Study Of Structural Control In Coupled Buildings

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SUMMARY:
Buildings coupled have been shown to be an attractive method to alleviate dynamic demands on structures. The principle of coupled buildings is that dynamic forces are transferred upon one another in such manner that they work as a group, and consequently reduce the responses of both structures. The focus of this paper is to assess various alternatives of control devices implemented as the coupled-link between the two buildings.

In this study two different structural control benchmark models have been considered: the 3 and 9-story S.A.C. models. Optimal placement and practical values for semi-active dampers were established. Different types of control strategies were considered for the coupled-link (active, passive and semi-active). The advantages and disadvantages of each strategy are examined in order to determine an appropriate control strategy. Based on the results, general conclusions and recommendations are given for further studies.

Keywords: Structural Control, couple building, semi-active damper.

1. INTRODUCTION

Structural engineering face the challenge on finding new and better ways to design structures, so are more resistant to the damaging effects of the dynamic forces (earthquake and wind). In a conventional structure the energy is absorbed by the inelastic deformation of their members. There are other methods that add new elements to the structure. Base isolation tries to reduce the input from the ground to the structure. Energy dissipation devices are elements that act like fuses since their objective is to take most of deformation of the structure. Finally, there are devices that could introduce new forces in an active o semi-active fashion. These methods are more sophisticated since require feedback from the system to function.

The coupling of buildings is another technique used to reduce the dynamic effects. There are some cases in which an existing building no longer satisfied the code and therefore requires a retrofit. A possible solution is to construct an adjacent structure and connect it to the original. In this case the new code requirements are cover for the two structures. This type of coupling was done at the building “h” at the Autonomous Metropolitan University in Mexico. In figure 1 is shown the original building with the two new adjacent structures at their East and West sides.

Couple of buildings is not necessary a solution to retrofit a current building. This technique is also tough as the original project. Having coupled buildings allows to reduce the cross sections of the structures connected and to control their dynamic behaviour during an earthquake or strong winds. Examples are around the world. Figure 2 shows the Triton plaza in Tokyo in which three buildings are coupled.

Figure 1. Building "h" and the two adjacent coupled buildings.

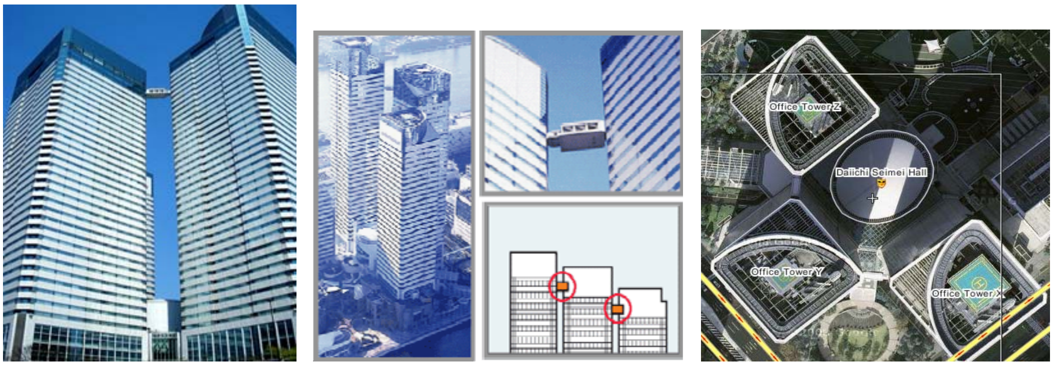

Figure 2. Triton square at Tokyo, Japan.

Given the potential of couple building, this paper is set to study the advantages this system with respect to a non-coupled. However, there are several aspects to be considered. How different the buildings should be, how many points of connection are required, what type of link is the best suited.

The objective of this paper is to study the semi-active control as the connection link in coupled buildings, compare different control strategies and analyze the dynamic behavior of the models, to improve their response to seismic loads.

2. PREVIOUS WORK

Christenson (2001, 2006) studied different configuration of coupled buildings and proposed some guidelines for the design of these structures. He did experimental test in coupled buildings to control the acceleration response. The connection link between buildings was done at only one point of contact. Zhu et al. (2001) proposed a semi-active control system for coupled buildings considering only two masses of one degree of freedom with favourable results. In 2003 Cimellaro realized scale experimental models of standard structures. Cundumi (2005) proposed an arrange of semi-active devices in coupled buildings without having a straight connection between them.

There are other coupled variants. Among other Fujimura et al. (2004) studied the coupled of buildings with two connection in parallel. Watanabe et al. (2010) analyzed control alternatives adding a base isolation system to coupled buildings.

3. COUPLED STRUCTURES OVERVIEW

The concept of coupling buildings consists in that the control structures exert forces on one another, so that their resistance to dynamic loads that given by the set of buildings. To understand the effect of the difference of masses among the buildings is presented an example of two one degree of freedom systems coupled (Figure 3).

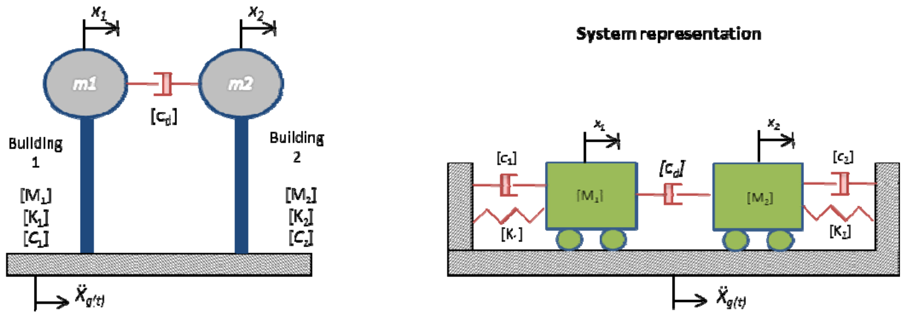

Figure 3. Single degree of freedom masses coupled.

Where the movement equation is given by:

$$m_i\ddot{x} + c_i\dot{x} + k_i x = F_{damping} + E_{earthquake}(t) \tag{3.1}$$

Using a State space representation

$$\begin{aligned} \dot{z}_1 &= A_1 z_1 + B_1 u_1 + E_s \ddot{x}_g \\ \dot{z}_2 &= A_2 z_2 + B_2 u_2 + E_s \ddot{x}_g \end{aligned} \tag{3.2}$$

In the same way

$$\begin{aligned} y_1 &= C_1 z_1 \\ y_2 &= C_2 z_2 \end{aligned} \tag{3.3}$$

Where vectors z_1 and z_2 are defined as:

$$z_1 = \begin{Bmatrix} x_1 \\ \dot{x}_1 \end{Bmatrix} \quad \text{y} \quad \dot{z}_1 = \begin{Bmatrix} \dot{x}_1 \\ \ddot{x}_1 \end{Bmatrix} \tag{3.4}$$

$$z_2 = \begin{Bmatrix} x_2 \\ \dot{x}_2 \end{Bmatrix} \quad \text{y} \quad \dot{z}_2 = \begin{Bmatrix} \dot{x}_2 \\ \ddot{x}_2 \end{Bmatrix} \tag{3.5}$$

From figure 3 it can be determined that the vector u_i (control force) is:

$$u_1 = F_1 = c_d(\dot{x}_1 - \dot{x}_2) \qquad \text{and} \qquad u_2 = F_2 = c_d(\dot{x}_2 - \dot{x}_1) \tag{3.6}$$

If the systems are coupled then the final equation is:

$$\begin{Bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{Bmatrix} = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix} \begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} + c_d \begin{bmatrix} B_1 T_1 C_1 & -B_1 T_2 C_2 \\ -B_2 T_1 C_1 & B_2 T_2 C_2 \end{bmatrix} \begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} + E_s \ddot{x}_g \tag{3.7}$$

Where T_1 and T_2 are define as:

$$T_1 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T \quad \text{y} \quad T_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T \quad \begin{matrix} \textit{Displacement} \\ \textit{Velocity} \\ \textit{Acceleration} \end{matrix} \tag{3.8}$$

A relationship between the masses of the systems is set as λ=m2/m1. The purpose of this set up is to determine the effect of difference between masses of the structures. Figure 4 shows the change of critical damping of the systems in function of the change in the damping of the connector.

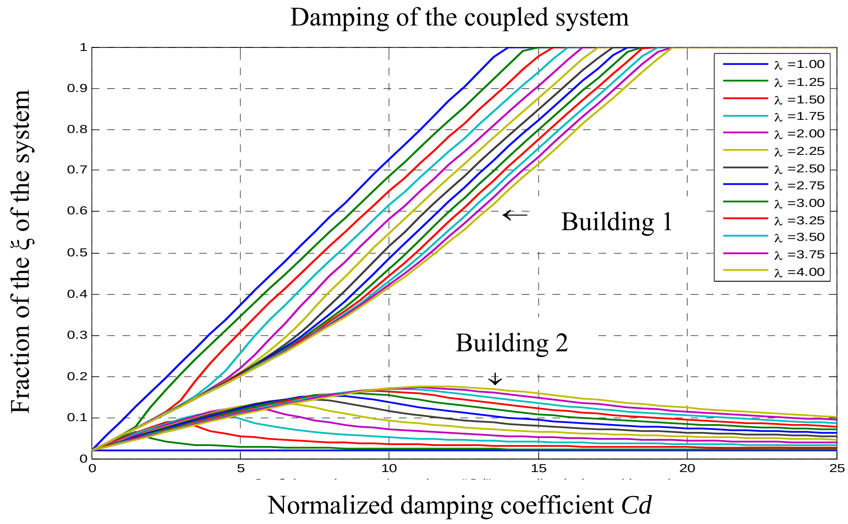

Figure 4. Damping variation with respect of the mass relationship among systems

It can be appreciated from figure 4 that, as the damping coefficient C_d increases (the connection becomes more rigid) the damping of the mass 1 (smaller mass) increases. In the same way, mass 2 (larger mass) increases until 18% of the critical damping. After that point decreases.

The coefficient λ can be represented as the relationship of the frequencies of the substructures ω_1/ω_2. If the stiffness of the subsystems 1 and 2 are equal, then the relationship of frequencies is equal to the square root of λ.

$$\frac{\omega_1}{\omega_2} = \sqrt{\lambda} = \sqrt{\frac{m_2}{m_1}} \tag{3.9}$$

As the coefficient λ increases (mass 2 is larger), the frequencies of the two systems have values much different among them. This is reflected in the clear distinction of two mode shapes in the system. If the value of λ is equal to the unity (same masses), only one mode of vibration is distinguished.

It is also investigated the influence of the connection damping C_d in the response of the system. Figure 5 shows the displacements of each substructure when subject to a white noise input.

The main conclusions from these figures are that as C_d increases (rigid connection) the displacements between structures are reduced until reaching an optimal C_d value. These optimal values will be different as λ change it. As the value of λ diminishes (structure becomes equal in mass) the capacity of control is reduced. So, having substructures with different frequencies increases the control effect in the coupled system.

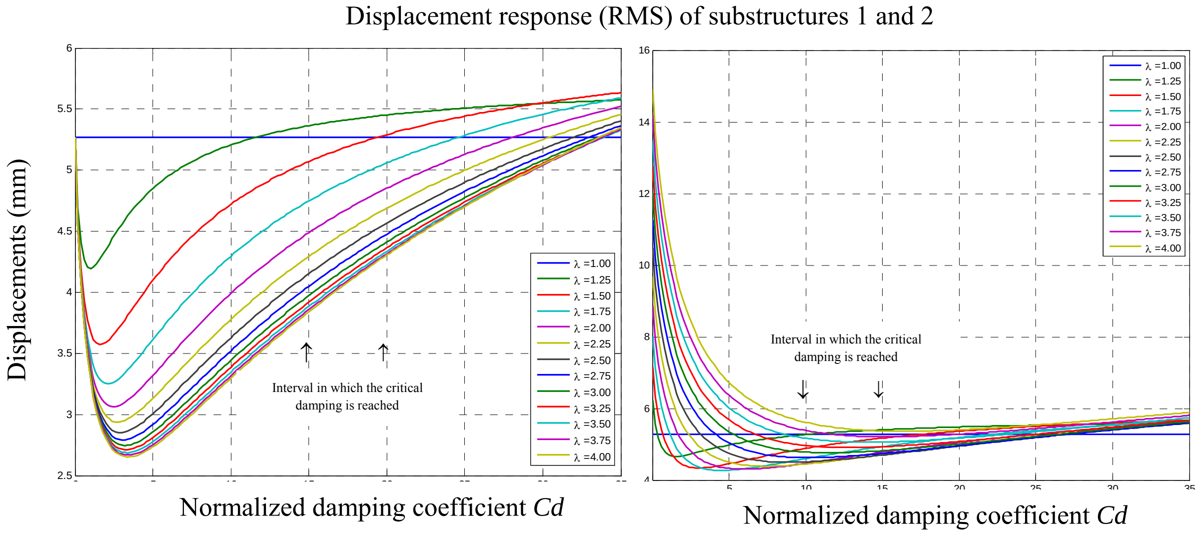

Figure 5. Displacement of the coupled system

4. STUDIED STRUCTURES

In this paper the benchmark SAC structures of 3 and 9 stories are used. These models were selected since their behavior is well known, and had been used in different studies. For space reason only the 3 stories building is presented in figures 6.

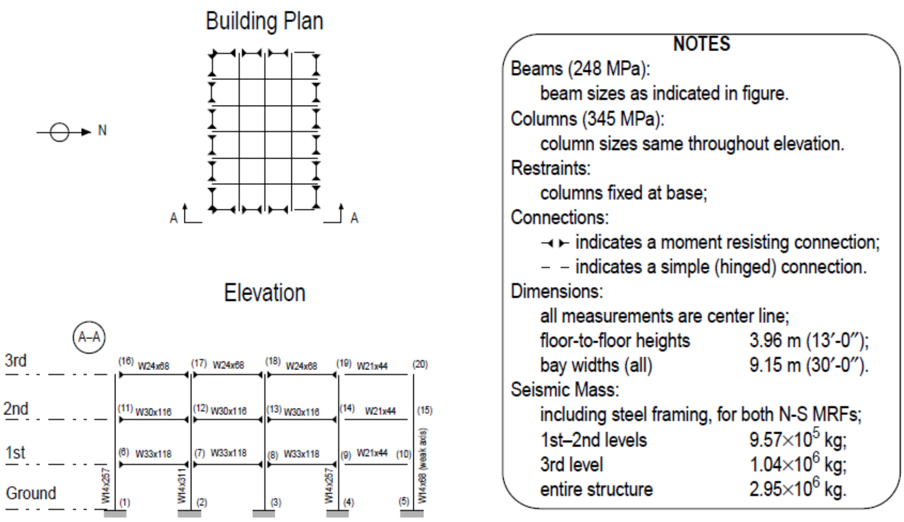

Figure 6. 3 Stories SAC building (Ohtory et al 2004)

The structures were modeled and reduced to a planar frame.

4.1. Dynamic behaviour of SAC structures

To understand the concepts of the coupled structures it is necessary to visualize how the control systems (active, passive or semi-active) modify the properties of the system. So, in this part of the study a damper is collocated in the last floor of each structure and its value changed (figure 3)

Figure 8 shows the variation in the percentage of critical damping of the system relative to the value of the damping coefficient (C_d) of the devices at the top of the structure.

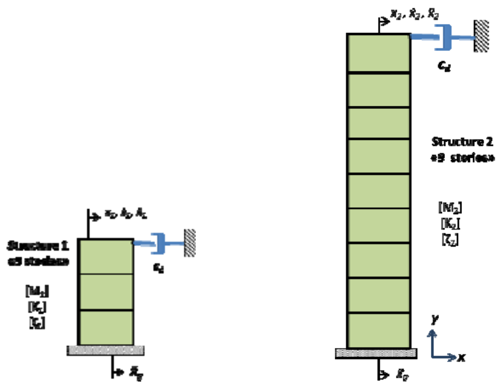

Figure 7. Position of a fixed damper on each of the SAC structures.

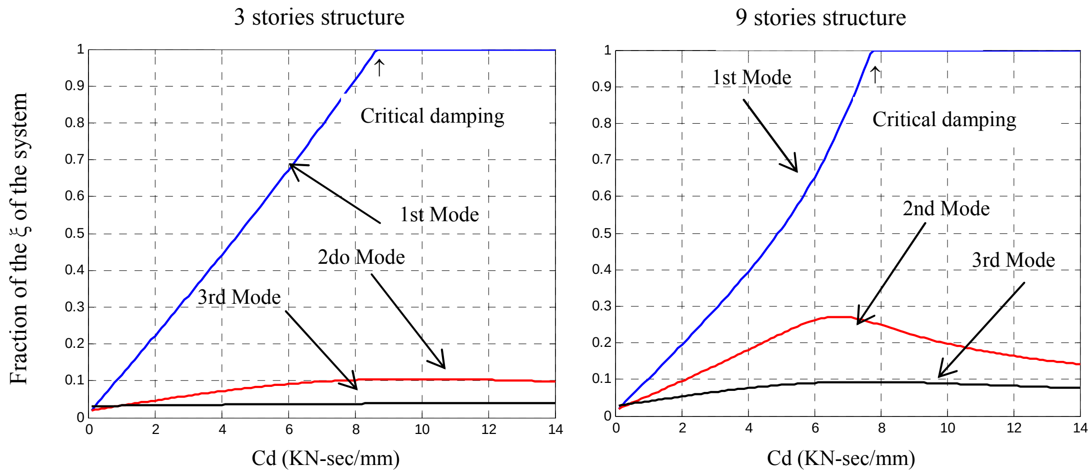

Figure 8. Variation of the critical damping of the system.

Since the external damper is collocated at top level of the structure, any modification in its value would not allow the roof to move, and therefore mainly affecting the first mode. The second and third modes are has some modification in the 9th story structure, but it is almost unnoticeable 3 story one.

In figure 9 is shown the RMS variation for displacements in function of the values of C_d for the 3 and 9 SAC structures.

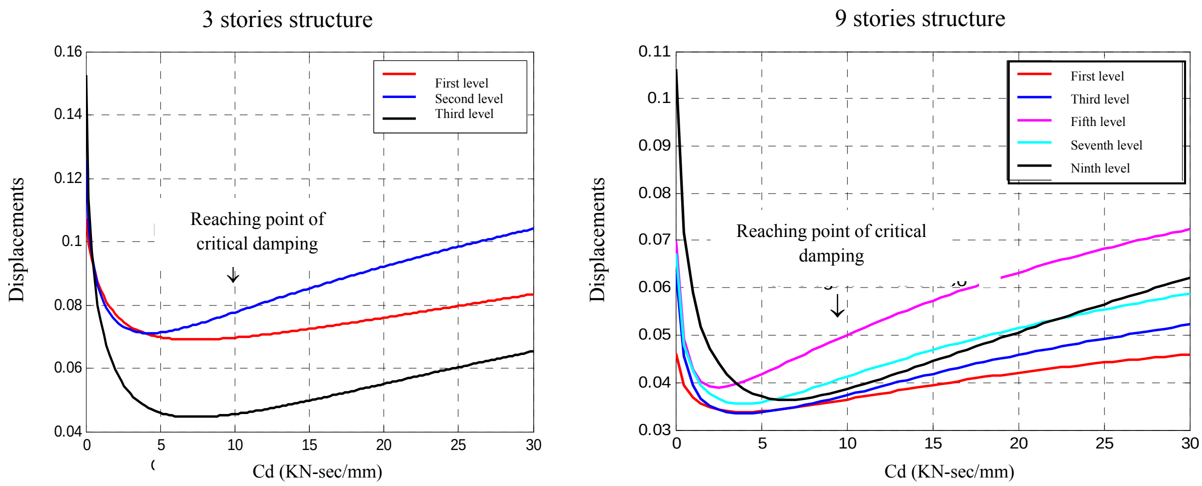

Figure 9. Variation of the displacements for 3 and 9 SAC structures.

The displacements for both of the structures reach a minimum. However it does not coincide at the same time for all of the modes.

5. CONTROL FOR COUPLED STRUCTURES

Up to now, it has been determine that coupling structures with different dynamic properties produce the best control results. Also, that the inclusion of a passive damper at the top of the building greatly affects the first mode.

The next step will be to couple the 3 and 9 SAC structures. It will be investigated the best position of the connection damper.

5.1. Optimal position of the connection device

The different models considered are shown in figure 10. All of them have only one device attached at different levels.

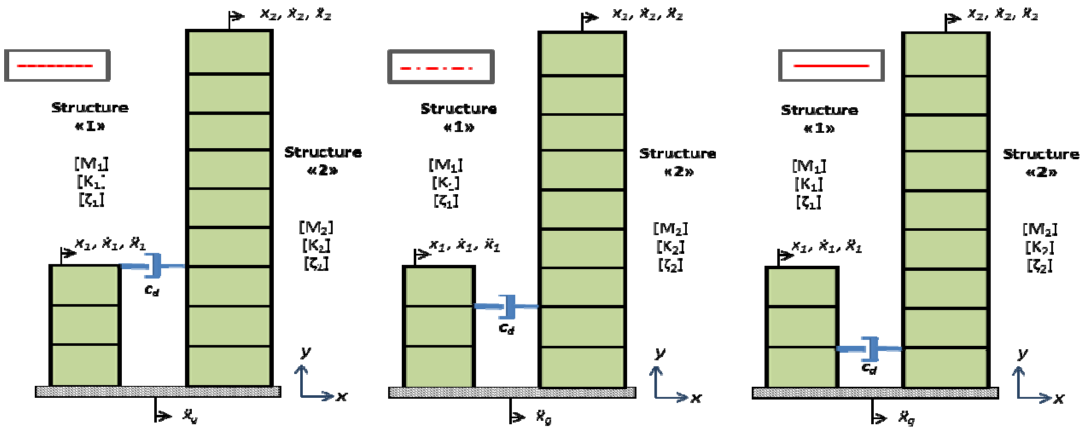

Figure 10. Models used to determine the best position of the damper.

These models were excited with a white noise at their base. The objective is to find the optimal C_d value for each of the configuration. The results for displacement, velocity and acceleration are shown in figure 11.

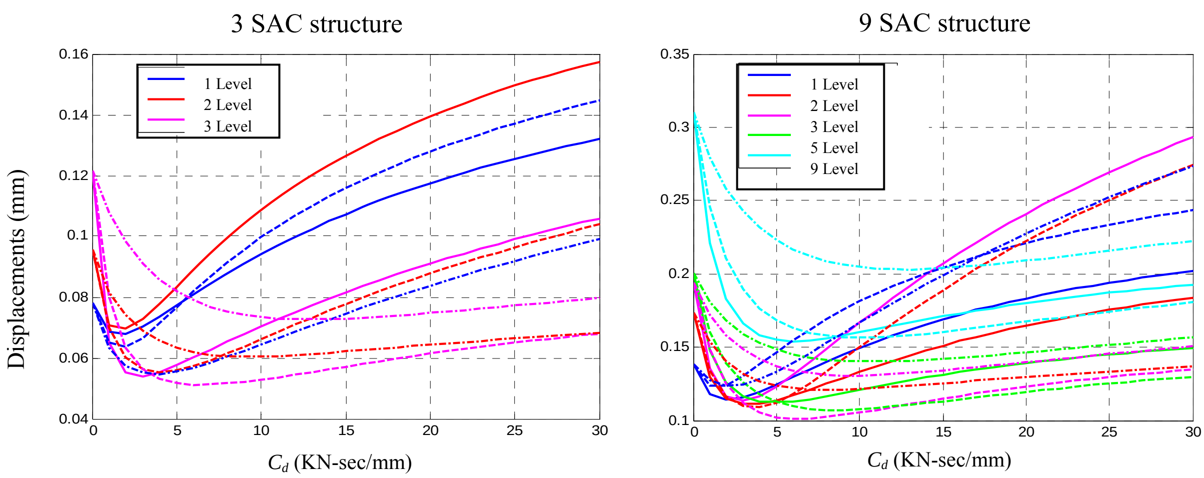

Figure 11. RMS displacement responses for the different positions of the dampers.

From the plot it can be appreciated that when the device is at the third level (discontinue line) the displacements are reduce for the 3 SAC structure with a small value of C_d. When the device is locate at the second level, the value of C_d required is greater. Finally, when the device is located at the first level, the control capacity is greatly reduced. Therefore is concluded that, if only one device is collocated in the structure, its best position is at the highest level.

The optimal C_d values obtained when the damper is in the third level is C_d = 4.5 KN-sec/mm. If it is considered that commercial values for damper are located a range between 1.0 and 50 KN-sec/mm, this optimal values can be achieved without problem.

5.2. Optimal number of devices

The following models were used to determine the optimal number of devices to be used. Given the previous results, it has considered fixed the device in the third level.

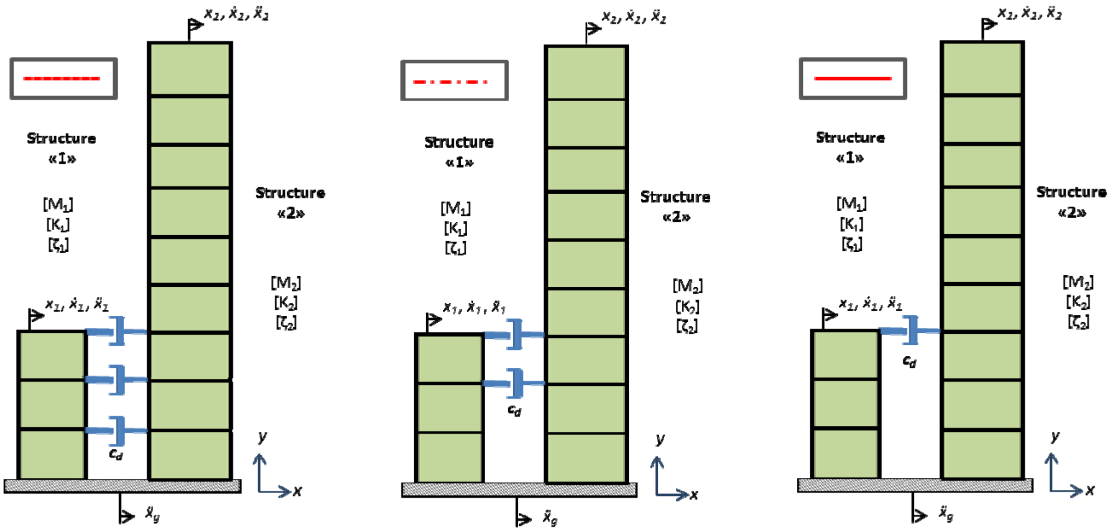

Figure 12. Models used to determine optimal position of the damper.

Figure 13 shows the RMS displacements of the models when excited by a white noise.

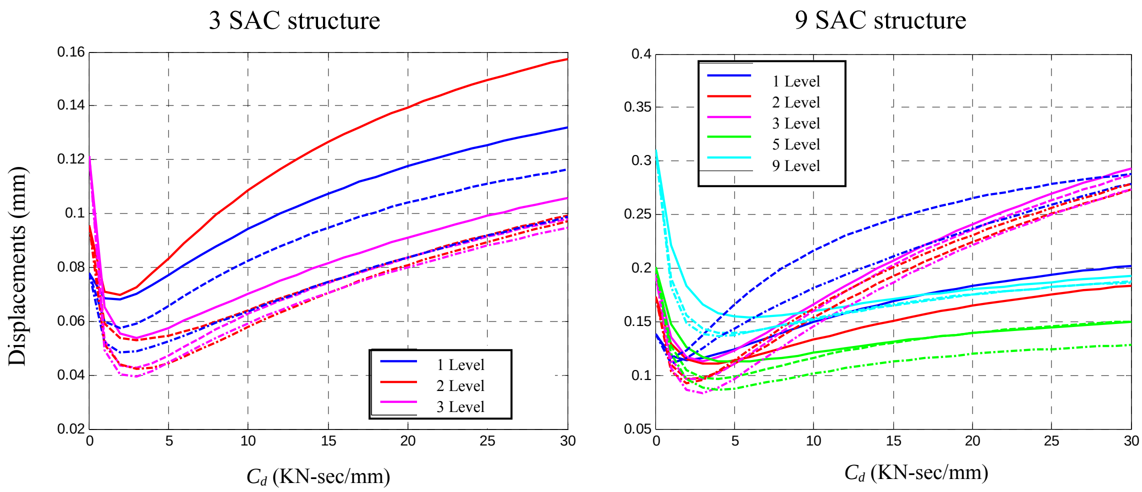

Figure 13. RMS displacement responses for the different number of the dampers.

Figure 13 shows that as the number of the devices used increases, the displacements decrease. If only the device in the third floor is considered, then the displacement of structure 1 goes from 12cm to 5.3cm. If two devices are included (third and second floor), the displacements are reduced to 4.5cm, and when the three devices are used the displacement is reduce to 4.2cm.

The reduction level of displacements between having one or three devices is not considerable. However the cost of having more than one damper could be important and therefore not justifiable.

6. CONTROL TYPES FOR COUPLED STRUCTURES

In this study were considered the use active and semi-active devices. The characteristics of these algorithms are well known in the literature. For space reason a detailed explanation of the theory behind is not presented.

The excitations used to prove the performance of the coupled structures are the earthquakes of: El Centro, Kobe and Taft. These records have a frequency content that excited short and medium height structure, as in the case of this study. The inputs has been widely use in the several studies.

Only two cases were studied. Couple structures with one and three devices as shown in figure 14.

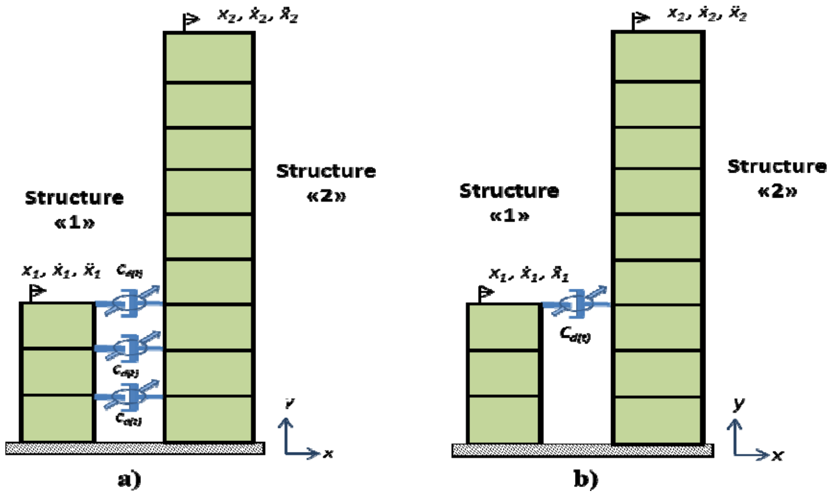

Figure 14. Coupled model studied

Tables 1 and 2 is present the reduction in percentage of the displacement of each of the structures. The displacements were measure at the roof of each structure. The comparison was done with respect of the structure without control.

Table 1. Reduction in % of maximum displacement only one damper is attached

	3 SAC structure			9 SAC structure		
System	El Centro	Kobe	Taft	El Centro	Kobe	Taft
Pasive	32.65	11.87	26.21	-7.6	-5.74	-14.13
Semi-active	64.51	52.13	49.08	0.64	5.86	0.55
Active	57.95	54.15	47.84	27.82	24.24	24.25

Table 2. Reduction in % of maximum displacement when three dampers are attached

	3 SAC structure			9 SAC structure		
System	El Centro	Kobe	Taft	El Centro	Kobe	Taft
Pasive	41.29	16.11	28	-12.38	-10.14	-37.37
Semi-active	66.39	54.92	43.29	0.43	10.62	1.46
Active	57.61	57.26	45.52	33.77	29.2	28.59

From table 1 it can be said that the semi-active control have the largest displacement reduction for the 3 SAC structure. Meanwhile for the 9 SAC structure is the active control that does it. Using more than one device increases the displacement reduction; however this is not significant.

7. CONLUSIONS

The coupling of structures is a viable alternative to sustain dynamic forces. Control is best achieved when the structures have clearly distinct frequencies. The mode shapes will change in function to point of connection among the structures.

The number of couple point has a great effect in the performance of the system. If several devices are used, then the reduction of the displacements increases. If only one device is used, the best location should be in the top level of the smallest structure.

Semi-active control strategy has a similar performance than the active control for the small structure. Active control has the best performance among the systems studied. The reduction level when using one or several devices is not relevant.

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