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Robust Simultaneous Optimization of Friction Damper for the Passive Vibration Control in a Colombian Building

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Abstract

The dampers robust optimization is a new area that has been studied in the last years, having a big impact in the optimal robust design of devices for the vibration control in structures subjected to dynamic loads due to natural hazards such as earthquakes. In this paper a new approach is presented taking into account the robust optimization of friction dampers, which is carry out using the Genetic Algorithm integrated with the computational routine based on the Central Finite Differences Method developed by the authors, which is able to deal with optimization problems involving discrete (positions of the dampers in the structure) and continuous (mechanical parameters of the dampers, in this case, the friction forces) design variables. Taking into account uncertainties in both structural and load properties, the dynamic structural response becomes stochastic. It is noteworthy that such methodology applied to friction dampers is innovative because there is a lack of studies on robust optimization associated with this type of damper in the literature. This device stands out among the passive devices due to the low cost of construction, installation and maintenance, as well as the high performance for vibration control. For illustration purpose, a typical concrete building from a Colombian city (Cúcuta) was considered, which is located in the northeast of the country, where a high seismic activity occurs. In this case of study the objective function is the minimization of the failure probability, this is, the failure occurs when the maximum inter-story drift is greater than 1% of the story height, as suggested by the Colombian Seismic-Resistant Standard (NSR-10). The results show that the proposed method was able to reduce the failure probability achieving good results using this sort of passive device.

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Keywords: Robust Simultaneous Optimization; Friction Dampers; Passive Vibration Control

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1. Introduction

The imminent risk of damage or collapse of civil structures located at regions with high seismic activity led to development several structural control methodologies. Colombia is located in north-west corner of South America continent within one of the most seismic activity areas of the earth, called ring of fire and corresponds to the shores of the Pacific Ocean. The tectonic positioning of Colombia is complex due to the fact that in its territory converge the Nazca plate, South American plate and Caribbean plate. The predominant fault in the country is north-south, coinciding with the direction of the three mountain ranges (Western, Central and Eastern) where there are a large number of seismic activity failures in the country, being one of the most active the region of Santander placing important cities of Colombian Eastern such as Bucaramanga and Cucuta.

This paper presents a robust optimization study of friction dampers, where the robust optimization usually find robust designs that are not very sensitive on the parameters´ variations while the optimal design provides the best performance of the system [1,2,3].

Due to the fact that the system depends on random parameters, structural response becomes random itself. Therefore, the main contribution of the present paper is to propose a methodology for robust optimization of passive friction dampers installed in structures subjected to real seismic record, in order to minimize the probability of failure of these structures. For this end, the Monte Carlo Simulation (MCS) is applied in order to quantify the statistics of stochastic system response, i.e. the probability of failure and the Latin Hypercube Sampling is employed to reduce the number of samples.

2. Problem Formulation

This section presents a clear explanation of the key issues for the development of this research listed below:

2.1. Motion equation

The differential equation governing the motion of a system of multiple degrees of freedom with friction dampers and subjected to earthquakes can be written as follows:

$$M\ddot{\vec{z}}(t) + C\dot{\vec{z}}(t) + K\vec{z}(t) = -MB\ddot{\vec{y}} - F_{fn}sgn(\vec{v}(t)) \tag{1}$$

Where M and K are the $n \times n$ size structural mass and stiffness matrices, respectively, and n is the number of degree of freedoms. The damping matrix (C) is proportional to M and K matrices, as $C = \alpha M + \beta K$. The n-dimensional vector $\vec{z}(t)$ represents the relative displacement with respect to the base and the differentiation with respect to the time is represented with a dot over the displacement vector symbol. B is a $n \times d$ matrix that contains the cosine directors of the angles formed between the base motion and the direction of the displacement considered degree of freedom (DOF). d is the number of directions of the ground motion and $\ddot{\vec{y}}$ is the d-dimensional ground acceleration vector of the seismic excitation. F_{fn} is the n-dimensional friction force vector and $\vec{v}(t)$ is the relative velocity vector between the two ends of the friction damper. [4,5]

A computational routine based on the finite differences explicit method was developed in MATLAB to solve the Equation 1, determining the dynamic response in terms of displacement of a system with friction dampers. The structure analyzed is a concrete, three-bay, 7-story building, 20 m high and 16.55 m wide, shown in Figure 1 a). The building is modeled as a finite element 2D-frame structure consisting of 49 elements and 32 nodes, this is, 96 DOF. The geometrical properties of the each structure's member are presented in Table 1. Considering mean values of the specific mass, elastic modulus presented in Table 2 and assuming coefficient of variation equal to zero for both random variables, the first three natural frequencies of the structure are: 1.9751, 4.5851 and 9.5161 Hz.

2.2. Operating mechanism of friction damper

The passive friction damper uses the solid friction mechanism proportioning desired energy dissipation with the aim to reduce the structural response. When the structure equipped with friction dampers is under a seismic excitation, two solid bodies sliding in relation to one another inside the friction damper allow the energy dissipation.

In this paper, it is used the numerical scheme of the friction damper Model A proposed by Miguel [5] (see Figure 1 b)). This damper used brass as material to generate friction and consequently energy dissipation. Thus, the control of normal force at the contact between the brasses is given by two compression springs. This model can be applied in structures subjected to any type of dynamic load, such as earthquakes, both in metallic structures and in concrete structures. It may be placed as diagonal bracing bars, as shown in the diagram of Figure 1 a). Besides, if the reader requires more information about the friction damper Model-A, the authors recommended read the Master dissertation of Miguel [5].

Table 1.Geometrical properties of the concrete structure.

Member number	Area [m^2]	Inertia moment [m^4]
1,2,3,8,9,10,15,16,17,22,23,24	0.2	0.0027
4,5,6,7,11,12,,13,14,18,19,20,21,25,26,27,28	0.12	0.0009
29,30,31,32,33,34,35,36,37,38,39,40	0.12	0.0009
41,42,43,44,45,46,47,48,49	0.06	0.0002

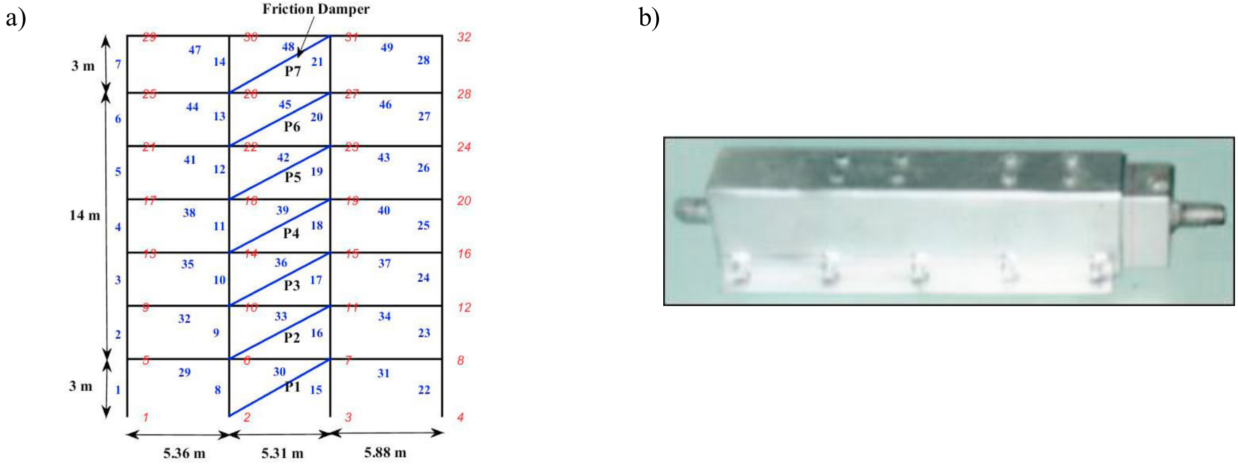

Fig. 1. (a) Three-bay 7-story concrete building with 7 friction dampers installed; (b) Friction damper Model-A.

2.3. Characterization of input random variables

In order to model the uncertainties of a dynamic scenario of Cucuta, several parameters of the studying building are modelled as random variables with the aim to represent typical population of structures of concrete in the city. Thus, the specific mass, Young´s modulus of the material and damping ratio for the first and second modes of the building are modelled as random variables to take into account uncertainties in the mass, stiffness and damping of the structure. Concerning the seismic load, in this paper was implemented a real seismic record corresponding to the Cordoba earthquake, which took placed in the Cordoba city, department of Quindío, Colombia in January 25 of 1999. Because of this earthquake 1185 people passed away, 8523 people were injured and caused serious damage in the cities of Armenia and Pereira as well as 28 nearby municipalities. The earthquake generated losses of the order of 1.591 USD million, corresponding to 1.88% of the National GDP (Gross Domestic Product) of that year [6]. The Peak Ground Acceleration (PGA) of this seismic record was normalized and modelled as a Lognormal random variable. Thus, the random variable parameters are presented in Table 2.

Since in many engineering problems a random variable cannot assume negative values due to the physical aspects of the problem, all the above mentioned parameters are modelled as uncorrelated random variables with Lognormal distribution with known mean and coefficient of variation (see Table 2). Thus, for each run of the computational routine based on the finite differences explicit method through Monte Carlo Simulation, the structure presents different parameters. Because of the response of the system depends on these random variables, it becomes random itself. On the other hand, to take into account uncertainties in the installed dampers, the friction forces of these devices are also assumed to be independent Lognormal random variables with known coefficients of variation and mean values given by the design variables.

Table 2. Mean values and coefficient of variation of the input random variables of the system.

Random variable	Mean value	Coefficient of variation (%)
Specific mass ρ	2500 $\mathrm{kg/m^3}$	8
Young's modulus E	35E9 Pa	8
Damping ratio ζ	0.01	10
Friction forces F_{fn}	Design variables	5
PGA (g)	0.5933	35

2.4. Latin Hypercube Sampling

The large computational effort inherent in the use of a Monte Carlo method is reduced by the use of the Latin Hypercube Sampling that provides an efficient way of generating variables from their multivariate distributions, taking samples from equally probable intervals [7,8].

The scheme developed by McKay, Conover and Beckman [9] selects n different values of a random variable as follows: The domain of the random variable is divided into n non-overlapping intervals of equal probability. A value of each interval is chosen randomly with respect to the probability density in the interval. The choice must be made in a random manner with respect to the density in each interval; That is, the selection should reflect the height of the density across the range. Besides, if the reader requires more information about the Latin Hypercube Sampling, the authors recommended read the papers [9, 10].

3. Optimization problem

Due to its ability to find global minimum, the Genetic Algorithm was chosen to perform the robust optimization of friction dampers. Thus, an improve Monte Carlo Simulation was adopted for carried out a large number N of simulations for each observation of each random variables cited above that produce N matrices of mass $\mathbf{M}_{s,i}$ and stiffness $\mathbf{K}_{s,i}$ $(i = 1, \dots, N)$. The appropriate floors for a maximum of two friction dampers in a civil structure of seven stories can be represented by discrete variables $(\vec{P} = \{1, .. n_p\}, being\ n_p = 7)$, where $\vec{P}$ is a n_p-dimensional vector of positions consisting of 0 (there is not a damper) and 1 (there is a damper). Therefore, the maximum number of ones (1) in $\vec{P}$ is n_d (in this paper, the maximum number of dampers in the structure is two). On the other hand, the mechanical parameter appropriate for each optimal damper located is better represented by continuous variables$(F_{fn} \in \Re^{n_d})$, and the allowed limit for the friction forces of each damper is: $75kN \leq F_{fn} \leq 95kN$. For purposes to ensure an optimal response preventing G.A. converges to a local optimum, the population of chromosomes was set at 20 and the maximum number of iterations was set at 30, thus at the end of the process the algorithm evaluate 600 objective functions.

Thus, in this paper the objective function is minimize the probability of failure of the structure and it is assumed that the failure occurs when the inter-story drift (d_{max}) exceeds the 1% of the first story's height (H_s). The inter-story drift is determined through the vector $\vec{z}(t)$, which is obtained solving the Equation (1) in the time domain using an integration step $\Delta t = 2 \times 10^{-4}$ s. Therefore, is possible to define a failure random variable D that represents the limit state of the system, as:

$$D\begin{cases}= 1, \quad \text{if } |d_{max}| \geq 1\%H_s \text{ (failure)} \\ = 0, \text{otherwise (no failure)}\end{cases} \tag{2}$$

The conditional failure probability P_f is estimated, counting the relative number of times that the response reaches the limit inter-story drift, and can be expressed as:

$$P_f = P[D = 1] = P[|d_{max}| \geq 0.01H_s] \tag{3}$$

For convenience of notation, the design variables are grouped into the vector $\vec{\mathrm{x}} = [\vec{P}, \vec{F}_{fn}]$ and the optimization problem can be propounded as:

$$\begin{array}{ll} \text{Find} & \vec{\mathrm{x}} \\ \text{Minimize} & \mathbf{J}(\vec{\mathrm{x}}) = P_f(\vec{\mathrm{x}}) \\ \text{Subjected to} & \begin{cases} F_{fn}^{min} \leq F_{fn}^{j} \leq F_{fn}^{max}, j = 1, .., n_d \\ n_p \text{(number of available positions)} \\ n_d \text{(maximum number of dampers)} \end{cases} \end{array} \tag{4}$$

In order to set the number of observations of the random variables to carry out the robust optimization based on the improved Monte Carlo Simulation, the converge of the statistical operators must be assessed. Thus, a converge study of the converge of the failure probability is performed and the results are shown in Figure 2 a). Thus, is possible to determine that is required a minimum of around 100 observations of the random variables to stabilize the converge curve of failure probability.

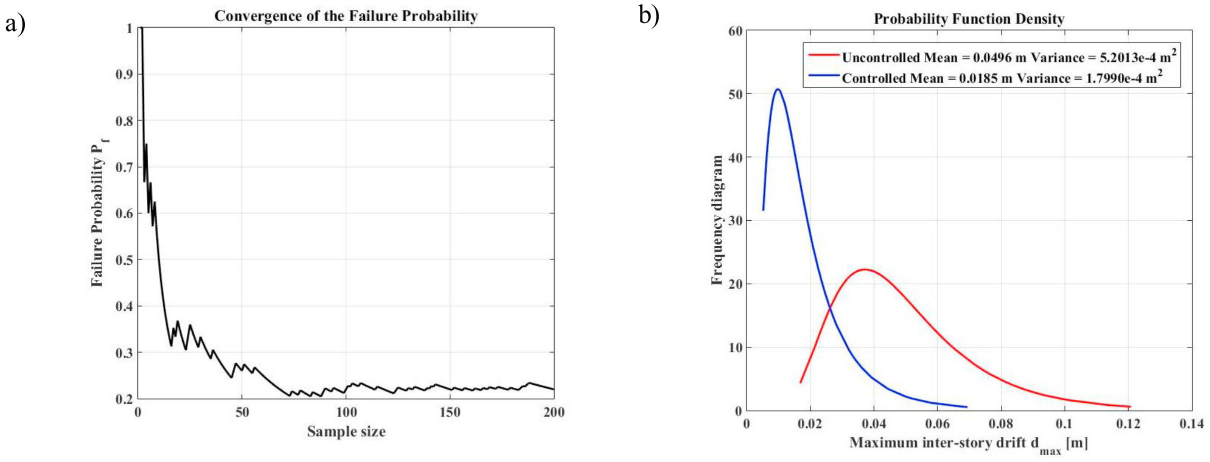

Fig. 2. (a) Converge curve of the failure probability; (b) Probability function density of Maximum inter-story drift.

In order to evidence the effectiveness of the methodology for the robust optimization of friction dampers exhibit in this paper, five scenarios are presented in the Table 3. The first scenario is the uncontrolled structure, this is, a structure without dampers; the second scenario is the structure equipped with 7 friction dampers (one in each story) where the sum of the friction forces of the seven friction dampers is equal to the 30% of the structure weight (estimated in $5.7082 \times 10^5\ N$); finally, the third, fourth and fifth scenarios presented the same robust design of the friction dampers (indicating that the best positions are the fifth and sixth stories $\vec{P} = \{5,6\}$), showed the failure probability obtained is the same, indicating that the proposed method is robust.

Additionally, Figure 2 b) shows the probability density function of the maximum inter-story drift for the uncontrolled structure (red curve) and the controlled structure (blue curve) by the robust design obtained in scenario 3 presented in Table 3. Observing, it is interesting to appreciate that besides the reduction of the expected value (over 62%) the variance is also considerably reduced (over 65%) in relation to the scenario of the uncontrolled structure and this is achieved with two friction dampers where the sum of their friction forces is equal to 30% of the weight of the structure.

Table 3. Robust design of friction dampers.

Scenario	Best Stories $\vec{P}$	Best friction forces F_{fn} [N]	Failure probability	Reduction (%)
1	Without dampers	Uncontrolled structure	0.85	No-reduction
2	[1 1 1 1 1 1 1]	2.4464×10^4	0.24	71.76
3	[0 0 0 0 1 1 0]	8.8955×10^4, 8.3255×10^4	0.15	82.35
4	[0 0 0 0 1 1 0]	8.8982×10^4, 8.3428×10^4	0.15	82.35
5	[0 0 0 0 1 1 0]	9.0874×10^4, 7.9499×10^4	0.15	82.35

4. Conclusions

The robust optimization studied in this paper is complex due the objective function is not-convex, and it includes both discrete and continuous design variables, therefore it must be resolved by a optimization methodology capable to handling this kind of problems. For this purpose, the Genetic Algorithm was implemented to determine the robust design of friction dampers through an improved Monte Carlo Simulation in order to reduce the failure probability.

The results showed the capacity of the developed assessment in solving the robust optimization problem of friction dampers, reducing the failure probability of a three-bay 7-story concrete building located in Cucuta, Colombia in more than 80%. The percentage of reduction of the expected value of inter-story drift obtained with the robust design of friction dampers is greater than 60%.

Therefore, this proposed methodology can be used as reliable tool for robust design of friction dampers, showed that the robust design of this passive device can be done in a safe and economic process.

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