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SEISMIC ENERGY RESPONSE OF TEN-STORY STEEL ROCKING FRAMES WITH COLUMN MID-HEIGHT UPLIFT AT FIRST STORY

Mitsumasa MIDORIKAWA[1], Naoto KOTANI[2], Taichiro OKAZAKI[3], Tetsuhiro ASARI[4], Tadashi ISHIHARA[5], Tatsuya AZUHATA[6]

[1] Prof., Faculty of Eng., Hokkaido Univ., Dr. Eng.
Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan
midorim@eng.hokudai.ac.jp

[2] Graduate Student of Hokkaido Univ.
Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan
kotani.naoto@frontier.hokudai.ac.jp

[3] Assoc. Prof., Faculty of Eng., Hokkaido Univ., Ph. D.
Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan
tokazaki@eng.hokudai.ac.jp

[4] Asst. Prof., Faculty of Eng., Hokkaido Univ., Dr. Eng.
Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan
asari@eng.hokudai.ac.jp

[5] Senior Research Engineer, Building Research Institute, Dr. Eng..
1, Tachihara, Tsukuba, Ibaraki, 305-0802 Japan
tishihar@kenken.go.jp

[6] Chief Research Engineer, Building Research Institute, Ph. D.
1, Tachihara, Tsukuba, Ibaraki, 305-0802 Japan
azuhata@kenken.go.jp

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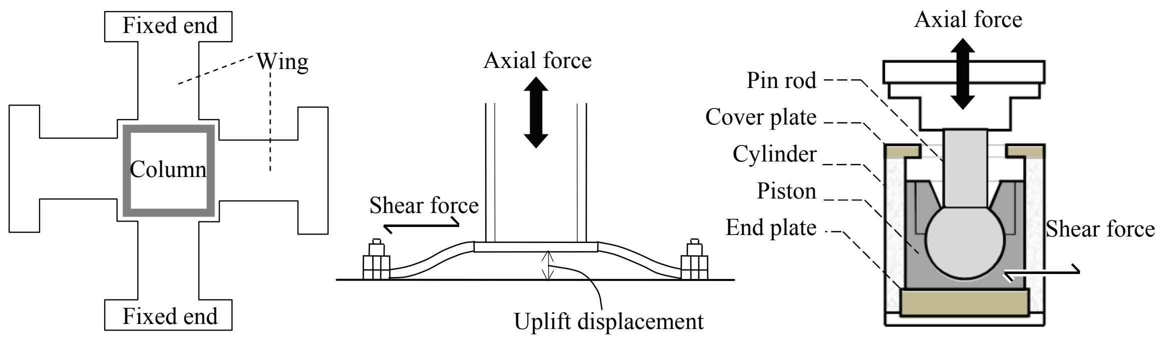
Abstract. *Lessons learned from past earthquake damage suggest the potential benefit of rocking systems that reduce earthquake damage. This paper evaluates a structural system that achieves a rocking mechanism by permitting uplift at the mid-height of the first-story columns (CMU system). Steel dampers installed in these columns dissipate the seismic energy and reduce deformation. Suggested system is compared with corresponding ordinary frame without rocking mechanism (Fixed system) in the view of energy response. For the ground motions examined in this study, the seismic energy input to the CMU system was 0.6 to 2.2 times that to the Fixed system, while the energy dissipated by the steel system was significantly smaller (0 to 57%) in the CMU system than in the Fixed system.*

1 INTRODUCTION

Observations from past earthquakes suggest that some buildings survived severe ground motion because of accidental uplift at their foundation [1, 2]. Motivated by such notion [3], the writers initially developed rocking systems that are provided with a mechanism that permit column-base uplift (CBU) [4]. The CBU system was achieved by placing the devices shown in Fig. 1a-b at the base of the columns. In this system, the column base is connected to the foundation through wing plates. The wing plates are designed to yield and dissipate energy when the column uplifts, while fully transferring the shear forces. The stable and reliable performance of this system has been demonstrated by large-scale shake table tests [4].

While CBU rocking systems can reduce seismic damage, the systems increase the likelyhood of damage in second-floor beams compared to fixed-base systems. Consequently, the writers propose an alternative rocking frame that allows uplift at the middle of the columns instead of the column bases. The column mid-height uplift (CMU) mechanism fully resists shear forces and is generally accompanied by steel dampers. Fig. 1(c) shows a CMU system accompanied with steel dampers that has been validated by cyclic loading tests [5]. The ball in the piston is free to rotate, and the piston can slide upwards. Shear forces are transferred fully by the piston bearing against the cylinder. Conceptually, the CMU rocking system can reduce story drift of the first story compared to the CBU system because the CMU system forces double-curvature bending of the first-story columns while the CBU system forces single-curvature bending [6]. In fact, an earlier study by the authors [5] suggests that the first-story drift will not be increased by the addition of CMU systems.

This paper describes a computational study of the CMU system. The potential benefit of the CMU system is examined through seismic input energy and energy dissipation. A series of nonlinear time history analyses was conducted on a ten-story steel building equipped with a CMU system [7]. For comparison, the analyses were repeated for cases where (a) steel damper was removed (denoted as CMU-ND) and where (b) the first-story columns were continuous and fixed to the foundation (denoted as Fixed).



(a) CBU mechanism (Plan) (b) CBU mechanism (Elevation) (c) CMU mechanism

Figure. 1 Uplift mechanism

2 ANALYSIS PROCEDURE

The seismic performance of buildings equipped with CMU systems is examined by nonlinear time history analysis. A commercial software [8] was used for the study. As shown in Fig. 2, the model was a single bay, ten-story frame representing the Y-3 elevation of a prototype steel building. A concentrated mass of 288 kN was placed at each beam-column node.

Concentrated plastic hinges were placed at both ends of each beam or column. The moment versus rotation relationship of the plastic hinge was defined by a trilinear curve capturing the yield moment and plastic moment. The steel system was proportioned according to the seismic code of Japan and the weak beam-strong column rule. The section, yield moment and plastic moment of each beam and column is shown in Table 1. The yield strength of steel is assumed to be 294 N/mm^2.

The CMU system was modeled using (a) a contact element that permits elongation but is does not contract, (b) a linear shear element, and (c) a bilinear element that models the steel dampers (see Fig. 3). The shear element had the same shear stiffness as the column over a length of 50 mm. In compression, the contact element had 10 times the axial stiffness of the column over the entire length. The bilinear element was fitted to experimental data: The initial stiffness was 10% the axial stiffness of the column (= 2.2×10^5 kN/m), the yield strength was 30% of the gravity load in the column (= 431 kN), and the post-yield stiffness was 3 and 1%,

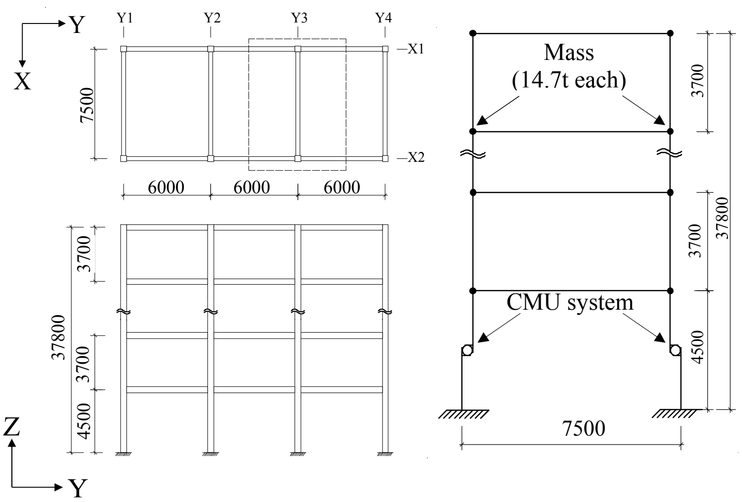
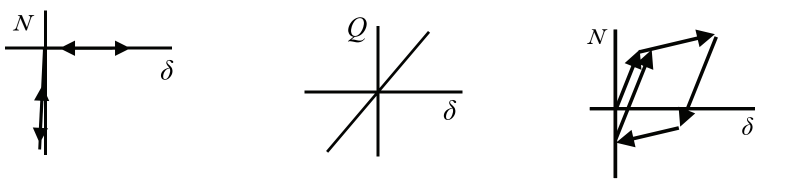


Figure 2 Analytical model

Table 1 Member sections

	Member section	Yield moment	Plastic moment
1-7F Column	□-500×500×25	2110 kN.m	2490 kN.m
8-10F Column	□-500×500×19	1660 kN.m	1940 kN.m
2-6F Beam	H-700×300×13×24	1630 kN.m	1840 kN.m
7-RF Beam	H-588×300×12×20	1130 kN.m	1270 kN.m



(a) Contact element (b) Shear element (c) Bilinear element

Figure 3. Elements comprising the CMU system

respectively, of the initial stiffness in the tension side and compression side. The building model equipped with this CMU system is referred to as the CMU model.

For comparison, analysis was repeated for two other cases: the bilinear element removed (CMU-ND model); and the first-story columns modeled with a continuous element with no CMU system (Fixed model). The first natural vibration period of the Fixed model (T_1) and CMU model (T_u) was computed as 1.34 s and 2.47 s, respectively. The first natural period of the CMU model was estimated using a model where, in one column, the CMU is replaced by a hinge and in the other column, the bilinear element is replaced by a linear element whose stiffness equaled the secant stiffness of the steel damper at an uplift rotation angle of 1/200.

Damping was proportional to the initial stiffness of the Fixed model with a damping ratio h=0.02. Viscous damping of the contact element and bilinear element were set to zero.

The model was subjected to four recorded ground motions listed in Table 2, each scaled to a peak ground velocity (PGV) of 0.5, 0.75, 1.0, and 1.25 m/s, resulting in a total of 16 analysis cases. Fig. 4 shows the energy spectrum for the four motions computed for damping ratio h = 0.1, while Fig. 5 shows the pseudo-velocity spectrum for damping ratio h = 0.05. A previous study by the authors [7] indicate that the vertical ground motion has minimal effect on the lateral response of structures with CBU systems. The same is believed to apply to CMU systems.

Table 2 Unscaled ground motions

Earthquake	Station	Analysis time	Direction	PGA (m/s^2)	PGV (m/s)
1994, Northridge	Tarzana	15 s	EW	17.4	1.14
1995, Hyogo-Ken Nanbu	JMA-Kobe	15 s	NS	8.18	0.91
2000, Tottori-Ken Seibu	Hino	21 s	NS	9.18	1.28
2004, Nigata-Ken Chuetsu	Yamakoshi	31 s	EW	7.22	0.87

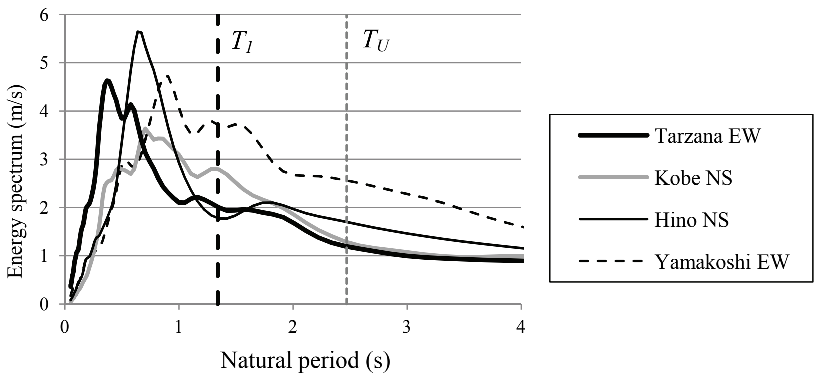


Figure.4: Energy spectra (h = 0.1)

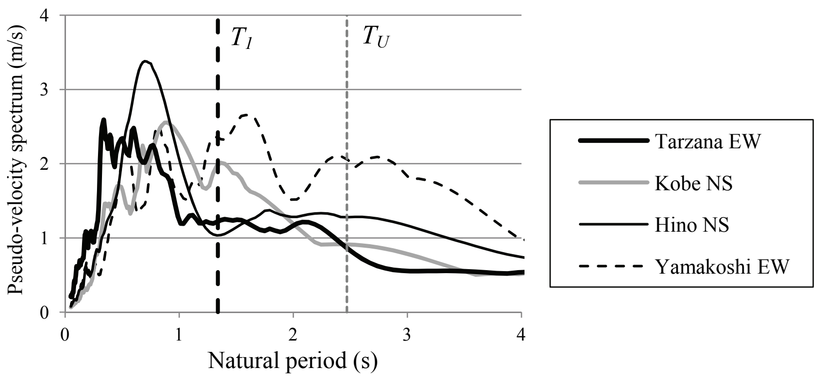


Figure 5: Pseudo-velocity spectra (h = 0.05)

3 ANALYSIS RESULTS

Fig. 6 shows the time history of the relative roof drift computed for ground motions scaled to a PGV of 1.0 m/s. In this paper, the relative roof drift refers to the roof drift minus the drift caused by rocking, i.e., the rigid body component associated with column uplift. The figure suggests that permission of column uplift resulted in reduction in shear deformation and elongation in response period. The response period was longer in the CMU-ND model than the CMU model. Fig. 7 plots the maximum roof drift and maximum relative roof drift obtained from each ground motion and for each PGV. The CMU and CMU-ND model recorded a larger roof drift than the Fixed model in 14 out of the 16 analysis cases. The maximum roof drift tended to be somewhat smaller in the CMU model than in the CMU-ND system: the presence of dampers reduced the maximum roof drift in 12 out of the 16 analysis cases. On the other hand, for all analysis cases, the CMU and CMU-ND models recorded a 1 to 60% reduction in relative roof drift compared to the Fixed model. The CMU system, with or without dampers, was more effective for ground motions Yamakoshi and Kobe, whose predominant period was close to the natural period of the structure, T_1 = 1.34 s, than for the other two motions.

Fig. 8 and 9 show the time history of column uplift displacement of the CMU and CMU-ND models, respectively, computed for ground motions scaled to a PGV of 1.0 m/s. The figures indicate that the presence of steel dampers reduced uplift displacement and mitigated high vibration modes. The ratio of maximum uplift displacement between the CMU model and CMU-ND model was 65, 60, 49 and 37%, respectively, for the Tarzana, Kobe, Hino and Yamakoshi record.

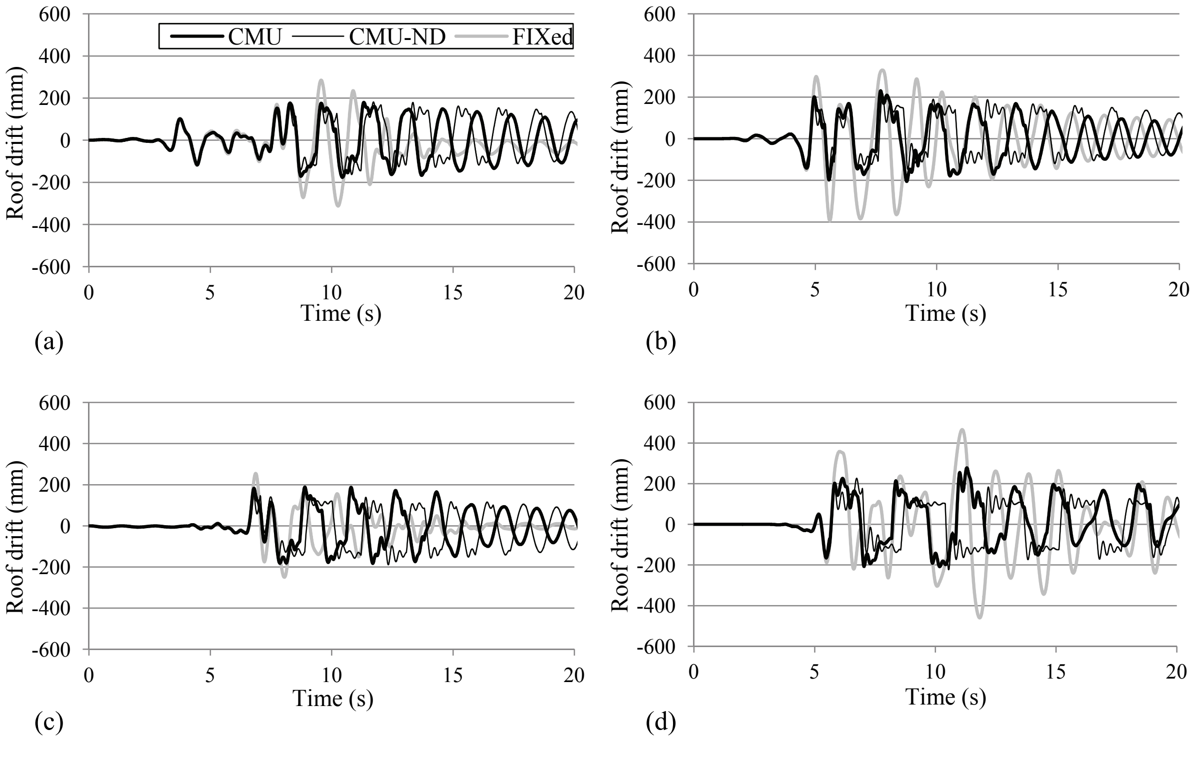


Figure 6: Time histories of relative roof drift: (a) Tarzana; (b) Kobe; (c) Hino; and (d) Yamakoshi record

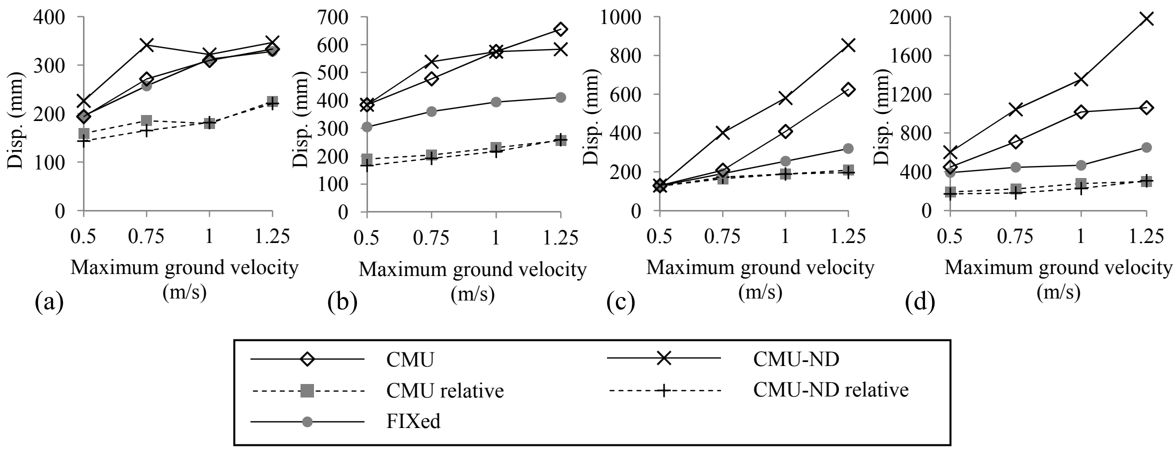


Figure 7: Maximum roof drift and relative roof drift:
(a) Tarzana; (b) Kobe; (c) Hino; and (d) Yamakoshi record;

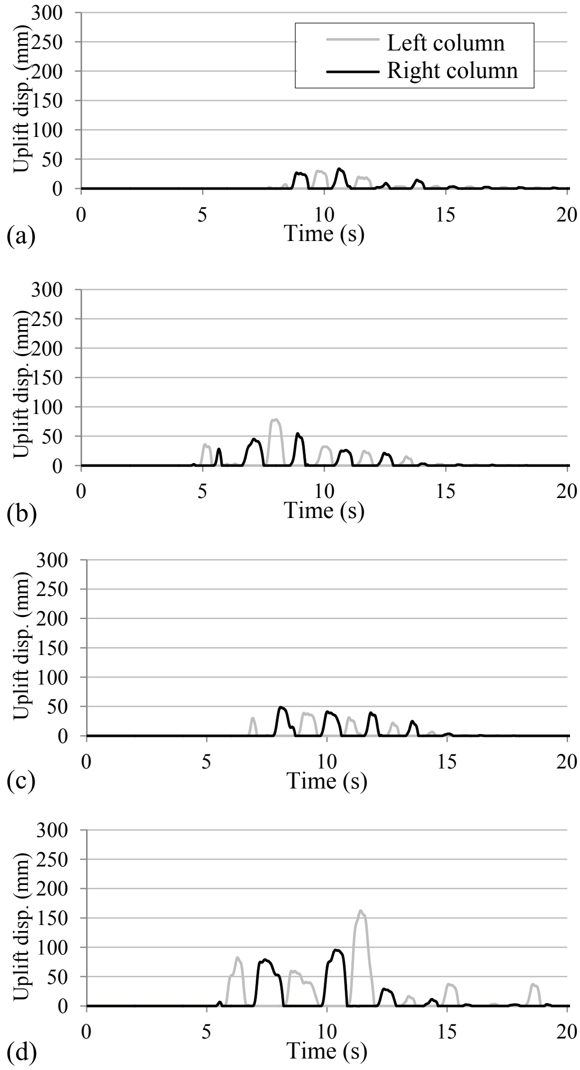


Figure 8: Time histories of column uplift displacement in CMU model: (a) Tarzana; (b) Kobe; (c) Hino; and Yamakoshi record.

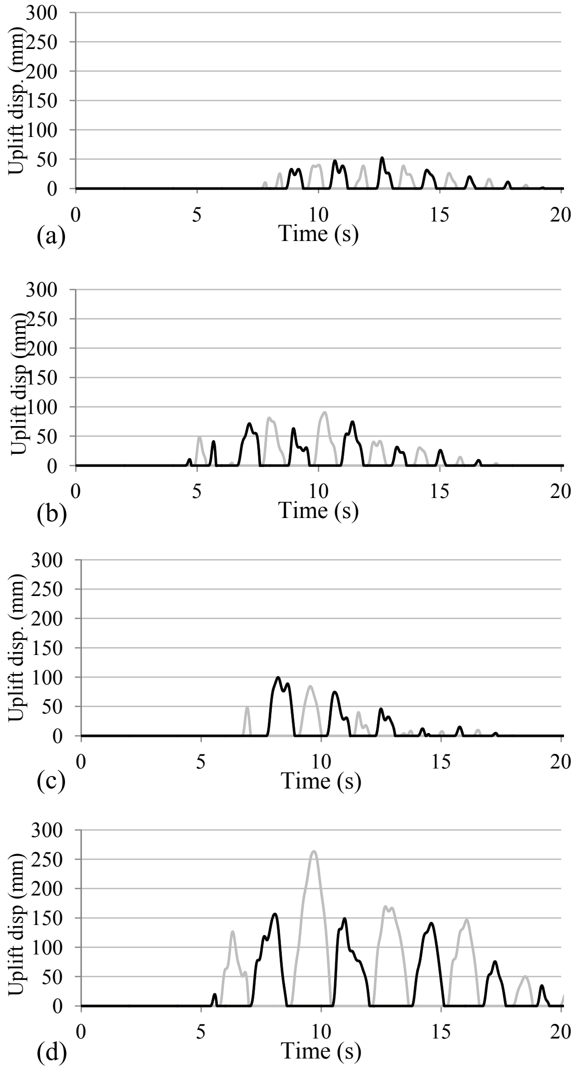


Figure 9: Time histories of column uplift displacement in CMU-ND model: (a) Tarzana; (b) Kobe; (c) Hino; and (d) Yamakoshi record.

4 DISCUSSION BASED ON ENERGY

The dynamic motion of a building structure subject to horizontal earthquake ground motion satisfies the balance of energy expressed by Eq. (1).

$$\sum \int_0^t F_e \dot{x} dt = \left(\sum \frac{1}{2} M\dot{y}^2 + \sum \frac{1}{2} M\dot{x}^2\right) + \sum C \int_0^t \dot{x}^2 dt + \sum Mgy + \sum \int_0^t F(x')\dot{x}' dt + \sum \int_0^t D(y')\dot{y}' dt \qquad (1)$$

Where, x: horizontal displacement of the mass relative to the ground, y: vertical displacement of the mass relative to the ground, F_e:seismic load (= $-M\ddot{z}_0$), $\ddot{z}_0$: horizontal ground acceleration, M: mass, C: damping coefficient, g: gravitational acceleration, $F(x')$: restoring force of a member, x': deformation of a member, $D(y')$: restoring force of a steel damper, and y': deformation of a steel damper. Summation is performed over all masses and all elements that comprise the structure.

Eq. (1) may be expressed in a compacted form as Eq. (2).

$$E_I = (E_{LK} + E_{VK}) + E_d + E_p + (E_s + E_h) \qquad (2)$$

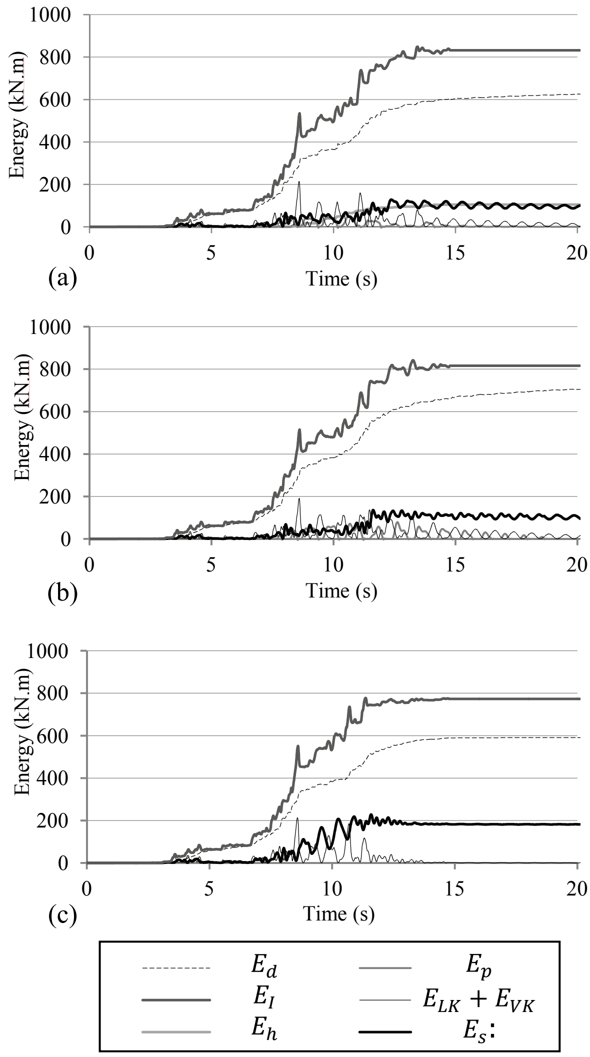


Figure 10: Energy response computed for Tarzana record; (a) CMU; (b) CMU-ND; and (c) Fixed model.

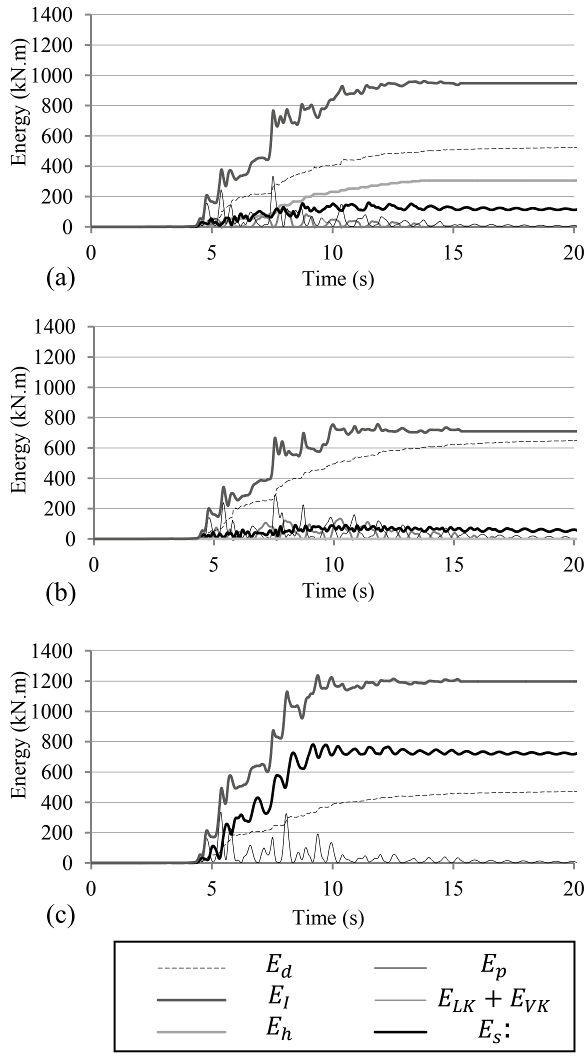


Figure 11: Energy response computed for Kobe record; (a) CMU; (b) CMU-ND; and (c) Fixed model.

Where, E_I: lateral input energy, E_{LK}: kinetic energy due to horizontal vibration, E_{VK}: kinetic energy due to uplift motion, E_d: energy dissipated by damping, E_p: potential energy associated with uplift, E_s: energy dissipated by the structure, and E_h: energy dissipated by the steel dampers.

Figs. 10 to 13 show the time history of energy response of the CMU, CMU-ND, and Fixed model, respectively, computed for ground motions scaled to a PGV of 1.0 m/s. For the Kobe and Yamakoshi records, the energy dissipated in the structure was one-fifth in the CMU and CMU-ND models compared to the Fixed model. These are the two records for which the CMU system effectively reduced the relative roof drift (see Fig. 6 and 7). For the Tarzana record, the energy dissipated in the structure was one-half in the CMU and CMU-ND models compared to the Fixed model. On the other hand, for the Hino record, the CMU-ND model dissipated double the energy in the structure compared to the Fixed model. These results suggest that, while the CMU system can be beneficial against many ground motions, there is a range of ground motions against which there may be no benefit.

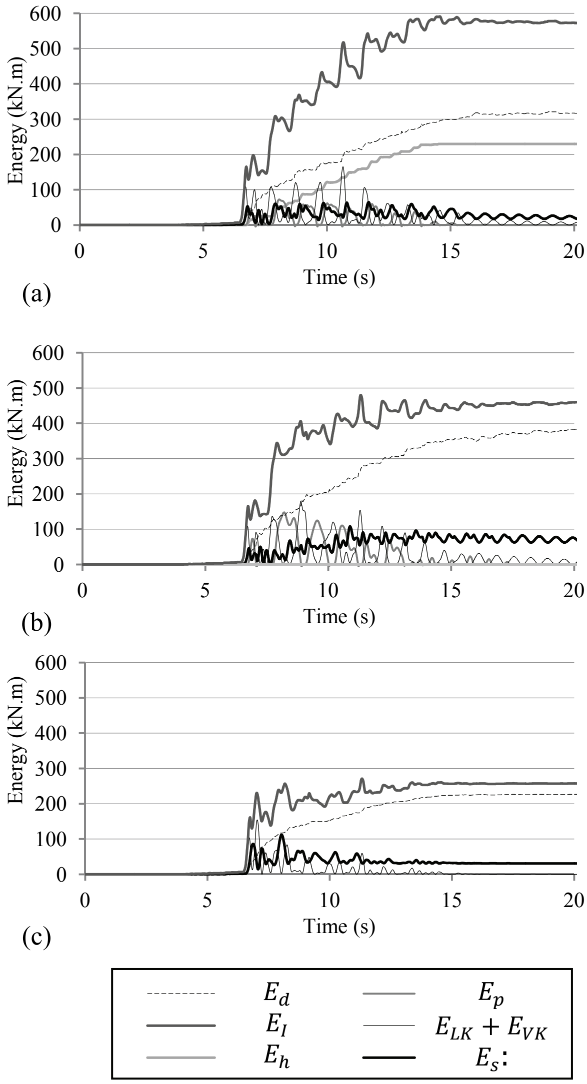


Figure 12: Energy response computed for Hino record; (a) CMU; (b) CMU-ND; and (c) Fixed model.

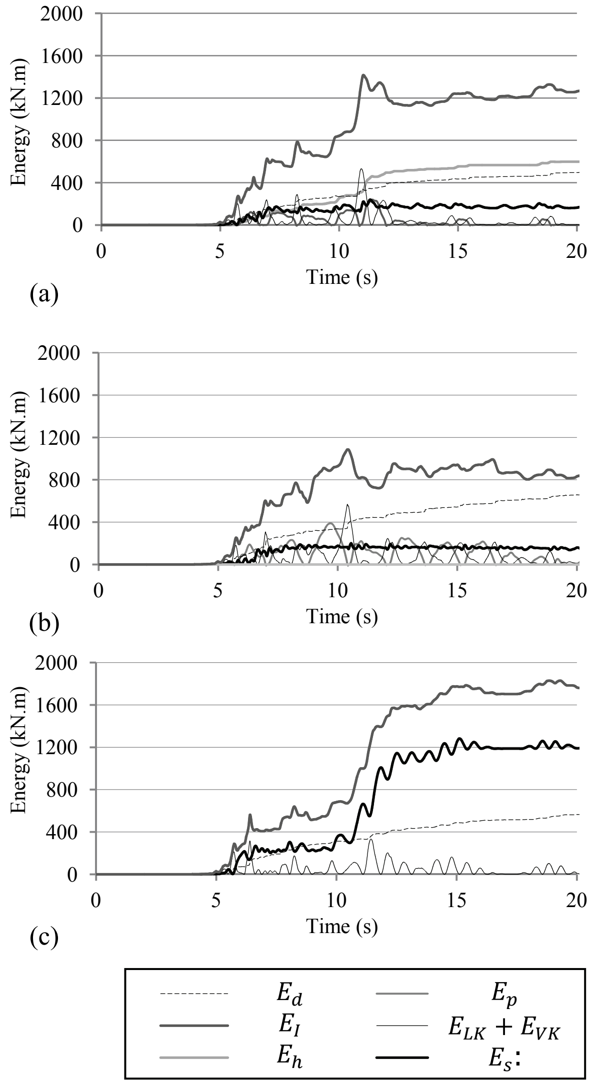


Figure 13: Energy response computed for Yamakoshi record; (a) CMU; (b) CMU-ND; and (c) Fixed model.

Table 3 lists the ratio E_h/E_I, the proportion of input energy that was dissipated by the steel dampers in the CMU model. The steel damper dissipated a substantial portion, up to 47%, of the input energy.

Tables 4 and 5 show the proportion of CMU system to CMU-ND in the input energy and the value of energy dissipated by the steel system of CMU system divided by that of CMU system respectively. For the same ground motion, the seismic energy input to the CMU system was 0.6 to 2.2 times that to the Fixed system. Nonetheless, as shown in Table 5, for the ground motions examined in this study, the energy dissipated by the steel system was significantly smaller (0 to 57 %) in the CMU system than in the Fixed system.

5 CONCLUSIONS

A series of nonlinear time history analyses was conducted on models of a ten-story steel building. One model had column mid-height-uplift (CMU) systems, equipped with dampers, placed in the first-story columns (CMU model). The second model had CMU systems with no dampers (CMU-ND model). The third model was an ordinal frame with no CMU system (Fixed model). The models were subjected to four recorded ground motions, each scaled to a maximum ground velocity of 0.5, 0.75, 1.0, and 1.25 m/s. The following are the findings from the analysis results:

- For the same ground motion, the seismic energy input to the CMU system was 0.6 to 2.2 times that to the FIX system. Nonetheless, for the ground motions examined in this study, the energy dissipated by the steel system was significantly smaller (0 to 57 %) in the CMU system than in the FIX system.
- Little difference was observed between the CMU system and CMU-ND system in terms of energy dissipation. However, the maximum roof drift in the CMU system was 50 to 110 % that in the CMU-ND system. The damper reduced the maximum roof drift in 12 out of the 16 analysis cases.

Table 3: E_h/E_I, the proportion of energy dissipated by steel dampers

maximum ground velocity	Tarzana	Kobe	Hino	Yamakoshi
0.5m/s	5%	30%	0%	34%
0.75m/s	16%	31%	11%	38%
1.0m/s	13%	32%	40%	47%
1.25m/s	13%	37%	45%	41%

Table 4: E_I computed for the CMU model divided by E_I computed for the CMU-ND model.

maximum ground velocity	Tarzana	Kobe	Hino	Yamakoshi
0.5 m/s	93 %	73 %	104 %	78 %
0.75 m/s	115 %	76 %	133 %	78 %
1.0 m/s	108 %	79 %	224 %	78 %
1.25 m/s	81 %	61 %	131 %	71 %

Table 5: E_S computed for the CMU model divided by E_S computed for the CMU-ND model.

maximum ground velocity	Tarzana	Kobe	Hino	Yamakoshi
0.5 m/s	3 %	14 %	100 %	2 %
0.75 m/s	32 %	13 %	35 %	8 %
1.0 m/s	48 %	16 %	57 %	14 %
1.25 m/s	56 %	19 %	47 %	17 %

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