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A NEW METHODOLOGY FOR THE OPTIMAL PLACEMENT OF DAMPERS ON TALL BUILDINGS

I. Brás(1), L. Guerreiro(2)

(1) *Student, Instituto Superior Técnico – Universidade de Lisboa, isabel.bras@tecnico.ulisboa.pt*
(2) *Associate Professor, Instituto Superior Técnico – Universidade de Lisboa, luis.guerreiro@tecnico.ulisboa.pt*

Abstract

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

One major problem on the design of solutions with viscous dampers is the definition of the dampers´ location, especially on tall buildings. The discussion is 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.

On this paper a new methodology for the optimal placement of dampers is presented. The methodology is based on the evaluation of the Power Spectral Density (PSD) of the interstorey velocity on the locations in analysis.

To improve the effectiveness of the solution, the dampers must be located in the places where the capacity to dissipate energy is higher.

The dampers must be located between storeys because they work as a result of the interstorey movement of the storeys to which they are connected. In the case of viscous dampers, what is important is the relative velocity of the interstorey movement. 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.

According to this method the optimal location of the dampers not only depends of the structure but also depends of the earthquake's characteristics.

On the paper some application examples are also presented.

Keywords: viscous dampers, tall buildings, optimal placement

1. Background and scope

It is well known that seismic action is one of the most destructive forces of nature and is responsible for large economic and social losses. Furthermore, collateral effects of an earthquake, such as fires and tsunamis, can't be overlooked. It is essential to adopt preventive measures and establish a path to reduce the damage on structures, which are directly related with the reduction of the structures' seismic risk.

At the same time, seismic risk is a function of seismic hazard, vulnerability and exposure [1]. Hazard is the exceedance probability of a certain level of severity of the natural event, in a site, and during an exposure period of time; and exposure reflects the value of the elements at risk [1].

Since vulnerability reflects the susceptibility of an element at risk being adversely affected by the natural phenomenon [1], it is associated with the structures' capacity to have a good performance during an earthquake. As such, vulnerability is the principal factor that engineers can control in order to reduce seismic risk.

As a result of changing the dynamic characteristic of a structure or giving the ability to dissipate an earthquake's energy, the use of seismic protection techniques improves the resistance of the structures [2]. If these kind of systems are applied to tall buildings, vulnerability and seismic risk is reduced, resulting in a lower damage on the structures.

It is also 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.

On the other hand, one should take notice that applying dampers on all the floors of a tall building can't be cost effective or impracticable. As a consequence, it is relevant to have practical guidelines in order to find the best locations to place the dampers.

1.1. Seismic protection techniques

Seismic protection techniques can be grouped, either 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 [3].

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 maintain its elastic behaviour. As a consequence, the ductility requirements are not as demanding as those necessary on buildings that are not equipped with this technology.

1.2. The optimal placement problem

The key focus of optimal placement methods is to identify the locations where dampers can dissipate the maximum amount of energy while accompanying the structure's deformation. "Ideally, any design procedure for optimal damper configurations should meet three conditions in order to be routinely applied in seismic design of multi degree of freedom structures: simplicity, practicality and efficiency" [4].

Optimal placement of dampers in tall buildings has been studied in the last years [5] [6] [7]. Nevertheless, there is not a single methodology in which the results are significantly better than the others. In fact, there are several optimal placement methodologies; and assumptions and limitations are different in each approach. Furthermore, there are methods that required a high computational-effort. In these cases, it is important to evaluate if the additional complexity and time expended by using advanced damper placement methods is justified by the improvements in building performance [5].

2. Viscous Dampers and dissipated energy

2.1. Operating mode

Fluid viscous dampers operate on the principle of fluid compression and circulation. As it is shown in Fig. 1 [8], chamber 2 becomes compressed when the piston travels through chamber 1 that are filled with fluid (green arrow). Then, the pressure difference between these two chambers causes fluid to flow through the orifices in the piston head (orange arrows). There is also an accumulation chamber for protection against fluid overstress (white arrows).

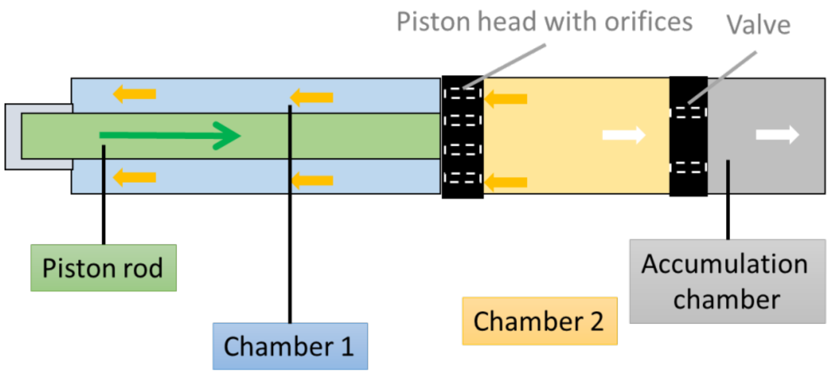


Fig. 1 – Viscous damper operating mode (adapted from [8])

2.2. Dissipation force

The dissipation force on viscous dampers varies only with the end to end velocity across the damper. This relation is expressed in Eq. (1) [9].

$$F=C|v|\alpha sign(v) \tag{1}$$

where the parameter α depends on the characteristics of the fluid (the damper is called linear in the case of α =1.0), the constant C varies with the dampers' dimensions and the variable v is the end to end velocity across the damper.

Therefore, 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.

2.3. Measure of the dissipated energy

The physical quantity that estimates the measure of the dissipated energy on viscous dampers is proportional to the square of the end to end velocity across the damper (2) [8]. For that reason, it is assumed that the measure of the dissipated energy is the expected value of the square of the end to end velocity across the damper.

$$E_{diss/cycle} = \mathrm{C}\int_0^{\mathrm{T}} \mathrm{v}^2 dt \tag{2}$$

As a result, if the dampers are assumed to be connected to consecutive floors, the measure of the dissipated energy is estimated by floor i ($E\left[V_i^2(t)\right]$) and it is expressed in Eq. (3) [8].

$$E\left[V_i^2(t)\right] = \int_{-\infty}^{+\infty} S_{v_i}(w)dw \tag{3}$$

To define $E\left[V_i^2(t)\right]$ it is necessary to obtain the Power Spectrum Density (PSD) of the interstorey velocity ($S_{v,i}(w)$).

On the other hand, $S_{v,i}(w)$ depends on the PSD of the action ($S_a(w)$) and also on the structurers' characteristics. This relation is expressed in Eq. (4) [10].

$$S_{v,i}(w) = |H(w)|_i^2 S_a\ (w) \tag{4}$$

Where H(w) is the transfer function of the interstorey velocity of the structure (between floor i and floor i-1), which is defined by floor i and that depends on the structures' characteristics.

Since the dampers' displacement is only in their axial direction, the transfer function must be measured in the dampers' direction. This means that it is necessary to take into account the damper's inclination. Regarding this, the transfer function H(w) proposed on this methodology is expressed in Eq. (5) [8].

$$H(w)_{\mathrm{i}} = \sum_n -FP_n\, \phi_{d_i}^{rel} \frac{-(2\xi p_n w^2) - w\,(p_n^2 - w^2)i}{(p_n^2 - w^2)^2 + (2\xi p_n w)^2} \tag{5}$$

where:

FP_n is the modal participation factor of mode n;

ξ is the damping coefficient of the structure without dampers;

p_n is the angular frequency of mode n;

w is the angular frequency;

and $\phi_{d_i}^{rel}$ is the relative displacement illustrated in Fig. 2 and it is expressed in Eq. (6) [8].

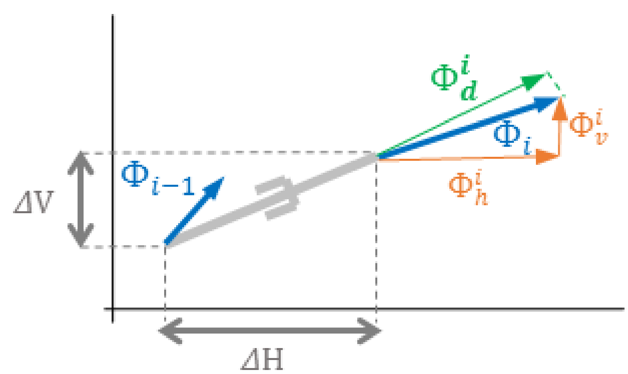


Fig. 2 – Vector component of the modal configuration in the damper's direction

$$\phi_{d_i}^{rel} = \frac{(\phi_h^i - \phi_h^{i-1})\Delta H + (\phi_v^i - \phi_v^{i-1})\,\Delta V}{\sqrt{\Delta H^2 + \Delta V^2}} \tag{6}$$

where:

ϕ_h and ϕ_v are, respectively, the horizontal and the vertical displacement of the modal configuration.

ΔH and ΔV are the length of the damper measured, respectively, in the horizontal and vertical direction.

The previous equation makes clearly that it is possible to use other solution than the application in two consecutive floors.

3. Optimal placement methodology

The design procedures using the methodology proposed are as follows:

1. Define PSD of the action (S_a)
2. Define transfer function (H(w)) by possible location
3. Calculate PSD of the velocity (S_v) by possible location
4. Calculate energy estimation ($E\left[V_i^2(t)\right]$) by possible location
5. Sort the values of ($E\left[V_i^2(t)\right]$)

In this final step it is necessary to define the total number of dampers (N_d) to be applied. Then it is possible to choose the best N_d locations where they can dissipate the most amount of energy, which means that it is possible to define the optimal placement: the locations chosen are where the value of $E\left[V_i^2(t)\right]$ is higher.

It is easy to understand that the optimal placement that results from the proposed methodology does not depend on the characteristic of the damper or neither on the number of dampers in the optimal placement – it only depends on its position, which is normally conditioned by the geometry of the building.

As a consequence, despite the optimal locations are perfectly defined at the end of step 5, it is important to verify the building performance concerning the number and type of dampers applied. Therefore, it can be tested several optimal placements depending on the number and type of dampers chosen. Furthermore, it is necessary to make an evaluation of the structure response which is essential to verify the efficiency of the solution.

4. Case study

4.1. Introduction

The purpose of this topic is to test the proposed methodology on some examples. Finally, it is compared the efficiency between the optimal placement and the uniform placement (one damper by floor).

The structures tested are three different frame-wall structures with twenty floors each. They are named from A to C and the dampers are placed between consecutive floors.

As said before, it can be tested several optimal placements depending on the criteria adopted on choosing the number and the type of dampers in the optimal placement. For instance, a possible solution is to choose all the dampers that dissipate energy above a certain level. However, since these criteria are independent on the methodology, in the case study it was simply decided to choose an optimal placement with ten linear dampers (N_d=10, half the total number of floors).

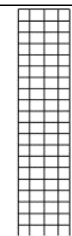
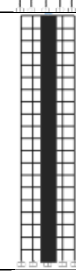
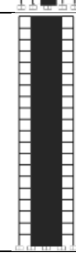
The standard frame structure in all these structures has four columns displaced laterally and one wall as a central element (frame element with a larger length than the columns). The wall's length increases from structure A to C. As a consequence, the wall behavior is becoming more preponderant from structure A to C.

The generic characteristics of these structures are presented in Table 1. More details about the dimensions of each wall are presented in Table 2.

Table 1 – Case study - generic characteristics

Number of floors	20
Height of the floors	4 m
Spacing between frames	5 m
Slabs' thickness	0,20 m
Concrete type	C40/50
Columns	0,80x0,80 m^2
Beams	0,25x0,75 m^2

Table 2 – Case study - wall's dimensions

Structure	Central element	Illustration
A	0,80x0,80 m^2	
B	5,0x0,20 m^2	
C	10,0x0,20 m^2	

4.2. Dissipated energy

The measure of the dissipated energy by each floor in structure A, B and C is shown from Fig. 3 to Fig. 5. The values are normalized for the maximum value obtained in each structure. Then, the maximum value in each graphic is unitary [8]. The result of sorting the values of the dissipated energy for each floor and choosing the ten locations where the dampers can dissipate the most amount of energy is presented with green points. As so, these points represent the ten dampers that dissipate the most amount of energy, which means that they are the optimal placement with this number of dampers.

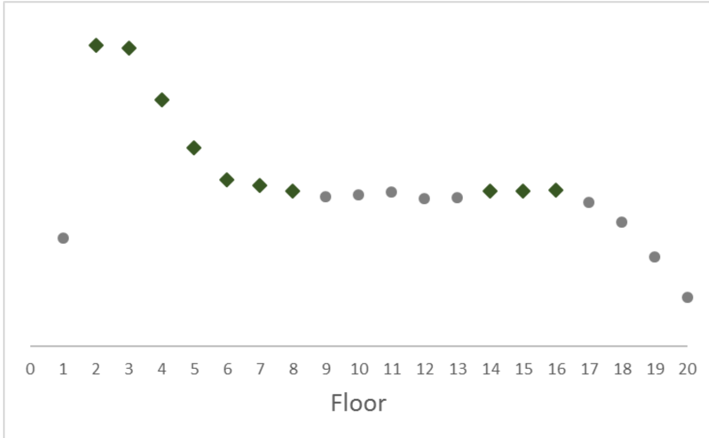


Fig. 3 - Energy dissipated by floor in structure A (adapted from [8])

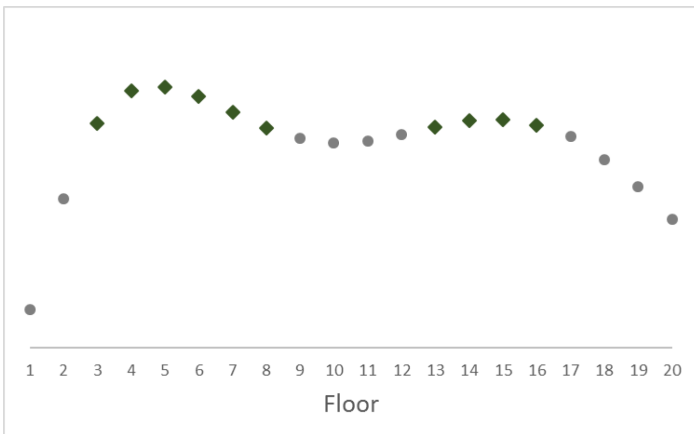


Fig. 4 - Energy dissipated by floor in structure B (adapted from [8])

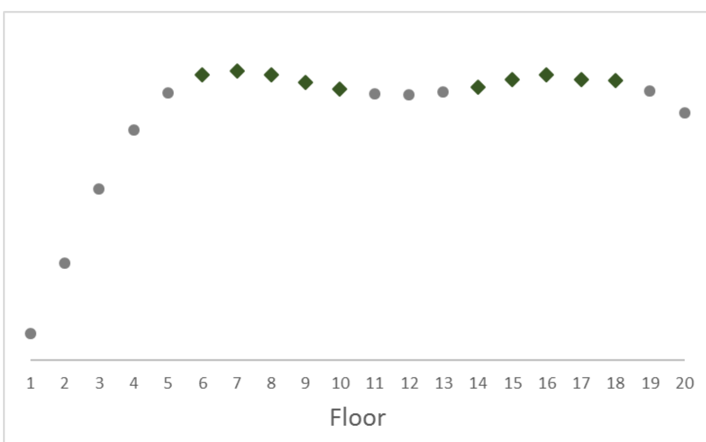


Fig. 5 - Energy dissipated by floor in structure C (adapted from [8])

4.3. Optimal placement

The optimal placement configuration is shown in Fig. 6 for the structures A, B and C [8].

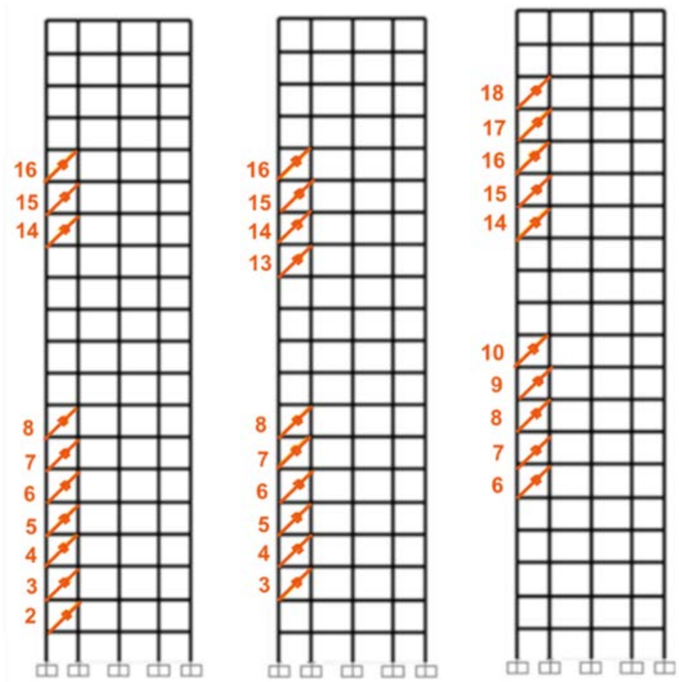


Fig. 6 – Optimal placement – left: A; center: B; right: C (adapted from [8])

As it is shown on the figure above that mixed frame-wall behavior influences the optimal placement. It is also clear that from structure A to C the optimal locations change from the lower to the upper floors.

Since the structures with predominant wall behavior leads to optimal placements on the upper floors and, on the other hand, optimal placements in frame structures have the dampers in the lower floors, and since the wall behavior is more predominant from structure A to C, this result confirms the expected results.

It is also shown that there are two different zones on the optimal placement: one zone with lower floors and another with upper floors.

These two evidences leads to the conclusion that this methodology is effective regarding the mixed frame-wall behavior.

4.4. Result Analysis – comparison between optimal placement and uniform placement

Finally, it is relevant to evaluate the methodology efficiency. However, this procedure is independent on the steps proposed on the methodology above.

In this regard, it was necessary to analyze the structures' response as a result of applying dampers on the optimal locations. This response is then compared to the structures response when using the uniform placement (one damper by floor).

Since these solutions must have the same global cost to be possible to compare both efficiency, in this evaluation some assumptions about the dampers' cost were made. Two conditions were adopted regarding this matter:

- It is assumed that dampers' cost is related with the dimensions and that this relation is linear;
- In each solution all the dampers are equal.

It is assumed that, as the constant C of the dampers is related to their dimensions, constant C is proportional to the dampers' cost. So it is implied that the parameter that is representative of the global cost of the dampers in a placement (C_{tot}) is related with the sum of all constant C of each damper.

Then, since all the dampers are the same, C_{tot} is given in Eq. (7), where N_d is the total number of dampers in a placement.

$$C_{tot} = N \times C \tag{7}$$

The response parameter used to evaluate the effectiveness of each solution was the horizontal displacement on the top floor. This displacement is a result of a non-linear time history analysis. The seismic action was simulated by ten artificial accelerograms compatible with the action specified in step 1 of the methodology. So that, the response parameter is the average value of the maximum values for each artificial accelerogram.

It was tested linear dampers and the results are shown in Fig. 7 to Fig. 9, structure A, B and C, respectively.

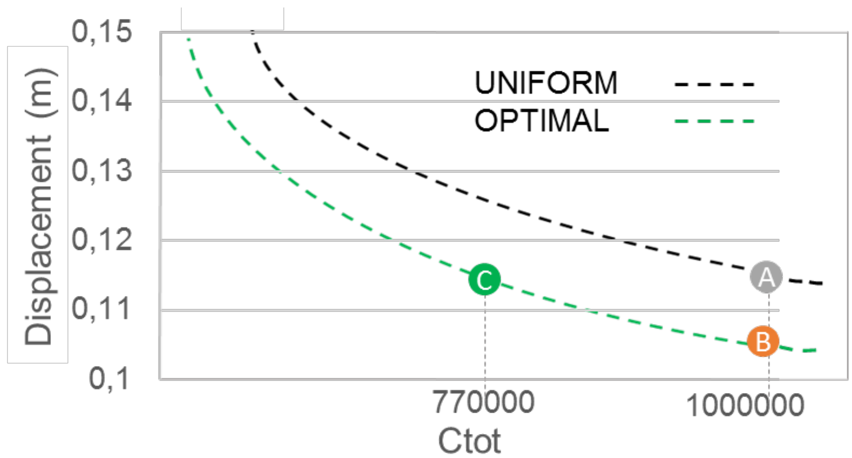


Fig. 7 – Comparison between optimal placement and uniform placement – Structure A

These results leads to the following conclusions:

- If it is compared the same value of C_{tot} in the two placements, uniform distribution leads to worst values of displacements (comparison between A and B)
- If it is compared two solutions with the same displacement target, the optimal placement leads to a reduction of the C_{tot} value (comparison between A and C).

In the case study, the target was a reduction in the displacement of the structure at the level of 50% of the displacement in the structure (without dampers), considering an intrinsic damping coefficient of 2% [8].

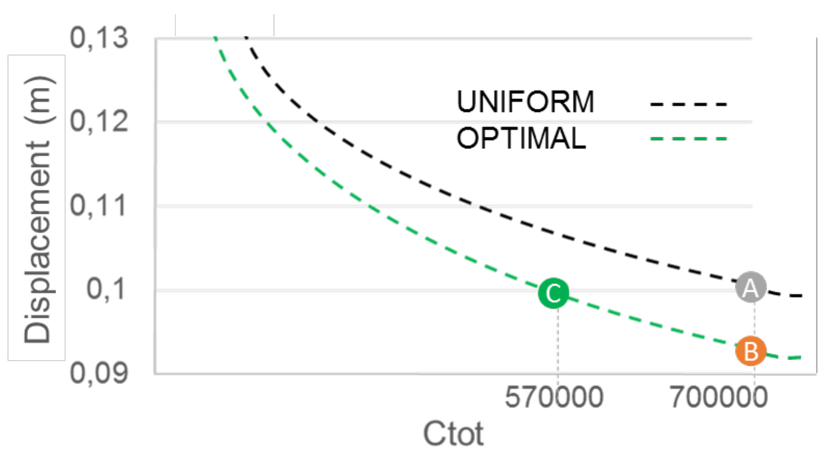


Fig. 8 - Comparison between optimal placement and uniform placement – Structure B

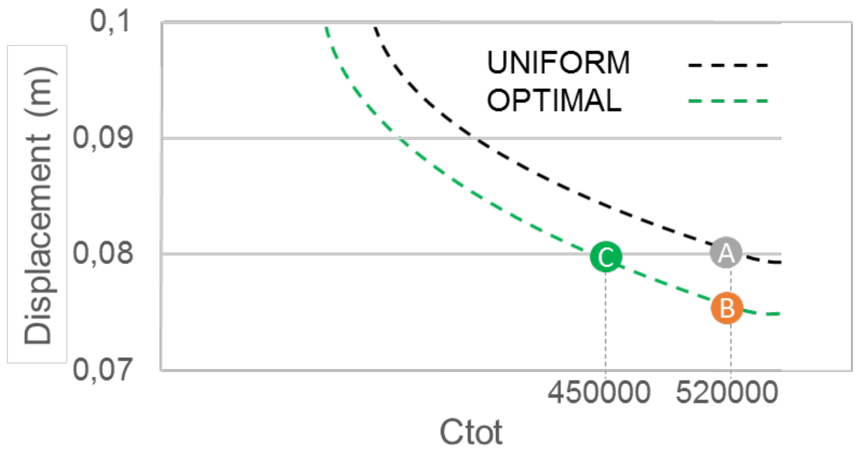


Fig. 9 - Comparison between optimal placement and uniform placement – Structure C

These results lead to an average reduction of C_{tot} of 18% for all three structures.

5. Conclusions

The methodology defines a simple and practical method that estimates the better locations to install viscous dampers in tall buildings. It leads to optimal placements that essentially depends on two parameters:

- The frequencies in which the earthquake's energy is higher.
- The dynamic characteristics of the building (evaluated without dampers).

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. Therefore, high frequency modes, in which modal configuration inverts its direction (inflexion zones), should not be ignored [8]. This means that in the definition of the transfer function, high frequency modes should be taking into account.

This methodology estimates the measure of the energy dissipated for each possible location to install the dampers: it is the expected value of the square of the interstorey velocity. The final step is to sort this values in order to choose the locations in which the dampers can dissipate more energy: where the expected value is higher.

This approach takes into account the position of the dampers to the evaluation of dissipated energy. Nevertheless, this methodology allows the dampers to be installed for any type of connection; and not only between consecutive floors (for instance, between floor i and floor i+2).

However, the dampers characteristics and the number of dampers in the optimal placements does not change the measure of the dissipated energy and neither the optimal locations. As a consequence, the optimal locations are independent on the type of dampers applied and the response of the structure is not explicitly evaluated. Therefore, it is relevant to evaluate the structure response in order to analyze the solution efficiency. It is emphasizing once again that this evaluation is independent on the methodology.

In this regard, the methodology has the advantage that after applying the five steps it allows several practical solutions to be tested. For example: different number of dampers on the optimal solution or different type of dampers.

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