Study on the use of passive control systems in the dynamic response of coupled buildings

Rafael C. C. Tavares[1], Marcus V. G. de Morais[2], Suzana M. Avila[2], Graciela Doz[1]

[1]*PECC, Postgraduate program in Structural Engineering and Construction, University of Brasilia (UnB)*
Campus Darcy Ribeiro, 70910-900, Brasilia-DF, Brazil.
rafael.caricchio@aluno.unb.br
[2]*PPG, Postgraduate program in Engineering Material Integrity, University of Brasilia (UnB)*
Campus of Gama (FGA), 72444-240, Brasilia-DF, Brazil

Abstract. Based on the increasing knowledge in the field of engineering and construction, driven by the rapid expansion of urban centers, building designs have prioritized optimizing physical spaces and maximizing housing potential. This approach has led to structures being built closer together and becoming slenderer, which has raised concerns about excessive oscillations and the risk of pounding between adjacent structures. To address these challenges, the technique of structural coupling has emerged as a promising solution. This technique involves using connecting elements, often achieved through vibration control devices, to link the adjacent structures. However, despite the positive results observed with this approach, further studies are still required to enhance its effectiveness. In this context, the present study explores the utilization of passive control devices for coupling, which can dissipate the energy of the main system and/or transfer it to secondary auxiliary systems. The study proposes a numerical approach in a multiple degrees of freedom (MDOF) system, incorporating passive dampers, to simulate and analyze the behavior of a reduced-scale model consisting of two coupled buildings. The results are presented, demonstrating the influence of control parameters on the proposed structural system in effectively controlling the dynamic responses of the buildings.

Keywords: Building coupling, Passive vibration control, Dynamic analysis, Seismic analysis

1 Introduction

Nowadays, constructions are becoming increasingly slender, which makes them more susceptible to vibration issues. While these vibrations might initially appear as comfort concerns, they have the potential to develop into significant structural problems. In this context, Klein *et. al.* [1] studied a solution, i.e., the coupling technique, to mitigate the phenomenon of pounding in adjacent structures, which were susceptible to severe damage when subjected to vibrations in different phases. This phenomenon mainly occurs in situations involving dynamic wind loads, and particularly during seismic events. The forces generated by impact and short-duration accelerations are not typically considered in the design of buildings, which can lead to significant global and localized structural issues [2].

The coupling technique allows the dissipation of energies from primary systems using vibration control devices, while also facilitating mode coupling effects by ensuring energy transfer between modes in buildings. The properties of the coupled system play a pivotal role in determining the magnitude and efficiency of reducing the dynamic response of the buildings [3]. The progress in engineering research has brought about more refined insights and knowledge that were previously absent, particularly regarding the behavior of coupled structures. Consequently, there has been a proliferation of proposals for control systems that reduce the dynamic response in structures. These includes various types of dampers, coupling configurations, and control methods, all geared toward identifying the most efficient solution for each dynamic load scenario and excitation frequency. Additionally, researches have introduced new methodologies, algorithms, and optimization techniques, aiming the achievement of the lightest, most efficient, economically viable, and effective solution possible for each situation in engineering structures.

Thus, in an effort to explore and examine the application of passive dampers in coupled buildings, a three-dimensional model was developed based on a reduced experimental model, employing SAP2000 software for this analysis. Furthermore, a Particle Swarm Optimization (PSO) model was used to assess the optimal connection parameters for the passive dampers between the structures. Both analyses incorporated excitations from three distinct seismic events: El Centro, Kobe, and Northridge earthquakes.

2 Mathematical formulation

The mathematical formulation derives from Bhaskararao and Jangid [4]. The equation of motion for a multi-degree-of-freedom (MDOF) system, taking into account two interconnected buildings equipped with viscoelastic dampers is shown in the eq. (1). It is assumed that the masses of the systems are concentrated at each floor and it is not considered soil-structure interaction

$$M\ddot{X} + (C + C_d)\dot{X} + (K + K_d)X = -MI\ddot{x}_g \tag{1}$$

where M is the mass matrix of the coupled system; C is the damping matrix of the coupled system; K is the stiffness matrix of the coupled system; C_d and K_d are the damping and stiffness matrices of the viscoelastic dampers, respectively; $\ddot{x}_g$ is the ground acceleration; I is the vector equal to unity; and X is the relative displacement vector with respect to the ground.

That equation is applied to simplified cases of shear frame models and two-dimensional scenarios.

2.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an optimization technique, inspired by the coordinated behavior observed in bird flocks and fish schools, that individual solutions, represented as particles, dynamically explore and adjust their positions in the search space based on their own experiences and those of their neighbors. PSO continuously retains information about the best-visited positions, both among the particles themselves and within their neighboring group. This approach effectively combines local and global search strategies, enhancing its ability to efficiently navigate the optimization landscape [5].

The formulation of objective functions is based on Peña [6] and Pippi et al. [7]. These equations are employed in a shear frame model to determine the optimized values of damping parameters in coupled systems. To achieve this, Eq. 2 presents the objective function 1 wherein the purpose is to minimize the square of the maximum relative displacements between the floors of the two adjacent buildings. The objective function described in Eq. 3 aims to reduce the sum of the squares of these displacements. Therefore, Eq. 4 represents the summation of the two objective functions.

$$f_{obj1} = \max\{\max(\{\Delta\}^1)^2 \max(\{\Delta\}^2)^2\}, \tag{2}$$

$$f_{obj2} = \sum_{i=1}^{n+m}(\{\mathit{\Delta})_i^1)^2 + \sum_{i=1}^{n+m}(\{\mathit{\Delta}\}_i^2)^2, \tag{3}$$

$$f_{obj} = f_{obj1} + f_{obj2} \tag{4}$$

$$\begin{matrix} \{\Delta\}_i^j = x_i^j \\ \{\Delta\}_i^j = x_i^j - x_{i-1}^j \end{matrix} \qquad 1 < i < n_{floors}, \tag{5}$$

where x_i^j is the calculated absolute displacement at each floor and $\{\mathit{\Delta}\}_i^j$ is the vector of relative displacement for each structure.

Building upon this, Peña [6] developed a numerical model in MATLAB where, using a coupled shear frame system, the optimized properties of control devices are determined: damping coefficient, stiffness, damper positions and quantities. This optimization model employs passive dampers.

3 Numerical 3D Model

The numerical analysis of the three-dimensional model simulating the coupling between two adjacent buildings was conducted using a finite element model (FEM) developed in the SAP2000 software by Pippi [8]. The model parameters were determined based on experiments conducted by Bernardes [9]. The boundary conditions, mass, and stiffness of the elements in the numerical model were tested, calibrated, and validated with the experimental model. As a result, they exhibited similar natural frequencies of the first three vibration modes [7].

For the analysis of this model, various damper configurations were adopted, varying parameters and positions based on optimization for each earthquake scenario, as well as different numbers of floors for both primary and secondary structures. A total of 63 different analyses were performed in this study. These analyses consist of the following combinations:

- Main Structure 10-story tall and secondary structure varying from 9 to 2-story tall
- Main Structure 9-story tall and secondary structure varying from 8 to 2-story tall
- Main Structure 8-story tall and secondary structure varying from 7 to 2-story tall

For each combination, analyses were conducted with the three different earthquakes, resulting in different optimized parameters for the passive dampers. These values involve distinct damping coefficient, stiffness, and positioning of these control devices.

A linear time-history analysis was employed for seismic evaluation of the dynamic response of the numerical model under these loads. Furthermore, the earthquakes were applied in the direction of the y-axis, which is the direction of lower inertia of the building. Figure 1 illustrates the finite element model structure in SAP2000 and the x-y-z axis.

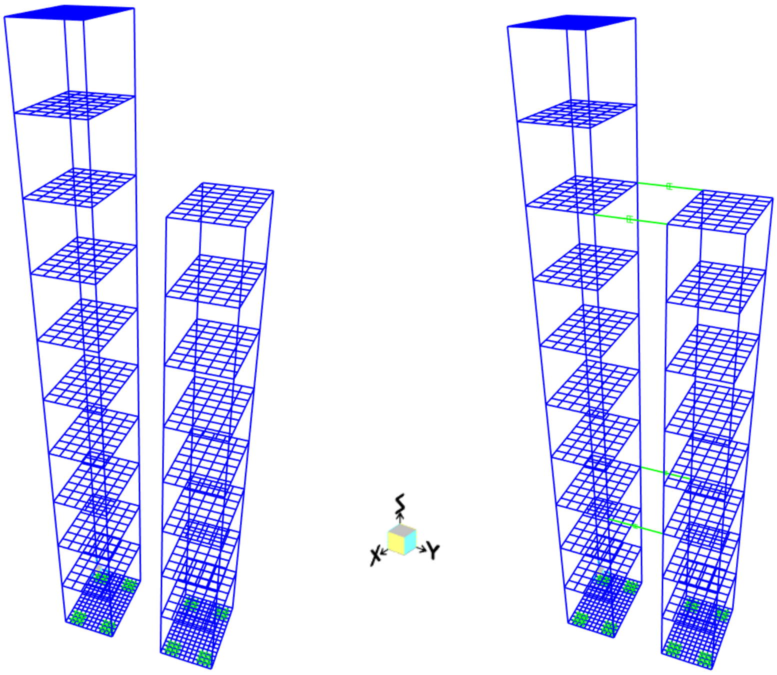

Figure 1. 3D Numerical model: (a) uncoupled model and (b) coupled model

4 Results

Table 1 displays the results of the natural frequencies of the uncoupled structures based on their heights. The results revealed that each structure is more susceptible to specific earthquakes according to their natural frequencies. For instance, the 9-story structure proved to be more sensitive to the Northridge earthquake due to excitation closely aligning with its natural frequencies. Notably, the uncoupled 10-story structure exhibited a maximum displacement of 82.52mm for this seismic event, while the 9-story structure experienced 133.58mm, and the 8-story structure had a displacement of 70.2mm.

Table 1. Natural frequencies of models (Hz)

Vibration mode	10 Floors	9 Floors	8 Floors	7 Floors	6 Floors	5 Floors	4 Floors	3 Floors	2 Floors	1 Floor
1º	4,16	4,47	5,13	5,96	7,06	8,56	10,74	14,13	20,05	33,47
2º	6,66	7,19	8,30	9,72	11,61	14,19	17,95	23,87	34,43	59,56
3º	12,99	13,85	15,51	17,54	20,21	23,74	28,79	36,55	49,95	82,18

Table 2 displays the results obtained from the particle swarm optimization (PSO) model conducted in MATLAB. For this case, optimal values of damping coefficient for passive controllers (c), their stiffness (k), and their position were determined to satisfy the previously highlighted minimum value of the objective function. Distinct values were adopted for these parameters in each analysis, resulting in a total of 63 different damper configurations. To prevent torsion in the building, damping coefficient values were halved and applied at both ends of the structure, as depicted in fig. (1).

Table 2. Results of PSO for structures with 10 and 8 floors

Earthquake	Dampers Positions	C (N s/m)	K (k/m)
El Centro	Floors 1 and 5	223,8178	0
Kobe	Floors 4 and 5	295,0006	0
Northridge	Floors 3 and 8	70,6023	0

As an example, the results obtained in the analysis conducted on the 3D model for the case, where the main structure had 10 floors and the secondary structure had 8 floors, is shown in Table 3. This table presents the maximum displacements for both the uncoupled and coupled structure scenarios, the reduction ratio, as well as the maximum story drift in the same situation.

Table 3. Results of 3D Model for structures with 10 and 8 floors

Earthquake	Floors (Structures 1 and 2)	Max disp. Uncoupled (mm)	Max disp. Coupled (mm)	Reduction Ratio	Story drift uncoupled (mm)	Story drift coupled (mm)	Reduction Ratio
El Centro	10	26,65	14,92	55,98%	4,06	2,14	52,7%
	8	18,2	10,74	59,01%	3,4	2,05	60,03%
Kobe	10	36,51	25,09	68,72%	5,55	3,82	68,83%
	8	20,98	15,55	74,12%	4,11	3,07	74,70%
Northridge	10	82,52	51,31	62,18%	51,26	7,78	15,18%
	8	70,2	36,08	51,40%	13,24	6,7	50,72%

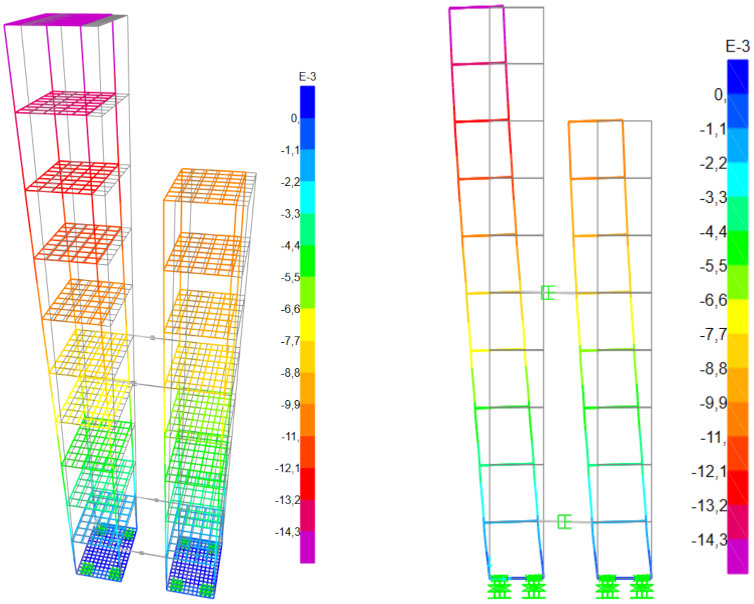

Figure 2. Displacements of coupled building, 10 and 8 floors, for El Centro earthquake

Figure 3 illustrates the outcomes of the conducted analyses, showing the reduction ratios of maximum displacements and maximum story drifts for different heights of main and secondary structures. The reduction ratio is calculated by dividing the maximum displacement of the coupled system by that of the uncoupled system. Different configurations are labeled with distinct colors; for instance, the label “10x8” signifies that the main structure consists of 10 floors and the secondary structure of 8 floors. The displacements of the coupled and uncoupled structures are evaluated in the main structures.

In general, the structure coupling technique resulted in significant reductions of the dynamic responses in the main structures. All tested combinations showed a decrease in the maximum displacements of the structure. There was a substantial reduction in these values, particularly in cases subjected to the Northridge earthquake. The reductions reached up to 80% (i.e., a reduction factor of 0.20), as observed in the case where the main structure had 9 floors and the secondary structure had 5 floors. Similarly, in cases with the El Centro earthquake excitation, reductions of up to 60% in the maximum displacement of the uncoupled structure were achieved. For the Kobe earthquake, reductions reached up to 52%. The reductions in maximum story drift had approximately the same magnitude, demonstrating the effectiveness of the coupling technique in these decreases.

However, there were cases where the attenuations were not significant, for example, in cases where the main buildings had heights close to the secondary building. Notably, in the “10x9" configuration subjected to the El Centro earthquake, the reduction was only 2% and 5% for the recorded maximum displacements and maximum story drift, respectively.

Table 4. Optimal configuration of maximum displacements for coupled system

Earthquake	Main Structure Height	Secondary Structure Height	Reduction Ratio (Coupled/Uncoupled)
El Centro	10 Floors	4 Floors	46%
	9 Floors	5 Floors	42%
	8 Floors	4 Floors	40%
Kobe	10 Floors	5 Floors	51%
	9 Floors	5 Floors	48%
	8 Floors	4 Floors	62%
Northridge	10 Floors	5 Floors	43%
	9 Floors	5 Floors	20%
	8 Floors	4 Floors	30%

Table 4 displays the optimal values for configurations with the greatest reductions in maximum displacements for coupled systems. The highest reduction for the El Centro earthquake, in percentage, occurred with the configuration of 8 stories for the main structure and 4 stories for the secondary structure, resulting in a displacement of 40% compared to the maximum displacement of the uncoupled system. In contrast, for the Kobe earthquake, the optimal configuration was achieved with the main structure having 9 stories and the secondary one having 5 stories, resulting in a maximum displacement equal to 48% of the displacement observed in the uncoupled system. Similarly, for the Northridge earthquake, the optimal configuration featured 9 stories for the main structure and 5 stories for the secondary structure, resulting in a percentage of maximum displacement in the coupled system compared to the uncoupled system of 20%, representing an 80% reduction in maximum displacement.

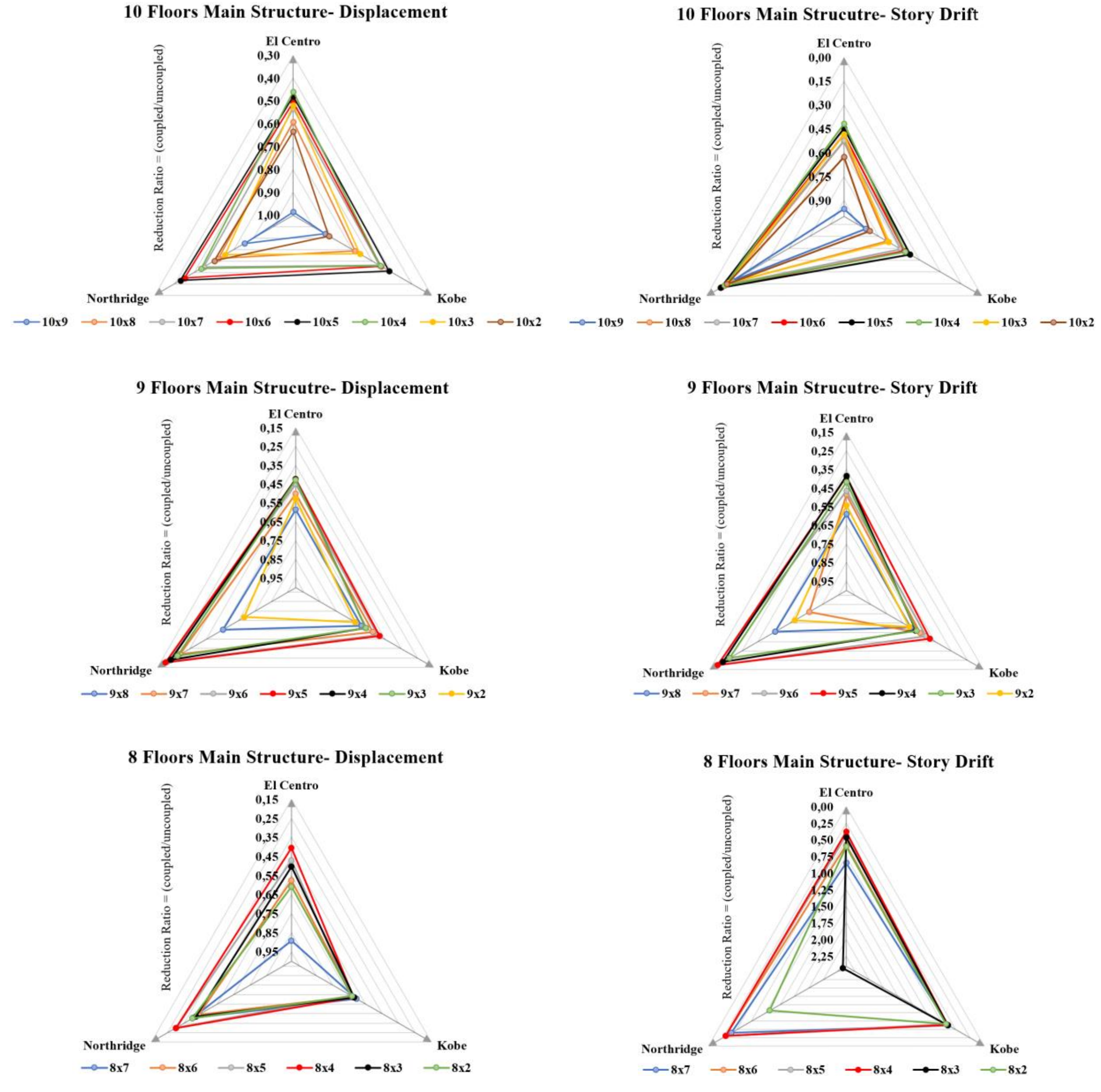

Figure 3. Reduction ration for different building configurations:
(a) Maximum displacement and (b) Maximum story drift

5 Conclusions

Several conclusions can be drawn from the analyses conducted using the 3D numerical model in conjunction with the MATLAB optimization model. It can be observed that the most significant reductions in maximum displacements are generally achieved when the secondary structure has a height roughly half that of the main structure. In the 10 floors main structure, the configuration with the secondary structure having 5 floors exhibits the highest reductions, showing a reduction ratio of 0.48, 0.51, and 0.43 for the El Centro, Kobe, and Northridge earthquakes, respectively. This configuration is only slightly less efficient than the one with 4 floors, which has a reduction ratio of 0.46 for the El Centro earthquake. Similar trends are observed for the 9 floors main structure.

In the case of the 8 floors main structure, the configuration with passive dampers on the secondary building with 4 floors proves to be the most efficient across all earthquakes when compared to other configurations, varying the height of the secondary building. Notably, cases where the smaller secondary structures were slightly shorter by only one floor (e.g., 10x9, 9x8 and 8x7 floors coupling configuration) exhibited less efficient reduction ratios overall. This could result from the dynamic properties being closely matched between the two structures, making them less efficient compared to other configurations.

Furthermore, all PSO results for all earthquakes and different configurations showed a damper stiffness value of 0. In other words, in all cases, the dampers did not affect the dynamic properties of the buildings since they lacked stiffness. It can also be observed that the damping values and their positions are influenced by external excitation.

While in most cases the coupling between the structures significantly reduces the values of maximum displacements and story drifts, in some situations, an increase in these values was observed for the 8 floors main structure configuration. There was a 7% increase in the relative maximum inter-story displacement in the 8x2 floors configuration during the Northridge earthquake and a 134% increase in the 8x3 floors configuration during the same earthquake.

The coupling technique has proven to be effective in reducing the dynamic responses of structures under external excitations. It is a solution that can be implemented to avoid structural issues due to pounding effects and excessive displacements. Its efficiency in reducing dynamic responses depends on various variables. These include the dynamic properties of each building, damper properties (e.g., stiffness and damping), the quantity and position of dampers, as well as the frequency of external excitation.

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