Design optimization for plane structures equipped with friction dampers

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Abstract

The work summarized in the present paper is about the numerical simulation of plane structures equipped with frictional damping devices. A numerical time integration method specifically tailored to deal with the non-regular character of Coulomb’s friction law, the $\theta$ method, was programmed in Matlab. It was conjugated with a genetic algorithm (from the Toolbox of Matlab) for the optimization of the slip forces of the frictional energy dissipators. The numerical models of five plane structures with structural walls of different sizes, with a frictional damper in each floor, were subjected to a set of seven real earthquake records in order to understand the importance of structural walls in the distribution of the dissipators’ slip forces. In order to simultaneously reduce displacements and accelerations a multi-objective optimization was used. Two types of dissipators’ maximal forces distributions were considered: uniform and non-uniform. It was concluded that the optimal distribution is not very different from the uniform one. The efficiency of the friction dampers as anti-seismic systems is emphasized by the comparison of the seismic response of the optimal designs with the uncontrolled frames.

Keywords: Passive seismic protection, Friction, Multi-objective optimization, Genetic algorithm

1. Introduction

One of the most destructive actions that a structure can be submitted to, is the seismic action which often results in substantial damage and loss of lives. The seismic response of a structure depends on its structural resistance and its ability to dissipate energy. Due to economic reasons it is not a good option to rely exclusively on the structural resistance. Current design rules (EC8) suggest that the capacity of energy dissipation should be guaranteed by the plastic deformation of the structural elements, which is a conventional design methodology that assumes a certain amount of damage in the structural elements. In order to prevent these damages and still get a good seismic behavior, several anti-seismic systems have been developed in the last few decades. These systems change the dynamic properties of the structures for better control of the response during an earthquake, therefore reducing damage and increasing safety. Structural control can be divided in four groups (Housner et al, 1997), passive control, active control, hybrid control and semi-active control. The object of this paper is one type of passive control; it aims to increase the ability of a structure to dissipate energy during an earthquake, which includes both seismic isolation and passive energy systems. There are several passive energy systems like viscoelastic dampers, friction dampers or yielding metallic elements. This paper will analyze the efficiency of friction dampers and optimize the design of plane structures equipped with friction dampers by the use of a genetic algorithm.

Friction dampers are anti-seismic devices that control the response of a structure by transforming the energy transmitted to the structure by the earthquake into heat, through the friction forces developing in pairs of contacting surfaces. In order to have a permanently elastic behavior of the structure, the friction devices are designed to slip regimes preventing the non-linear behavior in all structural elements. Those dampers may be used between structures or between consecutive floors in order to reduce the relative displacements. These devices can be installed in metallic, reinforced concrete or composite structures. Since they are light weighted, easy to produce, install and maintain, they are very economical when compared to other anti-seismic systems. For modelling these devices inserted in plane structures Coulomb's friction law is assumed: $f_s = \mu N$ is the maximal force where $N$ denotes the normal force and $\mu$ the coefficient of
friction.

Moreschi (2000) and Fallah and Honarparst (2013) have determined the optimum slip force of each damper in a structure with a genetic algorithm. Moreschi (2000) concluded that minimizing just displacements would increase accelerations too much so he minimized simultaneously displacements and accelerations and obtained irregular distributions of slip forces. He also concluded that when one enforces an uniform distribution of the slip force the response of the structure is not far from the one assuming varied distribution of the slip forces. Fallah and Honarparst (2013) used an optimization criteria with the objective of reducing displacements, accelerations and the base shear force; they extracted the same conclusions in (Moreschi, 2000).

The present paper presents a tool for optimization and analysis of linear viscoelastic structures equipped with friction dampers and subjected to earthquakes. The algorithm based on the θ method (Jean, 1999), programmed in Matlab (Matlab, 2014) for the analysis of linear viscoelastic structures subjected to earthquakes and equipped with friction dampers, is presented. Then, the genetic algorithm of the optimization Toolbox of Matlab is explained. An appropriate range of the maximum slip force is determined based on a non-linear time-history analyses for a set of seven selected earthquake records. Finally these two algorithms combined are used to optimize the slip forces of the friction dampers of five different structures by satisfying a multi-objective optimization problem.

2. Analytical modelling of friction dampers

2.1. Governing equations

A N-storey plane structure with lumped masses, equipped with frictional damping devices, where between two consecutive floors a viscous damper is associated in parallel with a set spring-friction damper associated in series is illustrated in figure 1.

The absolute displacement of the ground is represented by \(d(t)\) and the absolute displacement of the \(i\)-th floor by \(X_i\). The mass, stiffness and viscous damping coefficient below the \(i\)-th floor are represented respectively by \(m_i\), \(k_i\) and \(c_i\). In order to model the bracing system a spring with finite stiffness is introduced in the horizontal direction which requires the consideration of a new degree of freedom (with no mass associated) for each pair {spring, friction device}, represented by \(X_{b_i}(t)\). The total number of degrees of freedom of the system is 2\(N\). The amount \(f_{s_i}\) denotes the slip force of the \(i\)-th friction damper and \(k_{b_i}\) the stiffness associated with the bracing system both just below the \(i\)-th floor. The equations of motion for this model can be written in the vectorial form:

\[
M_T \ddot{x}_T(t) + C_T \dot{x}_T(t) + K_T x_T(t) = F(t) + Wr(t),
\]

where

\[
F(t) = \begin{bmatrix} -M1 \ddot{d}(t) \\ 0 \end{bmatrix}, \quad x_T(t) = \begin{bmatrix} x \\ \dot{x}_b \end{bmatrix}
\]

\[
M_T = \begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix}, \quad C_T = \begin{bmatrix} C & 0 \\ 0 & 0 \end{bmatrix}, \quad K_T = \begin{bmatrix} K & 0 \\ K_{bA} & K_{bB} \end{bmatrix},
\]

\[
K_{bA} = \begin{bmatrix} 0 & \cdots & 0 \\ -k_{b2} & 0 & \cdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -k_{bN} \end{bmatrix},
\]

\[
K_{bB} = \text{diag}(k_{b1}, \ldots, k_{bN}),
\]

2.1.1. Figure 1: Regular plane frame with \(N\) floors equipped with a mixed viscous and frictional damping, subjected to a horizontal prescribed motion by the foundation given by the displacement history \(d(t)\).
The impulsive version of Coulomb’s law is $i_{k+1}^t \in -f_s, h\sign(\dot{x}_i - \dot{x}_b)$, which is equivalent to a non-regular equation $i_{k+1}^t \equiv \proj_{[-f_s, f_b]}(i_{k+1}^t - c v_{k+1}^t)$, where $c$ is a strictly positive parameter (we used $c = 1$). Figures 2 and 3 show flowcharts of the $\theta$ method programmed in Matlab. The required data is the earthquake accelerogram, the mechanical characteristics of the structure included in matrices $M_T$, $C_T$, $K_T$ and $W$, the values of the $\theta$ method parameters and $T$, the time of simulation. We assume vanishing initial velocities and displacements. The equation (11) is adopted to calculate accelerations.

\[ \ddot{x}_T^k = \frac{x_{T+1}^k + x_{T-1}^k - 2x_T^k}{2h}. \] (11)

Figure 2: Time integration method ($\theta$ method).

Part A is explained in figure 3.

3. Genetic algorithm optimization

3.1. Introduction

Genetic algorithms are a family of computational models inspired by natural evolution (Whitley, 1994). The first algorithm of this family was introduced by Holland (1975). Genetic algorithms are based on natural selection where only the fittest individuals are likely to survive and reproduce themselves. In our optimization problem there is no analytical expression to be optimized, therefore it is not possible to use classical optimization methods based
Solve:
\[ x_{k+1} = \tilde{M}^{-1} \tilde{F} \]

Computation of relative velocity:
\[ \dot{x}^{k+1} = \dot{x}^{k+1} - \dot{x}^{k+1} \]

\[ p^{k+1,j+1} = p^{k+1,j} - c v^{k+1,j} \]

For \( i = 1, \ldots, N \):
\[ i^{k+1,j+1} = \text{proj}_{-f_s} \left( p^{k+1,j+1} \right) \]

Solve
\[ x_{k+1}^{j+1} = \tilde{M}^{-1} \tilde{F}^j + \tilde{M}^{-1} \tilde{W}^{k+1,j+1} \]

Check the convergence criteria:
\[ \| \dot{x}^{k+1,j+1} - \dot{x}^{k+1,j} \| < \varepsilon \]
\[ \| p^{k+1,j+1} - p^{k+1,j} \| < \varepsilon \]

Figure 3: Iterative process within each time step.

on the gradient. There are advantages in using the genetic algorithms for optimization problems such as for example preventing the convergence to local optima. Genetic algorithms also consider simultaneously several options in the search space and use probabilistic transition rules to continue the ecosystem evolution instead of using deterministic rules, like the algorithms based on the gradient.

3.2. Optimization
It is important to define three basic elements of genetic algorithms:

- **Individual**: A group of independent variables that represent a possible solution. In our problem an individual corresponds to a design of slip forces in all the friction dampers.

- **Gene**: One of the independent variables. In our case a gene is the slip force in one friction damper.

- **Population / Generation**: A set of individuals.

The optimization is achieved with the improvement of individuals from generation to generation. It starts with randomly generating the first population (it is also possible to define the initial population). The evaluation phase consists in the evaluation of each individual based on a given fitness function: for each individual it is assigned a fitness value
\[ \frac{f_i}{f} \]
where \( f_i \) corresponds to the evaluation of the individual and \( f \) the average of evaluations of the entire population. The higher the fitness value of an individual, the fittest it will be considered (Whitley, 1994).

The process of going from the current generation to the next consists of creating an intermediate generation by a selection operator and by the application of the crossover and the mutation operators to this intermediate generation with the aim of promoting an improvement between each two consecutive generations. Then the iterative process Evaluation \( \rightarrow \) Selection \( \rightarrow \) Crossover \( \rightarrow \) Mutation \( \rightarrow \) Evaluation ... is repeated until some stopping criteria is met. Figure 4 shows a flowchart with the sequence of operators used by the genetic algorithm.

Figure 4: Genetic algorithm: sequence of the algorithm's operators.
3.2.1 Genetic algorithm operators

3.2.1.1 Evaluation

All individuals of the population are evaluated according to the function that will be minimized (e.g., the displacement relative to the base or the absolute acceleration). The evaluation phase sorts the individuals in descending order of fitness: \( n = 1 \) is assigned to the best individual, \( n = 2 \) is assigned to the second best individual and so on. Then \( f_i = 1/\sqrt{n} \) is the evaluation of each individual. Rank is the name of this type of evaluation.

3.2.1.2 Selection

After the evaluation (based on the fitness values of the individuals in the population) the individuals are copied to an intermediate generation; this process is called Selection. Tournament was the type of selection chosen (see the justification in (Feliciano, 2015)): it selects the individuals by randomly choosing 4 individuals and copying the one with the best fitness value for the intermediate generation.

3.2.1.3 Reproduction

The reproduction specifies how the algorithm creates the next generation of individuals from the intermediate generation. It is important to define two values: (1) the size of the Elite population formed by the individuals that are copied directly to the next generation — the fittest individuals of the whole population — which ensures that the best candidates to the solution do not get lost in the process of reproduction, (2) the Crossover fraction, which specifies the number of individuals created by the crossover operator. In our case, we have chosen 5% of the population to be the size of the Elite population and 80% to be reproduced by Crossover, while the remaining 15% may or may not suffer Mutation after Crossover is applied.

3.2.1.3.1 Crossover

Crossover is an operation that creates a new individual for the next generation by combining the genes of two individuals of the intermediate generation. “Two point” was the type of crossover chosen which creates the new individual by generating randomly two integer values \( m \) and \( n \) between 1 and the dimension of an individual (\( m \) is the smallest), then it combines the genes of the parents. From 1 to \( m \) positions the genes are from Individual 1 and from \( m + 1 \) to \( n \) the genes of the Individual 2 and, finally, from \( n + 1 \) onwards the genes are again from the Individual 1. For example, with parents \( I_1 = [a\ b\ c\ d\ e\ f\ g\ h] \) and \( I_2 = [1\ 2\ 3\ 4\ 5\ 6\ 7\ 8] \), and with \( m = 3,\ n = 6 \), the new individual will be \( I_{\text{New}} = [a\ b\ c\ 4\ 5\ 6\ g\ h] \).

3.2.1.3.2 Mutation

This operator makes small changes in individuals in order to deviate them from the direction of convergence. The use of mutation allows for genetic diversity and for a wide search on search space. A Gaussian type mutation operator was chosen: it consists in adding a random number taken from a gaussian distribution with mean 0 for each entry (gene) of the vector representing the individual undergoing mutation.

3.2.2 Stopping criteria

Limiting the number of generations is the most common stopping criteria, it is also common to limit the number of generations in which there is no improvement on the best individual (stall generations). In our problem, the generations were limited to 200 and the stall generations to 50. The tolerance value between fitness values in consecutive generations is \( 10^{-3} \).

4. Numerical results

In this paper five structures have been considered to evaluate the distribution of the optimum slip force along the height (figure 5). In order to understand the influence of a structural wall, the first structure is a simple plane frame structure with 20 floors and 5 columns with 0.80 m × 0.80 m. The other four structures have a structural wall instead of the central column. Structures 2, 3, 4 and 5 have structural walls with 2.50 m × 0.20 m, 5.00 m × 0.20 m, 7.50 m × 0.20 m and 9.20 m × 0.20 m, respectively. The masses per floor and the first three natural frequencies for each structure are shown in the table 1.

<table>
<thead>
<tr>
<th>Structure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (t)</td>
<td>110.95</td>
<td>109.52</td>
<td>114.62</td>
<td>119.71</td>
<td>123.18</td>
</tr>
<tr>
<td>( f_1 ) (Hz)</td>
<td>0.4421</td>
<td>0.5597</td>
<td>0.7058</td>
<td>0.8121</td>
<td>0.8459</td>
</tr>
<tr>
<td>( f_2 ) (Hz)</td>
<td>1.3586</td>
<td>1.7819</td>
<td>2.5053</td>
<td>3.3351</td>
<td>3.7092</td>
</tr>
<tr>
<td>( f_3 ) (Hz)</td>
<td>2.5091</td>
<td>3.2860</td>
<td>5.0548</td>
<td>7.4778</td>
<td>8.6328</td>
</tr>
</tbody>
</table>

The mass and stiffness matrices were obtained with (CSI, 2014). A simple plane analysis was conducted (three degrees of freedom for each node) with the diaphragm option for each floor (the horizontal nodal displacements of a floor are equal). The stiffness matrix used was determined by the inversion of the flexibility matrix for the horizontal displacements. The Rayleigh type damping matrix was obtained by enforcing damping ratios of 2% for the first and fifth modes. The mass, stiffness and damping matrices are shown in Annex A of (Feliciano, 2015). Seven earthquake records have been selected from (PEER Ground Motion Database).
Figure 5: Schematic representation of the five structures considered. All have 20 storeys but structural walls of different sizes.

Earthquake records were uniformly scaled to have peak ground accelerations of 0.34g in order to enforce the mean response spectrum to be similar to the one in EC8 for Lisbon with a type B soil and a class of importance II. Table 2 shows the list of the seven earthquake records used in this study.

Table 2: Data on the seven accelerograms used in the simulations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Station</th>
<th>Direction</th>
<th>PGA (g)</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almiros</td>
<td>1980</td>
<td>Almiros</td>
<td>WE</td>
<td>0.0714</td>
<td>22.5792</td>
</tr>
<tr>
<td>Caldiran</td>
<td>1976</td>
<td>Malak</td>
<td>S49E</td>
<td>0.0975</td>
<td>28.35</td>
</tr>
<tr>
<td>Chuetu-oki</td>
<td>2007</td>
<td>Joetsu Kita</td>
<td>EW</td>
<td>0.1763</td>
<td>59.98</td>
</tr>
<tr>
<td>Darfield</td>
<td>2010</td>
<td>ADCS</td>
<td>N42W</td>
<td>0.1127</td>
<td>149.99</td>
</tr>
<tr>
<td>Irpinia</td>
<td>1980</td>
<td>Arienzo</td>
<td>270</td>
<td>0.0346</td>
<td>24.65</td>
</tr>
<tr>
<td>Managua</td>
<td>1972</td>
<td>Managua</td>
<td>ESSO</td>
<td>0.2628</td>
<td>47.88</td>
</tr>
<tr>
<td>Manjil</td>
<td>1990</td>
<td>Abbar</td>
<td>L</td>
<td>0.5146</td>
<td>53.48</td>
</tr>
</tbody>
</table>

We conducted a study aiming to understand the behaviour of the five structures equipped with friction dampers, and to determine for each earthquake-structure combination the most effective range of slip forces. With that purpose, before applying the genetic algorithm to optimize the slip force in the friction dampers, the peak displacement of the upper floor relative to the ground, the peak absolute acceleration of the upper floor and the peak base shear force were determined for uniform distributions of slip forces in the friction dampers, with an initial value of 50 kN in each one and increments of 50 kN. Figure 6 shows six graphs, three of Structure 1 subjected to the Managua earthquake record (on the left) and the other three of Structure 5 subjected the Manjil earthquake record (on the right). They represent the dependence of (i) the peak displacement of the upper floor relative to the ground, (ii) the peak absolute acceleration of the upper floor and (iii) the peak base shear force on the dampers’ slip force. A careful observation of the figure 6 leads us to conclude that it is important to use a multi-objective optimization due to the non-monotonous behavior of the accelerations. Moreover, if it aims just to reduce displacements, it will require a huge amount of slip force in the friction dampers making the structures too rigid and leading to very high accelerations. Thus, in order to optimize the slip forces of the dampers, the criterion used to evaluate each solution was to optimize simultaneously the peak displacement of the upper floor relative to the ground and the peak absolute acceleration of the same floor. For moderate values of the slip force reducing the peak displacement of the upper floor relative to the ground is equivalent to minimize the displacement of the first floor and consequently minimizing the base shear force. For high values of slip force reducing the peak absolute accelerations, also reduce the peak base shear force. Consequently, we decided to exclude in minimization criterion the peak base shear force. The objective function is then

\[ f = \sqrt{f_1^2 + f_2^2}, \]

with \( f_1 = \frac{x_{\text{max},c}}{x_{\text{max},s}} \) and \( f_2 = \frac{\ddot{X}_{\text{max},c}}{\ddot{X}_{\text{max},s}} \), where \( x_{\text{max},c} \) and \( x_{\text{max},s} \) represent the peak displacement of the upper floor with respect to the ground for the structure with and without dampers, respectively. The quantities \( \ddot{X}_{\text{max},c} \) and \( \ddot{X}_{\text{max},s} \) represent peak abso-
lute acceleration in the upper floor for the structure with and without dampers, respectively.

4.1. Determination of the optimum slip force
In this numerical study, the genetic algorithm presented on the previous section is applied to minimize the objective function (12) by the variation of the slip force on the friction dampers. Two different cases are taken into consideration: (1) uniform slip forces along the height of the structures and (2) varied slip forces. Thus, the number of variables in the first case is 1 and in the second case is 20. Consequently in the first case we used a population of 30 individuals and in the second case a population of 100, due to the requirement of a better search in the search space (20 variables instead of 1). In both cases we used a limit of 200 generations.

Table 3 presents the results of the optimization processes for the first case (uniform slip force). With the exception of the fifth structure, the optimal slip force for each structure increases with the dimension of the wall. This may reflect the fact that an increase of the dimension of the wall corresponds to an increase of the total mass and consequently the inertia forces. From structure 4 to structure 5 the effects of increasing the stiffness probably exceed the mass increase, which relieves the optimal slip force in the friction dampers. It should also be noted that, although the earthquakes have been rescaled for the same PGA they have different accelerations for the same period, which explains the different values of the slip force for the same structure observed in Table 3.

Table 3: Friction damper maximal forces for a uniform distribution. Values in kN.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Earthquake</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Almiros</td>
<td>724</td>
<td>1109</td>
<td>2323</td>
<td>2421</td>
<td>2128</td>
</tr>
<tr>
<td></td>
<td>Caldiran</td>
<td>608</td>
<td>500</td>
<td>611</td>
<td>1369</td>
<td>458</td>
</tr>
<tr>
<td></td>
<td>Chuets-oki</td>
<td>1504</td>
<td>1851</td>
<td>2846</td>
<td>2873</td>
<td>2972</td>
</tr>
<tr>
<td></td>
<td>Darfield</td>
<td>689</td>
<td>971</td>
<td>1388</td>
<td>1858</td>
<td>2040</td>
</tr>
<tr>
<td></td>
<td>Irpinia</td>
<td>1348</td>
<td>1058</td>
<td>1576</td>
<td>1831</td>
<td>1583</td>
</tr>
<tr>
<td></td>
<td>Managua</td>
<td>997</td>
<td>1931</td>
<td>3164</td>
<td>3626</td>
<td>3396</td>
</tr>
<tr>
<td></td>
<td>Manjil</td>
<td>913</td>
<td>1310</td>
<td>1380</td>
<td>1361</td>
<td>1376</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>969</td>
<td>1247</td>
<td>1898</td>
<td>2191</td>
<td>1993</td>
</tr>
</tbody>
</table>

The results of the optimization of the slip force for the second case (varied slip forces) are shown in figure 7; for each floor/damper of each structure the average optimum value for the seven earthquake records was registered. Again, on average, the optimal slip force increases with the dimension of the wall (with the same exception between the structures 4 and 5). Note that the optimum distribution of the slip force along the height is very similar to...
the uniform one.

Figure 7: Mean slip force in each damper for varied distribution of the maximal forces of the dampers (slip forces). From left to right: structure 1 to structure 5.

Figure 8 presents three graphics relative to the Structure 1 subjected to the Caldiran earthquake record. The left graph allows the comparison of the displacement relative to the ground on each floor at the instant of the peak displacement of the upper floor for (i) structure without friction dampers, (ii) structure with friction dampers and uniform slip force along the height and (iii) structure with friction dampers and varied slip force along the height. In the central graphic of the same figure the absolute accelerations are presented for the instant of the peak absolute acceleration of the upper floor, and the graphic on the right shows the inter-storey drift of each floor for the instant of peak inter-storey drift. Those graphics show that the friction dampers provide considerable reductions in the responses of the structure.

For comparison purposes the responses of the structures with and without dampers are also computed for a set of earthquake records and the average response between them is calculated. The mean values of the peak displacements of the upper floor relative to the ground are registered in Table 4 for the cases (i) without friction dampers (ii) with friction dampers and uniform slip force along the height and (iii) with friction dampers and varied slip force along the height. Table 5 and 6 show respectively the mean values of the peak absolute accelerations of the upper floor and the mean values of the peak base shear forces.

The effectiveness of friction devices is reinforced by Tables 4 and 5. There are huge improvements in displacements and accelerations for the structures equipped with friction dampers. The response for the varied distribution is similar to the response for the uniform distribution. Note that, as expected, the increase of accelerations is accompanied with an increasing of the wall dimensions and a decrease of displacements, since the wall rigidifies the structure. Take for example Structure 1: the inclusion of friction dampers with an uniform distribution improves the displacement in 76% and the acceleration in 67%, and when the distribution of the slip force is varied those improvements are 75% and 71%, respectively. This leads to the conclusion that enabling a varied slip force along the height relieves the slip force in some friction dampers (figure 7) in order to reduce the acceleration at the expense of a small increase in the displacement. Table 6 proves
that even without an optimization criteria explicitly minimizing the peak base shear force, the installation of friction dampers with the optimal slip force for the criteria used reduce substantially the peak base shear force with respect to the uncontrolled case. It is noted that the base shear force increases with the dimension of the wall (like accelerations do).

Table 6: Mean values of the peak base shear force for the earthquake records in table 2.

<table>
<thead>
<tr>
<th>Structure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled braced frame</td>
<td>19009</td>
<td>30627</td>
<td>84198</td>
<td>166335</td>
<td>239258</td>
</tr>
<tr>
<td>Controlled frame with uniform slip force distribution</td>
<td>8511</td>
<td>12980</td>
<td>30577</td>
<td>50639</td>
<td>70764</td>
</tr>
<tr>
<td>Controlled frame with varied slip force distribution</td>
<td>7685</td>
<td>12525</td>
<td>26510</td>
<td>49535</td>
<td>71336</td>
</tr>
</tbody>
</table>

Figure 9 emphasizes the effectiveness of the friction dampers in reducing displacements: it shows the time-history of the upper floor displacement relative to the ground for Structure 2 subjected to the Irpinia earthquake record without friction dampers and with friction dampers with uniform slip force along the height. This figure also shows that the use of friction devices not only reduces displacements but it reduces the duration of the vibration time too.

Figure 10: Comparison of the displacements relatively to the ground of the upper floor in Structure 2 subjected to Irpinia earthquake record with friction dampers with uniform or varied distributions of the slip force.

5. Conclusions

The optimal distribution of slip force of frictional dampers has been investigated. The effectiveness of these devices in improving the seismic responses of plane structures is shown. The time integration algorithm \( \theta \) method was presented; it was implemented in Matlab environment. In order to create a program that optimizes the slip force in the friction dampers, a genetic algorithm (from the Toolbox of Matlab) was conjugated with \( \theta \) method. A multi-objective optimization criterion to simultaneously reduce displacements relative to the ground and absolute accelerations was used. The dependence of displacements, accelerations and shear force on the slip force was shown; as expected, it was concluded that the greater the slip force, the smaller will be the displacements relative to the ground. However the dependence of accelerations and base shear force is not monotonous, which justifies the use of an optimization method of the genetic type.

For the purpose of study the optimal distribution of slip forces in the friction dampers, five plane structures with structural walls of different sizes, with a frictional damper in each floor, were submitted to a set of seven conveniently scaled real earthquake records. The displacements and accelerations were minimized with a genetic algorithm. Two types of slip force distributions were considered: (i) uniform, and (ii) non-uniform or varied. It has been noted that the increase of the size of the wall, which leads to an increase in the total mass of the structure, also leads to an increase of the slip force required in the friction dampers. It was concluded that the optimal distribution is not very different from the uniform one, and that the optimization criteria provide a good dynamic response of the structure.

As suggestions for future research it is proposed:

- A set of numerical simulations to identify design strategies based on the number of floors, mass-rigidity relationships and the content of
the frequencies of the earthquake, to avoid in practice the use of an optimization algorithm, and still being able to get results very close to the optimum ones.

- Development of a program that makes the 3D analysis of structures equipped with friction dampers in more than one direction.
- Implementation of an experimental program to validate the results provided in numerical analysis of frictional energy dissipation systems.

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References


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