THE RESPONSE OF STRONGBACK SYSTEM WITH DIFFERENT VISOCUS DAMPERS PLACEMENTS

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Abstract

In the present paper the seismic behavior of structural systems obtained by connecting a moment resisting frame structure with a vertical elastic truss, known in the literature as strongback, which acts as a mast by imposing to the structure a given lateral deformed shape, is investigated when coupled with viscous dampers.

The presence of the strongback, which has to be designed in order to remain in the elastic field under strong seismic ground motion, linearizes the lateral displacement profile of the adjacent frame through an exchange of mutual horizontal actions. The presence of the strongback should thus help in limiting undesired effects such as soft-storey and weak-storey mechanisms since a uniform distribution of inter-storey drifts along the height of the frame structure is achieved.

A frame structure equipped with dissipative devices and characterized by a known (e.g. linear) lateral deformed shape can be, at first approximation, reduced to an Equivalent Single Degree Of Freedom (ESDOF) system, characterized by an equivalent lateral stiffness, mass and damping coefficient. This simplification allows therefore to obtain an analytical relationship between the damping coefficient of each single device and the damping ratio of the entire system that can be used to size the damping system in the preliminary design phase. The work presents the results of numerical simulations to verify the effectiveness of the ESDOF procedure for different dampers configurations. In detail, inter-storey (IS) dampers placement is studied, either considering a uniform distribution of dampers at all inter-stories along the height of the frame or dampers allocated at one or few inter-storey.

Keywords: Strongback; Earthquake-Resistant Design; Viscous dampers, Numerical simulations.

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1. Introduction

Conventional steel concentrically braced frame structures have typically limited resistance towards seismic events, with tendency to form soft-storey and weak-storey mechanisms, damage concentration, P-Δ effects and residual drifts [1-9]. Thus, following the Performance-Based Seismic Design (PBSD) approach [10], some specific considerations during the design phase of frame structures should be applied in order to avoid concentration of deformations and damage in few storeys.

Among the various approaches adopted by several researchers to reduce damage concentration, such as dual systems [11-13], zippers [1, 14-18], rocking or uplifting systems [6, 19-21], one possible solution to enhance the seismic performance of frame structures is the one proposed by Lai and Mahin [22] and recently studied by the authors [23], referred to as "strongback system" (SB system). This system, connected to the traditional frame, acts as a mast, to help against the activation of soft and weak storey mechanisms, by ensuring the development of nearly uniform inter-storey drifts along the height of the building.

The first studies on the strongback systems were focused on the configuration of the vertical truss, going from the ground to the top storey, inserted as a bracing system within the frame structure by augmenting part of the bay with essentially elastic behavior under strong seismic actions [22]. The work by Palermo et al. [23] investigated the coupled static behaviour of a frame structure connected to an external strongback system with the aim of obtaining expressions of the mutual actions exchanged between the frame and the SB system. The results indicates that both distribution and the amplitude of such mutual actions is strongly influenced by the beam-to-column stiffness ratio. In particular, in case of flexible beams, large mutual actions and internal frame actions concentrate in the lower storeys, while the upper stories remaining practically unloaded.

The versatility of the strongback system lies upon the possibility of coupling its response with the use of different additional dissipative devices, such as Buckling-Restrained Braces (BRB), viscous dampers [24-27] or hysteretic devices [28-30] to increase the overall dissipative properties of the structure. Alternatively, a recent study conducted by Gioiella et al. [31] presented the possibility of exploiting the rocking motion of the strongback system, considered as a steel braced frame hinged at the base and rigidly connected to the frame structure at each floor. This system, referred to as "dissipative tower", aims at controlling both the global and local response of the coupled system by inserting a reduced number of viscous dampers.

In this paper, the dynamic behaviour of frames connected to a strongback system and equipped with supplemental viscous dampers is investigated. Thanks to the presence of the rigid strongback, which imposes a linear lateral deformed shape, the system can be reduced to a damped single-degree-of freedom system whose fundamental dynamic properties (period of vibration and damping ratio) can be analytically derived for different added dampers configurations. In particular, a particular configuration of dampers placed within consecutive storeys of the frame through diagonal elements (inter-storey placement IS) is analyzed.

2. Problem formulation and objectives

Since the aim of the study is to investigate the fundamental dynamic properties of frame structures connected to a strongback and equipped with supplemental viscous dampers, an idealized system is considered, similarly to the one analyzed in the work by Palermo et al. [23]. Henceforth, the term "system" will be used to indicate the frame connected to the external strongback and equipped with supplemental dampers. For this specific purpose, it is convenient to idealize the strongback as an external rigid truss pinned at the base and connected to the adjacent frame through horizontal rigid trusses (Figure 1a). It is assumed that the strongback is composed by rigid elements so that it rotates around the pinned base as a rigid body. The general configuration of supplemental viscous dampers here investigated is composed of diagonal viscous dampers inserted within the frame between consecutive storeys, according to an inter-storey damper placement (Figure 1b, such system will be referred to as IS system). In a IS system, due to the presence of the rigid strongback, all viscous dampers work for the same inter-storey velocity, thus enhancing their dissipative properties. For the next considerations, all added viscous dampers are assumed to have a linear force-velocity constitutive behavior.

2

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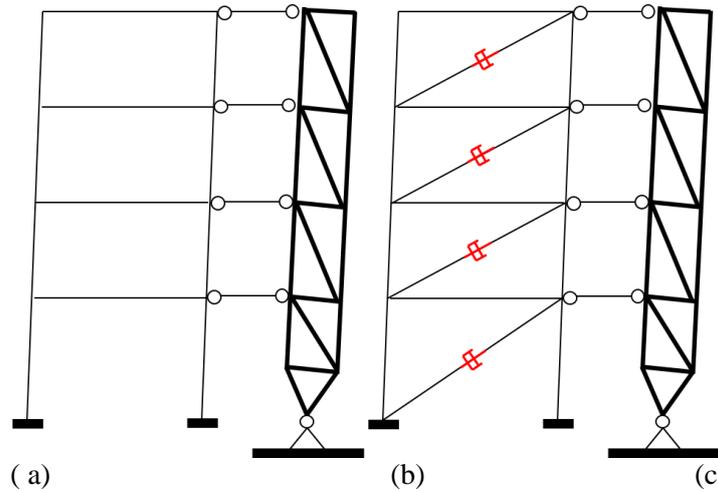(a)   (b)   (c)

Fig. 1 – (a) Frame connected to an external strongback; (b) IS system.

The geometrical configuration of each system can be described by assuming a system of coordinates (x, z) with origin at the base of the strongback (namely point O). The i-th storey is located at a height z_i. The lateral displacement of the i-th floor is indicated with u_i. It is assumed that the frame elements have a linear elastic behavior. The lateral stiffness of the i-th storey is denoted as k_i. The axial deformability of the frame members is neglected. Shear-type frames are considered. The kinematics of the strongback is completely described by the angle of rotation θ. According to these assumptions, when subjected to a generic set of external lateral forces, the system will globally develop a linear lateral floor displacement profile. The linear deformed shape of the frame is guaranteed by mutual actions H_i which are exerted between the frame and the strongback. In the work by Palermo et al. [23], analytical expressions of the mutual actions have been derived for different frame behaviors (namely, moment resisting shear-type frames and not-moment resisting frames), different distributions of static external forces and lateral storey stiffness k_i.

Under the above assumptions, from a global dynamic equilibrium perspective, the system can be exactly treated, without introducing approximations, as a generalized Single Degree Of Freedom (SDOF) system [32], since its motion is governed and fully described by the rigid rotation of the strongback.

In the work by Palermo et al. [33], specific dynamic equilibrium equations of the strongback system are derived and studied.

In the next section, the dynamic behavior of the considered IS system is investigated with the purpose of determining their fundamental dynamic properties (natural frequency and modal damping ratio).

3. Dynamic equilibrium of the IS damped systems

3.1 Equilibrium equations

In the present section, the attention is paid to the IS system (Figure 2).

Considering $\delta_i = u_i - u_{i-1}$ the i-th inter-storey drift, the inter-storey viscous damper located at the i-th inter-storey works for the inter-storey velocity $\dot{\delta}_i$ providing a damping force $F_{D,i}$ equal to:

$$F_{D,i} = \begin{cases} c_N \cdot \dot{\delta}_N & \text{for } i = N \\ c_{i+1} \cdot \dot{\delta}_{i+1} - c_i \cdot \dot{\delta}_i & \text{for } i = 1, 2, ..., N-1 \end{cases} \tag{1}$$

where c_i indicates the damping coefficient of the damper located at the i-th inter-storey .

3

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In free vibration conditions, the system is subjected to the inertia forces $F_{I,i}$, the elastic resisting forces $F_{S,i}$, the damping forces $F_{D,i}$ and the mutual actions H_i.
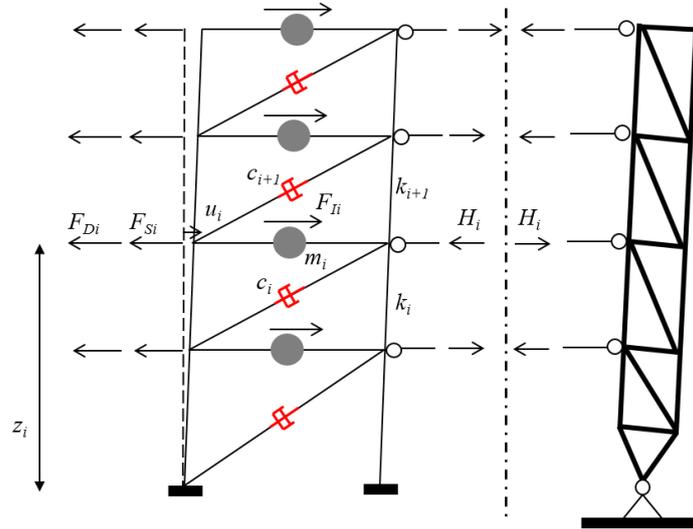

Fig. 2 – Dynamic forces acting on the IS system.

The whole system is globally in equilibrium if the following system of moment equilibrium equations is satisfied:

$$\begin{cases} \sum_{i=1}^{N} F_{I,i} \cdot z_i + \sum_{i=1}^{N} F_{S,i} \cdot z_i + \sum_{i=1}^{N} F_{D,i} \cdot z_i + \sum_{i=1}^{N} H_i \cdot z_i = 0 \\ \sum_{i=1}^{N} H_i \cdot z_i = 0 \end{cases} \qquad (2)$$

Again, from the rotational equilibrium of the strongback (Eq. 2b) the fourth term of Eq. 2a is identically null and Eq. 2a can be expressed as follows:

$$\sum_{i=1}^{N} \left(m_i \cdot \ddot{u}_i \cdot z_i \right) + \sum_{i=1}^{N-1} \left(k_{i+1} \cdot \delta_{i+1} - k_i \cdot \delta_i \right) \cdot z_i + k_N \cdot \delta_N \cdot z_N + \sum_{i=1}^{N-1} \left(c_{i+1} \cdot \dot{\delta}_{i+1} - c_i \cdot \dot{\delta}_i \right) \cdot z_i + c_N \cdot \dot{\delta}_N \cdot z_N = 0 \ (3)$$

Considering a uniform inter-storey height h, then the inter-storey drift is also uniform and equal to δ. In this case, the i-th floor height z_i and the lateral displacement u_i can be expressed as follows:

$$z_i = h \cdot i \qquad (4)$$

$$u_i = \delta \cdot i \qquad (5)$$

Thus, substitution of Eq. 6 in Eq. 3 leads to:

$$\left(\sum_{i=1}^{N} \left(m_i \cdot z_i \cdot i \right) \right) \ddot{\delta} + \left(\sum_{i=1}^{N-1} \left(c_{i+1} - c_i \right) \cdot z_i + c_N \cdot z_N \right) \dot{\delta} + \left(\sum_{i=1}^{N-1} \left(k_{i+1} - k_i \right) \cdot z_i + k_N \cdot z_N \right) \delta = 0 \ (6)$$

4

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3.1 Dynamic properties of the IS system

Eq. 6 represents the equations of motion of the damped SDOF system in the degree of freedom δ. The expressions of the damping coefficients and damping ratios of the equivalent SDOF system are reported in Table 1.

It can be of interest also to obtain analytical expressions of the damping ratio for the case of uniform IS system. A uniform IS system is a particular IS system with a uniform frame and equal inter-storey dampers placed at all inter-stories (with constant damping coefficients c_{IS}).

Table 1 - Damping coefficients and damping ratios in the general case and for the uniform systems.

System	Generalized damping coefficient	Damping ratio
IS: general case	$C^* = \sum_{i=1}^{N-1}(c_{i+1} - c_i) \cdot z_i + c_N \cdot z_N$	$\xi = \dfrac{\sum_{i=1}^{N-1}(c_{i+1} - c_i) \cdot z_i + c_N \cdot z_N}{2 \cdot \left(\sum_{i=1}^{N}(m_i \cdot z_i \cdot i)\right) \cdot \omega}$
IS: uniform case	$C^* = c_{IS} \cdot N \cdot h$	$\xi = \dfrac{c_{IS}}{2 \cdot m \cdot \omega} \cdot \left(\dfrac{6}{(N+1)\cdot(2N+1)}\right)$

4. Earthquake simulations

4.1 Analyzed systems and input ground motion

In this final section, numerical simulations are carried out with the purpose of estimating the effectiveness of the formulations for the evaluation of the damping ratios of IS system. In particular, a 6-storey uniform IS system subjected to an earthquake ground motion is considered as case study. A steel uniform moment resisting frame is considered for both cases. The frame columns are made with European HE320B profiles ($J_{max} = 3.08 \cdot 10^8\, mm^4$, $J_{min} = 9.27 \cdot 10^7\, mm^4$), while the beams are made with European IPE400 profiles ($J_{max} = 2.31 \cdot 10^8\, mm^4$, $J_{min} = 1.32 \cdot 10^7\, mm^4$). The truss elements of the strongback are made by hollow square cross-sections (having width equal to 200 mm and thickness equal to 50 mm) sized to be rigid enough to guarantee a linear lateral deformed shape. The floor mass m is equal to 1440 kN. The viscous dampers are sized to obtain specific values of viscous damping ratio (ξ_v), namely 10%, 20%, and 30% (clearly the total damping ratio will be the sum of the viscous damping ratio ξ_v and the inherent damping ratio ξ_h). The values of the damping coefficients corresponding to each target damping ratio $\bar{\xi}$ are reported in Table 2. They have been computed according to the analytical formulas of Table 1. For the sake of comparison, also the dynamic response of the frame connected to the strongback without any added damper (Frame+SB model) and of the bare frame (Naked model) are evaluated.

Dynamic time-history analyses are performed applying at the base of the structures the El Centro S00E record (Imperial Valley 1940 earthquake). An inherent viscous damping ξ_h =5% is considered. The numerical simulations are carried out using the Finite Element (FE) software SAP2000 v.18 [34]. Figure 6 displays the FE models of the case study systems.
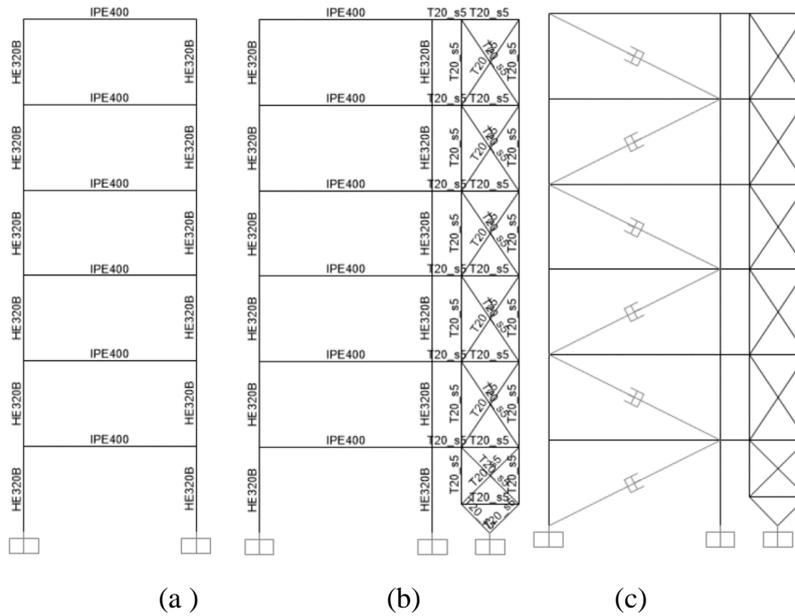
5

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(a)   (b)   (c)

Fig.6 - (a) Naked model; (b)Frame+SB model; (c) IS model.

Table 2 - Damping coefficients for the case study.

System	$\xi_v = 10\%$	$\xi_v = 20\%$	$\xi_v = 30\%$
$c_{IS} \left[\dfrac{kN \cdot s}{m} \right]$	476	952	1428

4.2 Results

The first mode deformed shape of the uniform bare frame and of the frame connected with the strongback are reported in Figure 7. The bare frame has a fundamental period equal to 1.28 sec and a first mode deformed shape that is typical of moment resisting frames with stiff beams (Figure 7a). As expected, the first deformed shape of the frame connected with the strongback is instead practically linear (Figure 7b) and the fundamental period slightly lower than that of the bare frame (1.20 sec vs. 1.28 sec).

6

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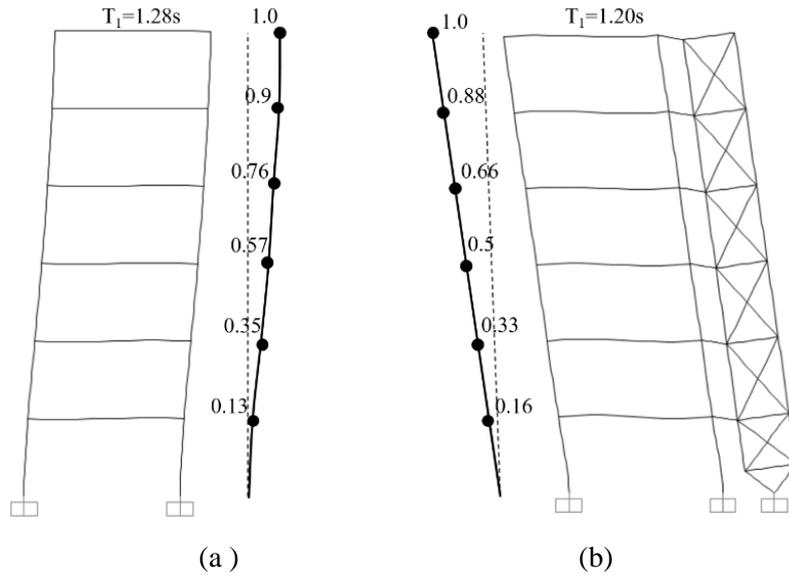
(a)   (b)

Fig.7 - (a) First mode shape of the uniform bare frame; (b) First mode shape of the uniform frame connected with the strongback.

Figure 8 shows the peak inter-storey drift ratio (ID_p) profiles of the different models which has been obtained from the dynamic time-history analysis. In particular the three damped models with ξ_v =30% are considered. For the three models with strongback system, the ID_p profile is practically constant along the height, thus indicating that the presence of the strongback leads to a almost linear peak lateral displacement profile. For the naked model, the ID_p is not constant along the height with values varying between 0.58 and 1.00 with an average value of 0.75. The average ID_p value of the naked model is close to the ID_p of the Frame+SB model, that is equal to 0.7. The damped IS model has reduced values of ID_p equal to 0.32, leading to reductions larger than 50% for $\xi_v = 30\%$.
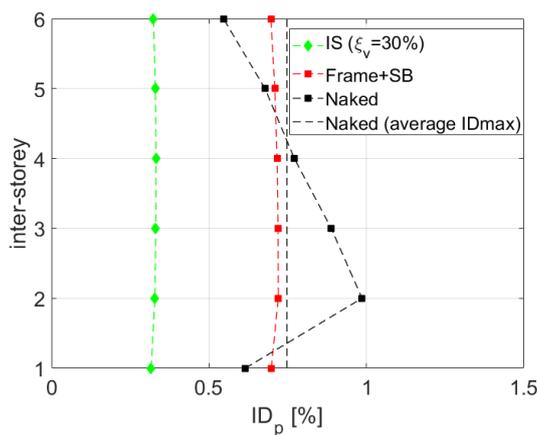

Fig.8 - IDp profiles for the different models as obtained from the dynamic time-history analysis.

The results clearly indicate that the truss system used as strongback, despite its flexibility due to the elasticity of the members, is effective in linearizing the peak displacement profile.

7

Submission No.:C000598
2. Seismic Performance of Structures
g. Seismic isolation and vibration control

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Strongback, Earthquake-Resistant Design, Viscous Dampers,...

In this regard, Figure 9a displays the reduction factors of the peak floor displacement as obtained from the numerical simulations as a function of the total damping ratio ($\xi = \xi_v + \xi_h$), computed as $\eta(\xi) = \dfrac{u_{roof,\xi}}{u_{roof,5\%}}$; $u_{roof,\xi}$ is the peak roof displacement of the system with added damper (model IS), while $u_{roof,5\%}$ is the peak roof displacement of the system without dampers (model Frame+SB).

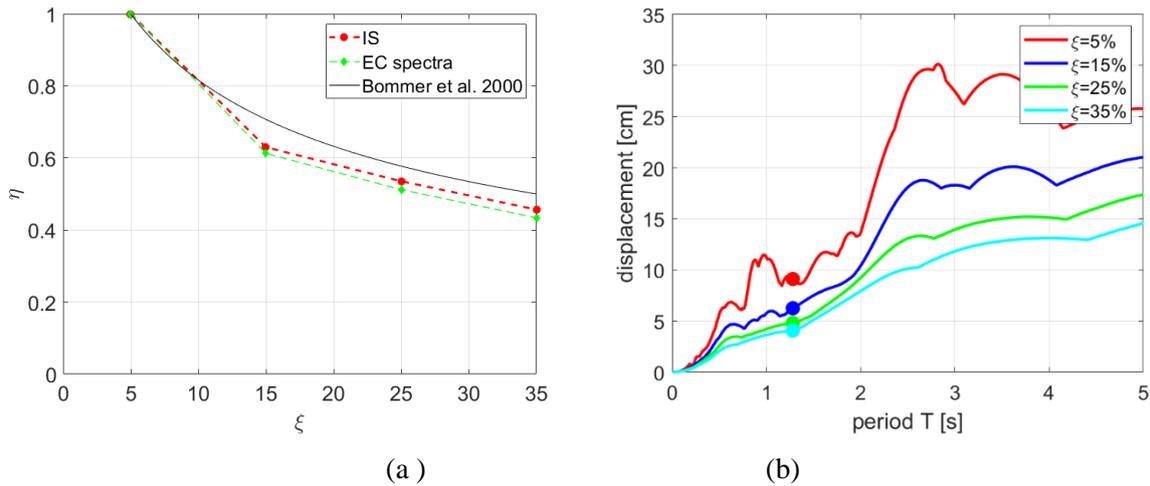(a)   (b)

Fig.9 - (a) Reduction factors from numerical simulations; (b) Displacement spectrum of El Centro ground record for different damping ratios.

The values of the reduction factors are compared with the ratios of the ordinates of the displacement spectra of the El Centro ground motion with different damping ratios, as computed at the fundamental period of the system: $\eta_{EC}(\xi) = \dfrac{S_{d,\xi}(T_1)}{S_{d,5\%}(T_1)}$; also the well-known formulation of damping reduction factor proposed by Bommer et. al [35] is displayed.

The reductions of the peak roof displacement of the two systems are close to each other and, of course, practically coincident with the reduction of the displacement spectra amplitudes computed at the fundamental period (Fig.9b). The results indicates that the damping system of IS model provides performances in line with the expectations and that the whole system can be effectively studied as a generalized SDOF system.

Conclusions

The paper illustrates the results of a study aimed at assessing the dynamic behavior of frame structures connected with a so-called strongback system, namely a rigid vertical truss system capable of imposing a linear lateral deformation along the height of the main frame, and supplemental dampers. The strongback limits potential dangerous effects associated to soft-storey mechanisms, while the supplemental dampers provide extra energy dissipation capabilities to reduce the whole peak displacement response. In detail, estimations of the fundamental dynamic properties of the system, namely the period of vibration and the first modal damping ratio, are derived. A specific configuration of added dampers is considered, having dampers inserted within the frame between consecutive storeys ("inter-storey" placement, IS). The fundamental dynamic properties are determined reducing the system to a generalized single degree of freedom system. For the special case of uniform systems (namely systems with uniform distributions of floor masses, lateral

8

2.0.13
2. Seismic Performance of Structures
g. Seismic isolation and vibration control

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Strongback, Earthquake-Resistant Design, Viscous Dampers,...

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stiffness and viscous dampers) simple analytical formulations are derived. The analytical formulations provide insight and allow comparing the effectiveness of the considered damped system in terms of total amount of damping coefficient necessary to achieve a given target damping ratio. Finally, the effectiveness of the analytical formulations is evaluated by means of numerical earthquake simulations carried out on uniform IS system considering the actual flexibility of the truss members. Finally, the results of the simulations confirm that the strongback is able to linearize the peak-displacement profiles under earthquake excitation and that the damping systems are capable of reducing the seismic response according to the expectations.

Acknowledgements

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