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SHAKING TABLE TESTS TO COMPARE SEMI-ACTIVE CONTROL ALGORITHMS FOR VARIABLE DAMPERS

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Abstract. *The authors present and discuss the main results of a experimental campaign performed on a near full-scale semi-actively controlled steel building, in the framework of a research program financed by the Italian Department of Civil Protection. Four control algorithms have been investigated through shaking table tests under seven different natural earthquakes. They belong to the family of control algorithms based on a sound physical sense, where semi-active devices are typically seen as smart damping devices for which the amount of dissipation can be quickly regulated: usually they require less measurements, which often are made in the close surroundings of the device; therefore, the computational effort is fairly moderate and, in principle, it could be sustained by small, battery-powered computing systems. After a literature review on semi-active control algorithms, the paper first summarizes the logic behind the ones adopted in the tests. Then a direct comparison among them is done on the basis of the results gained from the tests. Each of the control logics has been evaluated and compared each other in terms of effectiveness in the reduction of interstorey drifts and of amount of dissipated energy, leading to comments may be useful for the design of a semi-active control strategy based on the use of such kind of variable devices.*

1 INTRODUCTION

Dealing with semi-active (SA) structural control, where dissipative devices are usually adopted, the relative effectiveness of various control algorithms is highly questionable. In order to compare different logics, an experimental activity has been done in the framework of the JETPACS (Joint Experimental Testing on Passive and semi-Active Control Systems) Program financed by 2005-2008 ReLUIS Executive Project (sponsored by the Italian Department of Civil Protection). The SA controlled structural mock-up (Figure 1) is a near full scale 2-story steel frame, equipped with two SA bracing systems including two magnetorheological (MR) dampers designed and manufactured in Europe.

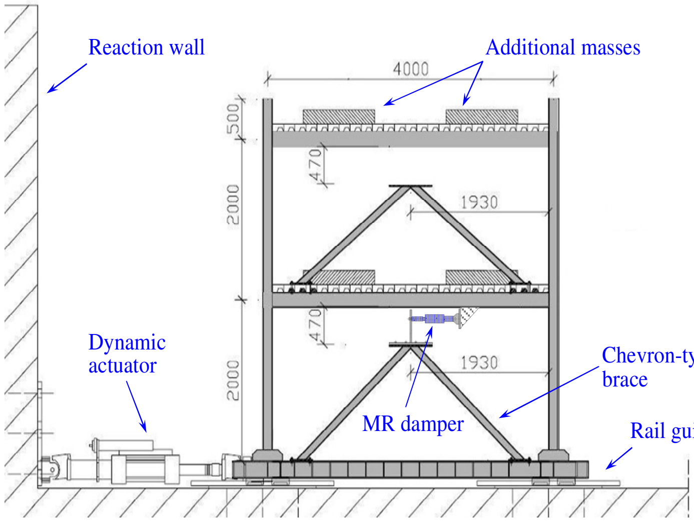

Figure 1: Experimental setup, with dimensions expressed in millimeters.

The tests have been performed by applying a set of earthquake records at the base of the structure, by utilizing a shaking table facility and four different control algorithms. All the considered control logics are "co-located", as they are able to change in real time the dynamical properties of the dampers according to the actual values of response quantities measured in the close surroundings of the dampers. They are much simpler to apply to real structures than control algorithms relying on a full state feedback. The first one (called "Energy") aims to maximize the amount of energy extracted by an SA damper and needs a flexible connection between the device and the floors among which the latter is installed. The second one ("Modulated Homogeneous Friction" - MHF) feeds the damper with a current proportionally to the last local maximum or minimum value of the 1st interstorey drift. The third control algorithm is referred to as "Sky Hook" since it aims to make the MR device mimics the behaviour of a damper constrained to the fixed space. The last investigated control logic ("Acceleration Reduction") aims to minimize the amount of absolute accelerations in the main structure, i.e. to minimize the energy transmission from the ground to the structure through the semi-active brace. Three of these algorithms are of bang-bang (i.e. ON-OFF) type and do not need any parameter to work. Their calibration consist only in setting the minimum (i_{min}) and maximum (i_{max}) values of current to be given to the damper in the OFF and ON condition, respectively. The other algorithm (MHF) belongs to the proportional type, feeding the damper with a current in the range [i_{min}, i_{max}] according to the instantaneous value of a specific response parameter. This logic is calibrated by setting the value of a gain constant, other than the i_{min} and i_{max} values.

The paper summarizes the logic behind the 4 adopted in the tests and shows the main experimental results they leaded to. A direct comparison among them is finally done in terms of effectiveness in the reduction of the structural response as well as in terms of capability to dissipate energy. The devices adopted for the tests were two full-scale prototype semi-active MR dampers manufactured by the German company Maurer Söhne, each being capable to react with a maximum force of about 30 kN with a stroke of ± 25 mm. The current in the dampers' circuit can be provided in the range 0÷3 A. Such dampers connected the base to the first floor of the frame through chevron type braces. Depending on the presence or not of stiffening plates above each brace, the link between each MR damper to the lower beam can be substantially rigid or flexible respectively (Figure 2). The electronic equipment used for the SA control of the devices is sketched in Figure 3 [1].

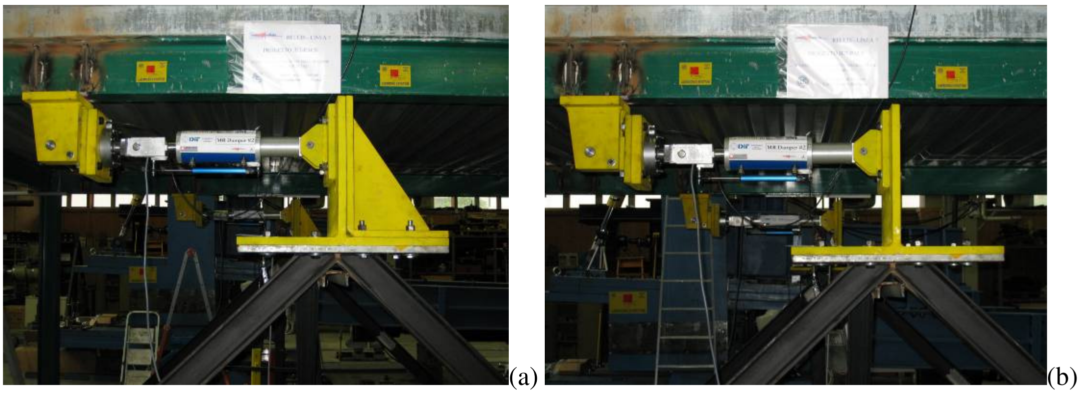

Figure 2: Two setup configurations, with (a) or without (b) stiffening plates behind the device.

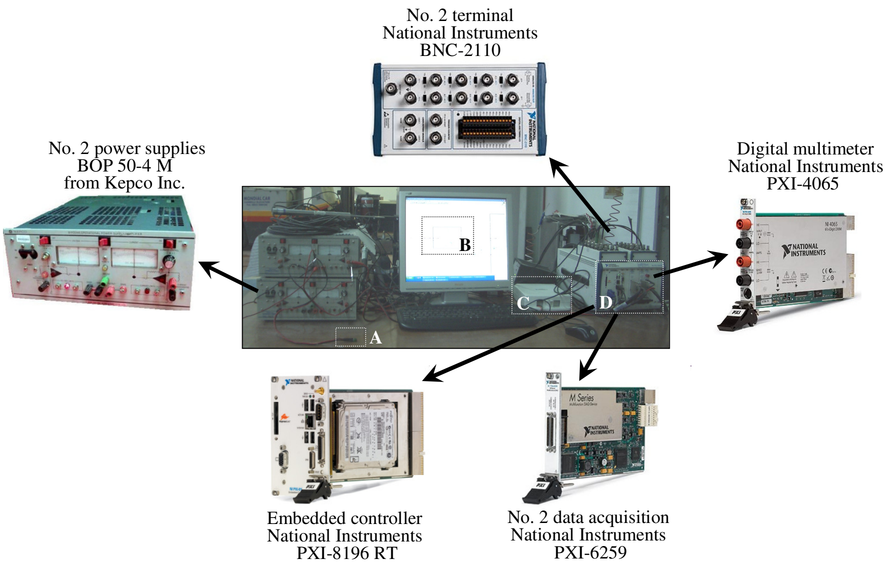

Figure 3: Main components of the electronic equipment adopted for the tests.

2 CONTROL ALGORITHMS ADOPTED FOR THE TESTS

The original formulation of the control algorithms has been modified to be used with SA MR dampers:

"Energy" algorithm: the 1st control algorithm aims to maximize the energy extracted by the SA damper from the structure [2]: when the force F_b acting on the semi-active brace and the velocity $\dot{x}_f$ of the point where the force is applied have the same sign, the power flows from the main structure into the semi-active damper, and the current feeding the magnetic coils should be set to its maximum value i_{max}; when there is a power flowing from the SA brace into the hosting structure, the damper should be set at its minimum value of the current, namely 0, so as to reduce as much as possible the power transmission to the hosting structure. In practice:

$$\begin{aligned} &if \quad F_b(t)\cdot \dot{x}_f(t) > 0 \quad then\ i(t) = i_{max} \\ &if \quad F_b(t)\cdot \dot{x}_f(t) \le 0 \quad then\ i(t) = i_{min} = 0 \end{aligned} \tag{1}$$

“MHF” algorithm: the 2nd control algorithm (“Modulated Homogeneous Friction”) was originally proposed by Inaudi [3], and modulates the current into the damper according to the actual response of the structure in terms of floor displacement. It is based on the definition of the “prior-to-peak” operator “*P*” related to the interstorey drift of the first floor $x_f - x_g$ (x_g is the ground displacement) and can be expressed as follows:

$$i(t) = g \cdot |P(t)| \tag{2}$$

where g is a gain constant, whose value has been assumed for each test such that the maximum intensity of current was given when the 1st interstorey drift ratio achieved the value of 0.005 (i.e. $x_f - x_g$ = 10 mm).

“Sky Hook” algorithm: the 3rd control algorithm aims to make the semi-active damper behave like a sky hook damper, i.e. a damper constrained to the fixed space [4-6]. Sky hook dampers guarantee an overall response reduction at all frequencies and tend to cancel resonance. During a dynamic excitation of the device, a real damper can mimic a sky hook one if its constant c_{real} can vary so as the force $c_{real}\cdot\dot{x}_f(t)$ becomes equal to the one $c_{sky}\cdot[\dot{x}_f(t)+\dot{x}_g(t)]$ of a sky hook viscous damper. Therefore, the control algorithm has to be expressed as:

$$\begin{aligned} &if \quad \frac{\dot{x}_f(t)+\dot{x}_g(t)}{\dot{x}_f(t)} \le 0 \quad then\ i(t) = i_{min} = 0 \\ &if \quad \frac{\dot{x}_f(t)+\dot{x}_g(t)}{\dot{x}_f(t)} > 0 \quad then\ i(t) = i_{max} \end{aligned} \tag{3}$$

“Acceleration Reduction” algorithm: the 4th control logic aims to minimize the amount of absolute accelerations in the main structure and, therefore, tries to minimize the energy transmission from the ground motion to the structure through the semi-active brace [7]. By considering the global dynamic balance, reducing the sum of elastic and dissipative forces leads to the reduction of the inertial force, hence of the absolute acceleration of a given mass. The logic imposes to take the device switched on if the elastic and dissipative forces have opposite signs (i.e. they tends to balance one each other), according to the following relations:

$$\begin{aligned} &if \quad x_f(t)\cdot[\dot{x}_f(t)-\dot{x}_b(t)] > 0 \quad then\ i(t) = i_{min} = 0 \\ &if \quad x_f(t)\cdot[\dot{x}_f(t)-\dot{x}_b(t)] \le 0 \quad then\ i(t) = i_{max} \end{aligned} \tag{4}$$

3 DESCRIPTION OF THE TESTS

The mock-up steel structure has been dynamically tested commanding the actuator to move the frame in the longitudinal direction, according to seven different European natural records. They are characterized by a mean acceleration spectrum compatible with the elastic response spectrum of the Italian Seismic Code OPCM 3274 [8] and of the Eurocode 8 [9] for soil type B and seismic zone 1. Figure 4 shows the superposition of the corresponding elastic acceleration spectra and the elastic response spectrum defined by the cited building code according to the parameters defined above. Two records (named 187 and 535) have demonstrated to be particularly damaging for the structure, even for the lowest intensity level (25%), so they are assumed as the main reference actions for the comparison of algorithms. The experimental activity consisted of 50 semi-active tests. Table 1 shows their characteristics. All the four control logics have been tested under the action of the heaviest earthquakes (187 and 535) allowing an effective comparison. The effectiveness of each control logic for a given earthquake at a certain input level has been also investigated repeating the same test with different values of imposed maximum intensity of current i_{max}. Table 1 also shows the type of connection of MR dampers to the chevron-type braces (flexible or rigid), depending on the algorithm. The control logic Energy requires a flexible connection (whose stiffness has been calibrated for this purpose) in order to work as described before, storing and dissipating energy in selected intervals of time, whereas the other control algorithms turned out to be more effective with a rigid link.

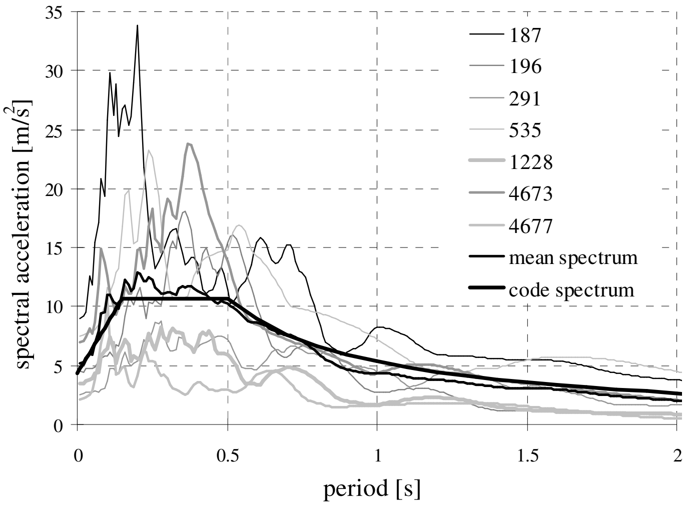

Figure 4: Elastic acceleration spectra (5% damping) of seismic inputs.

Earthquake signal	Input level [%]	Control algorithm	Maximum current [A]	Type of connection
187	50	Energy	1.0	Flexible
187	25, 50	MHF	1.5, 2.5	Rigid
187	25, 50	Sky Hook	1.0, 2.5	Rigid
187	25, 50	Acc. Red.	1.0, 2.0	Rigid
196	25, 50, 75	Energy	1.0, 2.5	Flexible
291	50, 100	Energy	1.0	Flexible
535	25, 50, 75	Energy	1.0, 1.5, 2.0, 2.5	Flexible
535	25	MHF	1.5, 2.5	Rigid
535	25	Sky Hook	1.0, 2.0	Rigid
535	25	Acc. Red.	1.0, 2.0	Rigid
1228	10, 25, 50, 75, 100	Energy	1.0, 2.5	Flexible
4673	50	Energy	1.0	Flexible
4677	50, 100	Energy	1.0	Flexible

Table 1: Experimental activity.

4 EXPERIMENTAL COMPARISON OF THE FOUR CONTROL ALGORITHMS

The control algorithms adopted for the above experimental activity are compared in the following in terms of capability to reduce the interstorey drifts as well as to dissipate energy. Finally they are compared according to six performance indexes accounting for different aspects related to the structural response (i.e. displacements, forces and energy demands). The most interesting results comes from tests performed using the 187 and 535 accelerograms scaled at 50% and 25%, respectively.

4.1 Comparison of the algorithms in terms of interstorey drifts' reduction

Each test has been analyzed in terms of floor horizontal displacements, leading to evaluate maximum interstorey drift values at the first and the second floor. Actually interstorey drifts are directly related to the structural and non-structural seismic demand to the frame [10]. For each algorithm, the current intensity corresponding to the greatest reduction of drifts has been selected. Figure 5 represents the corresponding peak interstorey drifts. The experimental data confirm that drift reduction achieved by SA control system, compared to the bare uncontrolled frame, can be close to 50%, consistently with the literature data based on numerical analyses. However, the response reduction provided by a SA control system can also be negligible, or even negative, depending on the occurrence of unavoidable misoperations [11] of the control algorithm as well as of delays in the control chain [12].

With reference to the 535-25% earthquake, Figure 6 reports, for 1 second time window corresponding to the most severe portion of the input motion, the superposition of 1st interstorey drifts for all the algorithms and the one relative to the uncontrolled structure. It allows a comparison of algorithms in terms of effectiveness, consistently with what already observed with reference to the peak values of the drift (Figure 5, right). Some remarks have to be given about the interstorey drift at the 2nd floor and the ability of control algorithms to manage it, also considering that neither measurements to be adopted in the control algorithms nor control forces existed at that floor. From Figure 5 one can observe that the 1-2 drift is often relatively large, sometimes overcoming the one corresponding to the uncontrolled structure. This can be explained as follows: *(i)* the presence of dampers only at the first floor of the building introduces an irregular distribution of damping over the height of the structure that affects the mode shapes; *(ii)* for the same reason the control system has little chances of actually control the drift at the second floor, that may strongly rise especially when the control forces excite, with their predominant frequencies, the second vibration mode of the structure.

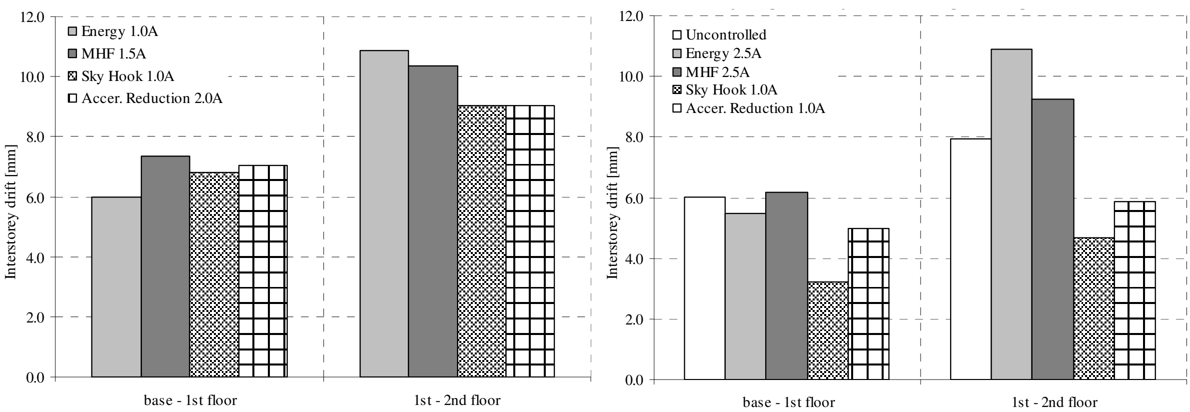

Figure 5: Comparison of algorithms in terms of peak interstorey drift demand: 187-50% (left), 535-25% (right) earthquakes.

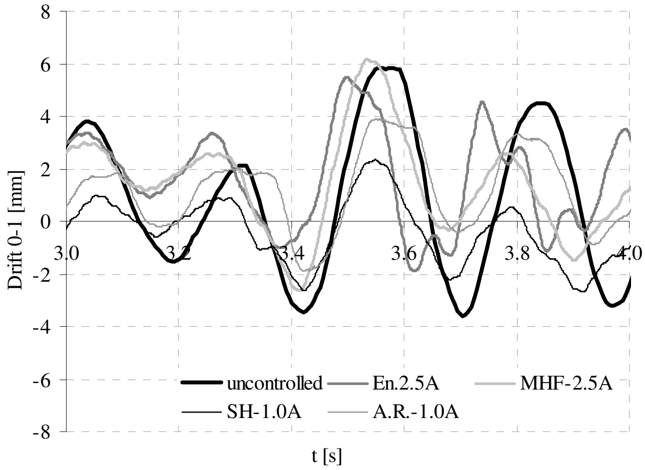

Figure 6: 1st interstorey drift response for a 1 second time window under the 535-25% earthquake: comparison of uncontrolled and SA controlled cases.

4.2 Comparison of the algorithms in terms of energy dissipation

The behaviour of the frame structure equipped with the semi-active bracing control systems has been analyzed also in terms of energy balance $E_{el}(t) + E_{kin}(t) + E_{diss}(t) = E_{inp}(t)$, where $E_{el}(t)$ is the elastic stored energy, $E_{kin}(t)$ is the absolute kinetic energy, $E_{inp}(t)$ is the seismic input energy, and $E_{diss}(t)$ is the dissipated energy. The instantaneous, final and maximum value of each one of the above energies have been computed in order to define, for each algorithm, the optimal value of the maximum current intensity i_{max}, i.e. the value corresponding to the minimum energy demand in the structure (the sum of elastic and kinetic energies is assumed as a measure of this demand). These values resulted to be coincident with those already found with reference to drifts and floor accelerations allowing to conclude that, for a given seismic input, the optimal calibration of each algorithm can be univocally defined. Table 2 reports for each test the maximum values of the input energy and of the sum of elastic and kinetic energies and describes the relative frequencies of occurrence of given threshold of energy, i.e., the percent occurrence of $E_{el} + E_{kin}$ values within given intervals of magnitude expressed in kJ.

The total input energy corresponding to a given earthquake resulted to be strongly dependent on the control algorithm adopted, allowing to highlight how the SA control via MR dampers is able to significantly modify the global dynamic properties of the structural system. In the two investigated cases, the Energy algorithm gives the largest amount of input energy, the Sky Hook logic the smallest one. This behaviour seems consistent with results in terms of drift and floor acceleration spectra shown in the previous section. As regard the sum of elastic and kinetic energies, the following comments can be drawn, for example, with reference to the 5 tests done with the 535-25% earthquake:

- the maximum value of $E_{el} + E_{kin}$ evaluated for each semi-active test again assumes the largest value for the Energy algorithm, even greater than the one corresponding to the uncontrolled case, highlighting a poor performance of the algorithm in this case; from this perspective the Sky Hook algorithm yielded the better performances;
- all the tested algorithms were able to bound most of the $E_{el} + E_{kin}$ values within the range 0.00-0.15 kJ, thus decreasing the number of strong cycles compared to the uncontrolled case; however, also in this case the Energy and Sky Hook algorithms corresponded to the worse and best response reduction respectively.

Control algorithm	max(E_{inp}) [kJ]	max(E_{el} + E_{kin}) [kJ]	Values of E_{el} + E_{kin} within intervals of magnitude [kJ]			
			0.00--0.05	0.05--0.10	0.10--0.15	0.15--0.80
Energy	1.01	0.79	87.6%	7.5%	1.1%	3.8%
MHF	0.93	0.38	87.4%	9.9%	0.7%	2.0%
Sky Hook	0.73	0.28	70.6%	26.3%	1.7%	1.4%
Accel. Reduct.	0.84	0.31	64.9%	29.7%	2.6%	2.8%
Uncontrolled	1.21	*0.41*	*53.5%*	*22.5%*	*13.8%*	*10.2%*

Table 2: Energy analysis referred to 5 tests done with earthquake 535-25%.

4.3 Synthetic comparison of the algorithms via performance indexes

The effectiveness of the four investigated control logics has been finally verified through six evaluation criteria related to the structural response and to the required performance of the control devices. They are defined as in Eq. (5). I_1 is related to the maximum peak interstorey drift ($max\ |\ d_{1,c}\ |$) of the 1st floor normalized by the corresponding value of the uncontrolled structure ($max\ |\ d_{unc,1}\ |$). I_2 is defined like I_1 but referred to the 2nd storey. I_3 is the ratio between the maximum value of the base shear and the one ($max\ |\ F_{b,unc}\ |$) registered during the uncontrolled test (m_i is the seismic mass of the i-th floor, $\ddot{x}_{tot,i}$ its absolute acceleration). I_4 is the maximum control force exhibited by the two MR devices normalized by the seismic weight W of the building (f_i is the force in the i-th device; i = 1, 2). I_5 is the maximum stroke Δ_i of the i-th control device normalized by the maximum 1st interstorey drift of the uncontrolled test. I_6 is the maximum value of the sum of elastic and kinetic energies normalized by the homologous value relative to the uncontrolled case.

They have been evaluated with reference to the 535-25% earthquake for which a larger amount of data is available for the comparisons. Figure 7 summarizes the results and allows a direct comparison of the algorithms. Almost for all the assumed criteria, the Energy algorithm leads to the worst performances, whereas Sky Hook to the best ones. Also the Acceleration Reduction algorithm determines a significant reduction of the structural response together with a fair behaviour of the control devices.

$$I_1 = \frac{\max_t \left| d_{c,1}(t) \right|}{\max_t \left| d_{unc,1}(t) \right|},\quad I_2 = \frac{\max_t \left| d_{c,2}(t) \right|}{\max_t \left| d_{unc,2}(t) \right|},\quad I_3 = \frac{\max_t \left| \sum_i m_i \ddot{x}_{tot,i}(t) \right|}{\max_t \left| F_{b,unc} \right|},$$
$$I_4 = \frac{\max_{t,i} \left| f_i(t) \right|}{W},\quad I_5 = \frac{\max_{t,i} \left| \Delta_i(t) \right|}{\max_t \left| d_{unc,1}(t) \right|},\quad I_6 = \frac{\max_t \left| E_{el}(t) + E_{kin}(t) \right|_c}{\max_t \left| E_{el}(t) + E_{kin}(t) \right|_{unc}} \tag{5}$$

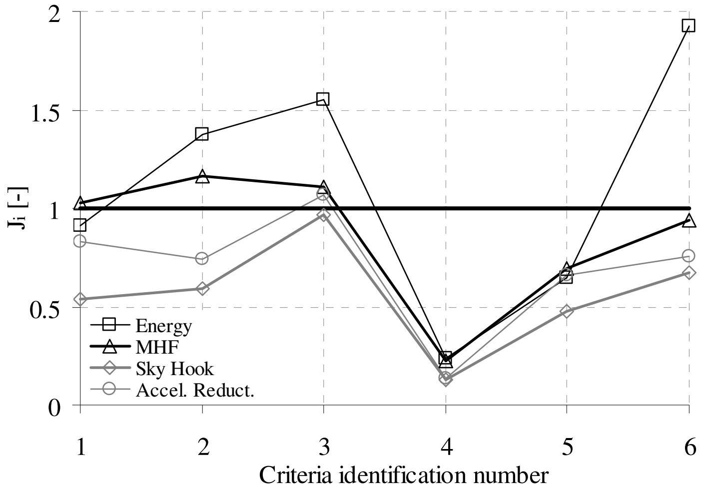

Figure 7: Performance indexes according to the 4 control algorithms (tests with 535-25% earthquake).

5 CONCLUSIONS

Four semi-active control algorithms have been investigated through shaking table tests on a near full-scale steel building, under seven different natural earthquakes. All the considered control logics are "co-located", as they are able to modify in real time the dynamical properties of the dampers according to the actual values of selected quantities representing the structural response in the close surroundings of the dampers. Three of these algorithms are of bang-bang type, while the forth algorithm belongs to the proportional type, feeding the damper with a current may range in a given interval according to the instantaneous value of a specific response parameter.

Although many control algorithms proposed in literature try to include the electric dynamics of the circuitry inside MR dampers, the matter can be satisfactorily addressed through an appropriate control hardware. In this way, the global reaction times of the SA damper can be bounded to 10 ms, leading to a negligible effect of the damper's internal dynamics.

In real applications, variations of the force provided by a MR damper are smooth also for control algorithms corresponding to sharp variations of the current inside the damper.

The experimental response reduction in terms of interstorey drift achieved by SA control system, compared to the uncontrolled frame, can be close to 50%.

Differently from passive control systems, reactive SA devices located only at few DOFs of a structure can increase the structural response at uncontrolled DOFs. This behaviour is dominated by the frequency content of the control action, rather than its discontinuous nature.

A SA control system can significantly modify the total input energy coming into a structure from a ground motion. Therefore, such an energy cannot be taken as a constant in evaluating the dissipation capabilities of a SA control system.

As possible future developments of the present work, the analysis of the floor response acceleration spectra [13] for each earthquake and each algorithm is programmed to explore how each algorithm modify the frequency content of the base accelerations throughout the height of the building. Finally a new experimental campaign on the same structures is programmed to assess the effectiveness of a "smart passive" control made by MR dampers and to compare it with the above SA strategies. In particular such tests will be performed calibrating the devices once before the test with a given intensity of current chosen according the intensity measures of the imposed strong motion [14-15].

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