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On the Optimum Placement of Dissipators in a Steel Model Building Subjected to Shaking-Table Tests

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Abstract: The following research presents the numerical and experimental results obtained on a reduced scale steel model of a medium-rise building structure dynamically protected with energy dissipaters. The steel-steel friction dissipates energy as the structure undergoes interstory drifts. A preliminary numerical analysis is performed to determine the best position of the friction dampers in the longitudinal frames. All the nodes of the numerical model have been assumed with the same bending stiffness. Shaking table tests have been performed, both in random vibration tests (to determine the natural periods and the dynamic characteristics of the model) and in earthquake simulation tests (to study the dynamic behaviour of the model with and without dampers). The results have been compared to those achieved during a previous experimental study based on the same model protected with only one friction damper for each longitudinal frame.

Keywords: Earthquake simulator tests, energy dissipation, friction dissipaters, optimum position, shaking-table tests.

1. INTRODUCTION

Energy Dissipating Devices (EDDs) are mechanical elements included in structures in order to reduce their response to earthquakes. They are designed to dissipate energy when the building undergoes interstory drifts. Many kinds of EDDs can be found in literature for the seismic protection of structures [1-7]. Some studies have been developed for viscous dampers [8-11] in near-field areas [12, 13]. In this research friction dampers have been considered. In detail, the devices utilized in this research consist of two sliding contact surfaces causing a major portion of the seismic energy to be dissipated, thus leaving the building structure in the elastic field in order to avoid its members yielding [14]; the dissipators principally involve steel-steel friction to dissipate energy and reduce the seismic response [15].

Friction devices increase the damping capability of the structural system; this is the reason why they are widely used in the seismic design of new buildings and in the retrofitting of existing structures.

In this paper the efficacy of EDDs in the seismic protection of buildings is analysed from a numerical and experimental points of view by performing a series of tests on a steel model.

Tests have been performed on a shaking table at the Applied Geophysics Laboratory of the Technical University of Catalonia, Barcelona, Spain.

In a previous study the steel model was designed and tested with only one dissipater [16, 17]. Consequently, a numeric to identification analysis was carried out on the model [18, 19].

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It had been very simple update the numerical model by just considering a different stiffness of the bolted nodes of the steel frame. More sophisticated and software-based identification examples regarding in-situ structures and consequent updating of their numerical models for existing masonry and reinforced concrete buildings [20, 21] and towers [22, 23] could be found extensively in literature. Especially updating is important when the structures are old historical ones with a high cultural value [24-28].

The present paper is divided in two parts: in the first part the description of the model, the dissipaters and the shaking table tests with only one dissipating device are presented. The second part shows the results on the numerical and experimental studies utilizing a higher number of friction dampers for the protected model.

2. DESCRIPTION OF THE REDUCED SCALE MODEL

2.1. Structural Model

Fig. (**1**) shows a drawing of the steel model utilized for the tests. The model is a 3-D steel moment resisting frame with 5 levels. It is 170 cm high, 144 cm wide and 77 cm deep. There are two bays opposite to each other.

The model consists of six continue columns made with L-shape 20x20x2 mm bars. The beams have a 20x10 mm rectangular section and they are bolted to the columns through plates welded to the beams. Fe360 steel has been utilised (σ_y=230 N/mm^2; σ_u=360 N/mm^2). The dimensions of the elements verify all the resistance and stability conditions under a concentrated vertical static load of 45 N on each beam and an equivalent horizontal static load determined from the International Building Code (IBC) 2009 [29]. As effect, the maximum stress induced in the beam by this load condition is about 149 N/mm^2 at the 4th level, while in the columns the maximum stress is about 12 N/mm^2 at the

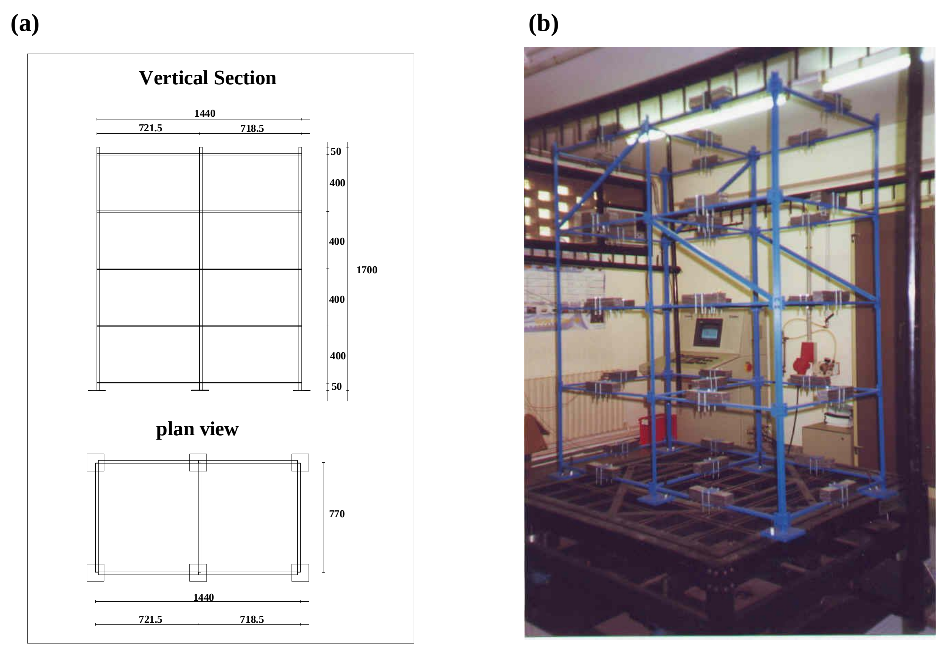

Fig. (1). Drawing (a) and photo (b) of the model.

1st level. The model allows changes in its stiffness and mass and it has the possibility to incorporate different passive control devices. Accelerometers on each level are able to measure directly the time-history response accelerations. A five lead strap load of 45 N has been applied on each beam with a total dimension of 200x50x5 mm in order to simulate the load on each level.

In the present study a model of a steel structure has been adopted with the aim of comparing the performance of the structure with and without dissipaters. The principal objective is not only to determine the efficacy of each dissipating device during the shaking-table tests but also the best position of the two friction dissipaters utilised in the tests in order to get a higher reduction of energy and vibrations in the structure. Moreover, a homogeneous material such as steel has been adopted, thus avoiding problems arising from a small non-homogeneous section. The elements utilised to build the frame have a reduced section, but their resistance and stability have been verified under the yielding strength limit. It is a very simple steel frame that is quite representative of a real-scale steel building. The performance of this structure determines the best choice about dissipaters installation and their position in the frame. The only constraint in the design of the scaled model has been the natural period chosen equal to 0.1s times the number of levels (T_1=0.1x4 = 0.4s). In fact the first level has been neglected because too close to the base to influence the 1st mode.

2.2. Friction Dampers

The dissipaters utilised in this study are friction dampers. They dissipate energy through steel-steel friction when the structure undergoes interstory drifts. They are designed to act at a certain level of the horizontal force and they have been applied to the model as diagonal braces. Basically, two parts of a brace with slotted holes are connected by mean of high strength bolts. Its Force-Displacement [F-δ] behaviour is a rigid-perfect plastic one with a wide hysteresis cycle and, consequently, a high energy dissipation (Fig. **2**).

The friction dampers have been designed and built as described in [16, 17]. They have been installed in substitution of the diagonals in order to compare the results obtained in both cases of protected and unprotected model.

3. DESCRIPTION AND RESULTS OF PREVIOUS TESTS

A first series of tests were performed to identify the model and to study more in detail its behaviour during an earthquake [16, 17]. It was considered a model without diagonals (*bare frame*), with a diagonal in both longitudinal frames between the 2nd and 3rd levels (*braced frame*) and protected by dissipaters in substitution of the diagonals (*protected frame*). A random excitation (*random noise with a broadband Fourier spectrum*) was applied to identify the model. A synthetic earthquake register with a broadband spectra (El Centro 1940) was utilised in the seismic simulation tests.

From the identification of the model the following values of the first natural period and the first natural frequency were determined:

bare frame $T_1 = 0.381$ s, $\omega_1 = 2.625$ Hz

braced frame $T_1 = 0.222$ s, $\omega_1 = 4.5$ Hz

From the seismic simulation tests the time and frequency responses of the bare, braced and protected frames were determined. These results gave the possibility to study the efficacy of the protection device utilised in the research.

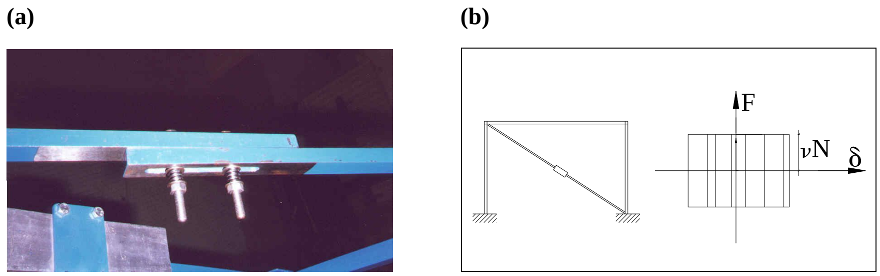

Fig. (2). Friction damper utilised in the dynamic tests. a) Detail of the dissipation node; b) Force-displacement (F-δ) diagram.

4. OPTIMUM PLACEMENT OF FRICTION DAMPERS

Starting from the values obtained during the previous shaking-table tests, a numerical bare model with the same value of the first natural frequency of the real model has been proposed.

The loads and geometric characteristics of the numerical model are very similar to the real one. The nodes are not rigid but they can rotate with a finite stiffness determined from the previous tests. This stiffness has been assumed constant for all the nodes of the frames.

The model of a frame with rigid joints in all the connections and at the base has been assumed. The principal reason is that this model is easier to adopt for practical applications. The model with semi-rigid joints is more precise and closer to reality, but it is too complex to be utilised in the normal practice by the end users (designers, structural engineers, producers, etc.). Moreover, from a preliminary study the response obtained with a rigid node model is very close to the real one. Therefore it is not worth adopting a more complex model, which needs more computational calculus and work. In addition, the principal aim of this part of the paper is to numerically compare the behaviour of protected and unprotected structures modelled with the same rigid frame, to determine the best position of the dissipative devices.

On the model obtained this way numerical and experimental analyses have been performed.

4.1. Description of the Model

In the model considered for the numerical analysis two diagonals have been installed in the longitudinal frame. All possible position combinations of these elements have been considered. The analysis has also been performed considering dissipaters in substitution of the diagonal braces. Fig. (**3**) shows the ten cases considered in the analysis. The objective was to numerically determine the response of the frames by only varying the position of the diagonals and, consequently, of the dampers. The structure with the best behaviour during an earthquake has been chosen for next shaking-table tests.

The numerical analysis has been performed with a finite element software, which considers the frame in the linear field while non-linearities are concentrated only in the dissipaters [30]. In this way the damage is concentrated only in the device without damaging the structure [31]. The yielding force of the friction devices has been considered equal to 75% of the maximum force obtained under an equivalent horizontal static load [32].

As input the same register of the previous shaking-table tests, that is a synthetic earthquake register with a broadband spectra, has been adopted.

In the shaking-table tests the experimental model has been equipped with two diagonals installed in the best position determined from the numerical simulation. Therefore the cases shown in (Fig. **3**) have been analysed both for unprotected and protected frames. As in the previous study, both diagonals have been substituted with friction dissipaters similar to the one utilised in the first series of shaking-table tests.

4.2. Results of the Numerical Simulation

As results of the numerical analysis Case 10 shows the frame with the best response during an earthquake. The results obtained from the numerical analysis of the frames are shown in detail in (Figs. **4-8**). The mechanical characteristics

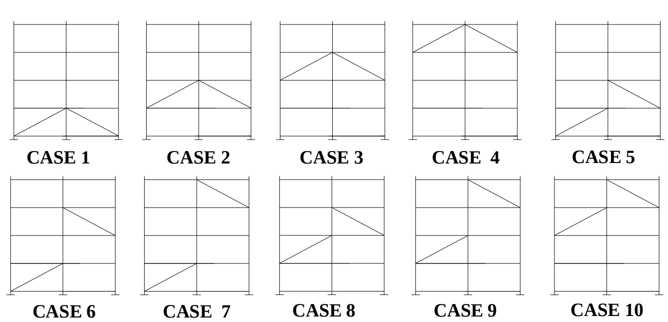

Fig. (3). Models of the frames corresponding to Cases 1, 2, 3, 4, 5, 6, 7, 8, 9, 10.

analysed are: maximum interstory drifts, maximum absolute accelerations, maximum displacement, maximum base shear, energy dissipation.

4.2.1. Maximum Interstory Drifts

The shape of the curves of the maximum interstory drifts for the protected frames is similar to the bare frame's one. It is slightly different in case 3, 5 and 6 (Fig. **4**).

Case 2 shows the best behaviour related to the interstory drifts as the soft-story effects are reduced if compared to the other cases: the drift reduces at the 4th and 5th floors even if slightly.

Case 4 shows the highest values of the interstory drifts, which are very close to those obtained for the bare frame. In this case very high differences appear between two adjacent floors.

In Fig. (**5**) the diagrams for Cases 1, 2, 5, 9, 10 have been analysed in detail and compared to the respective braced frames. They have been chosen because, when the frames are protected, they give the best results in the global behaviour if compared to the respective braced cases. As expected, the braced frames show a high reduction of the drift in correspondence of the levels equipped with braces. The presence of the friction dampers changes this behaviour being possible

(a) **(b)**

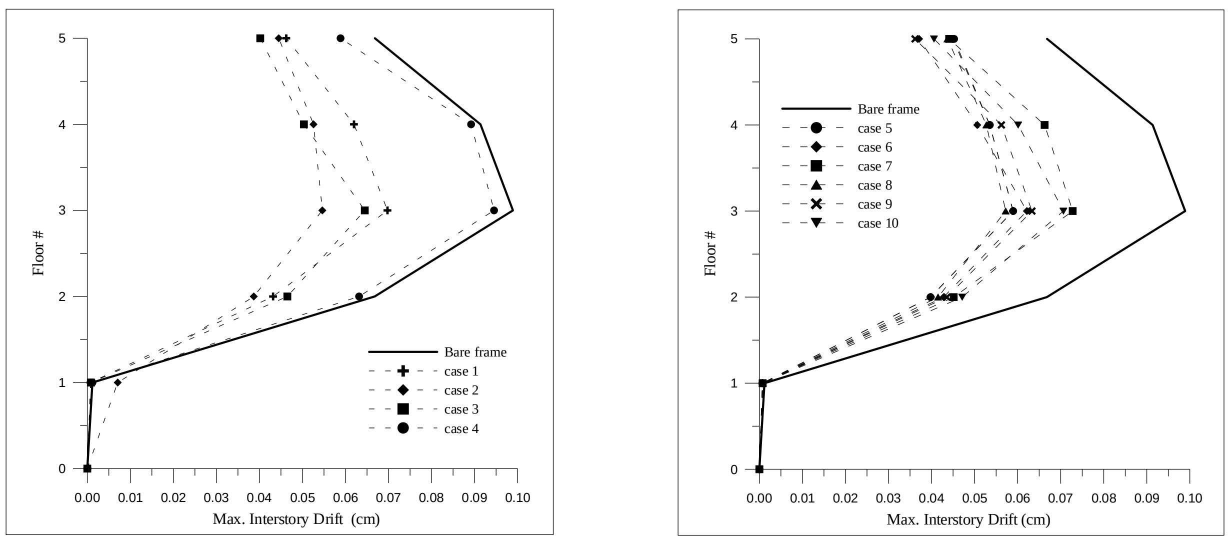

Fig. (4). a) Maximum interstory drift for Cases 1, 2, 3, 4 (*protected fra*me); b) maximum interstory drift for Cases 5, 6, 7, 8, 9, 10 (*protected frame*).

(a) **(b)**

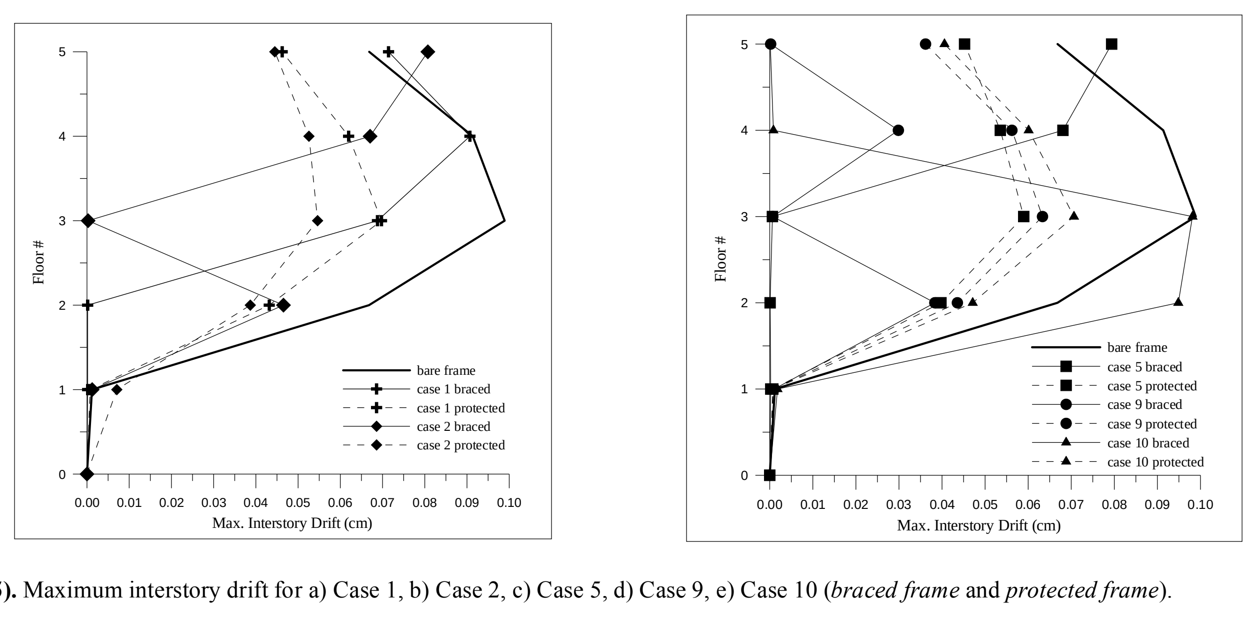

Fig. (5). Maximum interstory drift for a) Case 1, b) Case 2, c) Case 5, d) Case 9, e) Case 10 (*braced frame* and *protected frame*).

to displace them at these levels. It is due to the interstory displacement the possibility to have energy dissipation in the friction devices and, consequently, to reduce the accelerations in the structure.

4.2.2. Maximum Absolute Accelerations

In the last floors it is obtained a reduction of the acceleration, if compared to the respective braced cases (Fig. **6**).

In Case 4 the protected frame always shows the highest values of the maximum absolute accelerations except at the 4th level (Fig. **6a**). In Case 6, on the contrary, the protected frame shows values higher than the maximum absolute accelerations; these values coincide in the last level (Fig. **6b**).

4.2.3. Maximum Displacements

The maximum displacement is always higher in the protected frames if compared to the respective braced frames, except for Case 1 and Case 3 (Fig. **7**).

The highest increment is obtained in Case 6, related to the frame with the lowest period. Case 2 shows the lowest increment of the maximum displacement, while in Cases 1 and 3 the maximum displacement even reduces for the respective protected frames.

4.2.4. Maximum Base Shear

The maximum base shear has been normalized respect to the total weight of the frame (C_s=V/W) (Fig. **8**).

The protected frames show a reduction of the maximum base shear compared to the braced ones, with the exception of Case 4. The maximum reduction of the base shear is reached in Case 10, while the minimum reduction is obtained in Case 6.

4.2.5. Energy Dissipation

The maximum energy dissipation is obtained for Case 4 (Table **1**). Compared to Case 10 chosen for the shaking table tests, Case 4 shows higher values of the interstory drifts when they are protected. In addition, the maximum base shear increases of 26.26% if compared to Case 10.

On the contrary, the maximum displacement increases in Case 4, but it is lower than in Case 10. For Case 10 with protection, the maximum displacement is 0.08 cm that is higher than in Case 4, while for the corresponding braced frames, the maximum displacement increment for Case 10 is only 0.013 cm higher than in Case 4.

In summary the following tables (Tables **2-4**) describe the best behaviour obtained for all the ten different cases numerically analysed.

Table **2** shows the reduction percentages of the maximum acceleration amplifications on each floor, compared to the corresponding braced frames. Only Cases 2, 8, 9 and 10 are considered, as they are the only ones that showed a reduction at each floor. Compared to the other three cases, Case 10 showed a better behaviour as the reduction has been kept quite high on all the floors.

In Tables 3 and 4 the values of the maximum displacements and the maximum base shear are respectively shown in all ten examined cases for the braced and protected models.

In Table **3** the variation of the top displacement from the braced to the protected frames has been determined. Its value is expressed in percentage to show the increment of this characteristic. This value is very important in order to understand how equipment and non-structural components are fully protected in buildings incorporating energy dissipaters. During an earthquake if the increment is low, the performance of the protected structure will be improved because the rupture and the un-serviceability of equipment and non-structural elements is prevented. Moreover, a low value means that dissipaters can start to work for low displacements. From Table **3**, even a displacement reduction is obtained in Case 1 and in Case 3. On the contrary, the maximum increment is reached in Case 6.

In Table **4** the maximum reduction base shear for the protected frames has been compared to the braced ones for all the ten examined cases. A high reduction of this value means that the friction devices are working with a high dissipation

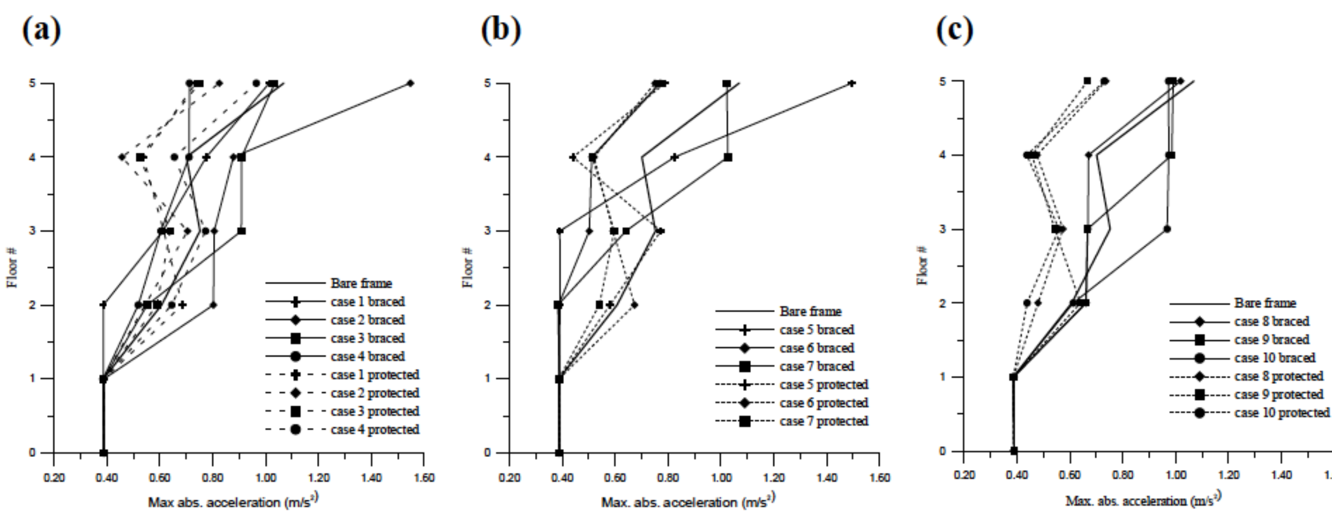

Fig. (6). Maximum absolute acceleration (*braced frame* and *protected frame*). a) Cases 1, 2, 3, 4; b) Cases 5, 6, 7; c) Cases 8, 9, 10.

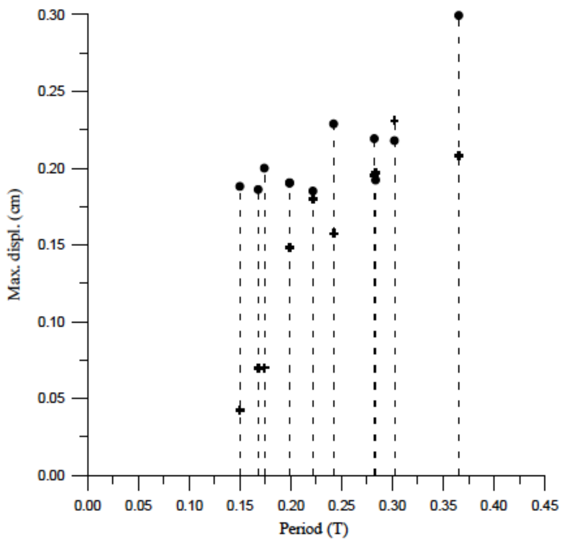

Fig. (7). Maximum displacement.

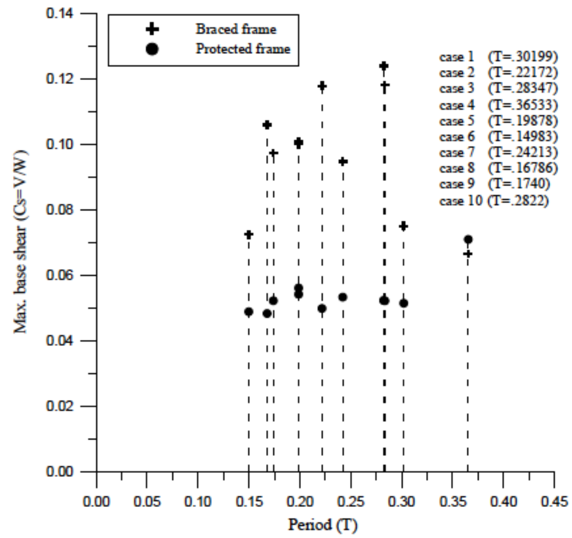

Fig. (8). Maximum base shear.

Table 1. Energy dissipation in the friction devices.

ENERGY DISSIPATED (Joules)					
FRAME	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**
	13.009E-2	15.054E-2	16.575E-2	28.670E-2	14.915E-2
FRAME	**CASE 6**	**CASE 7**	**CASE 8**	**CASE 9**	**CASE 10**
	16.457E-2	18.838E-2	16.400E-2	17.065E-2	19.096E-2

Table 2. Acceleration amplification in Cases 2, 8, 9 and 10.

Floor	CASE 2	CASE 8	CASE 9	CASE 10
1	46.67 %	27.87 %	32.73 %	25.03 %
2	47.99 %	29.12 %	53.72 %	55.12 %
3	12.53 %	14.12 %	18.55 %	42.31 %
4	32.19 %	27.56 %	3.05 %	28.49 %
5	0.6 %	0.52 %	0 %	0 %

of energy. In the table it is possible to notice that the maximum reduction of the base shear is obtained for Case 10.

Maybe Case 2 showed good results too, with high reduction of the examined characteristics, but for Case 10 a higher energy dissipation produced by the friction devices is obtained (Table **1**).

From all the results, during a seismic event the frame with the best performance is obtained for Case 10. Therefore, this model frame is adopted for next shaking-table tests.

5. EXPERIMENTAL STUDY

5.1. Description of the Shaking-Table Tests

Shaking-table tests have been performed on the model with braces and friction dampers in the best position corresponding to Case 10 (Fig. **9**).

The inputs utilised are random vibrations and a synthetic earthquake register with a broadband spectra. A scale factor s=1 has been adopted for all the tests. Only in a second series of earthquake simulator tests on the protected model a scale factor s=2.6 has been applied.

5.2. Results

As described in sect. 4 the best behaviour during an earthquake could be observed if the model defined as “Case 10” is adopted. In fact, if the diagonals are installed one between the 3rd and 4th levels and the other one between the 4th and 5th levels, the structure performance during a seismic event is highly reduced if compared to other possible cases.

Therefore, as the model of Case 10 has been adopted for the shaking-table tests, the following results obtained with this model show the best performance of the structure in response to a dynamic input when the diagonals are substituted with friction dissipaters.

Table 3. Maximum displacement variation [cm].

Case	Braced	Protected	Increm.[%]
1	0.231	0.218	-5.61
2	0.180	0.185	+2.80
3	0.195	0.192	-2.30
4	0.208	0.300	+43.88
5	0.149	0.190	+28.16
6	0.043	0.188	+342.3
7	0.158	0.229	+45.27
8	0.070	0.186	+166.58
9	0.070	0.001	+185.32
10	0.196	0.219	+12.12

Table 4. Maximum base shear variation [N].

Case	Braced	Protected	Reduct.[%]
1	5.515	37.83	-31.40
2	8.664	36.65	-57.70
3	8.685	38.37	-55.80
4	4.891	52.16	+6.65
5	7.402	39.82	-46.20
6	5.327	35.93	-32.55
7	6.97	39.20	-43.76
8	7.786	35.52	-54.38
9	7.158	38.39	-46.38
10	9.119	38.46	-57.82

Table **5** shows the values of the first and second frequencies of the experimental model together with the respective periods determined from the random vibration tests.

Only the first two natural frequencies have been determined because the frequency range of the table is [0-12.5 Hz]. Higher values of the frequencies are affected by the vibration frequencies of the equipment that moves the table.

In the bare frame the frequencies are lower than in the previous tests because the frame is less stiff and the bolts in the frame are loosened.

The braced frame, as expected, shows a higher increment of the frequency ω with respect to the bare one because the stiffness increases. The first natural frequency in the braced frame is lower than the first one determined in [3] where only one diagonal was installed between the 2nd and the 3rd levels. Moreover, in the braced frame the second natural frequency has not been determined because its value is higher than the maximum acceptable value for the shaking-table (12.5 Hz). That means that higher frequencies are more excited than the lower ones.

Fig. (9). The steel model with two dissipaters in position 10.

Table 5. Natural periods and frequencies of the model.

FRAME	T_1 (s)	ω_1 (Hz)	T_2 (s)	ω_2 (Hz)
Bare	0.4	2.5	0.11	9.094
Braced	0.2991	3.34375	/	/

In the case of protected frames, it is not possible to determine a peak frequency value but just a range of frequencies with higher values due to the non-linear behaviour of this system. In the protected frame (input scale factor s=1) the highest values of the response lies in a range between 2.5 Hz and 3.5 Hz with a maximum value at 3.438 Hz (Fig. **10a**). In the previous study two frequencies ranges were defined around the first two natural frequencies of the braced frame, 3.3-5.1 Hz and 8.3-9.5 Hz.

When the scale factor of the input increases more than the double (s=2.6), the frequency range of the highest response values lie between 0.7 Hz and 3.9 Hz with its maximum response in correspondence of a frequency equal to 2.313 Hz (Fig. **10b**).

In the previous study two frequency ranges around the natural frequency values of the braced frame were defined, 1.5-4 Hz and 9-10 Hz. The results of these tests are reported in (Fig. **11a**, **b**).

Table **6** shows the values of the acceleration amplification respect to the base. Except for the bare case, the maximum amplification is reached at the 2nd level. This value is reduced of about 35% in the protected frame (s=1). This reduction is more sensible on the 4th and 5th levels, where the friction devices have been installed. In the previous research the acceleration amplification generally increased towards the top with a maximum amplification value in correspondence of the last floor; for that frame the most important

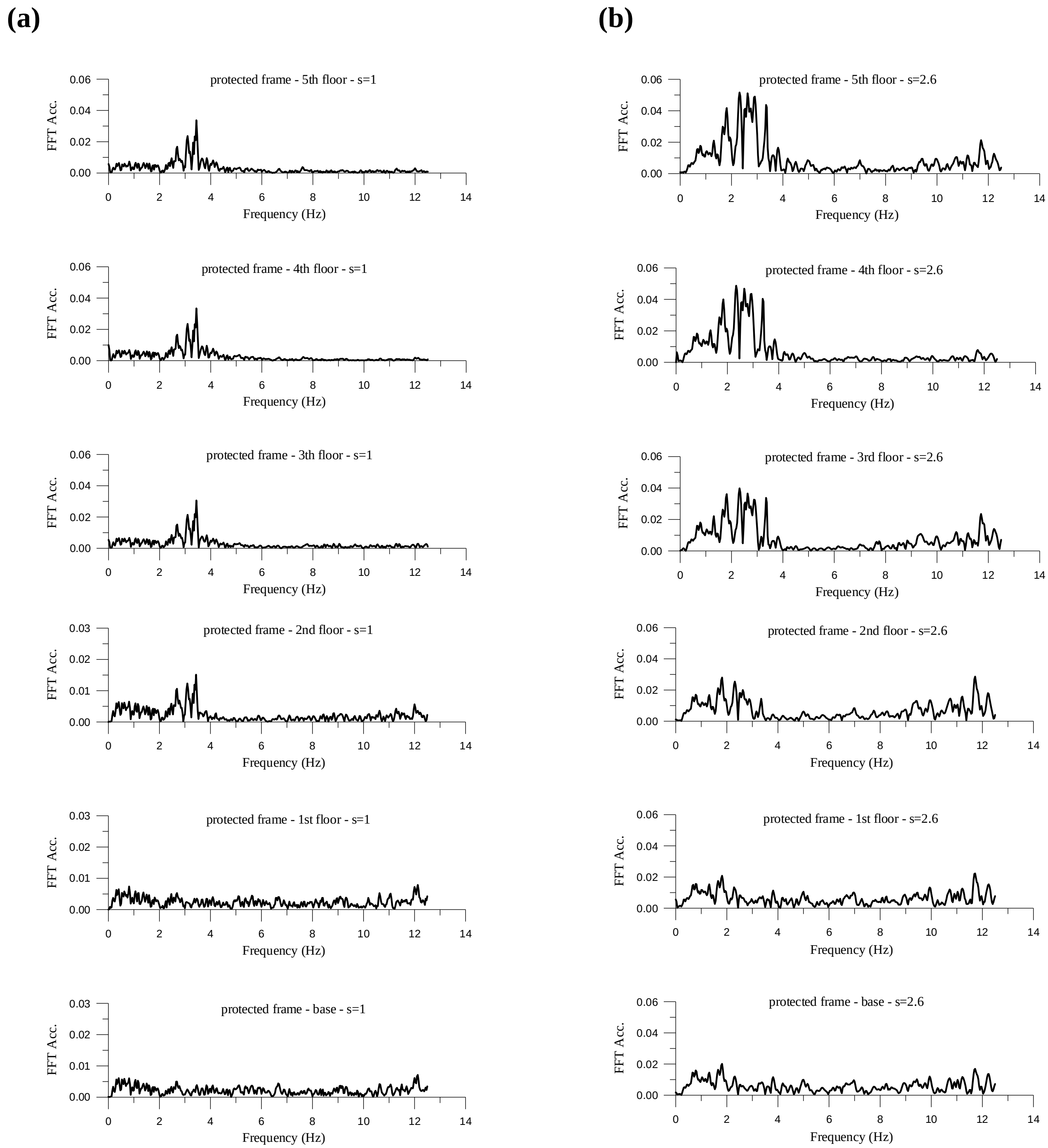

Fig. (10). Acceleration FFT for the protected frame. a) s=1; b) s=2.6.

mode shape was still the first one, while the most important mode shape for the frame analysed in this study is not the first one anymore, but a higher one.

In the previous study the maximum amplification ratio is found at the last level of the braced frame, while the maximum value for the protected structure is determined at the 5th level under the register with s=1. When the input is stronger (s=2.1), the top amplification reduces. It is even more than six times reduced respect to the amplification obtained for the braced frame, confirming that the friction dampers are working dissipating a great amount of energy.

Table **7** shows the values of the amplification of the acceleration FFT values at different levels. The maximum values gradually increase towards the top with a highest

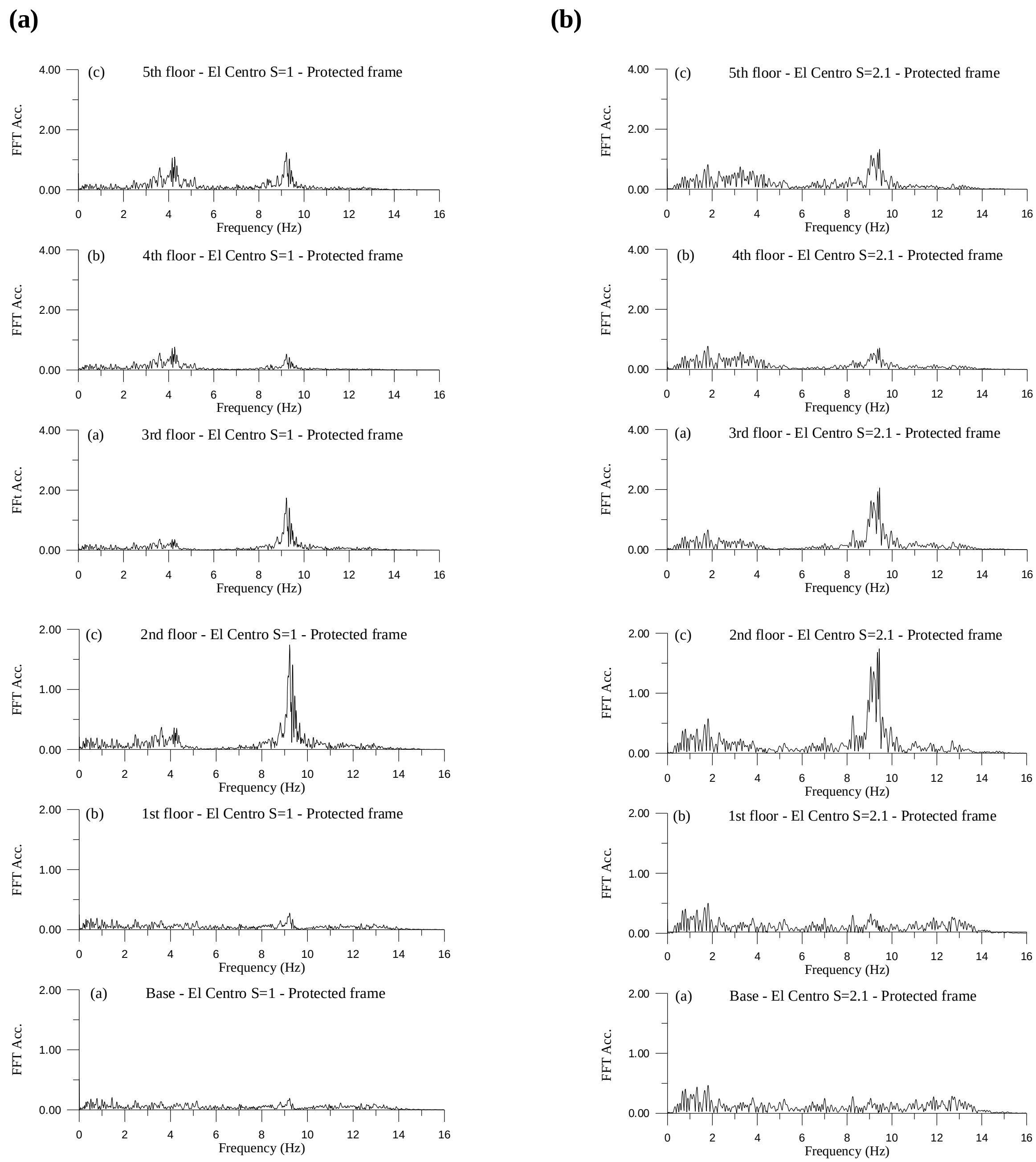

Fig. (11). Acceleration FFT for the protected frame in the previous study. a) s=1; b) s=2.1.

value at the last level; moreover the acceleration FFT values are highly reduced in the protected frames.

From Table **6** and comparing the response accelerograms to those obtained from the frame equipped with only one brace/dissipater it is possible to note the following.

5.2.1. Braced Frame

Accelerations are reduced in the last two floors and are higher in the 1st and 2nd levels if compared to the tests of the previous study.

5.2.2. Protected Frame (s=1).

The acceleration peaks are higher than in the previous study on the 1st and 2nd levels. On the 1st level the amplification is even higher than in a braced frame. A high resonance peak at the 2nd level around t = 19 s is noted.

At the 3rd, 4th and 5th levels the maximum acceleration value is reduced if compared to the values obtained in the previous study. In particular on the 5th level the acceleration is highly reduced, that is more than 30%.

Table 6. Acceleration amplification in case of one dissipater and two dissipaters installed in the bare frame.

MAX. ACC./MAX.ACC.TABLE						
Floor	Braced Frame		Prot. Frame (s=1)		Prot. Frame	
	1 dis.	2 dis.	1 dis.	2 dis.	1 dis.(s=2.1)	2 dis.(s=2.6)
1	0.928	1.380	1.099	1.661	0.930	1.410
2	2.328	2.745	1.588	2.203	1.366	1.666
3	2.409	1.632	1.783	1.449	1.742	1.266
4	3.350	1.953	1.358	1.023	1.192	1.286
5	5.360	1.914	2.742	1.215	2.030	1.533

Table 7. Amplification of the maximum value acceleration FFT at the different levels.

MAX. FFT ACC. /MAX FFT ACC. TABLE				
Floor	Bare Frame	Braced Frame	Prot. Frame (s=1)	Prot. Frame (s=2.6)
1	2.0538	2.1364	1.1069	1.1095
2	15.3790	15.9909	2.1238	1.4229
3	19.6822	28.9394	4.3038	1.9801
4	19.0098	29.3485	4.6976	2.4229
5	22.9829	30.0000	4.7398	2.5672

5.2.3. Protected Frame (S=2.6)

The acceleration values at the 1st and 2nd levels are higher than those acquired in the previous study because the input is higher than 19%. Nevertheless at the 4th level the acceleration peak has just a slightly increased value. Moreover, at the 3rd and 5th levels there is even a reduction of the peak accelerations respect to the results of the previous study showing the efficacy of these dissipaters in producing an increased energy dissipation.

CONCLUSION

On the basis of a previous structural and experimental study a steel frame protected by two friction dissipators has been examined. It is considered from a numerical point of view in order to get the best position of the devices in the frame to dissipate the highest amount of energy from a seismic event. The previous tests gave the possibility to calibrate the model determining more interesting characteristics, such as the quantity of energy dissipated in the presence of friction devices. The numerical design has been checked through a series of shaking-table tests on a real scale model subjected to the same signals.

The main conclusions of this research are:

- a simple numerical model allowed to calculate the best position of the friction devices in each frame in order to dissipate more energy from a seismic event;
- the presence of another friction damper affects more the last floors than the first ones where the acceleration amplification is increased;
- the acceleration amplification at different levels is more uniform in height than in the previous case of one dissipater for higher values of the input scale factor;
- during the shaking-table tests the simple friction dampers utilised in the model effectively dissipate energy reducing the damaging horizontal amplification accelerations at each level;
- the results obtained in the numerical analysis and from the shaking-table tests will be useful in the development of adequate codes for energy dissipating devices;
- the present study could determine a design criteria for practical application in order to assure the efficacy of the protection systems;
- more tests on models corresponding to Cases 2, 8 and 9 should be performed for comparison aims;
- in future researches other materials could be interposed among steel-steel friction surfaces in order to get a higher energy dissipation and, consequently, reduction of the responses.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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