3D ANALYSIS FOR ADJACENT COUPLED BUILDINGS CONSIDERING A SEISMIC LOAD ACTING TRANSVERSALLY

Augusto de S. Pippi [1], Suzana M. Avila [2], and Graciela N. Doz [1]

[1] PECC, Postgraduate program in Structural Engineering and Construction, University of Brasilia (UnB), Campus Darcy Ribeiro, 70910-900, Brasilia, Brazil.

[2] PPG, Postgraduate program in Engineering Material Integrity, University of Brasilia (UnB), College of Gama (FGA), 72444-240, Gama (Brasilia), Brazil.

Abstract: Structural control techniques have been effectively used to mitigate excessive vibrations in buildings. Due to the greater population density in urban centers, the demand for commercial and residential buildings has increased. In addition, the available spaces are smaller, resulting in taller, and therefore, more flexible buildings. As a result, dynamic forces such as earthquakes and strong winds can cause excessive vibration or until collapse of the structure. A control technique for buildings that is proving effective is the structural coupling. The principle of this technique is to couple two adjacent structures by connecting elements using different passive, active, semi-active or hybrid control devices. The models used to represent these adjacent buildings, in general, are linear models of multiple degrees of freedom considering shear frame. Thus, the main objective is to study the coupling of adjacent buildings, through a tridimensional structural model obtained from an experimental structure, and verify the efficiency of coupling when the seismic load acts transversally to the connection between the buildings. The models, connected by a passive control device, are subjected to an acceleration in the base using data from three different earthquakes. The mechanical properties, position and quantity of dampers were obtained through the optimization algorithm swarm of particles. This optimization was performed in a shear frame structural model, build also from an experimental model. The results showed that the structural coupling technique is efficient in reducing vibrations even for the seismic action acting transverse to the coupling. This was only possible due to the possibilities of different arrangement of the dampers that are possible when using a three-dimensional model.

Keywords: Dynamic Analysis, Passive Control, Structural Coupling, Seismic Analysis

INTRODUCTION

With the emergence of new materials, the constructions changed from robust and heavy structures for lighter and slimmer structural systems. Thus, buildings today are generally more affected by dynamic forces, consequently the problem of human discomfort due to vibration has become a major problem. In order to control excessive vibrations, structural control technologies are used. These techniques increase the reliability of structures, generate material savings, and make it possible to construct structures with high level restrictions on vibrations. Motivated by natural disasters such as the 1940 El Centro earthquake in the USA, 1995 Kobe earthquake in Japan, and most recently the 7.1 magnitude earthquake that struck central Mexico and left more than 350 victims, engineers have studied increasingly effective techniques for structural control. (Housner *et al.*, 1997; Kasai *et al.*, 2008; Raheem, 2014).

Essentially, the control techniques aim to install devices to absorb or add energy to the structure, reducing the amplitude of the vibrations. The types of control are more generally classified as passive, active, se mi-active and hybrid (Housner *et al.*, 1997; Soong and Dargush, 1997; Spencer and Nagarajaiah, 2003; Kim and Kang, 2011). A control technique for buildings that is proving effective is the structural coupling. This technique was first suggested by Klein *et al.* (1972), and has been gaining importance because of its effectiveness in preventing pounding between adjacent buildings. The principle of this technique is to connect two adjacent structures by different control devices. In this way, adjacent buildings exert control forces one over the other to reduce the dynamic response of each structure individually and the dynamic response of the coupled system. Several researches have already been done, highlighting the advantages for different types of connecting device, different heights and dynamic properties of the buildings (Westermo, 1989; Luco and De Barros, 1998; Xu *et al.*, 1999; Abdullah *et al.*, 2001; Christenson *et al.*, 2006; Pérez *et al.*, 2014; Patel, 2017).

The mentioned works show the efficiency of the coupling over several characteristics of adjacent buildings, as well as various types of connecting devices. In common, most works in this area use simplified shear frame models to verify efficiency and calculate the optimum characteristics of the coupling device. Since the response to dynamic excitations of the structure depends on its stiffness, damping and mass, the choice of the structural model is fundamental to ensure natural frequency values and displacements values with accuracy. The shear frame model is widely used in dynamic analysis to obtain these lower frequencies, and although it is an easy to use model, it is known to provide results that can differ from reality, besides not including the effect of axial deformations on the stiffness and bending of the

columns (Hurty and Rubinstein, 1967; Clough and Penzien, 2003; Ezeokpube and Osadebe, 2010; Mbanusi and Obodoh, 2016).

The use of the simplified shear frame model limits the seismic load acting parallel to the link of the coupled buildings. In addition, different damper configurations that are not parallel to the adjacent plane of the buildings are not allowed. In this sense, this work aims to numerically study the behavior for three-dimensional model for two adjacent buildings when they are connected by crossover linear passive dampers. The effectiveness of the coupling is verified if the earthquake reaches the system transversally to the connection. The verification of the efficiency of the shear frame model in the representation of an experimental structure can be verified in the works of Pippi *et al.* (2018) and Pippi (2018).

General considerations

To perform the numerical analysis, experimental data from Pippi *et al.* (2018) was used. The authors, to simulate the behavior of a building experimentally, elaborated a reduced model of a three-dimensional frame steel. The values of natural frequencies were obtained through two free vibration tests (one in the direction of lower inertia and the other in the direction of greater inertia), through an impact hammer test and the use of accelerometers.

The numerical analysis was divided into two steps. In the first step, the experimental structure was modeled considering a shear frame (SF) model, containing 10 floors (structure 1) and with the values of mass and stiffness obtained experimentally. A second structure was considered adjacent to the first one, however, containing the first 7 floors (structure 2). The two structures were subjected to a seismic excitation with data from the 1940 El Centro, 1994 Northridge and 1995 Kobe earthquakes applied in the direction of lower inertia of the structure. Then the models were connected with a passive control device. Using the Particle Swarm Optimization (PSO) method the optimum position and the ideal mechanical properties from connecting device were obtained. This first step was performed with the help of a routine developed by Pérez (2017) in MATLAB® software.

The PSO method is an evolutionary algorithm developed by Kennedy and Eberhart (1995) and is based on a population of individuals who adapt by returning stochastically to well-defined regions. Its advantage is the short calculation time when compared to other optimization methods. This method requires an objective function that will be minimized. The function used was based on the work of Bigdeli *et al.* (2016).

In the second step, a three-dimensional (3D) model of the experimental structure was elaborated in finite elements with SAP2000® software. The characteristics of mass, stiffness and boundary conditions are reproduced so that the differences in response between the numerical and experimental models are minimal. A second 3D structure containing the first 7 floors was considered adjacent to the first structure, considering the same values of mass and stiffness per floor. In the modeling, a frame element was used to represent the columns and floors, in which the grid analogy was used. For modeling the screws in basis, a spring element was used. The two structures were connected with passive devices using the damping and optimum position values obtained in the first step. The images of the experimental structure and the three-dimensional model in SAP2000® can be seen in Fig. 1.

(a)   **(b)**

Figure 1 – (a) Experimental model (b) Numerical Model.

In order to avoid additional twisting, two dampers were considered in the floor, each with half the damping coefficient obtained in the optimization. The earthquakes were considered to be transverse to the coupling of buildings. For this analysis, the dampers were allocated crosswise as show in Fig. 2. The dampers in parallel have no effect on reducing the amplitude of vibrations when the earthquake acts transversally (Pippi, 2018).
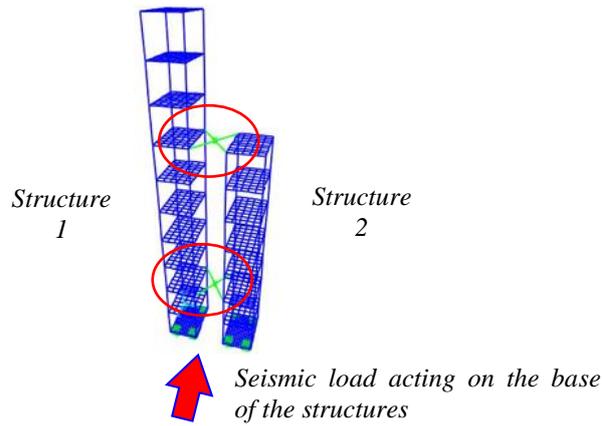
Figure 2 – Crossed dampers.

RESULTS AND DISCUSSIONS

The optimization performed to find the characteristics of the dampers was performed in shear frame model. The results are showed in Tab. 1.

Table 1 – Optimization results.

Earthquake	Structure	Dampers Positions	Damping Coefficient (N.s/m)	Stiffness Coefficient (N/m)	Story Drift (mm)
El Centro	1	Floors 2 and 7	146.40	0.00	0.66
	2				0.52
Kobe	1	Floors 6 and 7	281.52	0.00	0.99
	2				0.69
Northridge	1	Floor 7	94.55	0.00	1.93
	2				1.32

In the first stage, with the optimization algorithm, it was verified that all dampers have a coefficient of stiffness equal to zero, thus only a viscous fluid damper is effective.

In the second stage, each damper was installed crossed in 3D model, in the same position and with the same mechanical properties obtained in the optimization. The seismic load is acting transversally in structures. It is important to point out that these displacements are in the direction of earthquake action, where there is the higher inertia of the structures. The values found for maximum displacement and maximum story drift between floors for the two adjacent structures are shown in Tab. 3, the values in parentheses are the responses with the coupled structures.

Table 2 – Maximum results of the models.

Earthquake	Structure	Maximum displacement (mm)	Reduction	Maximum Story Drift (mm)	Reduction
El Centro	1	13.84 (7.99)	42%	2.19 (1.27)	42%
	2	2.51 (2.66)	-6%	0.58 (0.60)	-3%
Kobe	1	11.67 (8.99)	23%	1.89 (1.50)	21%
	2	5.93 (3.43)	42%	1.36 (0.82)	40%
Northridge	1	30.51 (17.61)	42%	4.82 (2.79)	42%
	2	7.00 (5.80)	17%	1.63 (1.36)	17%

The negative values in the table mean that the displacements increased. The natural frequencies obtained with the uncoupled and coupled analysis are the same for both structures. This agrees with the studies using viscous fluid dampers, in which their dynamic properties do not change, since the device increases damping of the structure and its mass is disregarded (Pérez, 2017). The Fig. 3 shows the normalized displacements and the story drift per floor for El

Centro earthquake in both structures. The Fig. 4 shows this displacement for Kobe earthquake and Fig. 5 for Northridge earthquake.
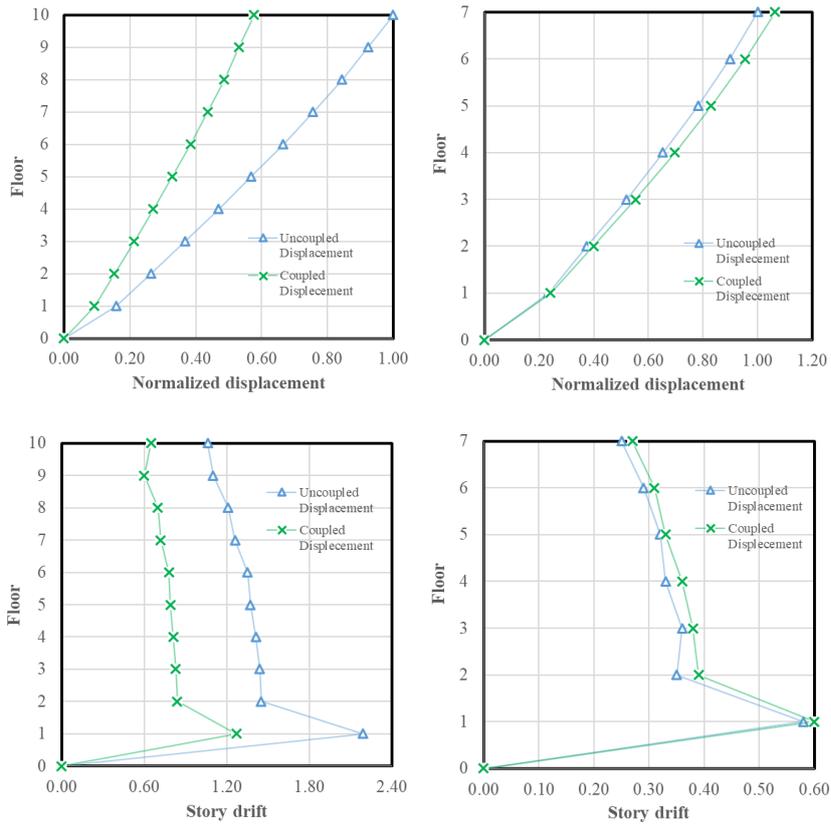

Figure 3 – Normalized displacement and story drift for El Centro earthquake.
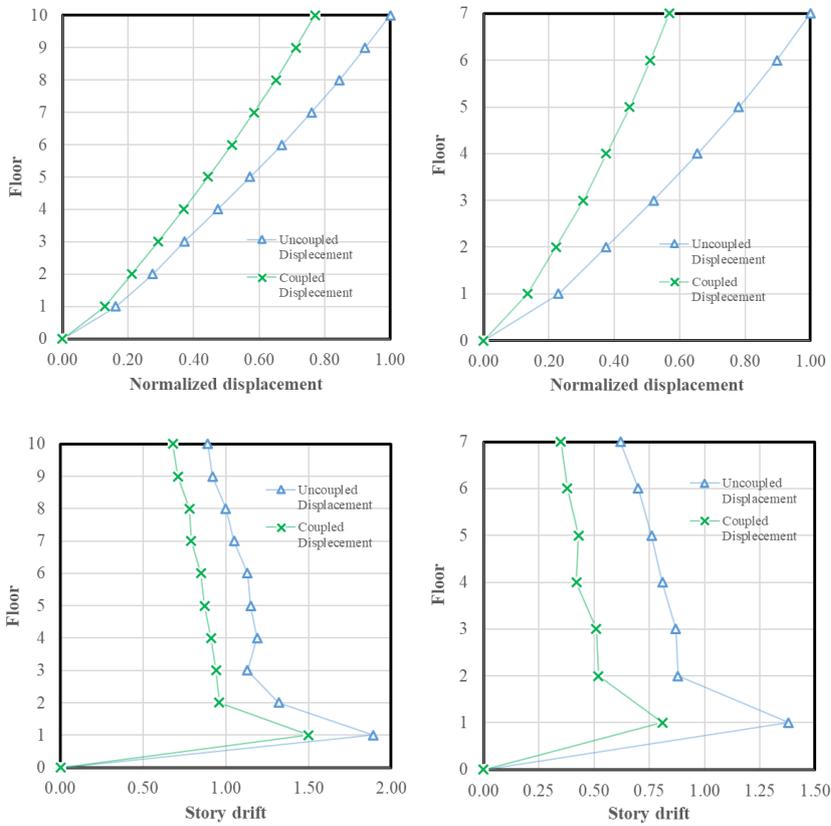

Figure 4 – Normalized displacement and story drift for Kobe earthquake.
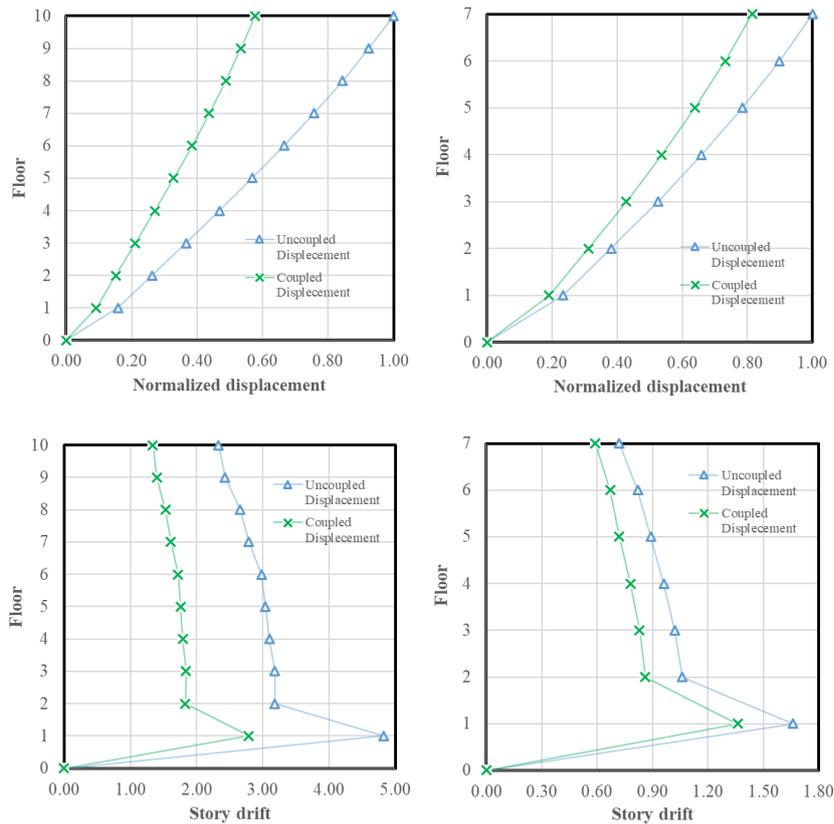
Figure 5 – Normalized displacement and story drift for Northridge earthquake.

It can be seen that the technique of coupling adjacent buildings had a good performance in reducing the amplitude of vibrations. However, for the El Centro earthquake in the minor structure the displacements and the story drift had a slight increase. Although the optimization was performed in a simplified shear frame model, which does not well represent the three-dimensional structure, the values obtained for the dampers resulted in a significant reduction of displacements (Pippi *et al.*, 2018). More information and results considering different configurations of dampers can be verified in the work of Pippi (2018).

CONCLUSIONS

An analysis of two adjacent coupled buildings was performed in this work. The position, quantity and mechanical properties of dampers were obtained by the particle swarm optimization. The dampers were positioned crosswise in the 3D model and the seismic load applied transversally to the plane of the coupling. The results showed that using crossed dampers achieves a good percentage of reduction in vibration amplitude, less in the smallest structure for the earthquake in El Centro. This may mean that an optimization performed in the three-dimensional model could be more effective, especially in relation to the cost of reducing the number and type of control devices. Unlike most of the cited works, the use of more complex models brings this flexibility to use different configurations of the dampers. Finally, it is shown that a certain degree of reliability can be achieved by the use of non-parallel dampers to connect adjacent buildings.

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REFERENCES

Abdullah, M.M., Hanif, J.H., Richardson, A., and Sobanjo, J., 2001, "Use of a shared tuned mass damper (STMD) to reduce vibration and pounding in adjacent structures", Earthquake Engineering and Structural Dynamics, V.30, No. 8, pp. 1185–1201.

Bigdeli, K., Hare, W., Nutini, J., and Tesfamariam, S., 2016, "Optimizing damper connectors for adjacent buildings. Optimization and Engineering", Springer US, V.17, No. 1, pp. 47–75.

Christenson, R.E., B.F. Spencer, J., Johnson, E.A., and Seto, K., 2006, "Coupled Building Control Considering the Effects of Building/Connector Configuration", Journal of structural engineering, Vol.132, No. 6, pp. 853–863.

Clough, R.W., and Penzien, J., 2003, "Dynamics of Structures" Computers & Structures, Berkeley. USA, 752p.

Ezeokpube, G.C., and Osadebe, N.N., 2010, "Effects of joint stiffening on the dynamic response of frames", Nigerian Journal of Technology, Vol.29, No. 1, pp. 5–12.

Housner, G.W., Bergman, L.A., Caughey, T.K., Chassiakos, A.G., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T.T., Spencer, B.F., and Yao, J.T. P., 1997, "Structural Control: Past, Present, and Future", Journal of Engineering Mechanics, V.123, No. 9, pp. 897–971.

Hurty, W.C., and Rubinstein, M.F., 1967, "Dynamics of Structures", Prentice-Hall of India Private Limited, New Delhi, India.

Kasai, K., Nakai, M., Nakamura, Y., Asai, H., Suzuki, Y., and Ishii, M., 2008, "Current status of building passive control in Japan", Proceedings of 14th World Conference on Earthquake Engineering, Beijing, China.

Kennedy, J., and Eberhart, R., 1995, "Particle swarm optimization", Proceedings of IEEE International Conference on Neural Networks, University of Western Australia, Perth, Western Australia, pp. 1942–1948.

Kim, G.C., and Kang, J.W., 2011, "Seismic response control of adjacent building by using hybrid control algorithm of MR damper", Procedia Engineering, Elsevier B.V., V. 14, pp. 1013–1020.

Klein, R E., Cusano, C., and Stukel, J.J., 1972, "Investigation of a method to stabilize wind induced oscillations in large structures", ASME Winter Annual Meeting, New York.

Luco, J.E., and De Barros, F.C.P., 1998, "Optimal damping between two adjacent elastic structures", Earthquake Engineering and Structural Dynamics, V.27, No. 7, pp. 649–659.

Mbanusi, E.C., and Obodoh, D.A., 2016, "Free Vibration Response of Double-Bay Multi-Storey Building Frames with Stiffened Joints", International Journal of Engineering and Computer Science, V.5, No. 5, pp. 16620–16638.

Patel, C.C., 2017, "Seismic analysis of parallel structures coupled by lead extrusion dampers", International Journal of Advanced Structural Engineering, Springer Berlin Heidelberg, V.9, No. 2, pp. 177–190.

Pérez, L.A., Avila, S., and Doz, G., 2014, "Seismic Response Control of Adjacent Buildings Connected by Viscous and Hybrid Dampers", Proceedings of the 32nd IMAC, Orlando, Florida, pp. 433–440.

Pérez, L.A.P., 2017, "Resposta dinâmica de edificações adjacentes acopladas: considerações sobre a interação solo-estrutura", Doutorado. Tese, Universidade de Brasília, Brasília, Brasil, 240p.

Pippi, A.S., 2018, "Resposta dinâmica para diferentes modelos de edificações adjacentes acopladas", Mestrado. Dissertação, Universidade de Brasília, Brasília, Brasil, 99p.

Pippi, A.S., Bernardes Junior, P.L., Avila, S. M., Morais, M.V.G, and Doz, G, 2018, "Limitations of a dynamic shear frame model based in a small-scale experimental steel structure", MATEC web of conferences, V.211, No. 14005.

Raheem, S.E.A., 2014, "Mitigation measures for earthquake induced pounding effects on seismic performance of adjacent buildings", Bulletin of Earthquake Engineering, V.12, No. 4, pp. 1705–1724.

Soong, T.T., and Dargush, G.F., 1997, "Passive Energy Dissipation System in Structural Engineering", John Wiley & Sons, Ltd., Chichester, England.

Spencer, B.F.J., and Nagarajaiah, S., 2003, "State of the Art of Structural Control", Journal of Structural Engineering, V.129, No.7, pp. 845–856.

Westermo, B.D., 1989, "The dynamics of interstructural connection to prevent pounding", Earthquake Engineering & Structural Dynamics, V.18, No. 5, pp. 687–699.

Xu, Y.L., He, Q., and Ko, J.M., 1999, "Dynamic response of damper-connected adjacent buildings under earthquake excitation", Engineering Structures, V.21, No. 2, pp. 135–148.