SHAKING TABLE TESTS ON SEISMIC RESPONSE REDUCTION EFFECTS OF ROCKING BUILDING STRUCTURAL SYSTEMS

by

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ABSTRACT

Shaking table tests are carried out to examine seismic responses of rocking structural systems with base plate yielding (base plate yielding systems) comparing with those of fixed-base systems and simple rocking systems. Furthermore a simple method using the equivalent one mass system to predict the base shear that base plate yielding systems suffer when they begin up-lifting response (critical base shear of up-lifting response) is proposed. It is concluded that the base plate yielding systems can reduce effectively the seismic response of structures and their critical base shear of up-lifting response can be predicted by the proposed method appropriately.

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

1. INTRODUCTION

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 [1][2]. Based on this knowledge, we are now developing the rocking systems that can cause rocking vibration under appropriate control during earthquakes [3].

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 [4]. 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 by tension force of the column during a strong earthquake, the building causes rocking vibration.

In this paper, shaking table tests are carried out to examine seismic responses of this type of rocking systems (the base plate yielding systems) comparing with those of the fixed-base systems and the simple rocking systems which are fixed only in the horizontal direction under the footing beams.

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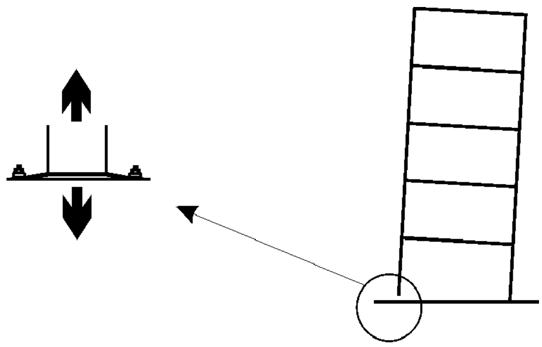
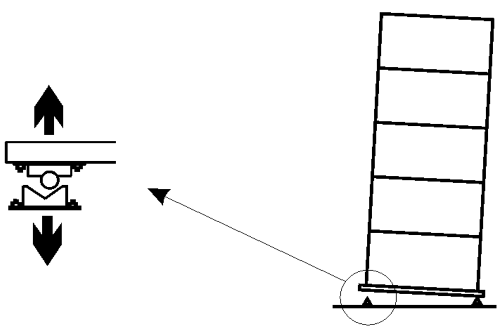
Outlines of the base plate yielding system and the simple rocking system are illustrated in Fig.1.

When we apply the base plate yielding system to real structures, we must adjust the physical characteristics of the base plate such as those dimensions and yield point, so that the building structures cause rocking vibration before they yield. Therefore we need to grasp the relation between the physical characteristics of the base plate and the critical base shear of up-lifting response. In the following, a simple method to grasp this relation is proposed and the applicability of this method is verified using test results.



(a) Base plate yielding system



(b) Simple rocking system

Fig. 1 Two types of rocking systems

2. SPECIMENS AND TEST METHOD

Specimens for the tests are composed of a steel frame shown in Photo. 1 and some structural components such as weak base plates attached to bases of the frame. Each floor height of the steel frame is 1m and total height is 5m. In the oscillation direction, the frame span is 2m. Each floor mass 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 Photo. 2 and Fig. 2. Thickness of the base plate is 6 mm or 9 mm. Material characteristics of steels used for base plates are shown in Table 3. In the following, the specimen with base plates whose thickness is 6 mm is referred to as BP6 model and the specimen with base plates whose thickness is 9mm is referred to as BP9 model respectively.

The structural component for the simple rocking system is shown in Photo. 3 and Fig. 3. In this component, shock absorbers can be installed between the upper and the lower part of it to weaken shock force which occurs when the structure lands after up-lifting.

Table 1 Mass of each story

Story	Mass (t)
RF	2.264
5F	2.292
4F	2.292
3F	2.292
2F	2.292
1F	1.456

Table 2 Cross sections of members

Column and beam	H148x100x6x9
Footing beam	H250x250x9x14

Table 3 Steels used for base plates

Model name	JIS	Yield point(N/mm^2)
BP6	SS400	334.18
BP9	SS400	300.86

Photo. 1 Specimen frame

Photo. 2 Base plate for BP model (1)

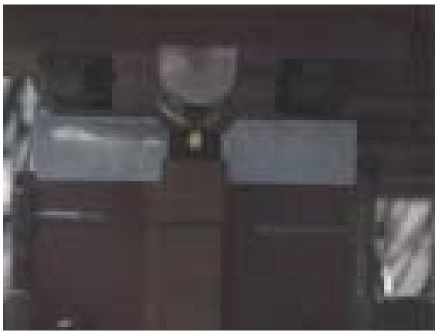


Photo. 3 Structural component for R model (1)

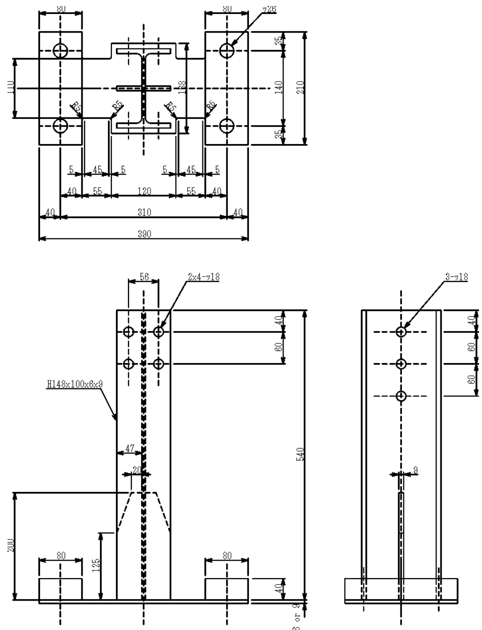


Fig. 2 Base plate for BP model (2)

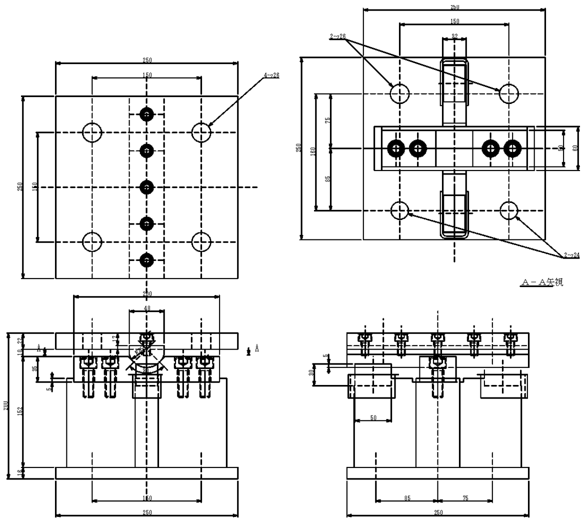


Fig. 3 Structural component for R model (2)

However, it was cleared that the test results for this specimen were not affected by the existence of the absorbers and the kind of them after the tests. Thus only the results that we get when using rubbers as the shock absorbers are shown in this paper. The specimen for the simple rocking system is referred to as R model.

The specimens are oscillated only in one direction, that coincides with the strong axis direction of columns. And in this direction, the frame shown in Photo.1 has no brace. The input ground motion used for the tests is 1995 JMA Kobe NS, of which the time scale is shorten to 1/√3.

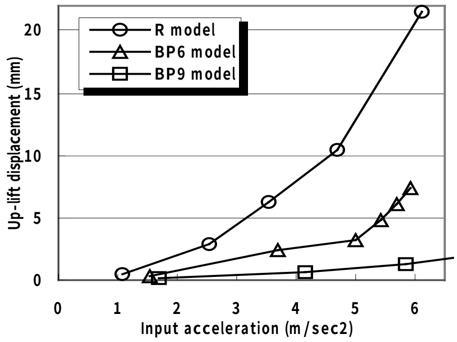
3. TEST RESULTS

Fig. 3 shows the relation between maximum input acceleration and response values of each model.

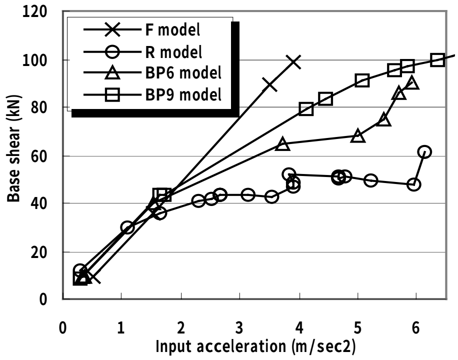
Up-lifting responses are small when the maximum input acceleration is nearly equal to 1.5m/sec2. These values of BP6 and BP9 models are almost 0.0. As the input acceleration becomes larger, the up-lifting responses increase monotonously. When the input acceleration becomes about 3.5 m/sec2, the up-lifting displacement of R model is 6.2 mm and that of BP6 model is 2.4 mm.

Base shears of all models are almost same each other when the input acceleration is smaller than 1.5 m/sec2. When the input acceleration becomes larger than 2.0 m/sec2, these values of R model are 40 kN to 50 kN and are constant approximately. And base shears of BP6 and BP9 models are also smaller than those of the fixed-base model (F model). In this study, base shears are evaluated as the summation of each story's horizontal force derived by multiplying each story's mass by each story's response acceleration. Each story's mass is derived by multiplying the summation of the mass of structural members and weights by 1.05 in order to evaluate the mass of bolts and steel plates in the connection.

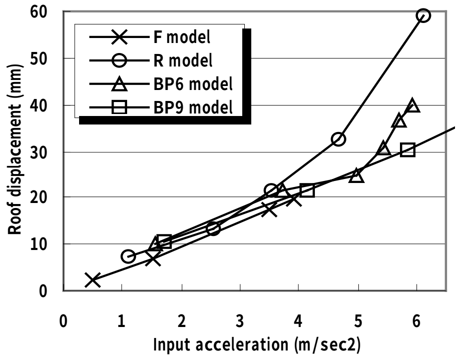
Roof displacements of all models are almost same when the input acceleration is smaller than 4.0 m/sec2. When the input acceleration is larger than 4.0 m/sec2, the displacement of R model is larger



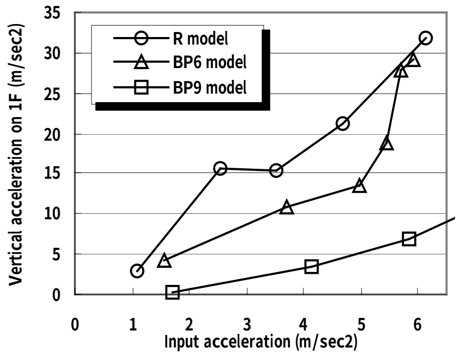
(a) Up-lifting



(b) Base shear

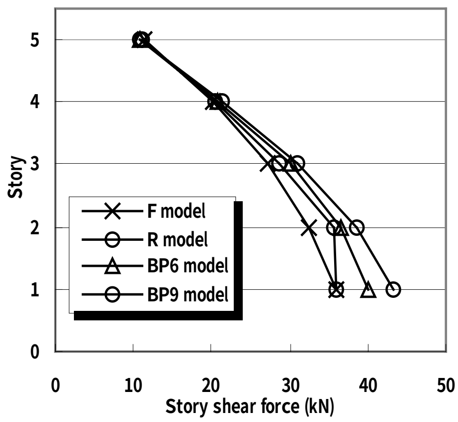


(c) Roof displacement

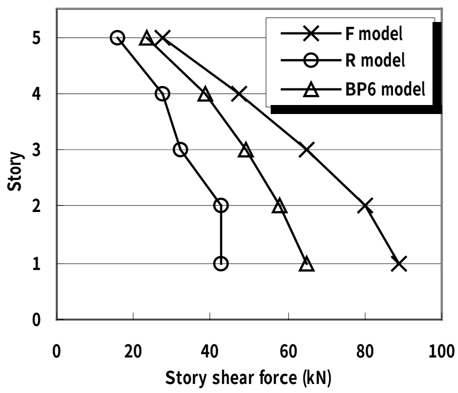


(d) Vertical acceleration around the base

Fig. 4 Maximum input acceleration vs. maximum response values



(a) Input acceleration: 1.5 m/sec2



(b) Input acceleration: 3.5 m/sec2

Fig. 5　Story shear forces

than those of the other models. It is thought the reason for this results are that the roof displacements of BP6 and BP9 model are smaller than those of R model and that hysteretic damping of base plates dissipates earthquake energy even when the specimens land.

Fig. 4 shows story shear forces of each model. These values are derived from the same method for the base shear. When the input acceleration is 1.5 m/sec2, the response values are almost same each other. When the input acceleration becomes 3.5 m/sec2, seismic response reduction effects of rocking structural systems can be observed clearly and all story shear forces of R and BP6 models are smaller than those of F model.

4. PREDICTION OF THE CRITICAL BASE SHEAR OF UP-LIFTING RESPONSE

To predict the critical base shear of up-lifting response, the moment balance of the equivalent one mass system shown in Fig. 6 is considered. The moment balance is expressed as Eq. (1).

$$M_u \cdot a \cdot H = M \cdot g \cdot \left(B/2\right) + n \cdot N_y \cdot B \qquad (1)$$

where,

Mu: the 1st effective mass in horizontal direction
a: horizontal response acceleration which occurs when the structure begin up-lifting response (critical acceleration of up-lifting response)
H: the 1st representative height
M: total mass
g: gravity acceleration
B: distance between columns
n: number of columns in the up-lifting side
Ny: tension yield strength of base plate

In the above equation, the first normal mode is needed to calculate the 1st effective mass *Mu* and the 1st representative height *H*. Now, we try to approximate this mode using horizontal story response acceleration distribution.

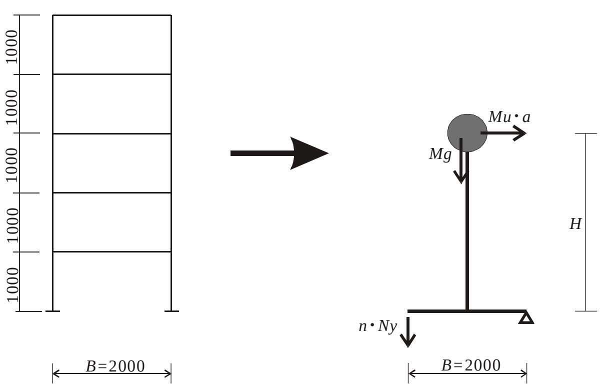


Fig. 6　Equivalent one mass system

Fig. 7 shows this distribution is shaped like the reversed triangle before and after up-lifting (Input acceleration is 15 m/sec2 and is 3.5 m/sec2). Thus the 1st effective mass *Mu* and the 1st representative height *H* are calculated assuming the normal mode shape is the reversed triangle. The 1st effective mass *Mu* of BP6 and BP 9 models is calculated as follows.

$$M_u = \frac{\left(\sum_{i=1}^{N} m_i \cdot {}_1u_i\right)^2}{\sum_{i=1}^{N} m_i \cdot {}_1u_i^2} = 9.83 \qquad \text{(t)} \qquad (2)$$

where,

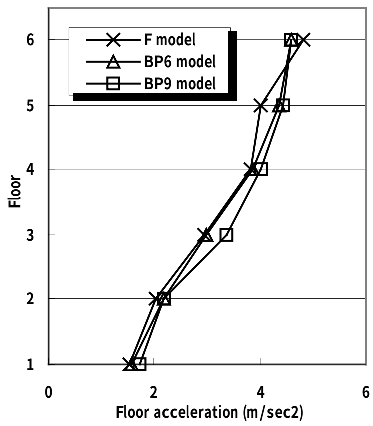
m_i: mass of each story

The 1st representative height *H* of BP6 and BP9 models is calculated as follows.

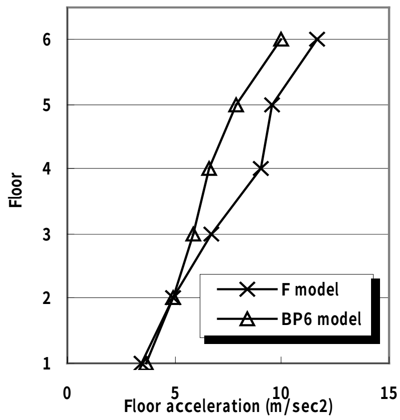
$$H = \frac{\sum_{i=1}^{N} m_i \cdot {}_1u_i \cdot h_i}{\sum_{i=1}^{N} m_i \cdot {}_1u_i} = 3.66 \qquad \text{(m)} \qquad (3)$$

where,

h_i: height of each story



(a) Input acceleration: 1.5 m/sec2



(b) Input acceleration: 3.5 m/sec2

Fig. 7 Each floor acceleration

The tension yield strengths of base plates of BP6 and BP9 models are calculated by Eq. (4) and Eq. (5) respectively.

[BP6 model]

$$N_y = \frac{n \cdot b \cdot t^2 \cdot \sigma_y}{2l} = 26.46 \qquad \text{(kN)} \qquad (4)$$

where,

n: number of base plates

b: width of base plate

t: thickness of base plate

l: length of base plate

σy: yield point of steel used for base plate

[BP9 model]

$$N_y = 53.61 \qquad \text{(kN)} \qquad (5)$$

By substituting *Mu* by Eq. (2) , *H* by Eq. (3) and *Ny* by Eq. (4) or Eq. (5) into Eq. (1), the critical acceleration of up-lifting response *a* is calculated as follows.

[BP6 model]

$a = 6.21$ (m/sec^2) (6)

[BP9 model]

$a = 9.23$ (m/sec^2) (7)

Furthermore the critical base shears of up-lifting response, which are approximated as the product between *Mu* and *a* are predicted by following equations.

[BP6 model]

$Q = Mu \cdot a = 61.10$ (kN) (8)

[BP9 model]

$Q = Mu \cdot a = 90.77$ (kN) (9)

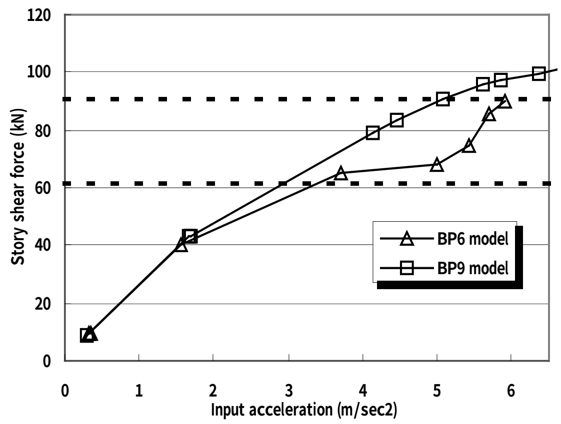


Fig. 8 Prediction of critical base shears of up-lifting response

In Fig. 8, the predicted values of the critical base shears of up-lifting response are compared with the corresponding test results. The figure shows the predicted values rather become underestimates to the test results, but they correspond each other with good agreements. When the input acceleration exceeds 5.0 m/sec2, the base shear of B6 model tends to ascend. It is thought the reason for these results is that tension displacements along the longitudinal direction become predominant under this input level. As for this point, we need to study furthermore by investigating the force deformation characteristics of base plates.

5 CONCLUSIONS

The earthquake responses of the rocking system with weak base plates (the base plate yielding systems) were examined comparing with those of the simple rocking system and the fixed-base system by shaking table tests. The results of this study are summarized as follows.

1) Base shears and story shear forces of BP6, BP9 and R models become smaller than those of F model, in the range of input acceleration where up-lifting response occur in these models.
2) Roof displacements of BP6 and BP9 models are not amplified extremely even in the range of input acceleration where those of R models become very large. And vertical acceleration around the frame base of BP6 and BP9 models is smaller than that of R models.
3) The simple method using the equivalent one mass system for prediction of the critical base shear of up-lifting response is proposed. And its applicability is ascertained using test results.

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