Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 385

THREE-DIMENSIONAL SHAKING TABLE TESTS ON THREE-STORY REDUCED-SCALE STEEL ROCKING FRAMES

M. Midorikawa[1], T. Ishihara[2], T. Azuhata[3], S. Takai[4], M. Kanagawa[5], H. Hori[6], T. Kusakari[7] and T. Asari[8]

ABSTRACT

The seismic response of three-story, one-by-two bay, one-third-scale steel rocking frames with column-bases allowed to uplift is evaluated and compared with that of fixed-base frames by three-dimensional shaking table tests. Four wings of a specially designed flexing base plate yielding due to tension of a column are installed at the bottom of each column of the first story in the rocking frames. The test structures were retested using four different frame conditions: uplift- and fixed-base frames; and, non-eccentric and eccentric frames in plan. They are vibrated in three different input-motion conditions; one horizontal, two horizontal and three components of the JMA Kobe record of the 1995 Kobe earthquake. It is shown that the maximum base shears and response deformation of the uplift rocking frames are effectively reduced from those of the fixed-base frames in both horizontal directions.

Introduction

It has been pointed out by past studies (Housner 1963; Rutenberg et al. 1982; Hayashi et al. 1999) that the effects of rocking vibration accompanied with uplift motion might reduce the seismic damage to buildings subjected to strong earthquake ground motions. The influence of uplift motion on the seismic behavior of building structures has been reasonably explained through the simple analysis (Meek 1975, 1978) followed by other studies (Chopra and Yim 1985; Yim and Chopra 1985; Oliveto et al. 2003; Wada et al. 2005; Ishihara et al. 2009).

Based on these studies, structural systems have been studied and developed which allow the rocking and uplift motion under proper control during strong earthquake motions (Clough and Huckelbridge 1977; Huckelbridge 1977; Kasai et al. 2001; Iwashita et al. 2002; Midorikawa et al.

[1]Professor, Graduate School of Engineering, Hokkaido Univ., Sapporo, 060-8628 Japan
[2]Senior Researcher, National Institute for Land and Infrastructure Management, MLIT, Tsukuba, 305-0802 Japan
[3]Division Head, National Institute for Land and Infrastructure Management, MLIT, Tsukuba, 305-0802 Japan
[4]Vice Director, Technical Research Institute, Nishimatsu Corp., Aikawa, Kanagawa, 246-0303 Japan
[5]Chief Engineer, Technical Research Institute, Nishimatsu Corp., Yamato, 242-8520 Japan
[6]Kajima Corp. (Former Graduate Student of Hokkaido Univ.), Tokyo, 107-8477 Japan
[7]Graduate Student, Graduate School of Engineering, Hokkaido Univ., Sapporo, 060-8628 Japan
[8]Assistant Professor, Graduate School of Engineering, Hokkaido Univ., Sapporo, 060-8628 Japan

2003, 2006). One of the features of an uplift rocking system is that the maximum strain energy associated with the structural deformation of the superstructure is reduced, because a portion of the total earthquake input energy exerted to the structural system is substituted by the potential and kinetic energy associated with the vertical motion of the structural system as shown in the previous work (Iwashita et al. 2003; Azuhata et al. 2004).

An uplift rocking system under research and development by the authors (Midorikawa et al. 2003, 2006) makes use of the uplift yielding mechanism of specially designed flexing base plates. When the base plates yield due to column tension during a strong earthquake motion, the columns uplift and allow the building structure to rock. Most of the previous studies mentioned above have evaluated the two-dimensional seismic behavior of an uplift rocking system. Although the three-dimensional seismic response of an uplift rocking system has been evaluated by the finite element analysis (Midorikawa et al. 2009), it has not been examined through an experimental study.

In this paper, the seismic response of one-third-scale three-story steel frames with column-bases allowed to uplift is evaluated and compared with that of fixed-base frames by three-dimensional shaking table tests. The three-dimensional seismic behavior of base-plate-yielding (BPY) rocking structural systems with and without eccentricity in plan is discussed that were retested in three different input-motion conditions; one horizontal, two horizontal and three components of the 1995 JMA Kobe ground motion record. The objective of the study is to improve the understanding of the three-dimensional seismic response of rocking frames subjected to strong earthquake motions and to validate the applicability of designing frames to enable the rocking response through column base-plate deformations.

Test Structures and Experimental Procedures

One-third-scale three-story, one-by-two bay braced steel frames were tested on the shaking table. The test structures were retested using four different frame conditions: uplift- and fixed-base frames; and, non-eccentric and eccentric frames in plan. The test structures are referred to as: BPY for uplift-base/non-eccentric; FIX for fixed-base/ non-eccentric; BPYEC for uplift-base/eccentric; and, FIXEC for fixed-base/eccentric models. The test structures are composed of yielding base plates, columns, girders, and bracing members, as shown in Fig. 1. The total height of the test structure is 3 m, 1 m for each story. The floor dimension is 4×2 m and the total weight of the test structure is 182 kN. In the longitudinal (X) direction, the test structure has two moment-resisting frames with two spans of 2 m each. In the transverse (Y) direction, the test structure has three braced frames with a span of 2 m. The bracing member is a high-strength steel bar of tensile strength of 980MPa with a diameter of 9.2 mm for non-eccentric models, and of 9.2 and 11 mm for eccentric models. These bracing members are prestressed to a half of the yield strength so that they resist both compression and tension forces. The eccentricity ratio of the eccentric distance to two-span length of FIXEC model in the longitudinal direction is 0.036, 0.037 and 0.036 at the first, second and third stories, respectively.

Yielding base plates of uplift-base model are installed at the bottom of each column of the first story in the test structures, as shown in Fig. 2. They have four wings that are each 110mm long and 60mm wide. The outside end of each wing of yielding base plate is constrained and connected to a steel foundation beam by a steel plate 40mm thick and two high-strength bolts (M24) so that plastic hinge lines are formed at both ends of each wing.

The test structures are vibrated in three different input-motion conditions; one horizontal, two horizontal and three components of the 1995 JMA Kobe record with its time scale shortened to 1/√3. Each test structure is subjected to the earthquake ground motion several times with the maximum input velocity of the vector sum of two horizontal components scaled to a range of levels to simulate various earthquake intensities from 0.05 to 0.5 m/s for uplift-base models and from 0.05 to 0.2 m/s for fixed-base models, respectively. Fig. 3 illustrates the acceleration response spectra for the 1995 JMA Kobe record.

The instrumentation was designed to measure both global structural response and local element response in critical portions of the test structures. The measured data include the following: horizontal accelerations on the shaking table, horizontal accelerations and relative horizontal displacements at each floor level, axial strains of the first-story columns and bracing members, and uplift displacements of the first-story column-bases. The maximum sampling frequency is 1000 Hz. The column shears are calculated from the moment distribution using measured values of strain gauges attached to the first-story columns. The base shear is estimated by summing the shears of the columns and bracing members at the first story. This value corresponds quite well with the base shear obtained from the mass and measured horizontal acceleration on each floor.

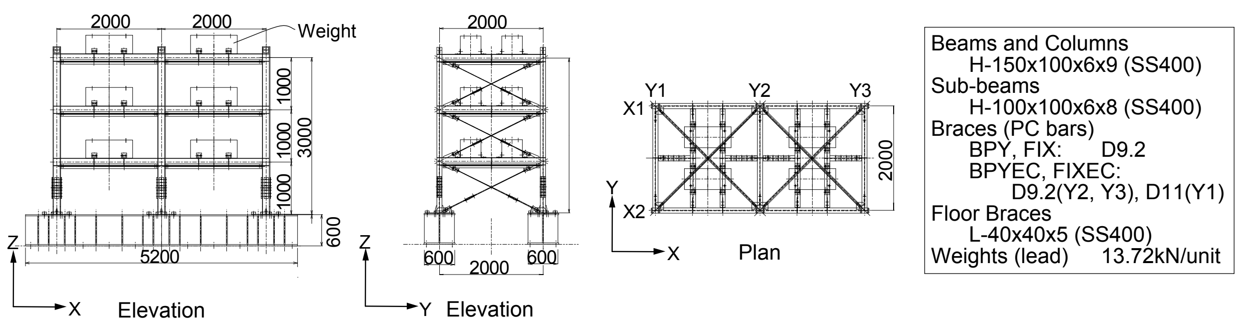
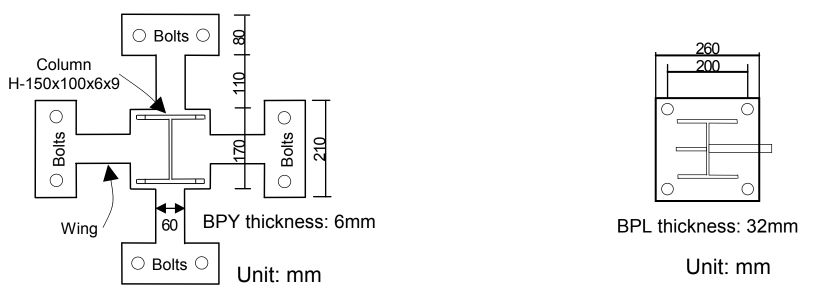


Figure 1. Test frame.



(a) Uplift yielding base plate

(b) Fixed base plate

Figure 2. Plan of base plate.

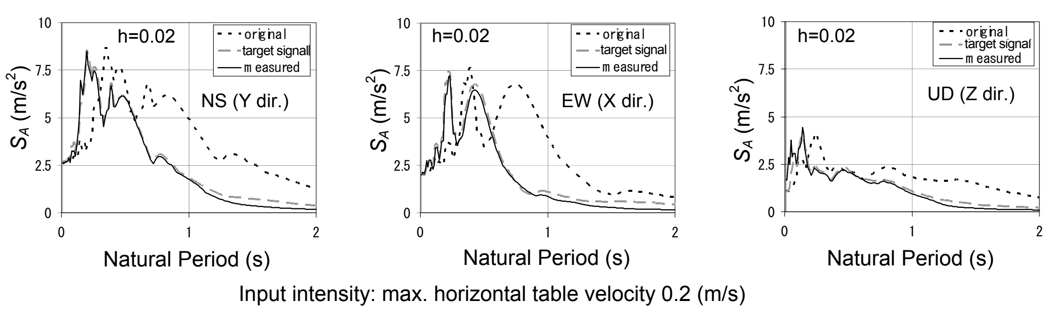


Figure 3. Acceleration response spectra of measured table accelerations.

Test Results and Discussion

Dynamic Characteristics of Test Structures

The fundamental natural periods and critical damping ratios for the first mode of the test frames estimated from the impact tests using a wooden hammer are listed in Table 1. The critical damping ratios were obtained from the bandwidth method. The fundamental natural period of BPY model is longer than that of FIX model by 28 % and 8 % in the longitudinal and transverse directions, respectively.

Table 1. Natural periods and damping ratios of the first mode.

Model		Period (s)	Damping ratio (%)
BPY	Long.	0.245	2.0
	Trans.	0.181	1.7
FIX	Long.	0.192	1.5
	Trans.	0.168	1.2
BPYEC	Long.	0.252	1.2
	Trans.	0.172	1.9

Time Histories of Roof Drifts and Base Shears

Figure 4 illustrates the time histories of the roof drift response of the test frames. The BPY and FIX models are indicated by black and gray lines, respectively. The response of FIX model indicated by dashed lines in Figs. 4 and 5 is extrapolated from the test results subjected to

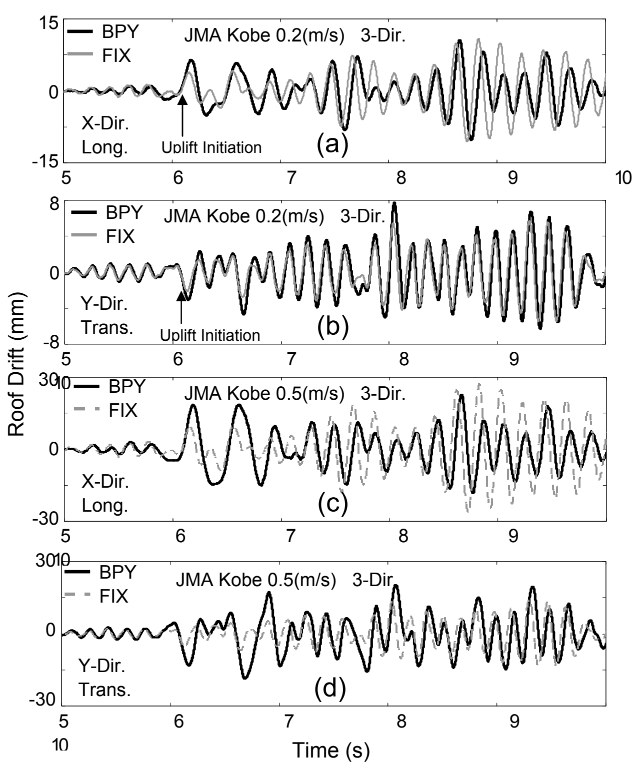


Figure 4. Time histories of roof drifts.

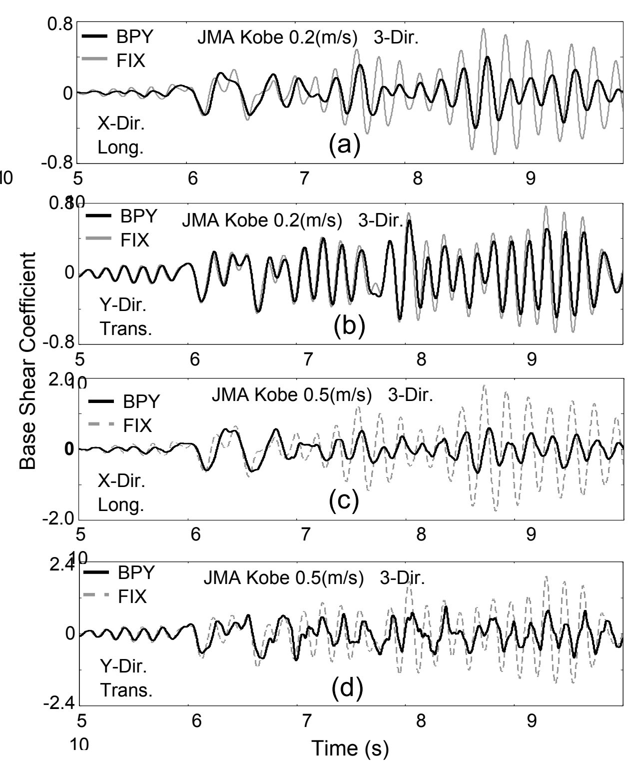


Figure 5. Time histories of base shears.

the maximum input table velocity of 0.2 m/s, based on the assumption that the response of FIX model is elastic as is observed in the tests. While the maximum roof drifts of BPY model are larger than those of FIX model in the transverse direction, the former are almost equal or smaller than the latter in the longitudinal direction.

Fig. 5 shows the time histories of the base shear response of the test frames. The base shears of BPY model are smaller than those of FIX model regardless of the input-motion intensity. Furthermore, the difference between two models also increases along with the increase of the input-motion intensity.

Relationships of Base Shear vs. Roof Drift and Uplift Force vs. Displacement

Fig. 6 shows the relationships of the base shear and roof drift of the test frames. The response of FIX model is kept in elastic in the test for the maximum input table velocity of 0.2 m/s. In the response of BPY model, the superstructure is kept in elastic but the plastic deformation of yielding base plates is produced in the tests for the maximum input table velocity of 0.2 and 0.5 m/s. The higher mode effect is observed in the hysteretic behavior of BPY model.

The relationships of the uplift force and displacement of uplift-bases of BPY model are illustrated in Fig. 7. The uplift force is estimated from the column axial force and the vertical component of brace axial force at the first story. In the figures, the effect of the dead loads,

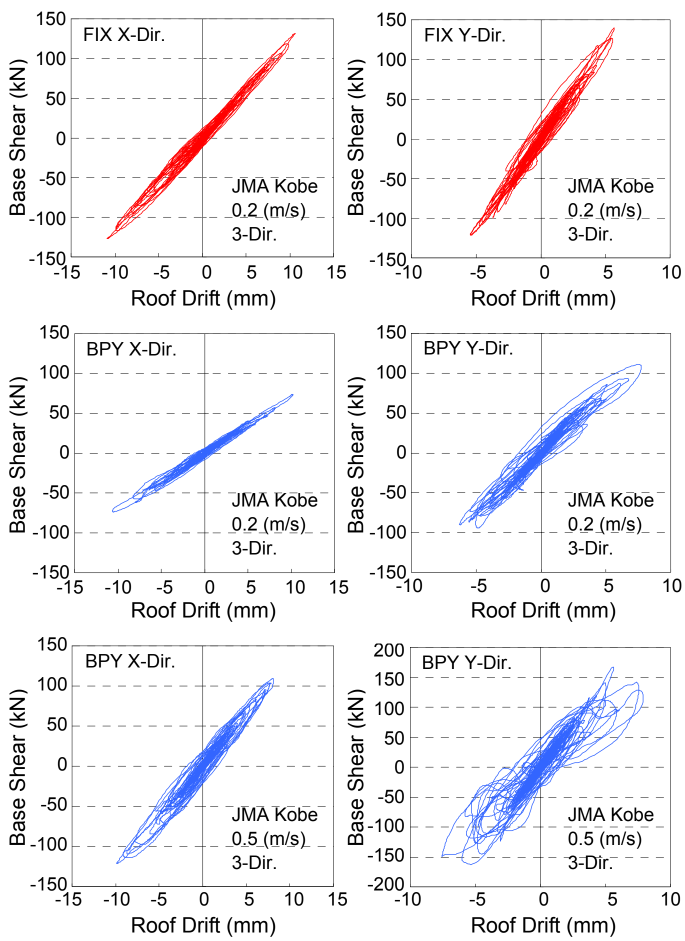


Figure 6. Base shear vs. roof drift.

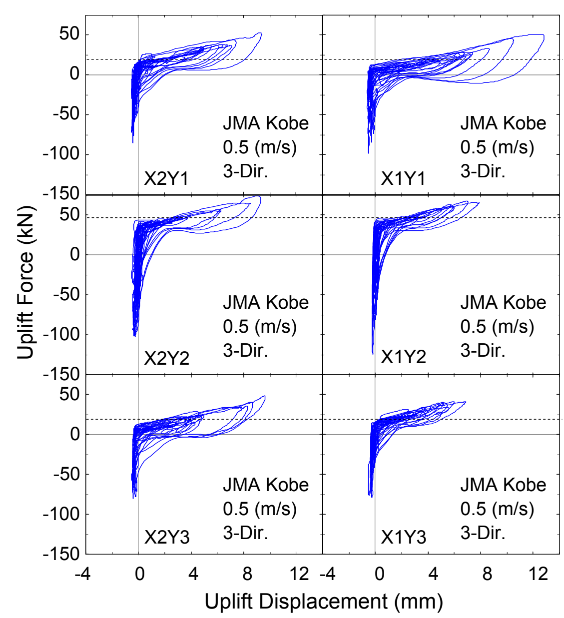


Figure 7. Uplift force vs. displacement of uplift-bases of BPY model.

whose estimated values are indicated by the dashed lines, is excluded since the initial values of strain gauges in each shaking test cycle were reset to zero positions in instrumentation. It is pointed out that the characteristics of uplift hysteretic behavior at the column base obtained from the results by the three-dimensional dynamic tests are consistent with the results by the statically cyclic loading tests of yielding base plates subjected to an uplift force (Ishihara et al. 2003).

Distribution of Maximum Response Envelopes along the Height

Fig. 8 shows the distribution of the maximum response envelopes of interstory drifts and story shears along the height of the test frames. The maximum interstory drifts of BPY model are smaller than those of FIX model in the longitudinal direction except for the first story. Although the maximum interstory drifts of BPY model are larger than those of FIX model in the transverse direction, the response values excluding the rocking component of BPY model are almost equal to or smaller than those of FIX model. When the maximum input table velocity is 0.2 m/s, the response reduction effect of BPY model is definitely observed and all story shears of BPY model are smaller than those of FIX model in both directions. It is revealed that the response deformation of the superstructure of BPY model is suppressed because of the rocking component of the response displacement.

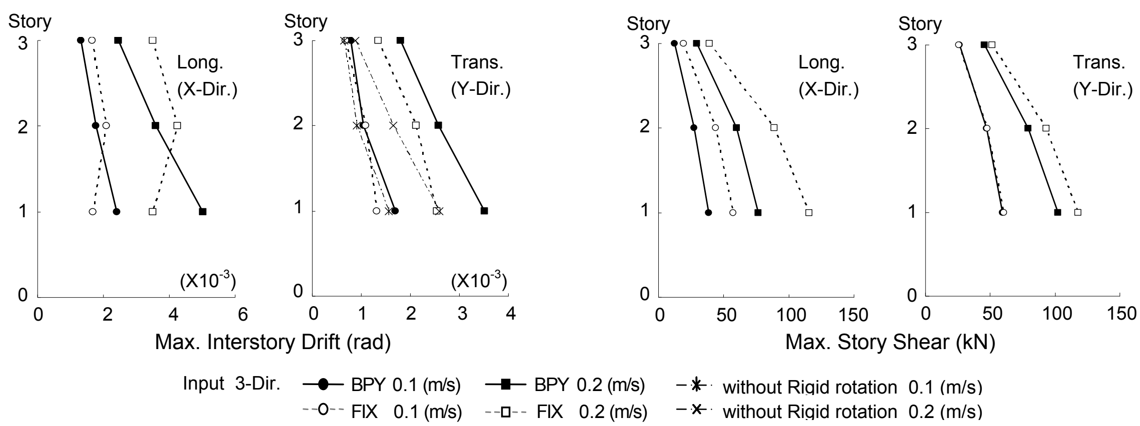


Figure 8. Distribution of maximum response envelopes along the height.

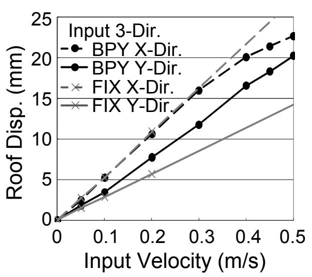
Relationships of Maximum Response vs. Input-motion Intensity

The relationships of the maximum roof drifts of the test frames and input table velocity are illustrated in Fig. 9(a). When the maximum input table velocity is less than 0.3 m/s, the response values are almost the same between both models in the longitudinal direction. Along with the increase of the maximum input table velocity over 0.3 m/s, the response values of BPY model become smaller than those of FIX model, and the difference between two models increases. In the transverse direction, the response values of BPY model are larger than those of FIX model by about 40 % regardless of the input-motion intensity.

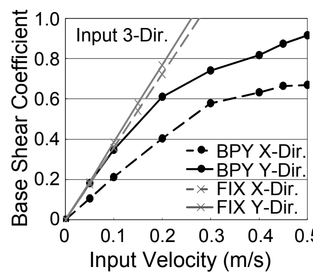
Fig. 9(b) shows the relationships of the maximum base shears of the test frames and input table velocity. The response values of BPY model are smaller than those of FIX model in both directions. Furthermore, the difference between both models increases in accord with the increase of the maximum input table velocity.

Fig. 9(c) illustrates the relationships of the maximum column axial forces of the test frames and input table velocity. In the figure, the column axial force does not include the effect of dead loads. The variable range of the axial forces is symmetrical in tension and compression before the uplift motion is induced within the maximum input table velocity of 0.1 m/s. The tensile axial forces for BPY model are limited to a relatively constant value after the uplift motion occurs. The compressive axial forces for BPY model are less than or about the same as those for FIX model. Consequently, the maximum column axial forces of BPY model never exceed those values of FIX model.

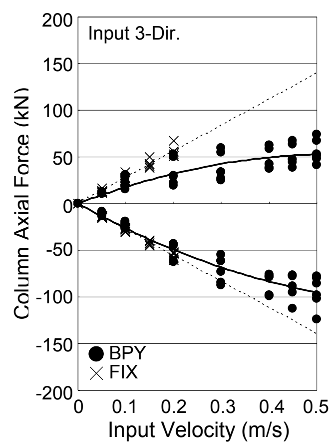
Fig. 9(d) shows the relationships of the maximum uplift displacements of uplift-bases of BPY model and input table velocity. The maximum uplift displacements get closer to the same values among all uplift-bases as the input-motion intensity becomes larger, and begin to increase at the maximum input table velocity of around 0.2 m/s at which the increase rate of the base shears obviously start to decrease.



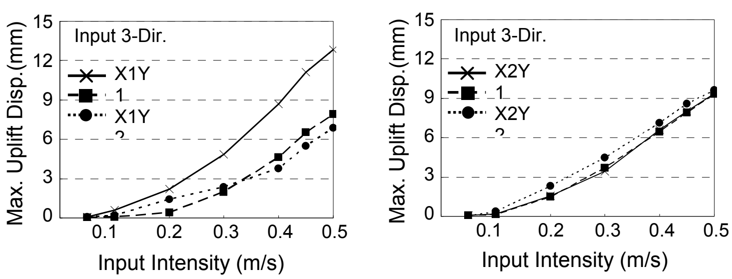
(a) Max. roof drift



(b) Max. base shear coefficient



(c) Max. column axial force

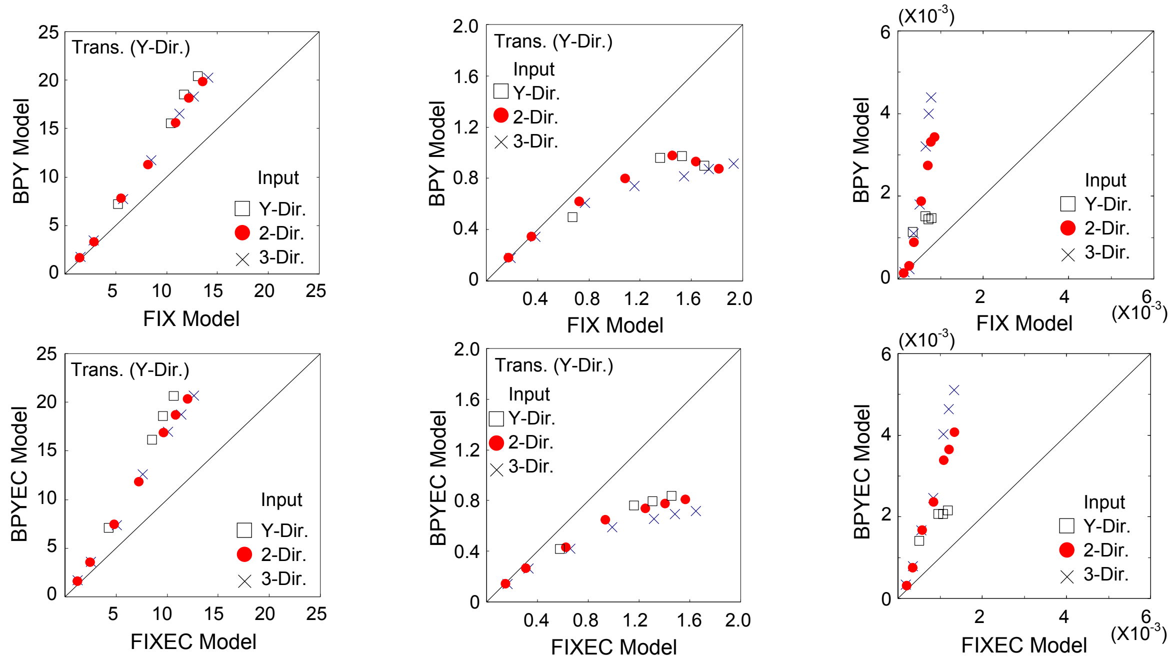


(d) Max. uplift displacement (BPY model)

Figure 9. Maximum response envelopes vs. input-motion intensity.

Maximum Response of Uplift- and Fixed-base Models with and without Eccentricity

Fig. 10 illustrates the comparison of the maximum response of uplift- and fixed-base models with and without eccentricity. As shown in Fig. 10(a), the difference of the maximum roof drifts between uplift- and fixed-base models is rather larger in the eccentric models. The maximum base shears of uplift-base models are limited to a certain value along with the increase of the input-motion intensity, as shown in Fig. 10(b), and are kept smaller than those of fixed-base models regardless of the presence or absence of eccentricity. The maximum roof rotations in plan are illustrated in Fig.10(c). The maximum roof rotations of BPY model are three to four times larger than those of FIX model among non-eccentric frames, and those of BPYEC model are about three times larger than those of FIXEC model among eccentric frames. In addition, the maximum roof rotations are affected by the multi-dimensional input motion, because they reach larger values in accord with the increase of the number of component of the input motion.



(a) Max. roof disp. (mm) (b) Max. base shear coefficient (c) Max. roof rotation (rad)

Figure 10. Comparison of max. response of uplift- and fixed-base models with and without eccentricity (upper row: without eccentricity, lower row: with eccentricity)

Conclusions

The results of the study are summarized as follows:

1) The maximum base shears of the uplift rocking frames are effectively reduced from those of the fixed-base frames in both longitudinal and transverse directions.

2) The response deformations of the superstructures of the uplift rocking frames excluding the rocking component of the response displacement are nearly equal to or smaller than the elastic response values of the fixed-base frames.

3) The maximum tensile forces of columns for the uplift rocking frames are limited to a relatively constant value less than those for the fixed-base frames after the uplift motion occurs, whereas the maximum compressive forces are almost equal to or less than those for the fixed-base frames. Consequently, the maximum column axial forces of uplift-base frames never exceed those values of fixed-base frames.

4) The maximum base shears of uplift-base frames are limited to a certain value along with the increase of the input-motion intensity, and are kept smaller than those of fixed-base frames regardless of the presence or absence of eccentricity.

Acknowledgments

This work has been stipulated by the Comprehensive Research and Development Project on Development of Performance Evaluation Method for Building Structures Using Innovative Structural Materials supported by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. The authors would like to acknowledge all project members for their useful advice and suggestions. The authors also express their gratitude to the task group members for their excellent support in the shaking table tests at the Technical Research Institute of Nishimatsu Corp. Part of this work is supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan under Grants-in-Aid for Scientific Research, Projects No. 19360244 and 21560607.

References

Azuhata, T., Midorikawa, M. and Ishihara, T., 2004. Energy dissipation mechanism and maximum response displacement prediction of steel frames with yielding base plates in uplift motion for seismic response reduction, *Journal of Structural and Construction Engineering, AIJ* 583, 61-68 (in Japanese).

Chopra, A. K. and Yim, S. C.-S., 1985. Simplified analysis of structures with foundation uplift, *Journal of Structural Engineering, ASCE* 111(4), 906-930.

Clough, R. W. and Huckelbridge, A. A., 1977. Preliminary experimental study of seismic uplift of a steel frame, *Report No. UBC/EERC-77/22*, EERC, University of California, Berkeley, Calif.

Hayashi, Y., Tamura, K., Mori, M. and Takahashi, I., 1999. Simulation analyses of buildings damaged in the 1995 Kobe, Japan, earthquake considering soil-structure interaction, *Earthquake Engineering and Structural Dynamics* 28(4), 371-391.

Housner, G. W. 1963., The behavior of inverted pendulum structures during earthquakes, *Bulletin of the Seismological Society of America* 53(2), 403-417.

Huckelbridge A. A., 1977. Earthquake simulation tests of a nine storey steel frame with columns allowed to uplift, *Report No. UBC/EERC-77/23*, EERC, University of California, Berkeley, Calif.

Ishihara, T., Midorikawa, M., Azuhata, T. and Wada, A., 2003. Hysteresis characteristics of column base for rocking structural systems with base plate yielding, *Journal of Constructional Steel, JSSC* 11, 51-56 (in Japanese).

Ishihara, T., Midorikawa, M. and Azuhata, T. 2009. Modal properties and free vibration of uplifting behavior of multistory buildings modeled as uniform shear-beam, *Journal of Structural and Construction Engineering, AIJ* 74(640), 1055-1061 (in Japanese).

Iwashita, K., Kimura, H., Kasuga, Y. and Suzuki, N., 2002. Shaking table test of a steel frame allowing uplift, *Journal of Structural and Construction Engineering, AIJ* 561, 47-54 (in Japanese).

Iwashita, K., Taniguchi, H. and Ishihara, T., 2003. Energy approach to the earthquake response of building allowing uplift at pile head, *Journal of Structural and Construction Engineering, AIJ* 564, 23–30 (in Japanese).

Kasai, K., Kanada, M. and Okuma, K., 2001. Real example for a passively controlled building with stepping column: analysis and full-scale damper experiment, *Proceedings, Passive Control Symposium 2001*, Structural Engineering Research Center, Tokyo Institute of Technology, Yokohama, Japan, 235-249 (in Japanese).

Meek, J. W., 1975. Effect of foundation tipping on dynamic response, *Journal of the Structural Division, ASCE* 101(7), 1297-1311.

Meek, J. W., 1978. Dynamic response of tipping core buildings, *Earthquake Engineering and Structural Dynamics* 6(5), 437-454.

Midorikawa, M., Azuhata, T., Ishihara, T. and Wada, A., 2003. Dynamic behavior of steel frames with yielding base plates in uplift motion for seismic response reduction, *Journal of Structural and Construction Engineering, AIJ* 572, 97–104 (in Japanese).

Midorikawa, M., Azuhata, T., Ishihara, T. and Wada, A., 2006. Shaking table tests on seismic response of steel braced frames with column uplift, *Earthquake Engineering and Structural Dynamics* 35(14), 1767-1785.

Midorikawa, M., Sudo, T., Asari, T., Azuhata, T. and Ishihara, T., 2009. Three-dimensional seismic response of ten-story steel frames with yielding base plates allowed to uplift, *Journal of Structural and Construction Engineering, AIJ* 74(637):495-502 (in Japanese).

Oliveto, G., Calio, I. and Greco, A., 2003. Large displacement behavior of a structural model with foundation uplift under impulsive and earthquake excitations, *Earthquake Engineering and Structural Dynamics* 32(3):369-393.

Rutenberg, A., Jennings, P. C. and Housner, G. W., 1982. The response of Veterans Hospital Building 41 in the San Fernando Earthquake, *Earthquake Engineering and Structural Dynamics* 10(3), 359-379.

Wada, A., Yamada, S., Ono, Y., Kobayashi, K. and Sasaki, Y., 2005. Shaking table tests of uplift behavior of buildings on elastic foundation during earthquake, *Journal of Structural and Construction Engineering, AIJ* 595, 57-64 (in Japanese).

Yim, S. C.-S. and Chopra, A. K., 1985. Simplified earthquake analysis of multistory structures with foundation uplift, *Journal of Structural Engineering, ASCE* 111(12):2708-2731.