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SEISMIC RESPONSE OF NONSTRUCTURAL ELEMENTS IN STRUCTURES WITH ENERGY-DISSIPATION SYSTEMS

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ABSTRACT

The use of seismic protective systems incorporating energy dissipation devices constitutes a promising approach for reduction of damage to non-structural components in structures of architectural significance, critical facilities, hospitals, museums, and buildings containing important electronic equipment. Given the current emphasis on high performance structures and the interest in the behavior of non-structural components, there is a need to assess the performance of secondary systems in structures equipped with seismic protective systems. An analytical study of buildings without and with seismic damping systems was conducted to investigate the dynamic response of secondary systems. The buildings were represented by steel frames designed by the procedures described in the 2003 NEHRP Recommended Provisions. Nonlinear response analyses were performed for the undamped frames and the damped frames equipped with different energy dissipation systems and for far-field, near-field, and soft-soil earthquake histories. The study shows that significant benefits may be provided by viscous damping systems in terms of reduced floor spectral accelerations and floor absolute velocities.

Introduction

By the time of the 1989 Loma Prieta earthquake, it became apparent that damage to nonstructural elements and building contents could result in serious casualties, severe building impairment, and major economic losses even when structural damage was not that significant. Recent attention to nonstructural components comes from the development of performance-based design, which necessitates coordination of the performance levels between structural and nonstructural components. Chapter 11 of the FEMA 273 and 274 documents (ATC 1997) represents the first attempt to provide design requirements for both force- and displacement-controlled nonstructural components using a performance-based approach. These provisions provide design requirements to achieve the performance levels of Life Safety and Immediate Occupancy. No specific acceptance criteria for nonstructural components for Operational Performance Level are provided in these guidelines.

The use of seismic protective systems incorporating energy dissipation devices constitutes a promising approach for reduction of damage to non-structural components in structures of architectural significance, critical facilities, hospitals, museums, and buildings containing important electronic equipment. Given the current emphasis on high performance structures and the interest in the behavior of non-structural components, there is a need to assess the performance of secondary systems in structures equipped with seismic protective systems.

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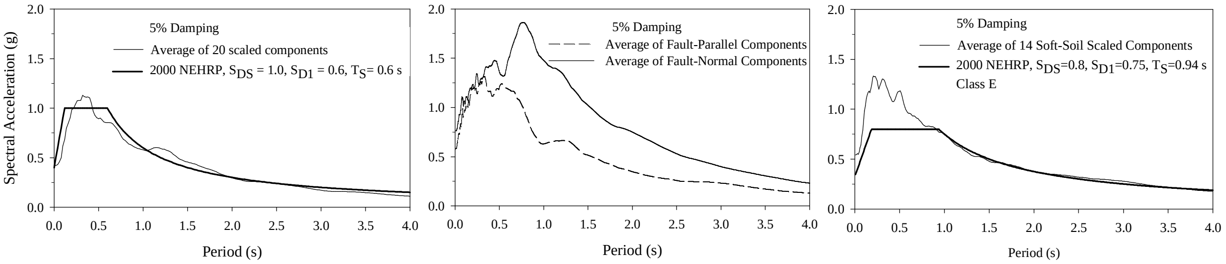
The 2000 and 2003 editions of FEMA's National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (BSSC 2001, 2004), and the 2005 edition of ASCE 7 Standard – Minimum Design Loads for Buildings and Other Structures (ASCE 2005) present simplified methods for analysis and design of buildings with damping systems. These procedures are largely based on studies that excluded the effects of near-field and soft-soil excitations (Ramirez et al. 2001).

Herein, an analytical study of the response of secondary systems in buildings without and with damping systems is presented, in which the buildings are represented by 3-story steel frames designed by the procedures of the 2000 NEHRP Recommended Provisions. That is, the buildings are not designed intentionally for improved performance – rather they are designed to just meet the safety and drift criteria of the 2000 NEHRP Recommended Provisions. Seismic performance is assessed through nonlinear response history analyses using three sets of ground motions representative of various site characteristics. The study shows that significant benefits may be provided by damping systems in terms of floor spectral accelerations and floor absolute velocities. A complete presentation of the results may be found in Pavlou and Constantinou (2004b).

Ground Motions

Three sets of earthquake records of various characteristics, magnitudes, and distances on building structures are employed in this investigation (Fig. 1). The sets include ground motions recorded at near- and far-field sites as well as soft-soil sites.

The first set comprised of 20 horizontal components of 10 far-field earthquake motions. The selection was based on the use of scaled earthquake records that on the average represent well a specific design-response spectrum. The second set of ground motions, assembled by Somerville et al. (1997), includes ten near-field motions on stiff soil selected from the suite of earthquake histories that had been developed for major crustal earthquakes in UBC Zone 4 as part of the SAC Steel Project. These time histories represent near-field ground motions from earthquakes having a variety of faulting mechanisms in the magnitude range of 6.7 to 7.5, and distance range of 0 to 10 km. The ground motions have been either recorded or modified to suit NEHRP site class D conditions. Fourteen horizontal components of seven soft-soil earthquake histories were included in the third set of motions. The magnitude of the earthquakes ranged from 6.7 to 7.5; the epicentral



(a) (b) (c)

Figure 1. (a) Average spectral acceleration of scaled far-field ground motions , (b) Average spectral acceleration of near-field fault-normal and fault-parallel components, (c) Average spectral acceleration of scaled soft-soil ground motions.

distance varied from 16 to 166 km; and the site conditions were characterized by site class E in accordance with the 2000 NEHRP Recommended Provisions. Details on the selection and scaling of these motions are presented in Pavlou and Constantinou (2004b).

Description of 3-story frames

Two reference frames were utilized in this study, herein referred to as the undamped frames. These frames were special steel moment frames in a three-story building (Fig. 2) without damping systems and they were designed to meet the minimum base shear and drift limits of the 2000 NEHRP Recommended Provisions.

Fig. 3 presents the design for the three-story reference frames. Four of these frames, with two in each principal direction, were used in a symmetric configuration in a building. The reactive weights corresponding to each frame at each floor level of the building are also shown in Fig. 3. These weights were held constant for all of the frames although some minor reduction in reactive weight was achieved with the use of smaller section sizes in the damped frames. The yield strength of all steel was assumed to be 345 MPa (50 ksi).

Frame 3S-UNDAMPED is assumed to be located at a site characterized by a design response spectrum with parameters $S_{D1} = 0.6$, $S_{DS} = 1.0$, and $T_S = 0.6$ sec per the 2000 NEHRP Recommended Provisions (Ramirez et al. 2001). Frame 3SS-UNDAMPED is assumed to be located on a soft-soil site characterized by a design response spectrum with parameters $S_{D1} = 0.75$, $S_{DS} = 0.8$, and $T_S = 0.94$ sec per the 2000 NEHRP Recommended Provisions.

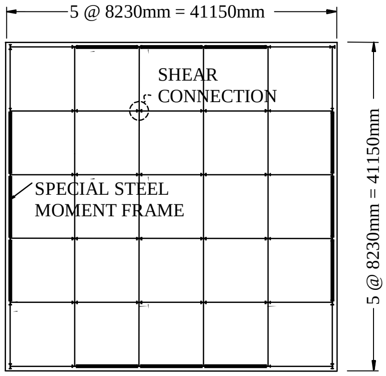
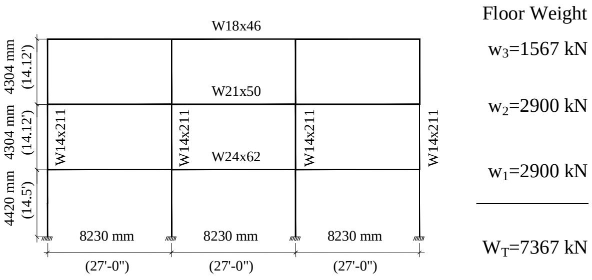
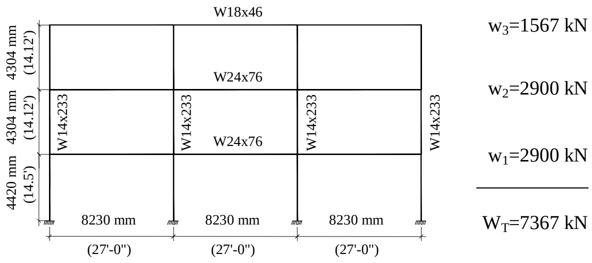


Figure 2. Plan view of the 3-story building



(a) 3S-UNDAMPED (V_{yo} = 2223 kN; W_o = 215 kN; V_y = 1626 kN)

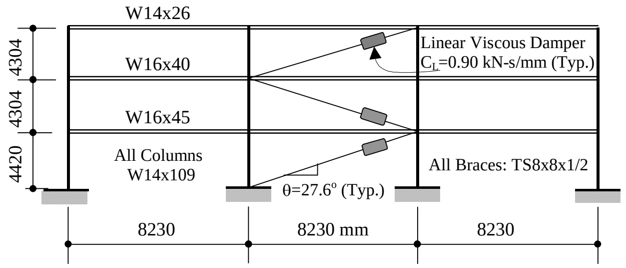


(b) 3SS-UNDAMPED (V_{yo} = 2300 kN; W_o = 248 kN; V_y = 1823 kN)

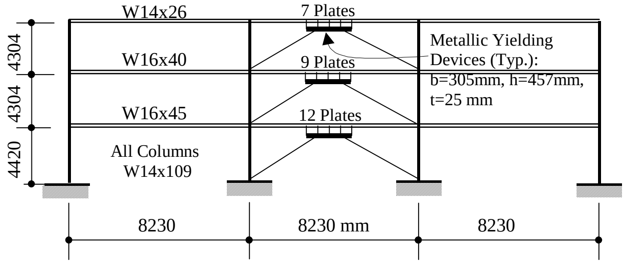
Figure 3. 3-story frames without a damping system

Three-story special steel moment frames with linear viscous, nonlinear viscous and yielding damping systems were utilized in this study. The damped frames exclusive of the damping systems were designed in accordance with the 2000 NEHRP Recommended Provisions to have a base shear strength, V_{ya}, in the range of 75 to 100% of V_y, where V_y is the base shear strength of the frame without a damping system (undamped frames) designed for seismic base shear V in accordance with 2000 NEHRP (note that the undamped frame designed for seismic base shear V has not been modified to meet the drift criteria). The damped frames have the same interstory heights, floor weights, and span dimensions as those of the undamped frames. Additional information on the design of the frames is presented in Pavlou and Constantinou (2004a, 2004b) and in Ramirez et al. (2001). The base shear strengths of the frames with damping systems are substantially lower than the base shear strengths of the reference frames that were designed to meet the drift criteria of the 2000 NEHRP Recommended Provisions. Ratios of V_{ya}/V_{yo} ranged between 0.55 for frame 3S75-LV10% and 0.73 for frame 3S100-LV20%.

Fig. 4 shows two of the six damped frames utilized in the analysis. A complete description of all frames utilized in the analyses may be found in Pavlou and Constantinou (2004b). The damped frames exclusive of the energy dissipation devices do not meet the drift limit of the 2000 NEHRP (less than or equal to $0.02h_{sx}$). Accordingly, damping systems were added to these structures to satisfy the drift criteria of the 2000 NEHRP.



(a) 3S75-LV10%



(b) 3S75-YD1

Figure 4: Frames with damping systems.

Nonlinear Response-History Analysis

Nonlinear response history analysis was performed using the program IDARC2D, Version 5.0 (Valles et al. 1996). In addition to the known capabilities of this program for the analysis of inelastic systems, new mathematical models for damper elements for seismic protection were incorporated and verified in this version. A large number of analyses were performed encompassing the undamped and damped frames with different energy dissipation systems and seismic excitations with far-field, near-field, and soft-soil characteristics.

Since most secondary systems are light by comparison with their (primary) supporting structural system, it is commonly assumed that there is no dynamic interaction between the two systems. Based on this assumption, the floor total acceleration history is used to compute a floor response spectrum from which the spectral acceleration demand on a nonstructural building component can be obtained. A floor response spectrum is the representation of the peak response of a single-degree-of-freedom oscillator of variable frequency subjected to the motion of a support point (floor) on the primary system. The damping ratio of this oscillator was assumed to be 0.05 for this study. Calculated response quantities include peak values of interstory drift, absolute floor velocities and accelerations, and floor response spectra in the range of 0.1 to 20 Hz. Additionally, information on plastic hinge formation of the frames analyzed provides details on the extent of inelastic action and damage in the frames with and without the damping systems.

Tables 1 through 4 present the response of the analyzed frames when excited by the three sets of seismic motions. Story drifts, floor velocities, and floor accelerations were calculated as the average of the peak values obtained from nonlinear response-history analyses for each ground motion. Floor spectral acceleration values correspond to the maximum of the average

Table 1. Comparison of responses of frames with and without damping systems. Analysis with far-field ground motions (set 1).

FRAME NOTATION	STORY	STORY DRIFTS (mm)	FLOOR VEL. (mm/sec)	FLOOR ACCEL. (g)	PEAK FLOOR SPECTRAL ACCEL. (g)	MAX. PLASTIC ROTATION	NUMBER OF PLASTIC HINGES
3S-UNDAMPED	3	82	1193	1.0	5.1	0.008	18 (22)
	2	81	836	0.7	2.9		
	1	51	677	0.8	3.7		
3S75-LV10%	3	82	893	0.4	1.3	0.007	20 (22)
	2	92	686	0.3	0.9		
	1	63	549	0.4	0.9		
3S100-LV20%	3	49	790	0.4	1.3	0.003	8 (22)
	2	62	653	0.4	1.0		
	1	40	557	0.4	1.0		
3S80-NLV10%	3	81	855	0.5	1.3	0.007	14 (22)
	2	86	662	0.4	0.9		
	1	58	542	0.4	3.6		
3S75-YD1	3	107	1049	0.7	3.0	0.011	22 (22)
	2	95	772	0.6	3.0		
	1	68	647	0.7	3.5		
3S75-YD2	3	70	1000	0.7	3.3	0.004	12 (22)
	2	78	802	0.7	4.2		
	1	54	674	0.8	5.2		
Value in parenthesis indicates the total number of potential plastic hinge locations (ends of each beam and bottom of 1st story columns)							

Table 2: Comparison of responses of frames with and without damping systems. Analysis with fault normal components of near-field ground motions (set 2).

FRAME NOTATION	STORY	STORY DRIFTS (mm)	FLOOR VEL. (mm/sec)	FLOOR ACCEL. (g)	PEAK FLOOR SPECTRAL ACCEL. (g)	MAX. PLASTIC ROTATION	NUMBER OF PLASTIC HINGES
3S-UNDAMPED	3	226	2154	1.2	4.0	0.023	26 (22)
	2	216	1618	0.8	2.8		
	1	148	1448	0.9	3.3		
3S75-LV10%	3	198	1562	0.5	1.5	0.029	26 (22)
	2	213	1323	0.5	1.0		
	1	176	1298	0.6	1.5		
3S100-LV20%	3	127	1695	0.6	1.7	0.029	22 (22)
	2	160	1503	0.6	1.4		
	1	129	1399	0.6	1.5		
3S80-NLV10%	3	189	1538	0.6	1.5	0.028	26 (22)
	2	204	1340	0.5	1.1		
	1	164	1320	0.6	1.4		
3S75-YD1	3	291	1784	0.8	2.7	0.026	36 (22)
	2	262	1458	0.7	2.6		
	1	180	1404	0.8	3.1		
Value in parenthesis indicates the total number of potential plastic hinge locations (ends of each beam and bottom of 1st story columns)							

Table 3. Comparison of responses of frames with and without damping systems. Analysis with fault parallel components of near-field ground motions (set 2).

FRAME NOTATION	STORY	STORY DRIFTS (mm)	FLOOR VEL. (mm/sec)	FLOOR ACCEL. (g)	PEAK FLOOR SPECTRAL ACCEL. (g)	MAX. PLASTIC ROTATION	NUMBER OF PLASTIC HINGES
3S-UNDAMPED	3	96	1405	1.1	5.1	0.015	22 (22)
	2	94	1012	0.8	3.0		
	1	58	878	0.9	3.6		
3S75-LV10%	3	98	1094	0.5	1.3	0.010	22 (22)
	2	112	844	0.4	0.9		
	1	78	737	0.4	1.2		
3S100-LV20%	3	58	1008	0.5	1.4	0.007	12 (22)
	2	76	852	0.3	1.1		
	1	50	743	0.4	1.1		
3S80-NLV10%	3	75	974	0.5	1.2	0.008	18 (22)
	2	93	817	0.4	0.9		
	1	65	733	0.4	1.1		
3S75-YD1	3	119	1220	0.8	2.9	0.015	24 (22)
	2	116	914	0.6	3.0		
	1	76	822	0.7	3.8		
Value in parenthesis indicates the total number of potential plastic hinge locations (ends of each beam and bottom of 1st story columns)							

Table 4. Comparison of responses of frames with and without damping systems. Analysis with soft-soil ground motions (set 3).

FRAME NOTATION	STORY	STORY DRIFTS (mm)	FLOOR VEL. (mm/sec)	FLOOR ACCEL. (g)	PEAK FLOOR SPECTRAL ACCEL. (g)	MAX. PLASTIC ROTATION	NUMBER OF PLASTIC HINGES
3SS-UNDAMPED	3	67	1398	1.1	5.1	0.009	22 (22)
	2	76	1055	0.8	2.9		
	1	57	855	0.8	3.4		
3SS75-LV10%	3	85	1113	0.5	1.4	0.006	18 (22)
	2	97	886	0.4	0.9		
	1	59	769	0.4	1.2		
Value in parenthesis indicates the total number of potential plastic hinge locations (ends of each beam and bottom of 1st story columns)							

spectral accelerations for each floor. Also listed in these tables are the maximum plastic rotation obtained from nonlinear response-history analysis for one representative ground motion. This motion produced response quantities in the frames that were similar in value to the average response calculated using the whole set of ground motions. Finally, the number of plastic hinges formed in each analyzed frame for this ground motion is reported along with the maximum number of plastic hinges possible to form a proper collapse mechanism. For the 3-story frame the maximum number of plastic hinges is 22 – two for each beam and one at the column bases.

Since the damped frames were designed for lower base shear strengths than the undamped building frames to achieve similar (or better) levels of performance (measured herein using displacements and plastic hinge rotations), the story drift comparison between frames with and without damping systems do not show any significant differences. The most indicative outcome is the reduction in absolute floor velocities obtained through the use of linear and nonlinear viscous damping devices. This reduction is of the order of 20% for the 3-story frames for the far-field ground excitation set (set 1) and is consistent along the floors of the frames. However the introduction of metallic yielding devices in the 3-story structure, frames 3S75-YD1 and 3S75-YD2, did not reduce the total floor velocity response but produced results similar to those obtained from analysis of the corresponding undamped frame.

Peak acceleration response is tabulated in Tables 1 through 4 for the different classes of seismic excitations. Clearly, the addition of damping devices in the frames resulted in overall significant reduction of floor accelerations. The reductions registered in the secondary system acceleration response are more significant in the case of systems with linear and nonlinear viscous dampers than for the metallic yielding devices. Similar trends are observed for all sets of ground motions. Analogous results were obtained from analyses of six-story frames with viscous damping systems (see Pavlou and Constantinou 2004b).

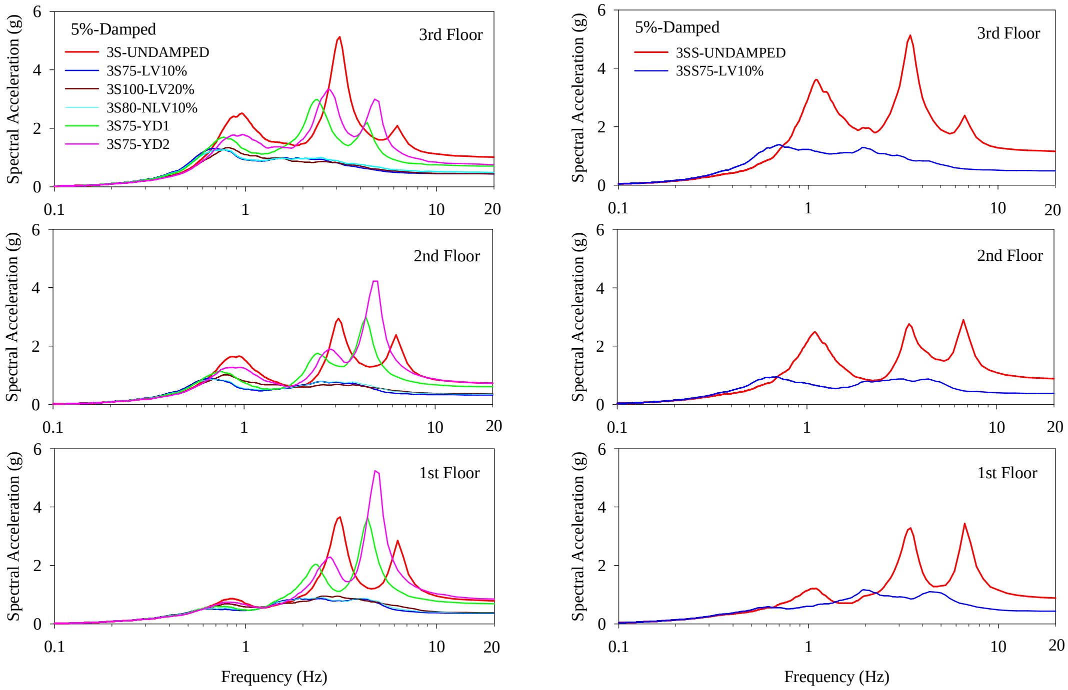
Moreover details on plastic hinge formation and maximum plastic hinge rotation are gathered for the damped and undamped frames to investigate the influence of damping systems on the extent of damage. Analyses performed on three-story frames using the far- and near-field ground motions revealed that frame 3S100-LV20% with the highly damped system exhibits, as expected, less plastic hinge rotation and forms a smaller number of plastic hinges than the lightly damped frame 3S75-LV10%. Frame 3S100-LV20% is more representative of a design for substantial improvement in structural system performance. Conclusively, buildings designed with viscous damping systems to meet the minimum criteria of the 2000 NEHRP perform, in terms of performance of the structural system, comparably to or better than buildings designed without damping systems.

However, the same conclusions cannot be drawn for the damped frame with metallic yielding devices 3S75-YD1. Information obtained from analyses for far- and near-field ground motions shows that the performance of this structural system is essentially the same or worse than that of the undamped frames. On the other hand, response of frame 3S75-YD2 in which the number of metallic yielding devices was doubled in comparison with 3S75-YD1, reveals improvement in structural system performance as seen by the reductions in drifts and plastic hinge rotations. However, this improvement in structural system performance was not accompanied by any reduction in secondary system response.

Despite the fact that the analyzed frames were not designed for near-field conditions, analyses were performed using near-field ground motions to provide evidence for the effect of damping systems on the response of non-structural components under substantial seismic loading. Tables 2 and 3 present the results for fault-normal and fault-parallel components of near-field ground motions. Results on story drifts and plastic hinge rotations for the fault-normal near-field motions indicate damage on the analyzed frames. However, even under significant inelastic action, the same benefits in terms of velocities, accelerations, and spectral floor accelerations with respect to secondary system response are obtained under these extreme conditions.

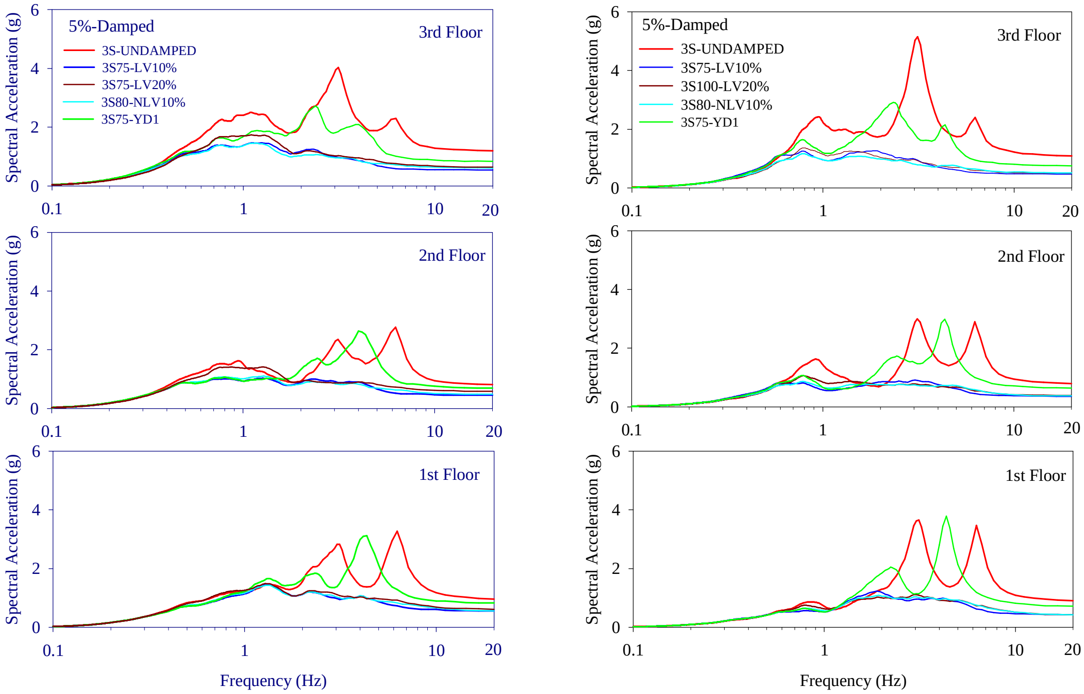
Figs. 5 and 6 present 5%-damped floor acceleration spectra of the analyzed frames with and without damping systems. The response spectra demonstrate the impact of the different damping systems on the response of flexibly-attached secondary systems. The floor acceleration spectra obtained from the analysis of the undamped frames declare the natural frequencies of the frames at the peaks of each plot. Particularly noticeable is the contribution from the fundamental frequency which is spread over a wider range of frequencies because of yielding. On the other hand, the natural frequencies of the damped structures (more flexible frames) are lower, shifting the peaks of the plots to the left.

A comparison of the response of the undamped and damped frames in the frequency range of 0.1 to 20 Hz, leads to the conclusion that substantial reductions in floor spectral acceleration can be achieved with the addition of linear and nonlinear viscous damping systems in the structure. The effectiveness of the fluid viscous dampers is especially pronounced for a wide range of frequencies (above 0.7 Hz), where reductions in the secondary system acceleration response by as large as 50% around the first natural frequency of the structure and as large as 75% around the second natural frequency, as compared with the undamped frame case, are observed. Importantly, the spectral acceleration response of the frames with viscous damping systems is ‘flattened’ for frequencies larger than the first natural frequency of the frame, since the higher modes are highly damped and effectively not excited.



(a) (b)

Figure 5. Floor response spectra of 3-story frames with and without damping systems for (a) far-field ground motions, and (b) soft-soil ground motions.



(a) (b)

Figure 6. Floor response spectra of 3-story frames with and without damping systems for (a) fault normal components, and (b) fault parallel components of near-field ground motions.

In contrast, the 3-story structure with metallic yielding devices, frames 3S75-YD1 and 3S75-YD2, behave in a different manner. These configurations shift the peaks of the floor acceleration spectra to smaller frequencies with all modes of vibration excited. It can be observed that reductions in the acceleration response is achieved for secondary systems around the first natural frequency of the frame, but this reduction is not as pronounced as for the viscous damped system. For larger frequencies the benefits are less definite or nonexistent. The system with metallic yielding devices appears as an undamped system with different stiffness characteristics and thus cannot produce a major change in the behavior.

The results presented for the other ground motion sets reveal similar behavior and benefits from the addition of damping devices to the frames. Moreover, it can be observed that in the case of the fault normal components of near-field ground motions (Fig. 6a) the contribution of the fundamental frequency is spread over a wider range of frequencies because of the substantial yielding due to the nature of the seismic motions.

Concluding Remarks

An analytical study aimed at investigating the use of damping systems as a means of passive protection for secondary systems was carried out. Moment-frame buildings with and without damping systems on stiff- and soft- soil sites as well as on sites with near-field characteristics were designed by the procedures described in 2000 NEHRP. Nonlinear response analyses were performed on the frames with various energy dissipation systems to investigate the dynamic response of secondary systems. The data obtained through nonlinear response analyses clearly demonstrate the passive protection offered to the secondary systems in buildings with damping systems designed in accordance with the 2000 NEHRP. Significant reduction of floor peak accelerations, floor total peak velocities, and floor spectral accelerations are more pronounced by the use of linear and nonlinear viscous damping devices. In contrast, yielding damping systems do not offer similar benefits.

With respect to the influence of damping systems on the performance of the structural frames, conclusions were drawn from the extent of damage these systems sustained. Details on plastic hinge formation and maximum plastic hinge rotation demonstrate that buildings designed with viscous damping systems to meet the minimum criteria of NEHRP 2000 perform, in terms of performance of the structural system, comparably to or better than buildings designed without damping systems. Moreover, damped frames with metallic yielding devices show a performance of the structural system which is marginally the same or worse than that of the undamped frames.

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