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A direct design procedure for frame structures with added viscous dampers for the mitigation of earthquake-induced vibrations

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Abstract

A direct procedure for the seismic design of building structures with added viscous dampers is described in this paper. The procedure is applicable to regular multi-storey frame structures which are characterized by a period of vibration lower than 1.5 s. It aims at providing practical tools for the direct identification of the mechanical characteristics of the manufactured viscous dampers as well as for the structural design of the frame members' so that a target level of performance is achieved. The design philosophy is to limit the structural damages under severe earthquakes. First, a target damping reduction factor is selected to achieve the desired reduction in the peak structural response. The linear damping coefficients of the equivalent linear viscous dampers are calculated taking advantage of modal damping ratios properties of classically damped systems. Then, simple analytical formulas for the estimation of peak inter-storey velocities are used, together with an energy criterion to identify the non-linear mechanical characteristics of the manufactured viscous dampers. Finally, the internal actions in the structural elements are estimated through the envelope of two equivalent static analyses (ESA), namely: ESA1 in which the naked structure is subjected to a first set of equivalent lateral forces, and ESA2 in which the structure, with rigid diagonal braces substituting the added viscous dampers, is subjected to a second set of equivalent lateral forces. At this preliminary stage of the research, the procedure is targeted for the preliminary design phase, since correction factors to improve the accuracy in the estimation of the peak inter-storey velocities needs to be calibrate. Therefore, for final design, non-linear dynamic analyses are recommended.

Keywords: Seismic design procedure, added viscos dampers; Equivalent static analyses;.

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1. Introduction

While for many years the seismic analysis and design of buildings have been carried out using methods based essentially on the concept of equivalent lateral forces, nowadays, analysis and design procedures are mostly based on the use of nonlinear dynamic analyses, which are available in most of common commercial software. The use of dynamic analyses was first introduced in the 1974 by the SEAOC Code (Seismology Committee 1974 [1]) for major structures "with highly irregular shapes, large differences in lateral resistance or stiffness between adjacent storeys".

As a consequence, when energy dissipation and base isolation systems were first proposed for the mitigation of the seismic actions (1980s), the use of dynamic analyses was already well established as standard practice for the seismic design of building structures. At this point, according to most actual seismic codes (such as Eurocode 8 [2] or the Italian NTC08 [3]), structures equipped with added viscous dampers can be analyzed and designed only by mean of non-linear dynamic analyses. Indeed, only U.S. building codes (such as ASCE 7-10 [4]) contain specific simplified procedure for analysis and design of buildings with passive energy dissipation systems. These procedures are grounded on the seminal research works carried out in the 1990s at the University at Buffalo (Constantinou and Symans 1992 [5] and 1993 [6], Ramirez et al. 2002 [7] and 2003 [8], Whittaker et al. 2003 [9]) and summarized in the MCEER-01 report [10]. An alternative procedure for the design of structures with passive dampers is described by and Levy and Lavan [19]. Nonetheless, none of these well established procedures have been yet incorporated in Eurocode provisions.

In the present work, a simplified procedure for the sizing of viscous dampers and structural elements of framed structures equipped with inter-storey viscous dampers is presented. At this stage of the research, the procedure is recommended for preliminary design only and therefore it does not represent an alternative to the more complex procedures such as those described in chapter 18 of ASCE 7-10 [4].

2. A direct five step procedure for the sizing of viscous dampers and structural elements

2.1. Procedure overview

A direct five-step procedure, synthetically schematized in the flow chart of Figure 1, is here described. It is grounded on basic principles of structural dynamics [17, 18]. Its aim is to guide the professional engineers through the dimensioning of the non-linear viscous dampers to be inserted in the frame and the design of the structural members so that a given performance objective is achieved. It integrates some results of previous research works developed by the authors during the last 10 years of research (Trombetti and Silvestri 2006 [11], Silvestri et al. 2010 [12], Palermo et al 2013a [13], 2013b [14] and 2016 [15]). Even though, in principle, the procedure is applicable even to yielding frame structures (with an appropriate choice of the overall behavior factor, see Palermo et al 2013 b[14 for details]), it is here presented assuming that the frames are designed in order to remain in the elastic range. The design philosophy is to limit the structural damages under severe earthquakes. With reference to an *N* storey-1 bay frame building with uniform distribution of added viscous dampers, subjected to the earthquake ground motion u_g (Figure 1b) , the steps of the procedures can be summarized as follows:

STEP 1: Identification of the performance objective, in terms of: (a) a selected reduction (expressed as a x %) of the base shear due to the presence of the added viscous damper expressed in terms of damping reduction factor : $\eta = 1 - x/100$; (b) equivalent damping ratio $\xi = \frac{10}{\eta^2} - 5$ (%). ($\xi = \xi_i + \xi_v$ is the sum of the inherent damping ξ_i , conventionally set equal to 0.05, plus the viscous damping ξ_v provided by the added dampers).

STEP 2: Evaluation of the linear damping coefficient of the single equivalent linear viscous damper (see derivation in Silvestri et al. 2010 [12]):

$$c_L = \xi \cdot \omega_1 \cdot m_{tot} \cdot \frac{N+1}{\cos^2 \theta} \quad (1)$$

Where ω_1 is the first mode circular frequency of the structure; m_{tot} is the total building mass, N is the number of stories of the building, θ indicates the damper inclination with respect to the horizontal direction.

STEP 3: Estimation of peak damper velocities v_{max} and peak inter-storey drifts ID_{max} under the design earthquake ($S_e(T_1,\eta)$ is the ordinate of the damped pseudo-acceleration response spectrum at the fundamental period of the structure considering the effect of the dampers through factor η) assuming a linear first-mode shape (see derivation in Palermo et al. 2016 [15]):

$$v_{\max} = \frac{S_e(T_1,\eta)}{\omega_1} \cdot \frac{2}{N+1} \cdot \cos\theta \tag{2}$$

$$ID_{\max} = \frac{S_e(T_1,\eta)}{\omega_1^2} \cdot \frac{2}{N+1} \tag{3}$$

Estimation of the peak damper force under the design earthquake:

$$F_{d,\max} = 2 \cdot \xi \cdot m_{tot} \cdot \frac{S_e(T_1,\eta)}{\cos\theta} \tag{4}$$

Estimation of the damper stroke under the design earthquake:

$$s_{\max} = \frac{S_e(T_1,\eta)}{\omega_1^2} \cdot \frac{2}{N+1} \cdot \cos\theta \tag{5}$$

STEP 4: Sizing of the damping coefficient of the commercial damper characterized by a non-linear force-velocity behavior of the power law type $F_d = c_{NL} \cdot sign(v) \cdot |v|^a$ where α is the exponent of the power law (see derivation in Silvestri et al. 2010 [12]):

$$c_{NL} = c_L \cdot (0.8 \cdot v_{\max})^{1-\alpha} \tag{6}$$

STEP 5: Estimation of the internal actions in the structural elements through the envelope of two Equivalent Static Analyses (ESA), namely:

- Equivalent Static Analysis 1 (ESA1): the naked structure (e.g. the structure without the added viscous dampers) is subjected to the following set of equivalent lateral force (Fi indicates the lateral force to apply at the i-*th* floor):

$$F_i = F_h \cdot \frac{z_i \cdot W_i}{\sum_{j=1,2,\ldots,N} z_j \cdot W_j} \qquad F_h = S_e(T_1,\eta) \cdot m_{tot} \tag{7}$$

  W_i is the seismic weight of the i-*th* floor; the distribution of the lateral forces relates directly to the assumed fist-mode shape.

- Equivalent Static Analysis 2 (ESA2): the structure with rigid diagonal braces substituting the added viscous dampers is subjected to a top floor lateral force:

$$F_2 = 2 \cdot \xi \cdot m_{tot} \cdot S_e\left(T_1, \eta\right) \tag{8}$$

The application of a lateral force at the roof level only directly relates to the assumed fist-mode shape and leads to the following estimation of the maximum axial force in the columns:

$$P_{i,\max} = \left(N - i + 1\right) F_{d,v,\max} = \left(N - i + 1\right) \cdot 2 \cdot \bar{\xi} \cdot m_{tot} \cdot S_e\left(T_1, \eta\right) \cdot \tan\theta \tag{9}$$

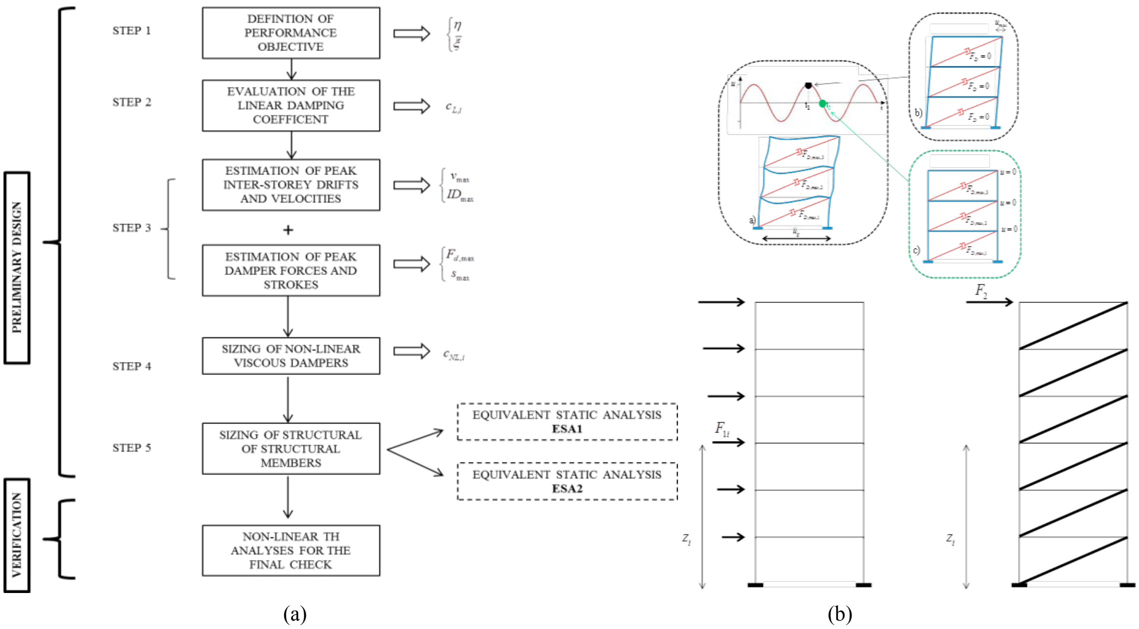


Fig. 1. (a) Flow-chart of the propose design procedure. (b) ESA1 and ESA2 equivalent static analyses.

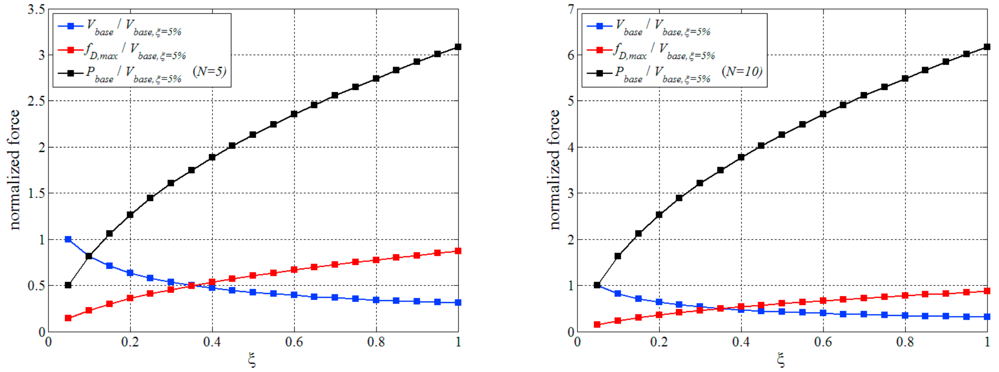
2.2. The rationale behind the equivalent static analysis ESA

During an earthquake, the internal flexural actions in the structural members (such as columns and beams) achieve their maximum values at the instant of maximum lateral displacements. On the other hand, the damper forces are maximized at the instant of maximum inter-storey velocities (approximately coincident with the instant of zero lateral deformation). In case of diagonal dampers placed among two adjacent stories (inter-storey placement), the forces exerted by the dampers transfer additional axial forces in beams and columns, which in some cases (see section 3) may govern the member structural design. So that, the maximum internal actions in the structural members can be estimated from the envelope of two following two equivalent static analyses:

- ESA1: is the static analysis of the naked structure subjected to a set of lateral forces producing the same lateral displacements as those developed at the instant of maximum lateral deformation.
- ESA2: is the static analysis of an appropriate structure schematization (e.g. the structure with diagonal rigid bracings replacing the diagonal viscous dampers) which provides the same axial internal actions in the structural member as those developed at the instant of maximum lateral velocity.

3. Discussion

Figure 2 displays the base shear V_{base}, the maximum damper force $f_{D,max}$ and the maximum axial force at the ground floor P_{base} as a function of the damping ratio (the case of a 5-storey and 10-storey building are considered). The curves are normalized with respect to the base shear of the naked structure ($V_{base,\xi=5\%}$). As expected, with increasing damping ratio, the base shear V_{base} decreases at the expense of an increase in $f_{D,max}$ and P_{base}. It can be noted that the curves of V_{base} (blue curve) and $f_{D,max}$ (red curve) intersect at a ξ value of around 0.35. With increasing the total number of stories, P_{base} increases as well and may become significantly large (for the 10-storey building even 4 times larger than $V_{base,\xi=5\%}$).



(a) (b)

Fig. 2. Base shear, maximum damper force and base axial force: (a) 5-storey building (N=5), (b) 10-storey building (N=10).

It is of practical interest to evaluate the necessary amount of damper forces to obtain a target reduction in the base shear ($\Delta V_{base} = V_{base,\xi=5\%} - V_{base}$). By making use of Eq. (3), it is possible to express directly the maximum damper force (and its normalized versions) as a function of the damping reduction factor:

$$F_{d,\max} = 2\left(\frac{10-5\eta^2}{\eta}\right)\cdot\frac{V_{base,\xi=5\%}}{\cos\theta} \tag{10}$$

$$\frac{F_{D,\max}}{V_{base,\xi=5\%}} = 2\frac{\left(10-5\eta^2\right)}{\eta\cdot\cos\theta} \tag{11}$$

$$\frac{F_{D,\max}}{\Delta V_{base}} = 2\frac{\left(10-5\eta^2\right)}{(1-\eta)\eta\cos\theta} \tag{12}$$

Figure.3 displays $F_{D,\max} / V_{base,\xi=5\%}$ η, and $F_{D,\max} / \Delta V_{base}$ versus $1-\eta$, respectively (for the case of $\theta = 45°$). In detail, Fig.3a illustrates the cost (in terms of maximum damper force normalized with respect to $V_{base,\xi=5\%}$) of achieving a prescribed performance (in terms of damping reduction factor). Fig.3b illustrates the cost/benefit ratio (i.e. maximum damper force normalized with respect to ΔV_{base}) corresponding to a prescribed reduction in the response parameter (i.e. $1-\eta$). For $1-\eta$ between 0.15 and 0.7 (e.g. η between 0.3 and 0.85, covering the range of added damping ratios between 10-30%), the ratio $F_{D,\max} / \Delta V_{base}$ is less than 1.0, which means that the benefit in terms of reduction of base shear is superior than the cost expressed by the maximum damper force.

Conclusions

A direct design procedure for the moment resisting frame buildings equipped with inter-storey viscous dampers has been presented. The procedure is aimed at guiding the structural engineer from the choice and sizing of the added viscous dampers to the dimensioning of the structural elements. It allows obtaining analytical estimations of peak displacements, peak inter-storey drifts and velocities, maximum forces in the dampers and maximum internal actions in the structural elements. Although the procedure can be further improved through an accurate calibration of the magnification coefficients accounting for the higher modes contribution, it is simple to apply and produces results of sufficient accuracy for the purpose of preliminary design of regular moment resisting frames.

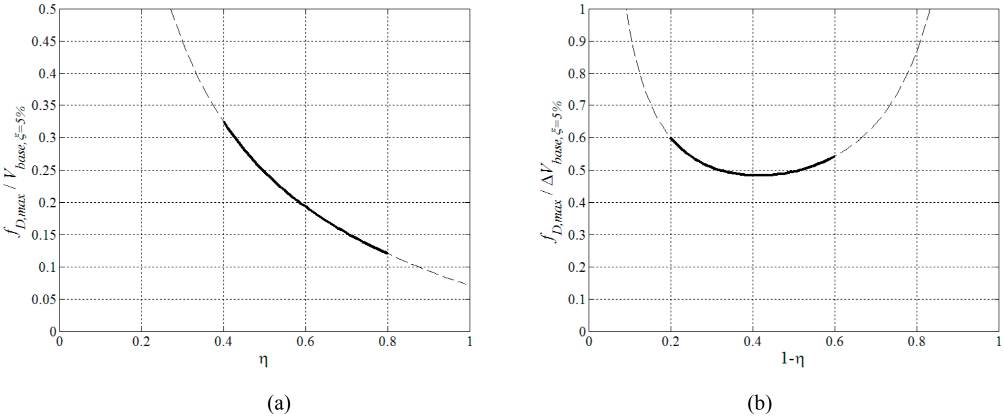


Figure 3: (a) $F_{D,\max} / V_{base,\xi=5\%}$ versus η; (b) $F_{D,\max} / \Delta V_{base}$ versus $1-\eta$.

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