

THREE-DIMENSIONAL SHAKING TABLE TESTS ON SEISMIC RESPONSE OF REDUCED-SCALE STEEL ROCKING FRAMES

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ABSTRACT

The seismic response of one-third-scale three-story steel frames with columns allowed to uplift is evaluated and compared with that of fixed-base frames by three-dimensional shaking table tests. The base plates with four wings, yielding due to tension of column, are installed at the bottom of each column of the first story of the rocking frames. The results are summarized as follows: (1) The maximum base shears of the rocking frames are effectively reduced from those of the fixed-base frames in longitudinal and transverse directions; (2) The response deformations of the superstructures of the rocking frames excluding the rocking component are nearly equal to or smaller than the elastic response values of the fixed-base frames; and, (3) The maximum column tensile forces for the 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.

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 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. 2003, 2006). One of the features of an uplift structural system is that the maximum strain energy associated with the horizontal deformation of a superstructure is reduced, because a portion of the total earthquake input energy exerted to the structural system is dissipated 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 structural 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.

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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 behavior of an uplift structural system. Although the three-dimensional response of an uplift structural system has been evaluated by the 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 columns allowed to uplift is evaluated and compared with that of fixed-base frames by three-dimensional shaking table tests. The inelastic three-dimensional behavior of base-plate-yielding (BPY) rocking structural systems is discussed that were retested under three different input-motion conditions; one horizontal, two horizontal and three components of the 1995 JMA Kobe record. The objective of the study is to improve the understanding of the seismic rocking response of structures subjected to strong earthquake motions and to validate the feasibility of designing steel frames to enable the rocking response through column base-plate deformations.

TEST STRUCTURES AND EXPERIMENTAL PROCEDURES

One-third-scale three-story, 2×1 bay braced steel frames were tested on the shaking table. The test frames were retested using two different base conditions: base-plate-yielding uplift-base (BPY model) and fixed-base (FIX model). The test structures are composed of yielding base plates, columns, girders, and bracing members, as shown in Figure 1. There is no significant difference between two frames in the longitudinal direction, and among three frames in the transverse direction. 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 a span 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 with a diameter of 9.2 mm and tensile strength of 980MPa. These bracing members are prestressed to a half of the yield strength so that they resist both compression and tension forces.

Yielding base plates are installed at the bottom of each column of the first story of the test structures, as shown in Figure 2. The base plates of BPY model 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 $1/\sqrt{3}$. Each test structure is subjected to earthquake ground motions 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 BPY model and from 0.05 to 0.2 m/s for FIX model, respectively. Figure 3 shows the acceleration response spectra for the 1995 JMA Kobe ground motion 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 calculated 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 measured accelerations and masses on each floor.

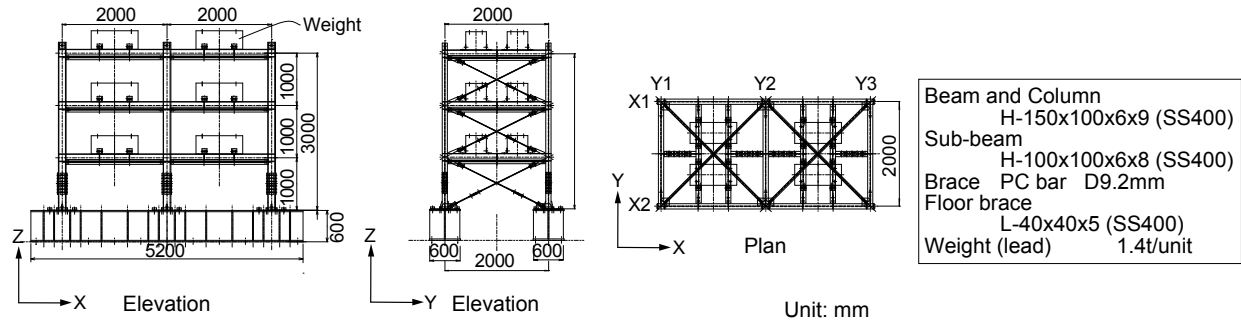
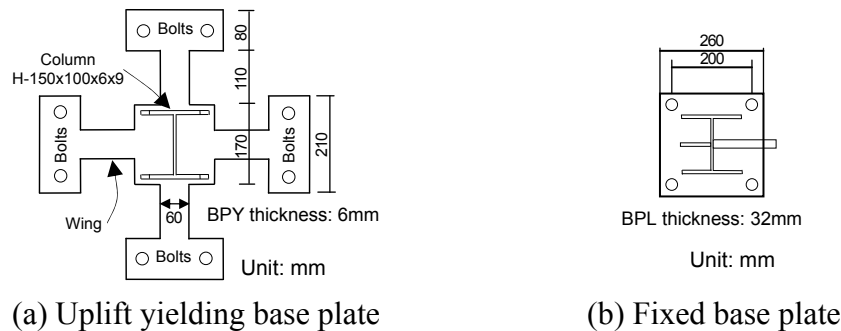


Fig. 1. Test frame.



(a) Uplift yielding base plate

(b) Fixed base plate

Fig. 2. Plan of base plate.

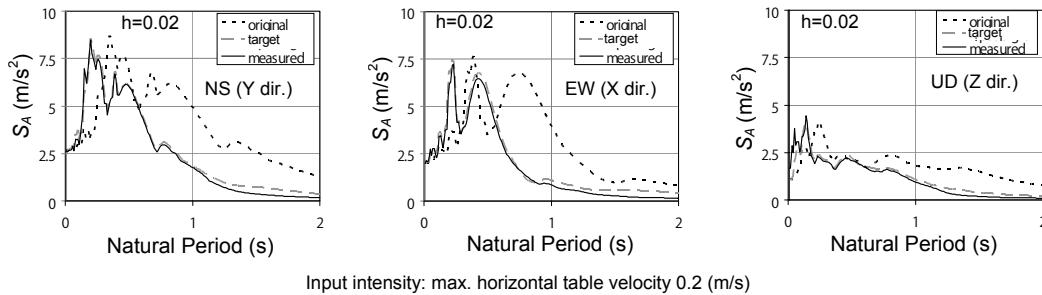


Fig. 3. Acceleration response spectra of measured table accelerations.

TEST RESULTS AND DISCUSSION

Dynamic Characteristics of Test Structures

The fundamental natural periods and the 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

Time Histories of Roof Drift, Uplift Displacement and Base Shear

Figure 4 illustrates the time histories of the roof displacement responses of the test frames. The BPY and FIX models are indicated by bold and thin lines, respectively. The responses of FIX model indicated by dashed lines in Figures 4 and 5 is extrapolated from the test results subjected to 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 displacements 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.

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

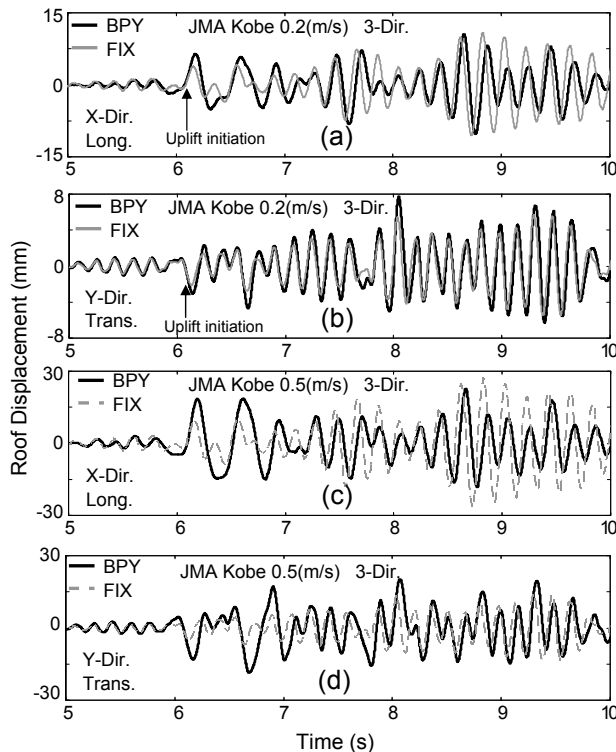


Fig. 4. Time histories of roof drift.

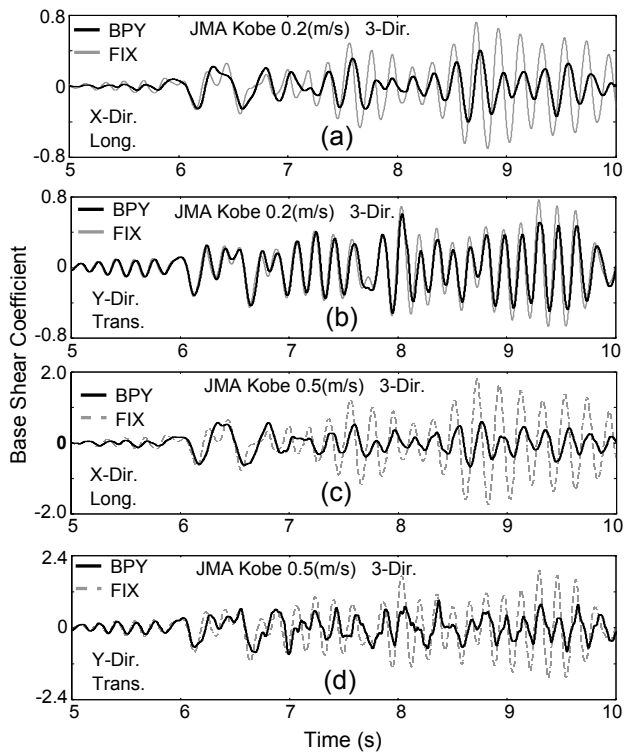


Fig. 5. Time histories of base shear.

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

Figure 6 shows the relationships of the base shear and roof displacement 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 yielding base plates are illustrated in Figure 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 figure, the effect of the dead loads 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 an uplift force (Ishihara et al. 2003).

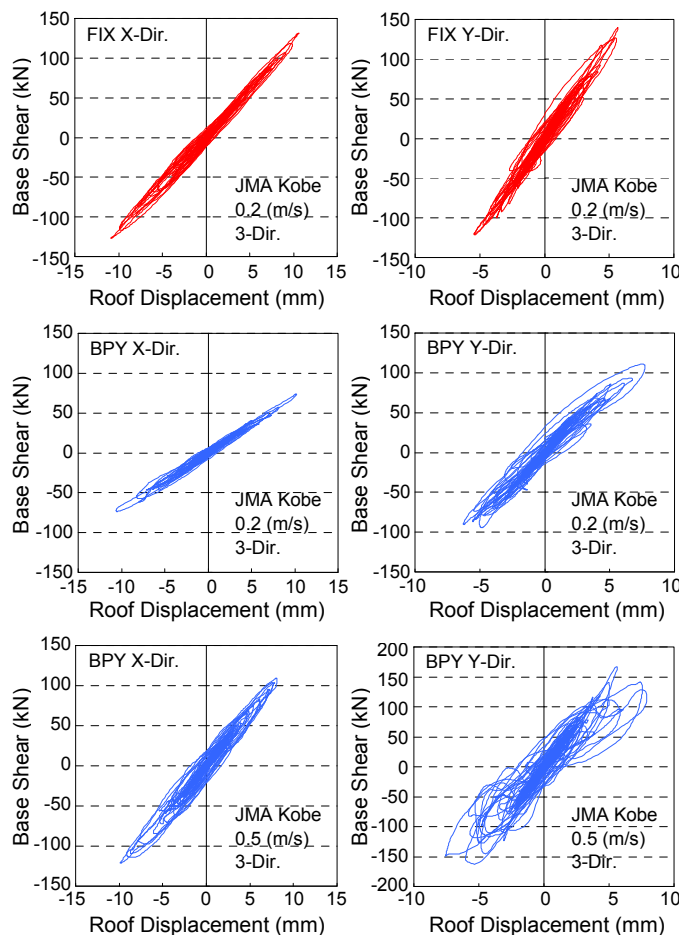


Fig. 6. Base shear vs. roof drift.

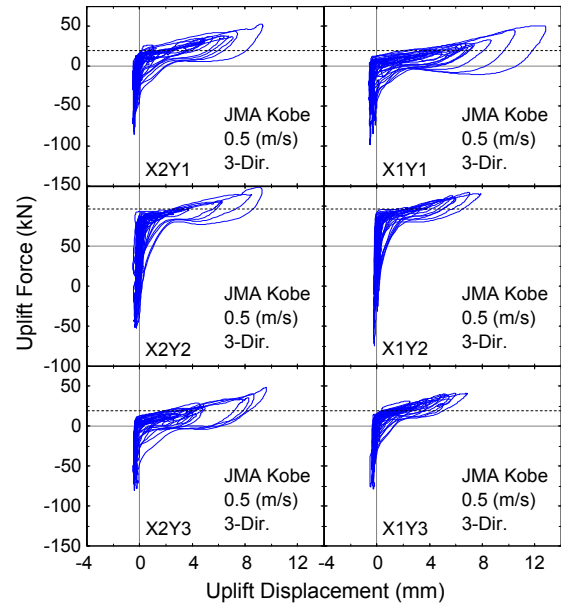


Fig. 7. Uplift force vs. displacement.

Distribution of Maximum Response Envelopes along the Height

Figure 8 shows the distribution of the maximum response envelopes of interstory drift and story shear 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 displacement of BPY model are almost equal to or smaller than those of FIX model. When the maximum input table velocity becomes 0.2 m/s, the response reduction effect of BPY model is clearly 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.

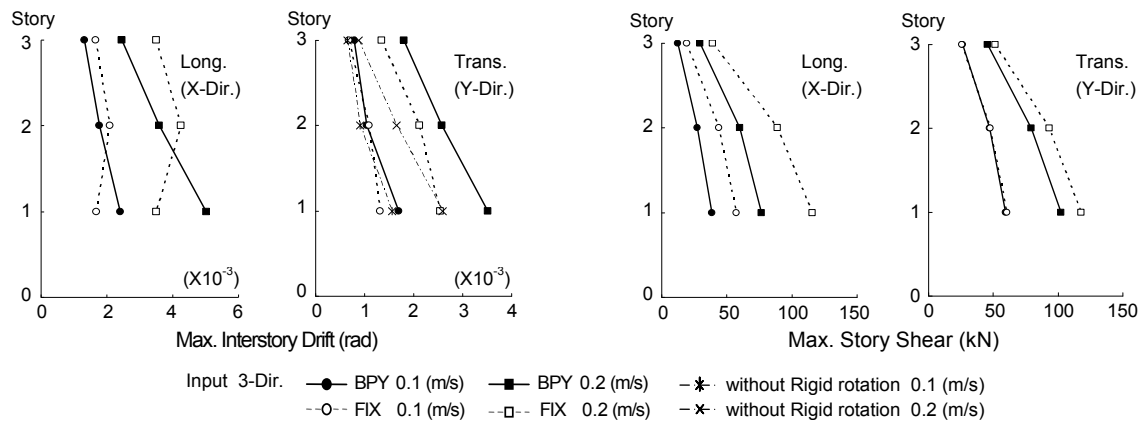


Fig. 8. Distribution of maximum response envelopes.

Relationships of Maximum Responses vs. Input-motion Intensity

The relationships of the maximum roof displacement 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 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 shear 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 velocity.

Fig. 9(c) shows the relationships of the maximum column axial force 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. 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.

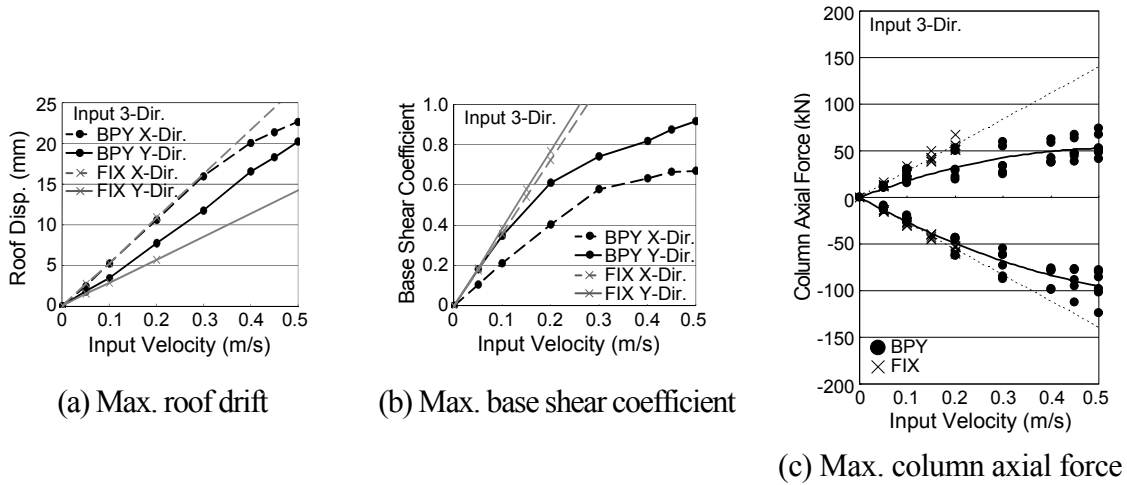


Fig. 9. Maximum response envelopes vs. input intensity.

CONCLUSIONS

The results of the study are summarized as follows:

- (1) The maximum base shears of the rocking frames are effectively reduced from those of the fixed-base frames in longitudinal and transverse directions.
- (2) The response deformations of the superstructures of the 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 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 BPY model never exceed those values of FIX model.

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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* **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.