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SHAKING TABLE TESTS OF STEEL FRAMES EQUIPPED WITH FRICTION DISSIPATORS AND SUBJECTED TO EARTHQUAKE LOADS

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SUMMARY

This paper presents a comparison between numerical and experimental dynamic responses of two building structures equipped with friction dissipators and subjected to earthquake loads. The numerical solution is based on an innovative staggered approach, consisting basically in a modification of the linear acceleration method, and it takes into account the continuous changes of the sliding-sticking conditions in the dissipators. The experiments were carried out at the Laboratory of Structural Dynamics of the University of Bristol on two reduced scale models of steel building structures (with one and two floors, respectively) subjected to a number of seismic inputs. Since the agreement is satisfactory, the numerical solution is well validated by comparison with the experimental results.

INTRODUCTION

Structural control

Structural engineers are concerned with the best performance of building structures when subjected to both gravitational and lateral forces. At the end of the 60's, a big impulse in the computer aided analysis and design methods was given to the structural design, and during the 70's, a new branch of the structural engineering was starting to grow up. This new approach, called structural control, considers the use of external devices specifically designed to absorb the input energy due to lateral forces, such as wind and earthquake loads (Soong and Dargush [1], Hanson et al. [2]). The protective systems studied by the structural control are classified in three major groups: active control, passive control and hybrid control (De la Cruz [3]).

This paper deals with passive control.

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Passive control

This approach consists in the incorporation of passive (i.e., nor powered neither 'smart') devices to the main structure to modify its dynamic parameters (basically, damping and stiffness) in order to reduce its response when facing the expected inputs (Akiyama [4]).

Fig. 1 shows a building structure equipped with energy dissipation devices located in every floor between the upper girders and. Among the existing energy dissipation devices, three major types are currently used: devices based on *yielding of metals*, *friction dampers* and *viscous* or *visco-elastic dampers* (Soong and Dargush [1]). Friction dampers are considered in this paper.

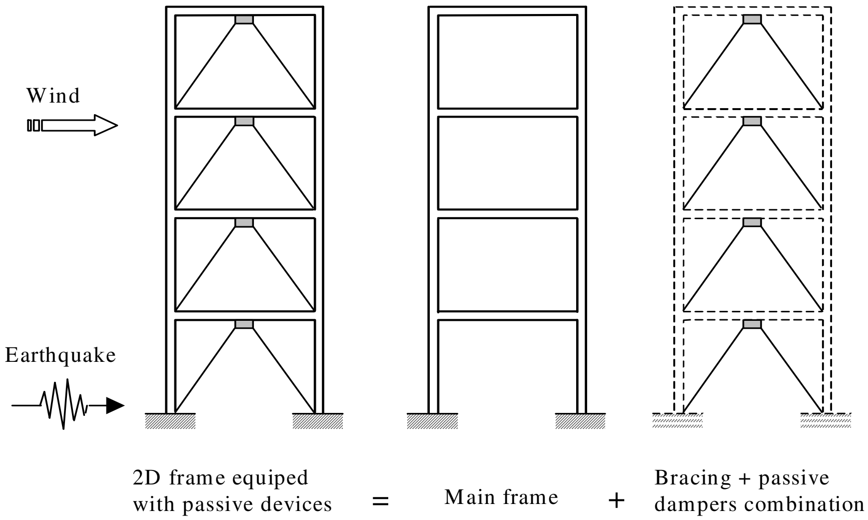


Figure 1. Structure equipped with energy dissipators (passive control) (De la Cruz [3])

Friction dampers

Friction dissipators (FDs) use frictional forces to dissipate energy. These devices can be used for seismic protection of buildings since they possess several advantages, such as: (*i*) high potential to dissipate energy (their hysteresis loops are almost rectangular; therefore, they enclose the biggest possible area for any given pair of maximum displacement and force values), (*ii*) controllable sliding force (through prestressing), (*iii*) great capability of absorbing energy, (*iv*) fatigue insensitivity and (*v*) behavior not seriously affected by the frequency contents and other properties of the driving force. However, their efficiency has been questioned, mostly because: (*i*) their highly non-linear behavior might generate high frequency response in the structure (Housner et al. [5]), (*ii*) lack of capacity to cut high resonance peaks and (*iii*) controversial durability. The existing numerical models are not always useful to clarify this issue, as these types of dissipators are difficult to simulate.

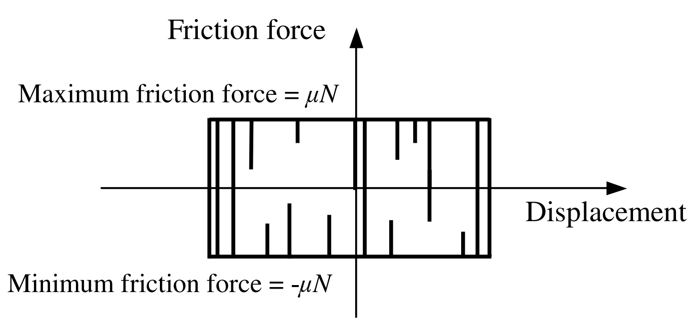


Figure 2. Dry friction hysteresis loops

There is a variety of friction devices that have been proposed for structural energy dissipation (Hanson et al. [2]). These devices differ in their mechanical complexity and in the material used in the sliding surfaces. However, if it is assumed that the friction coefficient is non-velocity dependent and the prestressing force is constant; almost all of them generate rectangular hysteresis loops typical of Coulomb's friction, as those shown in Figure 2 (Soong and Dargush [1]).

DEVELOPMENT

Constitutive model of dry friction

The static behavior of a single friction dissipator is described in this section. Fig. 3 shows the mechanical model of the contact problem.

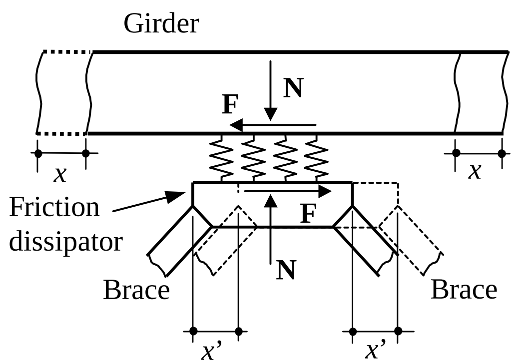


Figure 3. Mechanical model of a friction dissipator

In Fig. 3 x and x' represent, respectively, the horizontal displacements of the main frame and the dissipation device. Coefficient k' is the stiffness of the bracing system supporting the dissipator.

If there is sliding between the girder and the dissipator, the maximum friction force $F_{\max}$ is given by

$$| F| = F_{\max} = \mu N \tag{1}$$

as stated on Coulomb's law of dry friction (Chopra [6]).

Equations of motion of multi-story frames

In this section a building with N floors and incorporating friction dissipators is considered. The external excitation consists of a seismic motion; however, the case of wind loading can be similarly analyzed as shown next.

In order to model the dynamic structural behavior of the frame, it will be considered as a 2-D shear building. The degrees of freedom are the relative horizontal displacements between the floors (x_1, x_2, ..., x_N) and the dissipators (x'_1, x'_2, ..., x'_N). The number of degrees of freedom ranges between N (there is not sliding at any dissipator) and $2N$ (all dissipators are sliding simultaneously).

The equations of motion of the $2N$ degrees of freedom are:

$$
\begin{aligned}
m_1(\ddot{x}_1+\ddot{x}_g)+c_1\dot{x}_1+k_1x_1-c_2(\dot{x}_2-\dot{x}_1)-k_2(x_2-x_1) \\
-c'_2(\dot{x}'_2-\dot{x}_1)-k'_2(x'_2-x_1)=-F_1
\end{aligned}
$$

$$
m'_1(\ddot{x}'_1+\ddot{x}_g)+c'_1\dot{x}'_1+k'_1x'_1=F_1
$$

$$\dots$$

$$
\begin{aligned}
m_i(\ddot{x}_i+\ddot{x}_g)+c_i(\dot{x}_i-\dot{x}_{i-1})+k_i(x_i-x_{i-1})-c_{i+1}(\dot{x}_{i+1}-\dot{x}_i)-k_{i+1}(x_{i+1}-x_i) \\
-c'_{i+1}(\dot{x}'_{i+1}-\dot{x}_i)-k'_{i+1}(x'_{i+1}-x_i)=-F_i
\end{aligned}
$$

$$
m'_i(\ddot{x}'_i+\ddot{x}_g)+c'_i(\dot{x}'_i-\dot{x}_{i-1})+k'(x'_i-x_{i-1})=F_i
$$

$$\dots$$

$$
m_N(\ddot{x}_N+\ddot{x}_g)+c_N(\dot{x}_N-\dot{x}_{N-1})+k_N(x_N-x_{N-1})=-F_N
$$

$$
m'_N(\ddot{x}'_N+\ddot{x}_g)+c'_N(\dot{x}'_N-\dot{x}_{N-1})+k'_N(x'_N-x_{N-1})=F_N
$$

where $\ddot{x}_g$ is the ground acceleration; m_i, c_i and k_i are, respectively, the mass, the viscous damping and the stiffness coefficients of the main structure *i*-th floor and m'_i, c'_i and k'_i are the corresponding values of the bracing connecting both the dissipator and the main frame. F_i is the interaction force between the dissipator and the structure. The corresponding friction coefficients μ_i and the prestressing forces N_i limit the values of F_i:

$$
|F_i| \le \mu_i N_i \qquad (2)
$$

The set of 2*N* equations can be written in matrix form as:

$$
\mathbf{M}^{ss}\ddot{\mathbf{x}}^s+(\mathbf{C}^{ss}+\mathbf{C}^{db})\dot{\mathbf{x}}^s+\mathbf{C}^{dc}\dot{\mathbf{x}}^d+(\mathbf{K}^{ss}+\mathbf{K}^{db})\mathbf{x}^s+\mathbf{K}^{dc}\mathbf{x}^d=-\mathbf{M}^{ss}\mathbf{r}\ddot{x}_g-\mathbf{F} \qquad (3a)
$$

$$
\mathbf{M}^{dd}\ddot{\mathbf{x}}^d+(\mathbf{C}^{dc})^T\dot{\mathbf{x}}^s+\mathbf{C}^{da}\dot{\mathbf{x}}^d+(\mathbf{K}^{dc})^T\mathbf{x}^s+\mathbf{K}^{da}\mathbf{x}^d=-\mathbf{M}^{dd}\mathbf{r}\ddot{x}_g+\mathbf{F} \qquad (3b)
$$

Superscript *s* accounts for the structure and *d* for the dissipators: $\mathbf{x}^s = [x_1, x_2, ..., x_N]^T$ and $\mathbf{x}^d = [x'_1, x'_2, ..., x'_N]^T$. Eqs. (3*a*) and (3*b*) will be in its turn split in two subsets termed with subscripts *sl* (sliding) and *ns* (non-sliding). The degrees of freedom involved in each of them vary from instant to instant as the sliding conditions in the dissipators change. If the input consists of driving forces acting at every floor the right hand members of Eqs. (3*a*) and (3*b*) must be replaced by **P** – **F** and **F**, respectively, where vector **P** contains the excitation forces.

Numerical solution of the equations of motion of multi-story frames

At each generic instant *k* + 1 the response is computed from the one at the previous instant *k*. This problem is numerically solved by a modification of the step-by-step linear acceleration method, where three nested iteration loops are performed. These iteration loops involve the coupling quantities ($\dot{\mathbf{x}}^d_{k+1}$, $\mathbf{x}^d_{k+1}$, $\dot{\mathbf{x}}^s_{k+1}$, $\mathbf{x}^s_{k+1}$ and $\mathbf{F}_{k+1}$) and the estimated accelerations at step $k + 1$ ($\ddot{\mathbf{x}}^{s*}_{k+1}$ and $\ddot{\mathbf{x}}^{d*}_{k+1}$).

A complete explanation of the algorithm solution of the equations of motion can be found in De la Cruz [3] and in De la Cruz et al. [7].

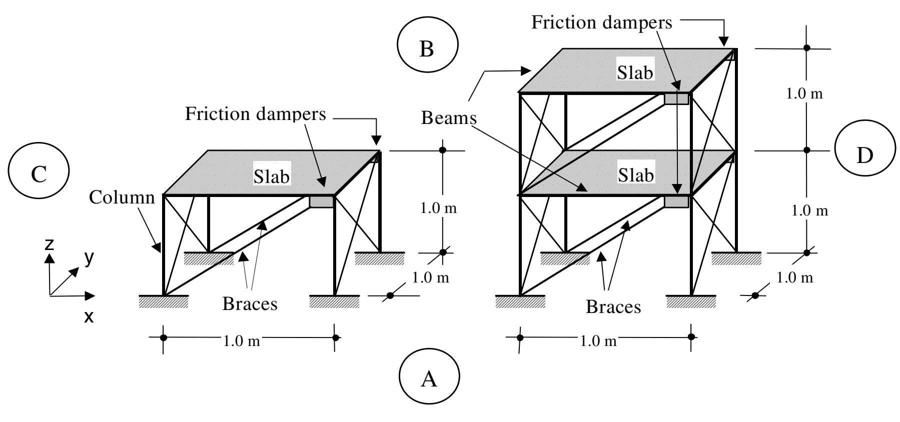
ALMA program

The ALMA program (**A**utomatic non**L**inear **M**atrix **A**nalysis) holds the algorithm above described (De la Cruz [3] and De la Cruz et al. [7]). It is a FORTRAN 77 source code and it is intended to solve the equations of motion of multi-story buildings equipped with friction dissipators. The input data have to be defined by the user in plain text files. ALMA reads the input data files and determines the dynamic response of each floor. The output data are saved as text files which can be visualized later with a graphics package (i.e., EXCEL®). In fact, the time-history responses shown in this paper were obtained in such a way.

Testing

The tests were carried out at the Laboratory of Structural Dynamics of the University of Bristol (Bristol, UK), between January and March, 2003, as a part of the so-called 'Ecoleader Project', sponsored by the European Commission. The experiments consisted in subjecting two reduced scale models of steel building structures (with one and two floors, respectively), to a number of seismic inputs (including sine-dwells and registered ground accelerations). The tested rigs were equipped with friction dissipators.

The tested rigs are depicted in Fig. 4. The member properties of the rigs are shown in the same figure.



(a) Single-story model (SSMFD) (b) Two-story model (TSMFD)

Element	Face	Section	Steel
Column	A, B, C, D	SHS 4 × 4 × 0.30 cm	Grade 43
Beam	A, B, C, D	SHS 4 × 4 × 0.30 cm	Grade 43
Brace	A, B	CHS 2.69 × 0.32 cm	Grade 43
Brace	C, D	2.5 × 0.3 cm Rect. bar	Grade 43

(c) Member properties

Figure 4. Tested rigs (De la Cruz [3])

An actual friction dissipator (FD) used in the tests is displayed in Fig. 5 and a schematic detail of the FD-brace connection is shown in Fig. 6.

Figure 5. Friction dissipator (De la Cruz [3])

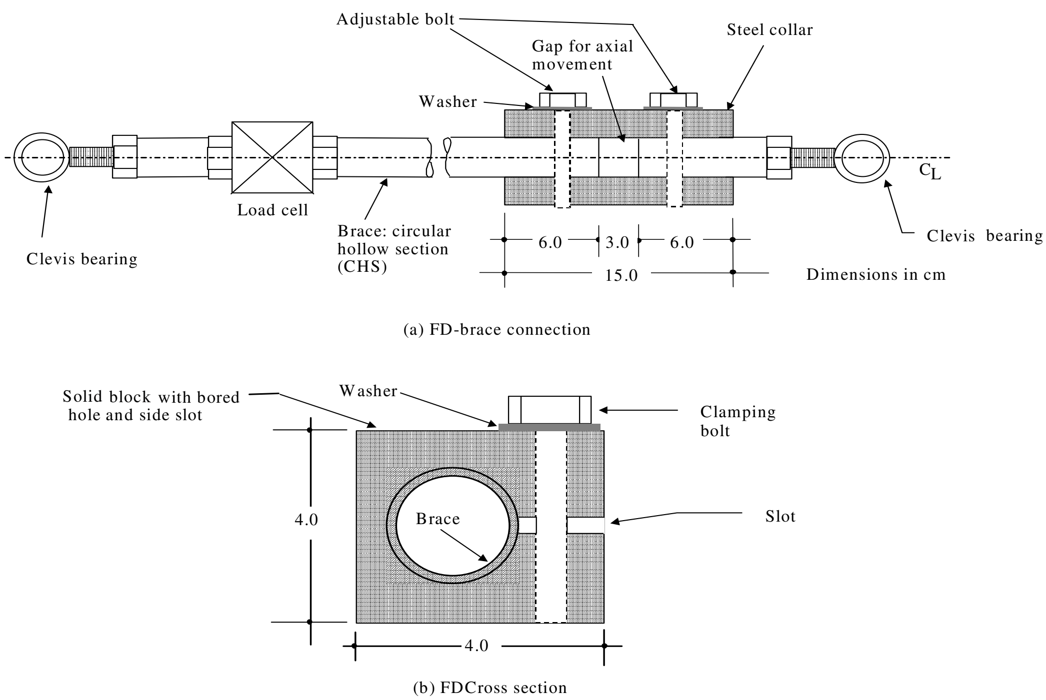


Figure 6. FD-brace connection (De la Cruz [3])

A total of 11 instruments (3 accelerometers on the base center, 2 accelerometers on the top, 2 big-displacement transducers on the top, 2 small-displacement transducers on the FDs and two load-cells on the braces) were used in the tests of the single-story model with friction dissipators (SSMFD). On the other hand, a total of 19 instruments (3 accelerometers on the base center, 2 accelerometers on the first floor and 2 on the top, 2 big-displacement transducers on the first floor and 2 on the top, 2 small-displacement transducers on the first floor FDs and 2 on the second floor FDs, and two load-cells on the first floor braces and 2 load-cells on the second-floor braces) were used in the tests of the two-story model with friction dissipators (TSMFD). In Fig. 7 the instrumented TSMFD is shown.

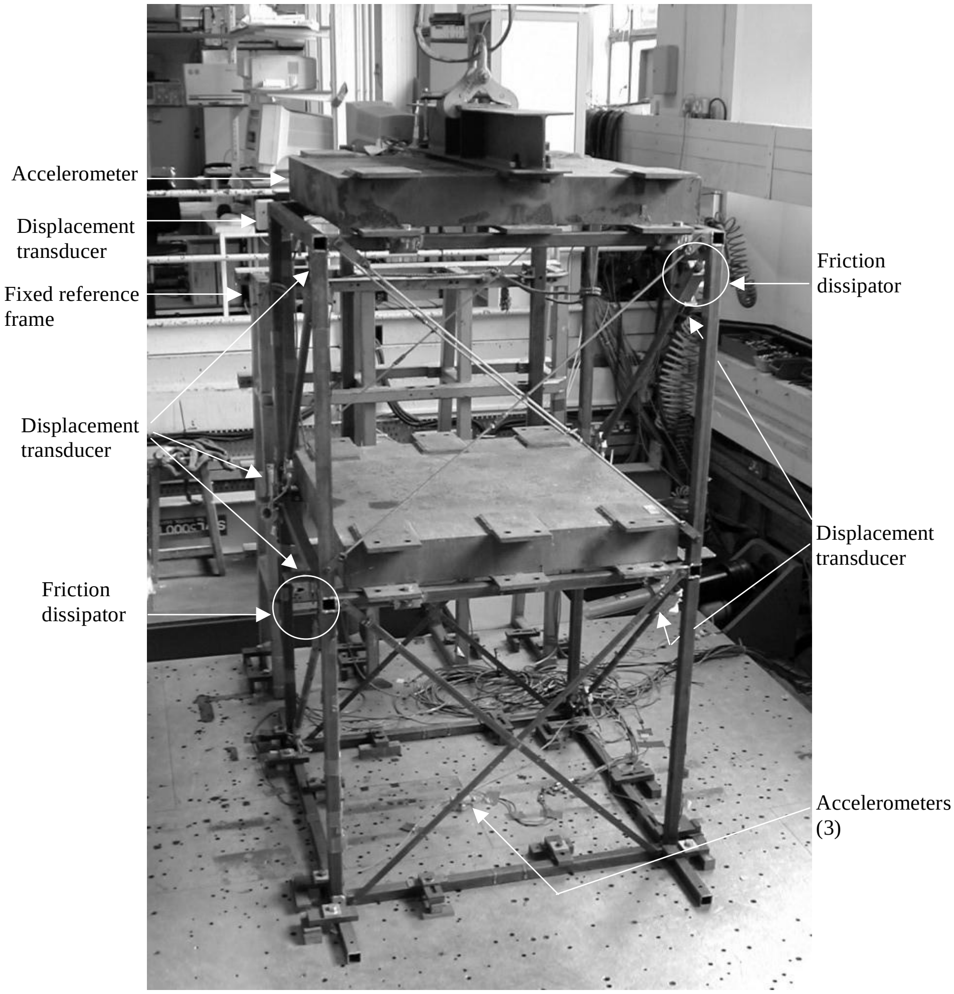


Figure 7. Instrumented TSMFD (De la Cruz [3])

Tables 1 and 2 summarize the dynamic parameters of the SSMFD and the TSMFD, respectively. These values were considered in all the numerical simulations using ALMA.

Table 1. Dynamic properties of the SSMFD (De la Cruz [3])

Main frame (average values)	Bracing system + FDs (average values)
m = 533.5 kg	m’ = 0.0
c = 83.932 N·s/m (ξ = 0.003141)	c’ = 0.0 (ξ’ = 0.0)
k = 334.597 kN/m	k’ = 2390.596 kN/m
T = 0.2509 s	

Table 2. Dynamic properties of the TSMFD (De la Cruz [3])

Main frame (average values)	Bracing system + FDs (average values)
$\mathbf{M}^{ss}=\begin{bmatrix}533.5 & 0\\ 0 & 552.5\end{bmatrix}$ kg	$\mathbf{M}^{dd}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$
$\mathbf{C}^{ss}=\begin{bmatrix}72.692 & -4.065\\ -4.065 & 68.688\end{bmatrix}$ N·s/m	$\mathbf{C}^{dd}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$
$\mathbf{K}^{ss}=\begin{bmatrix}808.375 & -351.467\\ -351.467 & 267.115\end{bmatrix}$ kN/m	$\mathbf{K}^{dd}=\begin{bmatrix}2262.777 & -968.889\\ -968.889 & 968.889\end{bmatrix}$ kN/m
$\mathbf{T}^{ss}=\begin{bmatrix}0.4797\\ 0.1470\end{bmatrix}$ s	

RESULTS

Some of the most relevant results are shown next to highlight the agreement between the numerical model and to give some insight about the ability of FDs to reduce the structural response. A full description of the experimental results can be found in De la Cruz [3].

Single-story model with friction dissipators (SSMFD)

Fig. 8 shows a comparison between the experimental and numerical responses for the ground acceleration displayed in the same figure. The black line corresponds to the response computed by ALMA and the grey line corresponds to the experimental results. Plots in Fig. 9 show that the agreement is satisfactory. Figs. 9 and 10 depict responses that correspond to the same input.

Fig. 9 shows the numerical responses of the bare, braced and protected (i.e., structure equipped with FDs) frames. The thickest black line corresponds to the SSMFD (protected frame) response, the thin black line corresponds to the braced frame and the grey line corresponds to the bare frame. The comparison between plots in Fig. 9 shows that the FDs reduce significantly the response compared to the bare frame, but the situation with respect the braced frame is rather unclear. This same situation was observed by Foti et al. [8].

Fig. 10 shows the experimental and numerical hysteresis loops in the friction dissipators set on the braces. Upper plots of Fig. 10 show the actual behavior of FDs does not follow Coulomb’s law (see Fig. 2); however, ALMA is able to reproduce the experimental response as shown in Fig. 8.

Two-story model with friction dissipators (TSMFD)

Fig. 11 shows the comparison between the experimental and numerical responses for the ground acceleration displayed in Fig. 11a. The black line corresponds to the response obtained by using the ALMA program and the grey line corresponds to the results from tests. Again, using ALMA, the responses of the first and second floor of the bare, braced and protected (i.e., structure equipped with FDs) frames were obtained and compared. The plots are shown in Fig. 12 and 13, respectively. The thick black line corresponds to the TSMFD (protected frame) response, the thin black line corresponds to the braced frame and the grey line corresponds to the bare frame.

Finally, Fig. 14 shows the experimental and numerical hysteresis loops of the first floor due to the friction dissipators set on the braces.

Plots in Figs. 11, 12, 13 and 14 allow deriving similar conclusions than those from Figs. 8, 9 and 10.

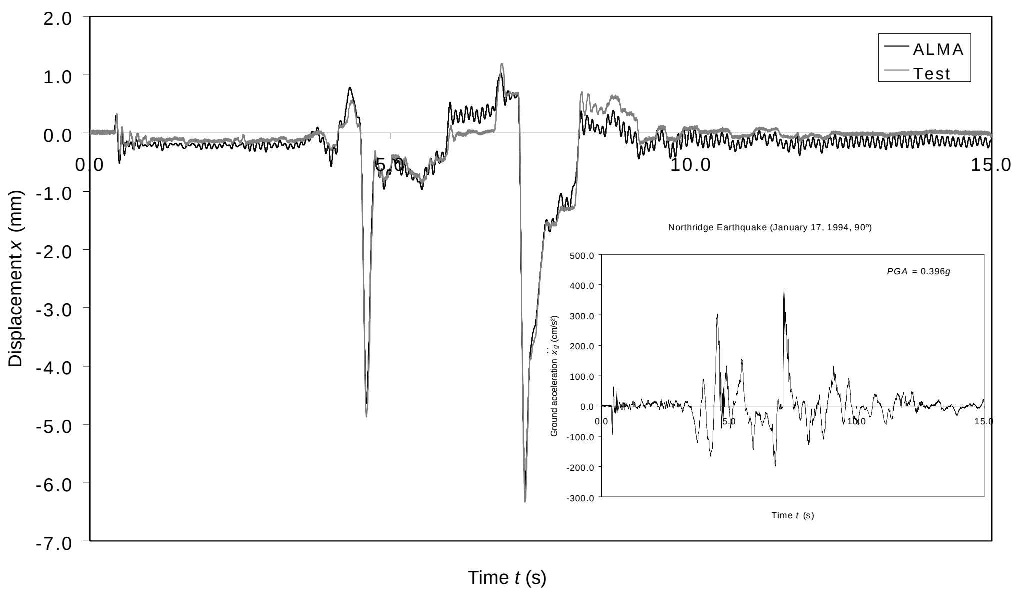


Figure 8. Numerical and experimental responses of the SSMFD for a ground acceleration (De la Cruz [3])

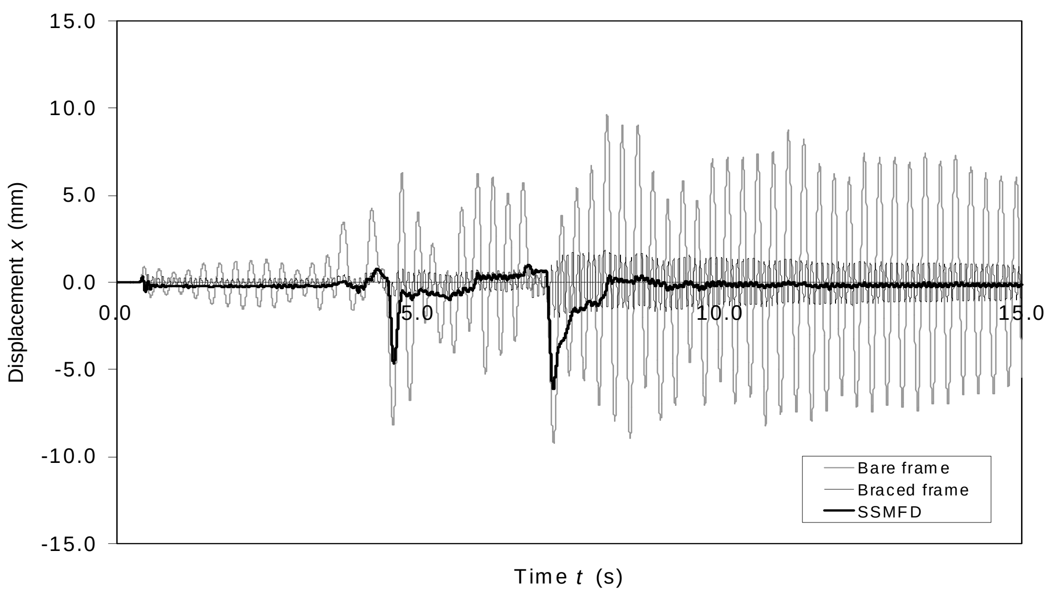


Figure 9. Numerical responses of the single-story model (bare, braced and protected frames)

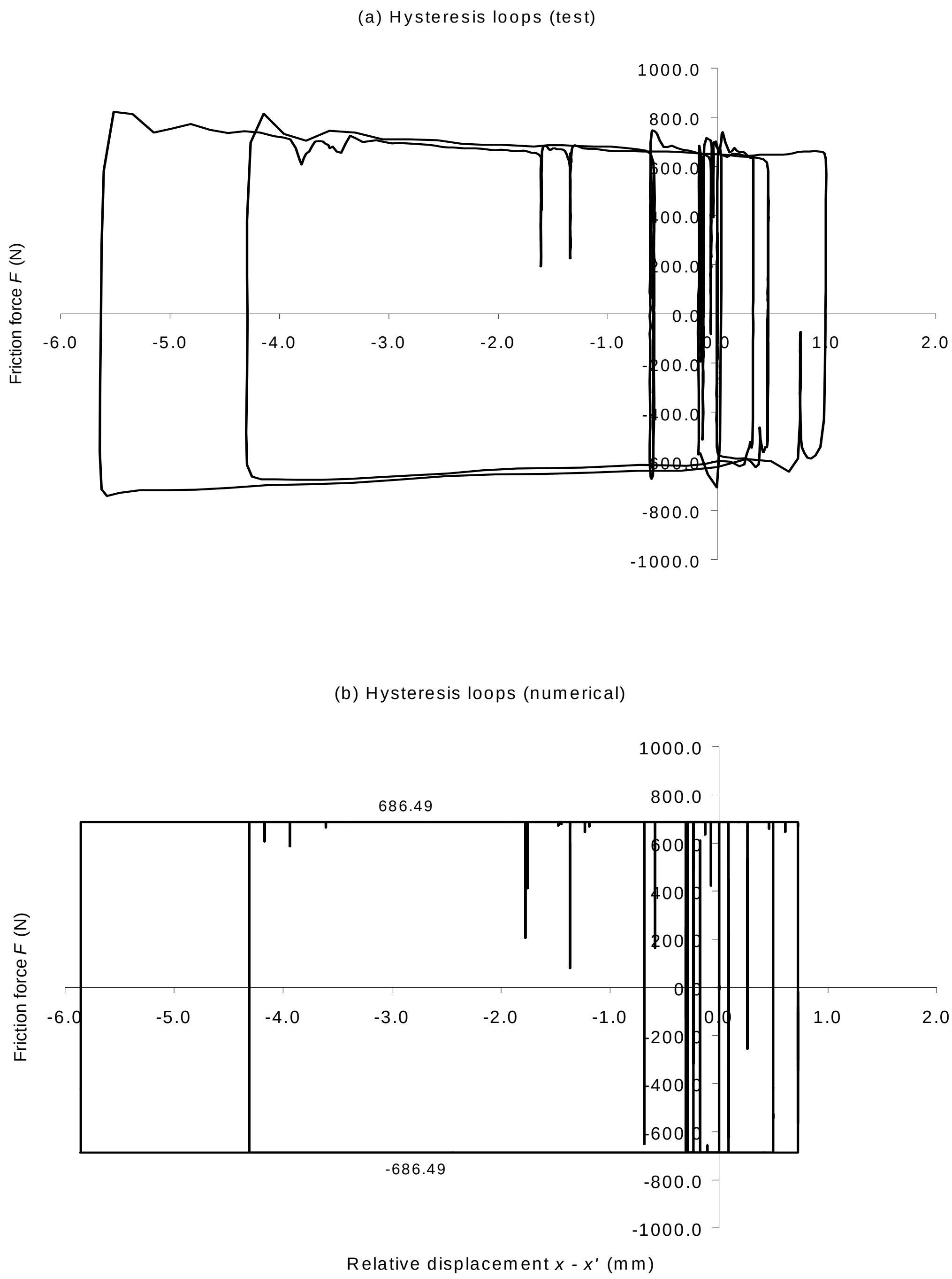


Figure 10. Experimental and numerical hysteresis loops of the SSMFD for a ground acceleration (De la Cruz [3])

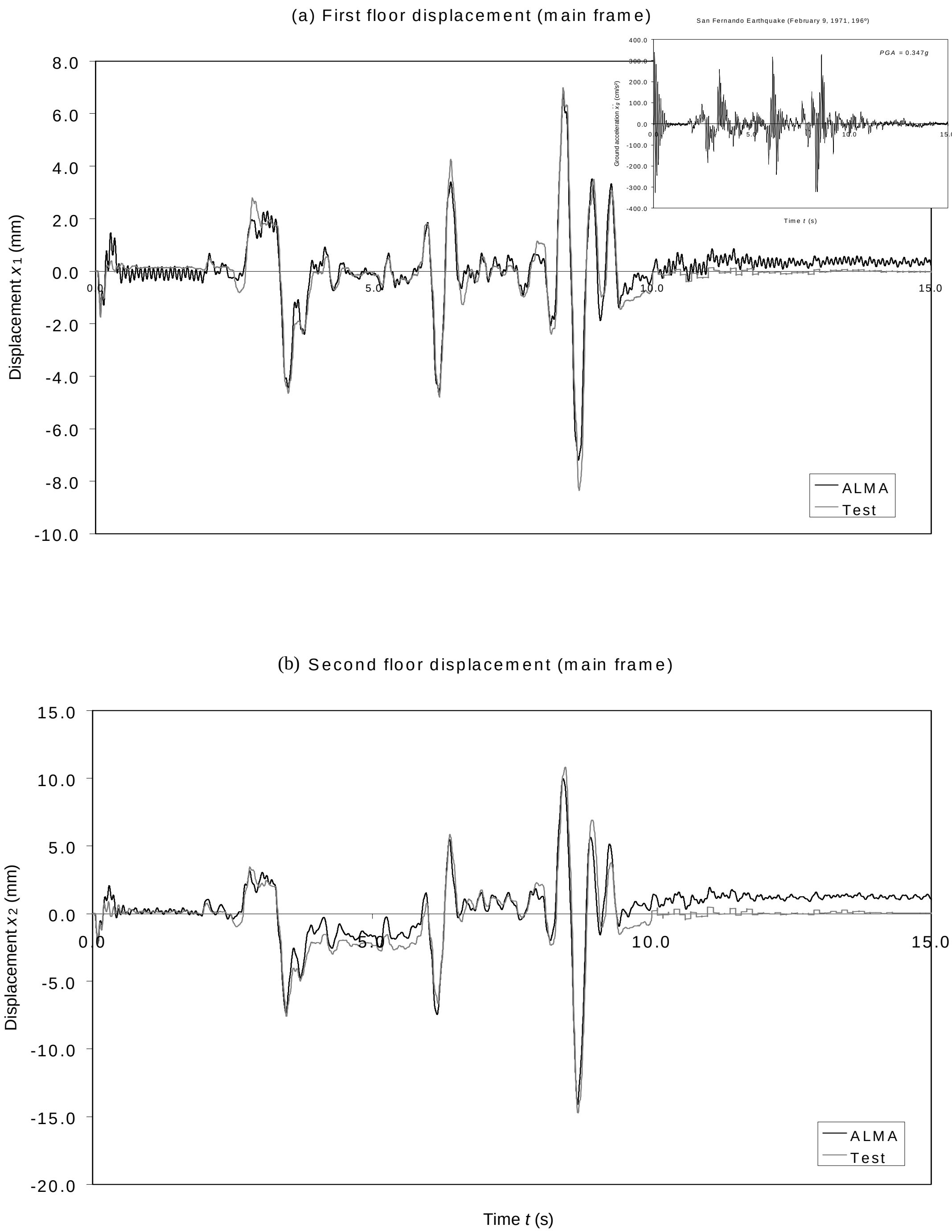


Figure 11. Numerical and experimental responses of the TSMFD for a ground acceleration (De la Cruz [3])

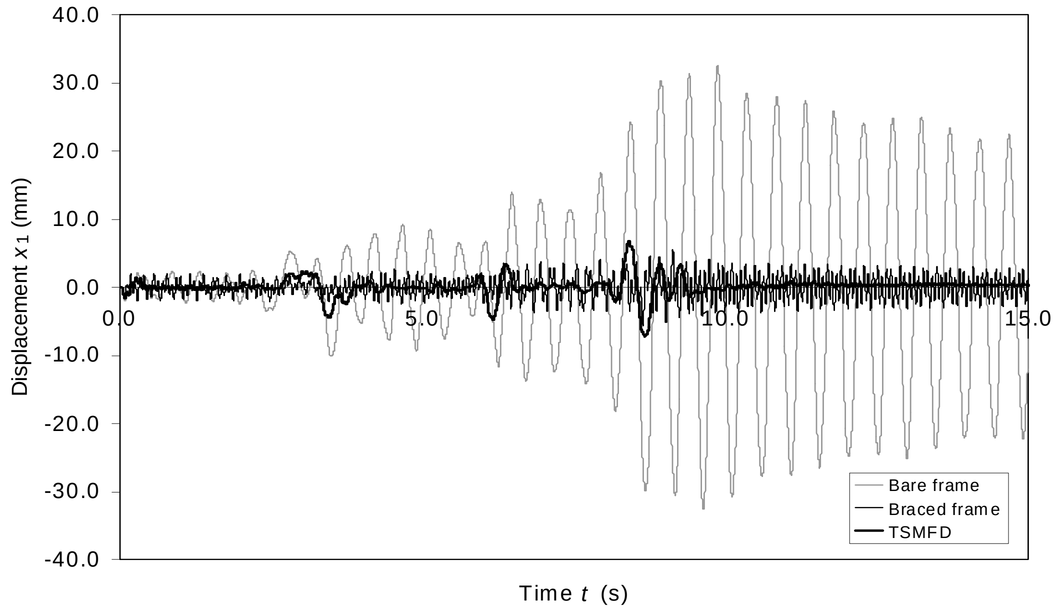


Figure 12. First floor responses (numerical) of the two-story model (bare, braced and protected frames)

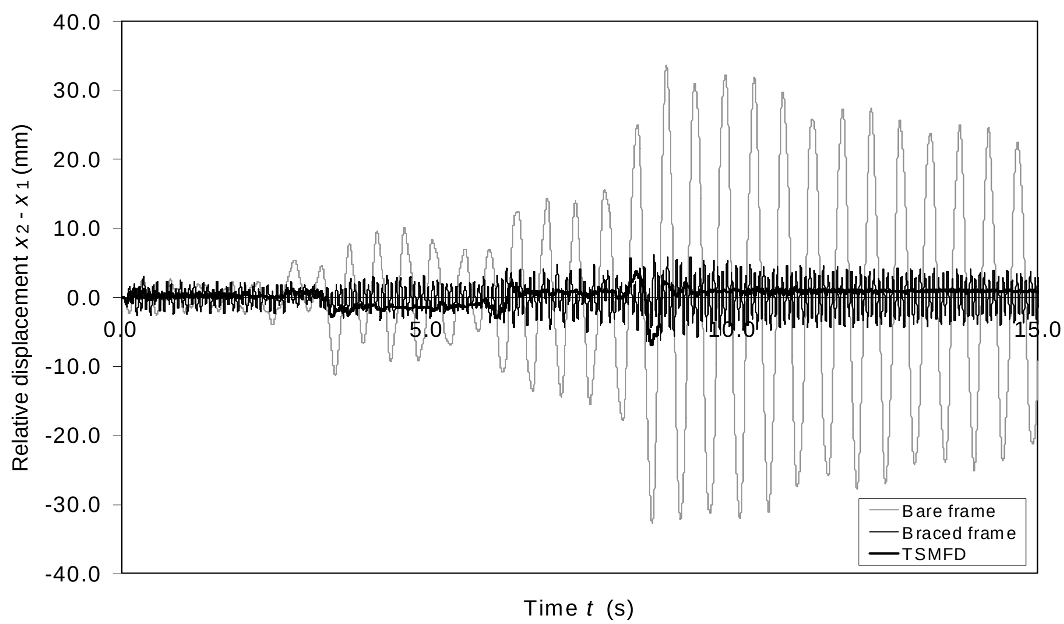


Figure 13. Second floor responses (numerical) of the two-story model (bare, braced and protected frames)

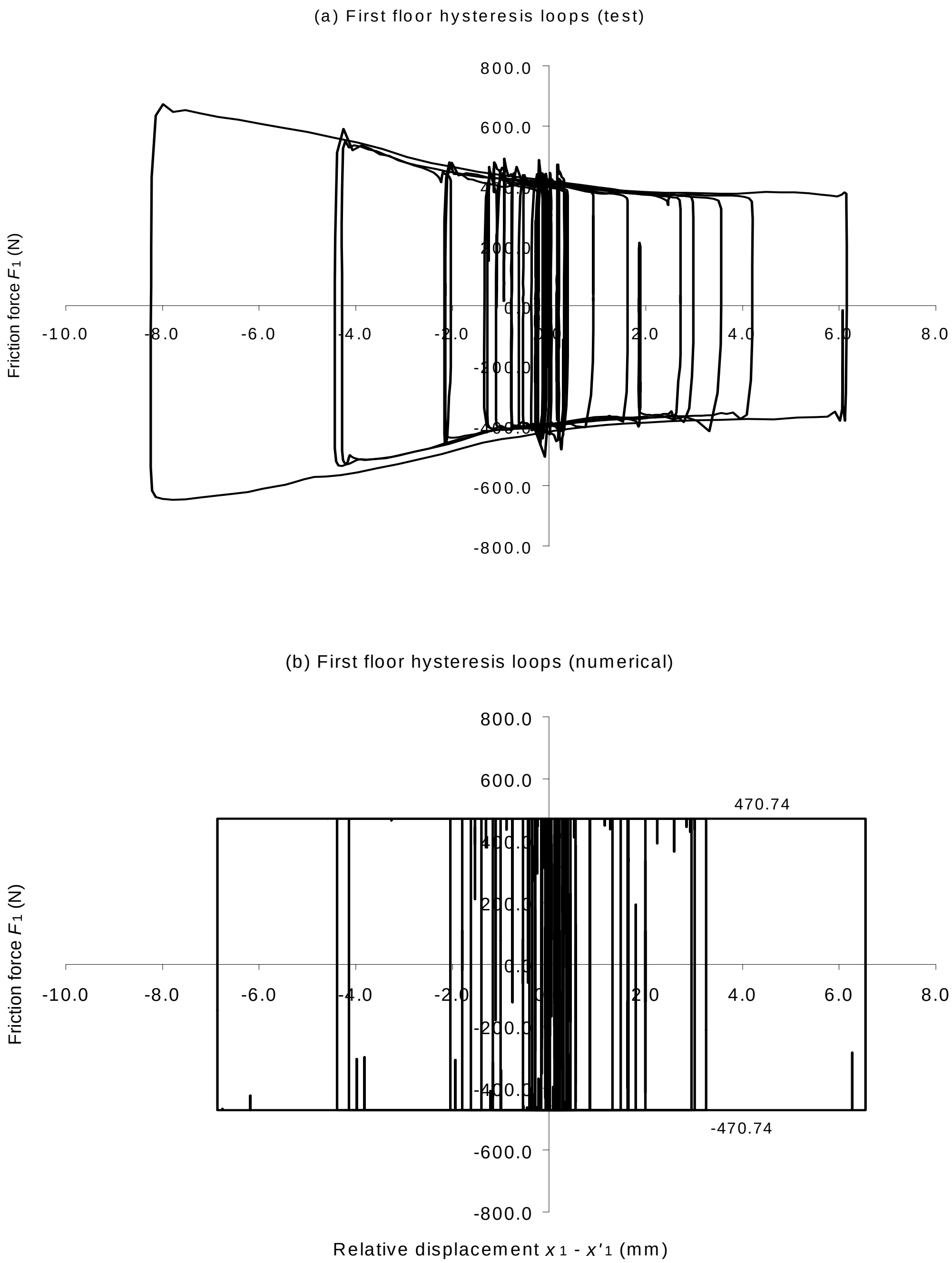


Figure 14. Experimental and numerical hysteresis loops of the TSMFD first floor for a ground acceleration (De la Cruz [3])

DISCUSSION OF RESULTS

The agreement between experimental —grey line— and numerical —black line— responses can be checked looking at the Figs. 8, 10, 11 and 14. Now, considering the hysteresis loops, the experimental results (Figs. 10 and 14) show also good agreement, which validates the numerical procedure as a useful tool to find the dynamic response of 2D buildings equipped with friction dissipators.

Regarding the efficiency of FDs, Figs. 9 and 13 proof that protected frames (thick black line) reach maximum displacements lesser than those reached by bare frames (grey line). However, in some cases, these figures show that the maximum displacements of the braced frames can be lesser than those reached by protected frames.

CONCLUSIONS AND FUTURE RESEARCH

Due to the highly non-linear dynamic behavior of friction dissipators, a reliable numerical model of buildings equipped with them is not easy to derive. Despite this inconvenience, in this paper an algorithm of solution of the equations of motion of buildings equipped with FDs and subjected to any type of time-varying external force was presented. This algorithm was implemented through a FORTRAN source code —ALMA.for program— and used to solve a number of 2D structures. In order to check the output from ALMA, laboratory tests on two reduced scale models were made. The results obtained using ALMA agree satisfactorily with those got from the experiments. Some of these results were shown here.

One of the objectives of carrying out the series of tests is trying to understand better the way FDs behave in order to assess its seismic efficiency and to improve the numerical procedure used here (ALMA program).

It is important to mention the role that laboratory tests play in the final design of friction dissipators as some interesting remarks can be made. Some of these remarks are described next:

- Due to the load-cells installed on the braces, the friction forces (forces along the braces) can be obtained easily. On the other hand, the lateral stiffness of braced bays equipped with FDs are not the same generally, not even for symmetric and parallel frames.
- Now, due to the difference between the stiffness of the braces on parallel faces, there is a twisting effect in the structure; therefore, a symmetrical behavior in both parallel faces (south and north) is difficult to achieve, even for a simple, regular models like those presented here. This fact points out the necessity to consider torsion forces for 3D buildings equipped with friction energy dissipators.

The main conclusions are:

- Friction dissipators are able to reduce the dynamic response when compared to the bare frames. This fact has been observed in virtually all the analyzed cases.
- Friction dissipators are able to reduce the dynamic response when compared to the braced frames only in some cases; in other cases, the maximum reduction is obtained using rigid connections instead (braced frames). Initial numerical results seem to indicate that the latter situation arises usually in stiff buildings (less than about 6-floor height). No satisfactory explanation for this behavior has been found so far.

Recommended future research:

- The ALMA program should be upgraded to be able to cope with asymmetric buildings (three degrees of freedom per floor).
- The distribution of the sliding force of the dampers along the height of the frame is an extremely important feature that deserves more attention in a further research, because probably it will govern the damage distribution (in this case, the energy dissipation demand on the dampers).
- Objective criteria to find the optimum value of the sliding force in the dissipators need to be derived.
- Future research should investigate the case when the structure undergoes some plastic behavior in beams or columns, in order to assess the efficiency of friction dampers in this situation.

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