JET-PACS PROJECT: DYNAMIC TEST ON STEEL FRAME EQUIPPED WITH HYSTERETIC ENERGY DISSIPATING BRACING SYSTEM

F. C. Ponzo[1], A. Di Cesare[2], C. Moroni[2], D. Nigro[2], M. Dolce[3] and R. Marnetto[4]

[1] *Professor, DiSGG, University of Basilicata, Potenza, Italy*

[2] *DiSGG, University of Basilicata, Potenza, Italy, email: antodice@yahoo.it*

[3] *Professor, Director of Seismic Risk Office, Dept. of Civil Protection , Rome, Italy, formerly DiSGG, University of Basilicata, Potenza, Italy*

[4] *Engineer, TIS SpA, Rome, Italy*

ABSTRACT :

An extensive experimental dynamic testing programme named JetPacs is being carried out at the Structural Laboratory of the University of Basilicata. The JetPacs Project has been developed within the RELUIS 2005-08 project (Research Line 7: Technologies for base isolation and control of structures and infrastructures), involving partners from different Italian universities. The tests are carried out on a 1:1.5 scaled 2-storey, 1-bay, three-dimensional steel frame model. Six different passive and semi-active Energy Dissipating Bracing (EDB) systems are, alternatively, used during the tests. The complete experimental program is presented in a companion paper presented at the same Conference [Dolce et al., 2008].
The elasto-plastic EDB system adopted for the tests presented in this paper is based on the hysteretic properties of steel elements that provide additional horizontal strength, stiffness and energy dissipation capability, to limit the interstorey drifts of the structural system. The structural model is subjected to three different sets of natural and artificial earthquake records, compatible with the Italian seismic code response spectra for A, B and D soil types. The seismic intensity is progressively increased until the design performance criterion is achieved.
The main objective of this experimental investigation is to evaluate the effectiveness of the EDB system in dissipating input energy and in reducing the seismic response of the structural model under moderate and strong earthquake. A further goal of this work is to verify the reliability of the simplified method used to design the mechanical characteristic of the devices.
In this paper, the design of the elasto-plastic devices, as well as the preliminary non linear time history numerical simulations on the mock-up equipped with the hysteretic bracing system, are described.

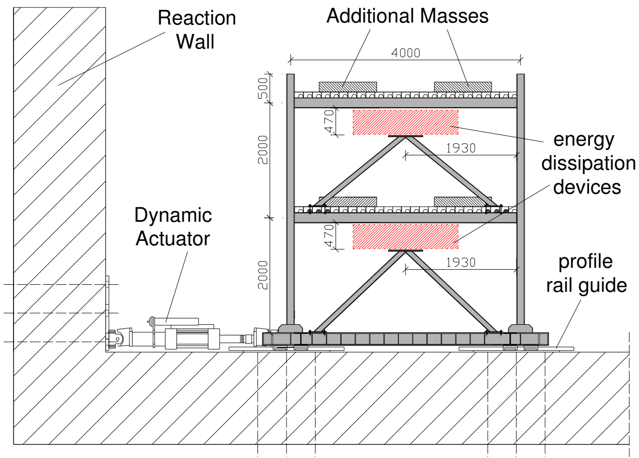
KEYWORDS: Energy dissipating devices, design method, passive control, numerical simulation, hysteretic devices, shaking table test

1. INTRODUCTION

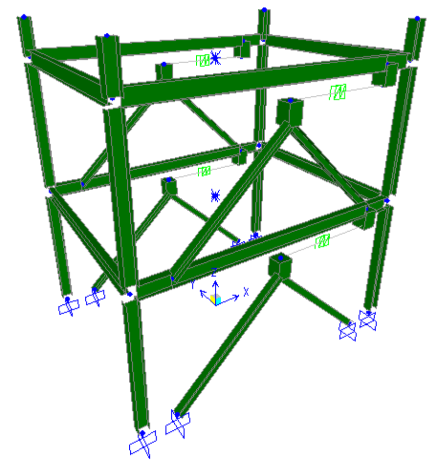
Traditional retrofitting techniques for framed structures are based on widespread strengthening of the structure and alternatively on the introduction of additional, very stiff, structural members. In recent times, innovative strategies for the passive control of structures have been studied and experimented, such as those based on the insertion of energy dissipating bracing systems in the frame. These techniques have shown their effectiveness in reducing seismic effects on existing frames, but extensive experimental investigations are required to provide reliable analysis and design data.
An extensive dynamic experimental testing programme, named JetPacs (Joint Experimental Testing on Passive and semiActive Control Systems), is scheduled to be carried out at the Structural Laboratory of the University of Basilicata [Dolce et al., 2008].
The JetPacs Project has been supported by several partners from different Italian Universities, which in turn have developed or studied a number of energy dissipation devices based on different materials and/or principles. During testing, a total of six different passive or semi-active energy dissipating devices based on currently available technologies (i.e. viscous and hysteretic damping) or innovative systems (i.e. shape memory alloy wires, magnetorheological fluids) are used. In particular, hysteretic elasto-plastic devices have been studied by the Research Unit of the University of Basilicata and presented in this paper.
The main design methods for displacement dependent systems known in the literature are based on the hypothesis of i) elastic structural behavior or ii) controlled yielding deformation of the structure. Methods assuming that all input energy is dissipated by bracing system [Filiatrault and Cherry 1988] belong to the first type. Perhaps more suitable for real application on existing buildings are the methods based on controlled yielding deformation of structure [Vulcano et al., 2002, Braga et al., 2002], for the optimization of costs and building performances.
This paper provides an overview of the new design procedure for hysteretic energy dissipating devices used for the JetPacs experimental application, compatible with the prescriptions of the new Italian seismic code [D.M. 14/01/08]. The preliminary numerical results of the non linear Time History Analysis (NTHA) are also reported.

2. EXPERIMENTAL MODEL

The experimental 2/3-scaled model for dynamic tests has been designed starting from a steel building prototype. Figure 1 shows the general layout of the experimental scaled model. The test model is a 2-storey steel frame, with one span in the test direction. The two floors are made of 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, having 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 the mass-similitude scaling, as described in the general report [Dolce et al., 2008]. Additional steel beams (HE220B) are realized at the base of the experimental model to be connected with the shaking table system of the test apparatus. Dead and live loads considered in the design of the prototype are those typical of a building for civil residence housing.
The steel frame has been modelled with SAP2000_Nonlinear [CSI, 2004], 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 rigid diaphragm constraints.
The model dynamic identification carried out on the non-upgraded model is presented in [Dolce et al., 2008].



(a) Frame X (Test) Direction



(b) 3-D numerical model

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

3. PERFORMANCE OBJECTIVE

The performance objective of the design was to prevent damage to structural members. Then it has been 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.

The design procedure of elasto-plastic devices for this experimental application aims to calibrate and to optimize the fundamental parameters of the energy dissipation system (strength, stiffness and ductility of braces) as a function of: (i) mechanical characteristics of the specimen; (ii) expected performance level; and (iii) seismic inputs. Below, the main steps of the iterative procedure and the criteria followed for the geometrical and mechanical design of the hysteretic energy dissipation devices, as better detailed in [Ponzo et al., 2007], are summarized.

The first step consists on a preliminary evaluation of the unstrengthened steel frame lateral resistance in the test direction, through a non-linear static analysis carried out considering two different distributions of horizontal forces, one proportional to the masses and the other one connected to the first modal shape, both applied in the center of masses of each floor. In the case of Jet-Pacs experimental model, the forces to be absorbed by energy dissipating systems under the design earthquake (Eurocode 8 spectrum for soil type B and Seismic Zone 1) have been calibrated in order to avoid any inelastic deformation of the structure. The results of non linear static analysis are shown in Figure 2 in terms of normalized base shear/model weight ratio and roof displacement/model height ratio. As can be seen in Figure 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, a maximum interstorey drifts (i.e. interstorey displacements divided by the clear height of the columns) of the order of 0.75% are found. The hysteretic 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 for high seismicity zones. Assuming a Safety Factor (SF) equal to 1.5, a target drift of approximately 0.5% is defined.

In the second step, starting from the smallest lateral resistance curve, reduced according to the transformation factor Γ of the first modal shape [DM 04/02/08], the equivalent elastic SDOF system capacity (F^*_y, d^*_y) has been obtained (curve w/o EDB of figure 3). The mechanical characteristics of the equivalent bracing system are determined by an iterative procedure as follows:

1. imposing a first hypothetical ductility value for the equivalent dissipating brace μ_c, as function of the considered dissipating devices typology. Such initial value is assumed equal to 10 for the hysteretic device adopted in the JetPacs project. Typically, the ductility of devices based on steel yield can reach higher values, greater than 20, with good stability of behavior for an adequate number of cycles [Dolce et al., 1996];
2. evaluation of the seismic force at j-th step ($F_{e,j}$) for the equivalent elastic SDOF system, as a function of the global dynamic characteristics of the braced structure and of the design earthquake. The force is obtained by multiplying the equivalent mass m^* of the model with the pseudo acceleration $Se(T^*)$ derived from the elastic response spectrum for the equivalent period T^* of the structure without EDB system [Dolce et al., 2008];
3. determination of the yield point (d_{cy}; F_c) of the equivalent bilinear brace (curve equivalent device of figure 3) starting from the available ductility μ_c fixed at point 1 and the maximum displacement of equivalent device d_{C0} corresponding to the elastic target displacement d^*_y of the model without EDB. The characteristics of the devices have been determined by means of "equal energy criterion" considering the equivalent elastic SDOF and the equivalent elasto-plastic SDOF of the model with EDB (curve with EDB of figure 3), as shown in Figure 3.

The procedure converges to solution when the difference between the elastic seismic forces evaluated in two consecutive steps is less than an acceptable tolerance: $|F_{e,j} - F_{e,j-1}| < \varepsilon$.

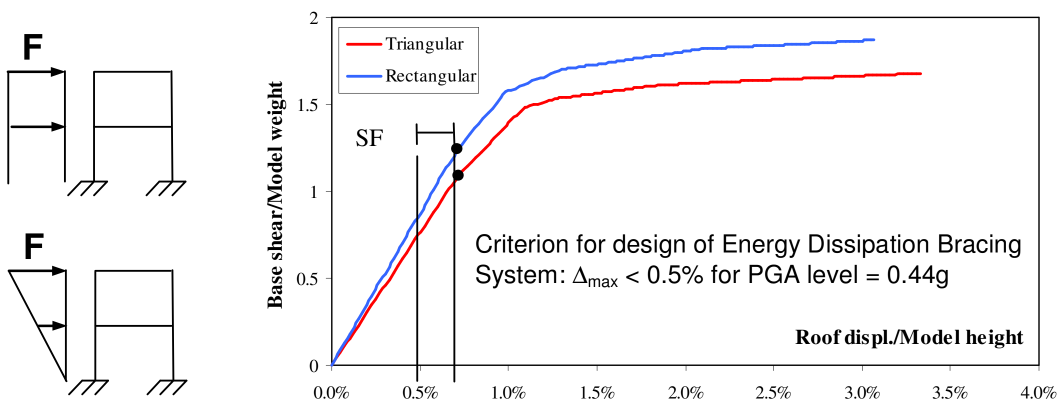


Figure 2 Push-over curves and yield point of the experimental model

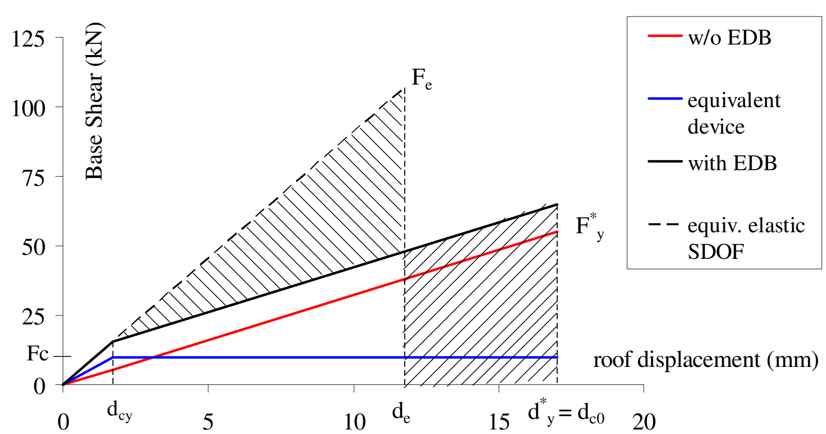


Figure 3 Equal energy criterion

The mechanical characteristics of the single devices along the height of the model are evaluated in the third step. Distribution of stiffness of equivalent elasto-plastic device k_c is made under the hypothesis that the ratio between structural stiffness k_i and equivalent bracing stiffness $k_{c,i}$ at the i-th storey is equal to the ratio between k_c and the stiffness of the equivalent elastic system of the structure k^*, as shown in equation 1. For the strength distribution the ratio between structural strength $F_{y,i}$ and equivalent bracing strength $F_{c,i}$ at the i-th storey is assumed equal to the ratio between strength of the equivalent bilinear device F_c and strength of the equivalent elastic system F_y^* of the original structure, as reported in equation 2.

$$\frac{k_{c,i}}{k_i} = \frac{k_c}{k^*} \quad \rightarrow \quad k_{c,i} = \frac{k_c}{k^*} \cdot k_i \tag{1}$$

$$\frac{F_{c,i}}{F_{y,i}} = \frac{F_c}{F_y^*} \quad \rightarrow \quad F_{c,i} = \frac{F_{y,i}}{F_y^*} \cdot F_c \tag{2}$$

The stiffness k_i and the strength $F_{y,i}$ of i-th storey of model are determined by linear static analysis.
Stiffness and strength of the equivalent i-th storey device are distributed among the single device ($k_{c,i,s}$; $F_{c,i,s}$) proportionally for the two storey devices.
Last step of the design procedure is the verification of the structure with hysteretic EDB system by means of non linear static analyses coherently with the prescription of [D.M. 04/02/08]. In case of JetPacs experimental model with hysteretic EDB system, this verify ication method results not applicable because of its strong post stiffness ratio, as you can see in Figure 3. Therefore, the verification of the designed devices is carried out by means of non-linear dynamic analysis, as described below.

4. HYSTERETIC DEVICES

The elasto-plastic devices considered in this paper are manufactured by TIS spa. They are 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, currently under patent process, is constituted by low-carbon U-shaped steel plates capable to dissipate 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 hysteretic EDB system consists of four elasto-plastic devices, two for each storey, mounted on the top of two stiff V-inverted steel braces (HEA100), as shown in Figure 6. Bolts ensure the rigid connection between the stiff braces and the hysteretic devices.
Various experimental studies on a large number of hysteretic device types [Dolce et al. 2001, 2005 and Cardone et al. 2005] and the analysis of real applications [9ISIED 2005] have shown that the typical force vs. displacement relationship is an elastic almost-perfectly plastic system, with very small post yield stiffness.
The strongly non linear behavior of the steel-based energy dissipating devices is modeled by using the non linear finite element available in SAP 2000. In case of JetPacs with hysteretic EDB system, *link* elements characterised by *Wen* hysteretic behaviour [Wen and Chopra, 2003] have been added to the non-linear model shown in Figure 1, to simulate the energy dissipating devices. The mechanical characteristics of the devices, obtained by the iterative aforesaid procedure, are summarized in Table 4.1.

Table 4.1 Mechanical characteristics of single braces

Device Type	Level	Yield Force (kN)	Elastic stiffness (KN/mm)	Design ductility
Hysteretic (TIS Spa, Italy)	I°	4.42	5.70	10
	II°	2.89	3.18	10

5. PRELIMINARY NUMERICAL ANALYSIS

In order to verify the designed EDB system, extensive Non linear Time History Analyses (NTHA) have been carried out using the numerical model described in the previous paragraph (see Figure 1b).

Three different sets of earthquake records compatible with the response spectra of the Italian and European seismic code for A, B and D soil types, selected in the *European Strong Motion Database* (ESMD) or generated, have been considered for analyses.
To ensure consistency with the scale of the experimental model, all acceleration profiles are scaled down in time by the factor $(1.5)^{1/2}$, while reference to a high earthquake intensity (Seismic Zone 1) is made. Non-linear dynamic analyses were carried out using the Direct Integration Method (Newmark).
The elaboration of the numerical outcomes emphasises the differences of seismic behaviour between the different model configurations, without and with the hysteretic EBD systems. The numerical seismic response of the experimental model in both configurations is compared in Figure 5, in terms of (i) storey displacement, (ii) interstory drift and (iii) base shear in the time. The analyses refer to a seismic input belonging to the set of Zone 1, Soil type B (named 000196xa in ESMD), whose response spectrum is very close to the design response spectrum with PGA = 0.44g [Dolce et al. 2008].
As can be seen, the seismic response of the structure drastically reduces in amplitude when EDB's is used. The maximum inter-storey drift (MID) permits to quantify the effectiveness of EDB system as a retrofitting technique for framed structures, being MID's strictly correlated to both structural and non structural damage at high seismic intensities.

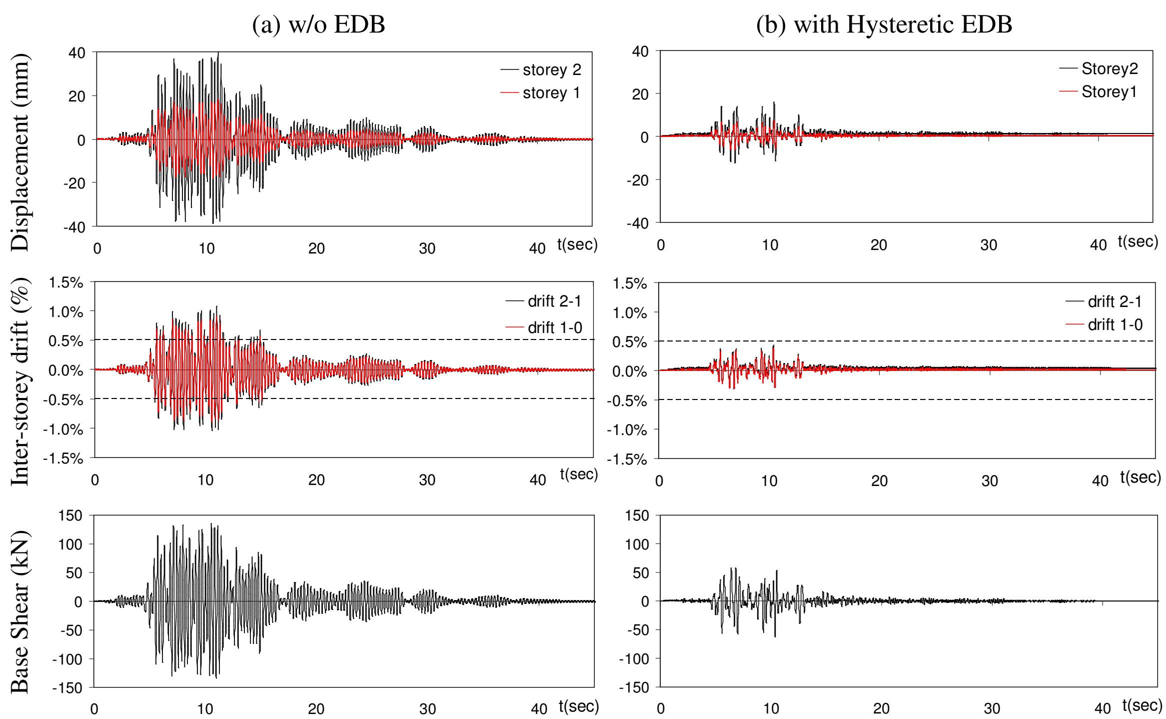


Figure 5 Time-histories of storey displacements, inter-storey drifts and base shear for the frame (a) w/o EDB's, and (b) with Hysteretic EDB's. Seismic responses generated considering the same accelerogram (000196xa ESMD) at 0.44g PGA.

In Figure 6 the force vs. displacement relationship obtained by preliminary numerical simulations for hysteretic energy dissipation devices at each floor is compared. The diagrams of Figure 6 refer to the same accelerogram and PGA value (0.44g) considered in Figure 5. Both dissipating devices have been effectively activated by the earthquakes, reaching ductility value consistent with their design values. The numerical simulations of mock-up equipped with hysteretic EDB system produce maximum inter-story drifts smaller than the drift limit (0.5%) for the considered sets of accelerograms and for a PGA relevant to ultimate limit state, as shown in Figure 7.

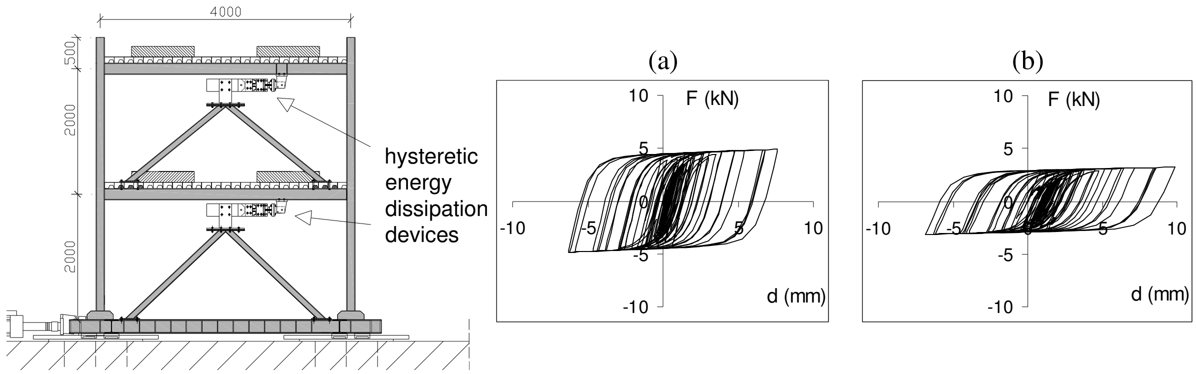


Figure 6 Numerical force-displacement cyclic behaviours of hysteretic EDB's (a) 1st floor and (b) 2nd floor, registered during NTHA at 0.44g PGA (000196xa).

Figure 7 compares the maximum interstorey drifts (mean values over 7 accelerograms) experienced by the frame w/o EDB's and with Hysteretic EDB's, considering three different sets of accelerograms, compatible 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). 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 0.5%, reaching values of the order of 1.2-1.4%, depending on the soil type considered. As a consequence, extensive plastic deformations are expected to occur in the frame w/o EDB's. The numerical simulations produce a mean value of maximum inter-story drifts smaller than the drift limit (Δ_{max} =0.5%), being equal to 0.35-0.45%, when the designed hysteretic EDB system is adopted. The structure is then expected to remain elastic under the design earthquake.

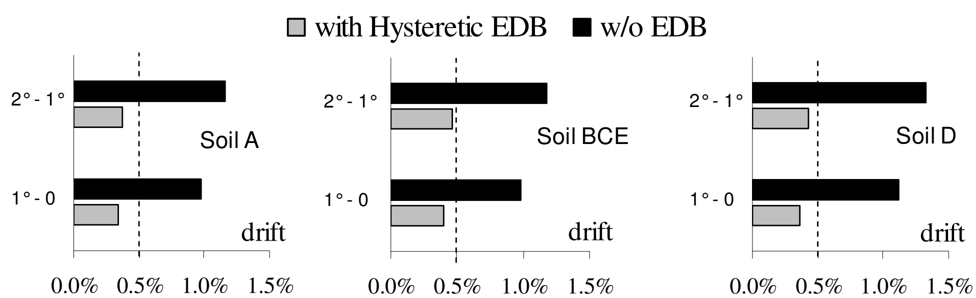


Figure 7 Comparison between the maximum interstorey drifts (mean values over 7 accelerograms) experienced by the frame w/o EDB's, and with Hysteretic EDB's, considering a set of accelerograms compatible with the EC8 elastic response spectra at 0.35g PGA, for (a) stiff soils (S = 1), (b) medium soils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

6. CONCLUSION

An extensive program of dynamic experimental tests, on a 1:1.5-scale model of a 2-storey three-dimensional steel frame, is being carried out at the Laboratory of University of Basilicata. Six different passive and semi-active Energy Dissipating Bracing (EDB) systems are, alternatively, used during the tests, including the hysteretic EDB system presented in this paper, which is based on the hysteretic properties of steel plates.
In this paper the design objectives, the general criterion to evaluate the mechanical characteristics of the hysteretic EDB system and preliminary numerical simulation analyses have been described. The performance objective of the design was to limit the maximum interstorey drifts below 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).

A preliminary Nonlinear Time-History Analysis (NTHA) investigation has been carried out to evaluate the seismic behavior of the model, considering three different sets of seven accelerograms, compatible (on average) with the elastic response spectra provided by the Italian Seismic Code for stiff, medium and soft soils.
The NTHA results proved the effectiveness of the hysteretic EDB system in reducing seismic effects, if compared to that of the frame without EDB, and the correctness of the design procedure. In fact, the simulated seismic response of the model with EDB system shows a maximum inter-storey drift, at high seismic intensities, which is smaller than the established yield limit, achieving an average reduction of the interstorey drift of the order of 2.5 - 3 times.

ACKNOWLEDGMENTS

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