Uniform damping ratio-based design method for seismic retrofitting of elastoplastic RC structures using viscoelastic dampers

Liyu Xie\textsuperscript{a}, Li Zhang\textsuperscript{a}, Chao Pan\textsuperscript{b}, Ruifu Zhang\textsuperscript{a,\textast}, Tianli Chen\textsuperscript{c}

\textsuperscript{a} Department of Disaster Mitigation for Structures, Tongji University, Shanghai, 200092, China
\textsuperscript{b} College of Civil Engineering, Yantai University, Yantai, 264005, China
\textsuperscript{c} School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an, 710055, China

\textbf{ARTICLE INFO}

\begin{tabular}{l}
Keywords: \\
Uniform damping ratio \\
Seismic retrofit \\
Viscoelastic damper \\
Energy dissipation
\end{tabular}

\textbf{ABSTRACT}

A simple design procedure is proposed for seismic retrofitting of existing structures using viscoelastic dampers (VEDs) based on the uniform damping ratio (UDR) concept to make full use of each damper. The UDR concept states that the equivalent damping ratios, which represent the energy dissipation capacities of the dampers, are the same for each installed VED. The stiffness and damping characteristic parameters of the damped structure can be formally decoupled using UDR-based derivations, which simplify the determination of the VEDs’ parameters. The generalized single-degree-of-freedom method and pushover analysis are adopted for a fast estimation of the seismic response of the damped elastoplastic structure. Taking the response reduction ratio as the design target, a seismic retrofit design procedure is proposed based on the UDR concept to meet the performance demand. Finally, a six-story frame is adopted to illustrate the proposed design method. The dynamic analysis results show that the seismic responses of the structure are well-controlled, as expected, and that the installed VEDs are used effectively. The conclusion can be drawn that the UDR-based design method for retrofitting an existing structure using VEDs is rational and effective.

\section{Introduction}

In the past few decades, the application of passive energy dissipation technology has been of great interest to many engineers and scholars for seismic risk mitigation in building structures [1–3]. Using energy dissipation devices (EDDs), the energy caused by earthquakes can be effectively absorbed and dissipated for structures with suitably placed dampers, and the reliability of the structures can be enhanced [1,4–7]. Therefore, the use of EDDs has increased substantially for the seismic retrofitting of structures. While some theories and methods have been presented for this technology, more detailed and deeper studies are still needed for the seismic retrofitting of existing structures with EDDs [2,8–10]. This is because, compared with the application of EDDs for new structures, the seismic retrofitting of structures using EDDs involves the original characteristics of the existing structures, making this process more difficult.

This study is mainly focused on the viscoelastic damper (VED), which was one of the earliest devices used as an EDD for structural response control [11–13]. These dampers are characterized by frequency and temperature dependence and the energy is dissipated through the shear deformation of the corresponding viscoelastic materials (e.g., polymeric material, rubber material, etc.). With the advantages of low cost, simple implementation, adding both damping and stiffness and activating at low displacements, VEDs are popular for structural retrofits to control wind and seismic responses [14–16]. The dynamic behaviors of VEDs are usually described using the classic rheological models (simple/generalized Kelvin and Maxwell model) and fractional derivative models [17–20]. Among these models, the classic rheological models are more often used in practice for the analysis and design of structural seismic retrofitting [17].

A simple, effective and reasonable design method is very important for the application of structural seismic retrofitting using VEDs. This process usually involves the determination of the VED’s locations and parameters (i.e., the storage stiffness, $K_d$, the loss stiffness, $K''_d$ and the loss factor, $\eta_d = K''_d/K_d$, etc.). For these purposes, numerous design methods have been suggested for structures with supplemental VEDs. In early VED applications, Zhang and Soong [13] proposed design procedures based on the control index, resulting in a sequential procedure for obtaining the optimal locations for VEDs. However, the structure is equipped with uniform dampers in this method, which cannot fully utilize these dampers. For seismic retrofit designs, Lee et al. [21] proposed a simplified design procedure for frame buildings using VEDs,

\textsuperscript{\ast} Corresponding author.

\textit{E-mail address: zhangruifu@tongji.edu.cn} (R. Zhang).

\url{https://doi.org/10.1016/j.soildyn.2019.105866}

Received 10 May 2019; Received in revised form 9 August 2019; Accepted 18 September 2019

0267-7261/ © 2019 Elsevier Ltd. All rights reserved.
and the stiffnesses of the VEDs installed at each story are determined using a trial calculation procedure. The design methods mentioned above are presented on the basis of assumed elastic structures. However, under strong ground motions, plastic behavior can occur in the primary structures. Hence, these design methods may not be reliable when the primary structures move into the plastic stage. Mazza and Vulcano [22] suggested a displacement-based design procedure for elastoplastic RC framed buildings using damper braces. Zhang et al. [23] presented the direct design method of VED parameters for damper structures based on the elastic-plastic response reduction curve, which is an extension for the research of the Japan Society of Seismic Isolation [24]. However, this curve is not easy to plot. Joaquin and Zhou [25] suggested a practical design method for new and retrofit buildings, obtaining the VED parameters using the shear forces instead of the story stiffnesses of the original structures, and the placement of the VEDs are determined according to the sequential procedure presented by Zhang and Soong [13]. With the objective of determining the optimal placement of VEDs and minimizing the cost, many optimal design methods are also presented by scholars using different algorithms. Fujita et al. [26] presented a gradient-based optimization methodology to obtain the optimal placement of VEDs. A genetic algorithm is employed by Zhao et al. [27] to optimally place the VEDs under a determined amount of viscoelastic material. Shmerling et al. [28] presented a robust analysis redesign iterative approach for the optimal seismic retrofit design of structures using dampers with the objective function of minimizing the cost. However, the complexity of the corresponding algorithms limited the application of these optimal methodologies in practice. To sum up, there is still a need to propose simple, effective, and reasonable design procedures for the seismic retrofit of structures using VEDs.

The uniform damping ratio (UDR) concept [29] is recommended for the seismic retrofit design of the structures in this study, which means that the equivalent damping ratios provided by the VEDs are equal for each story of the structure. This concept is presented to sufficiently utilize the VEDs, as the energy dissipation capacity of the VED is measured by the equivalent damping ratio. According to the UDR concept, the equation for the additional damping ratio is derived in which the added stiffness and damping effect of the VEDs are uncoupled, which makes the corresponding design procedure simpler. Additionally, it has been proven that the uncoupled stiffness characteristic parameter can be used to proportionally determine the storage stiffness of the supplemental VEDs, which can make the vibration mode shapes of the structure almost unchanged when the VEDs are installed [15]. This situation is usually expected for the seismic retrofit of a structure. Furthermore, using the generalized single-degree-of-freedom (SDOF) model and considering the elastic-plastic behavior of the primary structure, the seismic retrofit design procedures are presented that meet seismic performance demands of the assumed earthquake intensity. Finally, a six-story RC frame is used to illustrate the design method, and a time history analysis is performed for verification.

2. Illustration of the design theory

2.1. Details of the UDR concept

It is usually expected that all the dampers that are installed at the structure can work fully under dynamic loads. The energy dissipation capacity of a VED can be determined using the parameter of the equivalent damping ratio. Hence, to equally use all the dampers, the UDR concept is suggested, which assumes that the equivalent damping ratio of each installed VED at the structure is the same. The equivalent damping ratio of a VED, \( \zeta_{d,i} \), can be expressed as follows [30]:

\[
\zeta_{d,i} = \frac{E_{d,i}}{4\pi E_{sd,i}}
\]

(1)

where \( E_{d,i} \) is the energy dissipated in one cycle by the \( i \)th equipped VED and \( E_{sd,i} \) is the maximum strain energy of the \( i \)th VED in the same cycle. When the dampers are installed at the structures, the additional damping ratio of the dampers, \( \zeta_{a} \), can be calculated as follows:

\[
\zeta_a = \frac{\sum E_{d,i}}{4\pi \sum E_{sd,i}} = \frac{\sum E_{d,i}}{E_a + \sum E_{sd,i}}
\]

(2)

where \( \sum E_{d,i} \) is the total dissipated energy of all the VEDs, \( E_a \) is the maximum strain energy of the structure with VEDs, which can be expressed using the summation of the strain energies of the primary structure, \( E_a \), and all of the equipped VEDs, \( \sum E_{sd,i} \).

According to Eq. (1), the first term in Eq. (2) can be rewritten as follows when the equivalent damping ratio, \( \zeta_{d,i} \), of each VED is set to the constant, \( \zeta \), according to the UDR concept:

\[
\zeta_a = \frac{\sum E_{d,i}}{4\pi \sum E_{sd,i}} = \frac{4\pi \sum E_{d,i}}{4\pi \sum E_{sd,i}} = \frac{4\pi \sum E_{d,i}}{4\pi \sum E_{sd,i}} = \zeta
\]

(3)

Then, defining the second term in Eq. (2) as the stiffness characteristic coefficient, \( \kappa \), this term can be expressed as follows:

\[
\kappa = \frac{\sum E_{d,i}}{E_a + \sum E_{sd,i}} = \frac{E_{d,i}}{E_a}
\]

(4)

Now, the additional damping ratio, \( \zeta_a \), can be simplified as follows:

\[
\zeta_a = \zeta \kappa
\]

(5)

The parameter \( \kappa \) involves the stiffnesses of the VEDs. The details of this part are illustrated later. Eq. (5) shows that the uncoupled effect of the damping and stiffness characteristic parameters of the VEDs is achieved, which can greatly simplify the parameter decision procedure. These two parameters, \( \zeta \) and \( \kappa \), are taken into account as key parameters for the seismic retrofit design of structures using VEDs. It should be noted that \( \kappa \) impacts not only the additional damping ratio but also the stiffness of the dampened structure. A relatively large stiffness of the dampened structure can be beneficial for displacement control. However, a relatively low displacement can limit the energy dissipation capacity of the VEDs. Therefore, there needs to be a balance between the values of \( \zeta \) and \( \kappa \). The relevant parameters of VEDs with regard to \( \zeta \) and \( \kappa \) are discussed below.

2.2. VED parameters

The VEDs are usually connected to the primary structure with braces in series. These two components are installed on the primary structure together. Therefore, both the VED and brace need to be considered for the retrofit design of the structure. The interaction of the VED and brace in the frame structure is illustrated in Fig. 1. The Kelvin model [23,31] is used to represent the VED using a parallel-connected dashpot and spring, and the hysteretic behavior of the VED can be modeled by an elliptical shape under a certain sinusoidal excitation with a frequency, \( \omega \). The series-connected VED and brace are considered together as an equivalent viscoelastic damper (EVED) in this study, as shown in Fig. 1, because, except for the value of the corresponding parameters, the hysteretic behavior of the EVED is similar to that of the VED. Due to the series-connected interaction of the VED and brace, the forces of the VED, brace and EVED are equal. This equivalent relationship between the maximum forces of the VED, brace and EVED (\( F_{d,max} \), \( F_{b,max} \) and \( F_{evd,max} \)) is shown using the dashed line in Fig. 1.

As is shown in Fig. 1, the storage stiffnesses of the VED, \( K'_{d} \), and the EVED, \( K'_e \), are calculated using the ratios of the forces at the maximum displacement to the corresponding maximum displacements (\( u_{d,max} \) and \( u_{evd,max} \)). The relationships between the stiffnesses of the VED and the EVED can be expressed as follows:

\[
K'_e = \frac{\left(1 + \nu \right) K'_d + K_b}{K'_d + K_b} K'_d u_{evd,max}
\]

(6)
$K_v^* = \frac{\eta_0 K_d^2}{(K_d + K_b) + (\eta_0 K_d)^2}$

where $K_v^*$ is the loss stiffness of the EVED, $K_b$ is the stiffness of the brace, $\eta_0 = K_d' / K_d$ denotes the loss factor of the VED, and $K_d'$ is the loss stiffness of the VED. Then, the loss factor of the EVED can be derived as follows:

$\eta_v = K_v^* / K_v^* = \frac{\eta_0}{1 + (1 + \eta_0^2)K_d' / K_b}$

According to Eq. (1), the equivalent damping ratio of the EVED can be calculated as follows:

$\zeta_e = \frac{E_d}{4\pi E_s} = \frac{\pi k_v^2 u_{e, \text{max}}^2}{4\pi K_v' u_{e, \text{max}}^2 / 2} = \frac{\eta_v}{2}$

where $E_d$ is the energy dissipated by the VED, and $E_s$ is the maximum strain energy of the EVED. Note that the EVED can be regarded as a special VED, and the UDR concept and formulae mentioned in Section 2.1 are also applicable to the EVED (i.e., the equivalent damping ratios, $\zeta_e$, of the EVEDs are equal to the same constant, $\zeta$). It can be seen in Eq. (9) that the value of $\zeta_e$ depends on the loss factor, $\eta_v$. Hence, the UDR concept for the EVED can be approximately replaced by the uniform loss factor (ULF). This theory can be applied for the simplified design procedure proposed subsequently.

It has been discussed above that the values of $\zeta$ and $\kappa$ for the EVED should be balanced for a reasonable design. The values of $\zeta$ and $\kappa$ for the EVED involve the parameters $\eta_0$ and $K_v^*$, respectively. According to the studies by Lee et al. [21] and Fu and Kasai [31], for the VED, the typical values of $\eta_0$ usually range from 1 to 1.4, the values of $K_v^* / K_b$ range from 0.1 to 5 and $K_d' / K_b$ values ranging from 10 to 30 are also recommended, where $K_b$ is the story stiffness of the primary structure. To obtain a reasonable range for $\eta_v$, using Eq. (8) and setting $K_v^* / K_b = 20$, the values of $\eta_v$ can be obtained for different values of $K_v^* / K_b$ (i.e., $K_v^* / K_b = 0.1 - 5$) when the values of $\eta_0$ are set to 1 and 1.4, as shown in Fig. 2.

It can be seen in Fig. 2 that the values of $\eta_v$ are between 0.67 and 1.38 for a reasonable parameter set of the VED and brace. Furthermore, $\eta_v$ is smaller than $\eta_0$ for a certain damper and decreases with increasing $K_v^* / K_b$ for a certain set of $\eta_0$ and $K_v^* / K_b$. In practice, to obtain a better energy dissipation result, a smaller value of $K_v^* / K_b$ is usually applied. Moreover, the displacement of the brace is restricted, while the displacement of the VED is encouraged, which means that a relatively large stiffness for the brace and small stiffness for the VED are recommended. Consequently, the condition $K_b / K_v^* > 5$ is suggested.

![Fig. 1. Interactions and models of the VED and brace.](Image)

![Fig. 2. Relationships between $\eta_v$ and $K_v^* / K_b$.](Image)

According to the experiences and theories mentioned above, a reasonable range of $\eta_v$ can be rounded between 0.7 and 1.3 for a conservative consideration. Similarly, a reasonable range for $K_v^* / K_b$ can also be obtained, which is close to $K_v^* / K_b$.

For the seismic retrofit design of structures using VEDs, EVEDs are suggested to consider both the effect of the VEDs and the braces. Once the parameters of the EVED (i.e., $\eta_v$ and $K_v^*$, etc.) are obtained, the parameters of the VED can be calculated using Eqs. (6)–(8) after setting an appropriate value of $K_b / K_v$.

### 2.3. Generalized SDOF system

In this study, the widely used frame structure for seismic retrofitting is discussed. To reduce the computational consumption and simplify the design procedure, the generalized SDOF model is employed to illustrate the frame structure. For a typical frame structure, though the dampers are installed, it is still possible to enter the plastic state of the primary structure under the influence of severe seismic events. Hence, the structural plastic behavior is considered in this study. A multistory frame can usually be simplified to a shear lumped-mass system, which is also called a multi-degree-of-freedom (MDOF) model. According to
Fig. 3. Transformation of the frame structure to SDOF.

the assumption that the structure can deflect in only one shape throughout the vibration, which is usually the first mode of the structure, the MDOF model can be transformed into a generalized SDOF model, as shown in Fig. 3, where \( m_i \), \( K_{s,i} \), and \( u_i \) are the mass, stiffness and displacement of story \( i \), respectively. The normalized deflected shape of the MDOF is denoted as a shape vector, \( \Phi = [\varphi_0, \ldots, \varphi_i, \ldots, \varphi_n]^T \). Then, the normalized inter-story deflection vector can be denoted as 

\[
\delta = [\delta_0, \ldots, \delta_i, \ldots, \delta_n]^T = [\varphi_0, \ldots, \varphi_{i-1}, \varphi_i - \varphi_{i-1}, \ldots, \varphi_n - \varphi_{n-1}]^T.
\]

Defining the displacement vector, \( \mathbf{u} = [u_0, \ldots, u_i, \ldots, u_n]^T \), of the MDOF as \( \mathbf{u} = \Phi q(t) \) on the basis of a constant deflected shape where \( q(t) \) denotes the generalized displacement, the motion equation of the generalized SDOF system can be derived as follows [32]:

\[
M_{eq}\ddot{q}(t) + C_{eq}\dot{q}(t) + K_{eq}q(t) = -I_0^sM_{eq}\ddot{u}_q(t) + \ddot{q}(t)
\]

where \( M_{eq} \) is the equivalent mass of the SDOF system, \( C_{eq} \) and \( K_{eq} \) are the equivalent damping coefficient and equivalent stiffness of the SDOF system, respectively, \( I_0^s \) is the generalized excitation coefficient, and \( \ddot{u}_q(t) \) is the ground acceleration. These corresponding parameters can be calculated as follows:

\[
M_{eq} = \sum_{i=1}^{n} m_i\varphi_i^2
\]

\[
C_{eq} = 2M_{eq}\sum_{i=1}^{n} \frac{2\pi}{T_{eq}}
\]

\[
K_{eq} = \sum_{i=1}^{n} K_{s,i}(\varphi_i - \varphi_{i-1})^2
\]

\[
I_0^s = \sum_{i=1}^{n} m_i\varphi_i^2
\]

where \( T_{eq} = 2\pi\sqrt{M_{eq}/K_{eq}} \) is the equivalent period, \( \zeta_{eq} \) is the equivalent damping ratio of the SDOF system, which contains the inherent damping ratio, \( \zeta \), and the nonlinear hysteretic damping ratio, \( \zeta^* \), of the SDOF system.

Actually, some of the parameters above can be obtained through a simple pushover analysis for an elastoplastic primary structure. Performing the pushover analysis, the relationships between the story shear force, \( Q_i \), and the inter-story displacement, \( \Delta u_i = u_i - u_{i-1} \), can be obtained first. Then, these \( Q_i - \Delta u_i \) curves can be reduced to an \( S_0 - S_d \) curve, which also graphically represents the transformation of a MDOF system to a SDOF system, as shown in Fig. 4, where \( S_0 \) and \( S_d \) are the spectral acceleration and displacement, respectively. This \( S_0 - S_d \) curve is also called the capacity spectrum of the elastoplastic primary structure. The corresponding formulae are given as follows:

\[
S_0 = \frac{Q_i}{I_0^s \sum_{i=1}^{n} m_i\varphi_i}
\]

\[
S_d = \frac{u_i}{I_0^s}
\]

The story stiffness, \( K_{s,i} \), and the equivalent period, \( T_{eq} \), can be calculated as follows:

\[
K_{s,i} = \frac{Q_i}{\Delta u_i}
\]

\[
T_{eq} = 2\pi\sqrt{S_0 \over S_a}
\]

Using the equivalent bilinear curve of the capacity spectrum, as shown in Fig. 4, \( \zeta \) and \( \zeta_{eq} \) can be expressed as follows:

\[
\zeta = \frac{E_p}{4\pi E_s}
\]

\[
\zeta_{eq} = \zeta + \zeta^*
\]

where \( E_p \) is the plastic dissipated energy of the primary structure.

When the EVEDs (VEDs and braces) are mounted at the elastoplastic primary structure, considering the UDR concept and adding the stiffness and damping effects of the EVEDs, the equivalent stiffness, \( K^*_{eq} \), and the equivalent damping ratio, \( \zeta^*_{eq} \), for the damped SDOF system can be rewritten as follows:

\[
K^*_{eq} = \sum_{i=1}^{n} (K_{s,i} + K'_{s,i})(\varphi_i - \varphi_{i-1})^2
\]

\[
\zeta^*_{eq} = \zeta^* + \zeta^*
\]

where \( K'_{s,i} \) is the storage stiffness of the EVED installed at \( i \)th story, and \( \zeta^* \) is the nonlinear hysteretic damping ratio of the damped SDOF system. In this study, the primary structure is considered to install the EVEDs with a proportional stiffness to the primary structure (i.e., value with regard to \( k \)). Hence, the deflected shape of the damped structure can be considered to be almost unchanged compared with the primary structure.

According to Eq. (4), \( \kappa \) can be rewritten as follows on the basis of the unchanged deflected shape:
Fig. 4. Transformation of the $Q - \Delta u_i$ curves to the capacity spectrum.

Then, the ratio of $K_{eq}$ to $K_{eq}^*$ can be derived as follows:

$$\kappa = \frac{\sum_i E_{sid,i}}{E_s + \sum_i E_{sid,i}} - \frac{\frac{1}{2} \sum_{i=1}^n K_i \delta_i^2}{\frac{1}{2} \sum_{i=1}^n (K_{sid,i} + K_{sid,i}') \delta_i^2}$$

$$= \frac{\sum_{i=1}^n K_i' \delta_i^2 (\phi_i - \phi_{i-1})^2}{\sum_{i=1}^n (K_{sid,i} + K_{sid,i}')(\phi_i - \phi_{i-1})^2}$$

(23)

Then, the equivalent period, $T_{eq}^*$, of the damped SDOF system can be expressed as follows:

$$T_{eq}^* = T_{eq} \sqrt{1 - \kappa}$$

(25)

To calculate the equivalent damping ratio, $\xi_{eq}^*$ of the damped SDOF system, $\xi_{eq}^*$ can be expressed as follows:

$$\xi_{eq}^* = \frac{E_p}{4\pi E_s} \frac{E_p}{4\pi E_s} \left(1 - \frac{\sum E_{sid,i}}{E_s + \sum E_{sid,i}}\right) = \xi_{eq} (1 - \kappa)$$

(26)

Based on the UDR concept, substituting Eqs. (5) and (26) into Eq. (22), $\xi_{eq}^*$ can be written as follows:

Fig. 5. Flowchart of the seismic retrofit design procedure.

Fig. 6. Diagram of the structural plan and elevation.
2.4. Determination of the VED parameters

As mentioned above, for the seismic retrofit design of structures using VEDs, the effect of the VEDs and braces together can be considered as EVEDs, which can also be regarded as special VEDs. Hence, based on the UDR concept, ζ and κ can also be seen as two key design parameters to obtain the practical parameters of the EVEDs (i.e., ηe and K′e, etc.). Then, the parameters of the VEDs can be calculated accordingly. The relationships between the key design parameters and the practical parameters of the EVEDs for each story are discussed in this subsection.

It has been illustrated above that the UDR concept can be seen to be equal to the ULF concept, which means that the loss factor, ηe, of the EVEDs for each story can be set to the same constant to fully utilize each damper. Furthermore, since the loss factor is not very sensitive to the frequency dependence property of the VED, and the range for the value of ηe is smaller compared with K′/Ks, referring to Section 2.2, a reasonable assumption for the value of ηe is suggested to start the retrofit design of the existing structure in this study. The detailed design procedure is illustrated in Section 3.

The proportional stiffness distribution principle for the EVEDs is suggested to determine the storage stiffnesses of the supplemental VEDs used for the seismic retrofitting of existing structures. This principle means that the ratios of the storage stiffnesses, K′/Ks, of the EVEDs to the story stiffness, Ks,i, are assumed to be the same for each story of the target structure. This principle can lead to an approximately unchanged vibration mode shape after the installation of the VEDs, which is preferable for retrofitting.

Table 2
Shear force and story drift at the structural performance point.

<table>
<thead>
<tr>
<th>Story</th>
<th>Shear force Qi (kN)</th>
<th>Story drift θi (rad)</th>
<th>Inter-story displacement Δui (mm)</th>
<th>Story stiffness Ks,i (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2342</td>
<td>1/697</td>
<td>6.6</td>
<td>354.8</td>
</tr>
<tr>
<td>2</td>
<td>2245</td>
<td>1/347</td>
<td>12.1</td>
<td>185.5</td>
</tr>
<tr>
<td>3</td>
<td>2042</td>
<td>1/327</td>
<td>11.0</td>
<td>185.6</td>
</tr>
<tr>
<td>4</td>
<td>1667</td>
<td>1/400</td>
<td>9.0</td>
<td>185.2</td>
</tr>
<tr>
<td>5</td>
<td>1191</td>
<td>1/581</td>
<td>6.2</td>
<td>192.1</td>
</tr>
<tr>
<td>6</td>
<td>907</td>
<td>1/1050</td>
<td>4.0</td>
<td>158.8</td>
</tr>
</tbody>
</table>

(27)

Fig. 7. Relationships between story drift and shear force.

Fig. 8. Capacity spectrums and corresponding performance points.

Table 3
Pushover analysis results at the target spectral displacement point.

<table>
<thead>
<tr>
<th>Story</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear force Qi (kN)</td>
<td>3345</td>
<td>3206</td>
<td>2916</td>
<td>2381</td>
<td>1701</td>
<td>907</td>
</tr>
<tr>
<td>Story drift θi (rad)</td>
<td>1/430</td>
<td>1/211</td>
<td>1/195</td>
<td>1/232</td>
<td>1/323</td>
<td>1/588</td>
</tr>
</tbody>
</table>

Table 4
Parameters of the EVEDs for each story.

<table>
<thead>
<tr>
<th>Story</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss factor ηe</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Storage stiffness of EVEDs K′s,i (kN/mm)</td>
<td>199.6</td>
<td>104.3</td>
<td>104.4</td>
<td>104.2</td>
<td>108.1</td>
<td>89.3</td>
</tr>
<tr>
<td>Maximum damping force of EVEDs Fei,max (kN)</td>
<td>1687</td>
<td>1617</td>
<td>1471</td>
<td>1201</td>
<td>858</td>
<td>458</td>
</tr>
</tbody>
</table>

\[
\zeta_0 = \zeta_s + \zeta_\eta + \zeta_\kappa = \zeta_s + \zeta_0 (1 - \kappa) + \zeta_\kappa
\]
where $K_{e}$, $K_{s}$, respectively, and $\tilde{K}_{e}$ and $\tilde{K}_{s}$ denote the normalized versions of $K'_{e}$ and $K_{s}$, respectively, which also expresses the stiffness distribution modes of the supplemental EVEDs and the primary structure.

Since the proportional stiffness distribution principle is suggested to determine the storage stiffnesses of the supplemental EVEDs, the stiffness distribution mode of the supplemental EVEDs should be equal to that of the primary structure along the story height (i.e., $\tilde{K}_{e} = \tilde{K}_{s}$).

Then, Eq. (28) can be further derived as follows:

$$K_{e,i} = K_{s,i} \frac{K'_{e,\max} \delta^{T} \tilde{K}_{e} \delta}{K_{e,\max} \delta^{T} \tilde{K}_{s} \delta + K'_{e,\max} \delta^{T} \tilde{K}_{e} \delta}$$

Fig. 9. Layout of the VEDs at the Y-direction frames.

Fig. 10. Diagram of the response spectra.

Clearly, according to the derivations above, the parameter $\kappa/(1 - \kappa)$ can be used to proportionally determine the storage stiffnesses of the supplemental EVEDs for each story. The storage stiffness matrix, $K'_{e}$, can be written as follows:

$$K'_{e,i} = K_{s,i} \frac{K_{e,\max}}{K_{e,\max} + K'_{e,\max}}$$

Table 5 Parameters of the VEDs and braces.

<table>
<thead>
<tr>
<th>Story</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss factor $\eta_{di}$</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Storage stiffness $K'_{di}$ (kN/mm)</td>
<td>202.9</td>
<td>106.1</td>
<td>106.2</td>
<td>105.9</td>
<td>109.9</td>
<td>90.8</td>
</tr>
<tr>
<td>Maximum damping force $F_{di,\max}$ (kN)</td>
<td>1687</td>
<td>1617</td>
<td>1471</td>
<td>1201</td>
<td>858</td>
<td>458</td>
</tr>
<tr>
<td>Stiffness of braces $K_{b,i}$ (kN/mm)</td>
<td>3548</td>
<td>1855</td>
<td>1856</td>
<td>1852</td>
<td>1921</td>
<td>1588</td>
</tr>
<tr>
<td>Number of VEDs</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Loss factor $\eta_{di}$</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Storage stiffness $K'_{di}$ (kN/mm)</td>
<td>101.5</td>
<td>53.1</td>
<td>53.1</td>
<td>53.0</td>
<td>55.0</td>
<td>45.4</td>
</tr>
<tr>
<td>Maximum damping force $F_{di,\max}$ (kN)</td>
<td>844</td>
<td>809</td>
<td>736</td>
<td>601</td>
<td>429</td>
<td>229</td>
</tr>
<tr>
<td>Stiffness of braces $K_{b,i}$ (kN/mm)</td>
<td>1774</td>
<td>928</td>
<td>928</td>
<td>926</td>
<td>961</td>
<td>794</td>
</tr>
</tbody>
</table>

In practice, for seismic retrofit designs using VEDs, if a severely weak story exists in the target structure, the stiffness of the weak story...
should be increased first (e.g., by adding braces) and then the storage stiffness of the corresponding VED should be determined. Additionally, for VEDs with closed parameters, the VED types can be merged for convenience. For VEDs with extremely small parameters, the dampers are considered unnecessary and are, thus, removed.

3. UDR-based design procedure

The response reduction ratio is adopted herein to reflect the vibration control effect of the dampers and is used as a design control index in reference to the studies by Shen et al. [33] and Zhang et al. [23]. Then, the stiffness of the VEDs can be directly determined on the basis of the demand performance and without complicated trial calculations [15,21,22]. Combining the theories and concepts mentioned above, the response reduction ratio, $R$, for the EVEDs can be expressed as follows:

$R = \frac{S_s(\frac{T_{eq}}{\omega_c})}{S_{d}} = \frac{S_s(T_{eq}/\omega_c, \zeta_s, \zeta - \zeta_s)}{S_{d}}$  \hspace{1cm} (32)

where $S_{d}$ is the spectral displacement of the primary structure, and $S_s(\frac{T_{eq}}{\omega_c}, \zeta_s)$ is the spectral displacement of the damped structure, which can be further expressed using Eqs. (25) and (27).

Referring to the philosophy of the performance-based design, the seismic retrofit design procedures on the basis of the UDR concept are presented in the following steps, and the corresponding design flowchart is shown in Fig. 5.

1. For seismic retrofit design of existing structures, pushover analysis is performed and then the $Q_i - \Delta u_i$ curves can be obtained. Then, using Eqs. (15) and (16), the $S_s - S_{d}$ curve can be depicted. According to the capacity spectrum method, the structural performance point, $(S_{dp}, S_{dp})$, can be found by finding the intersection of the demand spectrum and the capacity spectrum. The story shear force, $Q_i$, and the inter-story displacement, $\Delta u_i$, of the structure at this pushover step of the structural performance point can be obtained accordingly.

2. The target performance (e.g., target roof displacement, $u_{nt}$, target story drift, $\theta_i$, etc.) of the structure should be set for the design’s seismic level. The demand response reduction ratio of the structure can be calculated as follows:

$R_{demand} = \frac{\text{Target performance}}{\text{Response of primary structure}}$  \hspace{1cm} (33)

where the response of the primary structure can be the roof displacement, $u_{nt}$, or ith story drift, $\theta_i$, at the pushover analysis step of the structural performance point. In addition, when the dampers are installed, the design condition, $R \leq R_{demand}/\lambda$, should be satisfied for the seismic retrofit design, where $\lambda$ is the safety redundancy index for increasing the reliability of the retrofitted structure [34,35].

3. Using Eqs. (32) and (33) and the design condition, $R \leq R_{demand}/\lambda$, the target spectral displacement of the damped structure can be calculated as $S_{d_{target}} = S_{dp} R_{demand}/\lambda$. Then, $Q_i$ and $\Delta u_i$ for the pushover

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Moment magnitude</th>
<th>Distance of epicentral (km)</th>
<th>Earthquake name</th>
<th>Station name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSW1</td>
<td>1976</td>
<td>6.5</td>
<td>33.32</td>
<td>Friuli_Italy-01</td>
<td>Codroipo</td>
</tr>
<tr>
<td>NSW2</td>
<td>1942</td>
<td>6.5</td>
<td>56.88</td>
<td>Borrego</td>
<td>El Centro Array #9</td>
</tr>
<tr>
<td>NSW3</td>
<td>1966</td>
<td>6.2</td>
<td>17.64</td>
<td>Parkfield</td>
<td>Cholame-Shandon Array #12</td>
</tr>
<tr>
<td>NSW4</td>
<td>1978</td>
<td>7.4</td>
<td>24.07</td>
<td>Tabas_Iran</td>
<td>Bonshorooyeh</td>
</tr>
<tr>
<td>NSW5</td>
<td>1979</td>
<td>6.5</td>
<td>23.17</td>
<td>Imperial Valley-06</td>
<td>Calipatria Fire Station</td>
</tr>
<tr>
<td>NSW6</td>
<td>1979</td>
<td>6.5</td>
<td>22.03</td>
<td>Imperial Valley-06</td>
<td>Delta</td>
</tr>
<tr>
<td>NSW7</td>
<td>1979</td>
<td>6.5</td>
<td>21.98</td>
<td>Imperial Valley-06</td>
<td>El Centro Array #13</td>
</tr>
<tr>
<td>NSW8</td>
<td>1983</td>
<td>6.4</td>
<td>23.78</td>
<td>Coalinga-01</td>
<td>Cantua Creek School</td>
</tr>
</tbody>
</table>

Fig. 11. Story drifts and shear forces of the primary structure under moderate earthquakes.
Fig. 12. Story drifts and shear forces for structure with and without VEDs.
analysis step of $S_{\text{d},i}$ can be obtained, and the corresponding story secant stiffness, $K_{\text{d},i}$, can be calculated to determine the parameter distribution of the EVEDs. For the primary structure, $T_{e,i}$ and $\zeta_s$ at the point $S_{\text{d},i}$ can also be calculated using the capacity spectrum.

4. The appropriate value of the ULF is selected using the recommended range of $\eta_e$ for the EVEDs (i.e., 0.7–1.3) in Section 2.3. Due to the frequency dependence of the stiffnesses of the VEDs (stiffness increases with increasing excitation frequency), a relatively small value of $\eta_e$ can be selected from the recommended range of $\eta_e$ for a conservative consideration. Then, the value of the UDR $\xi$ for the EVEDs can be calculated according to Eq. (9). Furthermore, the design parameter, $\kappa$, can be determined by using Eq. (32) and combining the parameters $T_{e,i}$, $\zeta_s$ and $S_{\text{d},i}$ obtained in Step 3 with the design response spectrum.

5. The parameters of the EVEDs for each story can be determined according to the formulae and discussions in Section 2.4. Then, the appropriate value of the ULF is selected using the recommended range of $\eta_e$ for the EVEDs (i.e., 0.7–1.3) in Section 2.3. Due to the frequency dependence of the stiffnesses of the VEDs (stiffness increases with increasing excitation frequency), a relatively small value of $\eta_e$ can be selected from the recommended range of $\eta_e$ for a conservative consideration. Then, the value of the UDR $\xi$ for the EVEDs can be calculated according to Eq. (9). Furthermore, the design parameter, $\kappa$, can be determined by using Eq. (32) and combining the parameters $T_{e,i}$, $\zeta_s$ and $S_{\text{d},i}$ obtained in Step 3 with the design response spectrum.

6. The existing structures are equipped with the appropriate VEDs and braces. The seismic performance of the damped structure should be checked using dynamic analysis to verify the retrofit effect. If the target performance for the design’s seismic level is satisfied, the design procedure can be stopped. If not, Steps 4–6 should be repeated until the target performance is achieved.

4. Retrofit design example

4.1. Model information

To illustrate the seismic retrofit design method using the VEDs proposed above, a typical six-story RC frame model is considered as an example structure, and the Y-direction of this structure is primarily analyzed. The plan, elevation and calculated earthquake direction of this structure are shown in Fig. 6. The section dimensions (width × height) of the beams and columns are listed in Table 1, and due to an opening in the floor at the shadow area of the 2nd story shown in Fig. 6, the section dimensions of this story are quite different from the other stories. The gravity loads on the floor are expressed as dead and live loads. The values of the dead loads for all the stories are 5.5 kN/m², and the values of the live loads for the first five stories and top story are 3 kN/m² and 5 kN/m², respectively. By considering the total dead loads, half of the live loads and calculating the weight of the structural members, the mass of each story is also determined and given in Table 1. According to the modal analysis results, the fundamental period of this structure is 1.27 s.

This RC frame was designed with the admissible tension method and for a moderate earthquake. According to the Chinese code for the seismic design of buildings [36], the peak ground acceleration (PGA) for the fortification earthquake is 200 gal. The site characteristic period, $T_{0,\text{r}}$, and structural inherent damping ratio, $\zeta_{0,\text{r}}$, are 0.4 s and 0.05, respectively. The design response spectrum is expressed as follows:

![Hysteretic loops of the EVEDs of each story under a moderate earthquake of the seismic wave NSW 1.](image)
This structure is built as a 3D beam-column element model and the program SAP2000 is adopted. The moment hinges are set to both sides of the beams to simulate the plastic behavior of this element. Accordingly, the P-M-M interactions are considered at both the ends of the columns. The trilinear moment-rotation backbone curves are used for the plastic rotational hinges. A concrete cubic compressive strength of 30 MPa and longitudinal steel bars and stirrups with yielding strengths of 335 MPa are set for the structure.

4.2. Design procedure for the exemplified structure

The pushover analysis is performed on the Y-direction of the primary structure to obtain the performance of this structure, and the corresponding lateral load pattern of the pushover analysis is the first mode distribution. The relationships between the story shear force, \( Q_i \), and the story drift, \( \xi_i \) (i.e., \( Q_i - \xi_i \) curves) are obtained, as shown in Fig. 7. Then, the corresponding \( S_{\xi_1} - S_{\xi_2} \) curve, which is called the capacity spectrum, can be calculated, as shown in Fig. 8. Using the capacity spectrum method, the structural performance point, \( (S_{\xi_2}, S_{\xi_1}) \) is found to be (65.0 mm, 113.0 gal). Accordingly, \( Q_i \) and \( \xi_i \) for the pushover analysis step of the structural performance point are listed in Table 2 and marked as red points on the corresponding response spectra of these waves, and the normalized design response spectrum, as shown in Fig. 10. Table 6 lists the characteristics of the natural seismic waves.

The time history analysis is first performed under a moderate earthquake (design earthquake intensity) for the primary structure. The PGA for a moderate earthquake is 200 gal. The story drifts and story shear forces under the dynamic analyses of the moderate earthquakes are shown in Fig. 11. It can be seen that the average story drifts for several stories under the moderate earthquakes are beyond the target story drift of 1/300. Then, the VEDs with the parameters listed above are installed at suitable places on the primary structure using the corresponding braces.

For the damped structure, time history analyses are performed under different seismic levels. The PGAs of frequent and rare earthquakes are 70 gal and 400 gal, respectively. Accordingly, the target drifts of frequent and rare earthquakes are set to 1/800 and 1/150, respectively. In addition, for comparison, the dynamic analyses under different seismic levels are also conducted on the primary structure. Under different seismic levels, the average story drifts and shear forces for the structure with and without VEDs are presented in Fig. 12. The results show that the displacement and shear force responses of the structure are effectively reduced and that the target performances are satisfied under different seismic levels, which verifies that the parameters determined using the UDR concept are reasonable.

As mentioned above, in this study, the VED and its corresponding brace are represented by an EVED to consider the effects of both of these components. Under a moderate earthquake, the hysteretic loops of the EVEDs for each story are checked for seismic wave NSW 1, as shown in Fig. 13. The loss factors of the EVEDs for each story are also expressed in Fig. 13. It can be seen that the loss factors of the EVEDs are approximately equal for every story. The full hysteretic loops show effective energy dissipation of the EVEDs, and the approximately uniform loss factors validate the UDR concept.

5. Conclusions

A simple seismic retrofit design method for elastoplastic structures using VEDs is proposed on the basis of the uniform damping ratio concept. The uniform damping ratio concept gives rise to design formulas for damped structures with VEDs. The parameter distribution principle is also established. A six-story RC frame is adopted to illustrate the seismic retrofit design procedure. Our conclusions are summarized as follows:

1. The uniform damping ratio concept can make full utilization of dampers and lead to uncoupled stiffness and damping characteristic parameters of VEDs, making the design of VEDs simple and convenient.
2. The response reduction ratio is employed as the design target to avoid a complicated trial calculation process in the proposed design.
procedure.

3. The seismic response of the instance structure can be mitigated as expected when VEDs are equipped using the proposed design procedure, which proves that the UDR-based design method is feasible and reasonable.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (No. 51978525 & 51778490), the Key Program for International S&T Cooperation Projects of China (No. 2016YFE0127600), the Fundamental Research Funds for the Central Universities (No. 22120180064), and the Natural Science Foundation of Shandong Province (No. ZR2018EE033).

References