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The "direct-five step procedure for existing buildings": development and first application

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Abstract

This paper provides design indications for the seismic retrofitting of existing frame buildings by means of fluid viscous dampers. They are based on a simplified procedure developed in the last years for new buildings and called "direct five-step procedure".
This design procedure, which must be then followed by appropriate verification of the seismic behaviour through non-linear dynamic analyses, consists of 5 steps and is based on a prefixed seismic performance, such as a target damping ratio. The procedure aims at the full definition of the mechanical characteristics of the commercial non-linear viscous dampers, and at the estimation of the maximum forces both in the devices and in the structural elements (columns).
In the case of new buildings, the objective of sizing the viscous dampers in such a way as to keep the structural elements within the linear elastic range even for "rare" earthquakes of high intensity is easily achievable.
In the case of existing buildings designed for vertical loads only, the introduction of a damper system is not generally sufficient to keep the structural elements in the elastic range. Thus, it might be necessary to accept local plastic excursion of the structural elements, by taking into account the ductility capacity (albeit probably limited) of the existing building (hysteretic dissipations associated with damage in beams and columns).
This paper reports the extension of the so-called "direct five-step procedure" to the case of existing buildings and its first application to a 6-storey frame structure case study, which is representative of reinforced concrete buildings designed for vertical loads only, before the enforcement of seismic codes.

Keywords: existing buildings; frame structures; fluid viscous dampers; design procedure; ductility capacity; applicative example

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1. Introduction

Fluid viscous dampers have already proven to be effective in the mitigation of the seismic effects in building structures [1,2]. However, their application is still limited. This is also due the lack of specific code indications and prescriptions. For instance, the Italian code (NTC 2018 [3]) does not explicitly consider damper systems. The normative point §7.10.4 deals only with isolation devices. The corresponding point §C.7.10.4 of the Circular [4] distinguishes between velocity-dependent dissipation devices and displacement-dependent devices, underlining the common goal of reducing deformations to contain damage and avoid collapse of the structure, and highlighting the importance of a preliminary analysis of the structure in the event that an intervention is carried out on an existing building. Nevertheless, the Circular does not suggest either pre-dimensioning/design formulas for the different types of dampers, or practical indications of how the ductile capacities of the existing structure could be taken into account.

A simplified procedure called "direct five-step procedure" was developed for the design of viscous dampers to be placed in new buildings in the last years by some of the authors [5,6,7]. This design procedure, which must be then followed by appropriate verification of the seismic behaviour through non-linear dynamic analyses, consists of 5 steps and is based on a prefixed seismic performance, such as a target damping ratio. The procedure aims at the full definition of the mechanical characteristics of the commercial fluid viscous dampers characterized by the non-linear force-velocity relationship ($F = c_{NL} \cdot v^{\alpha}$), and at the estimation of the maximum forces both in the dampers and in the structural elements (columns). In particular, it provides the following formula for estimating the damping coefficient, c_{NL} , for the commercial non-linear devices (assuming they are inserted according to the classical inter-storey placement and they are all equal to each other):

$$c_{NL} = \bar{\xi}_{\text{visc}} \cdot \frac{2\pi}{T_1} \cdot \frac{W}{g} \cdot \left(\frac{N+1}{n}\right) \cdot \frac{1}{\cos^2\theta} \cdot \left(0.8 \cdot \frac{S_e\left(T_1, \bar{\eta}\right)}{2\pi/T_1} \cdot \frac{2}{N+1} \cdot \cos\theta\right)^{1-\alpha} \tag{1}$$

The procedure also recommends a minimum value for the axial stiffness of the device (fluid + support rod):

$$k_{axial} \geq 10 \cdot \bar{\xi}_{\text{visc}} \cdot \left(\frac{2\pi}{T_1}\right)^2 \cdot \frac{W}{g} \cdot \left(\frac{N+1}{n}\right) \cdot \frac{1}{\cos^2\theta} \tag{2}$$

In the case of new buildings, the objective of sizing the viscous dampers in such a way as to keep the structural elements within the linear elastic range even for "rare" earthquakes of high intensity is easily achievable.

In the case of existing buildings designed for vertical loads only, the introduction of a damper system is not generally sufficient to keep the structural elements in the elastic range. Thus, it might be necessary to accept local plastic excursion of the structural elements, by taking into account the ductility capacity (albeit probably limited) of the existing building (hysteretic dissipations associated with damage in beams and columns).

In this paper the "direct five-step procedure for existing buildings" is introduced for the first time and an applicative example is carried out.

Nomenclature

F	dissipative force developed by the fluid viscous damper
c_{NL}	damping coefficient of the non-linear damper
v	velocity between the two damper ends
$\alpha = 0.15$	damping exponent of the non-linear damper
$\bar{\xi}_{\text{visc}}$	target damping ratio provided by the fluid viscous dampers
T_1	fundamental period of the structure
W	total seismic weight of the building
g	gravity acceleration (9.81 m/s^2)
N	total number of storeys of the building structure
n	total number of dampers at each storey for each direction

θ	angle of inclination of the damper with respect to the horizontal line
$S_e\left(T_1,\overline{\eta}_\xi\right)$	spectral ordinate at period T_1 evaluated considering $\overline{\eta}_\xi$
$\overline{\eta}_\xi = \sqrt{\dfrac{10}{5+\xi_{\text{intr}}+\overline{\xi}_{\text{visc}}}}$	target response spectrum reduction factor, due to intrinsic (ξ_{intr} = 5%) and target viscous damping ratio ($\overline{\xi}_{\text{visc}}$)
k_{axial}	axial stiffness of the diagonal dissipative brace (fluid + support rod)

2. The "direct-five step procedure for existing buildings"

For existing buildings, the insertion of dampers reduces the deformations and stresses acting on the structural elements, and, in the case of response beyond the elastic limit, the ductility demand. In the latter case, it seems appropriate to develop a design / dimensioning method that also takes into account the possibility of relying on the ductile capacity available (although probably limited) of the existing building being studied. In fact, for existing buildings designed for vertical loads only (often characterized by Capacity / Demand ratios around 0.20-0.30), in general, the introduction of a viscous damper system is not sufficient for a “full” seismic retrofit, such as to keep the structural elements in the elastic range (the maximum reduction of the seismic demand achievable due to the insertion of a system of inter-storey dampers is around 50%). It may therefore be useful to partly rely on the available ductility (i.e., hysteretic dissipations associated with damage to the structural elements).

It should also be noted that the NTC2018 code allows to consider the coupling of the two dissipation methods - viscous (in the dampers) and hysteretic (in the structural elements) - only with Non Linear Dynamic Analysis. This is mainly due to the fact that, in the definition of the design spectrum, the η reduction factor depends exclusively either on the damping ratio and therefore on the damper system, or on the behavior factor and therefore on the ductile capacities of the structural elements. However, in point 7.3.4.1, the NTC2018 code still requires the comparison with the results of a Response Spectrum Analysis, in order to control the differences in terms of global forces at the base of the structure.

In this respect, a revision of the “direct five-step procedure” has been studied to extend it to existing buildings and to consider the ductility capacity of the structural elements.

The only step that is changed from the original formulation for new buildings is Step 1, regarding the definition of the target performance objective (and corresponding reduction factor) and the possible design strategies. Hereafter the revised Step 1 is described, whilst the reader can refer to the previous papers for the other steps [5,6,7].

In Step 1, the target reduction factor of the response spectrum is evaluated as the ratio ζ_E between the maximum seismic action that can be tolerated by the structure and the maximum seismic action that would be used in the design of a new building, as per §8.3 of NTC2018, corresponding to the capacity/demand ratio (C/D) for the current structure:

$$\overline{\eta} = \zeta_E = \frac{C}{D} \tag{3}$$

Both C and D can be evaluated either at the global response level of the entire structure in terms of base shear - top displacement curve, as shown in Figure 1a, or at the local response level (e.g., bending moment, shear force) of the most stressed structural element (e.g., single column or beam). Hereafter reference is made to the global response level only. Regarding the capacity C: for each direction of entry of the earthquake, the capacity curve (pushover) of the existing building is constructed by means of non-linear static analysis. It is then useful to replace this with a bilinear curve according to the usual techniques (reported for example in §C7.3.4.2 of the Circular [4]). C is therefore assumed to be equal to the strength F_y^* (maximum base shear force that the structure can support) and the available ductility of the existing structure $\mu_{disp} = d^*_{\max,NL} / d^*_y$ is estimated, which corresponds, assuming the principle of equal displacement, to a maximum available behavior factor equal to $q_{\max} \cong \mu_{disp}$. Regarding the demand D (typically corresponding to a "rare" earthquake of high intensity, with PVR of 10% / VR): *D* is assumed to be equal to the base shear force for the equivalent linear structure, $V_{base,L}$, which can be obtained, depending on the desired level of approximation, either with a simple linear static analysis, or with a classic linear dynamic analysis with elastic response spectrum, or even with time-history but still linear dynamic analyses using a set of earthquake acceleration records consistent with the elastic spectrum.

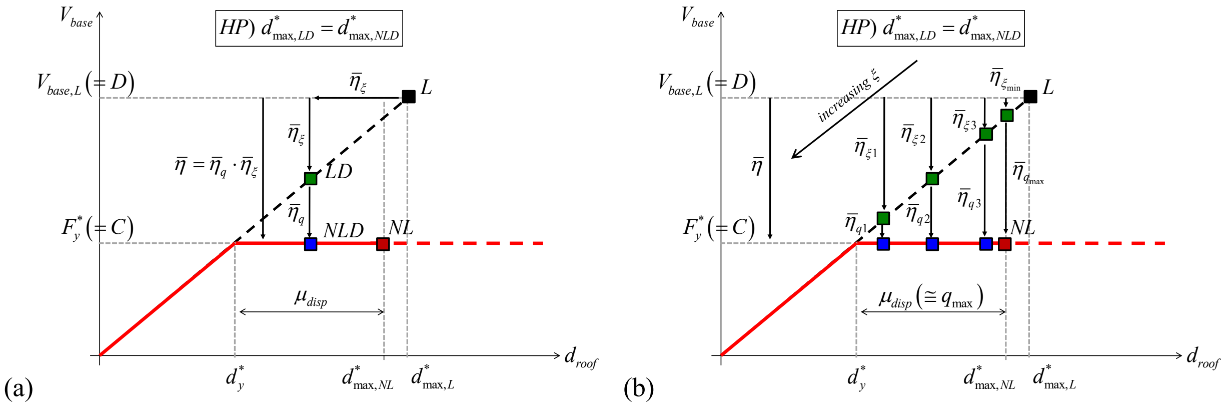


Fig. 1. (a) Illustration of the target performance point, identified by the blue square (NLD). NL = non-linear response of the existing structure as it is. NLD = non-linear response of the existing structure with dampers. L = response of the equivalent linear structure. LD = response of the equivalent linear structure response with dampers. (b) Illustration of the design strategies, based on a weighted distribution of the reduction factor of the seismic response between viscous dissipation and hysteretic dissipation.

Several design strategies can be defined based on a weighted distribution of the reduction factor of the target elastic spectrum (as described in Figure 1b), between the hysteretic dissipation in the structural elements ($\bar{\eta}_q = 1/q$, with $q < q_{\max}$, where $q_{\max}$ should be evaluated on the basis of the capacity curve of the existing building) and the viscous dissipation in the dampers (for subsequent design damper system):

$$\bar{\eta} = \bar{\eta}_q \cdot \bar{\eta}_\xi \qquad \text{from which} \qquad \bar{\eta}_\xi = \frac{\bar{\eta}}{\bar{\eta}_q} \tag{4}$$

The target damping ratio $\bar{\xi}_{visc}$ to be obtained with the additional viscous damper system (taking into account the presence of intrinsic damping equal to ξ_{intr} = 5%) is then identified as:

$$\bar{\xi} = \xi_{\text{intr}} + \bar{\xi}_{visc} = \frac{10}{\bar{\eta}_\xi^{\,2}} - 5 \qquad \text{from which} \qquad \bar{\xi}_{visc} = \frac{10}{\bar{\eta}_\xi^{\,2}} - 10 \tag{5}$$

It should be noted that, since the ductility resources of the existing structure are limited to μ_{disp}, the damping system must in any case be such as to provide at least a minimum damping ratio $\xi_{\min}$, corresponding to $\bar{\eta}_{\xi_{\min}} = \bar{\eta}/\bar{\eta}_{q_{\max}}$, where $\bar{\eta}_{q_{\max}} = 1/q_{\max} \cong 1/\mu_{disp}$.

3. The case study building

The reference building under consideration is supposed to be located in L'Aquila (Italy). It is a 6-storey reinforced concrete frame structure. Total height is 18.65 m. The inter-storey heights are equal to 3.4 m for the first floor, and 3.05 m for the remaining ones. In both directions the internal beams are with depth contained within the thickness of the floor, whilst the perimeter ones are with depth emerging from the floor. The floors are oriented along the longitudinal (X) direction and are assumed to be rigid in their plane, due to the presence of a 5 cm concrete slab. Each floor has a total thickness of 25 cm. Class C25/30 concrete and B450C steel are considered. The reinforcement bars in the columns guarantee at least 0.5% of the area of the concrete section and globally higher than 1%. The reinforcement bars in the beams guarantee at least 0.15% of the area of the concrete section, both in the tension area and in the compressed area, and in any case able to carry the maximum bending moments induced by a distribution of static vertical loads corresponding to permanent and variable loads at their characteristic value, without load partial safety factors (i.e., rare combination at the Serviceability Limit State). The non-linear response of beams columns is modelled with flexural plastic hinges placed at their ends. The non-linear (elastic-brittle) shear behaviour of the structural elements is not modelled. It is therefore implicitly assumed that the shear strength of all the structural elements has been adequately increased by means of structural reinforcement interventions (e.g., bands with fiber-reinforced polymeric materials) aimed at: (i) guaranteeing a shear strength higher than the shear force corresponding to the formation of bending plastic hinges (bending capacity suitably increased with overstrength factors), according to the hierarchy of resistances; (ii) increasing the ductile capacity of the cross-section.

Figures 2a and 2b show the building plan and the FEM model created in the SAP2000, respectively. The different colours refer to the different sections of the structural elements. The legend of the elements in the FEM model is reported in Table 2.

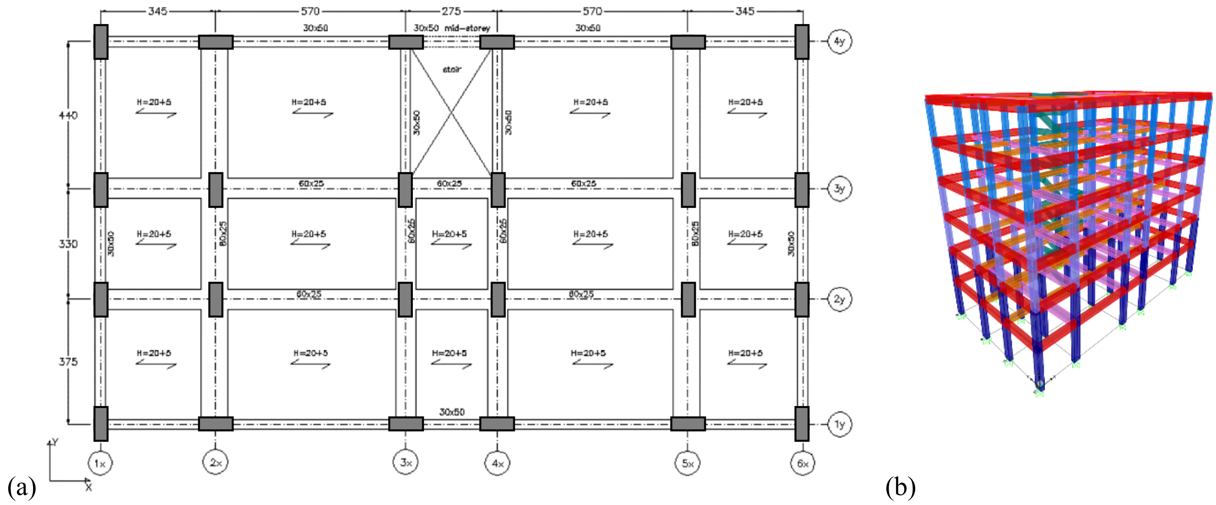


Fig. 2. (a) Building plan and (b) 3D FEM model of the building structure made in SAP2000.

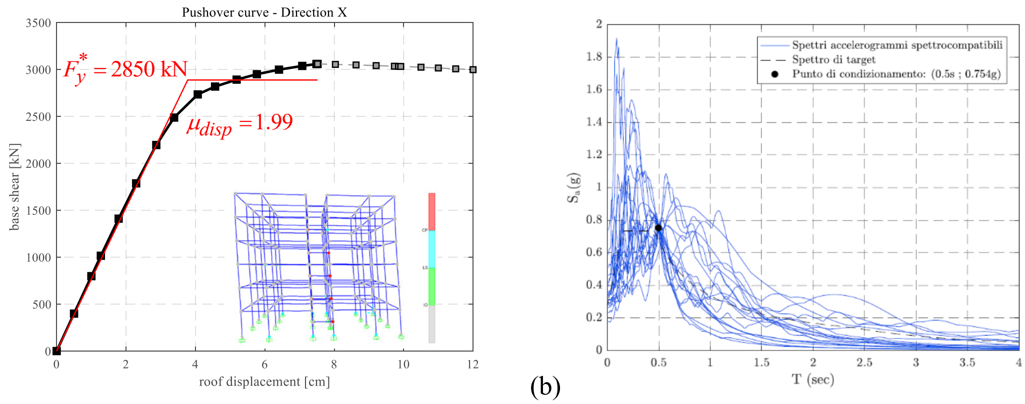
Table 1. Structural elements with relative reference colours in the FEM model.

Element	Cross-section	Colour	Element	Cross-section	Colour
Columns	40x30 cm^2		Stairwell beams	30x50 cm^2	
Columns	50x30 cm^2		Perimeter beams	30x60 cm^2	
Columns	60x30 cm^2		Internal beams along the X-direction	60x25 cm^2	
			Internal beams along the Y-direction	80x25 cm^2	

4. Analysis of the seismic performance of the case-study building in its current state

Separate seismic analyses along the X and Y directions are justified by the symmetric configuration of the case-study building and by the choice of neglecting the accidental eccentricity, that avoid coupled effects due to rotation. No vertical component of the earthquake action has been considered. The fundamental periods of the structure are equal to 0.795 s in the X direction and 0.693 s in the Y direction. For the sake of conciseness, in this paper, only the seismic response along the longitudinal X direction is presented.

In order to identify the ductile capacity of the existing building (assumed, as mentioned before, adequately reinforced in shear), a non-linear static analysis has been carried out with distribution of inertial forces derived from a uniform acceleration profile along the height of the building. Figure 3a shows the pushover curve (black colour) obtained along the X direction and the equivalent bilinear curve (red colour) obtained considering the established equal areas criterion. The bilinear curve allows to estimate both the strength in terms of maximum base shear that can be supported by the structure in the current state (which is around 2850 kN) and the available ductility of the existing building (which is around 2.0).



(a) (b)

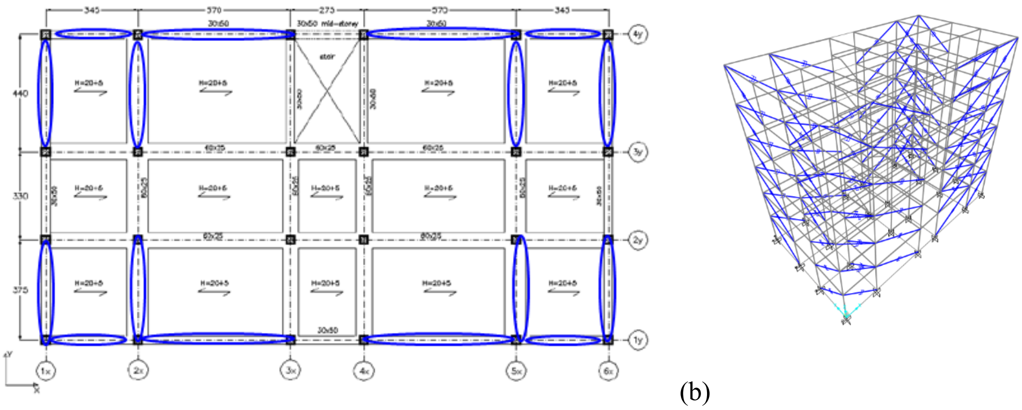
Fig. 3. (a) Results of the non-linear static analysis in terms of pushover and equivalent bilinear curves along the X direction. (b) Elastic spectrum and response spectra of set of the 20 natural accelerograms.

In order to evaluate the demand, and therefore the capacity/demand ratio, an equivalent static analysis has been carried out with an elastic spectrum corresponding to a 10% probability of exceedance in the reference period (shown in Figure 3b) for the L'Aquila site. The seismic masses are those associated with the rare SLS load combination. The total seismic weight of the building is 16006 kN. The total base shear along the X direction ($S_e\left(T_1 = 0.795s, \eta = 1\right) = 0.422g$) is equal to approximately 6750 kN and, therefore, the capacity/demand ratio of the building in the current state is equal to approximately C/D = 2850 kN / 6750 kN = 0.42.

For the non-linear time-history analyses with step integration, a set of 20 natural accelerograms has been considered, appropriately scaled to be consistent with the assumed elastic spectrum, respecting the condition of a spectral ordinate equal to 0.754g in correspondence with the conditioning period 0.5s. Figure 3b also shows the response spectra of the 20 seismic records.

5. Design of the viscous dampers system

For the design of the viscous damper system, the "direct-five-step procedure for existing buildings", here proposed for the first time, is adopted. The configuration of viscous dampers is characterized by 8 devices at each storey and for each direction. Figure 4 represents the layout of the dampers.



(a) (b)

Fig. 4. Scheme of the identified dampers configuration: (a) plan distribution and (b) 3D view.

The design strategy is based on a weighted coupling of hysteretic dissipation (ductility available in the structural elements) and viscous dissipation (additional system of viscous dissipators) and is detailed hereafter. The starting point is represented by: $\bar{\eta} = \zeta_E = C/D = 0.42$ and $q_{\max} = \mu_{disp} \cong 2$. Assuming three different ductility demands, the reduction factors and the target damping ratios are evaluated, and three viscous dampers systems are obtained:

- $q = 1.8 \rightarrow \bar{\eta}_\xi = \dfrac{\bar{\eta}}{\bar{\eta}_q} = \dfrac{0.42}{0.55} = 0.76 \rightarrow \bar{\xi} = 12\% \rightarrow \bar{\xi}_{visc} = 7\% \rightarrow c_{NL} = 122\ \mathrm{kN}\left(\mathrm{s/m}\right)^{0.15}$
- $q = 1.4 \rightarrow \bar{\eta}_\xi = \dfrac{\bar{\eta}}{\bar{\eta}_q} = \dfrac{0.42}{0.72} = 0.58 \rightarrow \bar{\xi} = 25\% \rightarrow \bar{\xi}_{visc} = 20\% \rightarrow c_{NL} = 334\ \mathrm{kN}\left(\mathrm{s/m}\right)^{0.15}$
- $q = 1.2 \rightarrow \bar{\eta}_\xi = \dfrac{\bar{\eta}}{\bar{\eta}_q} = \dfrac{0.42}{0.84} = 0.50 \rightarrow \bar{\xi} = 35\% \rightarrow \bar{\xi}_{visc} = 30\% \rightarrow c_{NL} = 501\ \mathrm{kN}\left(\mathrm{s/m}\right)^{0.15}$

6. Results of the time-history analyses as verification of the seismic performances

Several non-linear time-history analyses have been carried out for the three identified viscous dampers systems ($\bar{\xi} = 12\%$, $\bar{\xi} = 25\%$, $\bar{\xi} = 35\%$), using as input the set of seismic records described before. Four models have been compared: L = bare structure (without viscous dampers) modelled as linear with structural elements characterized by indefinitely elastic behaviour; NL = bare structure modelled as non-linear with structural elements characterized by flexural plastic hinges at their ends; LD = linear structure with non-linear viscous dampers (designed according to the here proposed procedure, as summarized in previous section); NLD = non-linear structure with non-linear viscous dampers.

Figure 5a shows the mean response (over the 20 seismic records) along the X direction, in terms of base shear vs. top roof displacement, for the case of viscous dampers leading to $\bar{\xi} = 12\%$, and the numerically obtained reduction factors as compared with the target values: $\bar{\eta} = \bar{\eta}_q \cdot \bar{\eta}_\xi = 0.55 \cdot 0.76 = 0.42$. The results (reduction factors) of the non-linear dynamic analyses show an excellent correspondence with what was estimated in the design phase.

Figure 5b summarizes all the results obtained for the four models (L, NL, LD and NLD) and for the three configurations of damper systems considered. A "modest" size ($\bar{\xi} = 12\%$) of the damper system, as expected, is not able to guarantee elastic behaviour of the existing building under the design earthquake, with a non-negligible global ductility demand (> 1.5). Thus, a large part of the available ductility capacity of the structure is therefore used, with consequent significant damage during seismic events. An "intermediate" size ($\bar{\xi} = 25\%$) and a “large” size ($\bar{\xi} = 35\%$) is partially and fully able, respectively, to guarantee elastic behaviour of the existing building under the design earthquake; accordingly, the global mean responses of the two LD and NLD systems are close to each other.

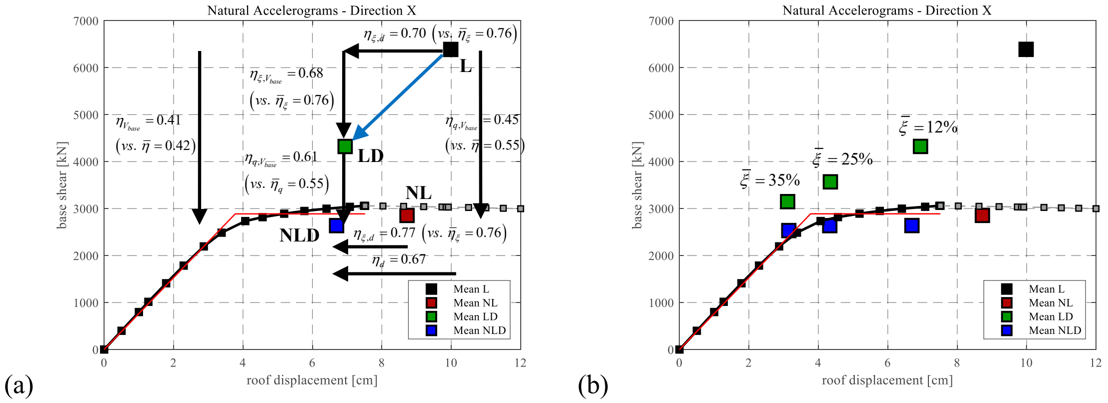


Fig. 5. (a) Structural response due to natural seismic events considering viscous dampers characterized by a damping ratio $\bar{\xi} = 12\%$ and actual reduction factors. (b) Results obtained for the three damper systems.

7. Conclusions

The results of this first application of the "direct five-step procedure for existing buildings" confirm the reliability of the method, which is based on the elastic pseudo-acceleration spectrum and aims to represent: (1) a preliminary design method of the viscous damper system; (2) a method for controlling and verifying non-linear time-history analyses. As a cautionary note, the applicability of this "mixed" design strategy for existing buildings, replacing the design strategy that sees the damper system sized to maintain the structural elements in the linear elastic range, is conditioned by a check about the prevalence of ductile (bending) on brittle (shear) damage mechanisms.

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