Visco-Re-Centring Energy Dissipating System for Seismic Protection of Framed Buildings

Felice Carlo Ponzo, Antonio Di Cesare and Domenico Nigro

***Abstract*—** Energy Dissipating Bracing (EDB) system using both Shape Memory Alloy (SMA) and viscous damper (VD) devices has been considered in order to control seismic vibrations on buildings. The basic mechanical properties of the SMA+VD were used in order to recentre the gravity-load resisting system to its initial configuration at the end of the seismic event and to increase the energy release during the seismic motion. A performance based design procedure for the evaluation of the mechanical characteristics of both SMA and VD devices, starting from an equivalent Hysteretically Damped (HD) EDB designed for the same inter-storey target drift, was proposed. In order to verify the effectiveness of the design method and the performances of the system a parametric study was developed considering numerical nonlinear time history analysis and an extensive program of dynamic experimental tests, has been carried out at the Structural Laboratory of the University of Basilicata considering a 1:1.5 scaled three-dimensional steel frame within the JetPacs project (Joint Experimental Testing on Passive and semi-Active Control Systems). In this paper the main results obtained by numerical nonlinear time history analysis (NTHA) are compared with experimental ones.

***Keywords*—**Shaking table tests, Energy Dissipation Bracing, Shape Memory Alloys, Performance Based Design

I. Introduction

Innovative strategies for seismic protection of framed buildings based on the use of Energy Dissipating Braces (EDB) have been developed and tested in the last years [2, 3, 7]. Special EDB systems, characterized by a strong supplemental re-centring capability, based on the superelastic properties of Shape Memory Alloy (SMA) wires, have been recently proposed [8]. The functioning principles and basic mechanical properties of the SMA-based re-centring devices exploited to re-centre the gravity-load-resisting system in its initial configuration at the end of the earthquake are described in [4]. The great potential of SMA braces has been confirmed by numerical [1, 13, 17] and experimental results [6, 15, 16] of recent research projects carried out on reduced-scale structural models, by means of shaking table tests [5], and on a full-scale prototype building, by means of release tests [4]. Suitable methods for the design of SMA braces, however, are still needed.

A new iterative procedure to design the mechanical characteristics of SMA+VD devices based on a equivalent hysteretic system, has been proposed [14], in which SMA-based re-centring devices is considered working in parallel with viscous dampers (VD). The design procedure evaluates the theoretical behaviour of the SMA+VD devices, described by means of double flag shape (FS) model, starting from an equivalent Hysteretic Device (HD), described by elasto-plastic (EP) model, designed to reach the same performance objective [12]. Both EDB systems are designed to limit inter-storey drifts in order to ensure the base frame remains elastic.

The design procedure was adopted to set critical design characteristics of the SMA +VD system used in a shaking table testing program carried out on a steel frame at the Structural Laboratory of the University of Basilicata (UNIBAS) within a wide research program, named JETPACS (“Joint Experimental Testing on Passive and semi-Active Control Systems”), which involved many Research Units working for the Research Line 7 of the RELUIS 2005-2008 project. Tests results were considered to suitably calibrate a numerical model used in a parametric study in order to check the robustness of the design procedure. In order to validate the proposed design procedure, this paper focus on the comparison between the experimental results of the tests with the experimental model equipped with both SMA and SMA+VD EDB’s configurations and the outcomes of several numerical non linear time history analysis (NTHA).

II. Design Procedure

The performance objective considered in design was to prevent damage for frame members. This objective can be achieved by establishing a threshold value of the maximum inter-storey drift (Δ_{max}) that does not exceed the limit of the yield inter-storey drift (Δ_y) of the frame, then ensuring the framed structure responds within its elastic range ($\Delta_{max}<\Delta_y$) during the shaking table tests.

During the design process a response spectra for high seismic zones and medium soil characteristics (Type B) was used. This spectra had a peak ground acceleration (PGA) equal to S*0.35 g=0.44 g, with S = 1.25 being the soil factor corresponding to Eurocode 8 [9].

The procedure considered to design the visco-recentring EDBs in this numerical application aims to calibrate the

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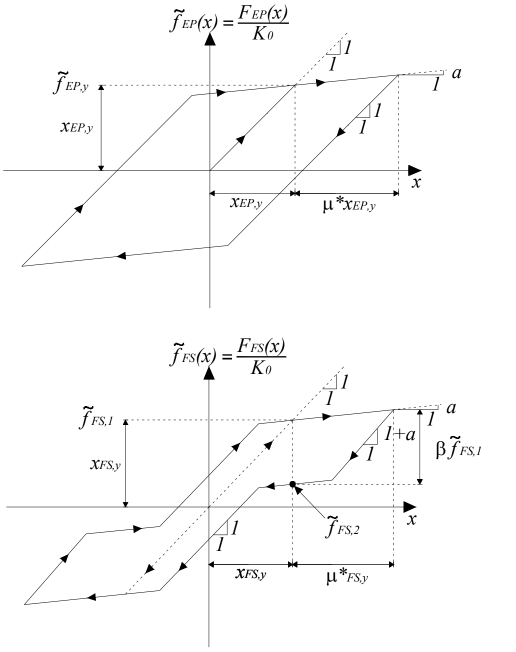
fundamental parameters of the SMA+VD devices (strength $F_{FS,1}$, stiffness K_0, re-centring parameter β and post-yield hardening ratio α, - Fig 1b) starting from an equivalent Hysteretic Damper (HD) designed for the same performance objective (characterized by a strength F_{EP}, stiffness K_0, ductile capability μ and post-yield hardening ratio α, see Fig. 1a).



a)

b)

Fig. 1. Equivalent models of (a) Elasto-Plastic (EP) and (b) Flag-Shaped (FS)

The behavior factor of Flag-Shaped models (Fig. 1b) strongly depends on their strength $F_{FS,1}$ and strength ratio β [12], defined as the ratio between the force amplitude of the elasto-plastic cycle and the activation force of the system:

$$\beta = \frac{F_{FS,1}(x_{FS,y}) - F_{FS,2}(x_{FS,y})}{F_{FS,1}(x_{FS,y})} \tag{1}$$

where: $F_{FS,1}$ and $F_{FS,2}$ are the force levels of the FS model at the "yield" displacement $x_{FS,y}$ in loading and unloading condition. The β-parameter accounts for the re-centering and energy dissipating capabilities of the device. It ranges from 0 (Bilinear elastic behavior) to 2 (Elasto-plastic behaviour).

The main steps of the iterative procedure are described in Fig. 2 and summarized below:

- STEP 1. Preliminary evaluation of the lateral resistance of the frame (i.e. w/o EDB systems). Non-linear static analysis can be performed in order to evaluate the maximum inter-storey drift related to the onset of yielding (Δ_y). A proper Safety Factor (SF) equal to 1.5 can be adopted to reduce Δ_y, so defining a target drift (Δ_{max}) [5, 16].

- STEP 2. Evaluation of the mechanical properties of the HD EDB system (EP model) given by strength $F_{EP,y}$, stiffness $k_0 = F_{EP,y} / x_{EP,y}$, design ductility and α =3% (see Fig. 1a). In the case of a frame structure the HD EDBs properties can be designed considering the simplified equal Energy/Displacement criterion detailed in [15, 16].

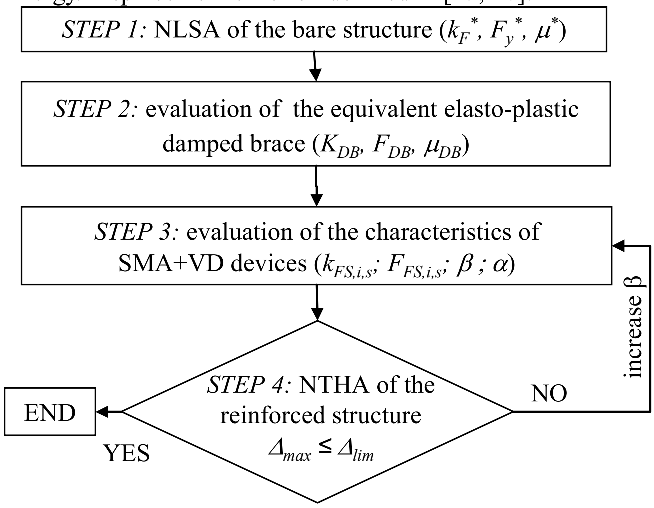


Fig. 2. Flowchart of the design procedure

- STEP 3. Determination of the cyclic behaviour of SMA+VD devices, captured by means of a double flag-shaped (FS) model. Starting from the parameters of the EP model, an equivalent FS model, characterized by $F_{FS,1} = F_{EP,y}$, $F_{FS,1} / x_{FS,y} = k_0$, α equal to that of the EP model and reaching the same ductility demand μ, could be defined by using a proper β-parameter ranking from 0.2 to 0.3. An optimal design value of β = 0.2-0.3 can be assumed for SMA+VD respectively, as the best compromise between adequate energy dissipation and full re-centring capacity of the FS model.

STEP 4. Verification of the structure upgraded with SMA+VD EDB's by means of nonlinear time history analyses, according with NTC 2008 [11]. If the system is not verified it is necessary to increase the β parameter. The velocity conditions imposed in STEP 3 are also controlled during this stage of the design procedure.

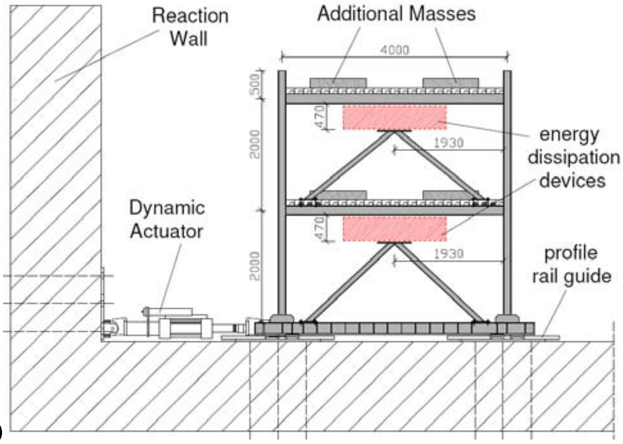
III. Experimental Model

Fig. 3a shows the general layout of the experimental 1/1.5 steel scaled model designed for vertical loads only and referring to a steel building prototype for civil housing. The test model was a two-storey steel frame, with a single span in the test direction. The two floors were made of a 100 mm thick steel-concrete slab, with plan dimensions of 4.2 m by 3.2 m. Main and secondary beams have the same steel section (IPE 180) at each storey. Similarly, all the columns have a constant cross section (HEB 140) along the height of the model. S235 grade steel was used, having a Young's modulus E = 206000 N/mm2 and a yielding strength f_y = 235 N/mm^2. The EDB systems considered in the experimental tests consist of four devices (HD or SMA/SMA+VD), two for each storey, mounted on the top of two stiff steel chevron braces (HEA100), as shown in Fig. 3. Bolts ensure the rigid connection between the stiff braces and the devices.

The hysteretic devices HD (manufactured by T.I.S S.p.A) and the visco-re-centring devices SMA+VD considered in this study have been designed, engineered and tested at the

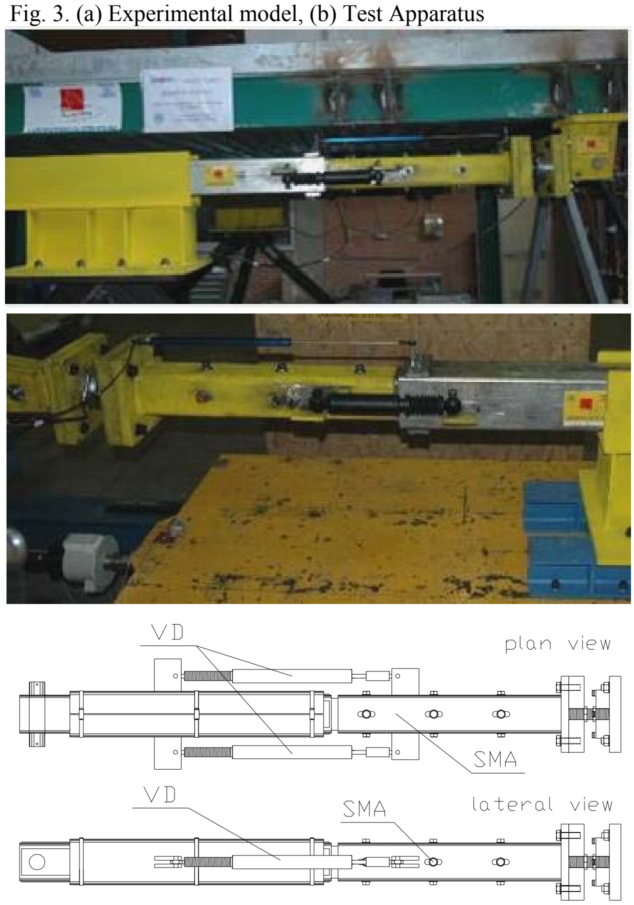
Laboratory of University of Basilicata. The hysteretic devices (HD) were based on the hysteretic properties of steel plates, capable of providing the necessary additional horizontal strength, stiffness and energy dissipation capacity whilst limiting inter-storey drifts. The particular technology adopted to realize these devices is based on low-carbon U-shaped steel plates capable of dissipating energy by means of yielding due to flexural mechanisms during the seismic motion. The particular mechanism allows to obtain a very large range of stiffness and strength values. The visco-re-centering devices (SMA+VD) were obtained by coupling uni-axial re-centering devices based on the super-elastic properties of pre-strained SMA wires with a couple of uni-axial viscous dampers (VD) units, mounted together and working in parallel. In particular, 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 [7], while the VD, based on the extrusion of a fluid inside a cylinder by a piston endowed with suitable orifices, are aimed at improving the energy dissipation capacity to β = 0.2-0.3.

a)



b)

Fig. 3. (a) Experimental model, (b) Test Apparatus



a)

b)

c)

Fig. 4. Overview of the SMA+VD device: (a) damper installed on the test structure; (b) experimental machine for device characterization tests; (c) scheme of device

IV. Numerical Model

The steel frame has been modelled using the Frame-type 3D finite elements of the SAP2000 Nonlinear code (CSI, 2004), as shown in Fig. 5. In order to account for 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 connections between the columns and the stiff beams at the base of the model have been simulated through perfect restraints, while, the in-plane behaviour of the floor slabs has been captured by means of rigid diaphragm constraints. The strongly nonlinear behaviour of the steel-based energy dissipating devices (HD) was modeled with SAP 2000 by using link elements characterized by Wen hysteretic behaviour added to the nonlinear model [14], while the force-displacement cyclic behaviuor of the SMA wire loops was made by a suitable combination of elastic-perfectly plastic and multi-linear elastic unidirectional link elements, while the VD by a damper link element [15].

The above described procedure was adopted to design the SMA and SMA+VD EDB systems for seismically protecting the steel model. The SMA+VD devices used have been described through a double flag shape (FS) model defined starting from an equivalent Hysteretic Device (HD) designed to obtain the same performance objective. The results for two different design options (HD1 and HD2) are shown in the Table 1.

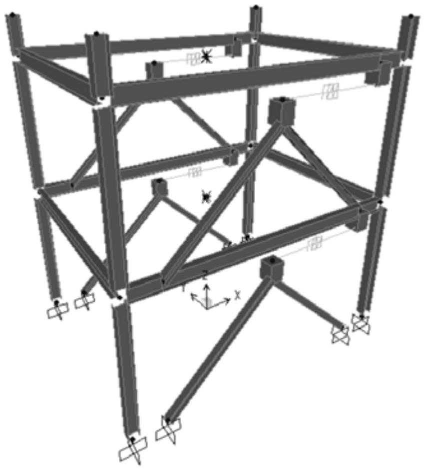
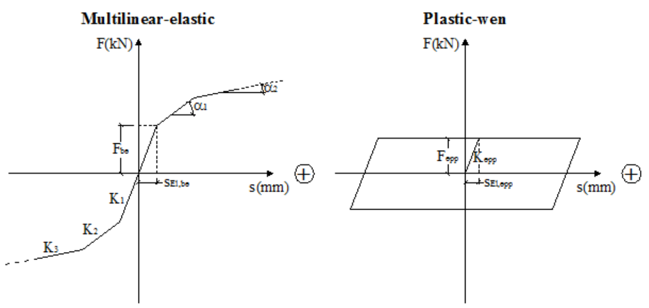


Fig. 5. Numerical model

Referring to Fig. 6 the characteristics of the varying components that make up the visco-recentring system can be determined by applying the conditions reported to the initial hysteretic damper obtained in STEP 2 at each level. Fig. 2 below shows the way in which the various systems working in parallel combine to make the flag shaped hysteretic response. The FS model is obtained by summing in parallel multilinear elastic (be), elasto-perfectly plastic (epp), and/or viscous (v) as shown in Fig. 2.



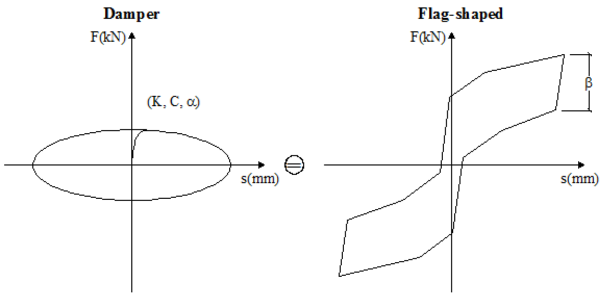


Fig. 6. Sum of models of a) Multilinear elastic (be), b) elasto-perfectly plastic (epp), c) viscous (v), d) flag-shaped model.

In the design of the SMA + VD the characteristics of the viscous element can be calculated imposing an equal velocity condition at the first level for the dissipative systems (ie. $v_{I,HD} = v_{I,SMA+VD}$) and hypothesizing a linear max velocity up the height of the building.

Table 1. Mechanical characteristics of the Visco-Recentring devices carried out by characterization test (1Hz)

Design option	Level	$F_{FSy\ s,i}$ (kN)	$k_{Es,i}$ (kN/mm)	β_i	α_i
SMA1+VD	I	7.5	8.0	0.3	2
	II	4.5	4.5	0.2	2
SMA2+VD	I	8.0	10.0	0.5	3
	II	7.5	8.0	0.3	2

V. RESULTS

The experimental program consisted of 99 tests on the model with different configurations of HD, SMA and SMA+VD [6] and on the bare frame (model w/o EDB), as summarized in Table 2.

Table 2 Summary of the experimental tests performed assuming different PGA intensities of the selected accelerograms for SMA, SMA+VD and w/o EDBs
(x = tests performed)

EQ n.	Configurations				
	SMA1	SMA2	SMA1+VD	SMA2+VD	w/o EDBs
1	x	x	x		x
2	x	x	x		x
3	x	x	x		x
1	x	x	x		x
2	x	x	x		x
3	x	x	x		x
1	x	x	x	x	
2	x	x	x	x	
3		x		x	
4	x		x		
5	x		x		
6	x		x		
7	x		x		
1	x	x	x	x	
2		x	x	x	

3					
4					
5	x		x	x	
6					
7	x		x	x	
1			x	x	
2				x	
3					
1				x	
2				x	
3					

Comparisons have been made between the structural experimental response with SMA, SMA+VD and HD EDBs, as well as the bare frame [14], and numerical results.

A set of 3 natural acceleration records, characterized by a spectrum compatible for zones of high seismicity and for medium soil characteristics (Type B), selected from the European Strong motion Database [10], have been considered for numerical analysis and experimental tests. Natural acceleration records were scaled by using a scale factor in order to match, on average, the Italian seismic code [11] and Eurocode response spectra [9]. To ensure consistency with the scale of the experimental model, all acceleration profiles were scaled down in the time by the factor (1.5)1/2.

The experimental outcomes on the frame equipped with SMA(1;2) and SMA(1;2)+VD EDB configurations, have been compared in Fig. 7, where the results of the tests carried out considering three main acceleration profiles (earthquake no. 1, 2 and 3) are shown in terms of (i) maximum inter-storey drifts (MID) (ii) maximum top floor acceleration (MA) and (iii) maximum Force (MF) in the energy dissipating devices.

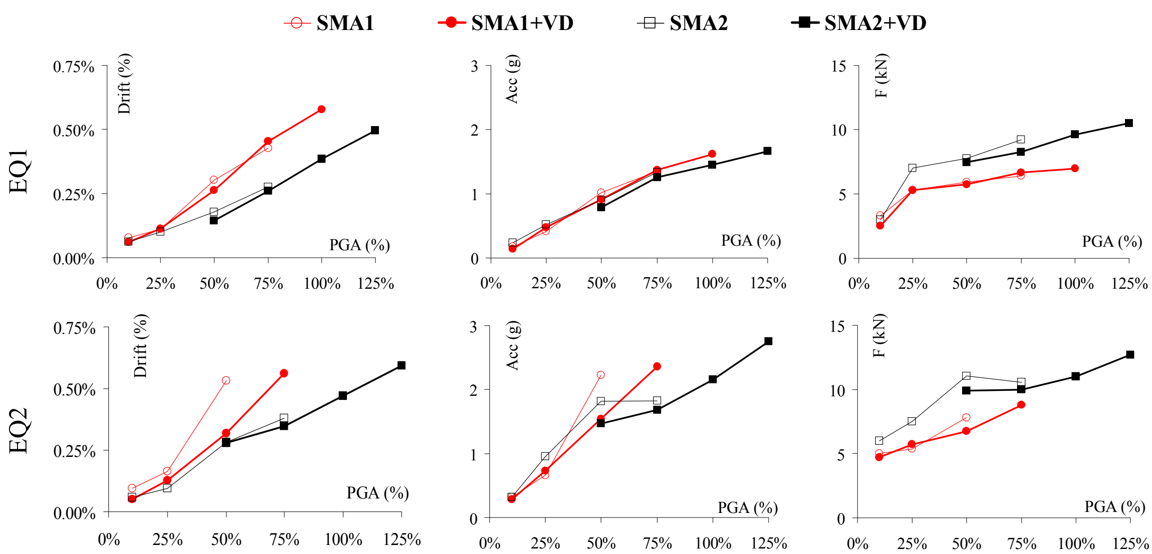
As can be seen, the MF in both SMA+VD configurations are similar to those registered on the frame without the VD component, while a significant difference of behaviour can be observed by changing the characteristics of SMA device (SMA1 or SMA2). Inversely, the MID is shown by SMA1 configurations, with and w/o VD component, while the MA results are comparable for all considered configurations.

It is worth noting that the VD effect becomes significant when the earthquake intensity exceeds a threshold value of the % PGA as a function of the yield strength $F_{FS,y}$ of the FS model and the acceleration profiles. For example, this threshold value, for earthquake n.2, is PGA 25% with SMA1 and PGA 75% with SMA2.

The experimental response of the model equipped with SMA2+VD EDBs is compared with the response of the model with SMA1+VD (Fig. 8a) and with SMA2 (Fig. 8b) in terms of time-history of inter-storey drifts and cyclic behavior of visco-recentring and self-recentring devices considering earthquake no. 2, PGA 75%.

Fig. 9 shows the comparison between the experimental and numerical outcomes, as an example, for the frame with SMA2+VD EDBs obtained with reference to earthquake no. 2, PGA 100%.

The presence of certain anomalies, due to the manufacturing tolerance, has been observed during the seismic motion (Ponzo et al. 2010b), namely: (i) small differences between experimental and ideal stiffness, (ii) slightly different behaviour of the device located on the two sides of the structure, with negligible torsional effects (iii), different behaviours of the VD located at different floors of the model, due to the different velocity to which they are subjected (3-5 Hz). Despite these anomalies recognized experimentally in the devices during shaking table tests, an acceptable agreement between experimental and numerical results is also found.



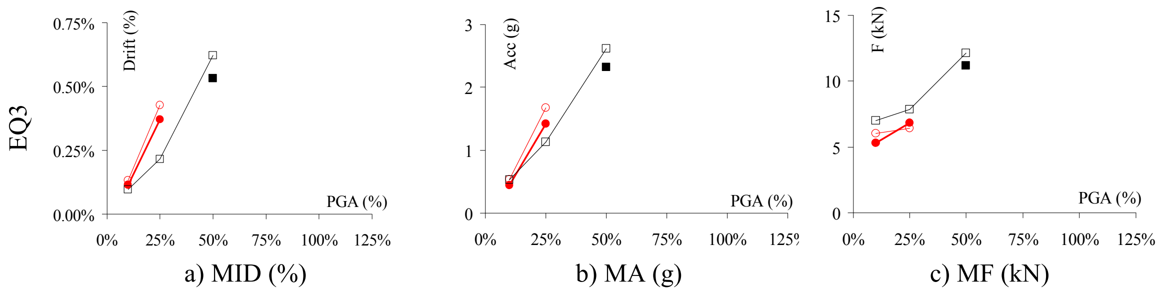


Fig. 7. Experimental results for the frame with SMA1, SMA2, SMA1+VD and SMA2+VD EDBs, for earthquakes n. 1, 2 and 3 at different intensities, in terms of: (a) MID, (b) MA and (c) MF

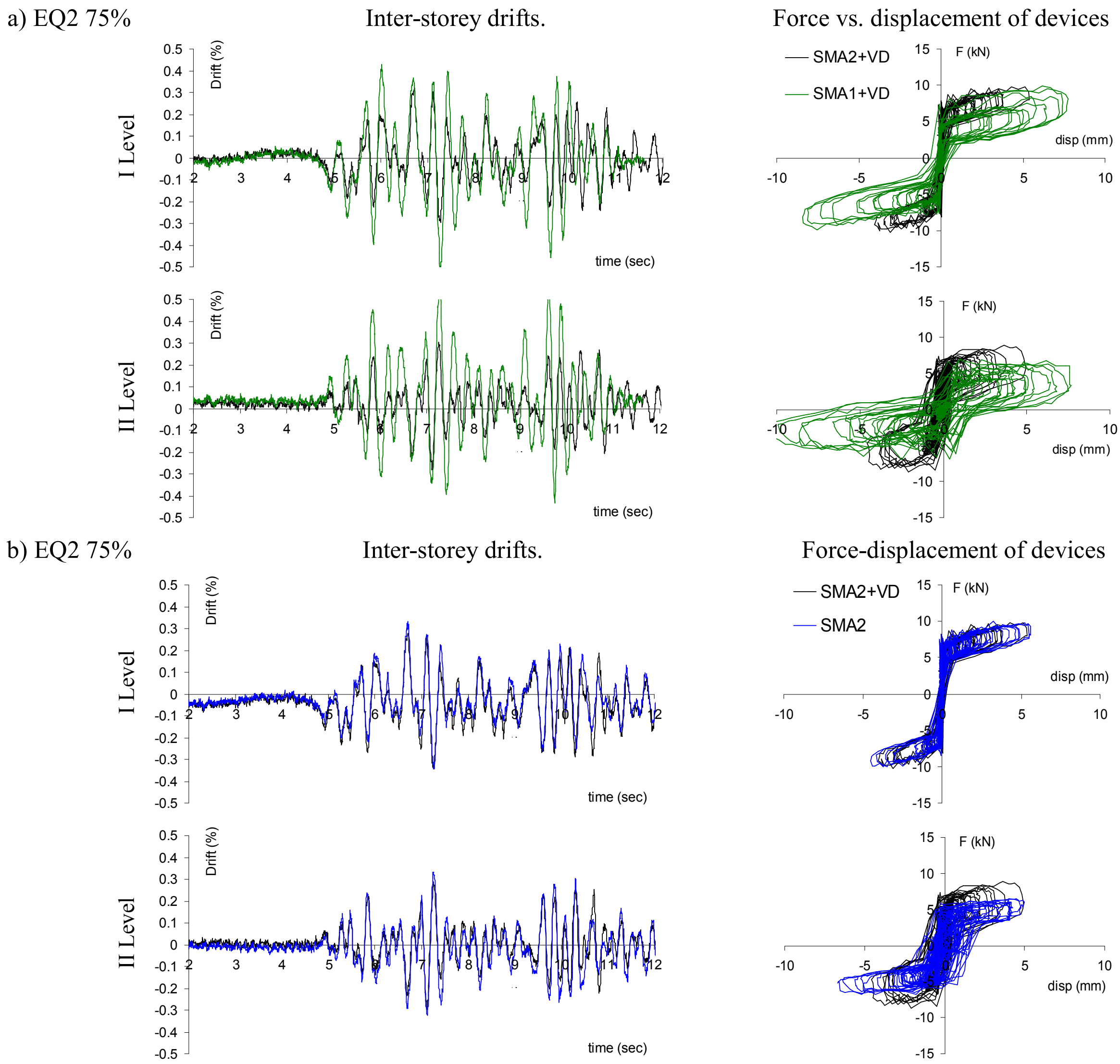


Fig. 8. Comparison of experimental time-histories of drift and force-displacement for visco-recentring devices at the two levels, earthquake n.2, PGA = 75%, between SMA2+VD EBD configurations: a) SMA1+VD; b) SMA2.

PGA 100% Inter-storey drifts. Force vs. displacement of dampers

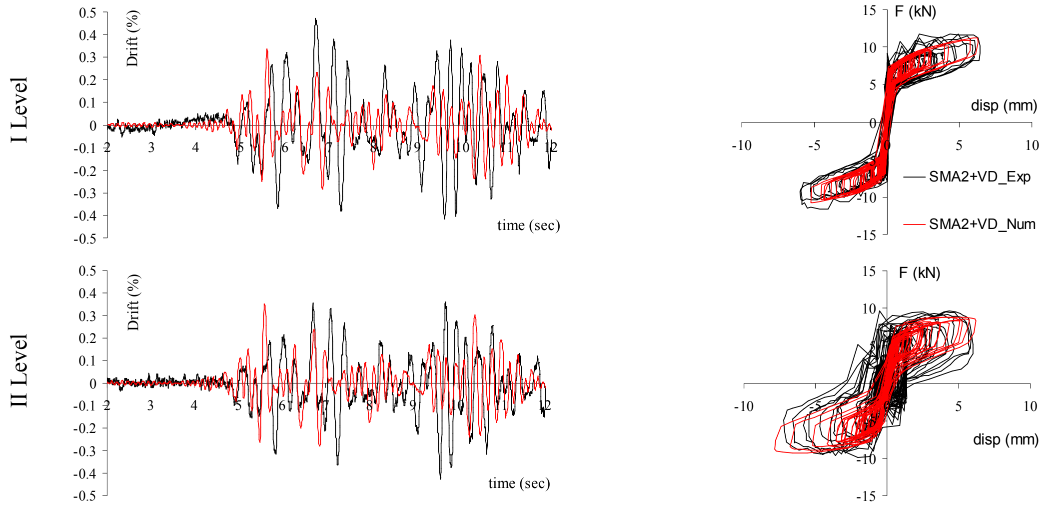


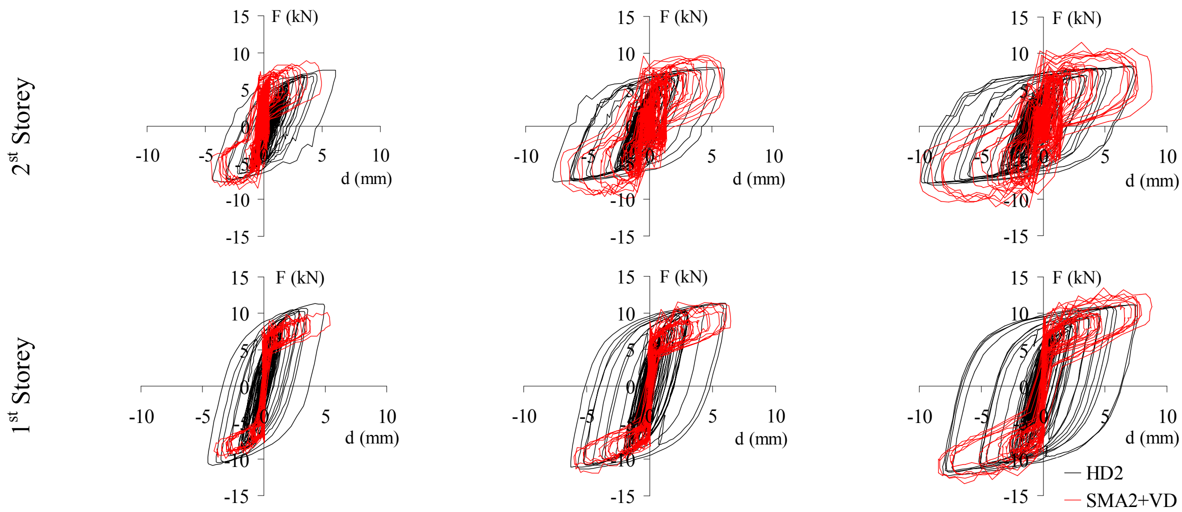
Fig. 9. Experimental and numerical Time-histories of drift and force-displacement of SMA2+VD devices, for earthquake n. 2, PGA =100% PGA 100%.

The comparison between the response of the structure with SMA(1;2) and SMA(1;2)+VD EDBs clearly points out the better vibration control of the structure due to the additional energy dissipation capacity provided by the VD devices. Basically, the presence of VD components permits the highest value of PGA% to be reached.

The Fig. 10 shows, instead, the direct comparison of the cyclic behaviour of the devices, obtained considering the frame with SMA2+VD and HD2 EDB's and making reference to the acceleration record 196, with PGA 75%, 100% and 125%. The presence of certain anomalies, due to the manufacturing tolerance, has been observed during the seismic motion [6]. Despite this, the experimental outcomes (Fig. 6) show that: i) yield strength, stiffness and post hardening ratio of the EP and FS model are almost similar, (ii) different values of β parameter at different storey are actually found (from 0.2 to 0.6), (iii) maximum displacement (or ductility demand) equal for the devices of the two EDB's are highlighted at both storey (this means an optimal activation of the dampers along the height); (iv) values of the mean inter-storey drifts results very close to the target value 0.5%.

The comparison between the response of the structure with SMA2, SMA2+VD and HD2 EDB's configurations, as well as the frame w/o EDB's, at different intensity of the seismic input (1228, 196 and 535) is reported in [15].

In particular, in Fig. 11 the experimental values of the (i) maximum inter-storey drift (MID) and ii) maximum top floor acceleration (MA) obtained by the model with SMA2, SMA2+VD and HD2 EDB's configurations, with reference to the seismic inputs named 1228 and 196 for PGA=25%, 50%, 75% and 100%, are reported. Fig. 11 clearly shows a reduction of the maximum drift at both the floor levels of more than 2 times when compared with that of the bare structure. Maximum inter-storey drifts exhibited a similar trend, with a maximum value of about 0.5%, the target drift of the design procedure, which is comparable with the maximum values observed for the bare structure subjected to accelerogram n. 2 at 25% of PGA. Comparing the SMA2+VD and HD2 EDBs, a comparable MID and MA for every intensity of seismic input (see Fig. 11) was found experimentally



PGA 75% 100% 125%

Fig. 10. Experimental behaviour of the frame with SMA2+VD and HD2 EDB's for TH 196, PGA 75%, 100%, 125%

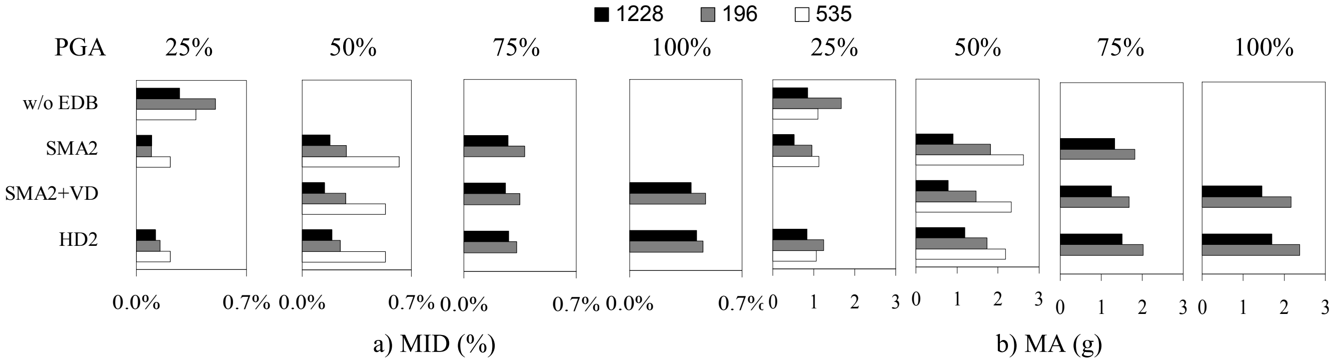


Fig. 11. Experimental results of the frame w/o EDBs and with SMA2, SMA2+VD and HD2 EDBs, earthquakes n. 1, 2 and 3, at PGA = 25%, 50%, 75% and 100%, in terms of: a) MID; b) MA.

VI. Conclusion

A Displacement-Focused Design (DFD) procedure has been proposed to evaluate the mechanical characteristics of a new Energy Dissipating Brace (EDB) system, based on the recentring properties of a Shape Memory Alloy (SMA) device coupled with viscous dampers (VD). The procedure enables the designer to obtain the mechanical characteristics of an equivalent visco-recentring system starting from the characteristics of a hysteretically damped braced system designed using a simplified method.

Two different ductility demand (μ_{DB}) values were considered in the design procedure used for visco-recentring systems (μ_{DB} =10 for SMA+VD1 and μ_{DB} =5 for SMA+VD2).

The proposed method was experimentally applied to design a series EDB solutions for the JETPACS model. During testing the seismic excitations were applied at increasing amplitudes expressed as a percentage of the peak ground acceleration of a set of natural earthquakes, up to a maximum value corresponding to the attainment of the design performance criterion: a limit value of the inter-storey drift selected to avoid yielding of the frame members (thus guarantee repeatability of the test).

The non linear seismic response of the experimental braced model has been analyzed comparing the effectiveness of the SMA+VD EDB's with the capacity of Hysteretic Dampers (HD) EDB's on controlling seismic vibrations. A comparable maximum inter-storey drift and maximum acceleration among SMA2+VD and HD2 EDB's, are experimentally found.

The response of the model with SMA+VD EDB's lead to a comparable level of protection for the framed structure with HD EDB's, limiting to 0.45% the maximum inter-storey drift experienced by the steel frame under the reference seismic input, not much less than the target value (0.5%). The proposed iterative design procedure showed their capability in reaching the performance objective, at least for the considered typology of device SMA+VD. Numerical and experimental outcomes also pointed out the fundamental role of the energy dissipation capacity of the VD in reducing the seismic vibrations of the structure and improves the performance of the EDB's.

A good agreement between experimental and numerical results obtained by NTHA using SAP2000 was observed. The effectiveness of the Visco-recentring bracing systems in reducing seismic effects is highlighted when compared to that of the structure without EDBs, achieving an average reduction of inter-storey drift in the order of 2.5-3 times.

Acknowledgment

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