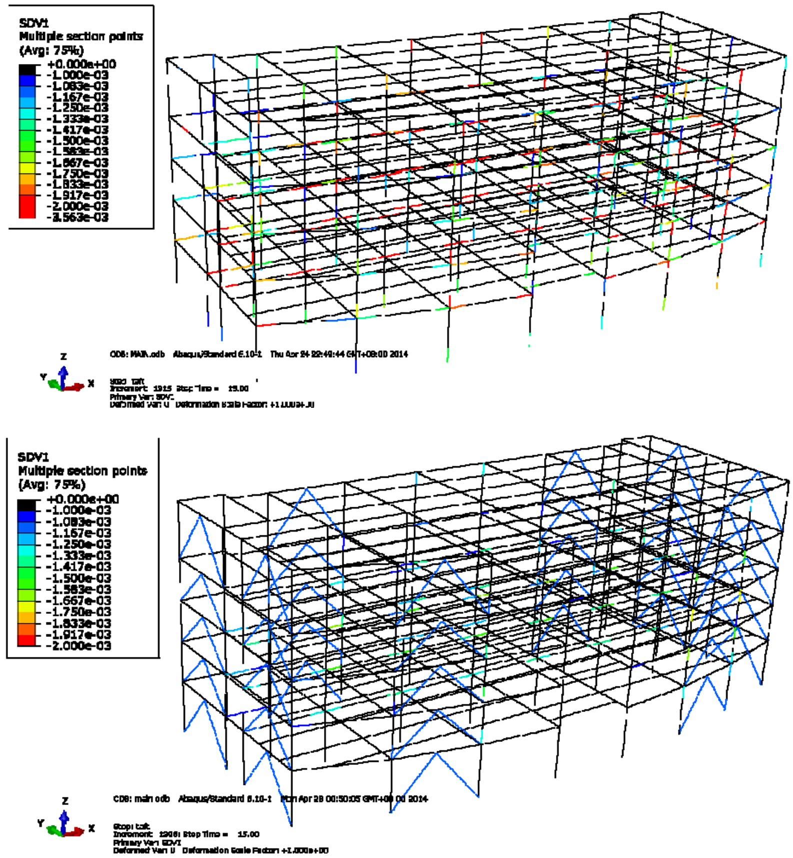


Fig. 12 Comparison of elastic-plastic yielding conditions under rare earthquake of intensity 8

element and metallic dampers were simulated by the CONN3D2 element (ELSET=AXIAL). The constitutive model of concrete and steel materials were adopted according to GB50010-2010 (i.e., China's *Code for design of concrete structure*), and a bilinear model was used to represent the hysteresis loops of metallic dampers. The corresponding elastic-plastic dynamic analysis was conducted with the explicit integration technology provided by ABAQUS, and the elastic-plastic inter-storey drifts of the pre-retrofit frame (ST0) and the retrofitted frame (ST1) were obtained and compared, as shown in Fig. 11. It can be seen that ST1 exhibits a much better performance under rare earthquake compared to ST0, and their elastic-plastic inter-storey drifts are all controlled within the allowable value of [1/80]. The same corollary can also be obtained through the comparison of yielding mechanism and failure mode between ST0 and ST1, as shown in Fig. 12, at time step of 15th second under the action of Taft N21E, there are a lot of beams and columns yield in ST0, while in ST1 the yield levels of structural components are effectively reduced and postponed. Thus it is concluded that the earthquake-damaged frame can be enhanced to acquire perfect earthquake-resistant capability or to meet different seismic design objectives by using metallic dampers.

A comprehensive cost analysis was also conducted by comparing the costs of two retrofit strategies: employing metallic dampers (MD) in this paper, and using viscous dampers (VD) in practice (Zhang *et al.* 2012). Here in this paper, 40 metallic dampers including damper categories of ***A***, ***B***, ***C*** and ***D*** were used to reach the target of increasing one degree of seismic precautionary intensity (i.e., from intensity 7 to intensity 8). However, for the same retrofit target, 56 viscous dampers with three different types (e.g., with desirable damping forces of 300 kN, 600 kN, and 900kN, respectively) were required in practice. It is also noteworthy that for MD strategy, since the added stiffness from MD is relatively large, the adjacent beams and columns, as well as foundation, may need to be additionally reinforced. While for VD strategy, it is generally accepted that storey drifts and shear forces can be simultaneously reduced, hence some additional enhancements may be unnecessary in most cases. Based on the current price level in China, the constructing cost of MD and VD strategies in this project are about 3.2 million RMB and 3.88 million RMB, respectively. However, if demolishment cost for structural decorations is considered, the comprehensive cost of MD and VD strategies are about 3.8 million RMB and 4.16 million RMB, respectively. Thus in this engineering case, MD strategy has the lower cost but needs the longer constructing period compared to VD strategy. In fact, MD and VD strategies, with their own advantages and disadvantages, are all suitable for retrofit of earthquake-damaged frame, and therefore decision of which one to employ depends on a comprehensive consideration of seismic safety, cost-effectiveness, and construction period, etc.

6. Conclusions

This paper presents a comprehensive design methodology for retrofit of earthquake-damaged frame structures by using metallic dampers. To simplify the design process, a philosophy of "added stiffness-based design under frequent earthquake and added damping-based design under precautionary earthquake" is proposed for design of metallic dampers, here the added stiffness and added damping can be obtained with certain displacement demand under frequent earthquake and certain shear force demand under precautionary earthquake, respectively. Configuration and design of metallic dampers in multi-storey structure are closely associated with the expected damping forces, while the vertical distribution of expected damping forces in this comprehensive design methodology is virtually determined based on storey strain energy of the structure.

Based on a detailed engineering case, it is concluded that the proposed design procedure is simple and practical, which can not only meet current Chinese design codes but also be used in seismic retrofit design of earthquake-damaged frame structure with metallic damper for reaching desirable performance objective.

The metallic dampers discussed in this paper are deemed to behave linearly or to have very limited nonlinear behavior under frequent earthquake, and therefore their energy-dissipation capacity added to the structure will not be taken into account in frequent-earthquake-based design (i.e., China's seismic design codes), which brings great difficulty to development and application of such metallic dampers. Thus, an available design methodology is still need to be established or advanced for considering added damping effect in frequent-earthquake-based design theory, especially for those metallic dampers which may early yield under frequent earthquake.

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