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Seismic Energy Response of Multi-story Steel Rocking Frames Allowing Column Mid-height Uplift at the First Story

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Abstract

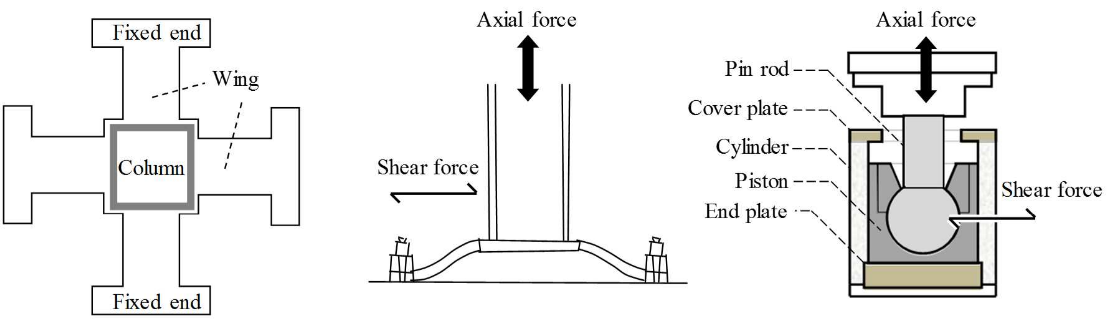
Observations from past earthquakes suggest that some buildings survived severe ground motion because of accidental uplift at their foundation. Such notion has motivated the development of rocking systems that permit some portion of the structure to uplift and rotate about a pivot. In this paper, the writers propose a rocking frame that allows uplift at the middle of the columns. The column mid-height uplift (CMU) mechanism fully resists shear forces and is generally accompanied by steel dampers. A series of nonlinear time history analyses was conducted on a model of a four, six and ten-story steel buildings equipped with CMU mechanisms. The CMU mechanisms was modeled using (1) a contact element (that permits uplift but resists compression), (2) a linear shear element, and (3) a bilinear element (that models steel dampers). The models were subjected to seventeen recorded ground motions, each scaled to a maximum ground velocity of 1.0 and 1.25 m/s. For comparison, the analyses were repeated for models where the bilinear elements were removed (CMU-ND model), and models where the first-story columns were continuous with no contact element (MF model). The results are summarized as follows: (1) Little difference was observed between the CMU model and MF model in terms of maximum roof acceleration. (2) Maximum roof drift was significantly smaller in the CMU model than in the CMU-ND model, especially if structure have high aspect ratio. (3) Energy dissipated by the steel system was significantly smaller in the CMU model than in the MF model.

Keywords: Rocking frame, Colum mid-height uplift, Steel damper, Earthquake energy response

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 mechanism was achieved by placing the devices shown in Fig. 1(a) and (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 likelihood of damage in second-floor beams compared to fixed-base systems. Consequently, the writers propose an alternative rocking system 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 mechanism 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 is free to 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 mechanisms.

This paper describes a computational study of the CMU system. The potential benefit of the CMU system is examined through roof drift, seismic input energy and energy dissipation. A series of nonlinear time-history analyses were conducted on a four, six and ten-story steel buildings (a) equipped with CMU mechanisms [7]. For comparison, the analyses were repeated for (b) buildings with CMU mechanisms but with no steel dampers (denoted as CMU-ND) and (c) buildings whose first-story columns were continuous and fixed to the foundation (denoted as MF).



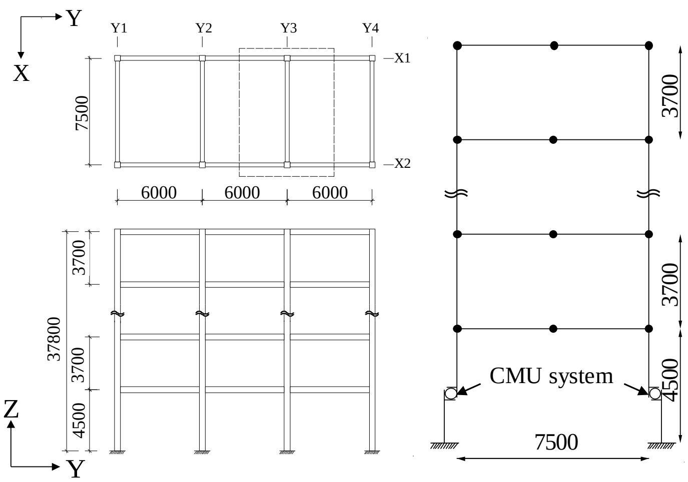
(a) CBU mechanism (Plan) (b) CBU mechanism (Elevation) (c) CMU mechanism

Fig. 1 – Uplift mechanism

2. Analysis Procedure

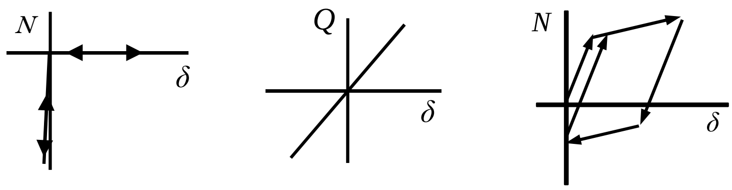
The seismic performance of buildings equipped with CMU mechanisms was examined by non-linear time-history analyses. A commercial software MIDAS [8] was used for the study. As shown in Fig. 2, the single-bay, four, six or ten-story frame represented the Y-3 elevation of a prototype steel building. A concentrated mass of 7.33 t was placed at each beam-column node and a mass of 14.7 t was placed in the middle of each beam. The steel systems were proportioned according to the seismic code of Japan and the weak beam-strong column rule. 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 yield strength of steel was assumed to be 294 N/mm^2.

The CMU mechanism was modeled using (a) a contact element that can elongate but 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 150 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% of the axial stiffness of the column, the yield strength was 30% of the gravity load supported by the column, and the post-yield stiffness was 3 and 1% of the initial stiffness in the tension side and compression side, respectively. The building model equipped with such CMU mechanisms is referred to as the CMU model. For comparison, analysis was repeated for three other models: identical to the CMU model except that the bilinear elements were removed (CMU-ND model); the first-story columns modeled with a continuous element with no CMU mechanisms (MF model); and internal hinges placed in the middle of the first-story columns (CMP model).



10-story model	
8-10F Column	□-500×500×19
1-7F Colum	□-500×500×25
7-RF Beam	H-588×300×12×20
2-6F Beam	H-700×300×13×24
6-story model	
4-6F Column	□-500×500×19
1-3F Column	□-500×500×25
3-RF Beam	H-588×300×12×20
2F Beam	H-700×300×13×24
4-story model	
2-4F Column	□-500×500×19
1F Column	□-500×500×25
Beam	H-588×300×12×20

Fig. 2 – Analytical model



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

Fig. 3 – Elements comprising the CMU system

Damping was proportional to the initial stiffness of the MF model with a damping ratio h=0.02. Viscous damping coefficient of the contact element and bilinear element were set to zero. The model was subjected to 17 recorded ground motions listed in Table 1, each scaled to a peak ground velocity (PGV) of 1.0 and 1.25 m/s. The horizontal components of the ground motion were compounded in the direction that maximizes the peak ground velocity (PGV). A previous study by the authors [7] indicates 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 1 – ground motion

Year	Event	Station
1966	Parkfield	Temblor pre-1969
1968	Tokachi	Hachinohe
1978	Miyagi	Touhoku
1979	Imperial Valley-06	El Centro Array #7
1979	Imperial Valley-06	Aeropuerto Mexicali
1980	Mammoth Lakes-01	Convict Creek
1980	Mammoth Lakes-01	Long Valley Dam
1984	Morgan Hill	Gilroy Array #2
1986	Palm Springs	Morongo Valley
1987	Superstition Hills-01	Wildlife Liquefaction Array
1989	Loma Prieta	Capitola
1994	Northridge-01	Tarzana - Cedar Hill A
1994	Northridge-01	Santa Monica City Hall
1995	Kobe, Japan	JMA Kobe
1999	Chi-Chi, Taiwan-03	CHY028
2000	Tottori, Japan	TTRH02
2004	Niigata-ken Chuetsu-oki	Yamakoshi

3. Analysis Results

The natural vibration period of MF, CMP, and CMU-ND model is shown in Table 2. The natural period of CMU-ND models was estimated using models that a placed hinge instead of CMU mechanism in one of the first-story columns.

Figs. 4 and 5 plot the time history of roof drift and relative roof drift, respectively, for the 10-story models for the JMA Kobe motion 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 plotted responses suggest how rocking motion, or the permission of column uplift, may reduce shear deformation and elongate response period. The response period of the CMU-ND model was longer than that of the CMU model because the steel dampers added stiffness to the latter model.

Table 2 – natural vibration period (sec)

	MF model			CMP model			CMU-ND model		
	1st mode	2nd mode	3rd mode	1st mode	2nd mode	3rd mode	1st mode	2nd mode	3rd mode
10 story	1.358	0.464	0.249	1.371	0.468	0.250	-	0.476	0.291
6 story	0.867	0.271	0.145	0.881	0.274	0.145		0.322	0.255
4 story	0.601	0.177	0.089	0.650	0.182	0.107		0.309	0.174

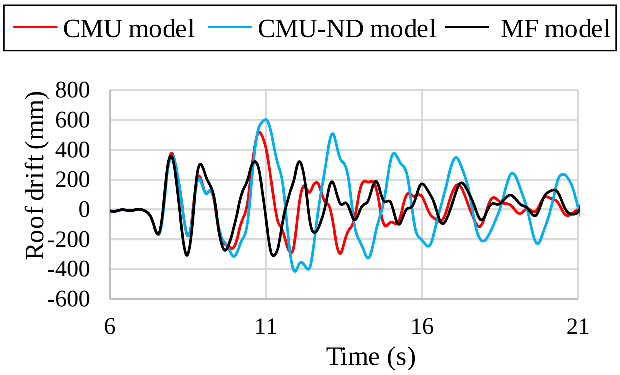


Fig. 4 – time history of roof drift (Kobe)

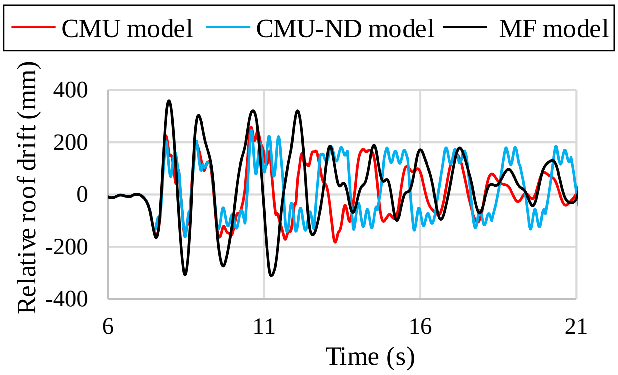
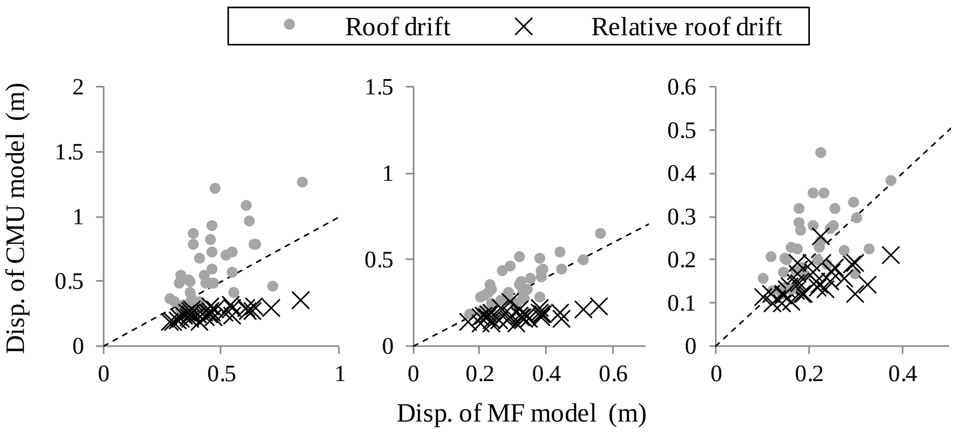


Fig. 5 – time history of relative roof drift (Kobe)

Fig. 6 compares the maximum roof drift and maximum relative roof drift recorded by the CMU models and MF models for all analysis cases (combination of story height and ground motions). The CMU model recorded a larger roof drift than the MF model in 77 out of 102 analysis cases. On the other hand, the CMU model recorded a smaller relative roof drift than the MF model in 98 out of 102 analysis cases.

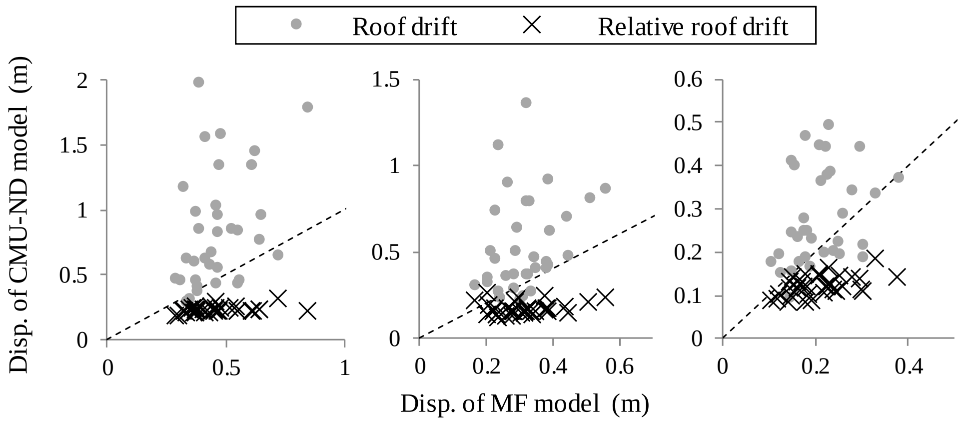
Fig. 7 compares the maximum roof drift and maximum relative roof drift recorded by the CMU-ND models and MF models for all analysis cases. Similar to the CMU models, the CMU-ND models benefitted from rocking motion, i.e., column-midheight uplift. Comparison between Fig. 6 and 7 indicate that the steel dampers are beneficial in reducing roof drift.

Fig. 8 compares the maximum roof acceleration recorded by the CMU models and MF models for all analysis cases. No significant variation in roof acceleration can be identified.



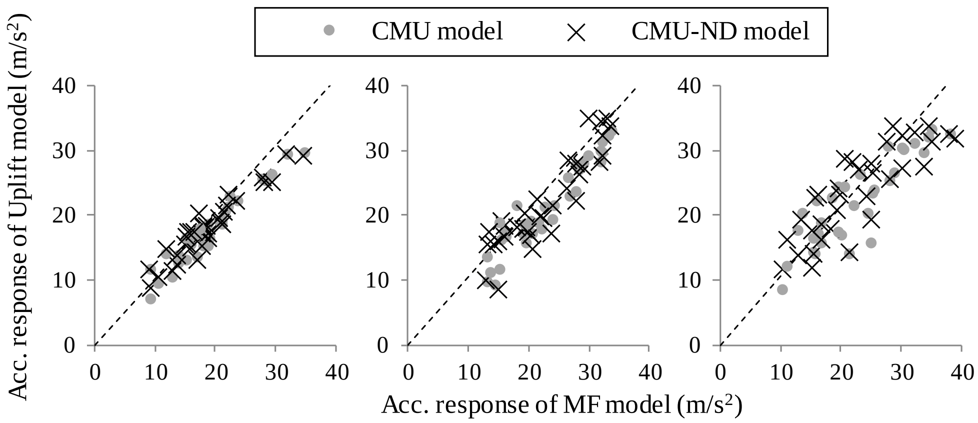
(a) 10-story (b) 6-story (c) 4-story

Fig. 6 – Comparison between CMU model and MF model by roof drift



(a) 10-story (b) 6-story (c) 4-story

Fig. 7 – Comparison between CMU-ND model and MF model by roof drift



(a) 10-story (b) 6-story (c) 4-story

Fig. 8 – Comparison between MF model and Uplift model by roof acceleration

4. Discussion Based on Energy Response

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

$$\sum\int_0^t F_e\dot{x}dt = \left(\sum\frac{1}{2}M\dot{y}^2+\sum\frac{1}{2}M\dot{x}^2\right)+\sum C\int_0^t \dot{x}^2dt+\sum Mgy+\sum\int_0^t F(x)\dot{x}dt+\sum\int_0^t D(x)\dot{y}dt \qquad (1)$$

In the above equation, x is the horizontal displacement of the mass relative to the ground, y is the vertical displacement of the mass relative to the ground, F_e is the seismic load ($= M\ddot{z}_0$), $\ddot{z}_0$ is the horizontal ground acceleration, M is mass, C is the damping coefficient, g is gravitational acceleration, $F(x)$ is the restoring force of a member, and $D(x)$ is the restoring force of a steel damper. Summation is performed over all masses and all elements that comprise the structure. Eq. (2) is a compact expression of Eq. (1).

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

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

Figs. 9 and plots the time history of each energy component of the CMU and MF model, respectively, computed for the JMA Kobe motion scaled to a PGV of 1.0 m/s. The column mid-height uplift in the CMU system effectively reduces the energy dissipated in the structure (E_s).

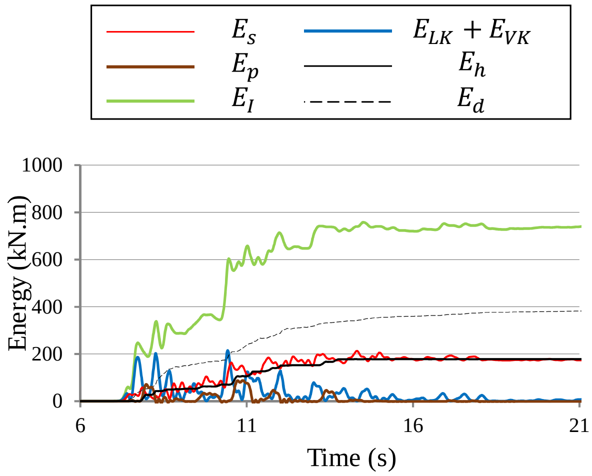


Fig. 9 – Energy response computed for Kobe record (CMU model)

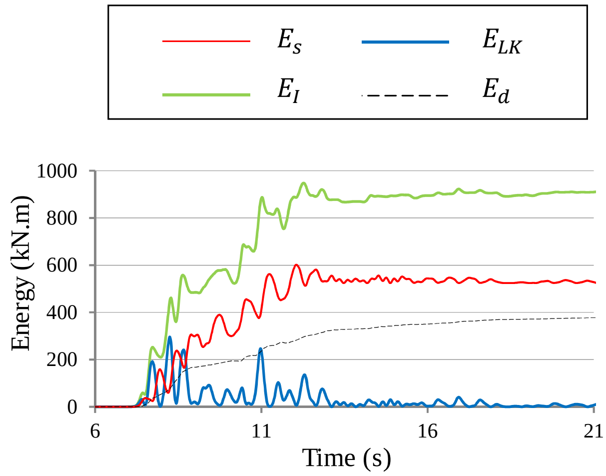


Fig. 10 – Energy response computed for Kobe record (MF model)

Fig. 11 compares the energy dissipated by the structure (E_s) in the CMU model, CMU-ND model and MF model. In 95 out of 102 analysis cases, CMU and CMU-ND models recorded smaller E_s compared the MF model. Even in analysis cases where the MF model recorded very large E_s, the CMU and CMU-ND models recorded small E_s.

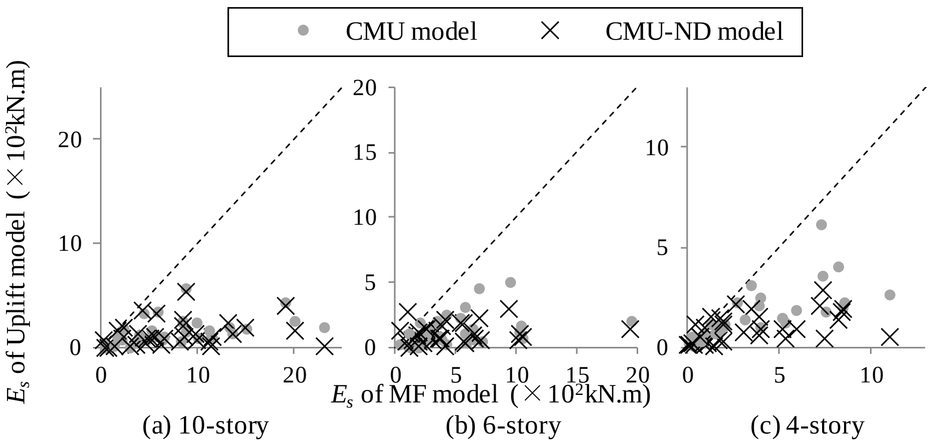


Fig. 11 – Comparison between MF model and Uplift model by E_s

5. Conclusions

A series of nonlinear time history analyses were conducted on models of 4, 6, and 10-story steel buildings. Three systems were compared: A system with column mid-height-uplift (CMU) mechanisms and dampers in the first-story columns (CMU model); a system with CMU mechanisms, but no dampers, in the first-story columns (CMU-ND model), and a system with continuous first-story columns (MF model). The models were subjected to 17 recorded ground motions, each scaled to a maximum ground velocity of 1.0 and 1.25 m/s. The primary the findings from the analysis results are listed below:

[1] Relative roof drift (roof drift minus drift caused by rocking motion) was significantly smaller in the CMU system and CMU-ND system than in the MF system.

[2] Roof drift was significantly smaller in the CMU system than in the CMU-ND system, especially if structure have high aspect ratio.

[3] Little difference was observed between the CMU system and MF system in terms of maximum roof acceleration.

[4] Energy dissipated by the steel system was significantly smaller in the CMU system than in the MF system.

6. Acknowledgment

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