METHODOLOGY FOR THE SEISMIC DESIGN OF STRUCTURAL SYSTEMS, INCLUDING PASSIVE CONTROL

Marcelo Rubinstein, Oscar Möller, Juan P. Ascheri
Instituto de Mecánica Aplicada y Estructuras, FCEIA, UNR, Argentina.

Alejandro Giuliano
Instituto Nacional de Prevención Sísmica, Argentina.

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SUMMARY:
A preliminary seismic design procedure for structural systems with or without passive energy dissipation devices is developed. The procedure is displacement-based and different levels of seismic performance are considered. For rare earthquakes and life safety performance level the yield displacement at the top of the system is determined by assigning relative strengths, based on a normalized base shear, to the elements of the system without energy dissipation devices. Then, the maximum displacement, based on ductility, damage indexes and interstory drift considerations, is computed and the required strength is obtained from inelastic design spectra. Finally torsional effects are included. A similar procedure is applied to passive control systems with energy dissipation devices where the yield displacement is that of the energy dissipation systems. Performance levels for frequent earthquakes are verified for both cases. Application examples are presented, capacity design procedure is used for the final design and the response is verified by inelastic analysis.

Keywords: preliminary seismic design; passive control.

1. INTRODUCTION

Within a performance-based environment it is currently accepted that seismic design be based on displacements, instead of forces (Vision 2000, 1995; Paulay, 2002; Priestley et al., 2007), and the acceptance criteria on limiting values of ductility, damage indexes (Fajfar, 1992) and interstory drift.

Besides, the application and development of passive control techniques by devices that use the relative displacements of structural elements to dissipate energy (Soong and Dargush, 1997) with the aim of concentrating damage in these devices, seem promising.

The design procedure developed is conceptually transparent, only a few and simple operations are used, it is based on displacements and focused on performance. It is applicable to structures with or without passive energy dissipation devices (PEDD).

The proposed methodology is described. The particular features corresponding to structures with or without PEDD are highlighted. One illustrative example for each case is presented and the performance is verified by inelastic static and dynamic analyses. Finally, conclusions and suggestion for future refinements of the methodology are proposed.

2. METHODOLOGY

The proposed methodology is based on displacements and it is applicable to multistory structural systems with or without PEDD. Two performance objectives are considered: life safety performance level for rare earthquakes (mean return period, T=475 years) and operational performance level for frequent earthquakes (T= 43 years) (Rubinstein et al., 2011).

Fig. 1 shows a generic structural system composed by planar components in two orthogonal directions with metallic yielding energy dissipation devices. Flat infinitely rigid slabs are assumed. Gravity columns are not shown. To get a system without PEDD, the dissipation devices and the assembly braces are eliminated (Fig. 1, 2). Besides, the connected walls (Fig. 3) are considered as one wall.

As the systems with PEDD and those without PEDD present particular features, a step-by-step procedure is then described for each case.

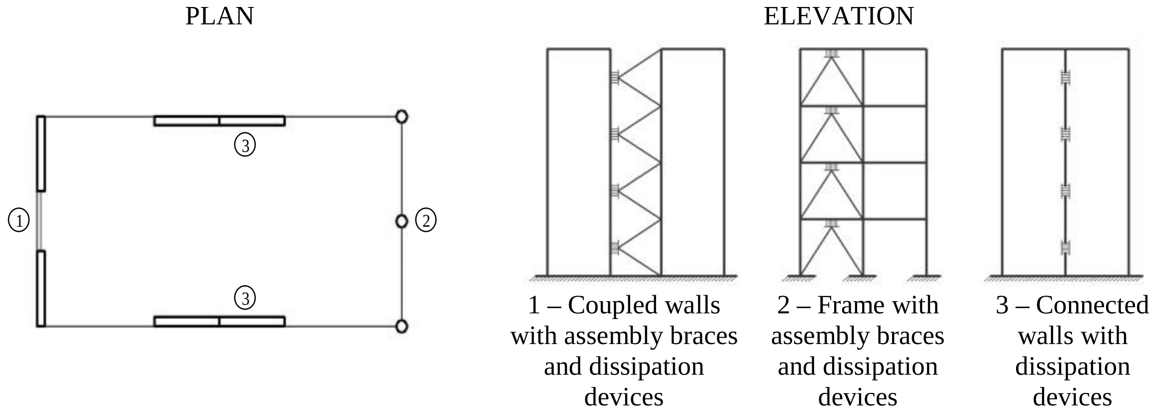


Figure 1. Structural system

2.1. Structural systems without PEDD

Fig. 2A shows the push-over curve of the system and its components. It will be used as reference to describe the procedure.

i) D_{yj}: yield displacement at the top of each component, obtained by first principles (Paulay, 2002; Priestley, 1998; Rubinstein et al., 2000).

ii) D_y: Top system yield displacement

$$D_y = \left(\sum_{j=1}^{n} \frac{p_j}{D_{yj}} \right)^{-1} \tag{2.1}$$

p_J: relative strength assigned to each component based on normalized total base shear

iii) Top limit displacements
Life safety performance level: The limit displacement at the top $D^L_{s.v.}$, is obtained comparing that based on ductility and damage indexes considerations (Fajfar, 1992) with that on interstory drift, whichever is less.
Operational performance level: For each component the limit displacement $D^L_{op.j}$, is obtained comparing $D_{y.j.}$, corresponding to the elastic response, with the one associated to the maximum interstory drift, whichever is less.

iv) Life safety performance level demands
With the ductility calculated by $C_T\ D^L_{s.v} / D_{y.}$, where $C_T < 1$ is a factor to account for torsion, the strength demand, V_u , and the period are obtained from constant ductility design spectrum for rare earthquakes.

Total displacement of each component, $D_{s.v.j}^{Total}$: translational displacement ($C_T\ D^L_{s.v.}$) and rotational displacements due to torsional moment are added. To compute the torsional moment, the strength eccentricity plus the accidental eccentricity is considered. It is assumed that the system is torsionally restrained thus the perpendicular walls responding in the elastic range control the twist.

It shall be verified:

$$D_{s.v.j}^{Total} \leq D_{s.v.j.}^{L} \qquad (2.2)$$

If not a redesign should be performed

v) Operational performance level demands
With the period and the elastic spectrum for frequent earthquakes, translational displacement, D_{op} , and base shear, V_{op} , are obtained.
Total displacement of each wall, $D_{op.j}^{Total}$: translational and rotational displacements are added. To compute the torsional moment, the stiffness eccentricity is used with the contribution of all walls in both principal directions.

It shall be verified:

$$D_{op.j}^{Total} \leq D_{op.j}^{L} \qquad (2.3)$$

If not, a redesign is necessary.

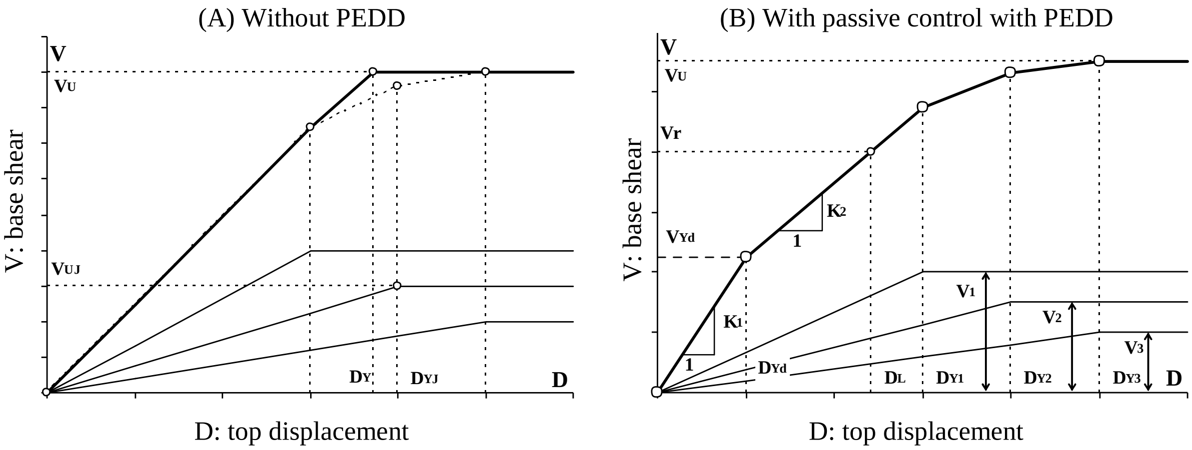


Figure 2: Push-over curves for a principal direction

2.2. Structural systems with PEDD

Fig. 2B will be used as a reference to describe the step-by-step procedure. Push-over curves of each component considering zero stiffness of the dissipation devices are shown in the Figure.

i) For frequent earthquakes operational performance level is required, that is elastic behavior of the dissipation devices (D_{yd}, V_{yd}).

Code effective flexural stiffness is used in the elastic range. The devices are considered as rigid connectors. Thus, two connected walls of length l are considered as one wall of length 2l and two coupled walls at a distance s are considered as one wall of length 2l+s. These assumptions are based on results from non linear static analyses (Rubinstein et al., 2009).

The stiffness k_1 of the system will be the sum of stiffnesses k_{1j} of each components obtained as described above.

With k_1 and the effective weight of the first mode, the base shear and the top displacement are obtained from the design elastic spectrum for frequent earthquakes.

Due to the high torsional stiffness of the structural system with elastic behavior of the dissipation devices, torsional effects are considered adopting V_{yd} and D_{yd} equal to 1.1 V_e and $1.1D_y$, respectively.
The base shear of the j component is:

$$V_{ydj} = \frac{k_{1j}}{k_1} V_{yd} \tag{2.4}$$

V_{ydj} will be used to design the dissipation devices.

ii) Required strength V_r:

For rare earthquakes, operational performance is required, that is, elastic response of the main structure and maximum interstory drift θ_{op} given by:

$$D^L_{op.j} = mín.\,(D_{yj}, \theta_{op} \cdot H, f \cdot D_{yd}) \tag{2.5}$$

Where : $f.D_{yd}$ is the local ductility available at the dissipation devices. According to results obtained from non linear static analyses, f = 8 may be used.

For the system:

$$D^L = C_T \cdot mín.\, D^L_{op.j} \tag{2.6}$$

where C_T is a reduction factor to account for torsional effects, that may be adjusted by iteration.

D^L and D_{yd} define the limit ductility μ_L. With μ_L and D_{yd}, and the design spectrum for rare earthquakes, the required base shear V_r is determined.

It should be noted that the design spectrum should correspond to the stiffness ratio k_2/k_1, Fig. 2(B). As k_2 depends on V_r a stiffness ratio should be adopted at the beginning and then proceed by successive iterations.

iii) Required strength for the structural system, $V_{u.}$

A relative normalized strength, p_j, is assumed and with k_2 and p_j, V_j is obtained.
The strength of each element is:

$$V_{uj} = V_j + \left(V_{ydj} - \frac{V_j}{D_{yj}} D_{yd} \right) \tag{2.7}$$

The term in brackets represents the contribution of the dissipation devices to the base shear. Finally:

$$V_u = \sum_{j=1}^{n} V_{uj} \tag{2.8}$$

iv) Total displacement of each element, D_j^{Total}

Translational and rotational displacements are added. To compute the torsional moment, $V_r \cdot e$, the stiffness eccentricity is used plus the code accidental eccentricity. The stiffnesses to be used for the components are the post- yield stiffnesses of their dissipation devices for those located in the direction being analyzed and the pre- yield stiffnesses of their dissipation devices for those on the orthogonal direction.

It shall be verified:

$$D_j^{Total} \leq D_{yj} \tag{2.9}$$

If the above condition is verified the preliminary design is finished and capacity design should be used in the final design. If not a redesign is required.

3. NON LINEAR STATIC AND DYNAMIC ANALYSES

The preliminary designed structure according to the proposed methodology and sized and detailed by capacity design, according to the new Argentine code INPRES-CIRSOC 103 (2005), is subjected to nonlinear static and dynamic analyses for design verification purposes. The acceleration time histories used are the same as those used to obtain the design spectra. Mean plus one standard deviation for each response parameter is obtained.

To model the system, the structure is discretized in vertical elements connected at each level by a rigid diaphragm . The model has three degrees of freedom per floor, two horizontal and one rotational around the vertical axis. (Möller et. al 2003). Each element is again discretized with bar elements to consider the different mechanisms contributing to the hysteretic behavior of the critical zones of the RC bars (Möller and Foschi 2003). Bar element is incorporated to represent the energy dissipation (Ascheri et. al 2009). It consists of three non linear springs located within an elastic bar representing the assembly braces of the physical device.

The stiffness of the system is evaluated by assembling the stiffnesses of each component, which are obtained from the stiffness of each bar element. Masses are lumped at each floor level. Rotary inertia and mass eccentricity are also considered. Rayleigh proportional damping is assumed. Gravity loads are included at each element. The lateral loads for the push-over or the accelerograms for time history analysis are applied to the global system. Accidental torsion is included by moving the center of mass.

4. EXAMPLES

4.1. Structural system with PEDD

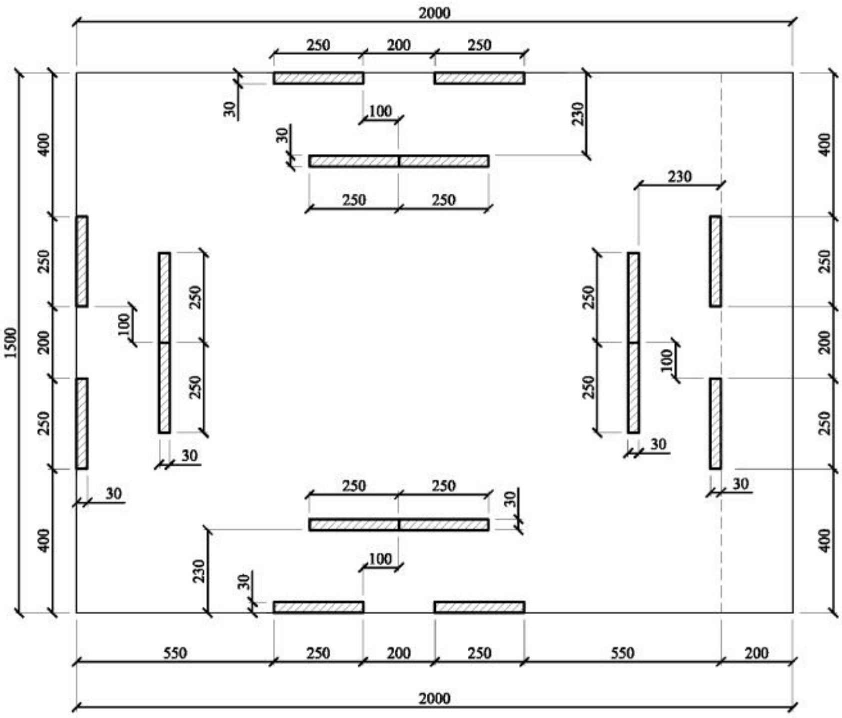
A five-story building with a rectangular plan (20mx15m) located in Mendoza city, Argentina, is considered.

Fig. 3 shows the plan layout with the vertical elements with metalling yielding devices for passive control.

Two pair of connected walls and two pairs of coupled walls are located in each direction. Fig. 4 shows the elevation of the components.

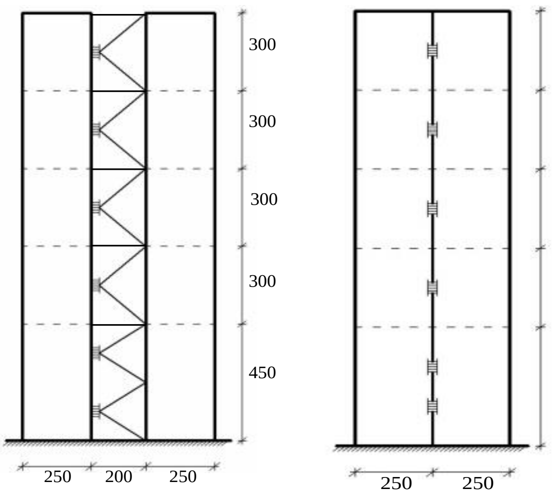
The input data are: $\theta_{op.}$ = 0,7%, C_T = 0,8 and design spectra obtained from a seismic microzonation study of Mendoza city (INPRES, 1995).

Results of the preliminary design are shown in the push-over curve of Fig. 5. The maximum total displacement obtained is 11,89cm < D_Y = 11,98cm.



Note: Slabs without beams. Columns for gravitational loads are not shown.

Figure 3. Plan layout



Dimension in cm

Walls depth: 30cm

Materials:

CIRSOC 201

Concrete: H-25.

Steel: ADN 420

Gravity loads at each level:

Dead load: 8KN/m^2

Live load: 2KN/m^2

Load factor f_1=0,50

Mass in each level: m=275,23 KNseg^2/m

Figure 4 Elevation of the components

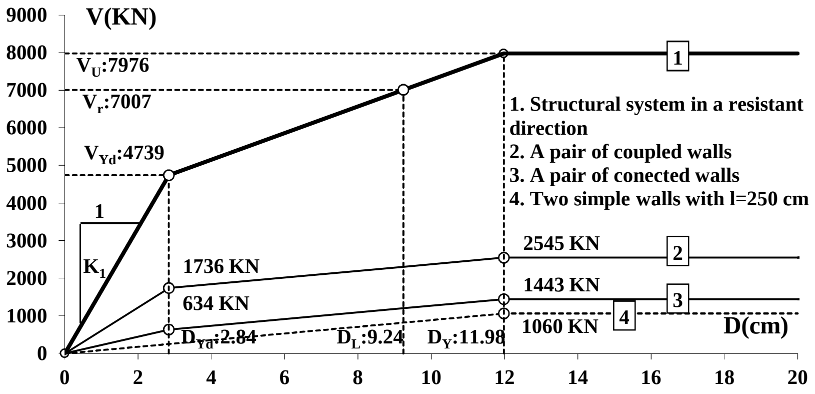


Figure 5. Push-over curves from the preliminary design.

4.2. Structural system without PEDD

The coupled walls of the above example are considered isolated and the connected walls are considered as only one wall of 5m length.

Input data:θ_{op}. = 0,7%, $\theta_{s.v}$. =2%, Park and Ang damage index: D.I.= 0,8 for each element .I.D. = 0,6 for the structural system and design inelastic spectra for rare earthquakes with a strain hardening of 2%.

Results of the preliminary design are shown in Fig. 6.

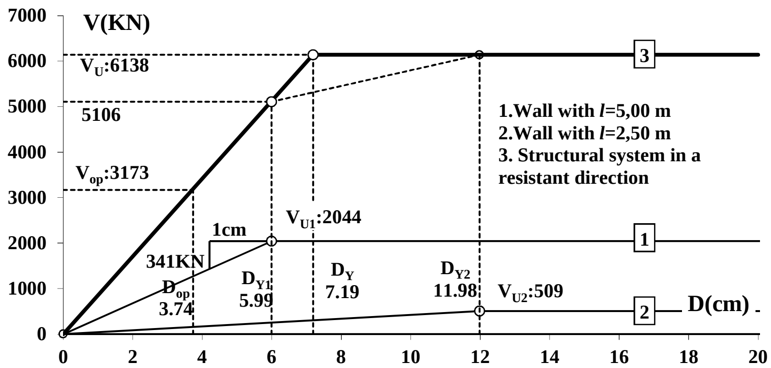


Figure 6. Push-over curves from preliminary design

Rare earthquake, life safety performance level:

Maximum total displacement: 18,7cm; limit displacement: 20,49cm.

Frequent earthquake, operational performance level:

Maximum total displacement: 4,04cm; limit displacement: 5,99cm.

4.3. Design verification with non-linear static and dynamic analyses

Figures 7 and 8 show the result from non-linear static analysis with the corresponding bi-linear response. For the sake of comparison, the pushover curve from preliminary design is included.

In this example the agreement is good at yielding of the system without PEDD and specially at yielding of the dissipation devices and the main structure with PEDD. It should be noted that strain hardening of the components is not considered in the preliminary design. Besides, the limit displacement, DU, at interstory drift of 2% is significantly greater than the limit displacement from the preliminary design controled by available ductility and damage index (27.84 vs 20.49).

Table 4.3.1 shows non-linear dynamic analysis results, where D: maximum displacement at the top, DIST (%): maximum interstory drift and V: maximum base shear.

For rare earthquakes and systems without PEDD, obtained results are similar to pushover results. For frequent earthquakes design criteria are fulfilled, that is, elastic behavior and interstory drift 0.70% .

For rare earthquakes and systems with PEDD, maximum displacement at the top is less than that corresponding to the preliminary design (9.81 cm vs 11.89 cm). On the contrary, maximum base shear shows the opposite, partially due to the absence of strain hardening in the preliminary design. Maximum interstory drift is greater than required because the actual distribution of forces in height is not linear as assumed in the preliminary design. For frequent earthquakes, design criteria are satisfied: elastic behavior of the dissipation devices.

Comparing the results obtained from the preliminary design with those obtained from the nonlinear analysis, it is observed that some results are conservatives while others are not.

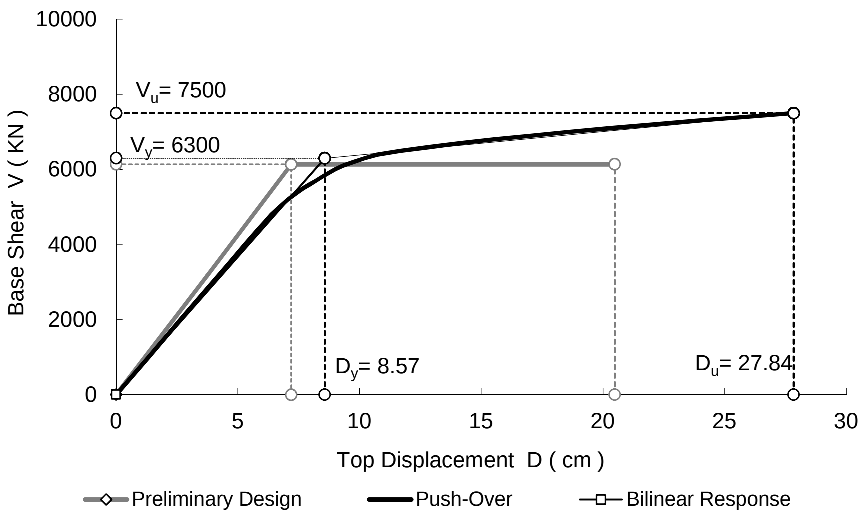


Figure 7. Push-over curves without PEDD.

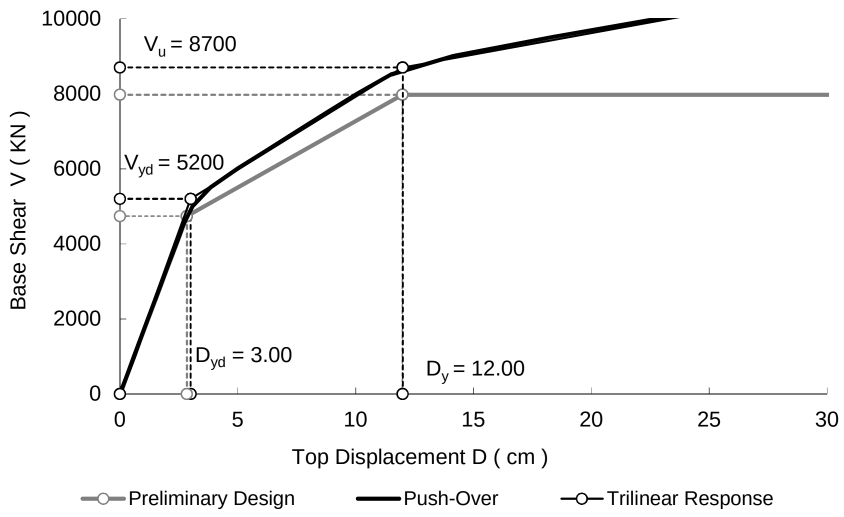


Figure 8. Push-over curves with PEDD

Table 4.3.1 Response from nonlinear dynamic analysis

	Without PEDD		With PEDD	
	Rare earthquakes	Frequent earthquakes	Rare earthquakes	Frequent earthquakes
D (cm)	28,28	4,59	9,81	2,67
DIST(%)	2,11	0,40	0,82	0,21
V(KN)	7.260,20	2.521,60	10.330,00	3.795,30

5. CONCLUSIONS

A methodology for preliminary seismic design of multistory structural systems with or without PEDD is developed. For systems without PEDD, two performance objectives were considered: rare earthquakes-life safety and frequent earthquakes-operational. For systems with PEDD, also two performance objectives were considered: rare earthquakes-operational and frequent earthquakes fully operational.

The methodology was applied to two illustrative examples: one with PEDD and the other without PEDD. It was shown that the methodology is conceptually transparent and only a few and simple operations are needed to perform a preliminary design.

The results obtained from an example system were verified by nonlinear static and dynamic analyses showing some differences acceptable for a preliminary design.

It is to be noted that the yield base shear of the dissipation devices is determined by the elastic design spectrum for frequent earthquakes. However, the base shear of the main structure is related to the difference between the required base shear from the inelastic design spectrum (corresponding to the maximum available ductility) for rare earthquakes, and the yield base shear of the dissipation system. In some cases, the strength ratio (main structure/ dissipation system) obtained is significantly low. The effects on design of this ratio should be analyzed in future studies establishing criteria to optimize it.

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