A SEISMIC RETROFIT METHOD FOR STEEL FRAMES WITH VISCOUS DAMPERS

George A. PAPAGIANNOPOULOS¹, George D. HATZIGEORGIOU², Nikos G. PNEVMATIKOS³

ABSTRACT

The purpose of this paper is to propose a seismic retrofit method for steel framed structures having supplemental linear or non-linear viscous dampers. The method starts with the numerical identification of modal damping ratios for specific seismic deformation levels of the steel framed structure. Employing these modal damping ratios, the steel framed structure is then subjected to linear elastic time-history analyses, using recorded accelerograms, and maximum values for interstorey velocities and storey shears are computed. Damping coefficients of the linear or the non-linear viscous dampers are determined by a specific formula where correction factors to interstorey velocities and storey shears are applied. To demonstrate the proposed method, a steel framed structure retrofitted with linear or non-linear viscous dampers is subjected to non-linear inelastic time-history analyses and interstorey drifts, interstorey velocities and damper forces are evaluated.

Keywords: Modal damping ratios; interstorey velocity; steel frames; seismic retrofit; viscous dampers

1. INTRODUCTION

A widespread method to obtain the seismic retrofit of existing steel structures, maintaining their geometric dimensions unchanged, involves the incorporation of fluid viscous dampers. Researchers have proposed several procedures for the seismic retrofit of steel structures using linear or non-linear fluid viscous dampers, e.g., Uriz and Whittaker (2001), Martinez-Rodrigo and Romero (2003), Lindorfer and Henkel (2006), Sorace and Terenzi (2009), Wang and Mahin (2017). In these retrofit procedures, the establishment of an equivalent (effective) damping ratio that should essentially lead to a specific target seismic performance, e.g., to a maximum inter-storey drift (IDR) is needed. The damping coefficient of the dampers can be easily determined to correspond to this equivalent damping ratio and the fundamental dynamic properties of the structure such as the vibration mode shape and the natural period. Existing formulae in literature provide this equivalent damping ratio for either linear or non-linear viscous dampers taking into account their configuration, i.e., diagonal, toggle brace etc. (Hwang et al. 2008). Other approaches to find this equivalent damping ratio have been proposed by Lee (2004), Occhiuzzi (2009) and references therein, and Diotallevi et al. (2012). A comparison of the most popular methods for computing the equivalent damping ratio of structures with damping systems has been performed by Charney and McNamara (2008).

The variation (distribution) of maximum interstorey velocities has been recognized as a key parameter for the evaluation of the along-height effectiveness and demand of viscous dampers (Adachi et al. 2013). This variation (distribution) seems to depend mainly on the modes (number of stories) of the structure under consideration. In building codes, e.g., ASCE 7-10 (2010), peak (design) interstorey velocity (IV) is approximately considered for the fundamental and higher modes using the design (maximum) IDR. This approximation permits the calculation of the maximum damping forces in terms

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of the design IDR. Moreover, building codes, e.g., ASCE 7-10 (2010) accept that the most effective way of placing viscous dampers is at storeys where large IDRs are exhibited. Therefore, the maximum IDR is used to estimate the maximum IV, without, however, providing an insight about the real relationship of IDR and IV maximum values. In literature so far, a relationship between IDR and IV has been formulated either by using simplified building models and the first mode shape (Palermo et al. 2016, 2017) or by employing single-degree-of-freedom systems and their maximum displacement (Hatzigeorgiou and Papagiannopoulos 2012, Hatzigeorgiou and Pnevmatikos 2014). Recently, Logotheti et al. (2018) proposed a formula that provides IV for specific IDR ranges of steel moment resisting frames (MRF).

This paper proposes a seismic retrofit method for steel MRFs with viscous dampers. The method starts by using equivalent modal damping ratios given for specific seismic deformation levels (in terms of IDR) of steel MRFs (Papagiannopoulos and Beskos 2010). Then, these modal damping ratios are employed in the context of linear elastic time-history analysis of the steel MRF using recorded accelerograms. From this analysis, the along-the-height maximum values for IVs and storey shears are found. Damping coefficients of viscous dampers are finally determined per storey using the aforementioned storey shears and IVs, the angle of orientation of the damper, and two correction factors. These correction factors serve to relate: a) the expected inelastic IVs for a specific IDR range with the elastic IVs and b) the expected inelastic story shears with the elastic story shears.

The proposed retrofit method is applied to a 12-storey – 4-bay steel MRF. This MRF is retrofitted either with linear viscous dampers or with non-linear ones and targets a specific IDR. The retrofitted frames are then subjected to non-linear time history analyses and results for IDR, IV and damper forces are obtained. On the basis of these results, the effectiveness of the proposed method can be discussed.

2. DETERMINATION OF THE DAMPING COEFFICIENT OF THE DAMPERS

The proposed retrofit method is presented for a 12-storey – 4-bay steel MRF. This MRF is regular orthogonal with storey height equal to 3.0 m and bay width equal to 5.0 m. The total dead and live load on beams is 27.5 kN/m. Diaphragm action is assumed at every floor due to the presence of a composite slab. The frame is designed according to Eurocodes 3 (2009) and 8 (2009), employing standard HEB, and IPE sections for columns and beams, respectively, and S275 steel grade. The design seismic load has been calculated using the design spectrum of Eurocode 8 (2009) that corresponds to peak ground acceleration (PGA) of 0.24g, soil class B and behavior factor equal to 3. Fixed-base conditions are assumed and column sections are oriented with their strong axis perpendicular to the plane of the frame. The sections of the frame are given in Table 1. In that table section expressions of the form 340 / 360 / 360 / 360 / 340 – 450 (1-4) 300 / 320 / 320 / 320 / 300 – 400 (9-12) mean that for storeys 1 to 4 exterior and interior columns are HEB 340 and 360, respectively, and all beams are IPE 450. The first four periods of this MRF are $T_1 = 1.50 \text{ sec}$, $T_2 = 0.50 \text{ sec}$, $T_3 = 0.29 \text{ sec}$ and $T_4 = 0.20 \text{ sec}$.

<table>
<thead>
<tr>
<th>Sections : columns (HEB) – beams (IPE)</th>
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<tbody>
<tr>
<td>and 300 / 320 / 320 / 320 / 300 – 400 (9-12)</td>
</tr>
</tbody>
</table>

Linear or non-linear viscous dampers (Taylor Devices 2016) are used for the retrofit of this MRF, thus, the aforementioned periods remain unchanged. Taking into account that damper forces are related to IV values, dimensioning of a viscous damper in terms of its damping coefficient $C$ can be performed on the basis of the following equation (Logotheti et al. 2018)

$$C = k \cdot V_{\text{storey}} / (IV^{1-\alpha} \cdot \cos^2\theta)$$

(1)

In Equation 1, $V_{\text{storey}}$ is the storey shear, $k$ is the percentage of storey shear that should be resisted by the viscous damper, $1-\alpha$ is an exponent (equals to 1 for a linear damper and less than 1 for a non-linear one), $\theta$ is the angle of inclination of the damper, and IV is the interstorey velocity given for specific
IDR levels in Logotheti et al. (2018). Calculation of damping coefficients $C$ is performed on the basis of Equation 1 for selected modal damping ratios and targets IDR = 0.7 – 0.9%.

### 2.1 Equivalent modal damping ratios from non-linear inelastic response

Non-linear inelastic time-history analyses of the 12-storey – 4-bay steel MRF under study are performed, employing the accelerograms of Table 2. These accelerograms were recorded at the proximity of faults (near-field earthquakes). Several details about these earthquake ground motions concerning location, date, recording station, moment magnitude $M_w$, soil type and PGA can also be found in Table 2. Regarding soil type, the abbreviations HR and SL correspond to hard rock and soil / alluvium, respectively.

The equivalent modal damping ratios for the aforementioned steel MRF are computed using the damping identification model of Papagiannopoulos and Beskos (2010). These equivalent modal damping ratios have been quantified from the non-linear inelastic response of the steel MRF and they are deformation dependent, i.e., they are computed so as to satisfy specific deformation limits. For the purposes of this work, equivalent modal damping ratios for IDR = 0.7 – 0.9% are found and are given in Table 3 for the first four modes of the steel MRF.

#### Table 2. Set of accelerograms used

<table>
<thead>
<tr>
<th>No.</th>
<th>Earthquake, Location</th>
<th>Date</th>
<th>Recording Station</th>
<th>$M_w$</th>
<th>Soil Type</th>
<th>PGA (m/sec$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>San Fernando, U.S.A.</td>
<td>09/02/1971</td>
<td>Pacoima Dam</td>
<td>6.6</td>
<td>HR</td>
<td>12.03</td>
</tr>
<tr>
<td>2.</td>
<td>Tabas, Iran</td>
<td>16/09/1978</td>
<td>Tabas</td>
<td>7.1</td>
<td>SL</td>
<td>9.09</td>
</tr>
<tr>
<td>3.</td>
<td>Imperial Valley, U.S.A.</td>
<td>15/10/1979</td>
<td>El Centro Array 7</td>
<td>6.5</td>
<td>SL</td>
<td>4.55</td>
</tr>
<tr>
<td>5.</td>
<td>Loma Prieta, U.S.A.</td>
<td>17/10/1989</td>
<td>Los Gatos</td>
<td>7.0</td>
<td>HR</td>
<td>5.53</td>
</tr>
<tr>
<td>6.</td>
<td>Erzincan, Turkey</td>
<td>13/03/1992</td>
<td>Erzincan</td>
<td>6.7</td>
<td>SL</td>
<td>5.05</td>
</tr>
<tr>
<td>8.</td>
<td>Northridge, U.S.A.</td>
<td>17/01/1994</td>
<td>Rinaldi Receiving St.</td>
<td>6.7</td>
<td>SL</td>
<td>8.22</td>
</tr>
<tr>
<td>9.</td>
<td>Northridge, U.S.A.</td>
<td>17/01/1994</td>
<td>Sylmar Converter St.</td>
<td>6.7</td>
<td>SL</td>
<td>6.00</td>
</tr>
<tr>
<td>10.</td>
<td>Kobe, Japan</td>
<td>17/01/1995</td>
<td>Takatori</td>
<td>6.9</td>
<td>SL</td>
<td>6.00</td>
</tr>
<tr>
<td>11.</td>
<td>Chi-Chi, Taiwan</td>
<td>20/09/1999</td>
<td>TCU 052</td>
<td>7.6</td>
<td>SL</td>
<td>3.42</td>
</tr>
</tbody>
</table>

#### Table 3. Equivalent modal damping ratios

<table>
<thead>
<tr>
<th>Accelerogram No.</th>
<th>Equivalent modal damping ratio</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.93</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.71</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.89</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.77</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.34</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.71</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.92</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.67</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.84</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.46</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

In Table 3, values of modal damping ratios equal to 0.99 essentially mean that the corresponding modes behave statically but have to be taken into account for accurate response calculations. From the values of Table 3, 2% percent damping has to be subtracted in order to take into account the inherent
viscous damping of the steel MRF in the linear elastic range of response.

2.2 Linear elastic time history analysis with equivalent modal damping ratios

Linear elastic time history analyses of the MRF using the modal damping ratios of Table 3 and the accelerograms of Table 2 are performed. The along-the-height maximum storey shears and maximum IDRs and IVs are found. These maximum storey shears can be considered as the forces required to obtain the IDR = 0.7 – 0.9% restriction. The maximum height-wise IDRs and IVs of the MRF for each one of the accelerograms of Table 2 are shown in Figures 1 and 2, respectively. Mean values for IDR and IV are also shown in Figures 1 and 2.

To estimate the expected inelastic IV values for specific IDR levels of MRFs, without needing to perform non-linear inelastic seismic analyses, Equation 2 can be used. This equation provides IV values for the IDR = 0.7 – 0.9% limit, where H is the storey number which can take values from 1 to 20.

\[
IV = 0.093 - 0.0007 \cdot H + 1.81 \cdot 10^{-10} \cdot e^H - 0.027 / H
\]  

(2)

This equation has been found after statistical analysis of the seismic response results for steel MRFs that relate IV with an IDR range (Logotheti et al. 2018). Figure 3 provides such a plot for the case of 0.7% < IDR ≤ 1.5%. Isolating the maximum and minimum values of IV in Figure 3, one constructs Figure 4, where the aforementioned Equation 2 is shown with a black line.
In Figures 1 and 2, the IDR = 0.7 – 0.9% limit as well as the values of IV from Equation 2 are also added. From Figure 2, it becomes evident that the IV values do not obey to Equation 2 because the modal damping ratios have been computed to satisfy an IDR but not an IV. Better results would be obtained if these modal damping ratios were computed for both IDR = 0.7 – 0.9% and IV = 0.065 – 0.085 m/sec (derived from Equation 2). On the other hand, Figure 1 reveals that the IDR values behave in a controlled way, satisfying the desired limits.

2.3 Modifications performed to calculate damping coefficients

Equation 1 that provides the damping coefficients of the dampers, cannot be used without performing the necessary modifications. More specifically, the modifications include the application of correction factors to $V_{\text{storey}}$ and IV. These modifications intend indirectly to take into account the dependence of $V_{\text{storey}}$ on elastic and damping forces and of IV on IDR.

To correlate IV values provided by Equation 2 with the elastic IV values shown in Figure 2, a simple correction factor $\lambda_1$ which is a polynomial function of height is used. This factor $\lambda_1$ multiplies the elastic IV values and targets the values 0.065 – 0.085 m/sec (derived from Equation 2). The general formula of this factor is found to be of the form of Equation 3. Parameters a-e in Equation 3 can easily be selected to correspond to the aforementioned IV values. The mean values of these parameters are: $a = 0.893$, $b = -0.539$, $c = 0.355$, $d = -0.168$ and $e = 0.023$. The correlation coefficient of the proposed Equation 3 for $\lambda_1$ is 0.71.

$$\lambda_{1,2} = a + b \cdot H + c \cdot H^2 + d \cdot H^{2.5} + e \cdot H^3$$ (3)

A heavily damped multi-degree-of-freedom elastic system exhibits its maximum storey shear force not at the state of its maximum displacement but at a state that essentially involves both displacement and velocity (Sadek et al. 2000). Therefore, maximum storey shear force has to be found by means of the absolute acceleration of the storey times the storey mass. To obtain this storey shear force, $V_{\text{storey}}$ in Equation 1 is multiplied by a correction factor $\lambda_2$ in the form of Equation 3, where parameters a-e are now different. The mean values of these parameters are: $a = 1.279$, $b = 0.634$, $c = -0.477$, $d = 0.243$ and $e = -0.033$. The correlation coefficient of the proposed Equation 3 for $\lambda_2$ is 0.73.

After the application of the correction factors $\lambda_1$ and $\lambda_2$ to IV and $V_{\text{storey}}$, respectively, one gets the damping coefficients for linear ($\alpha = 0$ in Equation 1) or non-linear ($\alpha = 0.6$ in Equation 1), viscous dampers. These coefficients are given in Figures 5 and 6 for linear and non-linear viscous dampers, respectively. It should be noted that in view of further investigation, $k = 1$ has been conservatively considered in Equation 1.

On the basis of the size of viscous dampers required to satisfy the damping coefficients of Figures 5 and 6 as well as of the fact that dampers of large size would increase the cost of retrofit, it was decided to install to the frame under study two smaller dampers in the outer bays and at all storeys.

![Figure 5. Damping coefficients for linear viscous dampers](image)

![Figure 6. Damping coefficients for non-linear viscous dampers](image)
3. RESULTS FOR THE RETROFITTED FRAME

Results from non-linear inelastic time-history analyses of the retrofitted MRF, subjected to the accelerograms of Table 2, are presented in the following. These results involve the maximum height-wise values for IDRs, IVs and forces of the viscous dampers. For comparison purposes, mean IDR and IV values as well as target IDR and IV (using Equation 2) values are also shown. According to ASCE 7-10 (2010) and its recent modifications, mean (average) values are permitted to be used since at least seven ground motions are used. Linear and non-linear viscous dampers having maximum allowable force 1500 kN and 1000 kN, respectively, have been considered.

Figures 7 and 8 display the height-wise variation of IDR and IV for the case of linear viscous dampers. From these figures it becomes evident that in terms of mean values, both IDR and IV satisfy the expected limits. However, a closer look at Figures 7 and 8 reveals that for the accelerograms No.1, 8, 9 and 10, the limit values of IDR = 0.9% and of IV = 0.085 m/sec are surpassed.

Attempting to interpret this violation of IDR and IV limit values, the height-wise variation of the maximum forces of the dampers and their mean values are shown in Figure 9. Figure 9 reveals that for the accelerograms No.1, 8, 9 and 10 the maximum allowable force of the dampers has been surpassed, while the mean damper forces are below 1500 kN. Even if the maximum allowable force of the dampers is increased, significant increases in axial forces of columns occurred as a result of the damper forces, leading to undesired plastic hinge formations at the top of the columns of the lower storeys. These plastic hinge formations are indicatively shown for the case of accelerogram No.8 in Figure 10 (right). The plastic hinge formations to the frame without dampers is also shown in Figure 10 (left) for comparison purposes.
Figures 11 and 12 display the height-wise variation of IDR and IV for the case of non-linear viscous dampers and it becomes evident that, in terms of mean values, the expected limits for IDR and IV are not satisfied. A closer inspection at Figure 11 reveals that for accelerograms No. 1, 4, 8, 10, the limit values of IDR = 0.9% are significantly surpassed, respectively. In Figure 12, the limit value of IV = 0.085 m/sec is significantly surpassed for all accelerograms.

Attempting to interpret this violation of IDR and IV limit values, the maximum damper forces and their mean values are shown in Figure 13. From this figure it can be concluded that for the accelerograms No.1, 8, 9 and 10 the maximum allowable force of the dampers of the lower storeys has been surpassed, while the mean damper forces are below 1000 kN. However, significant increases in axial forces of columns occurred as a result of the damper forces, leading to undesired plastic hinge formations at the top of the columns of the lower storeys. These plastic hinge formations are indicatively shown for the case of accelerogram No.10 in Figure 14.

The plastic hinge formations due to forces transmitted to the columns by the linear or the non-linear viscous dampers has been noted in literature (Uriz and Whittaker 2001, Seo et al. 2014, Dong et al. 2016) and should be viewed with caution along the lines of the overall frame retrofit in view of probable soft storey formation.

4. CONCLUSIONS

From the results presented in Figures 7-14, it can be claimed that the proposed retrofit method seems to work better in the case of linear viscous dampers, offering controlled IDR, IV and damper forces results. On the contrary, for the case of non-linear viscous dampers, the proposed retrofit method fails
to satisfy IDR and IV limits and should be re-visited. Corrections factors have been also considered to be represented by simple polynomial functions and most likely have to be revised with respect to their correlation coefficients. Finally, it should be also recalled that dimensioning of the viscous dampers was performed for $k = 1$, a consideration that may be conservative. Nevertheless, the effectiveness of the proposed retrofit method is evident from Figures 10 and 14 (worst cases from the analyses performed), where plastic hinge formations to frames in the presence of dampers take place in a smaller number of elements in comparison to the corresponding formations to frames without dampers.

5. REFERENCES


ASCE 7-10 (2010), Minimum design loads for buildings and other structures, American Society of Civil Engineers, Virginia, USA.


