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OPTIMAL DESIGN OF A TUNED LIQUID COLUMN DAMPER USING THE WHALE ALGORITHM

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Abstract

This research aims to obtain an optimal design for a tuned liquid column damper (TLCD) to reduce the response of a building using the whale optimization algorithm. TLCDs are energy dissipative substructures that are used to reduce the structural response of buildings to dynamic loads such as wind and earthquake. The most implemented devices are U-shaped TLCDs. These dampers have been the subject of research over the past decades and have attracted the attention of the structural control community. The minimization of the displacement RMS is used as the objective function in a general optimization scheme. Finding the optimal parameters allows maximizing the effectiveness of the device. The parameters to be optimized will be the damping ratio and the frequency ratio. The results obtained allow comparing the response of a structure without control and when the TLCD is implemented, thus concluding that there is a significant reduction in the structural response of the controlled structure.

Keywords: Structural control, tuned liquid column damper, whale algorithm, earthquakes.

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1 INTRODUCTION

The seismic-resistant design aims to ensure the safety of structures during a seismic event, seeking to minimize structural damage and preserve the lives of users. In recent years, the use of high-strength materials and modern construction techniques has been adopted, which means that structures are now lighter and more flexible, making them much more exposed to large vibrations caused by wind loads or earthquakes, resulting in discomfort for occupants and more significant structural impacts. Consequently, new methodologies and devices have been developed to reduce the structural response of buildings to dynamic loads [1].

The concept of structural control in civil projects has its roots in the empirical work of John Milne, a professor of engineering in Japan, who over 100 years ago built a small wooden house and placed it on bearings to demonstrate that the structure could be isolated from seismic movement [2]. This concept was subsequently incorporated into civil engineering with the purpose of protecting structures. Excessive vibrations generated by strong earthquakes can cause damage to structural elements and loss of life, making it necessary to implement devices that control the structural response to ensure the safety of the occupants. Control systems are divided into four categories: passive control systems, which do not require an external power source; active control systems, which require a power source; semi-active control systems, which are a variant of active systems that require less energy; and hybrid control systems, which combine two or more of the aforementioned systems.

In this paper, a passive control system will be analyzed. These devices respond to the movement of the structure, thereby working with the inertial forces and dissipating the vibrational energy of the structural system. This category includes base isolators, viscoelastic dampers, and mass dampers. [3]. Within the subcategory of mass dampers, there is the tuned liquid column damper (TLCD). This device has its origins when the German shipbuilder H. Frahm suggested using anti-roll tanks to minimize the rolling of ships induced by the movement [4]. Compared to other vibration reduction devices, TLCDs offer significant advantages, such as low installation costs, easy application to new buildings or the possibility of modernizing existing structures, and virtually no maintenance requirements [5]. In fact, a TLCD may not generate significant additional costs or weights if used as a water tank for supply or fire extinguishing [6]. This system consists of a set of rigid pipes integrated into the building and partially filled with liquid, generally water. Its operation is based on the dissipation of energy through the movement of the liquid in the container, due to the restoring force of the liquid, gravity, and the passage of the liquid through an orifice, thus generating a load loss [7].

One of the most effective methods for tuning control devices is the use of metaheuristic optimization algorithms due to their simplicity and flexibility. To obtain the optimal design parameters that ensure the best performance of the TLCD, this research will use the Whale Optimization Algorithm (WOA), which mimics the behavior of humpback whales in nature and their bubble-net feeding strategy, first surrounding the prey and then creating bubble nets for the final attack [8].

The purpose of this work is to find the optimal design parameters of a TLCD and use them to evaluate its performance by comparing the structural response of a 34-story building with and without control, emphasizing the reduction of the RMS displacement criterion.

2 THEORETICAL FOUNDATION

2.1 Tuned liquid column damper (TLCD)

The Tuned Liquid Column Damper is a control device used in structures, particularly high-rise buildings, to reduce the displacements of this type of structure when subjected to dynamic loads [9]. Different geometries for this device have been proposed in the literature, however, the most common is the U-shaped TLCD, the conventional TLCD is a U-shaped tube, partially filled with liquid [10] as illustrated in Figure 1. This structure is modeled as a single degree of freedom system. With the correct selection of damping parameters and frequency ratio, the non-linear relative motion of the liquid can absorb and dissipate the vibration energy of the system, which can be increased if hydraulic resistance is created using orifices installed in the horizontal part of the device [6].

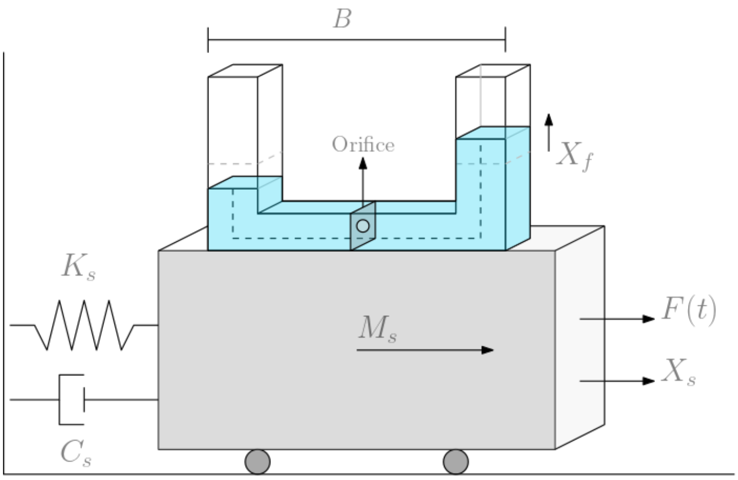

Figure 1: Schematic diagram of TMD in the SDOF system

Where the parameters presented in Figure 1 are:

X_s =Response of the primary system; X_f = Response of the damper fluid; M_s = Mass of the primary system; K_s = Stiffness of the primary system; C_s = Damping of the primary system; *F(t)*= Force acting on the primary system; *B*= Horizontal length of the liquid.

2.1.1. Equation of the TLCD system

The equation of motion of the control device [11] is shown next:

$$\rho AL\ddot{X}_f + \frac{\rho A\xi}{2}\left|\ddot{X}_f\right| X_f + 2\rho AgX_f = -\rho AB(\ddot{X}_s + \ddot{u}_g). \quad (1)$$

Where $\rho =$ density of water; *A*= Cross-sectional area; *L*= water column length; $\xi =$ Damping ratio and g=acceleration of gravity

2.2 Mathematical model of a TLCD controller in a multi-degree-of-freedom system

A schematic plane frame with *n* degrees of freedom equipped with a TLCD is shown on Figure 2. It is important to highlight that the relative displacement of the water column of this device is assumed as an additional degree of freedom in the analysis matrices. The stiffness, damping, and mass of the floor are represented, respectively, by stiffness constant k_i, damping constant c_i, and mass m_i, where i symbolizes the level of the structure.

Equation 2 governs the time-domain dynamic behavior of the controlled structure shown in Figure 2, when subjected to the action of the ground acceleration produced by an earthquake.

$$\boldsymbol{M}\ddot{\boldsymbol{X}}(t)+\boldsymbol{C}\dot{\boldsymbol{X}}(t)+\boldsymbol{K}\boldsymbol{X}(t)=-\boldsymbol{M}\left|\boldsymbol{1}\right|\ddot{u}_g(t) \tag{2}$$

Where $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are the mass, damping, and stiffness matrices defined below. These matrices are of order n+1 x n+1, where n corresponds to the number of degrees of freedom considered. $\boldsymbol{X}$, $\dot{\boldsymbol{X}}$, $\ddot{\boldsymbol{X}}$ are the n+1 x 1 order vectors of displacement, velocity, and acceleration, respectively. $|\boldsymbol{1}|$ is the vector of the location of the external forces, $\ddot{u}_g$ is the acceleration of the earthquake, and t is the time.

$$\begin{bmatrix} \boldsymbol{M}_s+m_d & \alpha.m_d \\ \alpha.m_d & m_d \end{bmatrix}\begin{bmatrix} \ddot{\boldsymbol{X}}_s \\ \ddot{\boldsymbol{X}}_f \end{bmatrix}+\begin{bmatrix} \boldsymbol{C}_s & 0 \\ 0 & c_{eq} \end{bmatrix}\begin{bmatrix} \dot{\boldsymbol{X}}_s \\ \dot{\boldsymbol{X}}_f \end{bmatrix}+\begin{bmatrix} \boldsymbol{K}_s & 0 \\ 0 & k_f \end{bmatrix}\begin{bmatrix} \boldsymbol{X}_s \\ \boldsymbol{X}_f \end{bmatrix}=-\boldsymbol{M}\left|\boldsymbol{1}\right|\ddot{\mu}_g(t). \tag{3}$$

Where m_d = mass of the device (mass of the liquid column); c_{eq} = equivalent damping of the device; k_f = stiffness of the liquid column and α = length ratio [12]. These parameters are defined in Equation 4.

$$m_d=\rho Al \qquad c_{eq}=2m_d\omega_d\xi \qquad k_f=2\rho Ag \qquad \alpha=\frac{B}{l}. \tag{4}$$

Where l = length of the liquid column; ω_d = natural frequency of the damper and g= acceleration due to gravity.

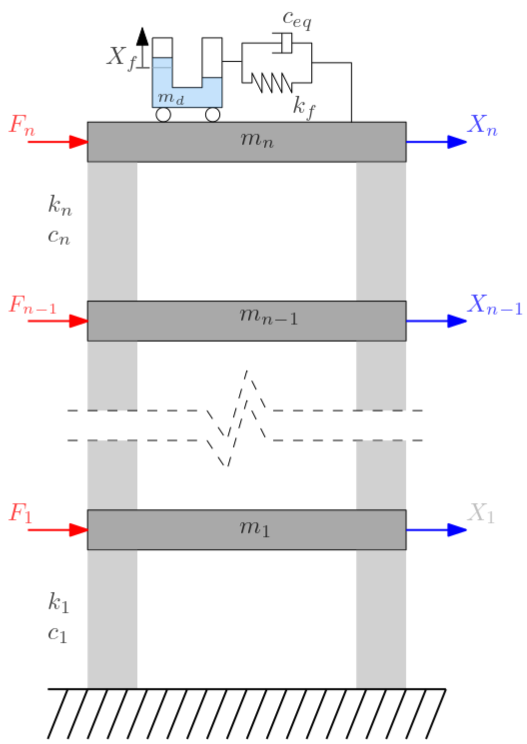

Figure 2: Frame structure with n degrees of freedom equipped with a TLCD

The motion equation of the system can be adapted to a state-space representation to facilitate the determination of the response of the structure as follows:

$$\begin{Bmatrix} \dot{\boldsymbol{X}}(t) \\ \ddot{\boldsymbol{X}}(t) \end{Bmatrix} = \begin{bmatrix} 0 & I \\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{C} \end{bmatrix} \begin{bmatrix} \boldsymbol{X}(t) \\ \dot{\boldsymbol{X}}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \boldsymbol{M}^{-1} \end{bmatrix} = -\boldsymbol{M}\,|\,\boldsymbol{1}\,|\,\ddot{u}_g(t) \tag{4}$$

2.3 Optimization process

For a fixed value of α and m_d the optimization process seeks to find the optimal design parameters of the frequency ratio χ and the damping ratio ξ, in order to minimize an objective function, which for this work is the RMS (root mean square) value of the maximum displacement of the structure, as stated in Eq. (5) and Eq. (6).

$$OF = min(max(RMS(X_n))) \rightarrow X_n = [X_1, X_2, X_3, ..., X_n] \tag{5}$$

Where:

$$\chi = \frac{\omega_d}{\omega_s} \rightarrow 0.5 \leq \chi \leq 2.0 \ \text{ y } \ \xi = \frac{c_d}{2 m_d \omega_d} \rightarrow 0.05 \leq \xi_d \leq 0.5 \tag{6}$$

This process is carried out using the Whale Optimization Algorithm (WOA), which is a nature-inspired metaheuristic optimization algorithm that mimics the hunting behavior of humpback whales; it is inspired by the bubble-net feeding strategy of whales. [13]

The use of this algorithm is based on various studies that support the use of WOA as an efficient tool in solving optimization problems in various fields of engineering. As indicated in [13], this algorithm, inspired by the cooperative hunting behavior of humpback whales, is capable of efficiently exploring the search space and avoiding stagnation in local optima, a common problem in traditional optimization methods.

In [14] the effectiveness of WOA in optimizing complex systems is demonstrated by combining it with fuzzy logic for the design and control of magnetorheological dampers. The results obtained show that this combination significantly improves the accuracy and performance of the system, achieving a better dynamic response and a greater ability to adapt to different operating conditions.

3 CASE STUDY

The proposed optimized control project will be installed in one of the towers of the "COUNTRY LIFE-OTOÑO" project (Figure 3), which is a residential housing project located in an area of intermediate seismic threat in Medellín (Antioquia). This tower has 35 floors with 5 floors for parking, 30 floors for residential use, and a floor area of 464.58 m². The structural system of the building is a Moment-Resistant Frame System. For the analysis of this structure, which has 3 frames in the X direction and 7 in the Y direction, the stiffness of the 10 frames is considered to perform a more realistic analysis of the behavior of the structure.

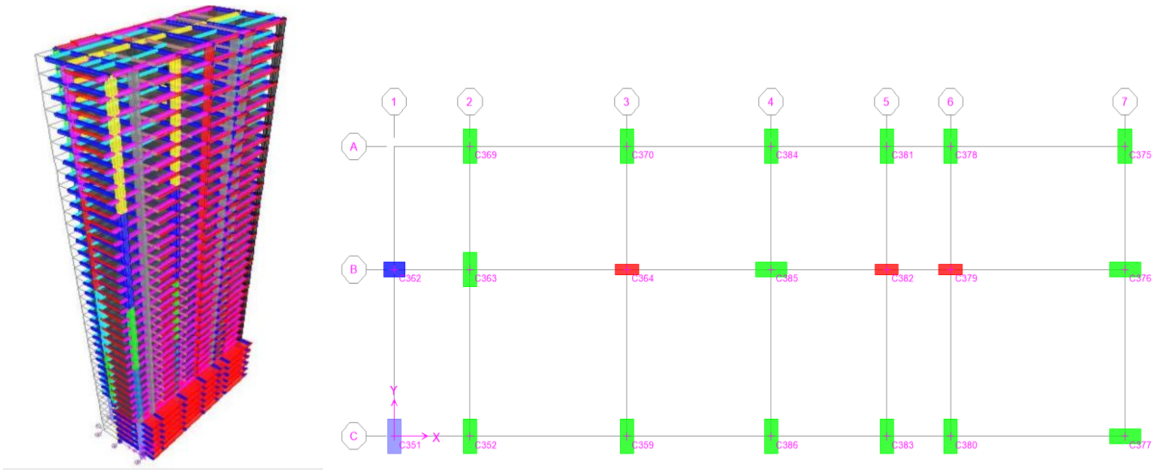

Figure 3: Country Life Building - Autumn Typical floor(b)

3.1 Properties of the structure

The following are the fundamental considerations assumed in the structural analysis conducted on the building:

3.1.1. Stiffness Matrix:

For this analysis, a concrete compressive strength of 28 MPa was used. A single degree of freedom per floor in the direction X was chosen, as the objective is to evaluate the displacement in this direction. The vertical and rotational degrees of freedom were condensed due to their minimal contribution to the lateral displacement of the structure.

The dimensions of the structural elements considered in the analysis are:

- Columns: Green 1.5m x 0.5m; red 1.2m x 0.5m and blue 1m x 0.7m (According to the distribution presented in Figure 3)
- Beams: 0.4m x 0.5m

3.1.1. Mass Matrix:

To determine this matrix, the mass was concentrated by floor, taking only the self-weight corresponding to each degree of freedom.

3.1.1. Damping Matrix:

The Rayleigh damping matrix is determined proportional to the mass and stiffness with a damping ratio of 5%; according to the first and last vibration modes of the structure.

Evaluating these matrices in Equation 1 allows to know the response of the building under the effect of different seismic records.

3.2 Seismic records

The structure model will be subjected to the effect of 3 ground motion acceleration records, which differ from each other in magnitude and frequency. They are presented below in Table 1.

Event	Year	Station	Component	Magnitude	PGA [g]	Duration [s]
El Centro	1940	El Centro (117)	S90W	6,9	0,348	53,73
Big Bear	1992	Big Bear Lake, CA	270	6,6	0,481	60,01
Chi- Chi	1999	Taichung, Taiwan	N90	7,62	0,469	108,00

Table 1: Seismic records used in the study. Taken from: Center for Engineering Strong Motion Data.

4 RESULTS AND ANALYSIS

MATLAB routines were used to simulate the behavior of the structure in response to the seismic records listed in Table 1, with an optimally designed TLCD installed at the top level of the building (level 34), as shown in Figure 2. It is relevant to highlight that for each ground motion, different results were obtained regarding the optimal parameters, as detailed in Table 2. This variability is a result of the diverse characteristics presented by the seismic records under consideration.

Test	Event	X	ξ
1	El Centro	0,91	9,1%
2		0,95	8,3%
1	Big Bear	0,89	17,8%
2		0,74	22,9%
1	Chi-Chi	1,19	47,7%
2		0,90	48,1%

Table 2: Optimization results with whale algorithm

4.1 Response of the controlled and uncontrolled structure

Analyzing the displacements at the upper level, which is where the structure experiences the biggest displacements, the responses illustrated in Figures 4, 5 and 6 are obtained. The controlled structure shows a considerable reduction in its displacements at most of the peaks. At the beginning of the response in the Big Bear and Chi-Chi seismic records, there is a greater displacement than in the uncontrolled structure; this could be due to the damper not having fully stabilized at that specific moment. However, subsequently, it contributes to the reduction of the overall movement of the structure.

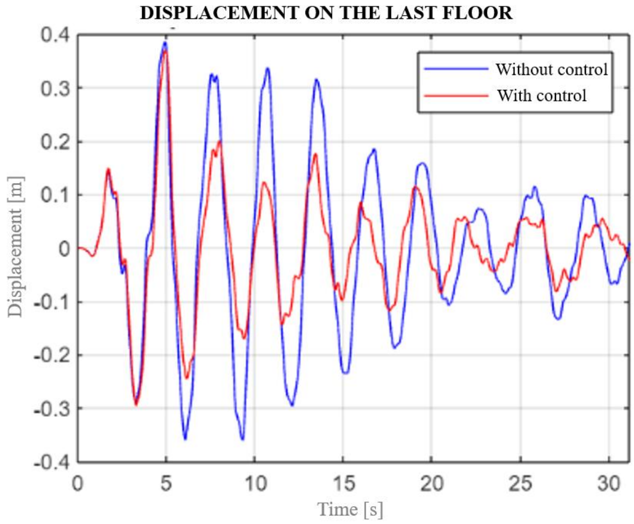

Figure 4: Displacement Comparison -Test 1 - Central earthquake

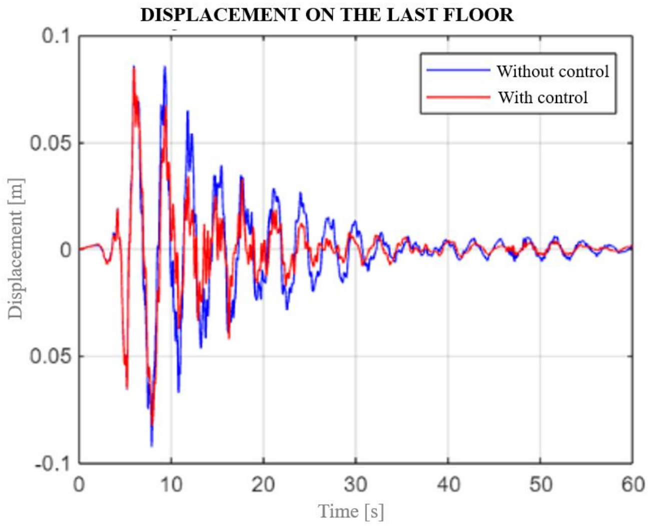

Figure 5: Displacement Comparison - Test 1- Big Bear earthquake

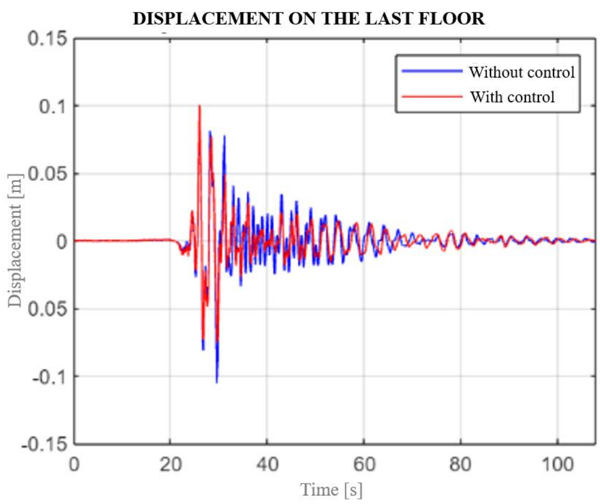

Figure 6: Displacement Comparison - Test 1- Chi-Chi earthquake

Figures 7, 8 and 9 show the results of the RMS displacement value for each level, which demonstrates how the response varies over time and providing a more precise average magnitude of the response. It is important to highlight the decrease in this value, as it is directly related to the objective function that was previously optimized.

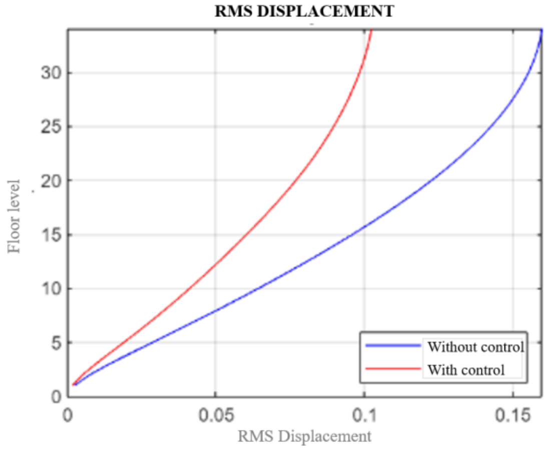

Figure 7: RMS displacement - Test 1- Earthquake at the center

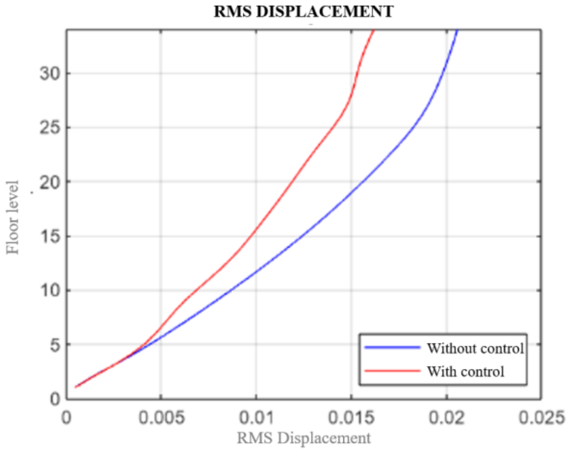

Figure 8: RMS displacement -Test 1- Earthquake Big Bear

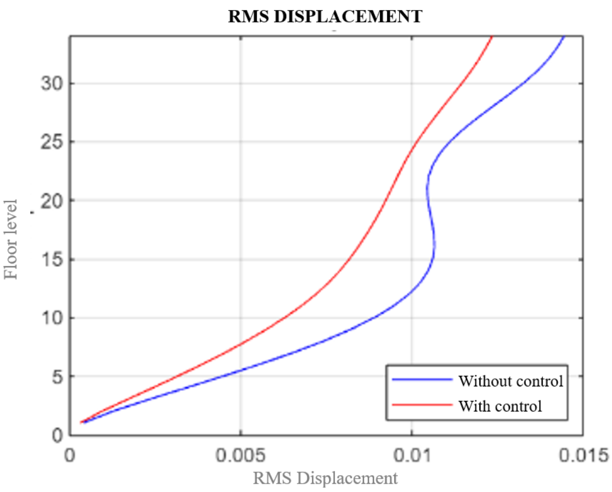

Figure 9: RMS displacement - Test 1- Earthquake Chi-Chi

5 CONCLUSION

The implementation of control devices in tall structures emerges as a strategy to reduce their response to seismic movements. The percentages of maximum displacement reduction at the top level for the El Centro, Big Bear, and Chi-Chi earthquakes may seem modest (1%, 8%, and 5% respectively), but a detailed analysis reveals a significant decrease in the average displacements throughout the entire excitation: 38%, 34%, and 23%, respectively. This performance demonstrates the ability of the coupled system to operate safely and predictably.

The effectiveness of TLCDs is influenced by the definition of their design parameters, so an optimization process is carried out to determine the optimal values of these variables, which translates into better performance in structural control. The reduction of displacements underloads is essential to maintain structural integrity and prevent severe damage to buildings. In this context, the implementation of control devices becomes an attractive alternative to help ensure the safety and stability of structures against dynamic loads.

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