13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2525

PERFORMANCE OF A SEMI-ACTIVE MR CONTROL SYSTEM FOR EARTHQUAKE PROTECTION

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SUMMARY

The experimental activity on the semi-active control systems does not match the relative theoretical research, so that the need to verify the theories formulated for a semi-active control strategy through applications to real structures is now very strong. This paper describes an experimental campaign, which has allowed to deeply examine some practical problems relative to the implementation of a smart system in a real structure. It shows the reduction of the response of a steel frame structure, controlled by a semi-active bracing system including magnetorheological devices as damping elements. This result is compared to the case of a passively operating control system, either experimentally or numerically investigated. The paper provides also a rather detailed picture of the kind of electronics adopted in the tests and of the time delays characterizing the control sequence of the semi-active bracing system.

INTRODUCTION

The implementation of semi-active control systems to protect building and bridge structures subjected to strong external excitations such as large earthquakes [1], is the object of several research efforts both from theoretical and experimental perspective. A semi-active control device is obtained by providing to a passive device the ability to be "smart", i.e. to self-adjust its own mechanical properties in real time according to properly selected control algorithms. The latters represent the operational logic driving the device’s instantaneous behaviour according to the structural response and/or the external dynamic excitation. The modification of the device’s parameters allows a semi-active control system to produce a temporary variation of the stiffness and/or damping characteristics of the structure in order to maximize the dissipated energy and eliminate the possibility of resonance. In practice, the energy supply needed by a semi-active control device for applying even large control forces is much smaller compared to an active control device. Besides, a semi-active control device, being typically small and compact, can be simply installed in a structure pretty much like a passive control device. Furthermore, it cannot drive the hosting structure to dynamic instability making the system highly reliable and its maintenance is much easier compared to active control.

In the field of civil structures, the validation of the concepts found in the relevant literature on semi-active control through real-scale experimental activities is actually an urgent requirement. The first application

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of active structural control was the 11-storey steel Kyobashi Seiwa Building constructed in Tokyo, Japan, in 1989. A new stage in the field of innovative earthquake-resistant strategies for civil structures began, and, since then, different types of active, hybrid and semi-active control systems have been implemented in tens of buildings. Nishitani and Inoue in [2] show an almost complete picture of the current state of control applications in the Japanese territory, having the largest number of applications in the world. The authors provide a chronologically ordered list of the 32 controlled buildings in Japan, and specify for each of them number of storeys, heights, locations, and type of actuators. 24 of them are high-rise buildings according to the Building Standard Law of Japan (buildings with heights of over 60 m), i.e., rather than issues related to the structural safety against severe earthquakes, they suffer the problem to become uncomfortable for occupants during strong winds, because of their high flexibility and their consequent long natural period. 16% of the above structures (5 buildings) are equipped with Active Mass Driver (AMD) system, 75% (24 buildings) with Hybrid Mass Dampers (HMD, i.e. a combination of TMD and AMD) system, 3% (1 building) with Active Variable Damper (AVD) system, 3% (1 buildings) with Active Variable Stiffness (AVS) system, and the last 3% (1 building) with a combination of Base Isolation and AVD. Only 9% of the structures, i.e. 3 low-rise buildings, have been equipped with semi-active control systems. As active structural control technology cannot be considered a viable strategy against severe earthquakes, the authors stress the importance of further research and development of semi-active control systems because they represent the most promising strategies based on the principle of less energy and better performance.

Tagami et al. in [3] show the results of stationary excitation tests and free vibration tests on an actual Japanese low-rise (11 storeys) building, equipped with semi-active switching oil dampers included in bracing systems. The experimental tests were carried out in both the 'uncontrolled' and the 'controlled' structural conditions, and showed that the response reduction was almost twice as much that associated to the passive counterparts. Nevertheless, the semi-active viscous device was efficacious even for very small values of the stroke, i.e. it could control vibrations caused not only by large earthquake but also by small earthquakes or strong wind.

Another full-scale application [4] is the installation of two semi-active mass dampers in a Japanese high-rise (24 storeys) steel building, whose upper floors are subjected to uncomfortable vibrations especially in the torsional direction due to strong winds. The mass damper system includes an oil damper semi-actively controlled by solenoid valves in the hydraulic circuit, and it has been designed to be effective also during large earthquakes inducing large stroke displacements and velocities. In fact, the solenoid valves can provide the optimum damping factor of the control system in the case of smaller vibrations under strong winds, and a larger damping factor in the case of larger vibrations occurring under the action of serious earthquakes.

Hiwatashi et al. [5] experimentally investigated a 3-story large-scale test frame either with a base isolation system, made up of four laminated rubber bearings and a semi-active MR damper, or with a semi-active magnetorheological (MR) damper installed through K-type braces at the first story. It is shown that, in the second control configuration, the structural response, in terms of displacement and acceleration, obtained under the input waves used for the shaking table tests (a sweep sinusoidal wave, white noise wave and different earthquake waves), decreases with the rise of the electrical current to the MR damper.

Also Morishian et al. [6] made another experimental application of a variable-damping MR fluid device on a 3-story small (100x200x660 mm) structural mock-up. The device is inserted between the top of a brace and the first floor, and a sine-sweep excitation test, with frequency slowly increasing from 2 to 20 Hz, showed the performance of the vibration control system in terms of displacements of the floors.

Even if some semi-active control applications have been carried out in the recent years, some practical important issues relative to the implementation process (system configuration, software/hardware integration, system status monitoring, measures, and control performance verification) have not been yet solved by the actual research efforts.

In practice, the available scientific literature has not yet given answers on some fundamental questions: the type and complexity of the equipment to be adopted in the experimental tests, the practical things still to be made to bring a semi-active control system outside of a lab for real-life applications, and the effective improvement in the reduction of the structural response associated to semi-active control systems compared to their passive counterparts. To the aim to contribute to the solution of the above questions, this paper describes the experimental campaign designed so as to verify the efficacy of a properly manufactured semi-active control system based on magnetorheological (MR) dampers for a steel structure. In the general view of the recently investigated semi-active devices, MR dampers can effectively materialize the concept of time-varying damping device: they are characterized by the possibility of continuously varying the intensity of the magnetic field inside its body by using low-power electrical currents, so that a wide range of physical behaviours can be commanded to the device. The dependence of their self-adjusting properties on electrical rather than mechanical modifications inside the devices, makes the operation of such devices fast (in the order of few milliseconds) and reliable [7].

EXPERIMENTAL SET-UP

The experimental campaign performed on a steel frame mock-up (named MISS) equipped with a semi-active bracings system (figure 1), has been one of the main objects of the EU funded SPACE (Semi-active and PAssive Control of the dynamic behaviour of structures subjected to Earthquakes, wind and vibrations) research project (5th FP, 1998-2002). It has been carried out by using the 6 degrees of freedom Multi Axes Shaking Table for Earthquake Reproduction located at the Structural Dynamics Testing Laboratory of ENEL.Hydro – ISMES (Bergamo, Italy) [8][9].

The tested structure

The 4-story steel frame structure is owned by ENEA and has been manufactured by using HEB100 beam elements to make 4 horizontal frames (3.3 × 2.1 m plan dimensions), bolted with an inter-story distance of 0.9 m at 6 vertical columns (HE100B) 4.5 m high. 4 concrete masses (each weighting 12.8 kN) are supported by each floor slab. The total weight of the structure is 226 kN and the steel grade is 275J0H, i.e. Fe430 of the Italian classification (characteristic ultimate strength f_{tk} = 430 MPa, characteristic yield strength f_{yk} = 275 MPa).

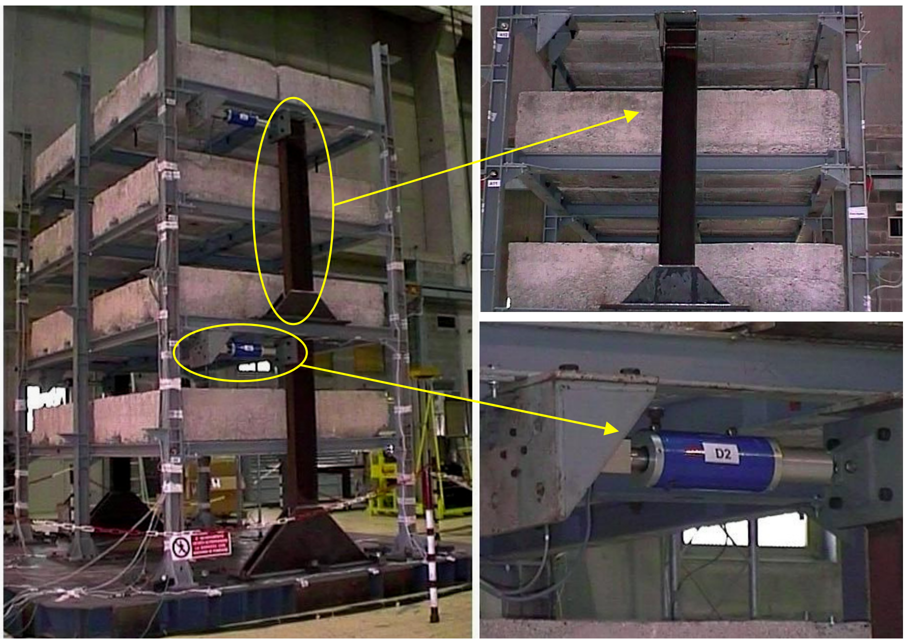

Figure 1. Tested structure: elastic brace and MR damper

The first three modal frequencies of the structure ω_1 = 13.82 rad/s, ω_2 = 54.66 rad/s, ω_3 = 117.50 rad/s have been provided by the experimental results of the sinusoidal single axis sweep tests aiming to characterize the uncontrolled (i.e., without bracing elements) structure.

The semi-active bracing system

A semi-active "smart" bracings system has demonstrated to be quite effective to help such a kind of structure, often equipped with braces, to resist lateral forces [10]. It is made up by three parts: an elastic brace, a semi-active device representing the time-varying damping element linking the brace to the hosting structure, and a control algorithm.

4 flexible braces (steel profiles IPE200) have been equipped on their top with a semi-active MR damper (figure 1), and have been mounted along the short edge direction of the frame, between ground and second floor (the lower one) and between second and forth floor (the upper one). The free length of the braces has been reduced by inserting reinforcing plates at the base, in order to obtain bracing stiffnesses of the same order of magnitude of the lateral stiffnesses of the frame, and therefore to optimize the effectiveness of the semi-active control system [11].

In the framework of the SPACE research project, the semi-active MR dampers (figure 2) have been designed and manufactured by the German firm Maurer Söhne (Munich), and experimentally tested to characterize their passive and semi-active operation. With the exception of the extra wires needed to feed the coils inside the body, the MR dampers look pretty much like conventional fluid viscous ones; besides, compared to other commercially available semi-active devices, they are very reliable because of the absence of moving parts like electrically controlled valves or mechanisms. Each prototype MR device has overall dimensions 712 × 200 × 250 mm and a mass, without connections, approximately equal to 16 kg; it can develop a maximum damping force of 50 kN along its longitudinal axis and the piston stroke is equal to ±25 mm. The electromagnetic circuit needed to generate the magnetic field in the device is implemented in a very innovative way, and the current in the circuit, in the range i = 0÷3 A, is provided by a power supply commanded by a voltage input signal.

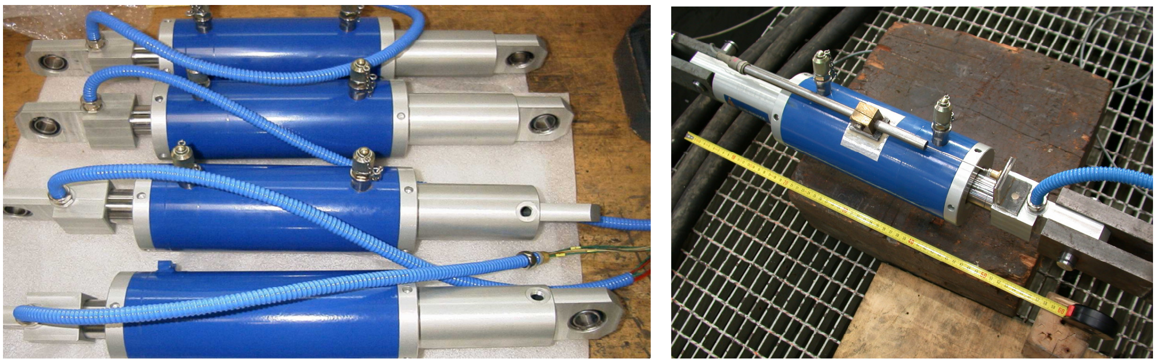

Figure 2. Prototype of MR dampers

The first part of the wide experimental campaign was aimed to investigate the mechanical behaviour of these dampers: it has been demonstrated that the classical linear Bingham model, commonly considered in literature to describe their dynamics, shows some limits if used to interpolate the experimental data relative to different current levels i and test frequencies. Instead, the following numerical "improved model" [7]:

$$F_d(U) = F_\eta + F_{dy} = C(i) \cdot |U|^{\alpha(i)} \cdot \mathrm{sgn}(U) + \left[F_{dy,\min} + \left(F_{dy,\max} - F_{dy,\min}\right) \cdot i / i_{\max}\right] \cdot \mathrm{sgn}(U) \quad (1)$$

expressing the MR damper's force as sum of two components due respectively to the fluid viscosity and to the magnetic field-induced yield stress, is able to closely fit the experimental data measured during the tests on the devices. The experimental characterization of the devices [7] has shown that both components depend on the current intensity in the coils inside the body of the damper. The first component (F_η) has to be assumed non-linearly dependent on the relative velocity U between the damper's ends in order to take into account the dependence of the damper's behaviour on the test velocity (figure 3): the viscous damping parameter C is linearly variable with the current in the coils inside the damper ($C(i) = 5.5 + 5.0 \cdot i$ [kNs/m]) and the power α is a quadratic function of the current i ($\alpha(i) = 0.0795 \cdot i^2 - 0.3475 \cdot i + 0.9$). The second component (F_{dy}) is given by a linear relationship with the current i and varies from a minimum value $F_{dy,min}$ = 0.6 kN (at i = 0 A) due to the friction force of the gaskets to a maximum value $F_{dy,max}$ = 28 kN (at i_{max} = 3 A) due to magnetic saturation.

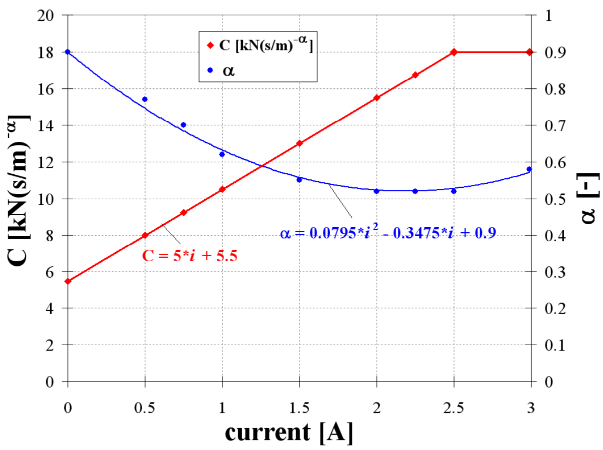

Figure 3. Improved model: constitutive laws of the viscous component's parameters

The second part of the experimental campaign has allowed to investigate the promptness of the semi-actively operating MR dampers through a statistical analysis of the experimental results of semi-active shaking table tests, performed by using a dedicated electronics. The time delays singled out in the control chain (acquisition-processing-actuation) have shown to be practically independent on the test frequency, and their mean values are about 10 ms in the on-off phase (i.e. after a switch off command to the device, current i from 3 A to 0 A) and about 13 ms in the off-on phase (i.e. after a switch on command to the device).

Instrumentation and dedicated electronics

The shaking table, used for the experimental tests on the controlled MISS structure, has been driven only along the transversal direction X of the frame.

Two separate hardware have been utilized for the acquisition of the structural response and for the control system. The scheme in figure 4 shows the experimental set-up of the building, i.e. the position of the most significant transducers on the shaking table and on the structure, whereas tables 1 and 2 list, respectively for the structural response and the control system, the channels acquired during the experiments, the instrumentation used and the measured physical quantities. Among them, the relative displacement between the MISS 2nd floor and the shaking table has been measured by using a rigid reference structure.

A specific electronic hardware and software (figure 5) has been acquired for the semi-active operation of the MR dampers. They consist of a real time National Instruments CPU (Pentium III, 850 MHz), two digital acquisition boards (DAQ boards) with a total of 16 inputs and 4 outputs (16 bits resolutions and 333 kHz sampling rate), the environment Labview Real-Time, and four operational power supplies (model BOP 50-4M) from Kepco Inc. (New York, USA). The latter are fully dissipative linear stabilizer for laboratory and systems applications, each having an output power of 200 W, a maximum input power of 450 W, and an output range of ±50 V. They have two bipolar control channels (voltage and current mode), selectable and individually controllable either from its front panel controls or by remote signals.

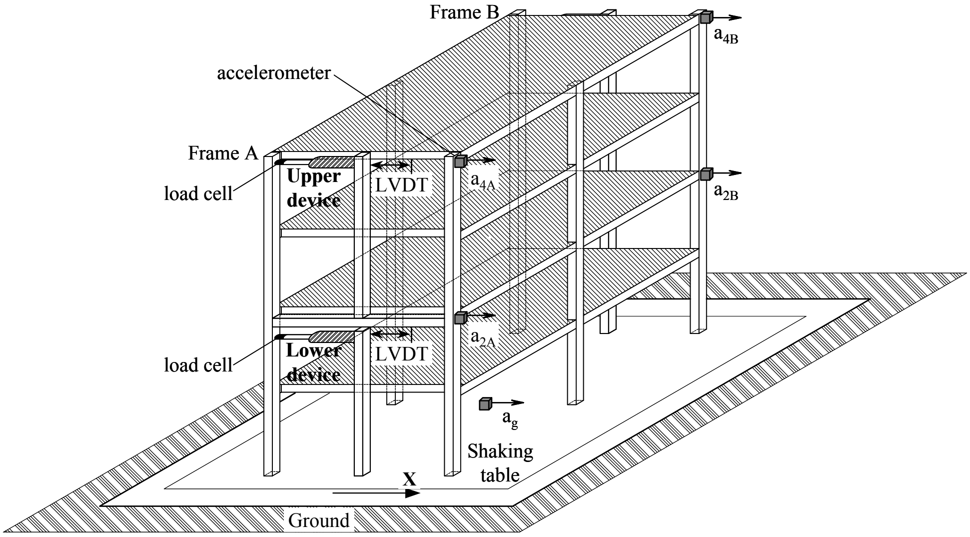

Figure 4. Experimental set-up

Table 1. Sensors for the response acquisition: acquisition channels, transducers and measured physical quantities

Channel	Transducer	Physical quantity acquired
ATx, ATy, ATz	Accelerometer	Accelerations of shaking table
A1÷A12	Accelerometer	Accelerations of the floors (X and Y directions)
R1x	LVDT	2^{nd} floor displacement relative to the shaking table
P1, P2	Voltage transd.	Voltage commanding the upper and lower devices
C1÷C4	Current transd.	Current supplied to the devices
LD1÷LD4	LVDT	Relative displacement in the dampers
FD1÷FD4	Load cell	Axial force on dampers piston

Table 2. Sensors for the control system: acquisition channels, transducers and measured physical quantities

Channel	Transducer	Physical quantity acquired
AT	Accelerometer	Acceleration of shaking table
AC1÷AC4	Accelerometer	Accelerations of the floors (X direction)
LD1÷LD4	LVDT	Relative displacement in the dampers
FD1÷FD4	Load cell	Axial force on dampers piston

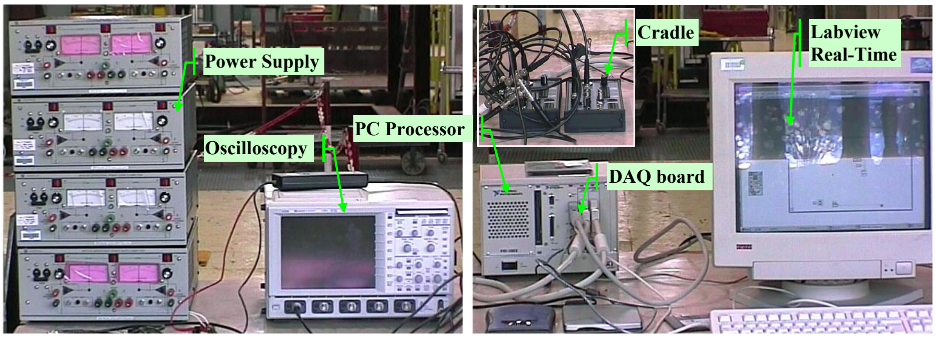

Figure 5. Dedicated electronics for semi-active tests

The power supplies have been used as current-drivers rather than voltage-drivers, in order to limit to few milliseconds the time needed to reach the steady-state phase of the current inside the dampers' electromagnetic circuit. Indeed, preliminary tests on the semi-active operation of the MR dampers have clearly showed that, in the case of a current driven feeding scheme, a sudden increase from 0 to 7.5 V of the voltage driving signal to the power supply makes the current inside the damper rise from 0 to the maximum value (≅ 3 A) in only approximately 7 ms, because the voltage difference at the edges of the coils reach for a short time a value near the saturation (≅ 50 V), and then settles down to a stable value of 11 V. Likewise, a sudden decrease from 7.5 to 0 V of the control command voltage can bring the current down from 3 to 0 A in about 5 ms, by producing a negative voltage spike of about 50 V.

CONTROL ALGORITHMS AND THEIR IMPLEMENTATION

The control algorithm represents the operational logic needed to drive the instantaneous behaviour of the semi-active devices, i.e. to make them capable of self-adjusting their own mechanical properties in real time according to a desired final effect.
The authors [12] have modified a simple control logic proposed by Inaudi & Hayen [13] for a variable-damping bracing system (VDB) including a time-varying linear viscous damping device, in order to obtain an effective control algorithm to be applied to a MR device with a time-varying magnetic field-induced plastic threshold (figure 6). The aim of the control logic is to maximize the energy extracted from the main structure, by keeping locked the VDB's MR damper during most of the operating time to transfer energy from the structure to the elastic brace, and unlocking it for short time intervals to dissipate in the damper the energy stored in the elastic element. The initial instants of these short intervals correspond to relative minima or maxima in the motion $x_f(t)$ of the points of attachment of the VDB on the hosting structure. In order to properly drive the control system, the natural frequency of the VDB system should be much higher than that of the controlled structure, whereas the damping behaviour should be selected so as to achieve a fast energy dissipation during unlocking intervals, and to concentrate the VDB's deformation mostly in the spring during locking phases.

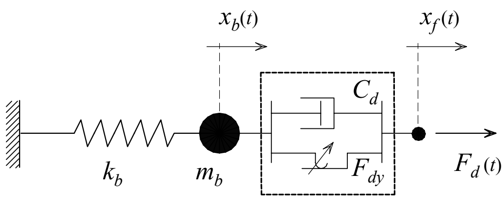

Figure 6. Variable-damping bracing system with MR device

In the analytical formulation of this control logic:

$$\begin{aligned} &\text{if} \quad F_d(t)\cdot \dot{x}_f(t) > 0 \quad \text{then } F_{dy}(t) = F_{dy,\max} \\ &\text{if} \quad F_d(t)\cdot \dot{x}_f(t) < 0 \quad \text{then } F_{dy}(t) = F_{dy,\min} \end{aligned} \tag{2}$$

the product of the damper's force $F_d(t)$ by the structural velocity $\dot{x}_f(t)$ represents the power flow from the main structure to the device, and $F_{dy,max}$ and $F_{dy,min}$ are the selectable damping values of the 2-stage device. During the storing phases, the power flow from the structure to the control system is positive and the VDB has to be tuned so as to achieve the maximum possible strain in the elastic element, i.e. the variable plastic threshold F_{dy}, controllable by the current feeding the coils inside the semi-active device, has to be set as high as possible. During the dissipation phases, the sign of the power flow changes to negative and the MR damper can dissipate the elastic energy stored in the brace by switching F_{dy} to its minimum value. A proper design of the control system is achieved when the strain of the brace goes fast to zero, and the elastic energy stored therein is dissipated in a time interval that is short if compared to the natural period of the frame.

ANALYSIS OF THE EXPERIMENTAL RESULTS

Figure 7 shows the time-histories and the acceleration response spectra (5% damping factor) of the seismic inputs imposed to the shaking table during the tests of the MISS frame mock-up. They are: the Tolmezzo (medium-rigid soil) record of the 1976 Friuli (Italy) earthquake, the second (N-S) component (Northridge) recorded in 1994 at Sylmar County Hospital parking lot (California), and a synthetic accelerogram generated according to Eurocode 8 for soft (CGS) soil conditions. The figure shows the accelerograms scaled up or down to the maximum level adopted during the tests.

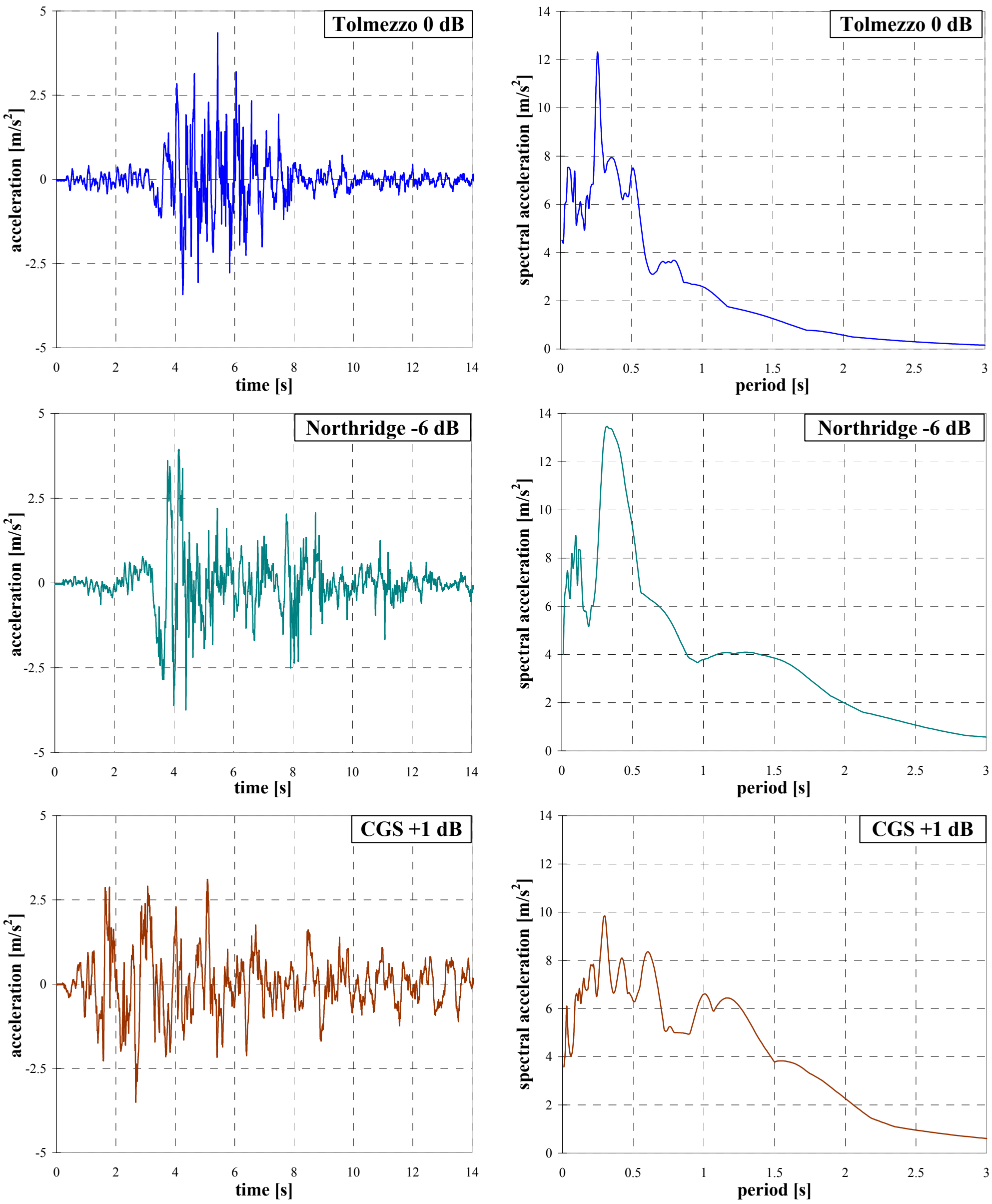

Figure 7. Scaled time-histories and spectral acceleration (5% damping) of seismic inputs

Four different structural configurations have been investigated for the seismic tests: an uncontrolled, or unbraced, configuration (i.e. without MR dampers), a "passive off" control configuration (i.e. no control signal provided to MR dampers), a "passive on" (rigid link) control configuration (i.e. a constant 2.5 A current provided to MR dampers), and a semi-active control configuration (i.e. a time-varying current input signal feeds the MR dampers according to the algorithm). In the "passive off" configuration the MR dampers behave almost like viscous devices; in the "passive on" configuration, the MR dampers represent a rigid link between the braces and the hosting structure.
For each control configuration, the seismic inputs have been applied at increasing amplitudes (i.e. increasing levels expressed in dB) up to a maximum value corresponding to the achievement of a limit value of the 2nd floor displacement (20 mm) or of the table's overturning moment (300 kNm). It is worth to point out that the maximum level reached in the semi-active configuration is 2.5 ÷ 4 times larger than that one reached in the uncontrolled configuration.

Reduction of the structural response

Figures 8 to 10, each relative to one of the considered seismic input (Tolmezzo, Northridge and CGS, respectively), show the experimental results, in terms of peak 2nd floor relative displacement and peak 4th floor absolute acceleration, for all the control configurations and the input levels. First of all, for any given earthquake and amplitude level, both displacements and accelerations in the "passive off" configuration are reduced with respect to the uncontrolled case, not shown in the figures. Comparing "passive off" and "passive on" cases, the latter condition corresponds to a more rigid structure, resulting in higher accelerations and lower displacements. However, in the semi-active configuration, the recorded displacements are recognized to be reduced of about 30% ÷ 40% with respect to the "passive on" case, whereas the maximum accelerations appears very close to those recorded in the rigid link configuration.
Figures 8 to 10 also show the displacement response reduction and the trend of the acceleration for different magnitude levels of a certain seismic excitation, and allow to observe that the larger is the magnitude of the excitation the higher is the effectiveness of the semi-active control system. Furthermore, it is worth to point out the strong dependence of the structural response in the "passive on" configuration on the input excitation, whereas the performances of the control system in the semi-active configuration seems to be quite independent of the recorded ground motion.

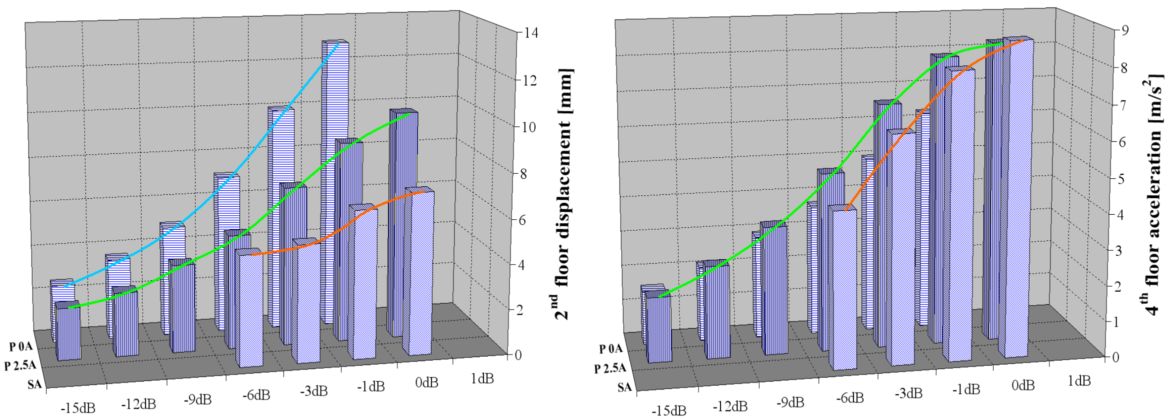

Figure 8. Tolmezzo: relative displacement of the 2nd floor and absolute acceleration of the 4th floor

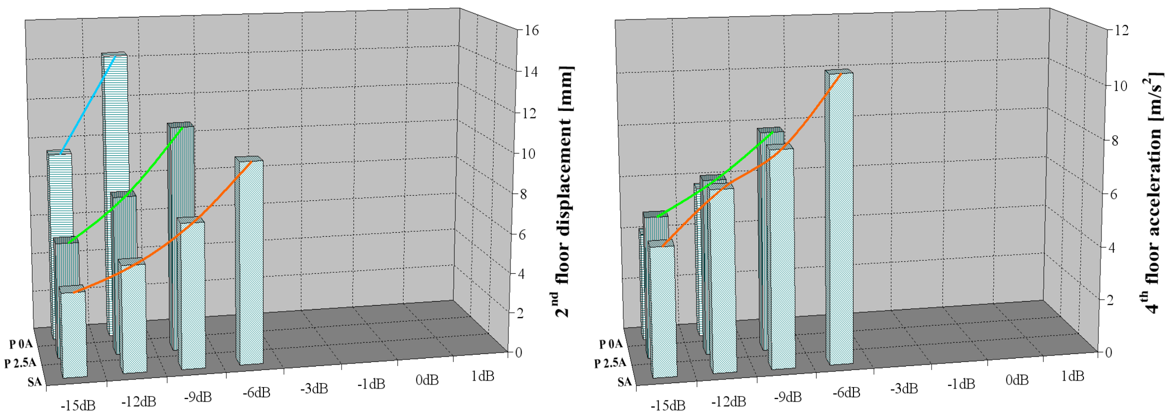

Figure 9. Northridge: relative displacement of the 2nd floor and absolute acceleration of the 4th floor

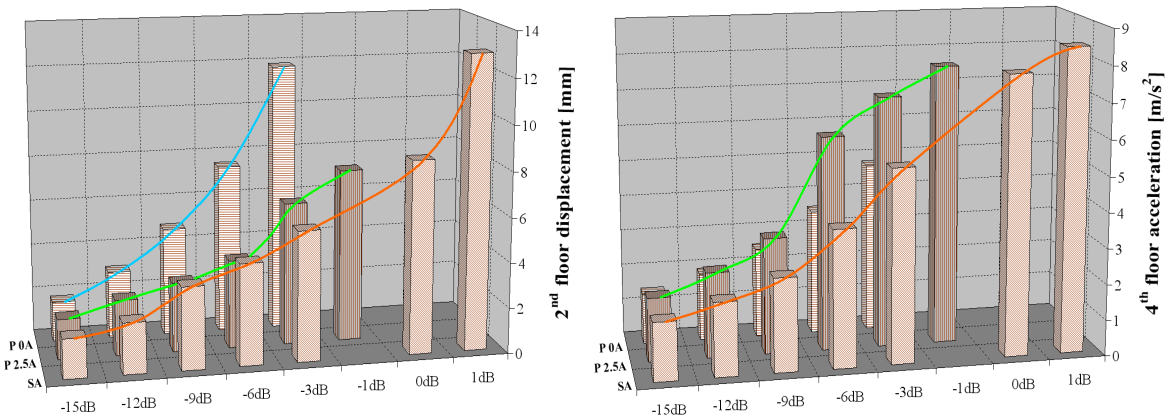

Figure 10. CGS: relative displacement of the 2nd floor and absolute acceleration of the 4th floor

Operating delays

The time delays characterizing the control sequence (acquisition-processing-actuation) of the semi-active bracing system can be described as follows:

- A time delay of the control electronics τ_c, including, consecutively, the time intervals associated to signal acquisition, to acquired signal processing through the control logic and to operations of the power supply. This last time interval starts when the driving signal (in output from the algorithm and in input to the power supply) is issued and ends when the current (in output from the power supply and in input to the device) begins to change.
- A time delay of the damper's electromagnetic circuit τ_e, i.e. the time interval starting when the current (in input to the device) begins to change and ending when the current reaches the commanded nominal value within a ± 5% tolerance.
- A time delay of the mechanical part of the damper τ_m, i.e. the time interval between the instant when the current (in input to the device) begins to change and the instant when the damper begins to adjust its mechanical behaviour.

Figure 11 shows the promptness of the semi-active MR device through a magnification of some time histories recorded during the seismic test performed under Northridge –9dB earthquake. The recorded signals are the displacement of the 2nd floor, the relative displacement between damper's ends, the force developed by the device, the driving signal and the current inside the damper. The delay τ_c of the control electronics, spanning from the moment when the power flow changes its sign to negative to the moment when the command signal is issued, is within 6 ms for both the on-off and the off-on phases (the delay of the power supply is within 5 ms). The delay τ_c could be shortened by using purposefully manufactured electronics instead of commercial hardware and software. The delay τ_e of the electromagnetic circuit, spanning from the issue of the command signal to the stabilization of the current into the damper at the commanded nominal value, is within 13 ms in both the on-off and the off-on phases. Lastly, the mechanical delay τ_m of the MR damper is within 10 ms (i.e. shorter than the electric delay) and measures the time interval from the control signal to the moment when the damper adjust its behaviour according to the received command.

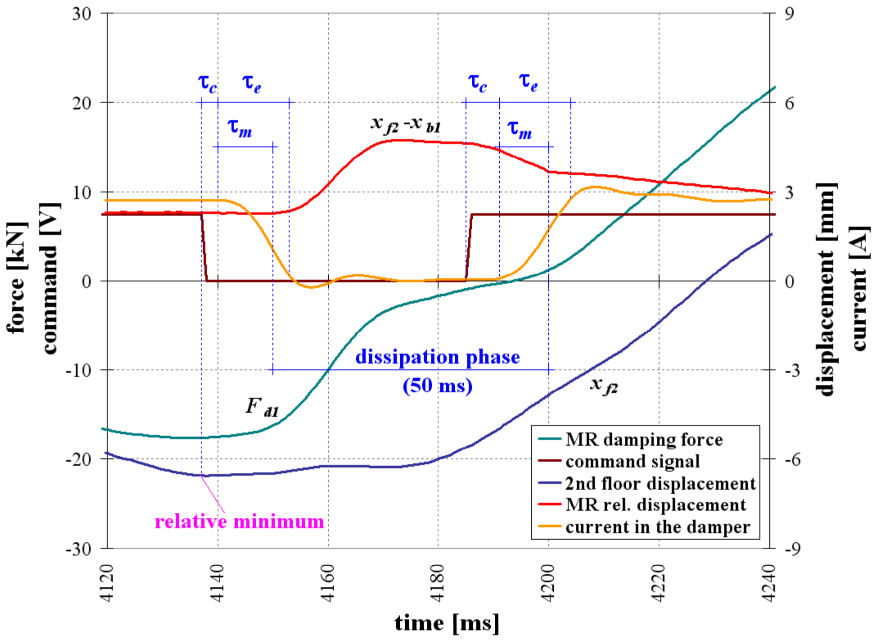

Figure 11. Semi-active operation of the MR damper: seismic test under Northridge –6dB

At any occurrence of the operational cycle of the controlling algorithm and for all of the tests performed, the total time delays $\tau_{off} = \tau_c + \tau_e$ and $\tau_{on} = \tau_c + \tau_e$ required by the current to reach 5% and 95% of the nominal value set by the algorithm in the on-off and the off-on phase, starting from the time when eq. (2) changes its sign, have been measured. A statistical analysis of such experimental data clearly shows that the mean values of such delays τ_{off} and τ_{on} are about 16 ms in the on-off phase and about 19 ms in the off-on phase [14].

Numerical-experimental comparison

Figure 12 shows a 6 (4+2) dynamic degrees of freedom model, able to reproduce the first four transversal modes of the experimentally tested MISS structure. The diagonal mass matrix, the full stiffness matrix and the proportional damping matrix of the uncontrolled building's 4-DOF model (i.e. without any bracing system) have been obtained from the tests performed in the uncontrolled configuration [15]:

$$\mathbf{M}_s = \begin{bmatrix} 5.679 & 0 & 0 & 0 \\ 0 & 5.679 & 0 & 0 \\ 0 & 0 & 5.679 & 0 \\ 0 & 0 & 0 & 5.679 \end{bmatrix} \quad [\text{ton}]$$

$$\mathbf{K}_s = \begin{bmatrix} 110754.0 & -63347.4 & 20153.3 & -2772.9 \\ -63347.4 & 83565.0 & -55312.2 & 14074.6 \\ 20153.3 & -55312.2 & 66792.6 & -27785.7 \\ -2772.9 & 14074.6 & -27785.7 & 15951.1 \end{bmatrix} \quad [\text{kN/m}] \tag{3}$$

$$\mathbf{C}_s = 2\alpha\mathbf{K}_s + 2\beta\mathbf{M}_s \quad [\text{kNs/m}]$$

where the coefficients $\alpha = 0.3978 \cdot 10^{-3}$ s and $\beta = 0.2585\ \text{s}^{-1}$ have been derived by assuming a damping ratio of 2.5% for the first two transversal modes.
The following modal frequencies and corresponding eigenvectors have been got from the above matrices:

$\omega_1 = 13.07$ rad/s, $\omega_2 = 49.83$ rad/s, $\omega_3 = 114.67$ rad/s, $\omega_4 = 183.09$ rad/s

$$\begin{array}{cccc} \phi_1 & \phi_2 & \phi_3 & \phi_4 \end{array}$$
$$\begin{bmatrix} -0.1006 & 0.2777 & -0.5745 & 0.6033 \\ -0.3126 & 0.5061 & -0.1520 & -0.6173 \\ -0.5326 & 0.1991 & 0.5225 & 0.4050 \\ -0.7124 & -0.4281 & -0.2576 & -0.1244 \end{bmatrix} \tag{4}$$

and show a very good agreement with the experimental data, mainly for the 1st and 3rd mode. The last 2 degrees of freedom correspond to the moving masses of the lower (m_{b1}) and upper (m_{b2}) "smart" bracing systems (brace + semi-active MR damper). They include ($m_{b1} = m_{b2} = 2\times0.17$ t) the mass of the two devices located at a same level, the participating moving mass of the two lower and upper braces, respectively, and the mass of connections and reinforcements. The global stiffnesses $k_{b1} = 2\times4400$ kN/m and $k_{b2} = 2\times1755$ kN/m of the braces at the lower and upper level, respectively, have been got by reducing of 35% ÷ 40% the design stiffnesses, i.e. by increasing the free lengths of the braces in order to take into account the whole compliance of the bracing system (reinforcing plates, bolted connections, etc.).
Finally, the mechanical behaviour of the MR damper has been simulated through the "improved model" of eq. (1). Therefore, the modeling of the variable-damping bracing system is characterized by five mechanical parameters: moving mass m_b of the semi-active system, stiffness k_b of the elastic brace, viscous coefficient C and power α in the viscous component of the MR damper's force, and magnetic field-induced threshold F_{dy} in the force's friction component.
The response of the tested structure, in terms of peak relative displacement and absolute acceleration, is shown in figure 13 for the considered seismic inputs and for six different configurations: the experimental ones ("passive off", "passive on" and semi-active) and three numerically investigated passive configurations corresponding to the adoption of an optimally designed linear viscous damper, to an optimally designed friction-like damper and to an optimal MR damper. It can be observed that the application of a semi-active control strategy to the MR dampers' operation allows the largest reduction of the structural displacements, even if this reduction is compared to optimally, rather than experimentally tested, designed passive devices.

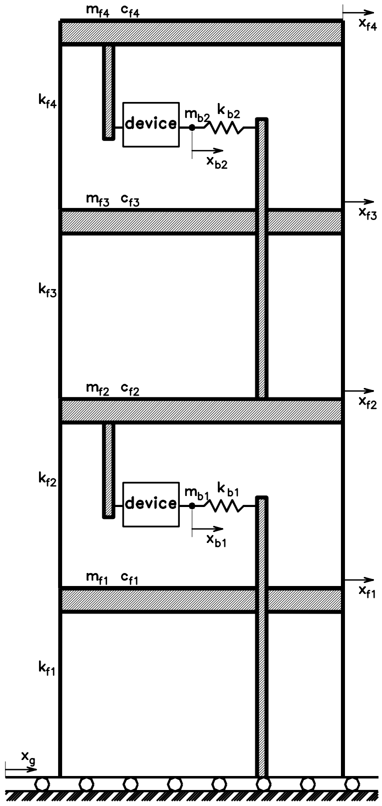

Figure 12. 6-DOF model of MISS structure

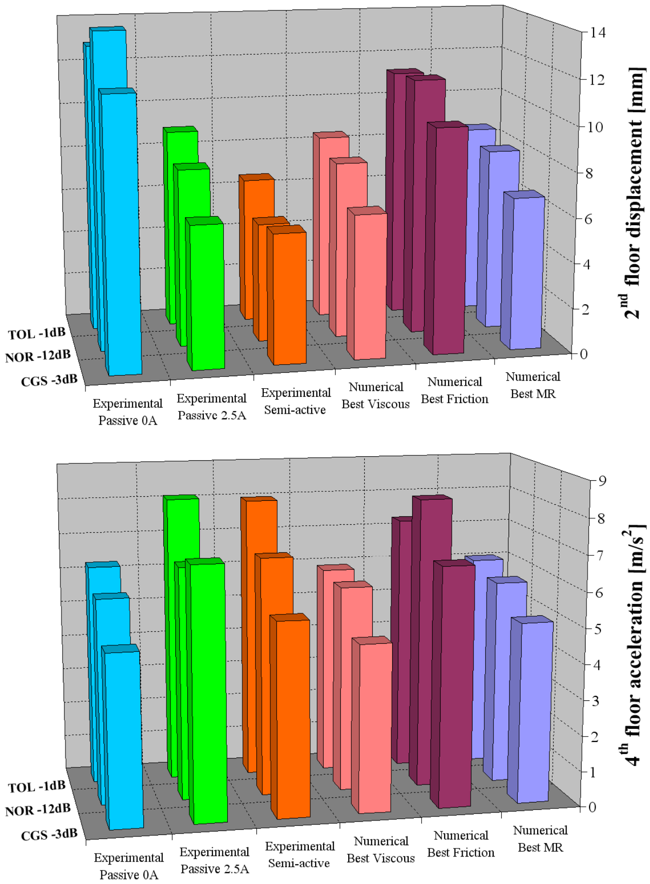

Figure 13. Experimental-numerical comparison

CONCLUSIONS

The experimental test campaign performed on a steel frame structure has provided the possibility to analyse the practical issues to be solved for the implementation of semi-active control systems in real structures.

The semi-active magnetorheological dampers implemented in the proposed control system look pretty much like conventional fluid viscous dampers, with the exception of the extra wires needed to feed the coils inside the body. The control electronics is made up by commercial parts, and the implementation of the driving control logic has demonstrated to be of ordinary difficulty.

This kind of semi-active devices, inserted in the bracing system of the tested structure, has proved to be rather effective to reduce the structural dynamic response under the action of different seismic inputs. The control algorithm, adopted for controlling the mechanical behaviour of the MR dampers, is based on the idea to maximize the energy extracted from the main structure, and it is able to reduce the maximum displacements recorded in the structure without significantly increasing the maximum accelerations.

The efficacy of the semi-active control system, in terms of reduction of peak displacements, is about 30% ÷ 40% with respect to the rigid linked bracing configuration. Besides, the use of a semi-active control strategy to drive the MR dampers' instantaneous behaviour produces the largest reduction of the structural displacements, even in comparison with optimally designed passive devices.

ACKNOWLEDGEMENTS

The research has been performed within the SPACE project (Semi-active and PAssive Control of the dynamic behaviour of structures subjected to Earthquakes, wind and vibrations), funded by the European Commission (5th FP, 1998-2002), Contract EVG1-CT-1999-00016. The authors would like to thank all the partners of the project: Maurer Söhne GmbH & Co. KG (D) for the manufacturing of MR devices; Bilfinger Berger Aktiengesellshaft (D) for the help in the design of the control device; Thales Underwater Systems (F) for the realization of the electronics of the control system; Kungl Tekniska Högskolan (S), for the study of MR fluids; ENEL.Hydro – ISMES (I) for the tests on the MR devices and the shaking table tests; ENEA, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (I) for making available the MISS mock-up and the design of its modifications; CESI (I); Tun Abdul Razak Research Centre (UK).

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