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OPTIMAL INSERTION OF VISCOUS DAMPERS INTO SHEAR-TYPE STRUCTURES: SEISMIC PERFORMANCES AND APPLICABILITY OF THE MPD SYSTEM

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SUMMARY

This paper provides illustrative examples regarding (a) the seismic performances offered by the MPD systems when applied to shear-type structures and (b) the implementation of MPD systems in actual building structures. As illustrated in a companion paper and in previous research works by the authors, the MPD system is an innovative system of added viscous dampers which is based upon the mass proportional damping component of Rayleigh viscous damping matrices and is characterized by a high dissipative efficiency. The seismic performances of two shear-type structures equipped with several systems of added viscous dampers (including, in addition to the MPD system, other optimal damping systems identified using genetic algorithms and inverse problem approach) are compared through numerical time-history simulations. The results, here obtained with reference to 40 historically recorded earthquake ground motions, confirm that systems characterized by dampers placed so that they connect each storey to a fixed point (as it is for the MPD system) display larger efficiency in energy dissipation than systems characterized by interstorey damper placement (traditional placement). The results also indicate that the forces exerted through the dampers of the MPD system and of the other damping systems considered are comparable in size. Two ways of implementing MPD systems in actual building structures are also presented: direct implementation (dampers connect each storey to the ground) and indirect implementation (dampers connect each storey of the base structure to a support structure: stiff vertical element, e.g. the conventional concrete core of the stairs/elevator typically found in r.c. constructions). Numerical results indicate that (provided that the support structure is characterized by a relatively large lateral stiffness) direct and indirect implementations lead to similar damping effect on the base structure without increasing the dynamic actions upon the support structure. Illustrative examples for the technical feasibility of both direct and indirect implementations are also provided.

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INTRODUCTION

In recent years various innovative technologies for protecting civil engineering structures from earthquakes have been developed and implemented [1,2]. Among these technologies, the use of added viscous dampers has proven to be quite effective in reducing the effects of seismic excitation upon building structures [1,2] and several research works have investigated the "optimal" way of inserting viscous dampers into shear-type structures [3,4,5,6,7].

The authors have already dealt with the problem of optimal damper insertion in shear-type structures [8,9,10,11,12,13,14,15,16]. Brief details follow of the concepts and fundamental results of this research.

The two limit cases of Rayleigh damping systems [8,9,10,11,12,13,14,15,16,17,18], MPD and SPD systems, are defined in terms of damper placement and damper sizing:

- *MPD system:* the dampers are placed in such a way as to connect each storey to a fixed point (ground or infinitely-stiff vertical lateral-resisting element, as illustrated in Figures 1a and 1b for a *3*-d.o.f. structure) and sized so that each damping coefficient c_j is proportional to the corresponding storey mass m_j;
- *SPD system:* the dampers are placed in such a way as to connect two adjacent storeys (Fig. 1c) and sized so that each damping coefficient c_j is proportional to the lateral stiffness k_j of the vertical elements connecting these two storeys.

In a companion paper [17]:

- the problem of optimal damper insertion in shear-type structures is faced using a physically based approach;
- the physically-identified optimal dissipative properties of the mass proportional damping (MPD) system are recalled;
- the analysis of Rayleigh damping systems leads to the fundamental distinction between damper placement an damper sizing. Three types of damper placements are defined: (1) interstorey (IS) placement which sees dampers placed between adjacent storeys, (2) fixed point (FP) placement which sees dampers placed in such a way as to connect each storey to a fixed point, and (3) FREE placement in which dampers may connect adjacent storeys, non adjacent storeys and storeys to a fixed point;
- genetic algorithms are used to identify damping systems characterized by an interstorey (IS) damper placement and "optimal" damper sizing, systems characterized by a fixed point (FP) damper placement and "optimal" damper sizing, and systems characterized by a "free" (FREE) damper placement and "optimal" damper sizing;
- the dissipative performances offered by the MPD system (as applied to two reference shear-type structures subjected to stochastic input) are compared with those offered by numerically identified optimal systems.

As a fundamental result, it is basically obtained that, under the equal "total cost" constraint, the MPD system and systems characterised by fixed point (FP) placement provide the largest dissipative effectiveness.

This paper provides illustrative examples regarding (*i*) the seismic performances offered by the MPD systems when applied to shear-type structures and (*ii*) the implementation of MPD systems in actual building structures.

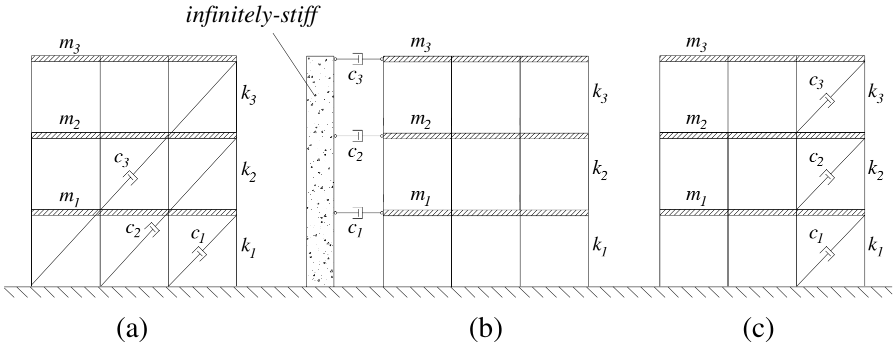


Fig. 1. (a,b) Fixed point (FP) damper placement and (c) interstorey (IS) damper placement.

THE TWO "REFERENCE" STRUCTURES

The numerical analyses presented in this paper are developed with reference to the same two shear type structures presented in the companion paper [17]. For the sake of convenience, these two structures are here reminded.

The first one is a 5-storey r.c. building structure with a rectangular layout of $30m \times 18m$ and an interstorey height of $h = 3.3m$. The structure consists of four frames arranged lengthways along the building plan ($30m$). In the analyses carried out herein, infinitely stiff beams (with respect to vertical columns) are assumed so that use of the two-dimensional shear-type schematisation of Fig. 2 is permitted [18]. The five stiffness values, the five storey mass values and the five resultant periods of vibration are set out hereafter:

$$k_1 = 1.2174 \cdot 10^9 \text{ N/m} \qquad m_1 = 5.4 \cdot 10^5 \text{ kg} \qquad T_1 = 0.578 \text{ sec}$$
$$k_2 = 0.7987 \cdot 10^9 \text{ N/m} \qquad m_2 = 5.4 \cdot 10^5 \text{ kg} \qquad T_2 = 0.252 \text{ sec}$$
$$k_3 = 0.4986 \cdot 10^9 \text{ N/m} \qquad m_3 = 5.4 \cdot 10^5 \text{ kg} \qquad T_3 = 0.180 \text{ sec}$$
$$k_4 = 0.2923 \cdot 10^9 \text{ N/m} \qquad m_4 = 5.4 \cdot 10^5 \text{ kg} \qquad T_4 = 0.131 \text{ sec}$$
$$k_5 = 0.1578 \cdot 10^9 \text{ N/m} \qquad m_5 = 2.7 \cdot 10^5 \text{ kg} \qquad T_5 = 0.091 \text{ sec}$$

The second structure is a 6-storey building model characterized by values of mass and lateral stiffness which do not vary along the building height. The lateral stiffness k_j of the vertical elements connecting each j-th storey to the one below is equal to $k = 4 \cdot 10^7$ N/m and the floor mass m_j of each j-th storey is equal to $m = 0.8 \cdot 10^5$ kg, with the first undamped circular frequency ω_I = 5.39 Hz (first period: $T_1 = 1.17$ sec). Interstorey height is h = 3 m and total height is h_{tot} = 18m. This structure has been selected for the sake of comparison with other research results regarding the optimal placement of added viscous dampers that are available in literature [4].

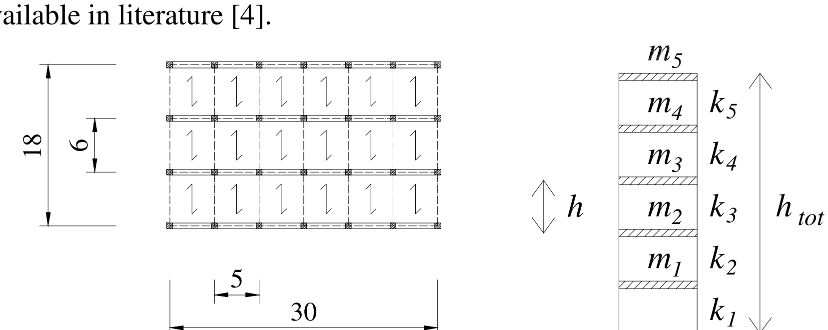


Fig. 2. Plan and shear-type schematisation of the 5-storey r.c. building structure.

THE SYSTEMS OF ADDED VISCOUS DAMPERS

Five systems of added viscous dampers are here considered for the 5-storey structure: the MPD, SPD, GIOIS, GIOFP and GIOFREE systems. Genetic algorithms were used to identify the "genetically identified optimal" (GIO) systems minimising the average of the standard deviations of the interstorey drifts angles (stochastic index *I* in companion paper [17]) in the cases of IS-, FP- and FREE-placements.
For the 5-storey structure, the equal "total cost" constraint is imposed with $\overline{c}$ equal to $2.729 \cdot 10^7\ \mathrm{N \cdot sec/m}$, so that the first modal damping ratio of the structure equipped with the SPD system is equal to $\xi_1^{SPD} = 0.05$. With reference to Fig. 3, the values of the damping coefficients of the GIOIS, GIOFP and GIOFREE systems are given in Table 1. Notice that the GIOFREE system presents no interstorey dampers. For comparison purposes, Table 1 also gives the values of the damping coefficients of the MPD and SPD systems.

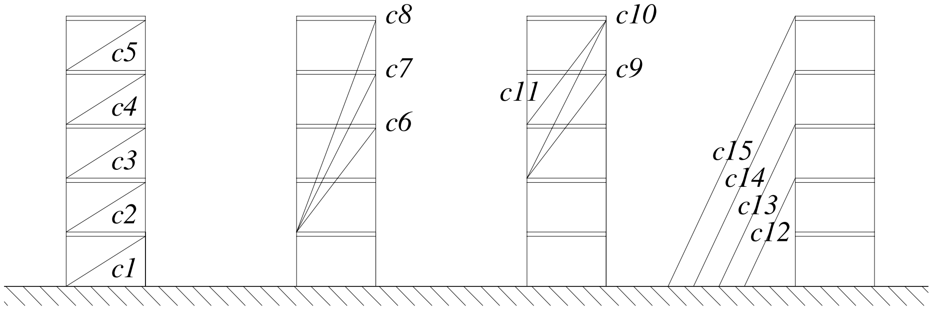


Fig. 3. All possible damper placements for the 5-storey shear-type structure.

Table 1. Damping coefficients [$\times 10^6\ \mathrm{N \cdot sec/m}$] and index *I* [$\times 10^{-3}$] of the SPD, MPD, GIOIS, GIOFP and GIOFREE systems for the 5-storey structure.

	SPD	MPD	GIOIS	GIOFP	GIOFREE	
c1	11.206	6.064	0	0	0	*c1*
c2	7.352	0	0	0	0	*c2*
c3	4.589	0	10.916	0	0	*c3*
c4	2.691	0	12.281	0	0	*c4*
c5	1.452	0	4.093	0	0	*c5*
c6	0	0	0	0	0	*c6*
c7	0	0	0	0	0	*c7*
c8	0	0	0	0	0	*c8*
c9	0	0	0	0	2.823	*c9*
c10	0	0	0	0	1.882	*c10*
c11	0	0	0	0	0	*c11*
c12	0	6.064	0	5.248	1.882	*c12*
c13	0	6.064	0	8.397	9.410	*c13*
c14	0	6.064	0	9.447	8.469	*c14*
c15	0	3.032	0	4.198	2.823	*c15*

Six systems of added viscous dampers are considered for the 6-storey structure: the MPD, SPD, GIOIS, GIOFP, GIOFREE and TAK systems. The TAK system being the damping scheme identified in the recent works by Izuru Takewaki [4] as "optimal" (for the 6-storey structure here considered) using an algorithm based upon an inverse problem approach, proposed by the same author [4]. The TAK system minimises the sum of amplitudes of the transfer functions of interstorey drifts evaluated at the undamped fundamental natural frequency within the restricted class of dampers placed between adjacent storeys (IS placement) and satisfy the "equal total cost" constraint. With reference to Fig. 4, the values of the damping coefficients of the MPD, SPD, GIOIS, GIOFP, GIOFREE and TAK systems are given in Table 2. Notice that the GIOFP and the GIOFREE systems coincide. Also, notice that the TAK system is very similar to the GIOIS system which minimises another performance index within the same class of IS placement.

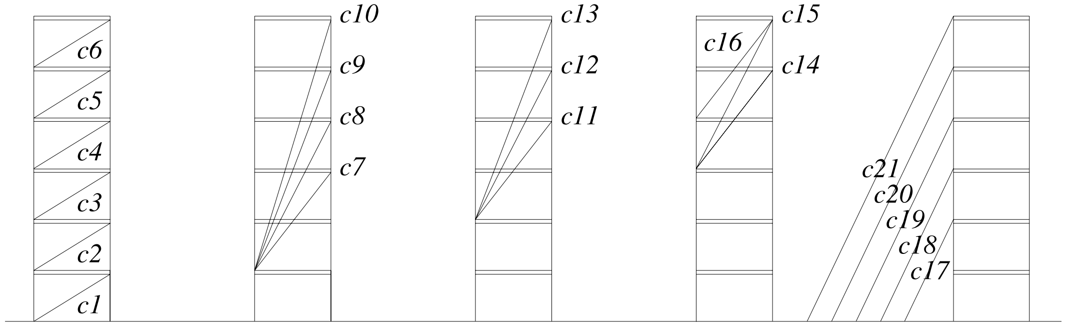


Fig. 4. All possible damper placements for the 6-storey shear-type structure.

Table 2. Damping coefficients [$\times 10^6$ N·sec/m] and index *I* [$\times 10^{-3}$] of the SPD, MPD, GIOIS, GIOFP, GIOFREE and TAK systems for the 6-storey structure.

	SPD	MPD	GIOIS	GIOFP	GIOFREE	TAK	
c1	1.50	1.50	3.91	1.02	1.02	4.80	*c1*
c2	1.50	0	3.13	0	0	4.20	*c2*
c3	1.50	0	1.96	0	0	0	*c3*
c4	1.50	0	0	0	0	0	*c4*
c5	1.50	0	0	0	0	0	*c5*
c6	1.50	0	0	0	0	0	*c6*
c7	0	0	0	0	0	0	*c7*
c8	0	0	0	0	0	0	*c8*
c9	0	0	0	0	0	0	*c9*
c10	0	0	0	0	0	0	*c10*
c11	0	0	0	0	0	0	*c11*
c12	0	0	0	0	0	0	*c12*
c13	0	0	0	0	0	0	*c13*
c14	0	0	0	0	0	0	*c14*
c15	0	0	0	0	0	0	*c15*
c16	0	0	0	0	0	0	*c16*
c17	0	1.50	0	1.53	1.53	0	*c17*
c18	0	1.50	0	1.70	1.70	0	*c18*
c19	0	1.50	0	1.70	1.70	0	*c19*
c20	0	1.50	0	1.53	1.53	0	*c20*
c21	0	1.50	0	1.53	1.53	0	*c21*

THE SYSTEMS RESPONSE TO SEISMIC INPUT

As illustrative examples of the overall dissipative performances offered by the selected damping systems, we report here illustrative results from an extensive series of numerical simulations carried out upon the two reference shear-type structures using as inputs 40 historically recorded earthquake ground motions. All seismic inputs are scaled to the same peak ground acceleration (PGA) of $0.3g$, and include, among the others: Imperial Valley, 1940, El Centro record; Kern County, 1952, Taft Lincoln School record; and Kobe, 1995, Kobe University record.

The maximum absolute storey displacements, absolute storey velocities, absolute storey accelerations and interstorey drift angles developed by the reference structures equipped with different damping systems have been numerically evaluated for each one of the 40 seismic excitations. For sake of conformity with the nomenclature of most recent works available in literature [19], the maximum absolute storey displacement (storey velocity, storey acceleration, interstorey drift angle) of a structure subjected to a single earthquake ground motion is here defined "peak floor displacement" ("peak floor velocity", "peak floor acceleration", "peak interstorey drift angle") and indicated with PFD (PFV, PFA, PIDA). Moreover, a graph, in which in the ordinates are reported the storeys of the structure and in the abscissas are reported the values of the PFD's (PFV's, PFA's, PIDA's), is here referred to as "PFD (PFV, PFA, PIDA) profile".

Seismic response of the 5-storey structure

Figures 5a, b, c, and d show, respectively, the average values of the PFD profiles ("average PFD"), the average values of the PFV profiles ("average PFV"), the average values of the PFA profiles ("average PFA"), and the average values of the PIDA profiles ("average PIDA") obtained for the 5-storey structure equipped with the five damping schemes considered, over all 40 earthquake ground motions.

As expected from the results of the systems response to stochastic input obtained in the companion paper [17], the largest average PFD values (see Fig. 5a) are those developed by the SPD and the GIOIS systems, whilst the smallest ones are those developed by the GIOFREE, GIOFP and MPD systems. To quantify the response reduction in PFD allowed by an MPD system, notice that the top-storey average PFD of the SPD system is about 70 mm, while that of the MPD system is about 20 mm (70% reduction).

The trend of average PFV values (see Fig. 5b) is roughly the same of that of average PFD values. The largest average PFV values being those developed by the SPD and the GIOIS systems, whilst the smallest ones being those developed by the GIOFREE, GIOFP and MPD systems. To quantify the response reduction in PFV allowed by an MPD system, notice that the top-storey average PFV of the SPD system is about 0.75 m/s, while that of the MPD system is about 0.23 m/s (69% reduction).

The average PFA values (see Fig. 5c) are roughly the same for all damping systems up to the 2nd floor (with slightly better performances offered by the MPD system). At the 3rd, 4th and 5th floors, the system response clearly differentiates, with the SPD and GIOIS systems providing the largest values and the MPD, GIOFP and GIOFREE systems the smallest values. To quantify the response reduction in PFA allowed by an MPD system, notice that the top-storey average PFA of the SPD system is about 9.64 m/s2, while that of the MPD system is about 3.69 m/s2 (62% reduction).

Once again, the largest average PIDA values (see Fig. 5d) are those developed by the SPD and the GIOIS systems (characterised by IS placement), whilst the smallest ones are those developed by the GIOFREE, GIOFP and MPD systems (basically characterised by FP placement).

Table 3 gives the coefficients of variation (COV), over 40 earthquake ground motions, for PFD's, PFV's, PFA's, PIDA's of the 5-storey r.c. structure equipped with SPD, MPD, GIOIS, GIOFP and GIOFREE systems. In general (except for the COV of PFA's), the MPD, GIOFP and GIOFREE systems show smaller values of the COV than those of the SPD and GIOIS systems (especially at the top-storey), thus indicating a "more stable" (with respect to the seismic input) system response. On the other hand, the values of the COV of PFA's are roughly the same for all five damping systems considered.

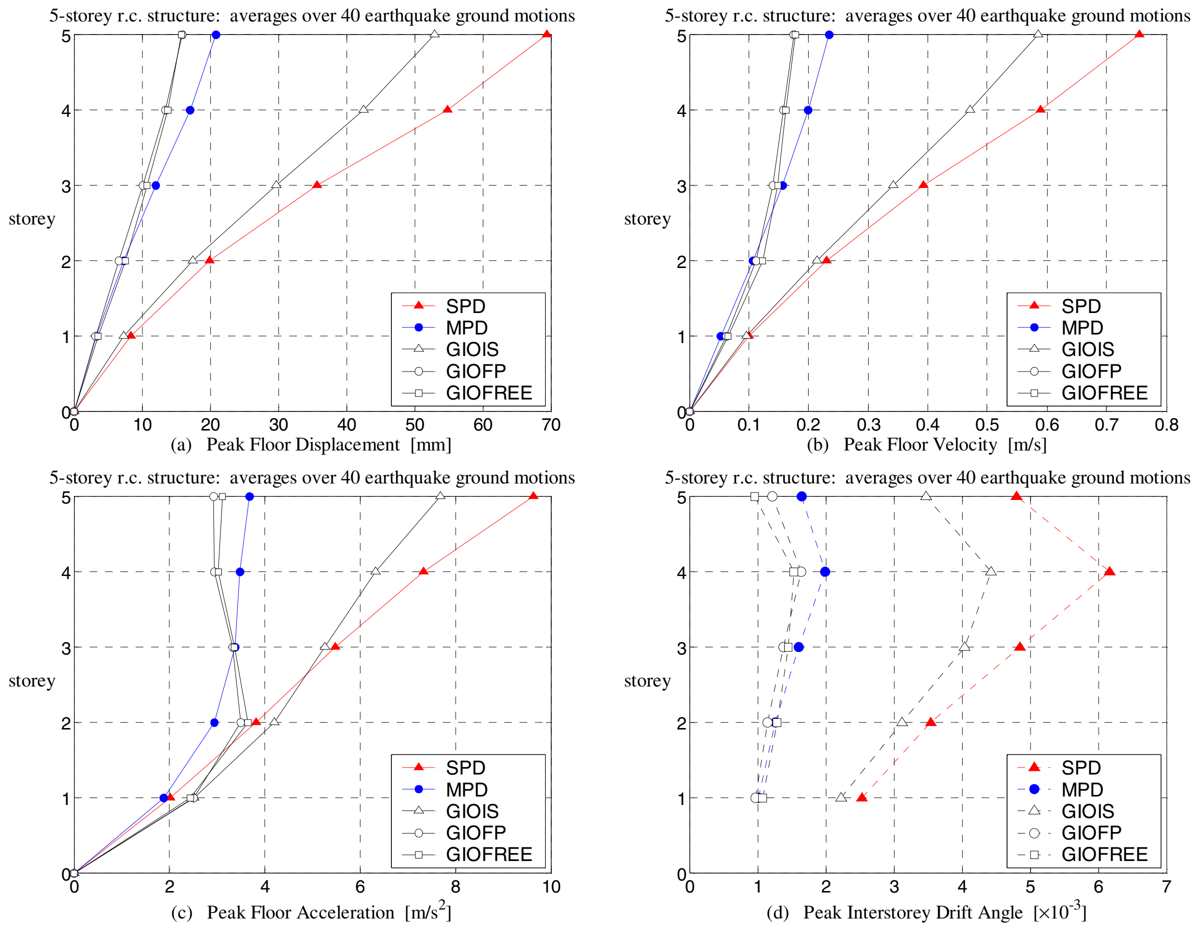


Fig. 5. Average values of PFD (a), PFV (b), PFA (c) and PIDA (d) profiles for the 5-storey structure equipped with SPD, MPD, GIOIS, GIOFP and GIOFREE systems over 40 earthquake ground motions.

Table 3. Coefficients of variation (over 40 earthquake ground motions) for PFD's, PFV's, PFA's, PIDA's of the 5-storey structure equipped with SPD, MPD, GIOIS, GIOFP and GIOFREE systems.

	Coefficients of variation for PFD's					Coefficients of variation for PFV's				
storey	SPD	MPD	GIOIS	GIOFP	GIOFREE	SPD	MPD	GIOIS	GIOFP	GIOFREE
1	0.47	0.28	0.41	0.21	0.21	0.35	0.16	0.24	0.25	0.21
2	0.48	0.30	0.42	0.24	0.23	0.39	0.13	0.28	0.17	0.16
3	0.49	0.33	0.44	0.30	0.29	0.43	0.17	0.33	0.16	0.17
4	0.50	0.36	0.45	0.36	0.35	0.45	0.24	0.37	0.21	0.21
5	0.49	0.37	0.45	0.38	0.38	0.43	0.26	0.39	0.24	0.22
average	0.49	0.33	0.43	0.30	0.29	0.41	0.19	0.32	0.21	0.20
	Coefficients of variation for PFA's					Coefficients of variation for PIDA's				
storey	SPD	MPD	GIOIS	GIOFP	GIOFREE	SPD	MPD	GIOIS	GIOFP	GIOFREE
1	0.29	0.46	0.41	0.50	0.47	0.47	0.28	0.41	0.21	0.21
2	0.21	0.35	0.23	0.41	0.38	0.48	0.28	0.40	0.22	0.20
3	0.24	0.25	0.18	0.28	0.26	0.49	0.29	0.41	0.22	0.22
4	0.33	0.17	0.25	0.19	0.19	0.46	0.25	0.42	0.20	0.24
5	0.33	0.18	0.29	0.17	0.17	0.39	0.19	0.38	0.18	0.23
average	0.28	0.28	0.27	0.31	0.29	0.46	0.26	0.41	0.20	0.22

Seismic response of the 6-storey structure

Figures 6a, b, c, and d show, respectively, the average values of the PFD profiles, the average values of the PFV profiles, the average values of the PFA profiles, and the average values of the PIDA profiles obtained for the 6-storey structure equipped with the six damping schemes considered, over all 40 earthquake ground motions.

As expected from the results of the systems response to stochastic input [17], the average PFD values (see Fig. 6a) developed by the structure equipped with the SPD system are larger than those developed by the structure with the GIOIS and TAK systems, while the smallest average PFD are provided by the MPD and GIOFP (which coincides with GIOFREE) systems. It should be noted that, for all systems considered, the average PFD increases progressively and smoothly (but less than linearly) proceeding from the bottom to the top of the structure so that the maximum interstorey drift occurs between the ground and the 1st storey. The absolute difference between the average PFD of the MPD and SPD systems increases progressively from the bottom to the top of the structure. To quantify the response reduction allowed by an MPD system with respect to the SPD system, notice that the top-storey average PFD of the SPD system is about 88 mm, while that of the MPD system is about 15 mm (83% reduction). Overall, the PFD's of the MPD system are one order of magnitude less than the PFD's of the SPD system.

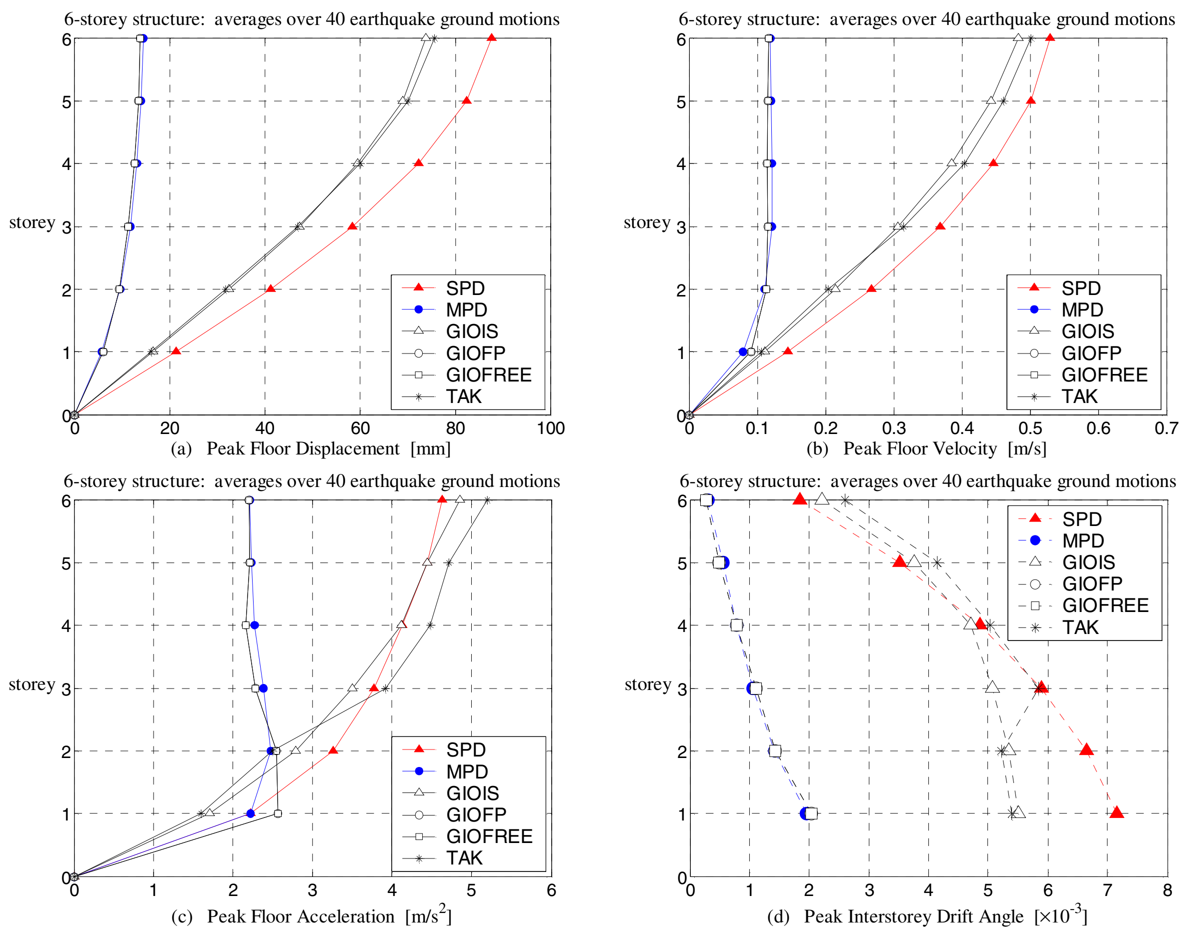


Fig. 6. Average values of PFD (a), PFV (b), PFA (c) and PIDA (d) profiles for the 6-storey structure equipped with SPD, MPD, GIOIS, GIOFP, GIOFREE and TAK systems over 40 earthquake ground motions.

Similar considerations can be made regarding the PFV, PFA and PIDA profiles. Only some meaningful differences are observed in the following.
The average PFA of the SPD system is equal to that of the MPD system at the 1st storey, then the systems response clearly differentiates, with the MPD system providing smaller average PFA values than the SPD system. Therefore, the absolute differences between average PFA values of the SPD and MPD systems increase from the bottom to the top of the structure, reaching their maximum value at the top itself. These differences being almost null at the first storey, and yet quite relevant at the second floor. Notice that the average PFA of the TAK system is the smallest one at the first storey and the largest one at the top-storey.
As far as PIDA profile is concerned, once again, the largest average PIDA are those developed by the SPD system, while the smallest average PIDA are developed by the MPD and GIOFP system. As previously anticipated by inspection of the average PFD profiles, the average PIDA decreases progressively proceeding from the bottom to the top of the structure for all damping systems considered. The MPD system being able to reduce of more than 70% the first storey average PIDA developed by the SPD system.

The forces through the dampers for the 6-storey structure

Given the differences observed between the dissipative effectiveness of systems characterized by an interstorey damper placement (SPD, GIOIS and TAK) and of systems which encompass also dampers connecting non adjacent storeys (MPD, GIOFP and GIOFREE), this section presents selected results regarding the maximum forces exerted through the damping devices of such systems, as applied to the reference 6-storey structure, under seismic excitation.
The maximum forces developed through the dampers (peak damper forces) are evaluated by means of a series of numerical simulations conducted using as base input again the 40 historically recorded earthquake ground motions of before (scaled to PGA = 0.3g).
Fig. 7 shows the sum of the peak forces developed in all dampers added to the structure (total damper force) under each one of the 40 earthquake ground motions. In most cases, the total damper force developed through all devices of all the damping systems is comparable in size. The differences being contained within values which do not substantially affect the design of such devices (i.e. differences which are not so relevant from the point of view of the design of the damper system and its supporting trusses).
Fig. 8a shows the average (over the 40 earthquake ground motions) of the sums of the peak damper forces developed by the 6-storey structure under the different damper configurations. It can be seen that the average of total damper forces is roughly the same for all damping systems: it is 910 kN for the SPD system, 1010 kN for the MPD system, 961 kN for the GIOIS system, 1015 kN for the GIOFP system (which coincides with GIOFREE system for the 6-storey structure) and 931 kN for the TAK system.
As far as each single dissipative device is concerned, Fig. 8b shows the averages (over 40 earthquake ground motions) of the peak damper forces, for each damper. With reference to the nomenclature of dampers of Fig. 4, it can be seen that the distribution of the damper forces throughout the height of the structure is the opposite for the MPD and SPD systems: the MPD system transmits the largest dissipative force at the top of the structure, whilst the SPD system transmits the largest dissipative force at the bottom of the structure.
To sum up, the better dissipative performances of the MPD system (and of systems characterized by FP placement) as compared to those of the SPD system (and of systems characterized by IS placement) do not come at the expense of larger damper forces. This result indicates that the MPD system is more effective in energy dissipation than the SPD system due to its intrinsic physical properties and not due to the development of larger damping forces.

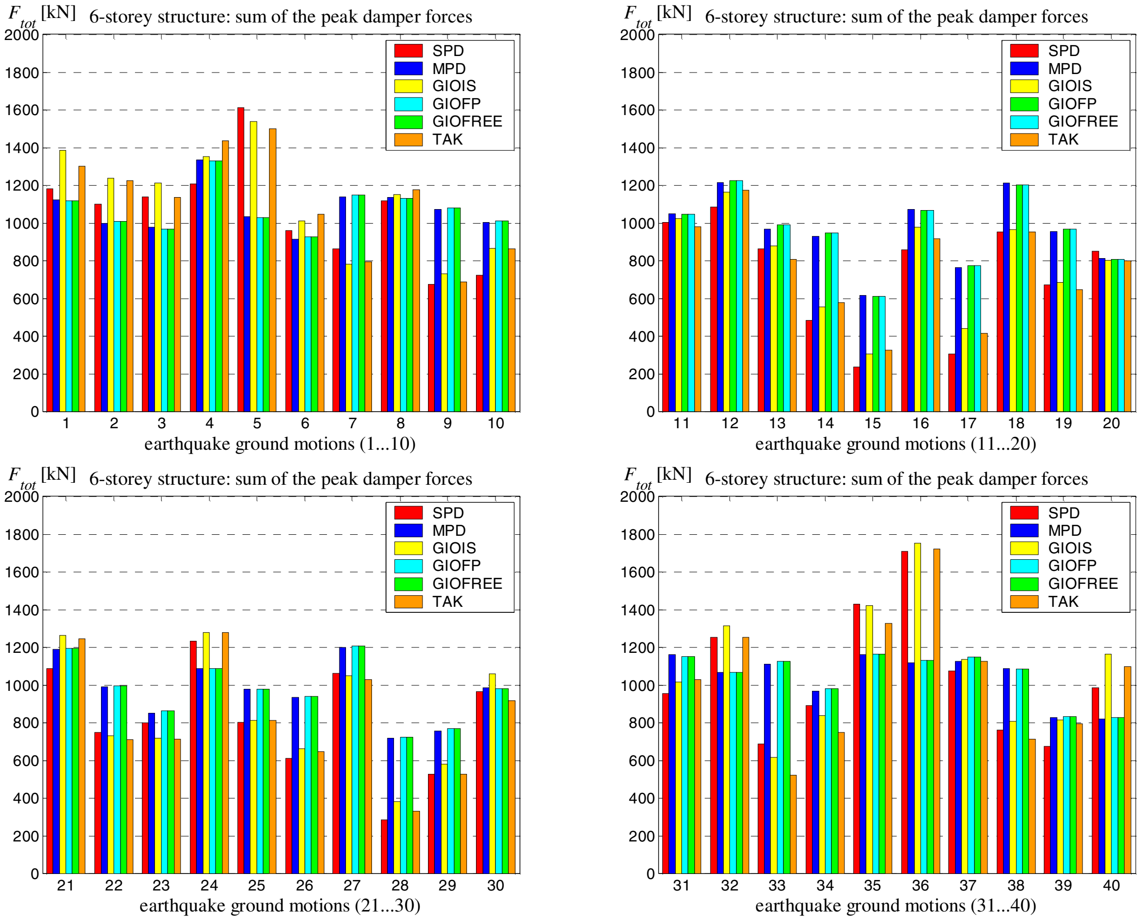
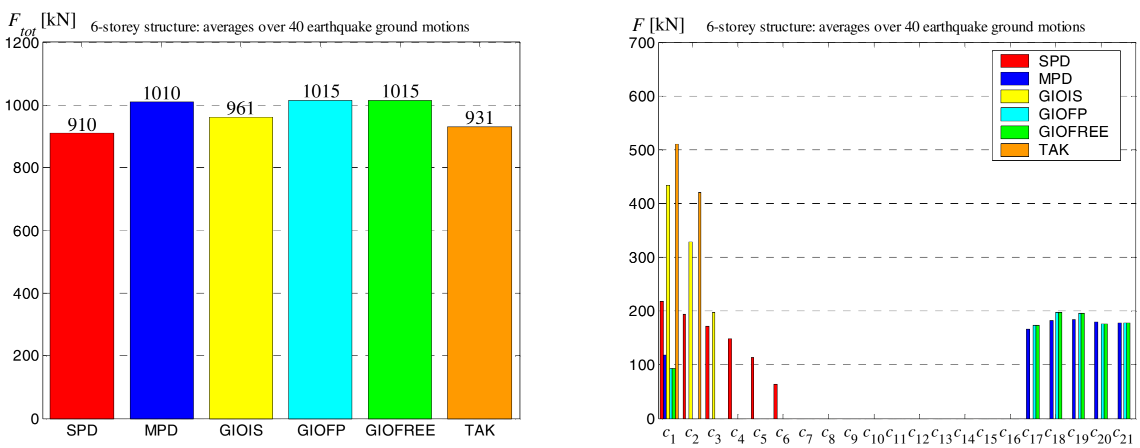


Fig. 7. Sum of the peak forces developed in all dampers added to the structure (total damper force) under each one of the 40 earthquake ground motions.



(a) (b)

Fig. 8. (a) Averages (over 40 ground motions) of the total damper force developed by the 6-storey structure under the six different damper configurations, and (b) averages (over 40 ground motions) of the peak damper forces for each damper.

APPLICABILITY OF THE MPD SYSTEMS

So far we have witnessed good damping performance offered by the MPD system (and by systems characterized by fixed point placement), but the issue of how to implement this damping scheme in real building structures still needs to be addressed.

Direct implementation of the MPD systems

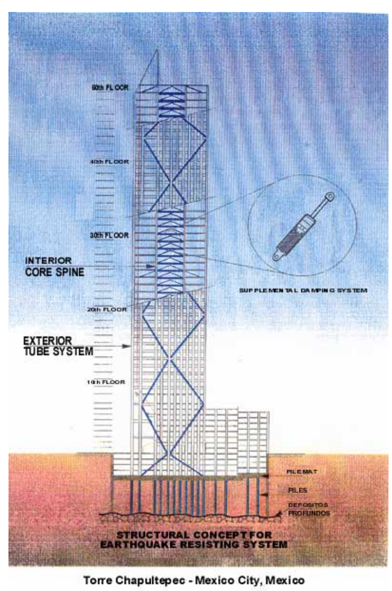
With reference to the schematic representation of Fig. 1a, a direct implementation of the MPD system (that leads to a damping matrix which corresponds to an exact MPD matrix, if damper sizing is chosen properly) can be obtained by placing dampers so that they connect each storey to the ground. In order to do so, it is necessary to introduce dissipative braces of considerable length. At the present time, the following technological solutions can be envisaged to overcome the length problem:

- use of the so-called “mega braces” of the Taylor Devices Company, already employed (not following an exact MPD scheme) for the Chapultepec Tower (best known as Torre Major and shown in Fig. 9) in Mexico City;
- use of the so-called “unbonded braces” [20] of the Nippon Steel Corporation, already employed (not following an exact MPD scheme) for the Osaka International Conference Centre [21], shown in Fig. 10a, and the retrofit of the Wallace F. Bennett Federal Building in Salt Lake City [22], shown in Fig. 10b;
- use of prestressed steel cables coupled with silicon dampers as proposed in the SPIDER European research project [23] whose schematic representation can be seen in Fig. 11.

“Mega-braces” have already been used successfully to connect floors which are 5 storeys apart and therefore the up to date technology is readily available to successfully implement direct MPD systems for building structures up to 5 storeys.

However, direct implementation requires the realization of specific construction details, which may prove to be costly.

(a)



(b)

Fig. 9. The Chapultepec Tower (best known as Torre Major) in Mexico City: (a) under construction and (b) schematic representation of the “mega-braces” of Taylor Devices Company

(a) (b)

Fig. 10. (a) Osaka International Conference Centre, (b) Wallace F. Bennett Federal Building

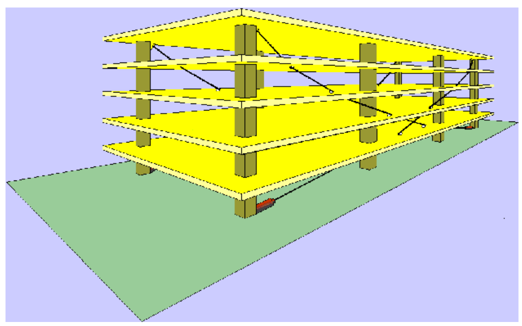


Fig. 11. Schematic representation of the damping cables of the SPIDER research project.

Indirect implementation of the MPD systems

With reference to the schematic representation of Fig. 1b, let's suppose to have next to the 5-storey reference structure to be damped (structure A) a "support" structure (structure B) with the same total number of storeys and the same floor masses m_j of structure A (see Figures 12a and b). Three different structures B are here considered: B2, B5 and B10, each one characterized by a lateral stiffness k_{Bj} equal to $k_{Bj} = p \cdot k_j$ with $p = 2,\ 5,\ 10$, respectively. The fundamental periods of structures B2, B5 and B10 are equal to 0.409, 0.259 and 0.183 sec, respectively. Structures B2, B5 and B10 are characterized by a Rayleigh damping matrix leading to $\xi_1 = 0.03$ and $\xi_2 = 0.07$, representative of internal damping. Structures B2, B5 and B10 can be used as "fixed point" to create an indirect implementation of the MPD system as given in Fig. 12c.

Fig. 13a shows how the dynamic response (in terms of storey shears) of structure A improves when it is linked with viscous dampers (characterized by MP sizing: $\alpha = 11.23$ sec^{-1}) to structure B characterized by different dynamic properties. Fig. 13b shows how the dynamic response (in terms of storey shears) of structure B changes due to the presence of viscous dampers that link it to structure A. Figures 13a and b indicate that, when structures A and B are linked, the dynamic response of structure A is largely improved, while the dynamic response of structure B is either unchanged or slightly improved. The best results are obtained for B5 and B10 structures: 50-60% reduction in the response of structure A (similar to the reduction obtained with the "direct" implementation of the MPD system) and 5-10% reduction in the response of structure B.

Fig. 14 represents the maximum absolute piston stroke of the viscous dampers connecting structures A and B: the largest strokes occur at the top-storey, are very similar for B2, B5 and B10 structures and are of limited amplitude (maximum value of 3 cm).

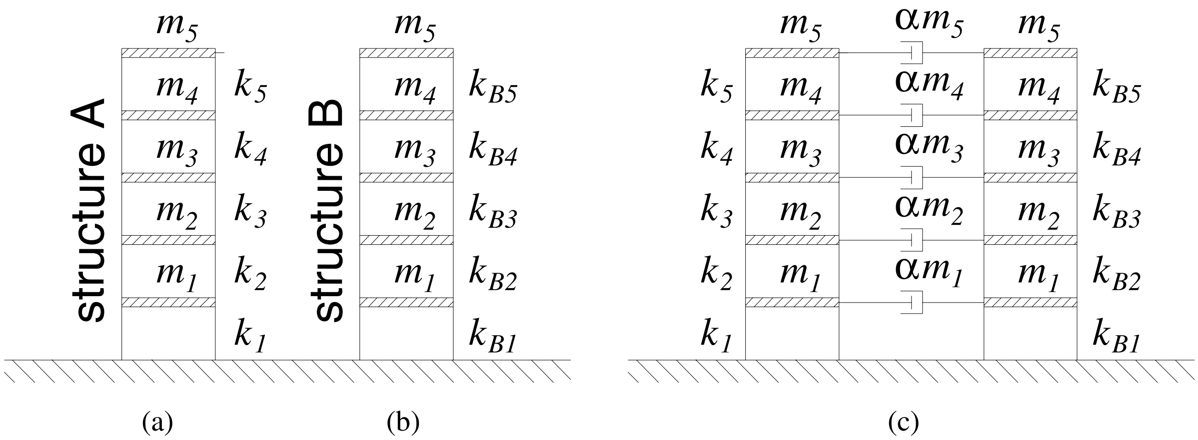


Fig. 12. (a) Structure A, (b) structure B and (c) coupled structures A & B.

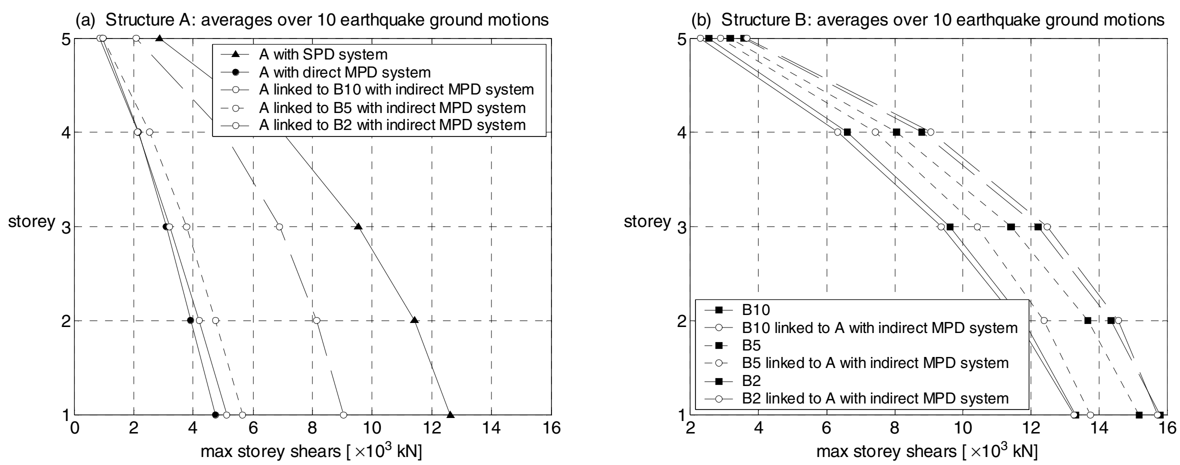


Fig. 13. Averages values (over 10 earthquake ground motions) of maximum storey shears for structure A (a) and structure B (b).

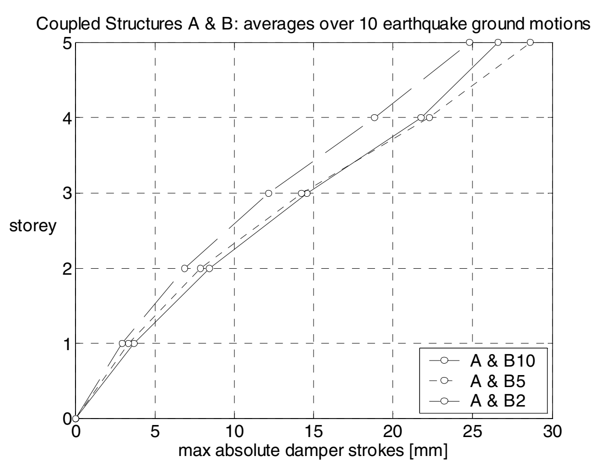


Fig. 14. Averages values (over 10 earthquake ground motions) of maximum damper piston strokes for coupled structures A and B.

CONCLUSIONS

In this paper, in order to confirm the results obtained (through a physically-based approach and by means of stochastic performance indexes) in a companion paper regarding the optimal dissipative properties of the mass proportional damping (MPD) system, numerical time-history simulations are carried out using 40 earthquake ground motions as base input. All the results confirm the better dissipative efficiency of the MPD system and of systems characterised by fixed point damper placement with respect to systems characterised by interstorey damper placement. It is shown also that the better dissipative performances of the MPD system (and of systems characterized by FP placement) as compared to those of the SPD system (and of systems characterized by IS placement) do not come at the expense of larger damper forces.
Both direct implementation (dampers connect each storey to the ground) and indirect implementation (dampers connect each storey of the base structure to a support structure: stiff vertical element, e.g. the conventional concrete core of the stairs/elevator typically found in r.c. constructions) of MPD systems have proven to be feasible and effective. In particular, indirect implementation can be obtained connecting a shear-type structure ("base" structure) to a "support" structure through viscous dampers. For given dynamic properties of the "support" structure, it is possible to provide a damping effect upon the "base" structure similar to that offered by direct implementation of the MPD system without increasing the dynamic actions upon the "support" structure.

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