COMPARING THE PERFORMANCES OF FRAMED BUILDINGS EQUIPPED WITH DIFFERENT DAMPERS CONFIGURATIONS

M. Palermo\textsuperscript{1}, V. Laghi\textsuperscript{2}, S. Silvestri\textsuperscript{3}, G. Gasparini\textsuperscript{4}, T. Trombetti\textsuperscript{5}

ABSTRACT

The present work presents a design procedure to compare the effectiveness of different viscous dampers placement in framed structures, in terms of system cost and effectiveness. The analytical procedure is developed from the selection of a specific deformed shape for the first vibration mode of the system, to evaluate the corresponding period of vibration and damping ratio through an equivalent single degree of freedom system. Once a target damping ratio and the corresponding desired reduction in the frame seismic response is assigned, the structure peak response registered under specific earthquake levels can be evaluated. From these parameters, the total cost expressed in terms of maximum required damper forces and its effectiveness expressed as the ratio of the total cost and the benefit (i.e. base shear reduction) are evaluated for each configuration of dampers. The procedure is finally specified for the case of linear along the height peak displacement profile for three specific dampers configuration: (i) inter-storey placement, referred to as stiffness proportional damping SPD; (ii) fixed point placement, referred to as mass proportional damping MPD; (iii) dissipative tower DT. The actual seismic behaviors of the designed structures are verified through non-linear time-history analyses.

\textsuperscript{1}Ph.D graduate researcher, Dept. of Civil and Environmental Engineering, University of Bologna, Italy (email: michele.palermo7@unibo.it)  
\textsuperscript{2}Ph.D student, Dept. of Civil and Environmental Engineering, University of Bologna, Italy  
\textsuperscript{3}Associate professor, Dept. of Civil and Environmental Engineering, University of Bologna, Italy  
\textsuperscript{4}Assistant Professor, Dept. of Civil and Environmental Engineering, University of Bologna, Italy  
\textsuperscript{5}Associate professor, Dept. of Civil and Environmental Engineering, University of Bologna, Italy

Palermo M, Laghi V, Silvestri S, Gasparini G, Trombetti T. A design procedure to compare the performances of framed buildings equipped with different dampers configurations. Proceedings of the 11\textsuperscript{th} National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.
Comparing the performances of framed buildings equipped with different dampers configurations

M. Palermo, V. Laghi, S. Silvestri, G. Gasparini, T. Trombetti

ABSTRACT

The present work presents a design procedure to compare the effectiveness of different viscous dampers placement in framed structures, in terms of system cost and effectiveness. The analytical procedure is developed from the selection of a specific deformed shape for the first vibration mode of the system, to evaluate the corresponding period of vibration and damping ratio through an equivalent single degree of freedom system. Once a target damping ratio and the corresponding desired reduction in the frame seismic response is assigned, the structure peak response registered under specific earthquake levels can be evaluated. From these parameters, the total cost expressed in terms of maximum required damper forces and its effectiveness expressed as the ratio of the total cost and the benefit (i.e. base shear reduction) are evaluated for each configuration of dampers. The procedure is finally specified for the case of linear along the height peak displacement profile for three specific dampers configuration: (i) inter-storey placement, referred to as stiffness proportional damping SPD; (ii) fixed point placement, referred to as mass proportional damping MPD; (iii) dissipative tower DT. The actual seismic behaviors of the designed structures are verified through non-linear time-history analyses.

Introduction

In the past decades, the insertion of viscous dampers in building structures has been used to reduce the seismic demand through the dissipation of part of the kinetic energy transmitted by an earthquake to the structure [1]. However, most of the research works on viscous dampers [2-8] aims at developing sophisticated numerical algorithms for dampers optimization, in terms of size and location, which are however unfeasible to be used by designers due to the computational expertise and time required.

Concerning structural analysis itself, it is common practice to refer to simple tools (such as response spectrum concept and the equivalent static analysis method) to understand and control the structural behavior under seismic excitation, even though these methods are surpassed by more sophisticated procedures (such as non-linear time-history analysis using appropriate earthquake ground motion records).

As far as the seismic design of structures equipped with viscous dampers is concerned, alternative approaches leading to practical design procedures for the sizing of the additional devices have been proposed in the last years: (i) Lopez Garcia presented a simple algorithm for optimal damper configuration assuming constant inter-storey height and straight-line first modal shape [6]; (ii) Christopoulos and Filiatrault estimated damping coefficient through trial and error procedure [9]; (iii) some of the authors developed a direct design approach called “five-step procedure” and further simplified in a “direct five-step procedure” in the latest works [10-12]. The last procedure in particular aims at guiding the professional engineers from the choice of a target reduction in the seismic response of a structural system to the identification of the corresponding damping ratio and the mechanical characteristics, in terms of damping coefficient values for chosen damping exponent, of the viscous dampers commercially available. The five-
step procedure is only applicable to the so-called inter-storey damper placement and fixed point damper placement.

In the present work, an alternative design procedure applicable to a generic damper placement is proposed. It is grounded on an Equivalent Single Degree Of Freedom system idealization and allows to rapidly compare the effectiveness of different dampers configuration under the same performance objective.

The ESDOF procedure

In the present section, the proposed design procedure is explained in each of the steps allowing to compute the damping coefficient $c_i$ required to guarantee the target seismic response in terms of reduction in the actions induced by the earthquake excitation. The Equivalent Single Degree Of Freedom (ESDOF) procedure is articulated in the following steps:

- **STEP 1: kinematic assumptions**
  First the deformed shape under seismic excitation is assumed in terms of a deformed shape vector $\phi$. Once the kinematics is assumed, it is possible to compute the horizontal storey drifts in terms of a single variable, such as the inter-storey drift $\delta_i$.

- **STEP 2: horizontal equilibrium in free vibration**
  Under free vibration, the multi degree of freedom system MDOF dynamic equilibrium equation along the horizontal direction might be expressed:

  \[ F_I + F_D + F_S = 0 \]

  where $F_I$, $F_D$ and $F_S$ are respectively the inertia forces, the damping forces and the elastic resisting forces.

  Or in matrix form:

  \[ M \ddot{u} + C \dot{u} + K u = 0 \]

  where $M$, $C$ and $K$ are the mass, damping and stiffness matrices, while $\ddot{u}$, $\dot{u}$ and $u$ are horizontal acceleration, velocity and displacement vectors, respectively.

- **STEP 3: Equivalent SDOF system**
  Thanks to the kinematic assumption, the dynamic equilibrium equation of the MDOF system might be expressed with the equation of an equivalent SDOF system having mass matrix $M^*$, damping matrix $C^*$ and stiffness matrix $K^*$:

  \[ M^* \ddot{u} + C^* \dot{u} + K^* u = 0 \]

  The natural frequency and damping ratio of the equivalent SDOF system might be calculated:
\[ \omega_{SDOF} = \sqrt{\frac{K^*}{M^*}} \]  
\[ \xi_{SDOF} = \frac{C^*}{2 \cdot M^* \cdot \omega_{SDOF}} \]  

- **STEP 4: target performance**

The target performance is expressed in terms of reduction in the seismic response (i.e. the base shear) of the system equipped with viscous dampers with respect to the bare frame. The percentage of reduction is evaluated through the formulation proposed by Bommer et al. [13]:

\[ \eta = \sqrt{\frac{10}{5 + \xi}} \]  

where \( \eta \) is the damping reduction factor and \( \xi = \xi_{in} + \xi_v \) is the equivalent damping ratio as the sum of the inherent damping ratio \( \xi_{in} \) and viscous damping ratio \( \xi_v \) resulted from the added viscous dampers.

- **STEP 5: linear damping coefficient \( c_i \)**

By imposing a specific target damping ratio \( \xi_{SDOF} = \bar{\xi} \) corresponding to a target reduction \( \eta \) (Eq. 6), and assuming a certain damper allocation, from Eq. 5 it is possible to compute the values of all damping coefficients \( c_i \) of the added viscous dampers.

- **STEP 6: peak seismic response**

The peak response of the structure equipped with linear dampers might be evaluated in terms by means of the following equation [12]:

\[ V_{base,\xi} = \beta \cdot m_{tot} \cdot S_{a,\xi} = \beta \cdot \sum_{j=1}^{N} m_j \cdot \ddot{u}_j \]  

Assuming the following relation between the peak storey acceleration, velocity and displacement through the fundamental frequency:

\[ \ddot{u}_i = \omega_{SDOF} \cdot \dot{u}_i = \omega_{SDOF}^2 \cdot u_i \]  

Eq. (7) may be rewritten as follows:

\[ V_{base,\xi} = \beta \cdot m_{tot} \cdot S_{a,\xi} = \beta \cdot \omega_{SDOF}^2 \cdot \sum_{j=1}^{N} m_j \cdot u_j \]  

By solving Eq. 7 for the specific kinematic assumption, the peak inter-storey drift \( \delta_i \) and velocity \( \dot{\delta}_i \) can be obtained, with whom the peak damper forces in each damper might be
- **Index of effectiveness**

The presented procedure is a useful tool to compare the effectiveness of different dampers configurations applied to the same frame structure, once the target reduction response is imposed. One possible parameter to be used to assess the effectiveness of the different solutions proposed might be the ratio between the “benefit” $B_{tot}$ induced by the added devices, expressed as the reduction in the base shear, and the total “cost” $C_{tot}$ expressed as the sum of the peak damper forces ($n_d$ is the total number of dampers in the system):

$$IE = \frac{B_{tot}}{C_{tot}}$$ (10)

$$C_{tot} = \sum_{j=1}^{n_d} F_{D,j}$$ (11)

$$B_{tot} = V_{\text{base,5\%}} - V_{\text{base,3\%}}$$ (12)

**Applicative examples to relevant systems**

In this section, the ESDOF design procedure is applied to three different systems which are then compared through their effectiveness in terms of “cost” and “benefit” evaluated. It should be noted that the solutions proposed are referring to the same $N$-storey bare frame system, having constant inter-storey height $h$ and bay width $b$ as well as uniform lateral stiffness $k$ and uniform floor mass $m$. A linear along-the-height horizontal displacement profile is assumed. The following systems have been analyzed (Figure 1):

- **DT – Dissipative Tower**: frame structure connected to a “dissipative tower”, considered as an external strongback system equipped with two equal viscous dampers at the base.
- **SPD – Stiffness-Proportional Dampers**: frame structure equipped with equal inter-storey dampers.
- **MPD – Mass-Proportional Dampers**: frame structure connected through equal fixed-point dampers to an external rigid core.
Figure 1. (a) DT system; (b) SPD system; (c) MPD system.

The analytical expressions of the different steps of the ESDOF procedure as specified for the three systems are summarized in Table 1.

<table>
<thead>
<tr>
<th>Step</th>
<th>DT system</th>
<th>SPD system</th>
<th>MPD system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Linear deformed shape</td>
<td>Linear deformed shape</td>
<td>Linear deformed shape</td>
</tr>
</tbody>
</table>
| 2    | moments equilibrium around O: \[
\sum_{j=1}^{N} m \cdot h^2 \cdot j^2 \cdot \phi + \left( c \cdot \frac{b^2}{2} \right) \cdot \phi + \left( k \cdot h^2 \cdot N \right) \cdot \phi = 0
\] | horizontal forces equilibrium: \[
\sum_{j=1}^{N} m \cdot j \cdot \delta + c \cdot \delta + k \cdot \delta = 0
\] | horizontal forces equilibrium: \[
\sum_{j=1}^{N} m \cdot j \cdot \delta + \sum_{j=1}^{N} c \cdot j \cdot \delta + k \cdot \delta = 0
\] |
| 3    | \( \omega_{SDOF} = \frac{k}{m \cdot (N+1) \cdot (2N+1)} \) \[
\xi_{SDOF} = \frac{c}{m \cdot \omega_{SDOF} \cdot N \cdot (N+1) \left( \frac{B}{h} \right)^2}
\] | \( \omega_{SDOF} = \frac{k}{m \cdot N \cdot (N+1)} \) \[
\xi_{SDOF} = \frac{c}{m \cdot \omega_{SDOF} \cdot N \cdot (N+1)}
\] | \( \omega_{SDOF} = \frac{k}{2 \cdot m \cdot N \cdot (N+1)} \) \[
\xi_{SDOF} = \frac{c}{2 \cdot m \cdot \omega_{SDOF}}
\] |
| 4    | \( \eta = \eta \) \[
\xi = \xi
\] | \( \eta = \eta \) \[
\xi = \xi
\] | \( \eta = \eta \) \[
\xi = \xi
\] |
### Numerical simulations

#### The input ground motions and the dynamic analyses

In order to state the validation of the proposed procedure, some earthquake numerical simulations are developed considering four 5-storey structures analyzed by means of Finite Element method, implemented using the SAP 2000 computer software (Figure 2).

The reference bare frame (NAKED model) is compared in terms of seismic response with the same frame coupled with an external strongback, which acts as “dissipative tower” (DT model), as well as the frame equipped with SPD dampers (SPD model) and MPD dampers (MPD model).

The frame structure used as bare reference is modeled as a shear-type steel frame with HE320B columns cross-section profile and IPE200 beams cross-section profile. The floor mass is considered uniform and equal to 353 kN, while the inter-storey height \( h \) and bay width \( b \) are set to 3 m and 6 m respectively. As far as the external strongback is concerned, it is realized as a stiff steel frame hinged at the base and connected at each floor by means of infinitely rigid members. The linear viscous dampers are modelled according to the ESDOF procedure assuming a target reduction factor equal to \( \bar{\eta} = 0.5 \).

Dynamic time-history analyses are performed applying at the base of the structures an ensemble of 7 artificial accelerograms generated using the software SIMQKE match the elastic response spectrum provided by the Italian Code [14] for a residential building located in Norcia, central Italy.

---

<table>
<thead>
<tr>
<th>Step 5</th>
<th>( c_D = 2 \cdot \xi \cdot m_\text{tot} \cdot \omega_l \cdot \left( \frac{h}{B} \right)^2 )</th>
<th>( c_{\text{SPD}} = \frac{\xi \cdot m_\text{tot} \cdot \omega_{\text{SDOF}} \cdot (N+1)}{\cos^2 \theta} )</th>
<th>( c_{\text{MPD}} = \frac{2 \cdot \xi \cdot m_\text{tot} \cdot \omega_{\text{SDOF}}}{N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 6</td>
<td>( F_D = \frac{2 \cdot \xi \cdot m_\text{tot} \cdot S_{a,\bar{\eta}=5%} \cdot \bar{\eta} \cdot \left( \frac{h}{3} \right)}{(2N+1)} )</td>
<td>( F_{D,i,\bar{\eta}} = \frac{2 \cdot \xi \cdot m_\text{tot} \cdot \bar{\eta} \cdot S_{a,\bar{\eta}=5%} \cdot \cos \theta}{(N+1)} )</td>
<td>( F_{D,i,\bar{\eta}} = \frac{2 \cdot \xi \cdot m_\text{tot} \cdot \omega_{\text{SDOF}} \cdot \bar{\eta} \cdot S_{a,\bar{\eta}=5%}}{(N+1)} )</td>
</tr>
<tr>
<td>Index of Effectiveness (IE)</td>
<td>( C_\text{tot} = \frac{4 \cdot \xi \cdot m_\text{tot} \cdot S_{a,\bar{\eta}=5%} \cdot \bar{\eta} \cdot (2N+1) \cdot \left( \frac{h}{3} \right)}{B} )</td>
<td>( C_{\text{tot}} = \frac{2 \cdot \lambda \cdot m_\text{tot} \cdot \bar{\eta} \cdot S_{a,\bar{\eta}=5%} \cdot \cos \theta}{B} )</td>
<td>( C_{\text{tot}} = \frac{2 \cdot \lambda \cdot m_\text{tot} \cdot \bar{\eta} \cdot S_{a,\bar{\eta}=5%}}{B} )</td>
</tr>
<tr>
<td></td>
<td>( B_{\text{tot}} = \lambda \cdot m_\text{tot} \cdot S_{a,\bar{\eta}=5%} \cdot (1-\bar{\eta}) )</td>
<td>( B_{\text{tot}} = \lambda \cdot m_\text{tot} \cdot S_{a,\bar{\eta}=5%} \cdot (1-\bar{\eta}) )</td>
<td>( B_{\text{tot}} = \lambda \cdot m_\text{tot} \cdot S_{a,\bar{\eta}=5%} \cdot (1-\bar{\eta}) )</td>
</tr>
<tr>
<td></td>
<td>( IE = \frac{\lambda \cdot (1-\bar{\eta}) \cdot \cos \theta}{2 \cdot \xi \cdot \bar{\eta}} )</td>
<td>( IE = \frac{\lambda \cdot (1-\bar{\eta})}{2 \cdot \xi \cdot \bar{\eta}} )</td>
<td>( IE = \frac{\lambda \cdot (1-\bar{\eta})}{2 \cdot \xi \cdot \bar{\eta}} )</td>
</tr>
</tbody>
</table>
Figure 2. The analyzed FE models: (a) NAKED; (b) DT; (c) SPD; (d) MPD.

Results

Table 2 presents the results of the four models analyzed, in terms of base shear, damping reduction factor, system “cost” and system effectiveness, reporting both the predicted values, evaluated with the ESDOF procedure, and the ones resulting from the non-linear time-history analyses performed.

The resulting reduction factor obtained from the time-history analyses $\eta_{\text{TH}}$ is lower (variation in the order of 10%) than the one predicted $\eta_p$ thus indicating that the procedure leads to a conservative estimation of the reduction of the peak structural response. As far as the cost and effectiveness of the solutions proposed are concerned, the total damping forces as evaluated from the time-history analyses are lower than the ones predicted, and consequently the effectiveness of the systems proposed are larger than the expected ones. Among the three solutions the system coupled with the “dissipative tower” (DT model) results to be the more effective in reducing the base shear, while the MPD results to be the one with less “total cost”.

Table 2. Results from the non-linear time-history analyses compared with the ones estimated with the ESDOF procedure.

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{base.p}}$</th>
<th>$V_{\text{base.TH}}$</th>
<th>$\eta_p$</th>
<th>$\eta_{\text{TH}}$</th>
<th>$F_{d,\text{tot.p}}$</th>
<th>$F_{d,\text{tot.TH}}$</th>
<th>$\text{IE}_p$</th>
<th>$\text{IE}_{\text{TH}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAKED</td>
<td>558 kN</td>
<td>481 kN</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DT</td>
<td>279 kN</td>
<td>139 kN</td>
<td>50%</td>
<td>29%</td>
<td>614 kN</td>
<td>435 kN</td>
<td>0,45</td>
<td>0,79</td>
</tr>
<tr>
<td>SPD</td>
<td>279 kN</td>
<td>178 kN</td>
<td>50%</td>
<td>37%</td>
<td>936 kN</td>
<td>579 kN</td>
<td>0,30</td>
<td>0,52</td>
</tr>
<tr>
<td>MPD</td>
<td>279 kN</td>
<td>188 kN</td>
<td>50%</td>
<td>39%</td>
<td>167 kN</td>
<td>136 kN</td>
<td>1,67</td>
<td>2,15</td>
</tr>
</tbody>
</table>
Figure 3 shows the displacement profiles of the three systems studied, compared with the bare frame (NAKED model). It can be noted that the SPD and MPD solutions lead to a similar peak displacement profile, with maximum inter-storey drifts at the bottom stories. The DT solution is instead characterized by an almost linear peak displacement profile thanks to the presence of the strongback system, confirming the results already found in previous work done by Lai and Mahin [15] and more recently by some of the authors [16].

![Figure 3. Displacement profiles of the FE models.](image)

**Conclusions**

A direct design procedure for frame structures equipped with generic configurations of viscous dampers has been presented. The analytical formulas of the procedure are aimed at guiding the structural engineer from the choice and sizing of added viscous dampers to the comparison of the performances of different dampers configurations. The procedure allows to obtain analytical estimations and predictions of the damping coefficients needed in order to reach the desired reduction in the frame seismic response, as well as a rapid way of comparing different solutions proposed by means of the efficiency evaluation, as ratio between the cost of the solution (in terms of total damping forces required) and benefit of the added viscous dampers (in terms of reduction in base shear).

The predictions of the ESDOF procedure are verified by means of dynamic time-history analyses performed on FE models, evidencing a certain degree of reliability, since the predictions are in general conservative. Nonetheless, given the rough order of approximation, the procedure appears suitable especially in the preliminary design phase, while for the final design more accurate procedures are recommended.

**References**


