JET-PACS PROJECT: DYNAMIC TEST ON STEEL FRAME EQUIPPED WITH VISCO-RECENTRING SYSTEM

F. C. Ponzo[1], D. Cardone[2], A. Di Cesare[2], G. Gesualdi[2], C. Moroni[2], D. Nigro[2] and M. Dolce[3]

[1] *Professor, DiSGG, University of Basilicata, Potenza, Italy*
[2] *Dept. of Structures, Geotechnics and Applied Geology , University of Basilicata, Potenza, Italy*
[3] *Professor, Director of Seismic Risk Office, Dept. of Civil Protection , Rome, Italy, formerly DiSGG, University of Basilicata, Potenza, Italy*
Email: felice.ponzo@unibas.it

ABSTRACT :

An extensive program of dynamic experimental tests, called JetPacs (Joint Experimental Testing on Passive and semiActive Control Systems), is being carried out at the Structural Laboratory of the University of Basilicata. The JetPacs Project is developed within the RELUIS 2005-08 project (Research Line 7), involving several partners from different Italian Universities. The tests are going to be carried out on a 2:3 scaled structural model derived from a 2-storey, 1-bay, three-dimensional steel frame, prototype building. Six different passive and semi-active Energy Dissipating Bracing (EDB) systems will be, alternatively, used during the tests. The complete experimental program is described in a companion paper presented at the same Conference.
In this paper, the design objectives, preliminary numerical simulation analyses, experimental program and set up of the tests on the mock-up equipped with the visco-recentring EDB system are outlined. Each visco-recentring device is obtained by coupling a velocity-dependent energy-dissipating device based on visco-fluids with a recentring device based on Shape Memory Alloy (SMA) NiTi wires. The energy dissipating devices are mounted on the top of a stiff V-inverted steel brace.
During the tests, the structural model will be subjected to three different sets of natural earthquakes, compatible with the response spectra of the Italian seismic code for soil type A, B and D. The seismic intensity will be progressively increased, up to the attainment of the performance objective adopted in the design.
The main objective of this experimental investigation is to evaluate the effects of the viscous and recentring components of the EDB system on the seismic response of the structure and to verify the effectiveness of the simplified method used to design the mechanical characteristic of the device.

KEYWORDS: Experimental Dynamic Tests, Energy Dissipating Bracing Systems, Shape Memory Alloys

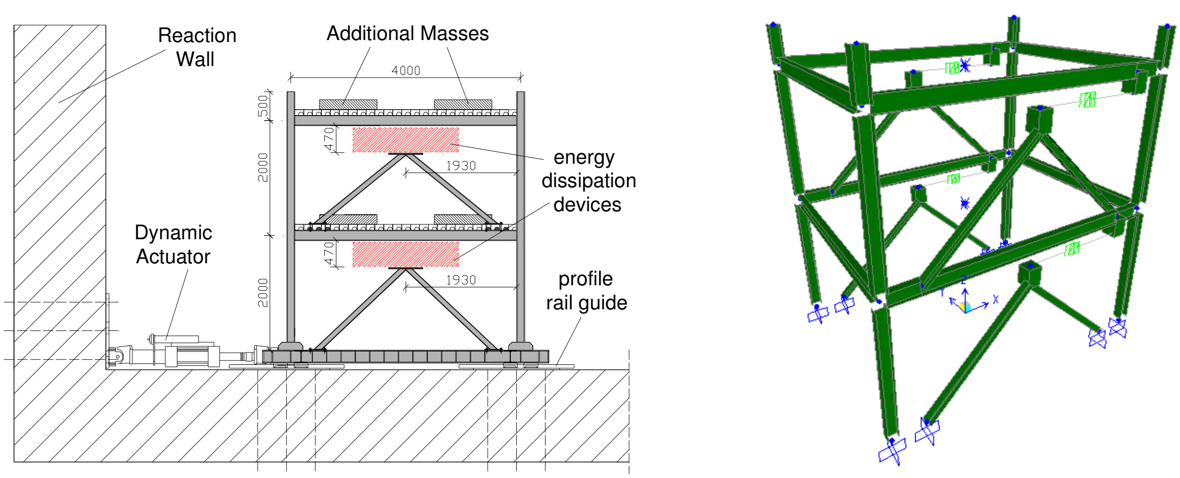
1. INTRODUCTION

Traditional retrofitting techniques for framed structures are based on the diffuse strengthening of the structure or on the introduction of additional, very stiff, structural members. In the last twenty years, innovative strategies, based on the use of Energy Dissipating Braces (EDB), have been developed and tested (Costantinou et al., 1998). In recent times, special EDB systems, with strong supplemental recentring capability, have been proposed by (Dolce et al., 2000). They are based on the superelastic properties of Shape Memory Alloy (SMA) wires (Duerig et al., 1990). The SMA EDB have been designed to be used in RC framed buildings, experiencing extensive plastic deformations under strong earthquakes. As a matter of fact, the supplemental recentring capacity of the SMA-device is exploited to recentre the gravity-load-resisting system in its initial configuration at the end of the earthquake (Cardone et al., 2004). The energy dissipating capacity of the structure is primarily provided by the hysteretic behaviour of the RC frame, produced by a strong-column-weak-beam inelastic mechanism.
Recently, a new solution of SMA-based EDB system has been proposed (Dolce et al., 2004). It is based on the coupling of SMA-based recentring devices with viscous-fluid units, mounted inside the SMA-based device and working in parallel with it. The SMA-based devices exhibit a cyclic behaviour which can be idealised as bilinear elastic, although some energy is also dissipated by SMA, typically resulting in 3-5% damping. The Viscous

Dampers (VD) exhibit a strongly nonlinear viscous behaviour, with high energy dissipation capacity and a good force control, even under large displacements.
Experimental investigations are needed to verify the effectiveness of the proposed visco-recentring EDB system in controlling the seismic response of the structure, as well as to define suitable guidelines for their design and implementation. The SMA+VD system has been then selected as one of the EDB systems to be tested within the JetPacs experimental project (Dolce et al., 2008). The main objective of the experimental investigation is to compare the seismic response of the structure equipped with SMA+VD EDB with that of the structure w/o any protection system. Further objective is to evaluate the effects of the viscous and recentring components of the SMA+VD system on the seismic response of the structure.
In this paper, the design objectives, preliminary numerical simulation analyses, experimental program and set up of the tests on the mock-up equipped with the SMA+VD EDB system are described.

2. EXPERIMENTAL AND NUMERICAL MODEL

The experimental 2/3-scaled model for dynamic tests has been designed starting from a steel building prototype. Figure 1(a) shows the lateral view of the experimental model in the longitudinal direction. The test model is a 2-storey steel frame, with one span in the longitudinal direction and interstorey height of 2m. The two floors are realized by a 100mm thick steel-concrete slab, with plan dimensions of 4.2m by 3.2m. Primary and secondary beams have the same steel section (IPE 180) at all the storeys. Similarly, all the columns have constant cross section (HEB 140) along the height of the model. The experimental model is realized using Fe360 grade steel, with Young modulus E = 206000 N/mm^2 and yielding strength f_y = 235 N/mm^2.
Additional masses have been placed on each slab, to take into account the non structural dead loads and a proper amount (30%) of live loads, as well as the contribution due to mass-similitude scaling, as described in (Dolce et al. 2008). Dead and live loads considered in the prototype design are those typical of a building for civil residence housing. The connection between experimental model and test apparatus is realized by means of stiff steel beams (HE220B) mounted at the base of the model (see Fig. 1(a)). More details on the shaking table system used during the tests can be found in (Dolce et al. 2008).



(a) (b)

Figure 1 (a) Structural model selected for the tests and (b) 3-D finite-element numerical model

The steel frame has been modelled with SAP2000_Nonlinear (Wilson 2002), using frame-type finite elements. The three-dimensional numerical model is characterised by 12 joints and 16 frame elements (8 beams and 8 columns). In order to take into account a possible nonlinear behaviour of the structure, suitable plastic hinges with an axial load-dependent behaviour have been inserted at the ends of each frame element. The connection between the columns and the stiff beams at the base of the model has been simulated through perfect restraints. The beam-column joints of the frame (realized with stiffened full-strength welded connections) have been modelled through stiff links with length equal to half height of the corresponding beam/column. Finally, the in-plane behaviour of the floor slabs has been captured by means of diaphragm constraints.

3. PERFORMANCE OBJECTIVE

The performance objective of the design was to prevent damage to structural members. The performance objective has been then expressed in terms of a threshold value of the maximum interstorey drift (Δ_{max}), lower than the yield interstorey drift (Δ_y) of the structure. The superstructure, therefore, is supposed to respond within its elastic range ($\Delta_{max} < \Delta_y$) during the shaking table tests.
In order to determine the yield interstorey drift, a pushover analysis of the structure in the as-built configuration (i.e. w/o EDB systems) has been performed with the numerical model shown in Fig. 1(b).
The pushover analysis has been conducted in the longitudinal direction of the frame, along which the seismic action will be applied during the experimental shaking table tests.
The normalized base shear vs. top displacement relationships obtained from pushover analyses of the model w/o EDB systems are shown in Fig. 2. The normalization of the pushover curves has been carried out by dividing the base shear by the weight of the structural model and the roof displacement by the height of the structure. As can be seen on the left hand side of Fig. 2, two different vertical distributions of lateral forces have been considered in the pushover analysis, according to the two different acceleration distributions assumed along the height of the structure: (i) an inverted triangular distribution and (ii) a uniform acceleration distribution, in which the lateral forces at each level are simply proportional to the total mass at that level. Little differences between the two curves are found.

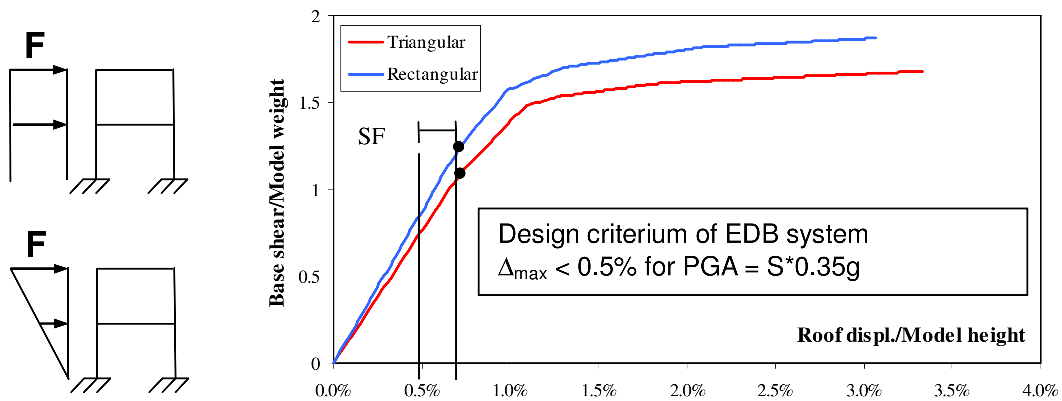


Figure 2 Push-over curves and yield points of the reduced scaled model

As can be seen in Fig. 2, the roof drift index (i.e. the top displacement divided by the total height of the structure) associated to the appearance of plastic deformations is equal to approximately 0.7%. Correspondently, interstorey drifts (i.e. interstorey displacements divided by the clear height of the columns) of the order of 0.75% are found. The visco-recentring EDB's have been then designed with the main objective of limiting the maximum interstorey drifts below (with a proper Safety Factor) the yield drift, for a Peak Ground Acceleration (PGA) of S*0.35g, being S the soil factor, equal to 1 for stiff soils, 1.25 for medium soils (type BCE), according to (ITCC, 2005). It is worth to observe that the design PGA considered in this study (0.35g) corresponds to that prescribed by the Italian Seismic Code (ITCC, 2005) for high seismicity zones. Assuming a Safety Factor (SF) equal to 1.5, a target drift of approximately 0.5% is defined.

4. VISCO-RECENTRING DEVICES

The visco-recentring EDB system considered in this study is obtained by coupling uniaxial recentring devices based on the superelastic properties of pre-strained SMA wires with uniaxial nonlinear viscous dampers based on the extrusion of a silicone fluid inside a cylinder by a piston endowed with suitable orifices. The functioning principles and basic mechanical properties of the SMA-based recentring devices are described in (Dolce et al. 2000). The SMA-based devices adopted in this study are of the same type as those described in (Dolce et al. 2000), except for a few details relevant to the steel mechanical apparatus of the device and its overall dimensions. The pre-strained SMA wires are always subjected to elongation, for any positive or negative mutual movements of the steel tubes, due to a special arrangement of wires, steel studs and holes, as described in (Dolce et al. 2000). Because of pre-strain, a threshold force to elongate wires is defined. Up to that force value, no relative movement of the steel tubes occurs and, then, a high initial stiffness is obtained, which is only governed by the axial flexibility of the steel tubes. The SMA-based recentring devices exhibit a cyclic behaviour that can be schematized as bilinear elastic (see Fig. 3), with an initial stiffness determined by the rigidity of the steel components and a post-“elastic” stiffness determined by the elongation of the SMA wires. The “yield” force of the device corresponds to the pre-stress force of the SMA wires. It can be calibrated by varying the number of wires and/or their pre-stain level. The SMA-based devices to be used in the JetPacs project is equipped with Ni-Ti 1mm diameter SMA wires. The SMA wires will be wrapped around two steel studs placed at a distance of 511mm.
In order to calibrate the number of SMA wire loops to be used at the each storey of the testing model, reference has been made to the results of previous experimental studies conducted within the ILVA-IDEM research project (Dolce et al. 2004). Two SMA-based recentring braces equipped with 10 1.78mm diameter SMA wire loops were tested at the Laboratories of the University of Basilicata. In figure 3, the experimental force-displacement cyclic behaviour at 1Hz frequency of loading of one of such devices is reported. It should be noted that, in terms of cross section area, 10 1.78mm diameter SMA wire loops corresponds to approximately 32 1mm diameter SMA wire loops. This observation has been exploited to get a reference cyclic behaviour for the calibration of the number of 1mm diameter SMA wire loops to be adopted in the EDB system under consideration.
As said before, each SMA device has been equipped with a couple of Viscous Dampers, aimed at improving the energy dissipation capacity of the system. In Figure 3 the experimental cyclic behaviour of a couple of viscous dampers at 3Hz frequency of loading is reported. As can be seen, the VD’s exhibit a strong nonlinear cyclic behaviour, with a limited sensitivity to velocity variations.

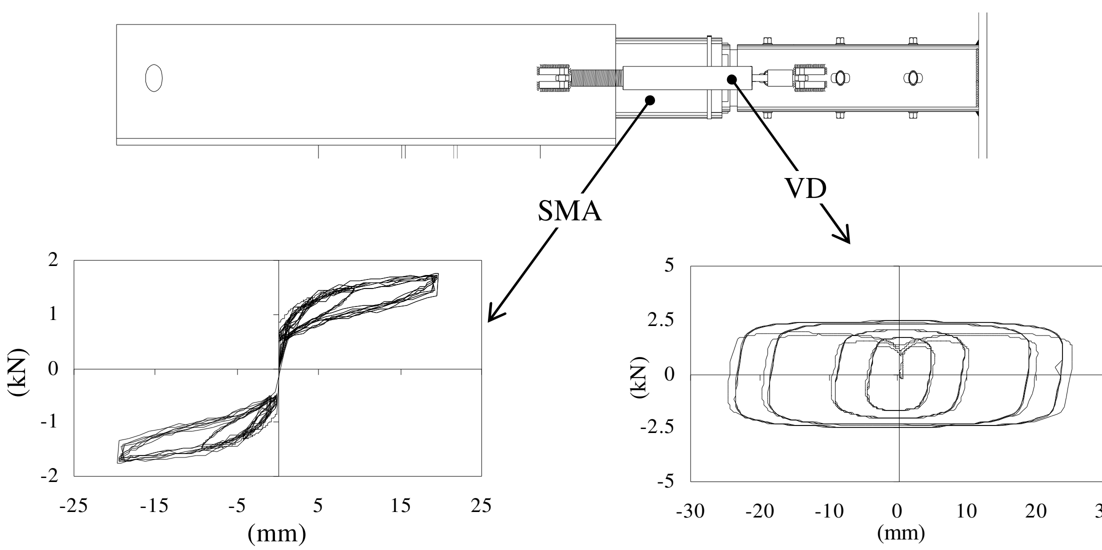
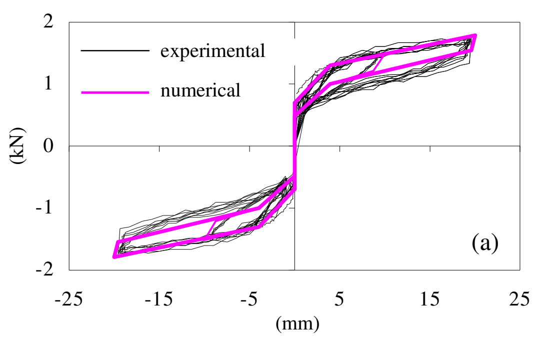


Figure 3 Layout of the SMA+VD device and typical experimental force-displacement cyclic behaviour of its components

The design of the SMA+VD devices to be mounted in the experimental model for the shaking table tests has been conducted through Nonlinear Time-History Analyses (NTHA). The numerical models used to describe the cyclic behaviour of the SMA and VD units of the device have been calibrated based on the results of previous experimental tests. In Figure 4 the experimental and numerical cyclic force-displacement behaviours of one 1mm diameter SMA wire loop (Fig. 4(a)) and one viscous damper (Fig. 4(b)) are compared. The experimental cyclic behaviour of one 1mm diameter SMA wire loop has been obtained by properly scaling down the force levels associated to the experimental behaviour of the device tested at the Laboratories of the University of Basilicata within the ILVA-IDEM project (see Fig. 3). The force-displacement cyclic behaviour of the SMA wire loops has been modelled by a suitable combination of several elastic-perfectly plastic and non-linear elastic unidirectional link elements. The optimal number of SMA wire loops, for each EDB, has been determined through extensive NTHA, as described in the next paragraph.
Viscous dampers have been modelled through nonlinear viscous unidirectional link elements, whose force response is governed by the well-known relationship: $F = c\, v^{\alpha}$, where c is the damping coefficient (taken equal to 0.61 KNsec/mm, for the device under consideration) v is the relative velocity between piston and cylinder and α the damping coefficient (taken equal to 0.3 for the device under consideration). The comparison between the experimental and numerical cycles of the VD (see Fig. 4(b)), proves the appropriateness of the values of the parameters adopted in the numerical model.
In the NTHA, the cyclic behaviour of the EDB's has been modelled by coupling, in parallel, the cyclic behaviour of SMA and Viscous devices (see Fig. 4). The EDB's of the first and second storey (see Fig. 1(a)), present the same VD while they differ for the different number of SMA wire loops used.



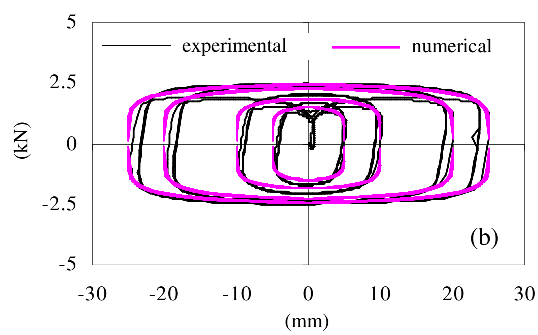


Figure 4 Comparison between experimental and numerical cyclic behaviour of (a) one 1mm diameter SMA wire loop at 1 Hz frequency of loading and (b) one viscous damper at 3Hz frequency of loading

5. PRELIMINARY NUMERICAL SIMULATION ANALYSES

Extensive NTHA have been carried out with SAP2000 (CSI, 2004.) on the numerical model of the frame with EDB's (see Fig. 1(b)), in order to determine the optimal number of SMA wire loops to be used in the EDB's of the first and second storey. The number of SMA wire loops has been gradually changed during the numerical simulation analyses, until the required performances (see par. 3) were attained. The optimal configuration of SMA devices derived from NTHA is characterised by 4@1mm diameter wire loops, for the EDB's of the first storey, and 2@1mm diameter wire loops, for the EDB's of the second storey.
Three types of seismic input, each defined by 7 spectrum-compatible accelerograms, have been used in the NTHA, whose characteristics of input are described in (Dolce et al., 2008).
The NTHA under consideration have been performed considering the complete EDB system, based on the coupling between SMA recentring devices and Viscous Dampers. At the end of the design process, a number of numerical simulation analyses on the frame with SMA device only, as well as on the frame w/o EDB's, have been carried out and the results compared to that of the structure with SMA+VD EDB's. The results of NTHA have been examined in terms of (i) maximum storey displacements, (ii) maximum interstorey drifts and (iii) maximum base shear. Figure 5 shows the time-histories of the storey displacements, interstorey drifts and base shear for the model (i) without EDB's, (ii) with SMA EDB's and (iii) with SMA+VD EDB's. The time-histories

of Fig. 5 refer to the same accelerogram (one whose response spectrum is very close to the design response spectrum) with PGA = 0.44g.

As can be seen, the seismic response of the structure drastically reduces in amplitude when EDB's are used. The comparison between the response of the structure with SMA EDB's (Fig. 5(b)) and with SMA+VD EDB's (Fig. 5(c)) clearly points out the better control of the displacement response of the structure when VD's are used, due to their higher energy dissipation capacity. As far as the base shear is concerned, instead, lower differences between the two types of EDB's are observed. It should be noted, however, that the shear forces in the columns can be significantly reduced when VD's are used. This is confirmed by Fig. 6, which compares the force-displacement cyclic behaviours of the EDB's, with and without VD's. The diagrams of Fig. 6 refer to the same accelerogram and PGA value (0.44g) considered in Fig. 5. As can be seen, the force levels in the SMA+VD EDB's, at their maximum displacement amplitude, result significantly greater than those in the SMA EDB's. This can be ascribed to the strongly nonlinear viscous behaviour of the dampers, which generates velocity-dependent maximum forces practically in-phase with the displacement-dependent maximum forces of the SMA device. As a result, lower shear forces in the columns of the frame with SMA+VD EDB's are found, at a given interstorey drift.

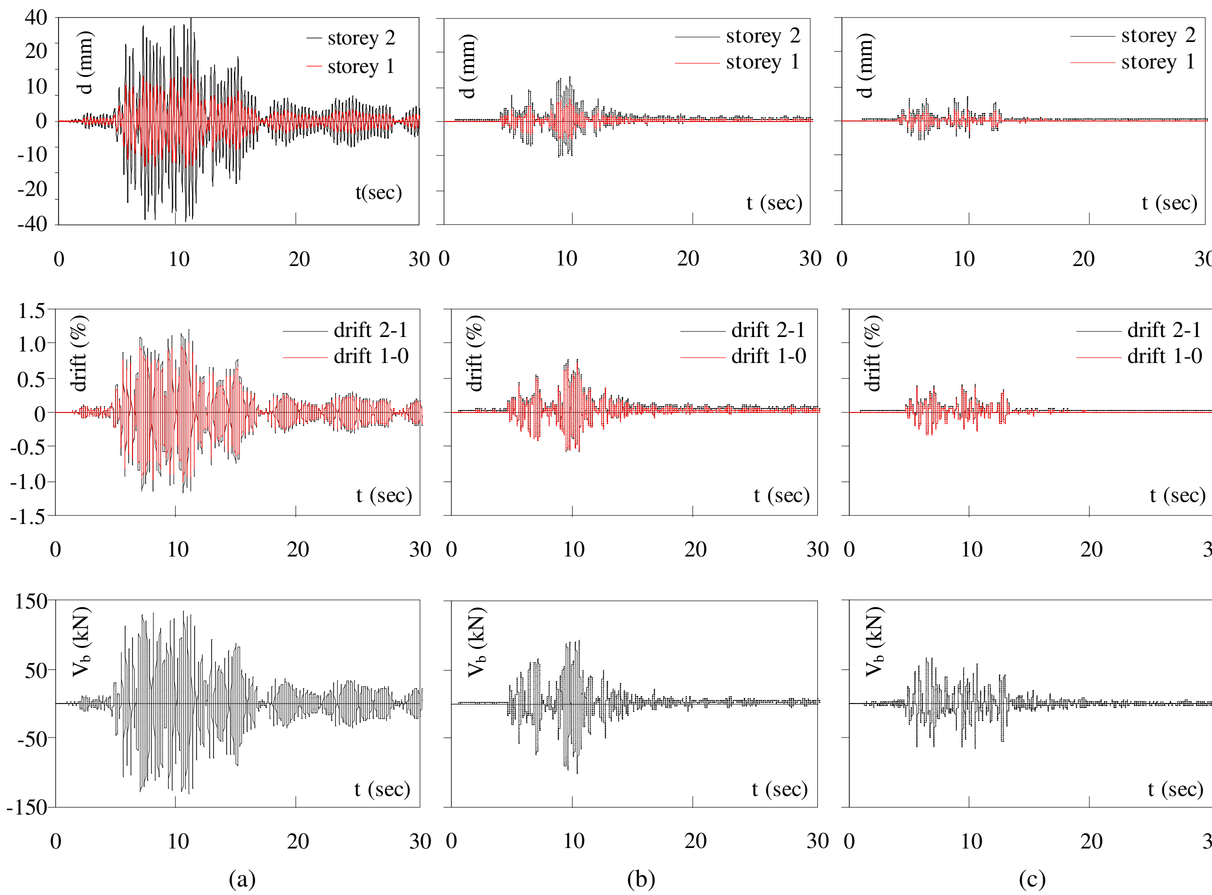


Figure 5 Time-histories of storey displacements, intertorey drifts and base shear for the frame (a) w/o EDB's, (b) with SMA EDB's and (c) SMA+VD EDB's. Seismic responses generated by the same accelerogram at 0.44g PGA.

Figure 7 compares the maximum interstorey drifts (mean values over 7 accelerograms) experienced by the frame w/o EDB's, with SMA EDB's and with SMA+VD EDB's, respectively, with the yield drift (thick broken line) and yield drift divided by SF = 1.5 (thin continuous line). Three different sets of accelerograms, compatible (on average) with the elastic response spectra provided by the Italian Seismic Code for stiff soils (S = 1), medium soils (S = 1.25) and soft soils (S = 1.35) are considered in Fig. 7. The PGA is always equal to 0.35g. As can be seen, the maximum interstorey drifts of the frame w/o EDB's largely exceed the yield drift, reaching values of the order of 1.2-1.4%, depending on the soil type considered. As a consequence, significant plastic deformations are expected to occur in the frame w/o EDB's. The maximum interstorey drifts drastically reduce when EDB's are used. In particular, they result of the order of 0.4% (i.e. by about 20% lower than the target value of the drift), when the visco-recentring EDB system is adopted. The steel frame is then expected to remain elastic under the design earthquake. The maximum interstorey drifts experienced by the frame with EDB based on SMA only result practically twice bigger as before, attaining the yield drift in most of the cases considered. This observation emphasises the fundamental role of the energy dissipation capacity of the VD's in controlling the seismic vibrations of the structure.

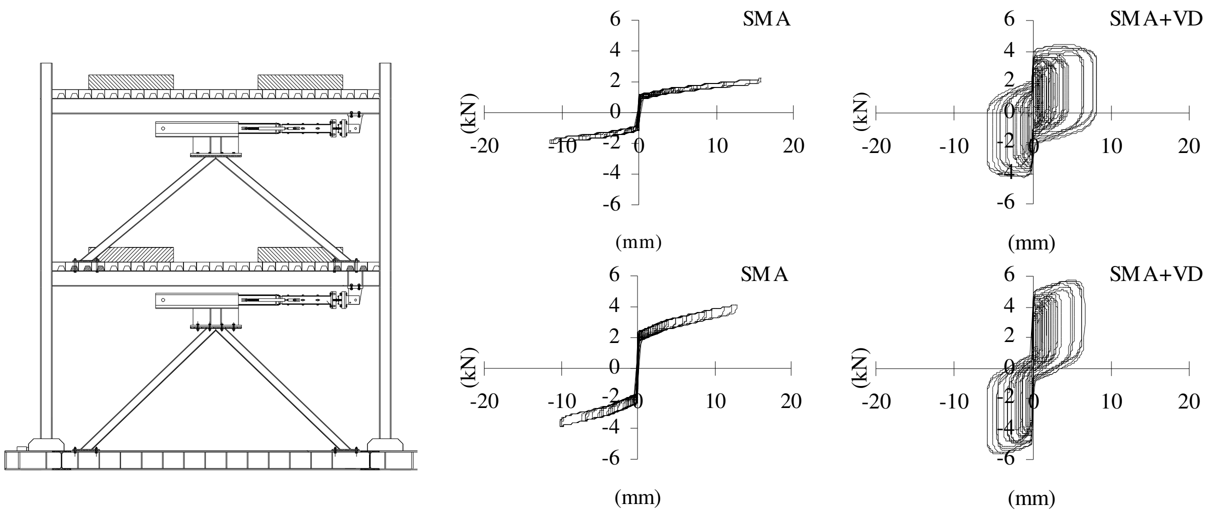


Figure 6 Numerical force-displacement cyclic behaviours of SMA EDB's (left) and SMA+VD EDB's (right), registered during NTHA at 0.44g PGA.

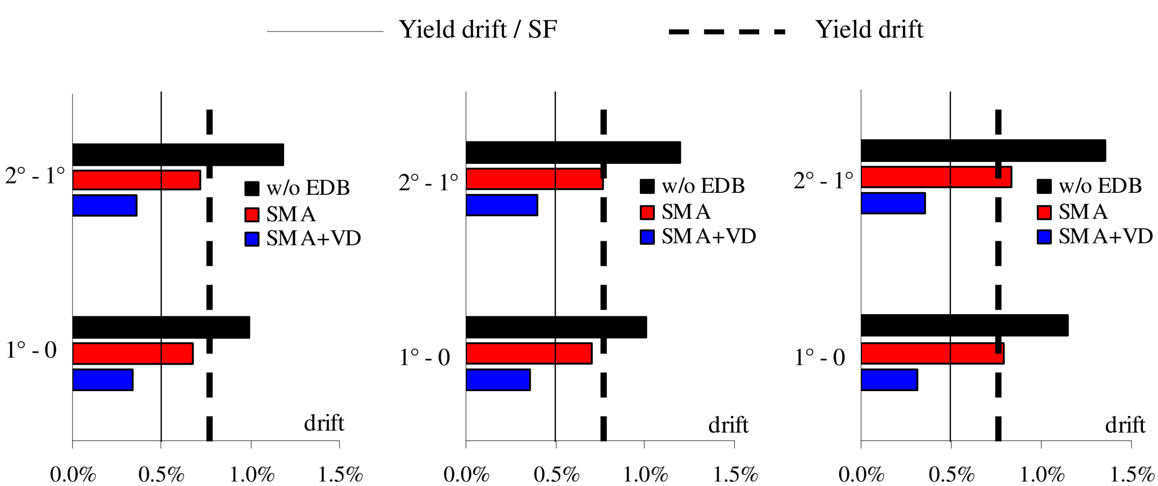


Figure 7 Comparison between the maximum interstorey drifts (mean values over 7 accelerograms) experienced by the frame w/o EDB's, with SMA EDB's and with SMA+VD EDB's, respectively, considering a set of accelerograms compatible with the EC8 elastic response spectra at 0.35g PGA, for (a) stiff soils (S = 1), (b) medium soils (S = 1.25) and (c) soft soils (S = 1.35).

6. CONCLUSION

An extensive program of dynamic experimental tests, on a 2:3-scale model of a 2-storey three-dimensional steel frame, is being carried out at the Structural Laboratory of the University of Basilicata. Six different passive and semi-active Energy Dissipating Bracing (EDB) systems will be, alternatively, used during the tests, including the visco-recentring EDB system designed, engineered and tested at the University of Basilicata.
The visco-recentring devices under consideration are based on the coupling between nonlinear Viscous Dampers (VD's) and recentring devices based on the superelastic properties of pre-strained Shape Memory Alloy (SMA) wires. In this paper, the design objectives and preliminary numerical simulation analyses for the design of the VD+SMA EDB system have been described. The performance objective of the design was to limit the maximum interstorey drifts below (with a proper safety factor) the yield drift (equal to 0.5%, based on pushover analysis), for a PGA of 0.44g, corresponding to that prescribed by the Italian Seismic Code for high seismicity zones and soils type BCE (medium soils). Extensive Nonlinear Time-History Analyses (NTHA) have been carried out to design a visco-recentring EDB system that comply with the aforesaid performance objective. NTHA have been carried out with three different sets of 7 accelerograms, compatible (on average) with the elastic response spectra provided by the Italian Seismic Code for stiff, medium and soft soils. The seismic response of the frame with visco-recentring EDB system has been compared to that of the frame with EDB based on SMA only and that of the frame without EDB. The NTHA results proved the effectiveness of the visco-recentring EDB system in protecting the steel frame from damage. They also pointed out the fundamental role of the energy dissipation capacity of the viscous dampers in reducing the seismic vibrations of the structure.
As a final remark it must be observed that the re-centring capability of the SMA devices can be fully exploited only by changing the current design philosophy, aimed at minimizing the ductility demands in the structural members. With a re-centring force system available along the height of the structure, it is possible to allow for great ductility demands in structural members, as the vertical-load-resisting structural system is always restored to its initial configuration at the end of the earthquake.

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