Seismic response three-dimensional analyses of ten-story steel frames with column uplift

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Abstract

Previous studies have suggested that rocking vibration accompanied with uplift motion might reduce the seismic damage of buildings subjected to severe earthquake motions. In this paper, the three-dimensional seismic response of base-plate-yielding rocking systems with columns allowed to uplift is evaluated and compared with that of fixed-base systems by finite element numerical analyses. The study is carried out using ten-story, one-by-three bay steel frames of a base-plate-yielding rocking system. Base plates that yield due to tension of columns are installed at the base of each column. The earthquake ground motions are the JMA record of the 1995 Kobe Earthquake and a synthesized motion. The maximum input velocity is scaled to examine the structural response at 0.50 m/s. The main findings from this study are as follows 1) The base shear coefficients of the uplift model are reduced to 68% to 82% of the fixed-base model subjected to one-dimensional input motions in the horizontal direction and to 59% to 76% of the fixed-base model subjected to two-/three-dimensional input motions. 2) The horizontal roof displacements of the uplift model almost increase relative to the fixed-base model. The ratio of the uplift to fixed-base models is from 0.89 to 1.25 in the case of one-dimensional input motions, and from 0.78 to 1.30 in the case of two-/three-dimensional input motions. 3) While the girders of the fixed-base model yield in bending at the second to eighth floors, those of the uplift model yield in bending only at the second and third floors.

Keywords: seismic response reduction, rocking vibration, steel frame, column uplift, yielding base plate.

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1 Introduction

It has been pointed out that the effects of rocking vibration accompanied with uplift motion may reduce the seismic damage of buildings subjected to strong earthquake ground motions [1, 2]. Based on these studies, structural systems have been developed which permit rocking vibration and uplift motion under appropriate control during major earthquake motions [3, 4].

A rocking structural system under development employs the yielding mechanism of base plates. When weak base plates yield due to tension of columns during a strong earthquake ground motion, the columns uplift and permit a building structure to rock. In this system, the yielding base plates dissipate some of the input seismic energy by the inelastic behaviour.

In this paper, the seismic response of a ten-story steel frame of base-plate-yielding rocking system is examined by the finite element analyses [5].

2 Analytical modelling and numerical analyses

A ten-story, one-by-three bay steel frame shown in Figure 1 was analyzed. The structure is modelled in two types of a three-dimensional frame; fixed-base model (nodal points of about 6000) and base-plate uplift (BPL) model (nodal points of about 7500).

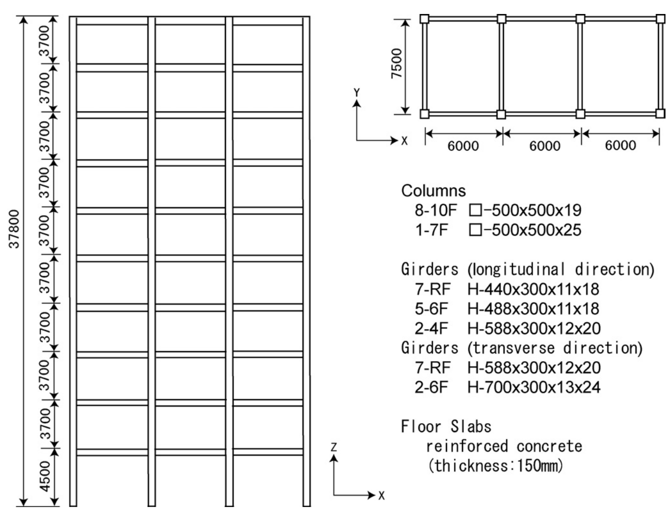


Figure 1: Ten-story steel frame (unit: mm).

The base plates and the columns of the first story are modelled using shell elements. The columns and girders at the second and upper stories are modelled using beam elements. The foundation beam is assumed to be rigid.

The yielding base plate shown in Figure 2 is fixed at each outside end of wing plate. Contact elements are employed between the base plates and the rigid foundation beam. The contact conditions such as the normal contact force and the tangential contact slip without friction are considered between the rigid foundation beam and the shell elements of base plates.

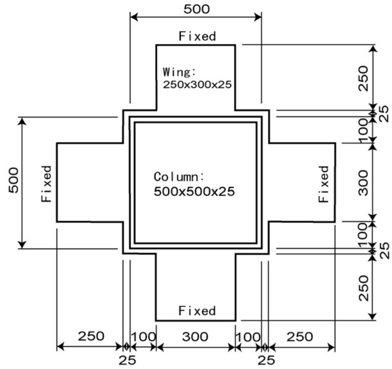


Figure 2: Plan of yielding base plate (unit: mm).

The base plate and the first story column are modelled with an elasto-plastic material considering a kinematic hardening rule with the Mises-Hencky yield condition. The characteristics values of steel are assumed; Young's modulus = 2.06 x 10^8 kN/m^2, post-yielding modulus = 2.06 x 10^6 kN/m^2, yield strength = 2.94 x 10^5 kN/m^2, Poisson's ratio = 0.3 and specific gravity = 7.8. The tri-linear moment-curvature relation is assumed in the columns and girders at the second and upper stories.

The reinforced-concrete floor slab of 150 mm thickness is modelled using two-dimensional stress elements that are connected to beam-to-column joints.

The weight of each floor is assumed to be 1150 kN. The masses of the analytical model are lumped at each nodal point of girders. The vertical components of masses are defined in order to capture vertical inertia effects associated with rocking. The vertical load corresponding to the lumped masses is applied to each node of the analytical model before starting the dynamic response analyses.

It is assumed that the viscous damping results from the initial stiffness-dependent effects. The critical damping ratio of 2%, that is stiffness-proportional type, is introduced to the first mode corresponding to the fixed-base model.

The numerical time integration in the analyses is the combined use of the Newmark method with constant acceleration and the Newton-Raphson method for equilibrium iteration within the time step of 0.01 second. The synthesized ground motion BCJ-L2 and the 1995 JMA Kobe record that are normalized in the maximum ground velocity of 0.50 m/s, are used as input for the dynamic response analyses. The duration is thirty seconds in the analyses. The JMA Kobe record is used in the analyses subjected to one-, two- and three-dimensional input motions, in which the NS and EW components are applied to the transverse and longitudinal directions of the analytical model, respectively.

3 Results and discussion

3.1 Pushover analyses

Figure 3 shows the relationships between the base shear and the roof displacement obtained from the pushover analyses for the fixed-base and BPL models. The base shear coefficient of the fixed-base and BPL models at the roof drift angle of 1/100 are 0.41 and 0.27 in the transverse direction, and 0.37 and 0.30 in the longitudinal direction, respectively. In the transverse direction, the base shear coefficient of the BPL model is 0.16 at base-plate uplift yielding, and 0.13 in the simple uplift model without base plates.

Although the base shear coefficient of the BPL model at the roof drift angle of 1/100 is much smaller than that of the fixed-base model, the increase of the base shear coefficient of the BPL model in the transverse direction is larger than the fixed-base model because of the hardening effects in the inelastic behaviour of yielding base plates.

Furthermore, the maximum responses from the dynamic analyses are plotted in Figure 3. There are some differences between the seismic and pushover analytical results because of the higher mode effects.

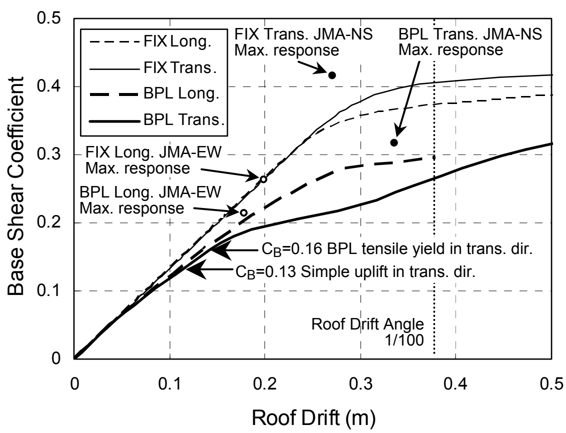


Figure 3: Base shear versus roof displacement.

3.2 Seismic response analyses

The natural periods of the fixed-base model are 1.26 seconds for the first mode in the longitudinal direction, 1.25 seconds for the second mode in the transverse direction and 1.04 seconds for the third mode in torsion, and those of the BPL model are 1.62 seconds for the first mode in the transverse direction, 1.42 seconds for the second mode in the longitudinal direction and 1.20 seconds for the third mode in torsion.

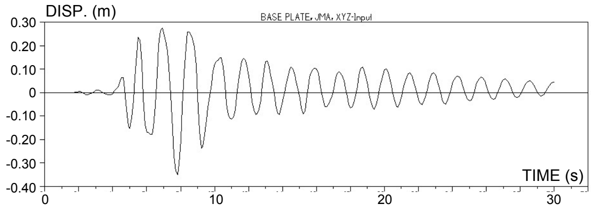
Figure 4 shows the time histories of the responses of the BPL model subjected to the three-dimensional input motion of the JMA Kobe record.

Figure 5 shows the corresponding time histories obtained from the analyses subjected to the one-dimensional input motion.

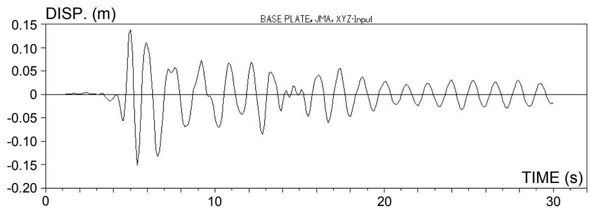
The maximum responses of the fixed-base and BPL models are summarized in Table 1. From this table, it is pointed out that:

1) The base shear coefficients of the BPL model are reduced to 68 to 82% of the fixed-base model subjected to one-dimensional input motions and to 59 to 76% of the fixed-base model subjected to two-/three-dimensional input motions.

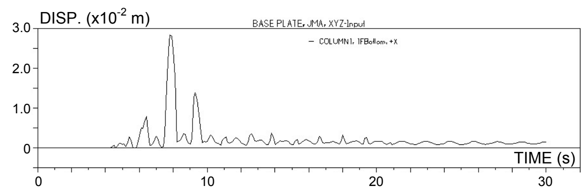
2) The horizontal roof displacements of the BPL model almost increase relative to the fixed-base model. The ratio of the BPL to fixed-base models is from 0.89 to 1.25 in the case of one-dimensional input motions, and from 0.78 to 1.30 in the case of two-/three-dimensional input motions. However, the ratios in the case of two-/three-dimensional input motions are between 1.14 and 1.15 when comparing in a vector sum in the two horizontal directions, and is therefore within the values in case of one-dimensional input motions.



(a) Roof displacement in transverse direction



(b) Roof displacement in longitudinal direction

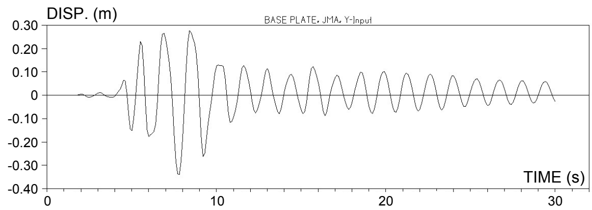


(c) Uplift displacement of outside column base

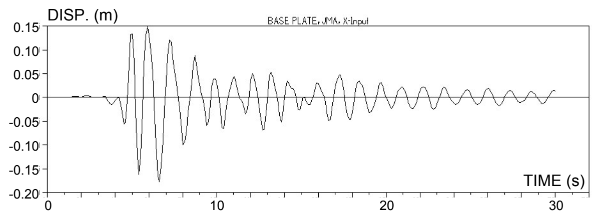
Figure 4: Time histories of displacement response of BPL model subjected to three components of JMA record.

3) The horizontal roof accelerations of the BPL model are reduced when compared to the fixed-base model. The ratio of the BPL to fixed-base models is from 0.72 to 1.01. On the contrary, the horizontal roof velocities are almost the same in two models.

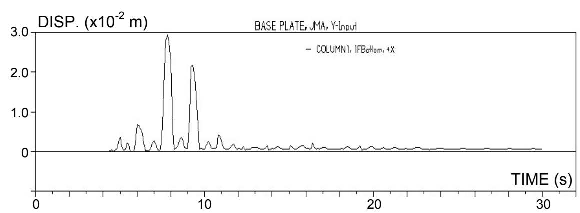
4) The uplift displacement of the BPL model is 35 mm in maximum, and is approximately 1/170 of the span length.
5) The velocities at the base of the BPL model are from 150 to 300 mm/s.



(a) Roof displacement in transverse direction
(one-dimensional input motion)



(b) Roof displacement in longitudinal direction
(one-dimensional input motion)



(c) Uplift displacement of outside column base
(one-dimensional input motion)

Figure 5: Time histories of displacement response of BPL model subjected to one component of JMA record.

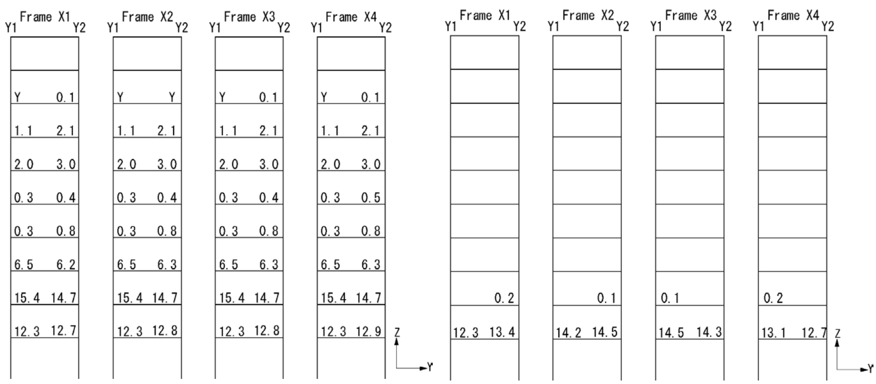
6) The uplift displacement of the BPL model results in the remarkably large cumulative plastic strain in the wing plate of the base plate, whose maximum values are from 25 to 80% in the case of one-dimensional input motions and from 37 to 38% in the case of two-/three-dimensional input motions. The location of the maximum value is the column-side end of the wing plate of the base plate. According to the static loading test results of yielding base plates [6], the maximum cumulative plastic strain reaches 138% in the test base plate with thickness of 25 mm and over 88% to 163% in the test base plate with thickness of 19 mm. Consequently, the maximum cumulative plastic strain obtained from the analyses are kept within the ultimate capacity.

Table 1: Maximum response values of frame models.

	Condition		Roof				Base			
Input	Base	Direction	Δ_h *1 (mm)	Δ_v *2 (mm)	Vel. (m/s)	Acc. (m/s^2)	δ_{up} *6 (mm)	V_{dn} *7 (mm/s)	C_b *8	$\Sigma\varepsilon_b$ *9 (%)
BCJ	Fix	Trans.	333	6.26	1.48	9.91	-	-	0.431	-
BCJ	BPL	Trans.	356	28.2	1.46	7.15	28.9	261	0.291	80.5
BCJ	Fix	Long.	322	4.67	1.56	10.40	-	-	0.401	-
BCJ	BPL	Long.	354	19.8	1.45	8.48	24.8	213	0.311	69.5
JMA	Fix	Trans.	272	5.93	1.95	9.57	-	-	0.421	-
JMA	BPL	Trans.	339	29.9	1.53	9.68	29.4	296	0.319	25.2
JMA	Fix	Long.	198	3.33	1.15	6.29	-	-	0.262	-
JMA	BPL	Long.	177	6.56	1.04	5.46	4.09	37.7	0.214	1.30
JMA (2com) *3	Fix	Trans. Long.	270 (0.99) *5 193 (0.97)	6.77	1.95 (1.00) *5 1.15 (1.00)	9.57 (1.00) *5 6.18 (0.98)	-	-	0.411 (0.98) *5 0.249 (0.95)	-
JMA (2com)	BPL	Trans. Long.	347 (1.02) 151 (0.85)	36.5	1.56 (1.02) 1.03 (0.99)	9.40 (0.97) 4.69 (0.86)	32.3 [0.96] *10	175	0.311 (0.97) 0.155 (0.72)	36.9
JMA (3com) *4	Fix	Trans. Long.	270 (0.99) 193 (0.97)	6.67	1.95 (1.00) 1.15 (1.00)	9.58 (1.00) 5.94 (0.94)	-	-	0.411 (0.98) 0.250 (0.95)	-
JMA (3com)	BPL	Trans. Long.	350 (1.03) 151 (0.85)	31.5	1.56 (1.02) 1.03 (0.99)	9.43 (0.97) 4.68 (0.85)	35.1 [1.05]	148	0.306 (0.96) 0.147 (0.69)	35.0

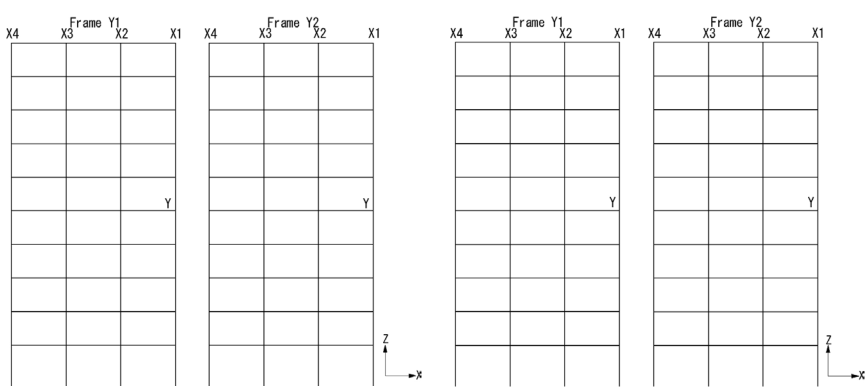
Notes) *1: horizontal roof displacement, *2: vertical roof displacement, *3: horizontal two-component input motion, *4: three-component input motion, *5: ratio of the value in the case of two-/three-dimensional input motion to the one in the case of one-dimensional input motion. *6: uplift displacement at column base, *7: landing velocity at column base, *8: base shear coefficient of structure, *9: cumulative plastic strain in wing plate of base plate, and, *10: ratio of the uplift displacement in the case of two-/three-dimensional input motion to the sum of the uplift displacements in the transverse and longitudinal directions in the case of one-dimensional input motion.

In Table 1 the numerals in the parentheses in the columns of roof displacement, roof velocity, roof acceleration and base shear coefficient indicate the ratio of the value in the case of two-/three-dimensional input motion to the one in the case of one-dimensional input motion. And the numerals in the parentheses in the column of uplift displacement indicates the ratio of the uplift displacement in the case of two-/three-dimensional input motion to the sum of the uplift displacements in the transverse and longitudinal directions in the case of one-dimensional input motion. It is suggested that the response of a structure subjected to two-/three-dimensional input motions is readily predicted from the response of that subjected to one-dimensional input motions, because these ratios of the BPL model in Table 1 are almost equal or less than unity.



Fixed-base model BPL model

(a) Transverse direction



Fixed-base model BPL model

(b) Longitudinal direction

Figure 6: Cumulative plastic curvature ratios of girders in transverse direction subjected to three components of JMA record.

Figure 6 shows the cumulative plastic curvature ratios at girder ends of the fixed-base and BPL models subjected to the three-dimensional input motion of the JMA Kobe record. The cumulative plastic curvature ratio is defined as the ratio of cumulative plastic curvature to yield curvature of girder section. While the girders of the fixed-base model yield in bending at the second to eighth floors in the transverse direction, those of the BPL model yield in bending at the second to third floors in the transverse direction. In addition, the cumulative plastic curvature ratios are almost the same in the transverse direction and quite small in the longitudinal direction in two models.

Furthermore, although the sectional force of columns does not reach the full plastic moment, the peak local stress in compression goes beyond the yield strength at the bottom of columns at the first story.

4 Summary and conclusions

The reduction of the three-dimensional seismic response of base-plate-yielding rocking systems with columns allowed to uplift is evaluated and compared with that of fixed-base systems by finite element numerical analyses, using ten-story, one-by-three bay steel frames of base-plate-yielding rocking system.

The results of this study are summarized as follows:

1) The maximum base shears and horizontal roof accelerations in the seismic response of the structures with column uplift are effectively reduced in the base-plate-yielding rocking system from those of the fixed-base system. The base shear coefficients of the uplift model are reduced to 68% to 82% of the fixed-base model subjected to one-dimensional input motions in the horizontal direction and to 59% to 76% of the fixed-base model subjected to two-/three-dimensional input motions.

2) The maximum roof displacements in the seismic response of the rocking structures are not much different from the response values of the fixed-base systems, but almost increase relative to the fixed-base model. The ratio of the uplift to fixed-base models is from 0.89 to 1.25 in the case of one-dimensional input motions, and from 0.78 to 1.30 in the case of two-/three-dimensional input motions.

3) The energy dissipation of the yielding base plates is expected to be effective in reducing the response displacement of yielding-base-plate rocking systems. While the girders of the fixed-base model yield in bending at the second to eighth floors, those of the uplift model yield in bending only at the second and third floors.

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