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Design of seismic protection of tall buildings using viscous dampers

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Abstract

The use of viscous dampers for the seismic response control on buildings is an effective solution and well known in the engineering community.

After setting a predefined goal on the building seismic behavior, for example the definition of the maximum interstory drift allowable, there are two major problems on the design of solutions with viscous dampers: the definition of the capacity of each damper; and the definition of each damper location. This second problem, the damper´s location, is focused on the discussion between the use of dampers in all over the height of the building or if it is possible to choose optimal locations and concentrate the dampers only on those places.

In this study, the dampers are assumed to be located along diagonals between stories to work with the inter-story movement of the nodes to which they are connected. In the case of viscous dampers, what is important is the relative velocity of the inter-story movement.

To get an initial value of the dampers´ characteristics a methodology based on the definition of an equivalent single degree of freedom system is proposed. 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.

After completing the definition of the characteristics of the dampers to be used on each interstorey location, the solution is improved using dampers only on the best positions. In the proposed methodology, the choice of the optimal location is based on the expected value of the square of the interstorey velocity, as a measure of the energy dissipated. To obtain these values, the evaluation of the PSD of the interstorey velocity is needed.

On both steps, the damper´s characteristic definition and their best location depends on the seismic action definition.

In this paper, the application of those methodologies to a 37 story tall building with 148m height is presented. The effectiveness of the methodologies are discussed and some improvements are proposed.

Keywords: viscous dampers, displacement control, tall buildings, optimal placement

1. Introduction

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, 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 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.

It is important to consider that the increased flexibility of tall buildings makes them very susceptible to displacements; as such, they have a high vulnerability. For this reason, it can be useful to guarantee a reduction of a flexible structure's displacements. Applying viscous dampers is an efficient solution to accomplish it.

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 characteristics neede to achieve a predefined displacement reduction.

In previous studies, the device's damping coefficient was arbitrated in order to achieve a predefined goal through a process of trial, and that is precisely what is intended to avoid with this new approach.

2. Viscous dampers

Seismic protection techniques can be grouped, into simple passive devices or more sophisticated active systems. Since active systems require energy to reduce a structure displacement, using these devices is more difficult than employing passive systems. Besides, passive protection techniques are perhaps the best known and these include seismic base isolation and passive energy dissipation (Buckle, 2000).

There are different types of energy dissipation systems, and these can be classified as hysteretic dampers, viscous dampers or viscoelastic dampers.

These devices dissipate the earthquake's energy. Therefore the structure's energy absorption is reduced, thus any significant displacements are controlled. As the seismic deformation is reduced it is possible for the structure to remain elastic. Consequently, the ductility requirements are not as demanding as those necessary on buildings that are not equipped with this technology.

Fluid viscous dampers operate on the principle of fluid compression and circulation. The dissipation force on viscous dampers varies only with the end-to-end velocity across the damper. This relation is expressed in Eq. (1) [2].

$$F_{damper} = C\,|v|^{\alpha}\,sign(v) \tag{1}$$

where the parameter α depends on the characteristics of the fluid, the constant C varies with the dampers' dimensions and the variable v is the end to end velocity across the damper. The damper is called linear in the case of α =1,0.

Energy dissipation is an effect of the movement between both ends of the damper and since the dampers are connected to the floors (most current solution), it is logical that the energy dissipation is an effect of the interstorey movement.

3. Methodology for the evaluation of the damper coefficient

The methodology developed consists in the evaluation of the damping coefficient C_{damper} to consider on each damper, evenly distributed along the building's facades, in order to reduce the maximum displacement at the top of the structure, to a certain target displacement.

It is well known that the use of energy dissipation systems leads to the reduction of the seismic structure's response. Therefore, the analysis of the maximum displacement at the top of the structure allows the evaluation of its behavior, 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.

Before defining the number of devices, their size and their location, it is vital to know the damping 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 [3]. When analyzing 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 [4].

3.1 Equivalent single degree of freedom oscillator

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

$$x = A \sin(pt) \tag{2}$$

$$v = A\, p \cos(pt) \tag{3}$$

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 $\alpha = 1{,}0$, the damping force is expressed by Eq. (4), where C is the system's damping coefficient and A is the end to end amplitude of movement in the damper ($A = x_{max}$).

$$F_{damper} = C\, A\, p \cos(pt) \tag{4}$$

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):

$$Area = \pi\, C\, p\, A^2 \tag{5}$$

The equivalent damping ratio is given by Eq. (6):

$$\xi_{eq} = \frac{2}{\pi} \frac{Area}{A_{rec}} \tag{6}$$

where A_{rec} expressed in Eq. (7) corresponds to the area of the rectangle that circumscribes the force-displacement cycle, assuming a linear elastic system with stiffness k.

$$A_{rec} = 4\, k\, A\, A = 4\, k\, A^2 \tag{7}$$

The structure's frequency in the absence of damping is given by Eq. (8), where k is the structure's stiffness and m the corresponding mass.

$$p = \sqrt{\frac{k}{m}} \tag{8}$$

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

$$C_{eq} = \xi_{eq}\, 2\, m_{eq}\, p_1 \tag{9}$$

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 we need to obtain with the protection system, the damping correction coefficient η recommended in EC8-1 [5], and expressed in Eq. (10), can be used as a starting point of the proposed method.

$$\eta = \sqrt{\frac{10}{5+\xi}} \geq 0{,}55 \tag{10}$$

The previous equation corresponds to a SDOF system's damping, for a damping correction coefficient greater 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 $(1 - \eta)$. For example, $\eta = 0{,}75$ corresponds of a reduction of 25% in the original displacements.

A 5% damping was considered for the structure without viscous dampers (RC structure). 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 ξ obtained from Eq. (10), includes the structure's 2% damping. Hence, the equivalent damping ratio for the dampers is given by Eq. (11):

$$\xi_{eq} = \xi - 0{,}02 \tag{11}$$

The equivalent single degree of freedom oscillator is defined based on the same approaches used in a pushover analysis. Assuming the mass in each floor equal to m_i, m_{eq} is given by Eq. (12), where ϕ_i is the configuration of the first vibration mode of the structure.

$$m_{eq} = \sum m_i \phi_i \tag{12}$$

The following transformation parameters [Eq. (13) and Eq. (14)] were considered, where Δ_{eq} is the maximum horizontal displacement at the top of the equivalent SDOF oscillator:

$$\Gamma = \frac{m_{eq}}{\sum m_i \phi_i^2} = \frac{\sum m_i \phi_i}{\sum m_i \phi_i^2} \tag{13}$$

$$\Delta_{eq} = \frac{\phi_{top}}{\Gamma} \tag{14}$$

The structure's first mode of vibration displacements are normalized, assuming ϕ_{top}=1,0.

3.2 Devices's damping coefficient

The damping coefficient to be adopted in each device takes into account the end to end deformation across the damper, through Eq. (15):

$$\Delta_{rel,i} = \frac{(\phi_H^i-\phi_H^{i-1})\Delta H+(\phi_V^i-\phi_V^{i-1})\Delta V}{\sqrt{\Delta H^2+\Delta V^2}} \tag{15}$$

where,

ϕ_H^i, ϕ_V^i - horizontal and vertical displacement of the first mode configuration, at the end joints.
ΔH, ΔV - 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. (16):

$$E_{eq} = \pi\, C_{eq}\, p\, (\Delta_{eq})^2 \tag{16}$$

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

$$E_{TOT} = \Sigma E_i = \Sigma \pi\, C_i\, p\, (\Delta_{rel,i})^2 \tag{17}$$

Assuming that all dampers are equal and evenly distributed along the building's height, C_{damper} will be the same in each floor. Thus, Eq. (17) is rewritten in Eq. (18):

$$E_{TOT} = \pi\, C_{damper}\, p\, \Sigma(\Delta_{rel,i})^2 \tag{18}$$

Assuming that the ratio of energy by unit mass of the structure and of the equivalent SDOF is the same, the C_{damper} can be obtained by Eq. (19).

$$C_{damper} = \frac{m_{TOT}}{m_{eq}}\frac{\Delta_{eq}^2}{\Sigma\Delta_{rel,i}^2}\, C_{eq} \tag{19}$$

where m_{TOT} is the participation mass of the structure mode considered in the analysis.

The following Fig. 1 illustrates the proposed methodology.

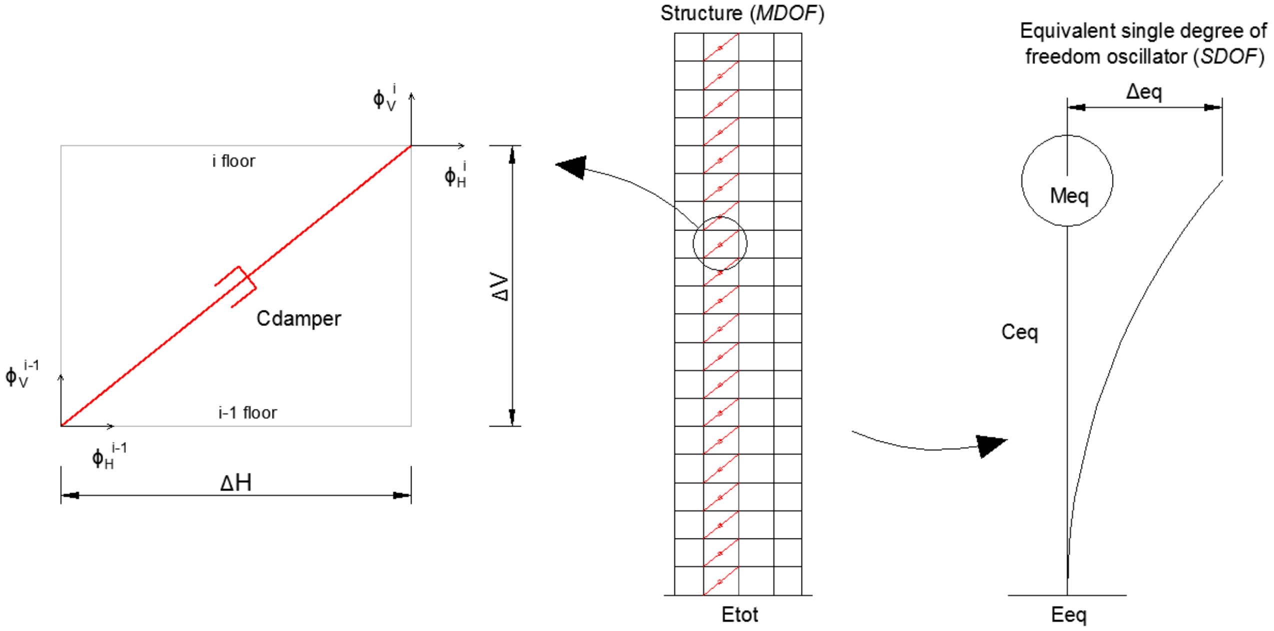


Fig. 1 – Illustration of the methodology for the evaluation of the damper coefficient

In conclusion, the design procedures are as follows:

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

4. Case Study

To test the application of the proposed methodology a 37 storeys reinforced concrete building was modelled. It was considered a constant storey height (4m), with a total height of 148m. The plan view presents a regular rectangular geometry with the smallest dimension according to Y (l_y = 27,95 m) and the largest dimension according to X (l_x = 43,40 m), both constant in height (Fig. 2). Frames in the outline of the building, and resistant walls in the inner core compose the lateral resisting structure.

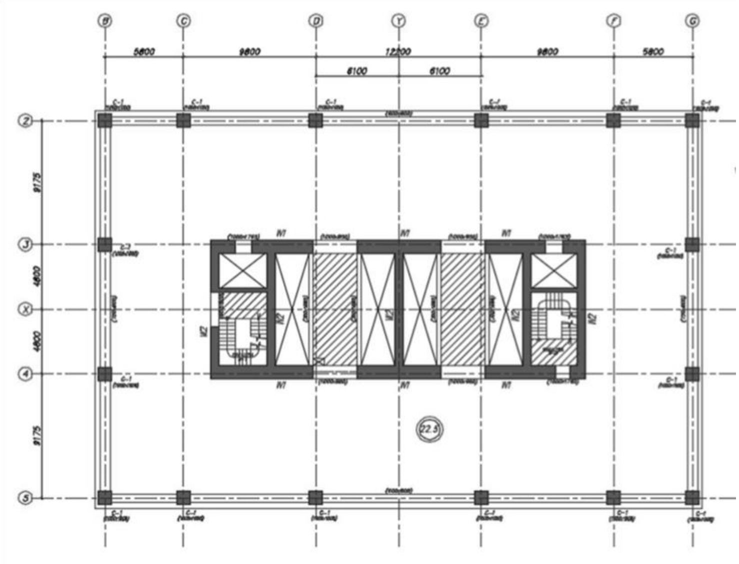


Fig. 2 – General plan of the building

To study the application of the methodologies described above in a tall building, a structure was modelled using the finite element analysis software SAP 2000 [6] (Fig. 3).

On Table 1 are presented the dimensions of the structural elements (beams, columns and walls) and the concrete class considered on each element.

Table 1 – Dimensions of the structural elements

Height (m)		**nº of storeys**	**Concrete**	**Wall W1 - thickness (m)**	**Wall W2 - thickness (m)**	**Columns dimensions (m)**		
from	to					a	x	b
128	148	5	C35/45	0,20	0,20	0,60	x	0,60
108	128	5	C35/45	0,20	0,20	0,75	x	0,75
88	108	5	C45/55	0,30	0,20	0,90	x	0,90
64	88	6	C45/55	0,50	0,20	1,10	x	1,10
36	64	7	C50/60	0,60	0,40	1,15	x	1,15
16	36	5	C60/75	1,00	0,50	1,25	x	1,25
0	16	4	C60/75	1,00	0,60	1,37	x	1,37

Height (m)		**nº of storeys**	**Concrete**	**Beams along X dimensions (m)**			**Beams along Y dimensions (m)**		
from	to			h	x	b	h	x	b
108	148	10	C35/45	0,80	x	0,60	0,75	x	0,60
64	108	11	C45/55	0,80	x	0,60	0,75	x	0,60
36	64	7	C50/60	0,80	x	0,6	0,75	x	0,60
0	36	9	C60/75	0,80	x	0,6	0,75	x	0,60

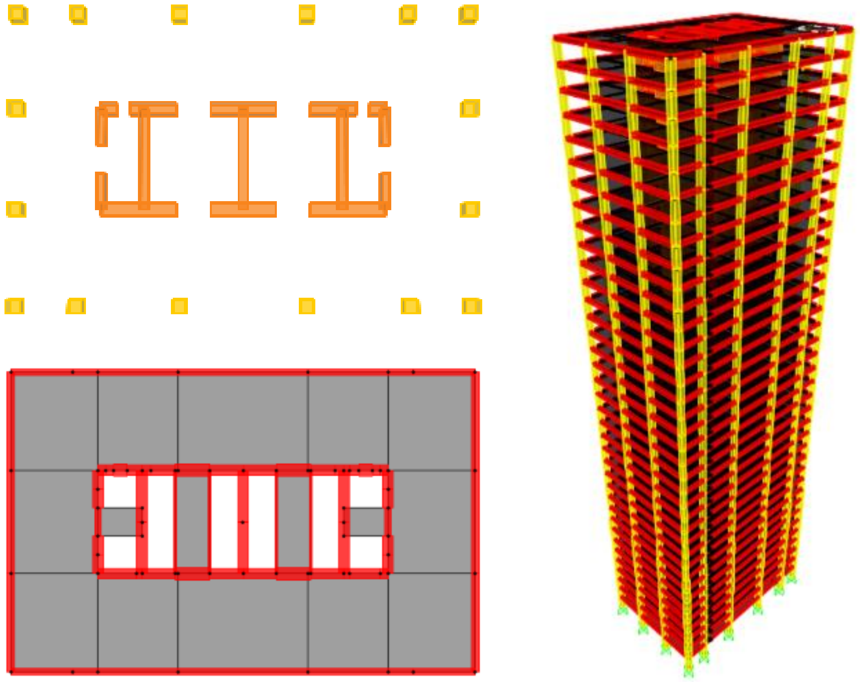


Fig. 3 – Structural model of the building

For the seismic analysis of the structure, 10 artificial accelerograms were generated according to EC8 [5] rules. A dynamic analysis has been undertaken. The dynamic characteristics of the first three modes are presented on Table 2. The configuration of the first three modes of vibration of the structure are illustrated in Fig. 4. Note that the deformations Ux and Uy represent the translation along the X and Y axis respectively.The total mass of the model is 62930 ton.

Table 2 - Frequency and mass participation factors for the first three modes of vibration

Mode	**Frequency (Hz)**	**Mass Participation Factors**	
		Ux (%)	Uy (%)
1	0,201	0,00	55,23
2	0,332	12,56	0,00
3	0,337	46,64	0,00

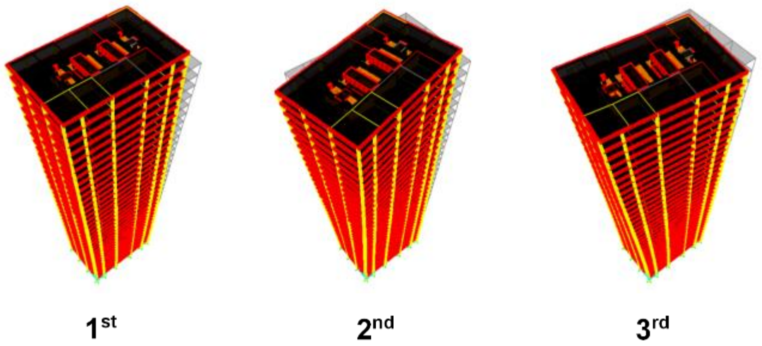


Fig. 4 - Configuration of the first three modes of vibration

4.1 Application of the methodology to determine the equivalent damping coefficient

According to the proposed methodology, the first step is to define the desired reduction. It was defined that the objective of this work is to reduce the response of the structure by 25%, being 1-η = 0,25. The second step is to determine the equivalent damping ratio on SDOF, given by:

$$\xi_{eq}= (\frac{10}{\eta^2} - 5) - \xi_i = 10{,}78\% \tag{20}$$

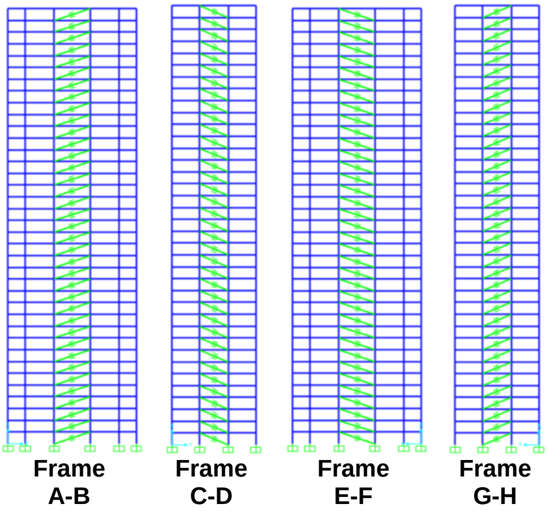
The dynamic characteristics of the model are determined, namely the period and frequency for all modes of vibration of the structure. The results for the first three modes associated with each of the main deformations are presented in Table 3.

Table 3 - Dynamic characteristic values of the first and third modes of vibration

Mode	1st	3rd
f (Hz)	0,201	0,337
p (rad/s)	1,264	2,117
Participation mass (ton)	34737	29325
Main deformation	Uy	Ux

The horizontal displacements of each storey (ϕ_i), associated to the deformed configuration of the first vibration modes for each respective deformation considered were normalized. This normalization was made assuming that the displacement at the top is unitary ($\phi_{top} = 1$).

The dampers were modeled throughout the height, in the central span, as shown in Fig. 5.



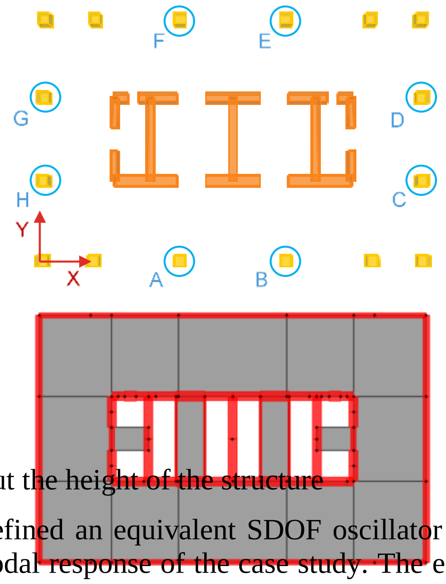


Fig. 5 – Distribution of dampers throughout the height of the structure

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In accordance with the described methodology, it will be defined an equivalent SDOF oscillator per each considered deformation direction (X and Y), based on the modal response of the case study. The equivalent mass of the SDOF is obtained using the normalized displacements, where the dampers in the AB and the EF frame work in the X direction and dampers in the CD and the GH frame work in the Y direction. It is now possible to obtain all the remaining characteristics of the SDOF (Table 4).

Table 4 - Dynamic characteristic values of the equivalent SDOF oscillator per main deformation

Deformation	Ux	Uy
m_{eq} (ton)	23583	21584
$\Gamma = (\Sigma\,\phi_i)/(\Sigma\,\phi_i^2)$	1,582	1,609
Δ_{eq} (m)	0,632	0,622

Having defined the equivalent SDOF oscillator, it is possible to calculate its equivalent damping coefficient (C_{eq}). In order to estimate the damping coefficient to be applied throughout the height of the structure, it is necessary to calculate the sum of the square of damper's relative displacement on each storey. Finally, the damping coefficient estimate to be applied to each damper throughout the height of the structure, in each direction, is determined. All these values are presented on Table 5.

Table 5 – Evaluation of C_{damper} values.

Deformation	Ux	Uy
C_{eq}	10953	5997
$\Sigma\,(\Delta_{rel,i})^2$	0.03649	0.02752
m_{eq} (ton)	23583	21584
m_{TOT} (ton)	29325	34731
C_{damper} (kNm^{-1}s)	149083	135683

The C_{damper} values obtained has to be divided by 2 because, on each storey, there are 2 dampers on each direction. That result in a value of 74542 kNm^{-1}s on direction X and a value of 67841 kNm^{-1}s on direction Y.

In the calculus, the obtained values were simplified to 75000 kNm^{-1}s in the X direction and 68000 kNm^{-1}s in the Y direction. The estimated damping coefficient were applied to each one of the dampers evenly throughout the height.

Fig. 6 illustrate the maximum displacement observed for the deformation U1 and U2 respectively throughout the height for the situations without dampers (before) and using the initial estimate (initial). The reduction of the maximum response at the top of the building corresponds to 28,8% for the X direction and 24,7% for the Y direction (see Table 6).

Table 6 – Results: displacement on top (m)

Displacement	Ux	Uy
Without dampers	0,264	0,312
With dampers	0,188	0,235
reduction	28,8%	24,7%

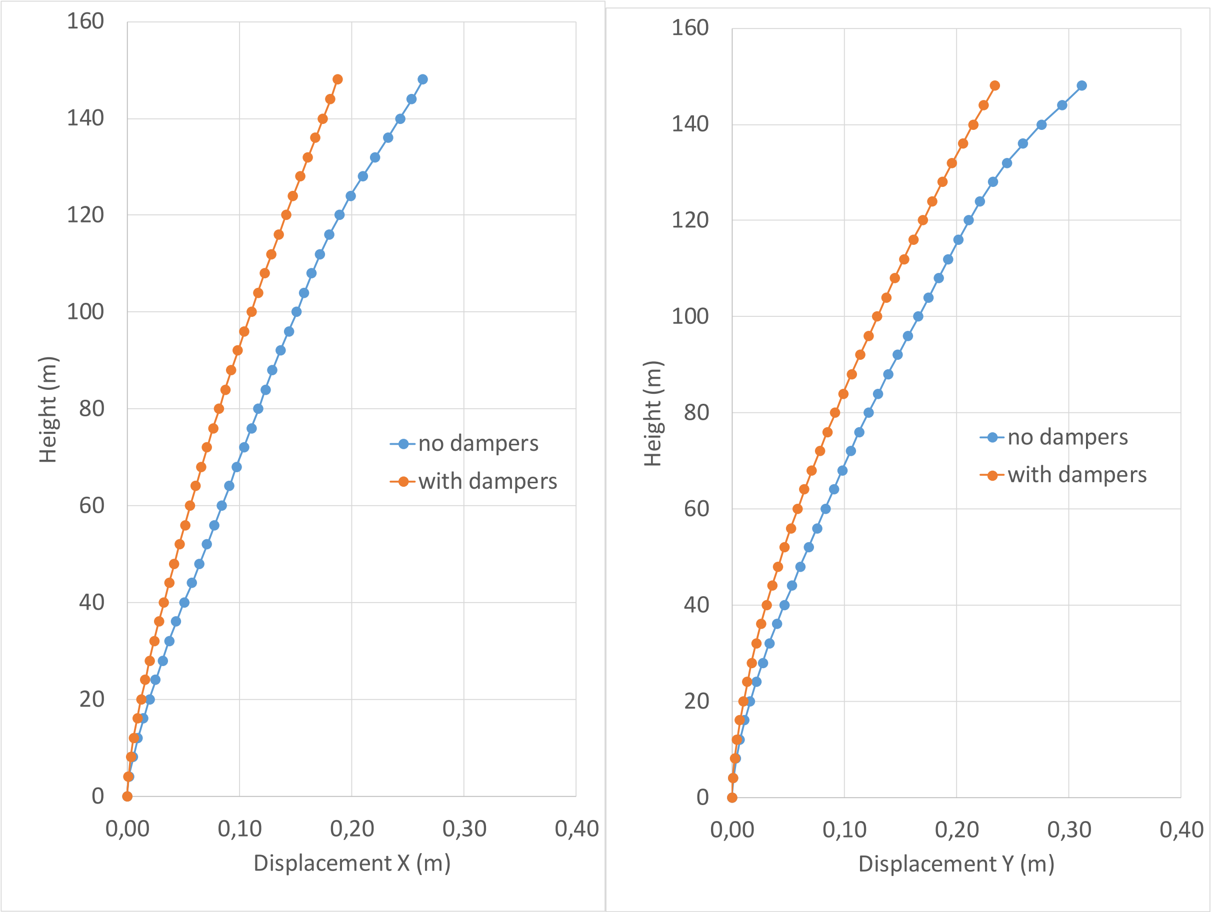

Figure 6 - Maximum displacement per storey and corresponding reduction

The results obtained are match the desired reduction on each direction with a slight difference on X direction (28,8% for a target value of 25%).

The increased reduction on the X direction can be explained with the analysis of the configuration of the third mode of vibration. This is the dominant mode in the X direction, but is associated with some torsion that results from the distribution on plan of the vertical resistant members. Since there is some torsion, the dampers located in the facades Y-oriented are also mobilized by the movement, and contribute for the energy dissipation related with this vibration mode. This was not considered in the C_{damper} estimation, since there were assumed independent models on each direction.

5. Conclusions

The proposed methodology describes a practical method to estimate the equivalent damping in tall structures with viscous dampers, assuming that all devices are equal and evenly distributed along the building’s facades.

Since the dissipated energy is caused by the interstorey movement of the building, the dynamic characteristic that most influence the optimal locations is the value of the modal configuration in each floor.

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.

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