Optimal placement of dampers on tall buildings

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Abstract

The use of damping systems is one of the seismic protection techniques that improve the seismic response of structures.

The problem of choosing the optimal location to install the dampers in tall buildings has been studied over the past years. The key focus is finding the location where dampers can dissipate the most amount of energy. The optimal placement is achieved when this condition is satisfied. The proposed methodology estimates the location where the dampers must be placed as to dissipate the maximum energy. The ultimate goal is cost reduction comparing the optimal placement to a uniform damper placement (one damper by floor).

Since the dampers are connected between storeys, the energy dissipation is the result of the interstorey movement. In the case of viscous dampers the dissipation force depends on the end to end velocity across the damper. The physical quantity that estimates the measure of the dissipated energy is the expected value of the square of the interstorey velocity. This value is obtained using the Power Spectral Density of the interstorey velocity, resorting to the transfer function of the structure.

This approach leads to optimal placements that depends not only on the dynamic characteristics of the structures but also on the proprieties of the seismic action.

In this paper it is also analysed the optimal placement in buildings with different frame-wall structures' behaviour.

Keywords: viscous dampers, tall buildings, optimal placement

1. Background and scope

It is well known that seismic action is one of the most powerful forces of nature. It has caused large economic and social losses. Also collateral effects, such as fires and tsunamis, can't be ignored.

Seismic risk is a function of seismic hazard, vulnerability and exposure (Sousa, 2008). Since vulnerability is related with the structures' capacity to have a good response during an earthquake, it is the principal factor that engineers can control in order to reduce seismic risk.

Seismic protection techniques are systems that improve the resistance of structures. So that, if these kind of systems are applied to the structures, the seismic risk can be reduced.

Seismic protection techniques

Seismic protection techniques can be simple passive devices (such as energy dissipation systems, base isolation and tuned-mass dampers) or more sophisticated active systems.

Energy dissipation systems is perhaps one of the best known technique (Buckle, 2000).

These systems dissipate the earthquake's energy. As a result, the structure seismic displacements are significantly reduced and allows the structure to remain elastic.

Passive energy dissipation devices can be classified as hysteretic dampers, viscous dampers or viscoelastic dampers.

The optimal placement problem

Optimal placement of dampers in tall buildings has been studied in the last years.

Nevertheless, there isn't 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.

The problem is to identify the locations where the dampers can dissipate the maximum amount of energy.

"Simplified sequential algorithm" (Lopez-Garcia, 2001) and "Optimal damper placement for minimum transfer functions" (Takewaki, 1997) are two of those methodologies.

"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" (Lopez Garcia et al, 2002).

2. Viscous Dampers

Operating mode

Fluid viscous dampers operate on the principle of fluid compression and circulation.

The operating mode is shown in Figure 1 (Brás, I., 2015).

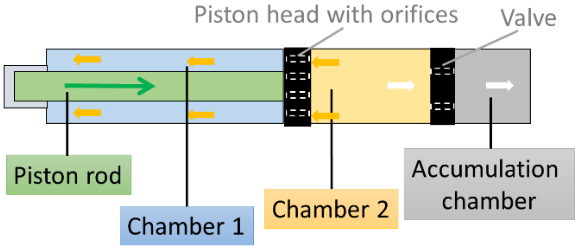


Figure 1 – Operating mode (viscous damper)

Chamber 2 becomes compressed when the piston travels through chamber 1 that are filled with fluid (green arrow). The pressure difference between the two chambers cause 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).

Dissipation force

The dissipation force on viscous dampers varies only with the end to end velocity across the damper. This relation is expressed in equation (1) (Guerreiro, 2003).

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

The α parameter 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.

The variable v is the end to end velocity across the damper.

As a result, 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. Measure of the dissipated energy

The physical quantity that estimates the measure of the energy dissipation on viscous dampers is the square of the interstorey velocity (Brás, I., 2015).

As a consequence, it is assumed that the measure of the dissipated energy is the expected value of the square of the interstorey velocity. Therefore, the measure of the dissipated energy is estimated by floor (E_f) and it is expressed in equation (2) (Brás, I., 2015).

$$E_f = E[X^2(t)] = \int_{-\infty}^{+\infty} S_v(w)dw \quad (2)$$

To define this value it is necessary to have the Power Spectrum Density (PSD) of the interstorey velocity (S_v).

S_v depends on the PSD of the action (S_a) and depends on the structurers' characteristics. This relation is expressed in equation (3) (Guerreiro, 2011).

$$S_v(w) = |H(w)|^2 S_a\ (w) \quad (3)$$

Where H(w) is the transfer function of the interstorey velocity of the structure and it is defined by floor.

Since the damper's 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.

It is easy to understand that the optimal placement that results from the proposed methodology does not depend on the characteristic of the damper – it only depends on its position, which is normally conditioned by the geometry of the building.

4. 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))

The transfer function proposed on this methodology is expressed in equation (4) (Brás, I., 2015)

$$H(w) = \sum_n -FP_n\, \phi_d^{rel}\, \frac{-(2\xi p_n w^2) - w\,(p_n^2 - w^2)i}{(p_n^2 - w^2)^2 + (2\xi p_n w)^2} \quad (4)$$

Where:

FP_n is the modal participation factor of mode n

ξ is the damping coefficient

p_n is the angular frequency of mode n

w is the angular frequency

and ϕ_d^{rel} is expressed in equation (5) (Brás, I., 2015)

$$\phi_d^{rel} = \frac{(\phi_h^i - \phi_h^{i-1})\Delta H + (\phi_v^i - \phi_v^{i-1})\,\Delta V}{\sqrt{\Delta H^2 + \Delta V^2}} \quad (5)$$

Where:

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

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

3. Calculate PSD of the velocity (S_v)
4. Calculate energy estimation E_f
5. Sort the values of E_f
6. Choose the optimal locations

In this final step it is necessary to define the number of dampers the optimal placement should have. Then it is possible to choose the floors where they can dissipate more energy (taking into account the order of E_f).
A simple example is shown in Figure 2.

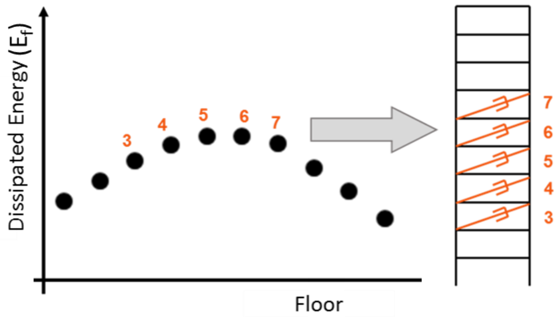


Figure 2 – Example of dissipated energy by floor and optimal placement

This figure illustrates one possible solution: the five floors where the dampers dissipate the most amount of energy.

5. Case study

Introduction

The purpose of this topic is to analyse the optimal placement in six different frame-wall structures. They are named from A to F.
The standard frame structure in all these structures is shown in Figure 3.

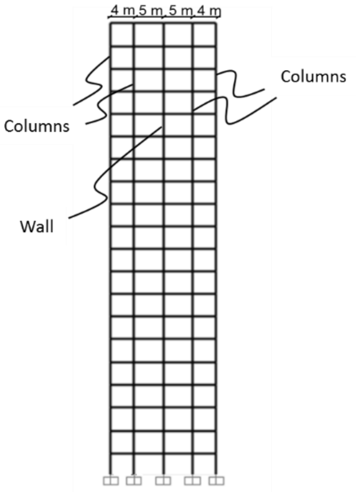


Figure 3 – standard frame structure of the case study

The wall's length increases from structure A to E. In structure F the wall's length is the same as it is in structure E but has a larger width. As a consequence, the wall behaviour is becoming more preponderant from structure A to F.

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

Number of floors	20
Height of the floors	4 m
Spacing between frames	5 m
Slabs' thick	0,20 m
Concrete type	C40/50
Columns	0,80x0,80 m^2
Beams	0,25x0,75 m2

Table 1 – Generic characteristics of the structures

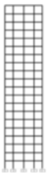
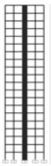
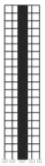
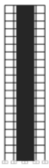
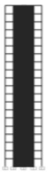
Structure	**Central element**	**Ilustration**
A	0,80x0,80 m^2	
B	2,5x0,20 m^2	
C	5,0x0,20 m^2	
D	7,5x0,20 m^2	
E	10,0x0,20 m^2	
F	10,0x1,0 m^2	

Table 2 – Wall's dimensions

For example, it was found the ten (half the number of floors) and the five (a quarter of the number of floors) optimal locations.

First of all, it is necessary to establish the six steps proposed on the methodology. This is done for each structure individually.

Since the structures with predominant wall behaviour leads to optimal placements on the upper floors (Brás, I., 2015); and, in the other hand, optimal placements in frame structures have the dampers in the lower floors (Brás, I., 2015), the purpose of this case study is to verify if this methodology is effective when the structure presents an intermediate behaviour between frame and pure wall.

A comparison between the global cost of the dampers in the uniform placement (one damper by floor) and the global cost in the optimal placement – ten optimal locations and five optimal locations – is also presented.

Dissipated energy

The measure of the energy dissipated by each floor in structure A, C and F is shown from Figure 4 to Figure 6. The dissipated energy in the other structures is detailed in (Brás, I., 2015).

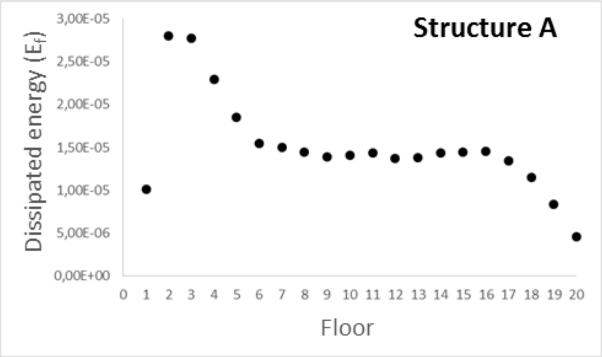


Figure 4 - Energy dissipated by floor in structure A

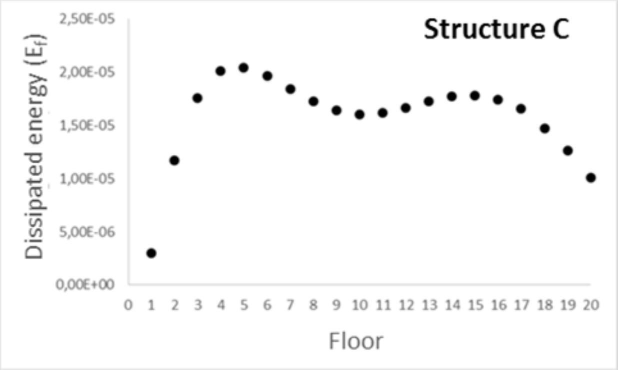


Figure 5 - Energy dissipated by floor in structure C

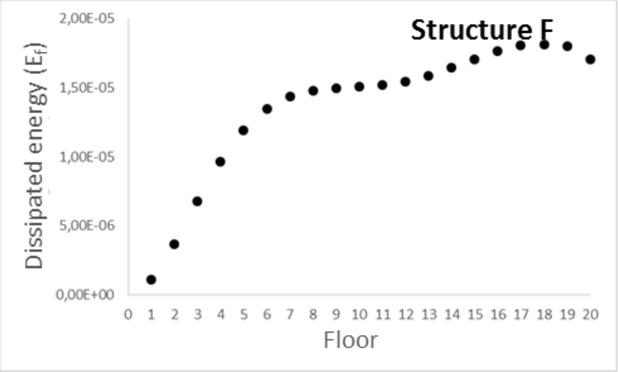


Figure 6 – Energy dissipated by floor in structure F

Optimal placement

The result of sorting the values of energy dissipated for each floor and choosing the ten locations where the dampers can dissipate the most amount of energy is shown in Figure 7 and Figure 8.

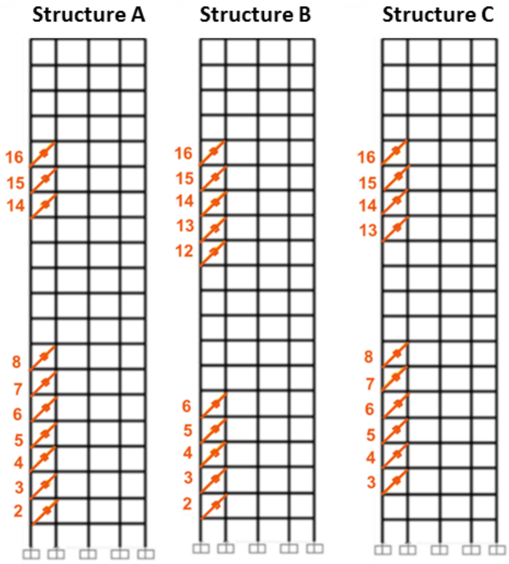


Figure 7 - Optimal placement (10 dampers) in structures A, B and C.

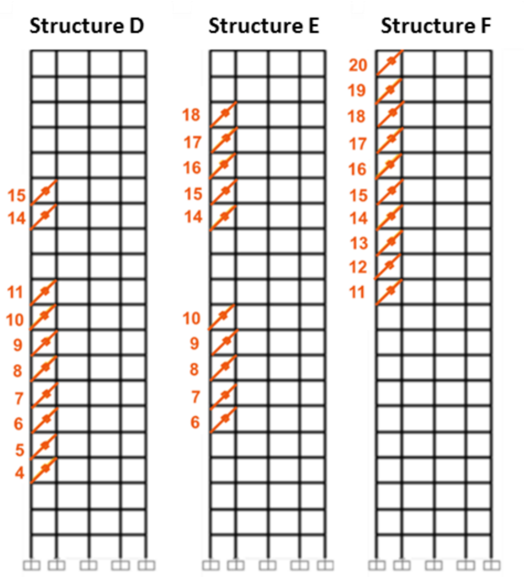


Figure 8 – Optimal placement (10 dampers) in structures D, E and F.

As it is shown on the figures above, from structure A to F the optimal locations change from the lower to the upper floors.

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 the mixed frame-wall behaviour clearly influences the optimal placement.

Cost reduce

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 assumed that the global cost of the dampers (C_{tot}), in each placement, is related with the sum of individual constant C of each damper.

The control 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 (Brás, I., 2015). The target was reduce to 50% of the displacement in the structure (without dampers), and considering only an intrinsic damping coefficient of 2%.

This displacement is a result of a non-linear time history analysis on *SAP2000* (CSI, 2011). It is the average value of the maximum values for each artificial accelerogram.

Two types of dampers were tested: linear (α=1,0); non-linear (α=0,3). Three placements were analysed: uniform, five optimal locations and ten optimal locations. The displacements values (Brás, I., 2015) were obtained for each type of damper, for each placement and for different values of C_{tot}.

A comparison between the cost in uniform placement and in the optimal placement (five and ten locations) is presented in Figure 9 (linear dampers) and Figure 10 (non-linear dampers).

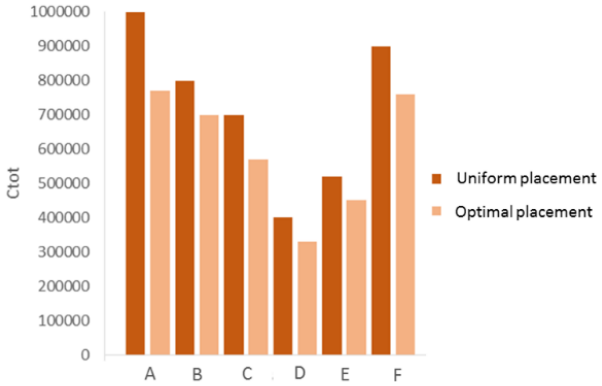


Figure 9 – Cost reduce (linear dampers)

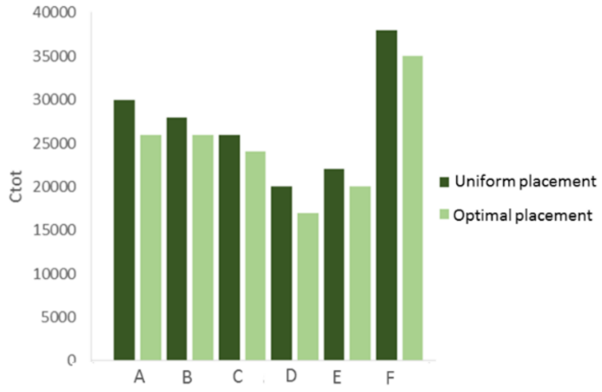


Figure 10 – Cost reduce (non-linear dampers)

As it is shown in the figures above, the global cost of the dampers in the optimal placement is less than the global cost in the uniform placement, in both cases of linear and non-linear dampers.

Conclusions

This methodology defines a simple method to estimate the measure of the energy dissipated for each floor: it is the expected value of the square of the interstorey velocity. The final purpose is to sort this values in order to choose the floors in which the dampers can dissipate more energy.

This approach takes into account the position of the dampers to the evaluation of dissipated energy. However, the characteristics of the damper and the number of dampers on the optimal placement does not change the measure of the dissipated energy.

The methodology proposed 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 interstorey displacement.

As a consequence, the frequencies in which the modal configuration of the floors changes its direction (inflexion zones), even for high frequencies of vibration, should not be ignored. This methodology take this into account (Brás, I., 2015).

This approach shown that mix frame-wall behaviour of the structure influence the optimal locations.

The methodology proposed revealed efficiency on the cost reduction between the optimal placement and the uniform placement.

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