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AN EQUIVALENT STATIC ANALYSIS PROCEDURE FOR STRUCTURES WITH ADDED VISCOUS DAMPERS

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Abstract

In the present paper the method of equivalent static forces (or lateral force method), widely used in earthquake engineering especially in the phase of preliminary design of regular framed structures, is extended to the case of structures equipped with added viscous dampers. The method is grounded on basic principles of structural dynamics and, under certain assumptions, allows to estimate the maximum damper forces and maximum internal actions in the structural members due to the design earthquake through analytical formulas only. In order to show its effectiveness, the method is finally applied for the retrofit through external steel "dissipative towers" (namely steel moment-resisting frames equipped with interstorey viscous dampers) of a 16-storey reinforced concrete building.

Keywords: equivalent static analysis, fluid viscous dampers, design procedure

1. Introduction

For many years, since the early developments of modern earthquake engineering in the ‘1960s, the seismic analysis-design of buildings has been carried out using methods grounded on the concept of equivalent lateral forces. Nowadays, even though much more sophisticate analysis tools, such as nonlinear dynamic analyses, are available also in commercial software, most of seismic codes still admit the use of equivalent static analysis for the design of relatively regular and simple structures (Eurocode 8 [1], NTC08 [2]). Moreover, it is nowadays often used by professional engineers in order to check the results of nonlinear dynamic analyses.

The use of dynamic analyses for major structures was first introduced in 1974 by the SEAOC Code [3] which recommended its use for “structures with highly irregular shapes, large differences in lateral resistance or stiffness between adjacent storeys”. Later on, with the rapid development of computer programs, the use of dynamic analyses has been established as standard practice for the seismic design of building structures. As such, when in ‘1980s novel technologies for the seismic protection of buildings, such as seismic isolation and dissipative devices, become to be adopted in the practice, the use of computer based simulations for the design of structures incorporating such new technologies appeared an obvious choice. Fundamental research works devoted to the development and evaluation of simplified procedures for analysis and design of buildings with passive energy dissipation systems has been carried out in the ‘1990 at the University at Buffalo summarized in MCEER-00-0010 report [4] and ASCE 7-10 (Chapter 18) [5] procedures, which are nowadays used in USA by professional engineers. Later on, most of the research works on viscous dampers [6-12] basically proposed sophisticated numerical algorithms for dampers optimization (i.e. damper size and location), sometimes leading to complex design procedures.

Alternative approaches leading to practical design procedures for the sizing of viscous dampers have been proposed in the last years: (i) Lopez-Garcia in 2001 [10] developed a simple algorithm for optimal damper configuration (placement and properties) in MDOF structures, assuming a constant inter-storey height and a straight-line first modal shape; (ii) Christopoulos and Filiatrault in 2006 [13] suggested a design approach for estimating the damping coefficients of added viscous dampers consisting in a trial and error procedure; (iii) Silvestri et al. in 2010 [14] proposed a direct design approach, referred to as the “five-step procedure”.

In the present work, simplified procedures for the sizing of viscous dampers to be inserted in framed structures and for the estimation of the maximum seismic actions in viscous dampers and structural elements are presented. The procedures represent the synthesis of the studies conducted at the University of Bologna during the last 10 years.

2. On the dimensioning of viscous dampers to be inserted in moment resisting frames

Fluid viscous dampers are hydraulic devices which dissipate part of the earthquake input energy through the flow a viscous fluid through orifices. The mechanical behavior of commercial devices is typically nonlinear:

$$F_d = c \cdot sign(v) \cdot |v|^{\alpha} \tag{1}$$

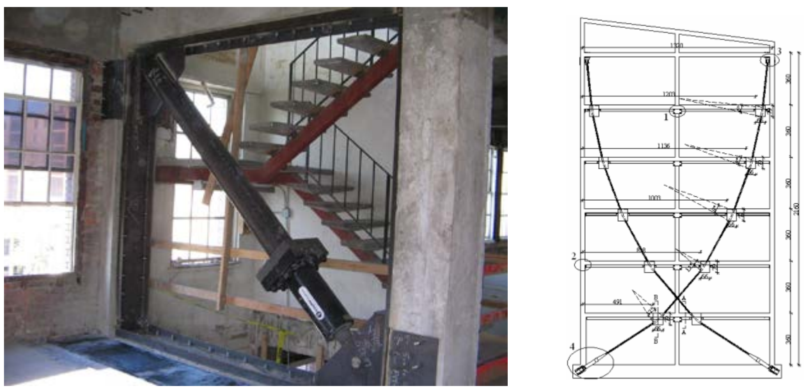
In Eq. (1) c is the damping coefficient, α is the damping exponent, v is the fluid velocity. In earthquake engineering it is convenient to quantify the dissipative capacity of a damper by mean of the damping ratio ξ which, for a single-degree-of-freedom system of mass m, stiffness k and damping coefficient c, represents the ratio between the damping coefficient c and the critical damping coefficient $c_{cr} = 2\sqrt{m \cdot k}$:

$$\xi = \frac{c}{c_{cr}} \tag{2}$$

For structures with no additional damping systems typical damping ratio values are around 2-5% and the dissipation is due to friction and hysteresis. On the contrary, structures equipped with additional viscous dampers may be characterized by equivalent damping ratio values even around 30%. A number of research studies focused on the relations between the amount of additional damping ratio provided by the viscous dampers and the related reduction in the structural response (deformations or stresses) typically referred in the scientific literature to as damping reduction factor η. Among all available formulations, Eurocode 8 suggests the use of the simple one proposed by Bommer et al. [15]:

$$\eta = \sqrt{\frac{10}{5+\xi}} \tag{3}$$

In practical applications and especially in the case of retrofit of an existing building, it is common to place the dampers between two consecutive floors according to the so-called inter-storey damper placement. In these cases the dampers are typically embedded into diagonal steel members as represented in Figure 1a. In this configuration it is clear that the efficiency of the damper in reducing structural deformations is reduced with respect to the same damper acting along the horizontal direction (according to the so-called "fixed point placement"). Moreover, the diagonal inclination of the damper determine the coupling of the horizontal and vertical motion under horizontal ground shaking which leads to additional internal axial actions in the columns transmitted by the dampers. This particular aspect will be briefly treated in the present paper.



(a) (b)

Fig. 1 – (a) A viscous dampers inserted into a frame; (b) damped cables (SPIDER project [16])

A comprehensive reference for the dimensioning of viscous dampers to be inserted in moment resisting frame structures is the MCEER-00-0010 report [4] which introduced two simplified procedure for the analysis and design of buildings equipped with added dampers: the Equivalent Lateral Force (ELF) procedure and the Response Spectrum Analysis (RSA) procedure. The former is based on the residual mode approach [17] and considers also yielding buildings. The structural response is calculated as the combination of the fundamental mode response and the residual mode response according to the SRSS combination rule. The ELF procedure can be rigorously and efficiently implemented in a computer code and has been satisfactory validated by means of various applicative examples, as the sample 3- and 6- storey frames reported in the work by Ramirez et al. in 2003 [17]. Although such design procedures appear quite straightforward and are of common use in USA, they have not yet incorporated in actual European building codes, thus limiting in Europe the use of fluid viscous dampers in practice. In the present paper, first a direct five step procedure for the damper sizing is described, then an equivalent static analysis procedure is presented with the purpose of providing simple tools for the design of structures with added interstorey viscous dampers.

3. A direct five step procedure for the sizing of inter-storey viscous dampers

The problem of the damper dimensioning in order to obtain a set of desired seismic performances (e.g. reduction of the base shear, limitation of the peak interstorey drift,…) has been faced by several researchers since the late '1990s and various sophisticate algorithms and procedures have been developed in order the reach the optimum damper placement. Nevertheless, the implementation of such procedures requires significant computational expertise which are beyond those of professional designers. On the other hand, since the early 2000 the authors have faced the same problem with the purpose of providing simpler, even though less optimized, procedures for the sizing of dampers capable of achieving desired performance objectives. As such, in 2010 [14] a five-step procedure has been proposed. The original procedure required the development of multiple dynamic analyses, namely linear time-history analyses for the sizing of the equivalent linear viscous dampers followed by nonlinear time-hystory analyses for the final sizing of the commercial dampers. More recently the procedure has been simplified leading to a direct (i.e. fully analytical) procedure [18].

The direct procedure which is here presented can be used for regular frame structures which mainly respond in the fundamental mode (fundamental period T_1<1.0 s and nearly linear first mode shape) which are equipped with equal dampers at all stories (uniform damper placements). Of course the assumptions are very specific and not of general validity. Nonetheless they allow to obtain simple analytical formulas which can be used in a preliminary design phase. The steps of the direct procedure are here summarized:

STEP 1: identification of the target damping ratio $\bar{\xi}$ leading to a certain target performance $\bar{\eta}$ (e.g. base shear, maximum inter-storey drift, …);

STEP 2: identification of the linear damping coefficients c_L for preliminary design purposes, by using the following formula:

$$c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \left(\frac{N+1}{n} \right) \cdot \frac{1}{\cos^2 \theta} \tag{4}$$

where m_{tot} is the building mass, N is the number of storeys, $\omega_1 = T_1 / 2\pi$ is the fundamental circular frequency, n is the total number of equally sized viscous dampers placed at each storey in a given direction and θ is the inclination of the dampers with respect to the horizontal direction.

STEP 3: eastimation of "working" velocities, $v_{\max}$, for the linear dampers:

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

with $S_e(T_1)$ equal to the ordinate of the elastic design spectrum at the fundamental period of the structure.

STEP 4: identification of the target characteristics of the actual non-linear viscous dampers (damping coefficient $c_{NL} = \overline{c_{NL}}$, exponent $\alpha = \bar{\alpha}$, and axial stiffness of the device $k_{axial} = \overline{k_{axial}}$), i.e. identification of a system of manufactured viscous dampers capable of providing the structure with similar performances to those obtained in Step 3 with the linear viscous dampers sized in Step 2, by using the following formulas:

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

$$k_{axial} \geq 10 \cdot c_L \cdot \omega_1 \tag{7}$$

STEP 5: verification of the performances of the structure equipped with the non-linear viscous dampers sized in Step 4 through non-linear numerical time-history analyses.

The combination of Eqs. (4) and (5) leads to the following expression of the maximum force in the viscous damper:

$$F_{D,\max} = \frac{2 \cdot \bar{\xi} \cdot m_{tot} \cdot S_e(T_1) \cdot \eta}{n \cdot \cos\theta} \tag{8}$$

Because we have assumed a linear first mode shape and equal dampers at all stories, the maximum damper forces are equal at all stories.

4. A simplified equivalent static analysis for buildings equipped with viscous dampers

Once the viscous dampers have been sized according to the direct five-step procedure, the structural analysis and design of the frame structure can be carried out according to the Equivalent Static Analysis ESA procedure here presented. It has to be noted here that, as any simplified procedure, the ESA procedure is subjected to several limitations and, at this stage of the research, appears suitable to be used for preliminary design only.

Let us assume that the structure responds mainly in the first mode when subjected to a horizontal ground motion and that the first mode shape is linear (Akkar et al. [19] showed by mean of finite element analyses that most real regular moment resisting frame buildings have nearly linear first mode deformed shapes). From fundamental principles of structural dynamics the envelope of the dynamic response in terms of maximum internal actions in the dampers and structural members (say beams and columns) can be obtained by considering the following two configurations (Fig. 2):

- deformed configuration 1: corresponding to the time instant t_1 of maximum horizontal (lateral) displacements, when both the inertia and elastic forces achieve their maximum values and the damping forces are almost null;
- deformed configuration 2: corresponding to the time instant t_2 of maximum horizontal (lateral) velocities (i.e. when the forces in the viscous dampers achieve their maximum values) , and the inertia forces are almost null.

Let us first focus the attention on the time instant t_1 of maximum horizontal (lateral) displacements. Since the horizontal velocities are almost null, the damper forces are almost null too, thus the maximum internal actions at instant t_1 can be calculated ignoring the presence of the dampers. The effect of the dampers is accounted by reducing the design lateral forces through the damping reduction factor:

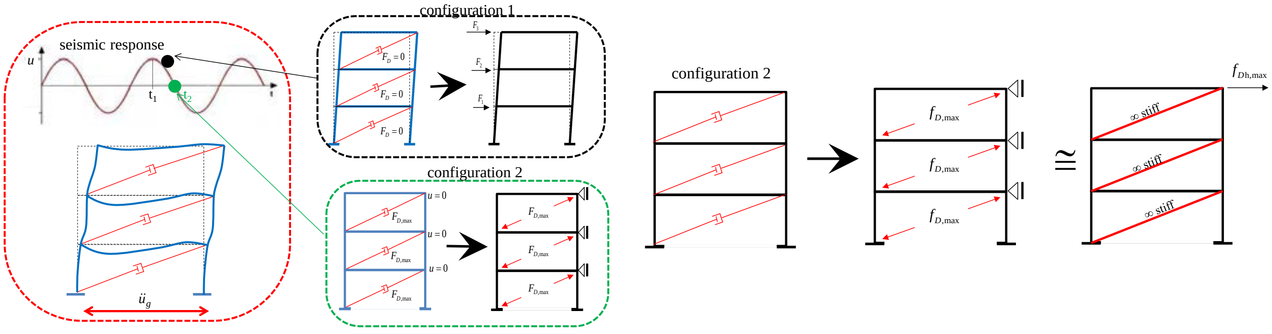
$$F_i = S_e\left(T_1\right)\cdot\eta\cdot\frac{W_i}{\sum_{i=1,2,\dots,N} W_i z_i} \tag{9}$$

where W_i is the i-th floor seismic mass, z_i is the height of the i-th floor. This first equivalent static analysis, herein referred to as ESA$_1$, is formally coincident with the conventional equivalent static analysis procedure for ordinary buildings with no added dampers.

Let us now focus the attention on the instant t_2 of maximum horizontal (lateral) velocities. At this time instant the maximum forces in the dampers can be estimated according to Eq. (8) and, given that all lateral floor displacements are almost null, the maximum internal actions in the beams and columns can be calculated by restraining the floor displacements, as schematized in Fig. 2b. From a practical point of view the internal actions in the beams and columns can be also calculated by considering a frame in which the viscous dampers are replaced by rigid diagonal trusses and subjected to a set of lateral forces equivalent to the resultant of the lateral components of the maximum damper forces $F_{Dh,\max}$ (Fig. 2b). This second equivalent static analysis will be herein referred to as ESA$_2$. From simple equilibrium considerations, it follows that in the case of equal maximum damper forces at all stories, the set of lateral forces to be used to perform the ESA$_2$ reduces to a top storey force only. The internal axial forces in the columns increase going from the top to the bottom, and, at the bottom storey they are equal to:

$$P_{base} = (N-1)\cdot\frac{2\cdot\xi\cdot W\cdot S_e\left(T_1\right)\cdot\eta}{n}\cdot\tan\theta \tag{10}$$

The damper sizing (five-step) and the structural analysis (ESA) procedures here presented can be synthetically schematized through the flow chart of Fig. 3.



(a) (b)

Fig. 2 – (a) The two configurations to be considered in the ESA procedure; (b) configuration 2: ESA_2

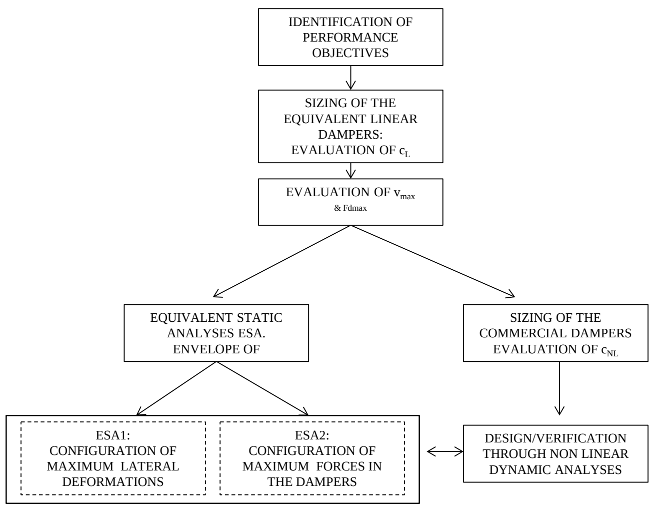


Fig. 3 – Flow chart summarizing the procedure for the damper sizing (five-step procedure) and for the seismic analysis of framed structures equipped with added viscous dampers (ESA procedure)

5. The retrofit of a 16-storey hospital building through dissipative towers

The procedures here presented are applied to design a retrofit intervention for a 16-storey RC hospital building located in Bologna (north Italy) and designed and constructed in the ‘1950s, thus prior modern seismic requirements were introduced in building codes. In particular, at that time, the area of bologna was not considered as seismic risk area and therefore no seismic design was required.

The building is made of four structural blocks having a transversal dimension in plan of 15 m and a height of 65 m. The structure is made by bidirectional RC moment resisting frames and is founded on RC shallow slab supported by piles. The first two natural period of the building are equal to 2.3 s (mainly translational along the y-direction) and 2.0 s (mainly translational along the x-direction). The seismic weight of block 2 is approximately equal to 120000 kN.

The usual seismic capacity of such building typology expressed in terms of ultimate base shear can be estimated around 0.02-0.05g. A possible solution to increase the seismic performances of the structure without interrupting the functionality of the hospital is based on the construction of dissipative towers composed by steel pinned frames having planar dimensions of 3.6 m × 3.6 m equipped with interstorey viscous dampers and connected to the hospital. Each dissipative tower is equipped with one damper acting along the y direction and two dampers acting along the x-direction. The dissipative towers, thanks to the presence of the viscous dampers, can dissipate part of the input energy and are dimensioned according to the procedure here presented in order to have a reduction of the base shear of around 50%. A total number of 192 dampers working along the y-direction

(12 at each storey) and 96 dampers working along the y-direction (6 at each storey) are inserted in the dissipative towers.

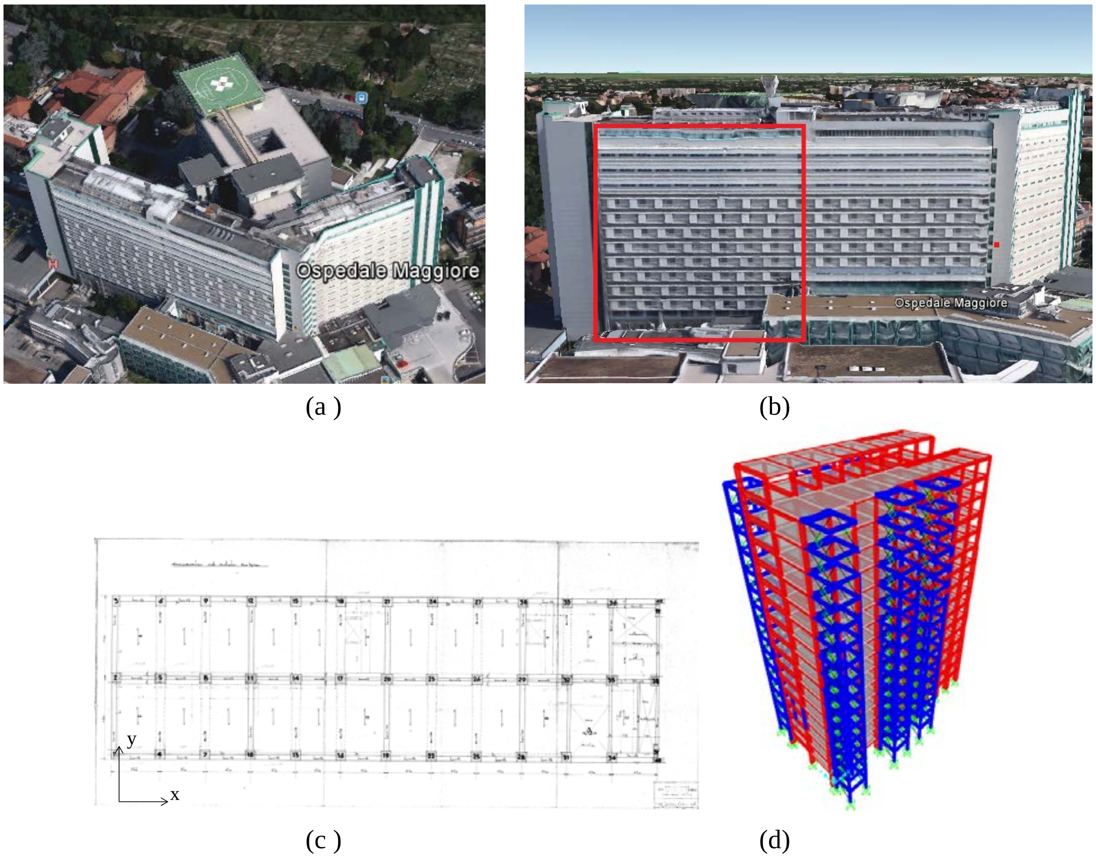


Fig. 4 – The 16-storey RC hospital building: (a) google earth view (b) The block 2; (c) plan of typical floor (original drawing); (d) Finite element model of block 2 with the 6 dissipative towers

5.1 The sizing of the added viscous dampers according to the direct five step procedure

For the sake of clarity the calculations required for the sizing of the dampers according to the direct five step procedure presented in section 3 are here fully developed considering the earthquake input along the x-direction only. The design elastic pseudoacceleration at 5% damping ratio $S_e(T_1)$ is equal to 0.2g. Similar calculations are required for the seismic input along the y-direction.

STEP 1: target damping ratio $\overline{\xi}$ =0.3 leading to a $\overline{\eta}$ =0.53.

STEP 2: linear damping coefficients c_L of each damper:

$$c_L = \overline{\xi} \cdot \omega_1 \cdot W \cdot \left(\frac{N+1}{n}\right) \cdot \frac{1}{\cos^2\theta} = 0.3 \cdot \frac{2\pi}{2} \cdot \frac{118889}{9.81} \cdot \left(\frac{16+1}{12}\right) \cdot \frac{1}{0.57} = 28070\left[kN \cdot s / m\right] \qquad (11)$$

STEP 3: "working" velocity, $v_{\max}$, for the linear dampers and maximum damper force:

$$v_{\max} = \frac{S_e(T_1) \cdot \eta}{\omega_1} \cdot \frac{2}{N+1} \cdot \cos\theta = \frac{0.2 \cdot 9.81 \cdot 0.5}{2\pi / 2} \cdot \frac{2}{16+1} \cdot 0.75 = 0.027\left[m / s\right] \qquad (12)$$

$$F_{\mathrm{D,max}} = \frac{2 \cdot \xi \cdot W \cdot S_e(T_1) \cdot \eta}{n \cdot \cos\theta} = \frac{2 \cdot 0.3 \cdot 118889 / 9.81 \cdot 0.2 \cdot 9.81 \cdot 0.5}{12 \cdot 0.75} = 792[kN] \tag{13}$$

STEP 4: non linear damping coefficients c_{NL} of each damper:
:

$$c_{NL} = c_L \cdot (0.8 \cdot v_{\max})^{1-\bar{\alpha}} = 56139 \cdot (0.8 \cdot 0.027)^{1-0.15} = 2155\left[kN \cdot s^{0.15} / m^{0.15}\right] \tag{14}$$

STEP 5: verification through non-linear time history analysis.

A set of 7 artificial ground motions compatible with the design spectra as per the Italian building code NTC08 [2] are generated using the software SIMQUAKE [20]. The pseudo-acceleration spectra at 5% damping ratio of the seven accelerogram is shown in Fig. 5 (the mean and mean plus one standard deviation spectrum are shown in solid and dotted red curves, respectively).

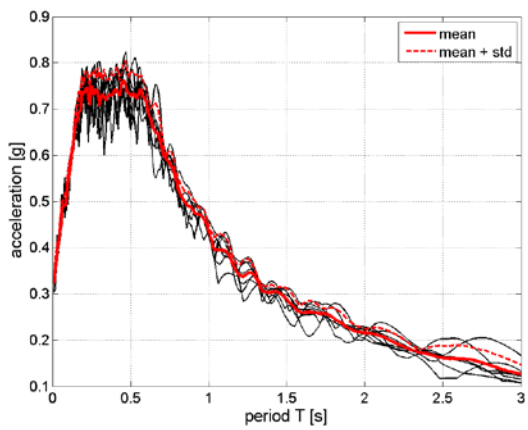


Fig. 5 – The pseudoacceleration spectra (5% damping ratio) of the seven artificial ground motions.

5.2 The dimensioning of the dissipative tower through ESA procedure

For the sake of conciseness, the attention here is limited to the estimation of the seismic maximum internal axial forces in the steel columns which basically governs their design. Following the ESA_2 procedure the maximum internal axial forces in the steel frame of the generic dissipative tower are estimated by considering the simple 2D model of the Tower in which the viscous dampers are substituted by rigid diagonal braces. Then the ESA_2 is conducted by performing a static analysis of the braced frame as subjected to a top storey horizontal force (Fig. 6):

$$F_{\mathrm{Dh,max}} = F_{\mathrm{D,max}} \cos\theta = 594[kN] \tag{15}$$

The maximum internal axial forces in the columns of the generic dissipative towers as obtained from the ESA_2 procedure are compared with those obtained from nonlinear time-history analyses. It can be noted that the simplified ESA method allows in this case to a quite accurate evaluation of the maximum axial forces in the columns. In particular for that specific case the discrepancies in terms of relative differences between the results of non-linear time history analyses and ESA predictions are less than 5%. For instance, at the base of the column schematically represented in Fig. 6 the relative difference in terms of maximum axial force is equal to -2%, thus indicating that for that specific column the maximum axial force as predicted according to the ESA procedure is a bit less than that obtained from the non-liner time history analyses.

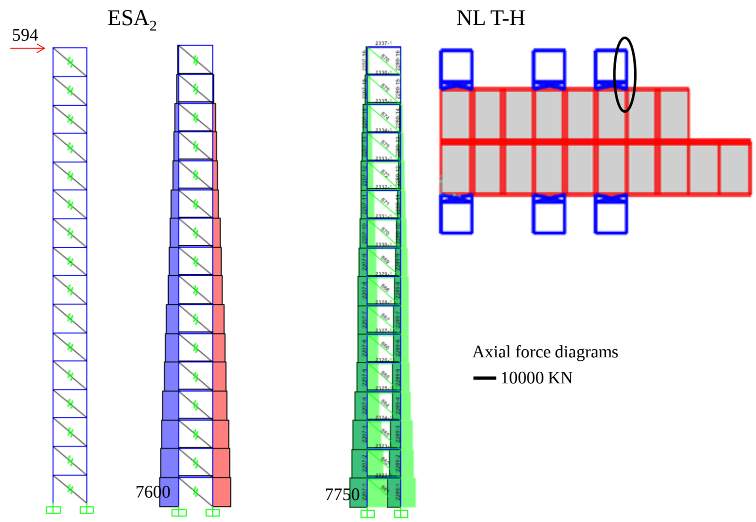


Fig. 6 – The axial forces in the columns of one dissipative tower as predicted by ESA_2 and nonlinear time history analysis

Conclusions

A simplified Equivalent Static Analysis (ESA) procedure for the preliminary seismic design of buildings with added viscous dampers has been presented. The maximum forces in the viscous dampers as well as the earthquake induced internal actions in the structural members (beams and columns) can be estimated by the envelope response of the two static analyses, namely ESA_1 and ESA_2.

The first static analysis, ESA_1, as the conventional equivalent static analysis for ordinary buildings, is performed on the naked structure accounting for a set of equivalent lateral static forces whose values are appropriately reduced to account for the presence of the added dampers. The second static analysis, ESA_2, is performed on a structural model of the building in which the viscous dampers are replaced by rigid braces. The set of the equivalent lateral forces to be used is equal to the resultant of horizontal components of the maximum damper forces at each floor. To show its predictive capabilities, the ESA procedure is used to design “dissipative towers” for the retrofit of a 16-storey RC hospital building.

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