EFFECT OF COLLISION WITH RETAINING WALL ON BASE ISOLATED SUPERSTRUCTURE USING SHAKING TABLE

H. Fukui¹, H. Fujitani², Y. Mukai³ and M. Ito⁴

ABSTRACT

Base-isolated systems have been demonstrated to be an effective method to prevent damage to building superstructures during earthquakes. However, when the deformation of a base-isolated story exceeds the design value under extreme earthquake ground motions, the building can collide with the surrounding retaining wall.

As part of this study, shaking table tests were conducted on a seismically isolated shear-type building model colliding with a stopper, and the superstructure responses were measured in the experiments. The input ground motions were scaled to various amplitudes to examine the pounding effects of the superstructure under different collision velocities. The retaining wall was installed as a hard-metal stopper with steel or rubber members attached to its surface to investigate various values of hardness. The effects of collisions were considered for different wall rigidities. The shaking table test results indicated that the story shear forces on the superstructure caused by the impact responses are strongly correlated with the collision velocity. In addition, the floor acceleration at the time of collision reaches larger values at the impact moment than the case without a collision, and it depends on the rigidities of the retaining wall. Such a large impact force propagates up from the impacting story to the superstructure.

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²Professor, ³Associate Professor, ⁴Assistant Professor, Graduate School of Engineering, Kobe University, Japan H. Fukui, H. Fujitani, Y. Mukai, M. Ito. Effect of Collision with Retaining Wall on Base Isolated Superstructure Using Shaking Table. Proceedings of the 11th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.
Effect of Collision with Retaining Wall on Base Isolated Superstructure Using Shaking Table

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ABSTRACT

Base-isolated systems have been demonstrated to be an effective method to prevent damage to building superstructures during earthquakes. However, when the deformation of a base-isolated story exceeds the design value under extreme earthquake ground motions, the building can collide with the surrounding retaining wall. As part of this study, shaking table tests were conducted on a seismically isolated shear-type building model colliding with a stopper, and the superstructure responses were measured in the experiments. The input ground motions were scaled to various amplitudes to examine the pounding effects of the superstructure under different collision velocities. The retaining wall was installed as a hard-metal stopper with steel or rubber members attached to its surface to investigate various values of hardness. The effects of collisions were considered for different wall rigidities. The shaking table test results indicated that the story shear forces on the superstructure caused by the impact responses are strongly correlated with the collision velocity. In addition, the floor acceleration at the time of collision reaches larger values at the impact moment than the case without a collision, and it depends on the rigidities of the retaining wall. Such a large impact force propagates up from the impacting story to the superstructure.

Introduction

Extreme earthquake ground motions can induce extraordinarily large deformations in the base-isolated story. Under these ground motions, the base-isolated building may collide with surrounding retaining walls. Then, the response of the superstructure can be amplified. Thus, it is important to investigate the behaviors of the superstructure when a base-isolated building collides with a retaining wall. Recently, in Japan, a 460-mm deformation was observed in a base-isolated hospital in Aso city during the 2016 Kumamoto Earthquake [1]. The original design was called for a deformation of 550 mm. There have been several reports that observed the maximum deformation of a base-isolated story, but none of these reports examined collisions with a retaining wall. In the U.S., there is one report about the collision of a base-isolated building during the 1994 Northridge Earthquake [2-3]. However, the collision in this case was the result of an obstruction in the clearance. Thus, it’s regarded that there are no reports about collisions in actual base-isolated buildings around the world. Owing to increasing concern about the performance degradation of base-isolated buildings under strong earthquakes in recent years, there have been several studies examining collisions between base-isolated buildings and retaining walls [4]. In order to evaluate

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the superstructure response during a collision with a retaining wall, effects of backfill soil, the restoring force characteristics of the base-isolated story, and the dynamic properties of the superstructure need to considered in the analysis [5-7]. Also, in order to experimentally evaluate these effects, collision tests were performed on a shaking table for a three-story base-isolated building model by Masroor et al. in 2012 [8]. In the other study, the three-dimensional behavior of a full-scale base-isolated building was investigated using the E-Defense shaking table [9-10].

In this study, the basic behavior of a superstructure placed upon a base-isolated story is examined using a shaking table during a collision with a retaining wall. Ground motions in the single direction are considered [11]. The story shear force on a superstructure and the floor acceleration are evaluated for a single impact. The effect on the response according to the collision velocity of the base-isolated story during collision and the rigidities of the retaining wall are investigated.

Collision test on base-isolated model against retaining wall using shaking table

Test specimen

The dimensions and component configuration of the testing model used in this study are shown in Fig. 1. Tables 1 and 2 list the specifications of the shaking table and the testing model. Each floor was supported by flat roller bearings, and the restoring force was provided by a coil spring. Coil springs had linear characteristics within their available strokes. The accelerometers used for measurements were servo accelerometers (measurements up to 40 m/s^2) and piezoelectric accelerometers (measurements up to 100 m/s^2). In this study, the authors mainly use values measured with servo accelerometers, but when measuring more than 40 m/s^2, the authors use values measured with a piezoelectric accelerometer. The relative story displacement was measured with a displacement transducer.

<table>
<thead>
<tr>
<th>Element</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>70kN (Sinusoidal)</td>
</tr>
<tr>
<td>Max. Acceleration (Load: 5,000kg)</td>
<td>10m/s^2 (Sinusoidal)</td>
</tr>
<tr>
<td>Max. Velocity</td>
<td>1.0m/s (Sinusoidal)</td>
</tr>
<tr>
<td>Stroke</td>
<td>±275 mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.1~20 Hz</td>
</tr>
<tr>
<td>Table Dimension</td>
<td>3000 mm×2000 mm</td>
</tr>
</tbody>
</table>

Table 1. Specifications of shaking table.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Mass (kg)</th>
<th>Story</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>503.5</td>
<td>Third</td>
<td>124.9</td>
</tr>
<tr>
<td>3F</td>
<td>482.2</td>
<td>Second</td>
<td>112.3</td>
</tr>
<tr>
<td>2F</td>
<td>478.2</td>
<td>First</td>
<td>136.0</td>
</tr>
<tr>
<td>1F</td>
<td>738.4</td>
<td>Base-isolated</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Table 2. Structural properties of testing model.
Input ground motions

The input ground motions used in these experiments are as follows: the NS component of the ground motion (Max acceleration 2.3 m/s²) observed in Hachinohe port in Japan during the Tokachi-Oki Earthquake in 1968, with the input factor scaled from 58 to 63% (called Hachinohe), the NS component of a ground motion (Max acceleration 3.4 m/s²) observed in El Centro, California, during the 1940 Imperial Valley Earthquake, with the input factor scaled from 95 to 102% (called El Centro), and the NS component of the ground motion (Max acceleration 5.6 m/s²) observed at the JR Takatori Railway Station during the South Hyogo Prefecture Earthquake in 1995, with the input factor scaled from 51 to 59% (called Takatori). The same set of the input motions were applied in both cases, with and without collisions, for the shaking table tests.

Test outline

The testing model was excited by the shaking table and collided with a stopper (Fig. 2) installed with a clearance gap of 200 mm in order to simulate a collision with a retaining wall. The acceleration of each floor and every relative story displacement were measured by a sampling of 2 kHz. In cases without collisions, the stopper was removed. In this study, even if the collision occurred multiple times, authors targeted only the first collision. During the measurement, accelerometers and displacement transducers were treated with a 100-Hz low-pass filter (LPF) for all stories. A rubber or steel member was attached on the stopper used in this test. To examine the effect on the superstructure owing to differences in the rigidity of the retaining wall, nitrile rubber (NBR) with a hardness of 50º, 70º, or 85º for the rubber member and steel member (SS400) were used. A compression test was performed on the rubber members based on the measurement method described in the JIS standard. Young’s modulus for each attachment member calculated from the material test results and for the steel member, are presented in Table 3.

Table 3. Young’s modulus of stopper attachment member.

<table>
<thead>
<tr>
<th>Young's modulus: E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber (Hardness 50º)</td>
</tr>
<tr>
<td>Rubber (Hardness 70º)</td>
</tr>
<tr>
<td>Rubber (Hardness 85º)</td>
</tr>
<tr>
<td>Steel</td>
</tr>
</tbody>
</table>
Story shear force responses of the superstructure

Calculation methods for collision velocity and story shear force

Based on the measured values in the shaking table tests, the relative velocity at the time of the collision between the base-isolated story and retaining wall (called the collision velocity \( \nu \) (mm/s)) was calculated, and its relationship with the story shear force \( (F \text{ (kN)}) \) on the superstructure was examined. The collision velocity was calculated as follows. The time history of responses of the base-isolated story and the first floor shown in Fig. 3. The time is determined as the “collision time”, at which the relative story displacement exceeds the clearance (gap) and the floor acceleration rapidly increases by the collision. Then, the time history of relative story velocity is obtained by differentiating the relative story displacement of the base-isolated story. The relative story velocity at 0.0005 s before the collision time is regarded as the “collision velocity”. In addition, the story shear forces are calculated from multiplying the story stiffness (shown in Table 2) by the relative story displacements obtained from the displacement transducers.

![Figure 3. Time history of responses of the base-isolated story and the first floor.](image)

Collision velocity vs. story shear force

Fig. 4 shows the relationship between the collision velocity and story shear force for each story for all three earthquake inputs. For the collision cases, the story shear forces were plotted with the maximum story shear force observed at the time of collision. For cases without collisions, the story shear forces were plotted with the first peak of the story shear force after the displacement of the base-isolated story reached the length of the clearance. In the cases without collisions, the collision velocity was considered as the velocity when the relative story displacement of the base-isolated story exceeded the clearance. As an index of accuracy of the correlation line for each attachment member (steel = solid line, hardness of 85º = dotted line, hardness of 70º = dashed line, and hardness of 50º = dash-dotted line and without collision = long dashed line), the coefficient of determination \( (R^2) \) is noted below these figures. All correlation lines were defined to pass through the same point when the value of \( \nu \) was 0. The point of \( F \) at this time (\( \nu \) is 0) is based on the value of \( F \) in the case without a collision. For each story, it is noted that the story shear force has a linear relationship with the collision velocity with a strong correlation. Since the correlation line for each of the rubber hardness values is considered to be similar, the plots in Fig. 4 indicate that the story shear forces in the superstructure depend less on the rigidities of the retaining wall.
The amplification ratio of the story shear force (A) during a collision compared to the same case without a collision is presented in Fig. 5. While there is a clear tendency increasing amplification ratio of the shear force responses when the collision velocity increases, the effect of the wall rigidities has less influence on the story shear force. The correlation line as shown in Fig. 5 takes the value of A as 1.0 when the collision velocity is 0. Fig. 5 shows that when the collision velocity is 100 mm/s or lower, the story shear force amplification is slightly larger than 1.0, and the effect of the collision is quite small. However, when the collision velocity is around 500 mm/s, the story shear force amplification becomes about 3.0 or more. Thus, it is confirmed that the collision has a strong effect on the superstructure response. Validation of the linearity of relationships can apply to formulate a response prediction method for the story shear force on the superstructure during a collision. By using a numerical analysis of the story shear force in the case without a collision, the amplified responses of the superstructure seem to be evaluated by considering the amplification ratio within the linear elastic range of the retaining wall.
Effects of collision on floor acceleration and inertia force

In the previous section, the relative story displacement and the estimated story shear force (called the story shear force, calculated by displacement) were discussed. In this section, the influence of the floor acceleration during a collision is examined. Fig. 6 shows the time history of the floor acceleration during El Centro at 100%, comparing with and without a collision to the stopper that attached rubber hardness of 50°. An instantaneous increase in the acceleration response is evidently observed for each floor during a collision. The increase in the floor acceleration is particularly notable on the first floor. Figs. 7, 8 and 9 show the time history of the floor accelerations during El Centro at 100%, comparing with and without a collision for three cases: hardness of 70°, 85°, and steel. According to the increase in the rigidities of attached stopper elements, a significant increase in the acceleration on the first floor during a collision was observed. In the upper stories, however, the influence of the rigidities of attached stopper elements was not significant for the floor accelerations.

Fig. 10 shows the relationship between the collision velocity and the maximum acceleration ($M_A$ (m/s²)) for each floor during the three types of earthquake input. For the collision cases, the acceleration was plotted with the maximum floor acceleration during a collision. For the cases without collisions, the evaluation method for the maximum acceleration and collision velocity are the same as described in the previous section of “Collision velocity vs. story shear force”. For each story, it is noted that the floor acceleration has a mostly linear relationship with the collision velocity. The larger gradient of the correlation line can be seen in the larger rigidity of attached stopper elements (rigidity of the retaining wall).
Figure 8. Time history of floor acceleration. (El Centro 100%; Collision; Hardness 85°)

Figure 9. Time history of floor acceleration. (El Centro 100%; Collision; Steel)

Figure 10. Collision velocity vs. maximum floor acceleration relationships.
Story shear force obtained from accelerations

The inertia force in each floor was calculated by the mass of the floor and measured floor acceleration. The story shear force was calculated (called the story shear force, calculated by acceleration) as the sum of the inertia force above the considered story. As an example, Fig. 11 shows a comparison of the time history of the story shear forces calculated using two approaches: the story shear force (calculated by acceleration) and the story shear force (calculated by displacement) during El Centro at 100% for the case without a collision. In the case without a collision, both of the time histories of the story shear forces have accurate correspondence throughout the test. Fig. 12 shows a comparison of the time history of the story shear force, calculated using two approaches during El Centro at 100% for a case with a collision using rubber with hardness of 70°. In the case with a collision, there is a difference in the story shear forces at the time of collision for each story. When the larger rigidity of attached stopper elements or the faster collision velocity is given, the difference between the story shear forces calculated using two approaches becomes larger.

![Figure 11. Time history of story shear force. (El Centro 100%; Without collision)](image1)

![Figure 12. Time history of story shear force. (El Centro 100%; Collision; Hardness 70°)](image2)

Comparison of maximum story shear force for each story

Fig. 13 shows the maximum story shear force for each story using different attached stopper elements. In the case without a collision, both the story shear force (calculated by acceleration) and the story shear force (calculated by displacement) have similar values. In the case with a collision, both of these story shear forces show an increasing response compared to the cases without a collision. Therefore, the influence of a collision on the superstructure can be confirmed by comparing the maximum story shear forces in the case of a collision with those in the case without a collision. Because of an instantaneous increase in the floor acceleration, the difference
between the maximum story shear force (calculated by acceleration) and the maximum story shear force (calculated by displacement) are confirmed. In the case without a collision, the story shear forces on the superstructure are calculated either as the restoring force or sum of the inertia force above the considered story. These two evaluation values are considered theoretically equivalent. By contrast, during a collision, in addition to the story shear force in response to the restoring force, an inertia force due to the instantaneous increase in the floor acceleration is considered to have different effects from the story shear force that contribute to the relative story displacement.

Conclusions

In this study, the authors conducted a collision test of a base-isolated structure model with a retaining wall using a shaking table. Using the relative story displacement and the floor acceleration responses of the superstructure measured at collision time, the influence on the superstructure during a collision were discussed. The findings are shown below.

(1) The relationship between the maximum story shear force and the collision velocity was confirmed to be mostly linear for all stories. In this study, various rigidities of the rubber member and the steel member for the stopper attachment at the colliding part were used. Variations in the rigidity of the retaining wall were simulated; however, the story shear forces did not have remarkable differences depending on the rigidity of the attachment members.

(2) The relationship between the amplification ratio of the story shear force and the collision velocity was found to be mostly linear for all stories on this testing model under the current experimental conditions in this study, regardless of the rigidities of the retaining wall and the difference of the earthquake input. The shear force amplification ratio during a collision velocity of around 500 mm/s was about three times or more than the ratio without a collision.

(3) The relationship between the maximum floor acceleration and the collision velocity was confirmed to be mostly linear for all stories. The maximum floor accelerations changes depending on the differences in the rigidities of the retaining wall under the same collision.
velocity. Large increases in the floor acceleration were observed during collisions with larger rigidities of attached stopper elements.

(4) The story shear force was calculated from the sum of inertia force (the story shear force, calculated by acceleration). These values were compared with the story shear force calculated from the relative story displacement (the story shear force, calculated by displacement). These two ways of shear force evaluation agree well for the case without a collision. However, in the case with a collision, a difference between the story shear force (calculated by acceleration) and the story shear force (calculated by displacement) was observed because of an instantaneous increase in the floor accelerations.

Acknowledgments

The part of this study were supported by JSPS grant No.R2904 in the program for Advancing Strategic International Networks to Accelerate the Circulation of Talented Researchers.

The authors wish to acknowledge Gilberto Mosqueda, Professor of University of California San Diego, for his help in interpreting the significance of the results of this study.

References


