Methodology to support the design of buildings' seismic protection using viscous dampers

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**ABSTRACT**

The use of passive seismic protection of buildings with viscous dampers is an already proven and a very requested solution, mostly on tall buildings. There are already several examples of this kind of applications, not only in new structures, but also in seismic rehabilitation of old buildings. The solution is based on the application of viscous dampers along the height of the building’s facades.

One of the major problems in the design of these systems is the definition of the capacity of each damper to obtain a predefined goal, for example, a certain reduction on the structure's response.

The proposed methodology is based on the definition of an equivalent single degree of freedom system, considering only the contribution of the first vibration mode. It offers a reliable first guess on the definition of the dampers capacity, assuming that all the dampers are equal and evenly distributed along the building's height.

The determination of the equivalent damping attends the definition of a global solution with viscous dampers. The present work describes the methodology and the result of its application in six frame-wall structures.

**Keywords:**

Viscous dampers; Passive seismic protection of buildings; Tall buildings; Equivalent damping

1. **Background and scope**

A seismic event is an unpredictable natural geological phenomenon, which is considered one of the most destructive natural disasters, both socially and economically. The design of structures in zones of high seismicity, like Japan or USA, contributed to the technological development and investigation in seismic engineering, mainly in the seismic protection of buildings. Therefore, there has been a significant development of new technologies aiming to reduce the impact of seismic action on buildings.

Seismic protection of buildings can be assured through passive energy protection systems, applying viscous dampers, a solution that is generally suitable to tall buildings. There are already many examples of application across the globe, both in new structures or in seismic rehabilitation of buildings.

In order to obtain a predefined goal, such as the reduction of the structure’s response, the development of this kind of seismic protection lacks an accurate initial estimate of the damper’s capacity. In previous studies the device’s damping coefficient was arbitrated in order to achieve the predefined goal, namely through a process of trial, and that is precisely what is intended to avoid with this new approach.

2. **Seismic protection techniques**

Seismic protection techniques can be divided in passive, active or semi-active. Passive seismic protection systems include energy dissipation and base isolation that do not require exterior energy. Active systems, on
the other hand, require power source to control the structure’s movement. Lastly, semi-active systems need only energy to change the device’s technical features [1].

The reduction of the structure’s vulnerability can be achieved by reducing its seismic response, through the use of energy dissipation systems. This type of seismic protection became accessible through investment and research in this area, being present in Portugal, mainly in bridges [2].

Energy dissipation systems can be classified as hysteretic dampers, viscous dampers or viscoelastic dampers. These devices provide energy dissipation capacity to the structure, and must be applied to go along with the structure’s movement, maximizing the damper’s deformation and optimizing its performance [1]. The damper’s purpose is to dissipate the earthquake’s energy transmitted to the structure, preventing significant deformations through energy absorption.

2.1. Viscous dampers

Viscous dampers, according to the principle of fluid compression and circulation, are able to dissipate energy through the application of a resisting force over a finite displacement. During seismic action the energy generated by the imposed movement is transmitted to the damper, which forces the passage of a high-viscosity fluid through very small orifices, using a cylinder piston system (Figure 1).

![Viscous damper's components](adapted from [3]).

The dissipation force depends on the end to end velocity across the damper, through the relation expressed in Eq. (1) [2].

\[ F = C |v|^\alpha \text{sign}(v) \]  

(1)

Where \(C\) and \(\alpha\) correspond to damper’s coefficients and \(v\) is the end to end velocity across the damper.

The energy dissipation capacity in each cycle is a measure of the damping that the device provides to the structure. The dissipated energy is given by the inner area of the cycle measured in the force-displacement graph [2].

The smaller the \(\alpha\), the greater the damper’s energy dissipation capacity. For the same value of the \(\alpha\) parameter, \(C\) increases the inner area of the cycle. Thus, the higher the \(C\), the higher the damper’s energy dissipation capacity, and therefore the higher the damper’s efficiency.

Nonlinear dynamic analysis, considering time domain, is the only way to study the response of a structure with viscous dampers. For this purpose, seismic action is defined through an acceleration series over time. A series of artificial accelerations was primarily defined, compatible with the local seismic action [4].

3. Methodology

The developed methodology consists in the evaluation of the damping coefficient \(C\) to apply on each damper, in order to reduce the maximum displacement at the top of the structure, to an objective displacement.
It is well known that the use of energy dissipation systems leads to the reduction of the structure’s seismic response, towards a given seismic action. Therefore, the analysis of the maximum displacement at the top of the structure allows the evaluation of its behaviour, before and after the installation of the dampers.

The proposed methodology is based on the modal configuration of the structure’s fundamental mode, considering an equivalent single degree of freedom oscillator.

### 3.1. Fundamental vibration mode

Before defining the number of devices, their size and their optimal location, it is vital to know the damping that is needed to be developed by the use of dampers.

However, current methods do not define what level of damping a structure can achieve when viscous dampers are introduced [5]. When analysing those methods, higher vibration modes exhibit minimal influence in the definition of this kind of seismic protection system. Therefore, to assess the effect of viscous dampers in buildings it is sufficient to account only on the structure’s first vibration mode. Furthermore, viscous dampers provide an additional damping and stiffness to the structure’s higher modes, which could lead to the complete rejection of the higher vibration modes contribution [3].

### 3.2. Equivalent single degree of freedom oscillator

Assuming that the system has a sinusoidal response, displacement (2) and velocity (3) are given by:

\[ x = A \sin(pt) \]  \hspace{1cm} (2)

\[ \dot{x} = A p \cos(pt) \]  \hspace{1cm} (3)

Where, A and p are, respectively, a constant that depends on the movement’s initial conditions, and the structure’s frequency in the absence of damping.

Assuming that \( \alpha = 1 \), the damping force is expressed in Eq. (4), where C is the system’s damping coefficient.

\[ F_{damp} = C A p \cos(pt) \]  \hspace{1cm} (4)

In this expression A in this expression is the end to end amplitude of movement in the damper.

The dissipated energy is given by the inner area of the cycle, measured in the force-displacement graph, thus, the energy dissipation is given by Eq (5):

\[ \text{Area} = \pi C p A^2 \]  \hspace{1cm} (5)

According to [6], the equivalent damping ratio is given by Eq (6):

\[ \xi_{eq} = \frac{2}{\pi} \frac{\text{Area}}{\text{Area}_{rec}} \]  \hspace{1cm} (6)

Where \( \text{Area}_{rec} \) corresponds to the area of the rectangle that circumscribes the force-displacement cycle, as shown in Figure 2.
The structure's frequency in the absence of damping is given by Eq. (8):

\[ p = \sqrt{\frac{k}{m}} \]  

(8)

Where \( k \) is the structure's stiffness and \( m \) the corresponding mass.

Therefore, the equivalent damping coefficient is given by Eq. (9):

\[ C_{eq} = \xi_{eq}^2 m_{eq} p_1 \]  

(9)

Where \( m_{eq} \) is the mass of the equivalent single degree of freedom oscillator, and \( p_1 \) is the structure's frequency, associated with the first vibration mode.

In order to estimate the equivalent damping coefficient that is needed to obtain with the protection system, the damping correction coefficient \( \eta \) recommended in EC8-1 [7], and expressed in Eq. (1), can be used as a starting point of the proposed method.

\[ \eta = \sqrt{\frac{10}{5+\xi}} \geq 0,55 \]  

(10)

The previous equation corresponds to a SDOF system's damping, for a damping correction coefficient less than or equal to 0.55. Thus, the expression above only serves as a support for the estimate of the equivalent damping of structures with viscous dampers.

The structure's modal damping can be determined knowing in advance the predefined goal in the structure's response. The known percentage reduction is given by \((1-\eta)\).

A 5% damping was considered for the structure without viscous dampers. It corresponds to a current RC building whose maximum deformation, due to a seismic event, causes excessive concrete cracking. On the other hand, for a structure with viscous dampers, considering that these devices limit deformation, a 5% damping would be exaggerated. Thus, a 2% initial damping was assumed.

The value of \( \xi \) obtained from Eq. (10), includes the structure's 2% damping. Hence, the equivalent damping ratio for the dampers is given by Eq. (11):

\[ \xi_{eq} = \xi - 0,02 \]  

(11)

The equivalent single degree of freedom oscillator is defined based on the same approaches used in a pushover analysis. Assuming the mass equal in each floor, \( m_{eq} \) is given by Eq. (12).
\[ m_{eq} = m \sum \phi_i \]  

Where \( \phi \) is the configuration of the first vibration mode of the structure.

Considering the following equations Eq. (13) and Eq. (14):

\[ \Gamma = \frac{m_{eq}^2}{\sum m_i \phi_i^2} \]  
\[ \Delta_{eq} = \frac{\phi_{top}}{r} \]  

Where \( \Delta_{eq} \) is the maximum horizontal displacement at the top of the equivalent single degree of freedom oscillator.

The structure’s first mode of vibration displacements are normalized, assuming \( \phi_{top} = 1.0 \).

Given that \( m \) is constant on each floor, Eq. (14) is rewritten in Eq. (15).

\[ \Gamma = \frac{\sum \phi_i^2}{\sum \phi_i^2} \]  

### 3.3. Device’s damping coefficient

The damping coefficient to be adopted in each device takes into account the end to end modal deformation across the damper, through Eq. (16):

\[ \Delta_{rel,i} = \frac{(\phi_{H,i} - \phi_{H,i}^{-1}) \Delta H + (\phi_{V,i} - \phi_{V,i}^{-1}) \Delta V}{\sqrt{\Delta H^2 + \Delta V^2}} \]  

\( \phi_{rel,i} \) and \( \phi_{rel,i} \) are, respectively, the horizontal and the vertical displacement of the first mode configuration, at the end joints of the dampers. \( \Delta H \) and \( \Delta V \) are the length of the damper measured, respectively, in the horizontal and vertical direction.

Since the dissipated energy is given by the inner area of the cycle, through Eq. (5), the dissipated energy in the equivalent single degree of freedom oscillator can be provided by Eq. (17):

\[ E_{eq} = \pi C_{eq} \rho \Delta_{eq}^2 \]  

On the other hand, the total dissipated energy of the structure equals the sum of the dissipated energy in each damper, given by Eq. (17).

\[ E_{TOT} = \sum E_i = \sum \pi C_i \rho \Delta_{rel,i}^2 \]  

Assuming that all dampers are equal and evenly distributed along the building’s height, \( C \) will be the same in each floor (\( C_{damper} \)). Thus, Eq. (18) is rewritten in Eq. (19):

\[ E_{TOT} = \pi C_{damper} \rho \sum \Delta_{rel,i}^2 \]  

Lastly, matching the previous equations, the device’s damping coefficient is given by Eq. (20).

\[ C_{damper} = \frac{\Delta_{eq}^2}{\sum \Delta_{rel,i}^2} C_{eq} \]  

The following Figure 3 illustrates the proposed methodology.
In conclusion, the design procedures are as follows:

1. Define the structures response reduction, in comparison with the 5% damping response \((1 - \eta)\)
2. Determine the equivalent damping ratio on a SDOF \((\xi_{eq})\)
3. Normalize the displacements of the first vibration mode configuration \((\phi_{top} = 1,0)\)
4. Define the equivalent single degree of freedom oscillator
5. Calculate the equivalent damping coefficient on a SDOF \((C_{eq})\)
6. Calculate the damper’s relative displacement on each floor \((\Delta_{rel,i})\)
7. Calculate the damping coefficient \((C_{damper})\)

### 4. Case study

The case study considers a set of six reinforced concrete frame-wall structures, developed in a previous study [8]. To evaluate the structure’s response, the horizontal maximum displacement at the top of each model is compared, with and without linear viscous dampers \((\alpha=1,0)\). The SAP2000 [9] code was the chosen tool to perform this study.

The seismic action was defined through 10 series of artificial accelerations, considering a type 1 earthquake (Portuguese code) sited in Lisbon, in type B ground. The seismic event presents a 30 seconds duration of stationary movement.

The standard structure consists of a twenty-storey frame with four spans, where the central element is a wall, and the remaining are columns. The wall’s width increases from the first to the last model, consequently, the wall behaviour gains predominance.

The generic characteristics of each model are presented in Table 1. On Table 2 detailed information about dimensions and mass properties is presented.

Regarding the viscous damper’s modelling, SAP2000 uses Maxwell’s rheological model (Hooke and Newton in series) through a Link element [9].
5. Results and discussion

Firstly, the maximum horizontal displacements of the structure without dampers were determined. They result in the average of the maximum displacements, obtained for each one of the 10 accelerograms that define the local seismic action. Secondly, the displacements of the structure with viscous dampers were determined. Each damper assumes the device’s damping coefficient calculated through the proposed methodology, and presented in Table 3. Primarily, it is considered as a predefined goal a 30% reduction in the structure’s seismic response (step 1). Hereinafter, the following steps of the methodology are performed, until the determination of the device’s damping coefficient is achieved.

Table 3: Device’s damping coefficient.

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\text{damper}}$ (kNm$^{-1}$s)</td>
<td>18106</td>
<td>34761</td>
<td>115165</td>
<td>541235</td>
<td>22709</td>
<td>36861</td>
</tr>
</tbody>
</table>

Figure 4 exhibits, for each model, the horizontal displacement evolution by floor, before and after the damper’s application.

Table 4 shows, for each model, the maximum horizontal displacement at the top of the building, without and with viscous dampers.

Table 4: Maximum horizontal displacement at the top of the building (cm).

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{h,\text{max}}$ without dampers (cm)</td>
<td>17.2</td>
<td>1.4</td>
<td>14.8</td>
<td>13.9</td>
<td>11.0</td>
<td>11.1</td>
</tr>
<tr>
<td>$\delta_{h,\text{max}}$ with dampers (cm)</td>
<td>11.8</td>
<td>11.3</td>
<td>10.6</td>
<td>9.8</td>
<td>8.4</td>
<td>8.6</td>
</tr>
</tbody>
</table>
The percentage reduction of the displacement at the top of the structure, after the dampers application, is determined by Eq. (20). The values obtained are shown in Table 5.

\[
\text{Response reduction (\%)} = \frac{\delta_i - \delta_D}{\delta_i}
\]  

(20)

Where \(\delta_i\) and \(\delta_D\) are, respectively, the maximum horizontal displacement at the top of the structure without and with viscous dampers.

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response reduction (%)</td>
<td>32</td>
<td>31</td>
<td>28</td>
<td>30</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 5: Response reduction of the structure with viscous dampers.

The results from Models A to D, present reductions very approximate to the initial goal, the 30% reduction in the structure’s seismic response. However, models E and F deviate from the predefined goal. Model D achieves exactly the aimed response reduction, nevertheless, the damping coefficient is the highest, when confronting with the remaining models \((C_A=18106 \text{ kNm}^{-1}s; C_D=541235 \text{ kNm}^{-1}s)\).

Table 6 shows, for each model, the corresponding relative error percentage, obtained from Eq. (21).

\[
\text{Relative error (\%)} = \frac{\text{Red}_{\text{obj}} - \text{Red}_{\text{obt}}}{\text{Red}_{\text{obj}}}
\]  

(21)

Where \(\text{Red}_{\text{obj}}\) and \(\text{Red}_{\text{obt}}\) are, respectively, the reduction objective and the obtained reduction.

Models E and F reveal a significant relative error, whereas other models exhibit errors below 7%.

The insufficient response reduction in models E and F, may be justified by the predominance of the wall effect, due to its geometric characteristics. The panel where the damper is installed reveals a rigid body movement, as both floor rotation and inter-storey drifts, increases with height, as happens in wall type structures. For this reason the alignment where the damper is located experience reduced axial deformation.

The energy dissipation is more efficient when the axial deformation in the viscous damper is maximum. As a result, given that the alignment of the damper only experiences rotation movement - following the cantilever deformation of the wall structure - it does not exhibit sufficient elongation to ensure the required energy dissipation. Therefore, the use of diagonal viscous dampers in structures whose wall behaviour is predominant is not recommended, as it does not contribute to a significant reduction in the response.

Furthermore, the results obtained may be explained due to the fact that the proposed methodology considers only the fundamental vibration mode, since higher vibration modes reveal greater influence in wall structures.

In order to achieve higher displacement reductions in this kind of structures, a higher value of damping in the devices would be required. This is not at all reasonable due to the significant increase in the cost of this type of seismic protection technique.

Models A to D accomplish the predefined target, thus, the proposed approach is considered adequate. They present a frame behaviour, i.e. pure shear deformation, due to the frame behaviour domain. Considering an extreme situation of pure shear behaviour, the damper’s elongation and deformation ensures the required energy dissipation. Therefore the structure’s response reduction is achieved.
Dampers deformation on the 15th floor of model A and E are presented in Figure 5-(1) and Figure 5-(2), respectively.

For Model E to obtain the same level of axial deformation as Model A, an higher force level is required. To achieve a total displacement of 0.004 m, Model E needs a 500kN force, whereas Model A reaches the same value with just a 300kN force. In wall type structures, dampers require a much higher force to reach the energy dissipation obtained in a frame structure. Therefore, the presented methodology is not suitable to structures whose wall effect is relevant.
6. Conclusions

The proposed methodology describes a simple and practical method that estimates the equivalent damping in tall structures with viscous dampers, assuming that all devices are equal and evenly distributed along the building’s facades. The definition of the damping coefficient essentially depends on the structure’s behaviour. Accurate results appear in frame-wall structures whose frame behaviour has greater predominance. On the other hand, same type structures, but predominantly influenced by the effect wall, do not show favourable results. Even the diagonal damper’s application is questionable, since a high damping coefficient is required in order to achieve a significant reduction in the structure’s seismic response.

The end to end relative displacement of the damper is crucial to define the device’s damping coefficient. Disregarding its contribution has a significant impact on the results. Simplification of this methods must be avoided.

After applying the seven steps proposed, the methodology offers a reliable first guess on the equivalent damping. It allows the development of other procedures to improve the distribution of devices, in order to define a global solution with viscous dampers.

REFERENCES


