SIMPLIFIED EVALUATION AND DESIGN PROCEDURE BASED ON DISPLACEMENTS FOR RC BUILDINGS WITH VISCOUS DAMPERS

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ABSTRACT

Supplemental damping is being used for seismic damage control purposes in the retrofit of existing and the design of new buildings. In this paper this goal is achieved by introducing, within a displacement-based design method, the contribution of devices that dissipate part of the input earthquake energy, and thereby reduce the displacements of the structural systems to meet those considered as targets. This paper briefly describes a displacement-based seismic design method for frame structures considering the use of viscous dampers and damage control. To consider the non-proportional damping produced by the viscous dampers, in a conventional modal spectral analysis the effect of non-proportional damping matrix is approximated by equivalent modal damping ratios. The framework of this method is constructed around the concept of a reference bilinear single degree of freedom system, with properties associated to those of the fundamental mode of the inelastic multi degree of freedom system, from which its performance under seismic design conditions may be approximated. As illustrative example, the displacement-based design of an eight-storey reinforced concrete building with added linear viscous dampers is presented. The considered seismic demand is the NS component of the 2017 Morelos - Puebla earthquake in Mexico recorded at the Culhuacán site. In this example, it is observed that the performance calculated with a non-linear step-by-step analysis, for a structure designed with the procedure proposed, represents, with a good approximation, the target design performance.

Keywords: Displacement-based seismic evaluation and design, damage control, linear viscous dampers, non-proportional damping approximation, modal spectral analysis.

1. INTRODUCTION

The main objective of seismic design is to guarantee adequate behaviour of a building by accomplishing given design performance levels (PL) when subjected to earthquake scenarios which may occur during its service life. Based on this objective, during the recent past the design methods based on forces have been used, however these methods cannot guarantee performance under design conditions; for this reason performance-based design methods have been developed, particularly those based on displacements as these parameters are acknowledged the most relevant to performance, e.g., Panagiotakos and Fardis (1999), Priestley et al. (2007), López and Ayala (2012). Nevertheless, there are many situations where it is not possible to guarantee the PLs considered due to architectural restrictions and/or code related issues. For this reason, it is necessary to consider other strategies to satisfy the PL, such as the use of passive energy dissipation devices e.g., viscous dampers, which dissipate part of the input earthquake energy and, as a consequence, reduce the displacements of the structure and the corresponding earthquake induced damage. Moreover, in the cases when it is required to add a large amount of supplementary damping to satisfy the PLs (i.e., $\xi_{\text{dampers}} > 15\%$), and this amount is neither practical nor reasonable, e.g., Hwang et al. (2013), the alternative is to accept damage...
in the structure, by using performance-based design procedures adapted to include passive energy dissipation devices.

The most appropriate procedure to analyse structures with viscous dampers is the dynamic step-by-step analysis; nevertheless, current design practices and most building codes recommend for the seismic evaluation and design of structures the use of modal spectral analysis with seismic demands given by design spectra. Due to this situation, in the majority of cases in which viscous dampers are used as passive energy dissipation devices, the associated damping matrix is non-proportional leading to non-classical eigen-values and vectors, making the conventional modal spectral analysis used in the practice of the seismic design of structures, impossible to apply.

To overcome this limitation, Constantinou and Symans (1992) proposed an approximate simplified procedure, in which the effect of the viscous dampers is considered as supplemental modal viscous damping. In this procedure, the approximate amount of damping, associated to the viscous dampers, is easily determined in terms of the dynamic properties of the structure such as the mode shapes and periods. Using this approximation, López-Garcia (2001), proposes a simplified sequential search algorithm to calculate the distribution of dampers and damping coefficients according to interstorey velocities. Along the same lines, Hwang et al. (2003) propose a damper distribution based on storey shear strain energy. The assumption of non-proportional damping as proportional is not always appropriate because it can produce significant errors in the response of structures, Veletsos and Ventura (1986). As a consequence, diverse studies focusing on the development of simplified procedures based on the use of modal spectral analysis for structures with viscous dampers have been carried out.

This paper presents a simplified displacement-based seismic evaluation and design procedure which considers explicitly a combination of damage control and added viscous damping to comply with target design displacements. To illustrate the application of this method and evaluate the performance of structures designed with the method proposed, an eight-storey reinforced concrete building is designed. The additional damping required by the structure under design conditions with the accepted damage distribution is calculated using the approximation proposed. To distribute the nominal damping coefficients of the devices that produce the design amount of damping, assuming that they are located at the central spans of each floor, a procedure using as relative weights of these damping coefficients the drifts in the structure. As design seismic demand, the NS component of the Culhuacán record of the 2017 Morelos - Puebla earthquake in Mexico is considered. The design obtained, is evaluated by comparing the interstorey drifts and overall structural performance. The accuracy of the results is assessed by comparing the performances extracted from the results of the step by step non-linear dynamic analysis of the structure designed with the target design performance. Finally, some conclusions about the design method and the results obtained are presented stressing the most relevant advantages of the displacement-based design of structures with viscous dampers and damage control.

2. DISPLACEMENT – BASED SEISMIC DESIGN PROCEDURE WITH VISCOS DAMPERS AND DAMAGE CONTROL

2.1 Fundamentals of the procedure proposed

The procedure proposed is based on the assumption that the performance of a non-linear multi-degree of freedom (MDOF) structure may be approximated from the performance of a reference simplified non-linear single-degree of freedom (SDOF) system, normally associated to the fundamental mode of the structure, Ayala (2001). The principle of this evaluation/design method is that the non-linear capacity curve of a MDOF structure may be approximated by a bilinear curve, using the equivalence of deformation energies corresponding to the real capacity curve and its bilinear approximation, and that, in accordance with basic principles of structural dynamics, the bilinear capacity curve of the reference SDOF system, also referred to as the behaviour curve of the reference system, may be directly extracted from this capacity curve. The behaviour curve of the reference system is obtained from the results of two conventional modal spectral analyses, one for the elastic phase of behaviour, structure without damage, and other for the inelastic phase, structure with the assumed distribution of damage. The slope of the first branch of the behaviour curve represents the elastic stiffness of the reference SDOF system.
whereas the slope of the second branch, the stiffness corresponding to the inelastic range. The slope of this second branch is defined by a previously assumed damage distribution associated to the proposed maximum displacement of the target PL. To satisfy the target PL of the structure with viscous dampers, the spectrum is modified to consider the added damping due at the effect of these energy dissipation devices.

2.2 Added damping consideration

As mentioned above, most seismic analysis procedures for structures with viscous dampers consider the effect of these devices in the response of the structure by assuming a proportional damping matrix, approximation of the actual non-proportional damping matrix. This assumption, however, is not strictly valid, as the response of the structure may show significant errors when compared against that obtained using a step-by-step dynamic analysis of the structure with non-proportional damping matrix. To minimize the errors involved in this approximation, this paper proposes a correction to the original procedure. This correction is described in the following paragraphs:

The equation that describes the dynamic equilibrium of a MDOF structure can be written as:

\[ [M]\ddot{u}(t) + [C]\dot{u}(t) + [K]u(t) = \{p(t)\} \]  

(1)

where:

- \([M]\) = Mass matrix
- \([C]\) = Damping matrix
- \([K]\) = Stiffness matrix
- \({p(t)}\) = Force vector
- \({u(t)},{\dot{u}(t)},{\ddot{u}(t)}\) = Displacement, velocity and acceleration vectors

For a structure with viscous dampers, the damping matrix can be represented as:

\[ [C] = [C_0] + [C_D] \]  

(2)

where:

- \([C_0]\) = Inherent damping matrix (assumed as proportional)
- \([C_D]\) = Damping matrix associated to the viscous dampers (non-proportional)

Since the damping matrix associated to the viscous dampers is non-proportional, neither to the mass nor to the stiffness matrices, it is possible to approximate it as the sum of a proportional damping matrix ([C_{DP}]) and a residual damping matrix ([C_{DR}]), i.e.,:

\[ [C_D] = [C_{DP}] + [C_{DR}] \]  

(3)

The first order approximation of the proportional matrix, also referred as Rayleigh damping matrix may be written as:

\[ [C_{DP}] = a_{0D}[M] + a_{1D}[K] \]  

(4)

To uncouple the equilibrium equations given by Equation (1) the following change of coordinates is required: \({\{u(t)\}} = [\Phi][x(t)],[\ddot{u}(t)],[\dot{u}(t)],[\ddot{u}(t)] = [\Phi][\dddot{x}(t)],\) to give:

\[ [M][\dddot{x}(t)] + [C][\dddot{x}(t)] + [K][\dddot{x}(t)] = \{p(t)\} \]  

(5)

where:

- \([\Phi]\) = Normalized modal matrix
Pre-multiplying each term in Equation (5) by $[\phi]_i^T$ gives

$$
[\phi]_i^T [M][\phi]_i [\ddot{x}(t)] + [\phi]_i^T [C][\phi]_i [\dot{x}(t)] + [\phi]_i^T [K][\phi]_i [x(t)] = [\phi]_i^T [p(t)]
$$

(6)

Assuming that the inclusion of viscous dampers in the structure does not significantly modify the modal characteristics of the structure, a set of uncoupled dynamic equilibrium equations expressed in terms of modal coordinates $\ddot{x}_i(t)$ is obtained:

$$
\ddot{x}_i(t) + 2 (\xi_{0i} + \xi_{DPI}) \omega_i \dot{x}_i(t) + [\phi]_i^T [C_{DR}] [\phi]_i \dot{x}(t) + \omega_i^2 x_i(t) = [\phi]_i^T [p(t)]
$$

(7)

where:

- $\omega_i$ = Frequency for mode $i$
- $\xi_{0i}$ = Inherent viscous damping ratio for mode $i$
- $\xi_{DPI}$ = Proportional viscous damping ratio of devices for mode $i$
- $\Gamma_i$ = Modal participation factor

Even though the term $[\phi]_i^T [C_{DR}] [\phi]_i$ is not a diagonal matrix, experimental evidence has shown that as the damping ratio of a structure is increased, the contribution of the higher modes of the structure to its total response may be ignored, Hwang et al. (2003). As a consequence, for practical applications, in the approximate method proposed only the contribution of the fundamental mode of the MDOF system is usually considered. Based on this consideration the damping ratio associated to the residual damping matrix can be expressed as:

$$
\xi_{DRI} = \frac{[\phi]_i^T [C_{DR}] [\phi]_i}{2 \omega_i}
$$

and Equation (7) rewritten as:

$$
\ddot{x}_i(t) + 2 (\xi_{0i} + \xi_{DPI} + \xi_{DRI}) \omega_i \dot{x}_i(t) + \omega_i^2 x_i(t) = [\phi]_i^T [p(t)]
$$

(8)

where:

- $\xi_{DRI}$ = Residual viscous damping ratio of devices for mode $i$

The proportional viscous damping ratio associated to the added devices can be calculated using the energy based approximation proposed by Constantinou and Symans (1992):

$$
\xi_{DPI} = \frac{T_i \sum_{j=1}^{nd} C_j (\cos \theta_j) (\phi_i - \phi_{i-1})^2}{4 \pi \sum_{j=1}^{m} m_j \phi_j^2}
$$

(9)

where:

- $T_i$ = Natural period of vibration of mode $i$
- $\theta_j$ = Angle of the viscous damper $j$
- $\phi_i$ = Horizontal modal displacements of mode $i$
- $C_j$ = Damping coefficient of the damper at storey $j$

The residual viscous damping ratio of the devices for mode $i$ can be defined as:

$$
\xi_{DRI} = \frac{[\phi]_i^T [C_{DR}] [\phi]_i}{2 \omega_i} = \frac{[\phi]_i^T [C_{D} - C_{DP}] [\phi]_i}{2 \omega_i}
$$

(10)

Thus, ignoring the response contribution of higher modes, the total damping ratio for the first mode is defined as:

$$
\xi_{Design1} = (\xi_{01} + \xi_{DPI} + \xi_{DRI})
$$

(11)
3. DISPLACEMENT-BASED DESIGN METHOD

In accordance with the aforementioned concepts, the application of the displacement-based design method proposed to structures with viscous dampers intended to satisfy the life safety limit state, LSLS, can be summarized in the following steps:

1. Preliminary configuration and dimensioning of the elements of the structure according to engineering judgement and/or designer experience. The objective of this step is to define a realistic stiffness distribution of the structural elements throughout the height of the structure, so that design displacement shape are in accordance with those of real structures.

2. Modal analysis of the elastic bare structure designed in the previous step. From this analysis, the modal participation factor PF, the fundamental period of the structure, $T_E$, and the displacement shape $\phi$ of the fundamental mode are obtained. From this displacement shape, the spectral yield displacement of the reference SDOF, $S_{dy}$, may be calculated using the following equation:

$$S_{dy} = \frac{IDT_y H_k}{PF_1^E (\phi_{k,1} - \phi_{k-1,1})}$$

where:

- $IDT_y$ = Yield interstorey drift
- $H_k$ = Height of the critical storey $k$ (where maximum drift occurs)
- $PF_1^E$ = Modal participation factor of the fundamental mode (elastic structure)
- $\phi_{k,1}$ = Modal shape ordinate of the critical interstorey, $k$

3. Definition of a design damage distribution for the PL in accordance with the characteristics of the structure and the design demands, using a strong-column weak-beam strategy and considering the contribution of the viscous dampers added to the structure. Structural damage is introduced at the ends of the elements, where damage is accepted to occur under design
conditions by adding hinges with zero or residual rotational stiffness, equal to a reduced bending stiffness of the damaged element sections.

4. Modal analysis of the damaged bare structure to obtain the fundamental modal shape, participation factor and period, $T_D$, and, from this period, the slope of the second branch of the idealized bilinear behaviour curve of the reference SDOF system. From this modal shape, the target spectral displacement of the reference SDOF, $S_{dPL}$, is obtained using the following equation:

$$S_{dPL} = \frac{IDT_{PL} H_k}{PF_1^D (\phi_{k,1}^D - \phi_{k-1,1}^D)}$$  \hspace{1cm} (14)$$

where:

$\text{IDT}_{PL} = \text{Interstorey drift of PL}$

5. Calculation of the target yield and ultimate spectral displacements of the reference SDOF system, $S_{dy}$ and $S_d$, respectively, corresponding to the fundamental mode using the results of modal analysis. Its ductility, $\mu$, and post-yielding to initial stiffness ratio, $\alpha$, are obtained using Equations (15) and (16)

$$\mu = \frac{S_{dPL}}{S_{dy}}$$  \hspace{1cm} (15)$$

$$\alpha = \left(\frac{T_E}{T_D}\right)^2$$  \hspace{1cm} (16)$$

6. Modification of the effective viscous damping ratio from the inelastic displacement spectrum for the given $\mu$ and $\alpha$, until the spectral displacement associated to the fundamental period is equal to the target spectral displacement of the structure (step 4). See Figure. 1:

![Inelastic displacement spectrum](Figure_1_Inelastic_displacement_spectrum.png)

Figure. 1. Inelastic displacement spectrum
7. Calculation of the damping coefficients of the viscous dampers, using Equation (11), where the proportional part ($\xi_{DP1}$) may be defined using the Constantinou and Symans (1992) proposal, Equation (17), and the residual part $\xi_{DR1}$ as defined by Equation (10). The damping coefficient for each interstorey is calculated in proportion to the relative modal displacement drifts normalized with the interstorey height of the building.

$$C_t = \frac{4 \pi \xi_{DPi} \left( \sum_{i=1}^{nd} \frac{\Phi_i - \Phi_{i-1}}{H_j} \right) \left( \sum_{i=1}^{n} m_i \Phi_i^2 \right)}{T \sum_{j=1}^{nd} \left( \cos \theta_j \right) \left( \frac{\Phi_i - \Phi_{i-1}}{H_j} \right)^3}$$  \hspace{1cm} (17)

$$C_j = \left( \frac{\left( \frac{\Phi_i - \Phi_{i-1}}{H_j} \right)}{\sum_{i=1}^{nd} \left( \frac{\Phi_i - \Phi_{i-1}}{H_j} \right)} \right) C_t$$  \hspace{1cm} (18)

where:

$H_j$ = Height of the storey $j$

8. Determination of the yield strength, $R/y/m$, using the period of elastic model $T_E$ in the inelastic strength spectrum, corresponding to the values of $\mu$ and $\alpha$ previously calculated. See Figure. 2:

9. Calculation of the ultimate strength, $R_u/m$, of the reference system using the following equation:

$$\frac{R_u}{m} = \frac{R_y}{m} \left[ 1 + \alpha (\mu - 1) \right]$$  \hspace{1cm} (19)

Figure. 2. Strength per unit mass spectrum for $\mu$ and $\alpha$, associated to the PL

10. Determination of the design forces of the elements using the results of three different analyses: a gravity load analysis of the undamaged structure, a modal spectral analysis of the undamaged structure, using the elastic design spectrum scaled by the ratio of the strength per unit mass at the yield point of the behaviour curve and the elastic pseudo-acceleration for the initial period, $\lambda_E$, and a modal spectral analysis of the damaged structure, using the elastic spectrum scaled by the ratio of the difference of the ultimate and yield strengths per unit mass and the pseudo-acceleration for the period of the damaged structure, $\lambda_D$. Each modal spectral analysis considers the total viscous damping ratio ($\xi_{Design}$). The design forces are obtained by adding the forces
due to gravity loads and the forces of the modal spectral analyses of the undamaged and damaged structure.

11. Determination of the design of every structural element in accordance with the forces obtained from the analysis of the simplified models and using the applicable design rules. The design process must be carried out in such a way that the design criteria of the code do not alter significantly the expected performance.

4. APPLICATION EXAMPLE

To illustrate the application of the design method developed in this paper, an eight-storey reinforced concrete building (see Figure. 3 (a)), was designed. The nominal properties of the materials used in the design are: for the concrete, a compressive strength $f'_c=3.00\times10^4$ kN/m$^2$, a modulus of elasticity $E_c=27.00\times10^9$ kN/m$^2$, and a weight density $\gamma=23.53$ kN/m$^3$, and for the steel reinforcement a yield stress $f_y = 4.50\times10^5$ kN/m$^2$ and a modulus of elasticity $E_s = 2.00\times10^8$ kN/m$^2$. Based on the results of the preliminary design of the frame, the sections of the structural elements were defined; i.e., 0.70 x 0.70 m for all columns, and 0.60 x 0.30m for all beams.

To validate the results obtained from the displacement-design method proposed, the seismic design demand considered was the response spectra of the NS component of the 2017 Morelos – Puebla earthquake in Mexico recorded at the Culhuacán site. To validate the seismic performance of the designed structure, the drifts, obtained from the non-linear step-by-step analysis of the structure, were compared with the maximum drift considered as design target. The non-linear step-by-step analysis was carried out with the CSI (2007): Perform 3D V5 program with the following considerations: 1) nearly elasto-plastic bilinear stable hysteretic behaviour for all beams and columns, 2) non-classical damping matrix due to the incorporation the viscous dampers, 3) nominal yield moments for beam and columns obtained from the design method proposed and 4) the drift considered as design target was 0.015, as specified by the current FEMA 368 (2001) to satisfy the LSLS.

4.1 Results of the design method proposed

According to the structural configuration and the dimensioning of structural elements of the proposed preliminary design, the model of the bare structure was built and its modal analysis was carried out. From the results obtained, the vibration periods for the undamaged structure for dominant x and y translations, $T_{DX}=1.5s$ y $T_{DY}=1.2s$, were extracted. Subsequently an acceptable damage distribution, was proposed. For this case, the beams of levels 1 to 5 in X direction, and 1 to 3 in Y direction were considered to be damaged at both ends and all columns were assumed undamaged. The modal analysis for this model was carried out to obtain the corresponding vibrations periods of the damaged structure $T_{DX}=2.9s$ y $T_{DY}=2.1s$. Figure. 3 (c) shows the distribution of damage used in this design.

The properties of the behaviour curve for the structure complying with the PL of the LSLS are shown in the following table:

<table>
<thead>
<tr>
<th>Direction</th>
<th>$T_E$</th>
<th>$T_D$</th>
<th>$\alpha$</th>
<th>$\mu$</th>
<th>$S_d_{LS}$</th>
<th>$R_Y$</th>
<th>$R_{LS}$</th>
<th>$\lambda_E$</th>
<th>$\lambda_D$</th>
<th>$\xi_{Design}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1.5</td>
<td>2.9</td>
<td>0.26</td>
<td>1.2</td>
<td>0.015</td>
<td>3.4</td>
<td>3.5</td>
<td>0.281</td>
<td>0.104</td>
<td>0.225</td>
</tr>
<tr>
<td>Y</td>
<td>1.2</td>
<td>2.1</td>
<td>0.35</td>
<td>1.2</td>
<td>0.015</td>
<td>6.5</td>
<td>6.7</td>
<td>0.655</td>
<td>0.105</td>
<td>0.100</td>
</tr>
</tbody>
</table>

The arrangement of viscous dampers proposed in this example is shown in Figure. 3(b), i.e., one damper per storey in Y direction and two dampers per storey in X direction. Using Equations (15) and (16), the damping coefficients of these devices were calculated (See Table 1).
Table 2. Damping Coefficients of viscous dampers

<table>
<thead>
<tr>
<th>Level / Damping Coefficient (MN·s/m)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction X</td>
<td>3.15</td>
<td>10.99</td>
<td>21.28</td>
<td>31.91</td>
<td>40.99</td>
<td>46.94</td>
<td>50.04</td>
<td>51.77</td>
</tr>
<tr>
<td>Direction Y</td>
<td>2.28</td>
<td>7.4</td>
<td>13.02</td>
<td>16.92</td>
<td>18.92</td>
<td>20.11</td>
<td>20.84</td>
<td>21.27</td>
</tr>
</tbody>
</table>

Figure 4 shows the maximum interstorey drifts calculated using step-by-step analyses for four different cases: (a) bare structure, (b) structure with dampers (non-proportional damping matrix), (c) structure design with the method proposed and the damping coefficients calculated by the Constantinou and Symans (1992) proposal and (d) structure with the correction proposed in this paper. It may be observed that when the bare structure is subjected to the design seismic demand corresponding to the LSLS, some interstoreys lightly exceed the target drifts for this limit state (IDTLSLS). However when the viscous dampers are added to the structure, the interstorey drift prescribed by the code is not exceeded at any interstoreys. In addition, the design procedure with the correction proposed gives a better approximation when is compared with the results of the non-linear step by step analysis (see Figure. 5). With regards to the damage distributions, the results of the design procedure proposed show the same damage distribution than that obtained from the results of the non-linear step-by-step analysis.
Figure 4. Interstorey drifts in the example building

(a) Direction X

(b) Direction Y

Figure 5. Errors interstorey drifts

(a) Direction X

(b) Direction Y
5. CONCLUSIONS

This paper presented the formulation and a practical application of a new displacement-based seismic evaluation/design method for structures originally equipped with viscous dampers and/or when these devices are used as a retrofit measure. To validate the design method proposed, the performance of the designed structure was obtained using non-linear step-by-step dynamic analysis considering as seismic demand the same demand used for its design. From the analysis of the results obtained, the following conclusions may be extracted:

1. For the building designed with the method proposed, the maximum interstorey drifts, produced by the design demand applying the correction, are closer to those obtained from the non-linear step-by-step analysis of the structure, considering a non-proportional damping matrix, than those of the procedure without the correction. Nevertheless, considering that the design interstorey drift is recommended to limit the damage of the LSLS, both results can be considered satisfactory. However, to guarantee this conclusion it is necessary to carry out additional evaluation/design examples, considering structures of different configurations and subjected to different seismic demands.

2. The distribution of damage, used as target within the design procedure proposed was reproduced in the results of non-linear step-by-step analysis of the structure with a non-proportional damping matrix. This result was due to the correction to the added damping coefficient in the procedure, something that guaranteed that the response of the structure was reduced, and the accomplishment of the design objective of controlling the distribution of damage in the structural elements.

3. The comparison of the effort involved in the application of this method using computational tools available in most design offices, e.g., SAP2000 (CSI, 2006) and the quality of results obtained with those of other design methods, place it as an excellent design tool, since requires only two modal spectral analyses.

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7. REFERENCES


