TESTS OF FRICTION ENERGY DISSIPATORS FOR SEISMIC PROTECTION OF BUILDINGS

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ABSTRACT

This paper presents unidirectional shaking table tests of two steel frames; they are reduced scale models of two building structures with one and two floors, respectively. Such frames incorporate friction dissipators at every floor. The inputs are sine-dwells and artificial and registered earthquakes; some of the sine-dwells generate near-resonance motion and some of the earthquakes contain pulses corresponding to near-fault effects. The main objectives of these experiments are: (i) to collect a wide range of results useful to calibrate a numerical model derived by the authors, (ii) to contribute to clarify some of the most controversial issues about friction dissipators (introduction of high frequencies in the response, behavior for inputs containing pulses, capacity to cut resonance peaks, self-generated eccentricities), (iii) to understand better their dynamic behavior, (iv) to give an insight on the feasibility and reliability of using simple friction dissipators for seismic protection of building structures and (v) to characterize the hysteretic behavior of these devices.

KEYWORDS: Passive Control, Friction Dissipators, Experiments, Shaking Table Tests.

1. INTRODUCTION

This paper focuses on friction dissipators. Such devices have several advantages compared to other dissipators: (1) high energy dissipation capacity per cycle at a given amplitude, since the hysteresis loops are near rectangular; (2) virtually boundless dissipation capacity, mainly limited by the wearing of the sliding surface and (3) controllable sliding threshold through transversal prestressing force. In spite of the relevant existing background about friction dissipators there are still open questions:

- The energy dissipated per cycle is proportional to the maximum displacement instead of being proportional to its square as in viscous or viscoelastic dampers. This fact can be relevant for inputs containing either sudden pulses or unexpectedly high amplitudes. Moreover, resonance peaks cannot be properly cut (Den Hartog 1985).
- Due to the frequent and sudden changes in the sticking-sliding conditions and to the abruptness of the relative motion switching, high frequencies might be introduced in the response. This might be relevant both for human comfort conditions and for damage in non-structural elements.
- Given the inherent uncertainty of the values of the sliding forces $\pm \mu N$, some twist effects might arise, even in symmetrical buildings (De la Llera, Almazán and Vial 2005).
- Durability is open to discussion, mostly due to the high sensitivity of the friction coefficient to the conditions in the sliding surfaces.

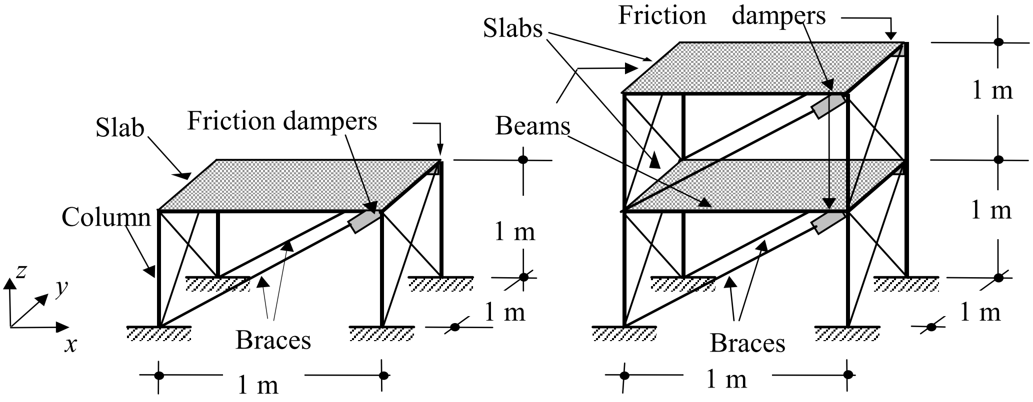
Most of these issues are controversial; to clarify them is difficult, either by testing or by numerical simulation. Reported experiments (Filiatrault and Cherry 1987; Fitzgerald et al. 1989; Richter et al. 1990; Whittaker et al. 1991; Aiken, Whittaker and Kelly 1993; Grigorian, Yang and Popov 1993; Yang and Popov 1995; Wu and Ou 2003; Morgen and Kurama 2004; Ng and Xu 2006; Vial et al. 2005; Ricles et al. 2006; Zhu, Zhang and Lu 2006; Tsai et al. 2008) do not yield enough information about the hottest questions as they are mostly oriented to check the global validity of particular devices or assemblies. The numerical simulation constitutes a challenging issue as the dynamic behavior of structures with friction dissipators is highly nonlinear, as discussed previously. Moreover, the proper simulation of the high frequency motion can be particularly difficult. The existing models are either computationally costly (based on Lagrange multipliers or penalty methods) or rather inaccurate (based on bilinear or elasto-plastic simple models).

This work belongs to a bigger research project aiming to clarify these issues using an integrated numerical and experimental approach. The final objective is to investigate the efficiency of friction dissipators for seismic protection of buildings (De la Cruz 2003). The project consists of the following stages: (i) developing a new numerical model of the dynamic behavior of buildings equipped with friction dissipators (De la Cruz, López Almansa and Oller 2007), (ii) testing laboratory models of building structures incorporating friction dissipators, (iii) calibrating the proposed numerical model with these experimental results and with other ones available in the technical literature and (iv) performing a numerical parametric assessment of the seismic efficiency of friction dissipators using the proposed model. The first three stages are already completed while the fourth one is still in progress. This paper focuses on the experiments (second stage). It is remarkable that this research is not restricted to any particular device rather to all the dissipators whose hysteretic behavior can be roughly described by near rectangular loops. Inside the framework of the abovementioned research project, these tests pursue the following objectives:

- To collect a wide set of experimental results useful to calibrate the proposed numerical model.
- To contribute to clarify some of the aforementioned controversial issues (introduction of high frequencies in the response, behavior for inputs containing pulses, capacity to cut resonance peaks and self-generation of twisting motion).
- To better understand the dynamic behavior of friction dissipators.
- To give an insight on the feasibility of using simple, yet robust and reliable friction dissipators.
- To characterize the hysteretic behavior of these devices, as to allow their implementation in design-oriented computers codes.

The experiments are designed to reach these goals, yet accounting for the time, availability and budget constraints.

2. TESTS DESCRIPTION



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

Fig. 1. Tested models

The experiments consist of unidirectional shaking table tests of two 3D steel frames, designed as reduced scale models of building structures with one and two floors, respectively. Such frames incorporate a pair of friction dissipators in each level. A deeper description of the tests can be found in the reference De la Cruz (2003). The experiments were carried out in the BLADE laboratories of the University of Bristol (UK). Fig. 1 sketches the two tested frames. Fig. 1 shows that the steel frames have plan symmetry and are rigidly braced in the y direction as only the motion in the orthogonal direction is of interest; no twisting effects are expected. The braces in x direction are interrupted by the friction dissipators. The geometrical parameters as well as the added masses are mainly selected to provide natural periods similar to those of real buildings. The tested frames can work, along x axis, under three different conditions: (i) without braces, (ii) with all the friction dissipators blocked (any sliding is prevented) and (iii) with normal operation of the dissipators (sliding is not prevented). Such conditions are termed next as *bare frame*, *braced frame* and *protected frame*, respectively. These conditions correspond to feasible situations of real buildings; hence, proper efficiency of the dissipators requires than the protected frame performs better than both the bare and the braced one. Only the protected frames were tested. The responses of the bare and braced frames were computed for comparison purposes; linear behavior was assumed.

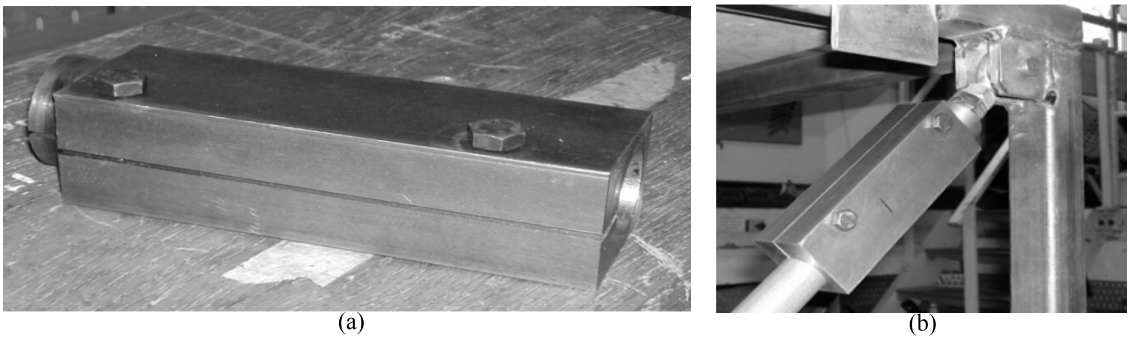

(a) (b)

Fig. 2. Friction dissipator

All the dissipators are alike. Consist of a hollow block of stainless steel with a cut along its length. The hole is shaped as a cylinder whose axis goes along the length of the block to hold the circular brace. Fig. 2a shows a lone device and Fig. 2b displays a dissipator mounted in a brace. Two transversal smaller holes were drilled to hold two adjustable bolts to control the prestressing normal force between the dissipator and the held brace. The movement of the device along the brace is prevented by connecting rigidly its upper end and allowing only sliding of the lower one (Fig. 2b). The sliding surfaces of the dissipator and the brace were thoroughly smoothed.

The two rigs (shown in Fig. 1) were mounted on a shaking table and underwent several types of unidirectional dynamic excitations: sine dwells and scaled registered and artificial earthquakes. For the single story model, the sine dwell and the Northridge Earthquake are selected to discuss controversial issues about friction dissipators. The frequency of the sine dwell signal is extremely close to the natural frequency of the bare frame (4.14 Hz); hence, while the dissipator keeps sliding the motion is near resonance. The Northridge Earthquake contains pulses generated by near-source effects. For some inputs the identified values of the positive and negative sliding forces are different. This indicates that the friction dissipators do not behave like simple Coulomb models; this fact is taken into account in the numerical simulations. At each experiment the measured quantities are: (a) table acceleration and displacement, (b) floor accelerations and displacements, (c) friction forces and (d) sliding displacements in the dissipators.

3. NUMERICAL VS. EXPERIMENTAL RESULTS

This section presents numerical and experimental results; three major purposes are pursued: (a) to discuss some issues about the actual behavior of the dissipators, (b) to investigate the influence of irregularly shaped hysteresis loops and (c) to further validate the accuracy and reliability of the proposed model, mainly under modeling uncertainties. The tests are simulated with a numerical algorithm developed by some of the authors (De la Cruz 2003 and De la Cruz, López-Almansa and Oller 2007). Fig. 3 displays experimental hysteresis loops of the first floor dissipator for the two-storey model. The input is an artificial earthquake. In the vertical axis positive values of the friction force correspond to tension and in the horizontal axis positive values of the relative displacement between the brace and the device correspond to elongation, i.e. the brace is coming out of the block (see Fig. 2b). Fig. 3 shows that the actual hysteretic behavior of the dissipators does not fit the Coulomb model. Two major irregularities can be observed: (a) the sliding branches are non flat but the forces tend to grow as the brace is coming into the block and (b) the sliding forces are different at the superior and inferior branches. Both circumstances can be observed, more or less intensely, in the other experiments. To understand such behavior it should be kept in mind that the loops are described clockwise. The first irregularity can be explained by the increase of the sliding length as the brace penetrates inside the block. The second irregularity corresponds to an asymmetric behavior that is also observed in the static calibration tests (De la Cruz 2003); no fully satisfactory explanation has been found. The first irregularity can not be accounted for by the proposed numerical model, but it is able to cope with the second one. To evaluate its relevance, Fig. 4 shows a comparison between the numerical values of the first floor displacement response determined with the proposed model by considering the actual unequal values of the sliding forces and by taking the average of such forces. Plots in Fig. 4 show a good agreement, indicating a rather negligible influence of the difference between the superior and inferior sliding forces (Fig. 3). This conclusion is corroborated by similar comparisons for other inputs and structures, both for displacements and accelerations (De la Cruz 2003).

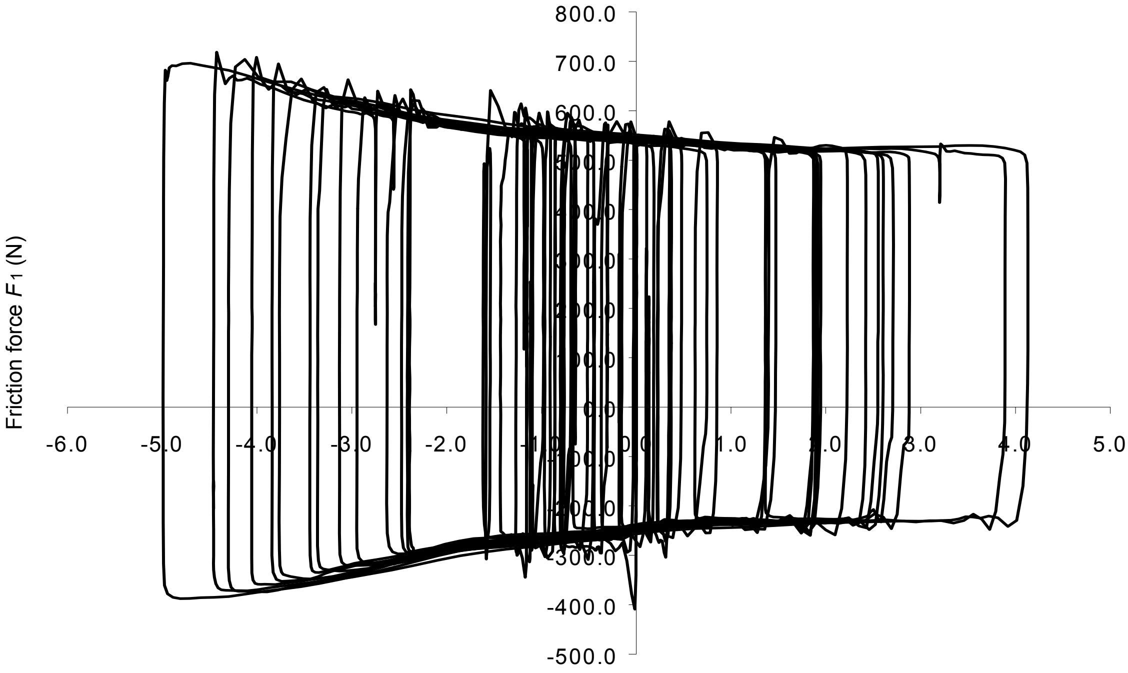


Fig. 3. Experimental hysteresis loops of the first floor dissipator in the two-storey frame for an artificial earthquake

To assess the validity of the proposed model to simulate the response, Fig. 5 shows the experimental and numerical first floor displacement. Plots in Fig. 5 show that, in spite of the irregular shape of the loops shown by Fig. 3, the agreement between numerical and experimental results is satisfactory.

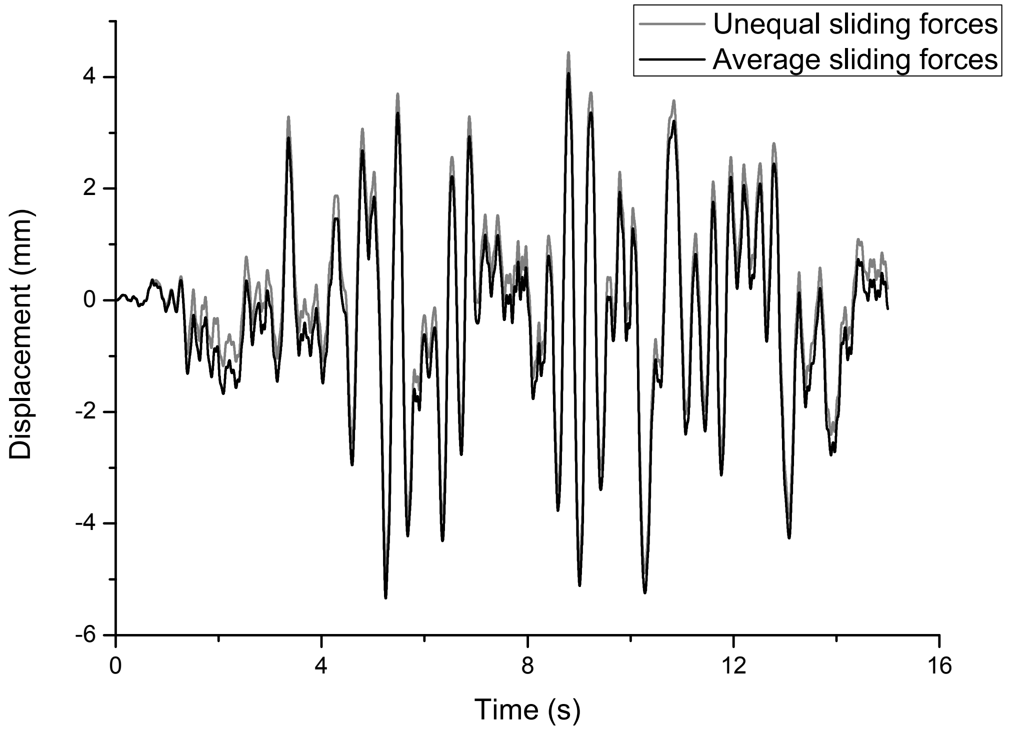


Fig. 4. Numerical time history responses of the two-storey frame for an artificial earthquake. First floor displacement

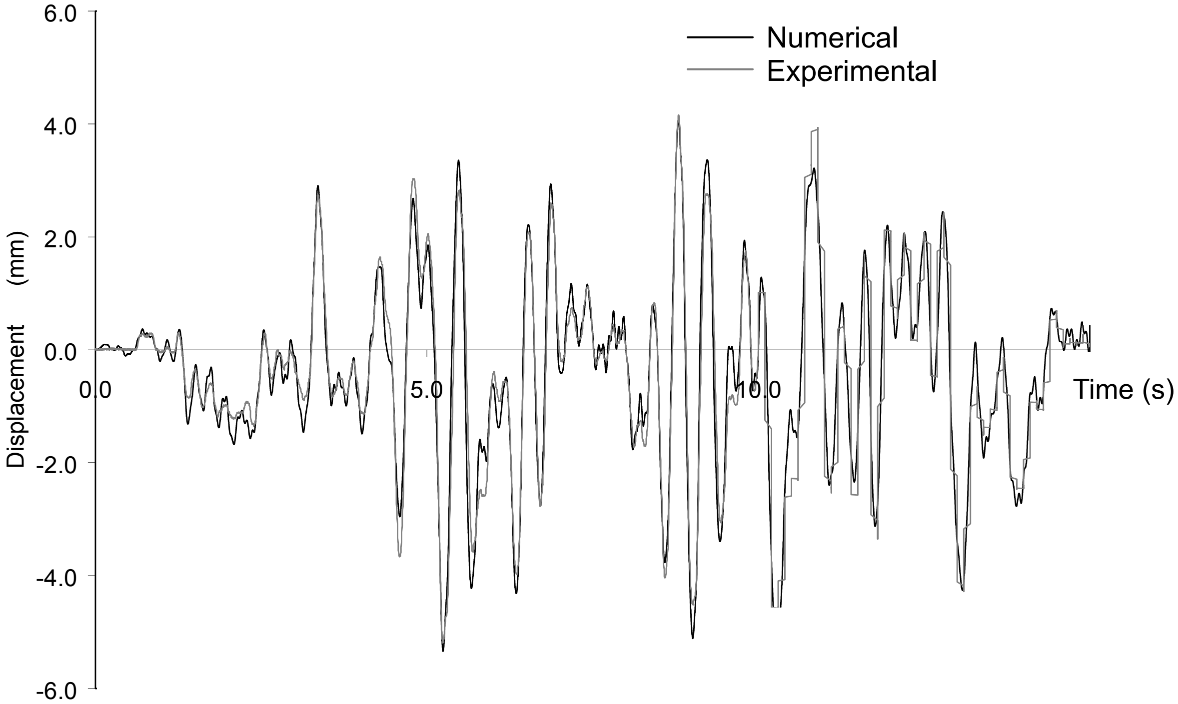


Fig. 5. Numerical and experimental time history responses of the two-storey frame for an artificial earthquake. First floor displacement

4. CONTROVERSIAL ISSUES

Behavior for inputs containing pulses. Fig. 6 displays the response of the single-story model for the Northridge Earthquake. The input table acceleration is also displayed to show that, as discussed previously, such input contains pulses. The bare, braced and protected frames are considered; the response of the protected frame is experimental while those of the bare and braced frames are numerical. The comparison among the three plots in Fig. 6 shows that the response of the protected frame is significantly smaller than that of the bare frame; this tendency is also observed in the other cases (De la Cruz 2003). However, the balance between the protected and braced frames is unclear since the maximum response is larger for the protected frame while such trend is inverted for the average value. The protected frame response exhibits two peaks which correspond to the pulses in the input; hence, apparently, for strong crests the friction dissipators are not sufficiently efficient in reducing the maximum displacement. To help to understand why such peaks are not properly cut, the time history of the friction force F is plotted in Fig. 7. In Fig. 7 the sliding and sticking conditions can be clearly distinguished: sticking corresponds to friction forces smaller than μN while sliding corresponds to $F = \pm \mu N$. Just before the input pulses there is sticking and, hence, the response is not properly reduced; once the sliding is resumed, the peaks are immediately cut. To understand his better, it should be kept in mind that the behavior of the structure under sticking and sliding conditions is completely different: while sticking, the protected frame behaves like the braced one since there is no energy dissipation and only a stiffening effect is provided. Conversely, while sliding, the frame behaves piece-wisely similarly to the bare frame, but with a decreased input since the friction force is constant and opposes motion. About this issue, it can be concluded that for inputs containing pulses the friction dissipators are useful to reduce the response compared to the unbraced bare frame; regarding the comparison between dissipators and rigid braces (protected vs. braced frame), further research is needed.

Capacity to cut resonance peaks. The frequency of the sine dwell signal (4 Hz) is close to the natural frequency of the single-story bare frame (4.14 Hz). Moreover, during sliding such frequency is not significantly changed since the friction force is essentially piecewise constant; it should be kept in mind that the sliding condition is frequent during intense inputs. Therefore, in this case the protected frame behaves roughly like if its natural frequency were the one of the bare frame; hence, the motion can be considered near-resonance. Fig. 8 shows the response of the single-story frame to the sine dwell. Two responses are plotted: protected frame (experimental results) and bare frame (simulated results). Plots from Fig. 8 show that the friction dissipators are clearly able to cut the resonance peaks. It should be kept in mind that the damping coefficient of the bare frame is extremely low ($\xi_1 = 0.003141$) and therefore such resonance peaks are impressively high.

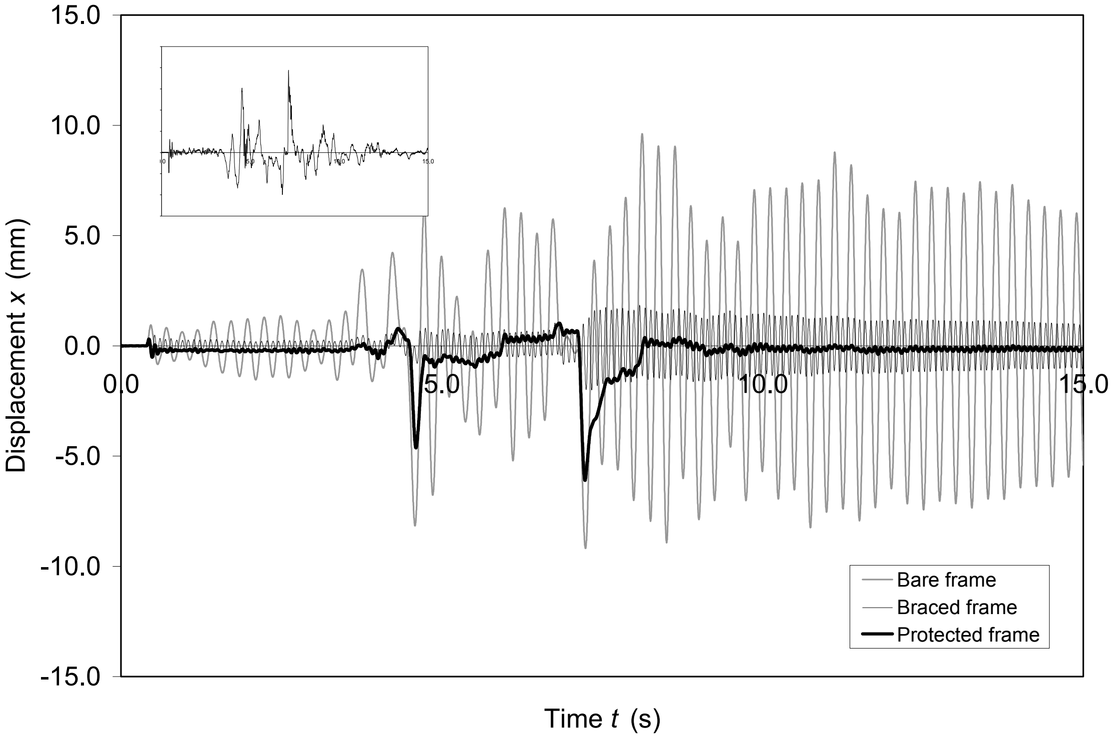


Fig. 6. Numerical and experimental time history displacement responses of the single-story frame for the Northridge Earthquake

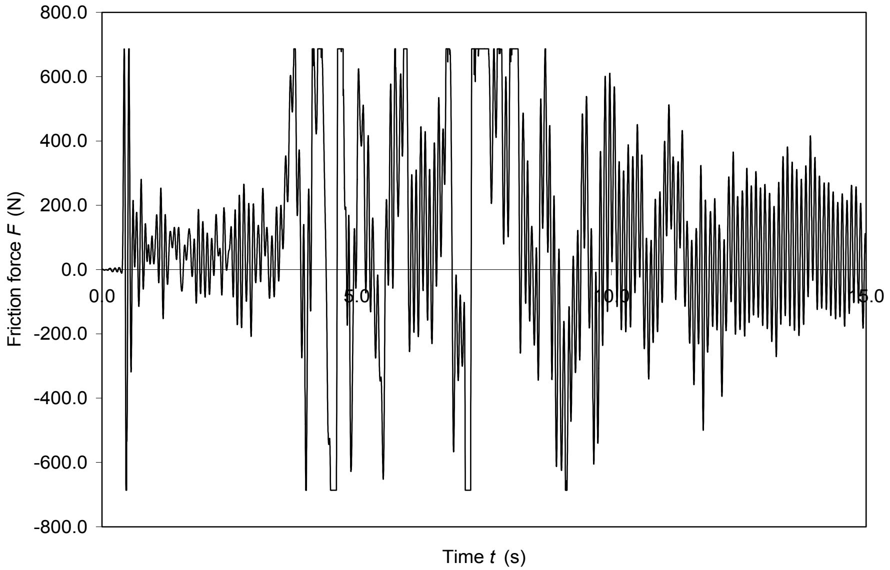


Fig. 7. Numerical time history of the friction force responses of the single-story frame for the Northridge Earthquake

Introduction of high frequencies in the response. The abrupt shift of the friction forces every time the sliding motion in the dissipators reverts might introduce high frequencies in the response, mainly in the acceleration. To try to clarify this issue, the experimental frequency contents of the input and of the response have been compared. Fig. 9 shows, for the two-storey building under a sine dwell excitation, the magnitudes of the discrete Fourier transforms of the driving input acceleration and of the second floor acceleration response, respectively. The comparison between the spectra in Fig. 9 shows that the same peaks can be observed in the input and in the output; it allows to conclude preliminarily that no additional frequencies have been introduced in the response. If similar analyses are performed in the other tests, equivalent results are obtained.

Self-generated eccentricity. Since the sliding forces μN are random, accidental differences in between the behavior of the front and rear frames can generate twisting effects. Fig. 10 shows the experimental friction forces in the two dissipators of the single-story frame for the Northridge Earthquake. Fig. 10 shows that the self-generated torsional motion could be neglected. This is also observed in the other analyzed cases.

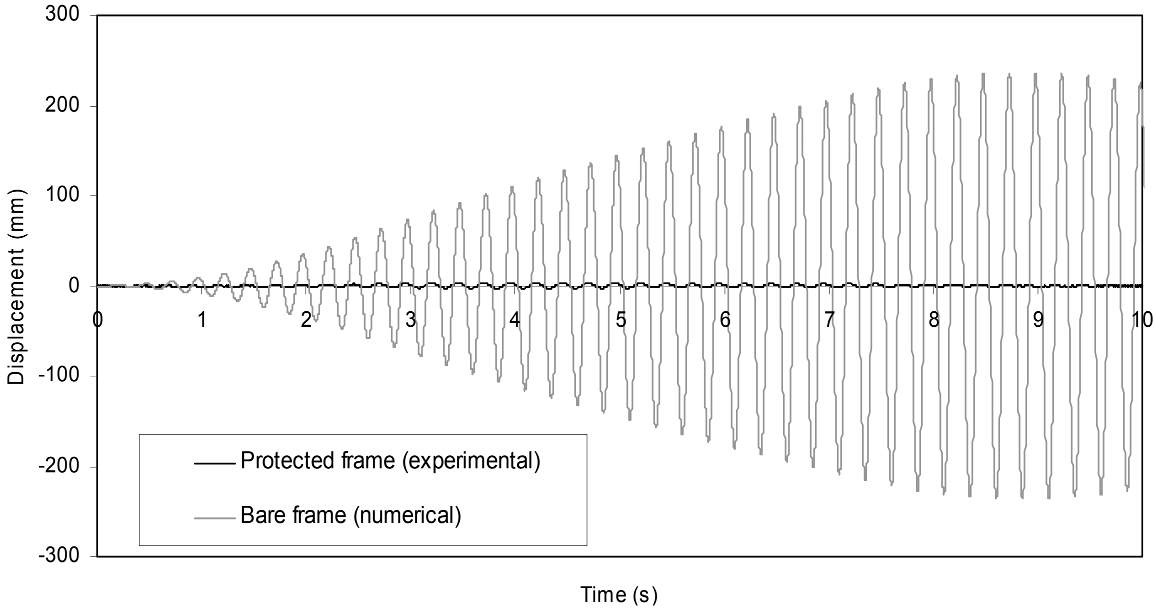


Fig. 8. Time history displacement responses of the single-story frame. Sine dwell input

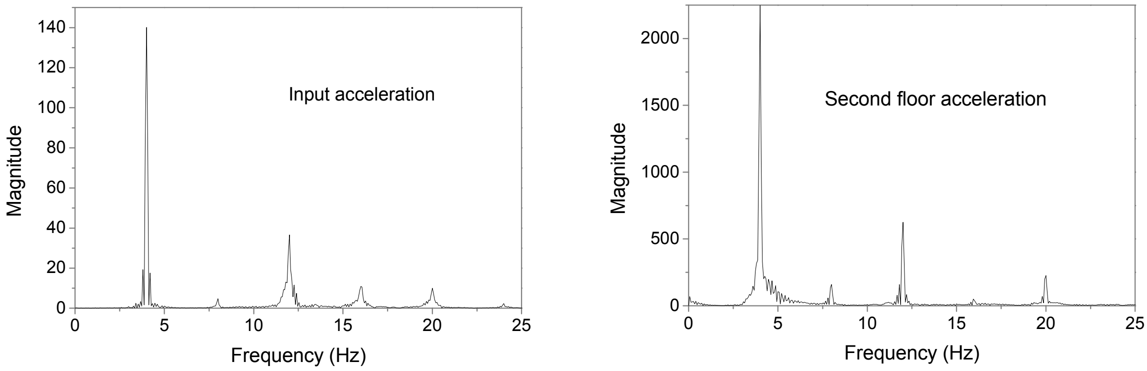


Fig. 9. Comparison between the Fourier transforms of the input and of the output of the two-storey frame. Sine dwell input (4 Hz)

5. CONCLUSIONS

- **Experimental results to calibrate the numerical model**. Experimental results useful to calibrate the proposed numerical model have been collected. The numerical and experimental results agree even for near-resonance behavior and dissipators with irregularly shaped hysteresis loops.
- **Behavior for inputs containing pulses**. The considered dissipators are useful to reduce the response compared to the bare frame; regarding the braced frame the situation is unclear.
- **Capacity to cut resonance peaks**. These dissipators are able to cut the resonance peaks, even the sharper ones corresponding to low damped structures.
- **Introduction of high frequencies in the response**. The comparison between the input and output spectra shows that the peaks are similar. Hence, it can be preliminarily concluded that no additional frequencies have been introduced.
- **Self generated eccentricity**. The lateral stiffness of the front and rear frames equipped with the friction dissipators are rather balanced. Hence, there is no significant induced twisting effect.
- **Feasibility of simple friction dissipators**. The considered devices are simple and have performed rather satisfactorily. The durability and operation under saturation conditions have not been deeply investigated.
- **Characterization of the hysteretic behavior**. The hysteresis loops have been roughly characterized. The

dependency on the observed irregularities is numerically investigated.

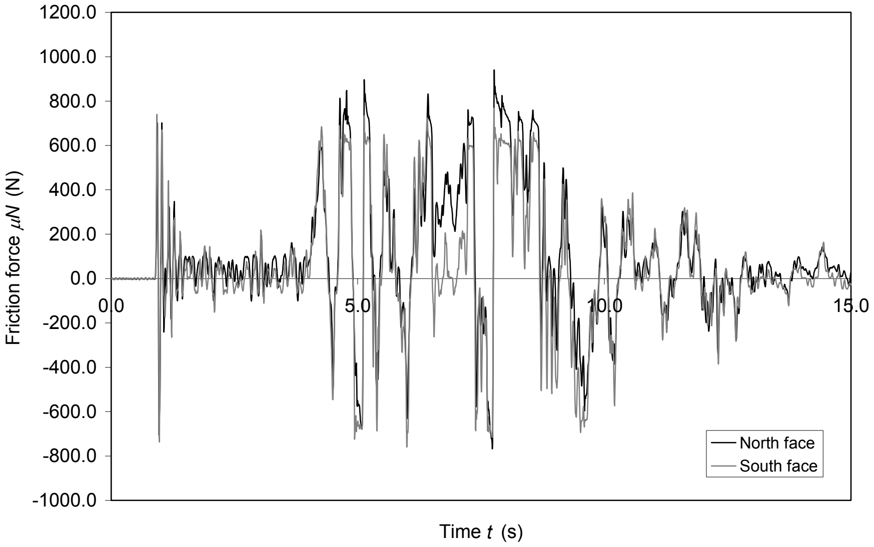


Fig. 10. Comparison between the experimental front and rear friction forces of the single-story frame. Northridge Earthquake

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