EFFECTS OF ROCKING VIBRATION WITH BASE PLATE YIELDING ON EARTHQUAKE RESPONSES OF BUILDINGS

by

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ABSTRACT

It is pointed out that effects of rocking vibration (up-lifting response) can reduce the seismic damage of buildings subjected to strong earthquake ground motions. Based on this knowledge, we are now developing the rocking systems that can cause rocking vibration under appropriate control during earthquakes. One of these systems has weak base plates at the bottom of each steel column of the first story. When the weak base plates yield during a strong earthquake, the building causes rocking vibration. This paper examines the effects of rocking vibration with base plate yielding on earthquake responses of buildings. It is concluded that the rocking systems with weak base plates can reduce earthquake responses of buildings by causing rocking vibration, based on nonlinear time history analyses.

KEY WORDS: Rocking system
Base plate
Earthquake response reduction
Smart structure

1. INTRODUCTION

We are now developing the rocking systems that can reduce earthquake responses of buildings by causing rocking vibration. Some researchers report that effects of rocking vibration can reduce the seismic damage of the buildings subjected to strong earthquake ground motions [1][2]. The concept of rocking systems is based on these studies.

The rocking system can be regarded as one of smart structural systems. Smart systems are defined as structural systems with a certain-level of autonomy relying on the embedded functions of sensors, actuators and processors that can automatically adjust structural characteristics, in response to the change in external disturbances and environments, toward structural safety and serviceability as well as the elongation of structural service life [3]. Although the rocking system has neither specific devices nor computer control systems, it satisfies this definition. It is thought the rocking system is one of the simplest smart structural systems.

One of the rocking systems we are developing has weak base plates at the bottom of each steel column of the first story. When the weak base plates yield during a strong earthquake, the building causes rocking vibration.

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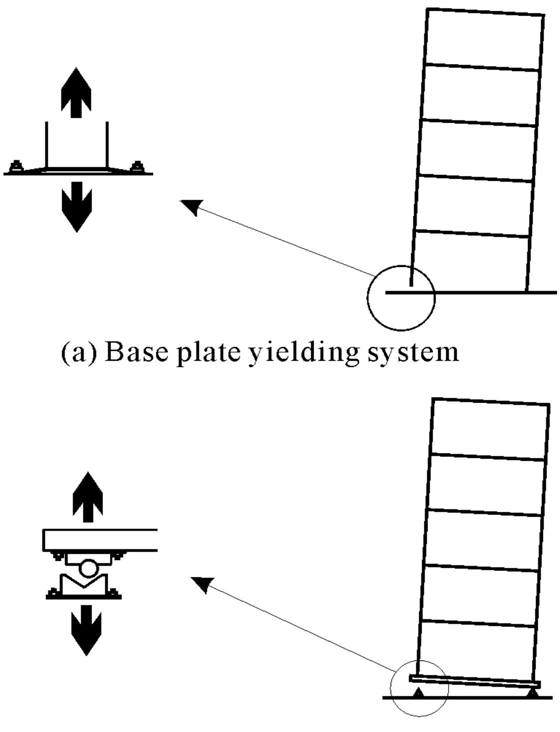
In this paper, the earthquake responses of this rocking system (the base plate yielding system) are examined comparing with those of the simpler rocking system (the simple rocking system) and the fixed-base system. Outlines of the base plate yielding system and the simple rocking system are illustrated in Fig.1.

2. NONLINEAR SEISMIC ANALYSES OF THE ROCKING SYSTEMS

2.1 Structural models for analyses

Structural models for analyses are composed of a steel frame as shown in Photo.1 and some devices such as weak base plates attached to bases of the frame. Each floor height of the steel frame is 1m, total height is 5m and floor plan is 2m * 3m. Each floor weight is shown in Table 1. The cross sections of the members are shown in Table 2. The base plate for the base plate yielding system is shown in Fig.2. Thickness of the base plate is 6mm or 9mm. And the device for the simple rocking system is shown in Fig.3.

These structural models will be also examined by shaking table tests.



(a) Base plate yielding system

(b) Simple rocking system

Fig.1 Two types of rocking systems

Table 1 Weight of each story

Story	Weight (tw)
RF	1.132
5F	1.146
4F	1.146
3F	1.146
2F	1.146
1F	0.728

Table 2 Cross sections of members

Column and beam	H148x100x6x9
Footing beam	H250x250x9x14

Photo.1 Specimen

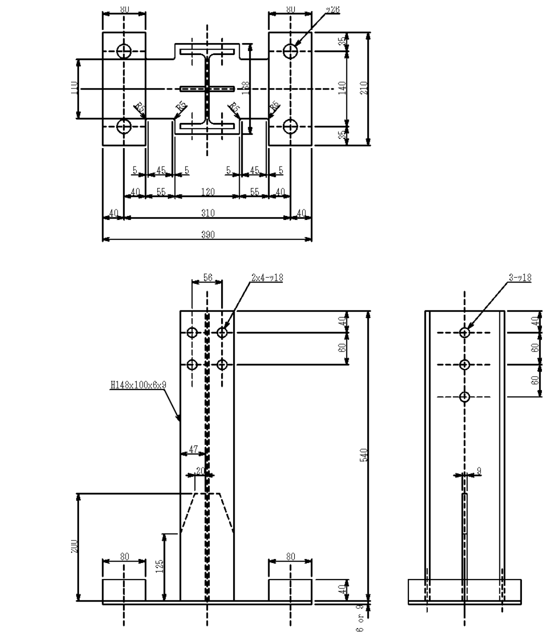


Fig.2 The base plate of the base plate yielding system

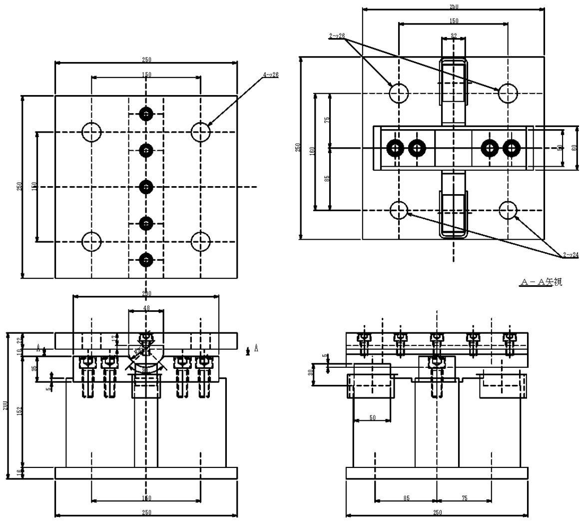


Fig.3 The device for the simple rocking system

2.2 Analytical method

Mathematical models of the structural systems are shown in Fig.4. The steel frame with fixed bases is modeled as shown in Fig.4 (a). The base of the base plate yielding system is modeled as shown in Fig.4 (b). And the base of the simple rocking system is modeled as shown in Fig.4 (c). Mass of

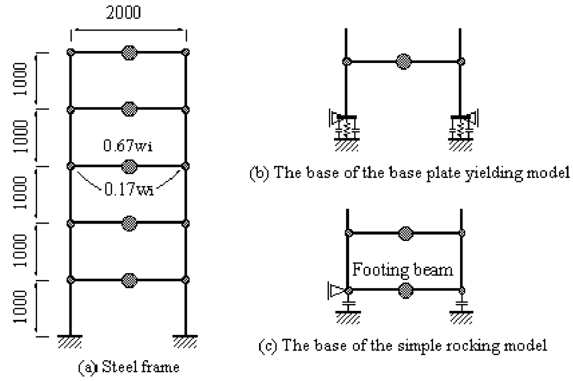
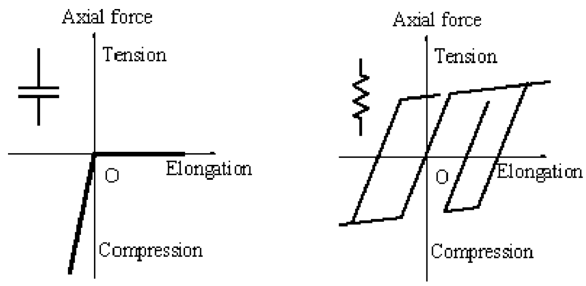


Fig.4 Mathematical models



(a) (b)

Fig.5 Restoring force characteristics of springs

structures is concentrated on three points on each floor. On bases of the base plate yielding system and the simple rocking system, springs that can support only compressive axial forces are arranged. The restoring force characteristic of these springs is shown in Fig.5(a). Furthermore, springs that present base plates are arranged on the bases of the base plate yielding system. The restoring force characteristic of these springs is a bi-linear type whose inelastic stiffness is 0.01 times the initial stiffness as shown in Fig.5(b). The physical values of the bi-linear type springs are shown in Table 3.

The earthquake ground motions used for analyses are 1940 El Centro NS and 1995 Kobe NS. The time scale is shortened to $1/\sqrt{3}$. The input acceleration is adjusted using input acceleration amplification factors in the following chapter. The time interval of step-by-step integration is

0.001sec, and the duration time is 5 sec. Damping is Rayleigh-type, and the first and the second damping factors are 0.5% respectively, which are constant still after yielding of structures.

Table 3 Physical values of springs for base plates

Model name	B1	B2
Initial stiffness [tf/cm]	79.8	269.4
Yield strength [tf]	2.38	5.35
Yield displacement [cm]	0.03	0.02
Rotational stiffness [tf cm/rad]	128	432

3 RESULTS OF ANALYSES

Fig.6 shows story shear forces of each model. These values are normalized by the corresponding values of the fixed-base model. In this figure and following figures, symbol R means the simple rocking model (R model) and symbol B1 and B2 mean the base plate models (B1 model and B2 model). The thickness of base plates of the B1 model is 6mm and that of the B2 model is 9mm. Fig.6 shows that story shear forces of the R model and the B models are reduced to 60-80% of those of the fixed-base model for the El Centro earthquake motion, and are reduced to 60% for

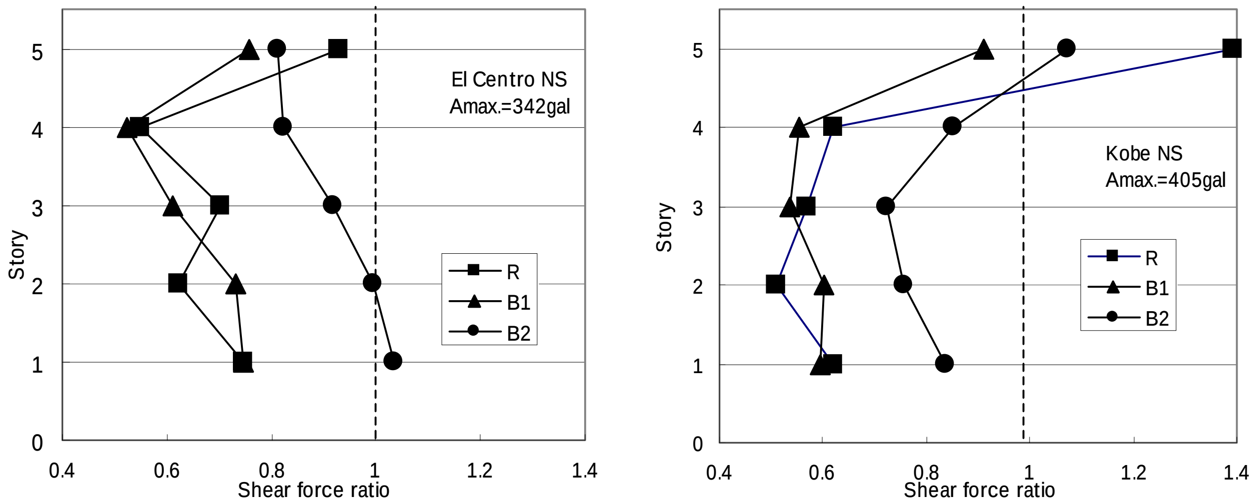


Fig.6 Shear force ratio of each story for 1940 El Centro NS and 1995 Kobe NS

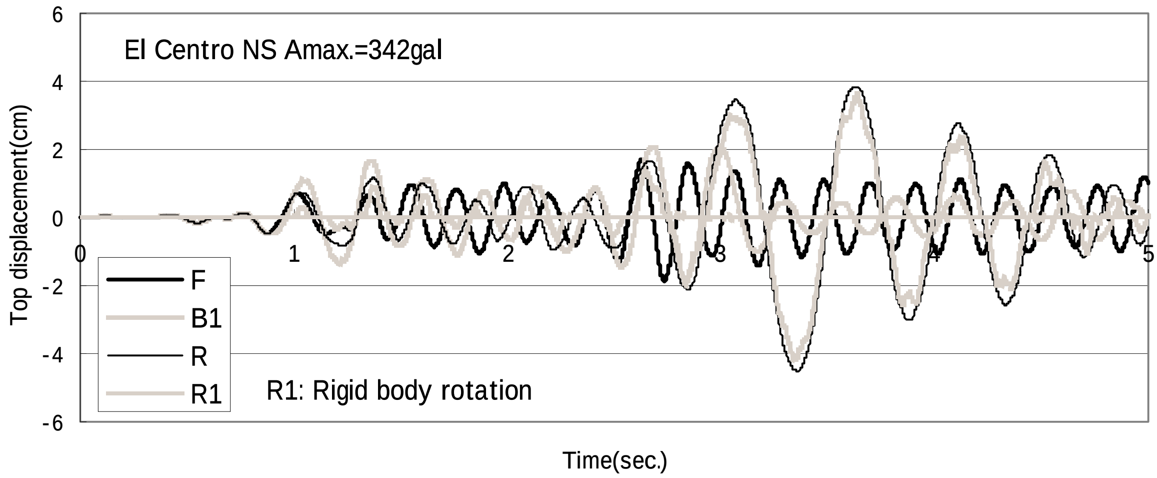


Fig.7 Time histories of top displacements of each model

the Kobe earthquake motion except on the top story. Earthquake responses of the B1 model are less than those of B2 model that has thicker and stronger base plates.

Fig.7 shows the time histories of top displacements of each model and rigid body rotations of the R model. The top displacements of the R model become large and its period is getting longer obviously after 3 second. It is also shown that rigid body rotations, which occur with structural models inclining, occupy most of the top displacements and elastic deformations of the frame are small. The maximum top displacement of the B1 model also exceeds that of the fixed-base model a little, but after 3 second, it is less than that of the fixed-base model.

Fig.8-10 show the responses calculated using El-Centro ground motions adjusted with various input acceleration amplification factors. The abscissa shows the input acceleration amplification factor. The responses of a pin base model (P model) are also shown as reference. And in this figure, arrow symbols show the point on which the plastic hinge occurs in the frame.

Fig.8 shows base shear coefficients. The difference in responses of analytical models is not observed clearly for 0.5 of the input acceleration amplification factor, because the rocking vibration is not caused. But when the input acceleration amplification factor exceeds 1.0, we can see the difference in the responses of these models. Base shear coefficients of the P model and the F model are almost constant after yielding of the frame. The responses of the B2 model are similar to those of the P model. The responses of the R model and the B1 model are smaller than those of the P model. It is shown that the B model also yields, when the base shear of the B model exceeds yield strength of the P model presented

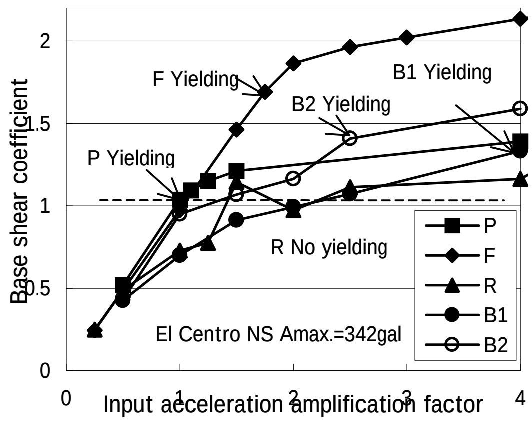


Fig.8 Base shear coefficient vs. input acceleration amplification factor

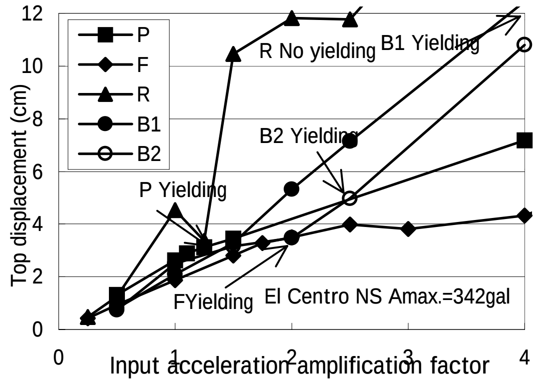


Fig.9 Top displacement vs. input acceleration amplification factor

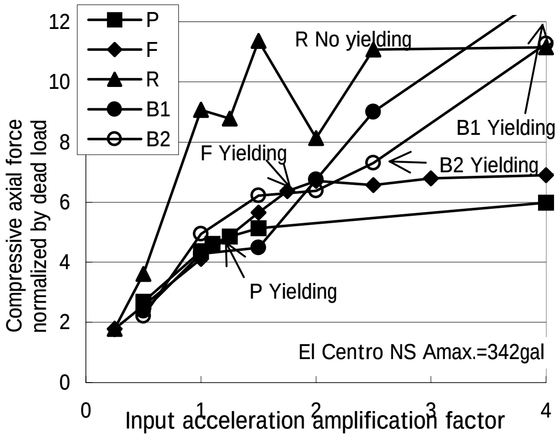


Fig.10 Compressive axial force normalized by dead load vs. input acceleration amplification factor

by a dotted line in the figure. Because rotational stiffness of column bases is relatively small and it is similar to those of the P model. The smallest input acceleration amplification factor which makes the analytical model yield is 1.1 for the P model, 1.75 for the F model, 2.5 for the B2 model and 4.0 for the B1 model. The R model remains elastic in the Figure. According to this result, the structure can be kept in elastic range to larger input acceleration and the structural demands can be relaxed by accepting the rocking vibration without fixing the foundations like current design methods.

Fig.9 shows top displacements. When the input acceleration amplification factor becomes larger, the top displacement of the R model increases rapidly by rocking vibration. Those of the F model become constant, when the input acceleration amplification factor is greater than 2 and the frame yields. Those of the B model increase lineally with the increase of the input acceleration amplification factor, because the up-lifting response increases with the base plates yielding.

Fig.10 shows the maximum compressive axial forces of the first story's columns normalized by dead load supported by them. Compressive axial forces of the column in the R model are larger than those in the other models, because more intensive shocks occur when structure lands. The larger the input acceleration amplification factor becomes, the larger the compressive axial force becomes. But when the input acceleration amplification factor reaches a certain level, the compressive axial forces become constant. On the other hand, the compressive axial forces of B1 and B2 models increase in proportion to the input acceleration amplification factor. But these are smaller than those of R model, because the top displacements are smaller and hysteretic damping of base plates dissipates earthquake energy.

4 CONCLUSIONS

The earthquake responses of the rocking system with weak base plates (the base plate yielding systems) were examined comparing with those of the simpler rocking system and the fixed-base system by nonlinear time history analyses. The results of this study are summarized as follows.

1) Story shear forces of the base plate yielding systems are reduced as much as those of the simpler rocking system. And the top displacements and axial forces are less than those of the simpler rocking system.

2) The top displacements and axial forces of the base plate yielding systems are almost similar to those of the fixed-base system under a certain input level.

3) From the above items 1) and 2), it was cleared that the rocking system with weak base plates is effective to reduce earthquake responses of buildings.

In the near future, the structural models for the rocking systems analyzed in this paper will be examined by shaking table tests.

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