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EVALUATION OF DAMPING EFFECT OF SUPERSTRUCTURE BY OIL DAMPERS IN COLLISION OF BASE-ISOLATED BUILDING

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Abstract

Base-isolated systems have been shown to be one of the most effective methods to minimize the damage to building superstructures during earthquakes. However, when the deformation of a base-isolated story exceeds design considerations under extreme earthquake ground motions, the building might collide with a displacement-limiting device such as the surrounding retaining wall. Recently, several numerical studies have been conducted to ascertain characteristics of the superstructure of base-isolated building during a collision with the retaining wall, but such cases have not been validated experimentally.

For this study, shaking table tests were conducted on a seismically isolated shear-type building model colliding a load cell which can measure the force of the impact force with a retaining wall, and the superstructure response was measured in the experiments. The retaining wall was installed as a hard-metal stopper with rubber members to investigate various values of retaining wall rigidity. The strong impact force propagates from the impact story up to the superstructure, causing large floor acceleration and relative story displacement with much larger values than without collision.

To reduce the increase of the response on the superstructure during a collision, oil dampers were installed in each layer of the superstructure. The shaking table test results indicate that the floor acceleration and relative story displacement of the superstructure are strongly correlated with the collision velocity, with slight dependence on the retaining wall rigidity. Also, the damping effect by installing oil dampers to the superstructure were verified as well.

Furthermore, using a collision analysis model, the same experiment was compared with the analysis. In the experimentally obtained results, high-frequency components that have no effect on the displacement were found in the floor acceleration. By cutting off the high-frequency components considering the highest natural frequency of the test specimen, the floor acceleration from the experiment was determined properly, and the numerical simulation and experimentally obtained results showed good agreement. The collision analysis model can not only reproduce the experiment, but can be used to study a wider range of base-isolated buildings that could not be done due to specification of the test specimen and shake table and study further on the damping effect of superstructure in retaining wall collision.

Keywords: Base- isolated, Collision, Numerical Simulation, Oil Damper, Shaking Table,

1. Introduction

Base-isolated systems have been shown to be one of the most effective methods to minimize the damage to building superstructures during earthquakes. However, when the deformation of a base-isolated story exceeds design considerations under extreme earthquake ground motions, the building might collide with a displacement-limiting device such as the surrounding retaining wall. Evaluation of this scenario requires elucidation of superstructure behaviors when a base-isolated building collides with a retaining wall. In Japan, 300 mm deformations were observed in the base-isolated story of a building in Kushiro city during the 2003 Tokachi-Oki Earthquake [1] having a design deformation clearance of 550 mm. For the U.S., one report described collision of a base-isolated building during the 1994 Northridge Earthquake [2-4] that amplified the building response. However, the result of this case was a collision with an obstruction that was closer to the building than the rated clearance. No report of the relevant literature describes a full collision of an actual base-isolated building, although a large deformation in base-isolated systems has been reported. Recently, several studies have examined collisions between base-isolated buildings and retaining walls [5-9]. A design method [10-12] is also conceivable to allow collision with the retaining wall and reduce the increase of the response of the superstructure. However, it is necessary to correctly evaluate the response characteristics of the building during a collision.
For this study, shaking table tests were conducted on a seismically isolated shear-type building model colliding a load cell which can measure the force of the impact force with a retaining wall, and the superstructure response was measured in the experiments. To examine the damping effect of the response on the superstructure during a collision, oil dampers were installed in each layer of the superstructure. Furthermore, using a collision analysis model, the same experiment was compared with the analysis.

2. Shaking Table Tests of Base-Isolated Model Colliding Against Retaining Wall

2.1 Test specimen

The dimensions and component configuration of the testing model used in this study are shown in Figure 1. Table 1 list the specification of the testing model. Each floor was supported by flat roller bearings, and the restoring force was provided by coil springs. Compression springs were used in the superstructure, and tension springs were used in the base-isolated story. The compression spring and the tension spring both exhibited linear characteristics within their available strokes. In the superstructure model shown in Figure 1, each steel floorboard represented the degree of freedom for a shear-building-type model. The coefficient of viscous damping of each story was found using RD method [13].

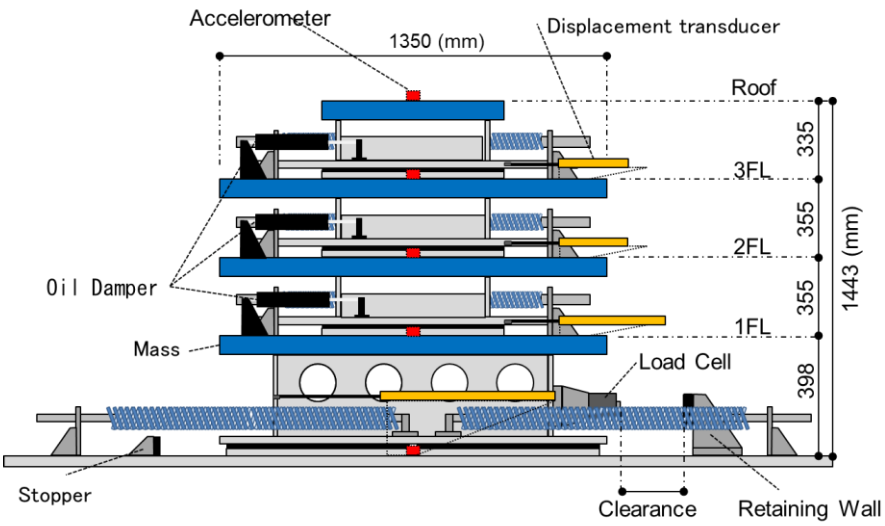


Fig. 1 – Configuration of base-isolated testing model

Table 1 – Structural properties of the testing model

Floor	Mass (kg)	Story	Stiffness (N/mm)	Damping coefficient (N・s/m)
Roof	611.3	Third	138.1	1145.2
3F	611.3	Second	221.5	1622.4
2F	611.3	First	213.4	1539.5
1F	713.2	Base-isolated	11.7	430.6

Natural Frequency (Hz)	Mode			
	1st	2nd	3rd	4th
Base-isolated	0.32	2.11	3.70	5.32

2.2 Input waves

The input waves used in these experiments were half-sine waves with the frequency of 1.6Hz. The maximum acceleration was 3m/s^2, with the input factor scaled from 23% to 35% by 1% increments. The lower limit of the input factor range is the minimum input at which the collision occurs. The upper limit of the input factor range is determined by the system capacity governed by the initiation of uplift in the model.

2.3 Testing procedure

When the testing model was excited by the shaking table, the load cell attached to the first floor collided with the retaining wall installed with a clearance gap of about 150mm (Figure 1). The acceleration of each floor and relative story displacement of each story were measured using a sampling of 1 kHz. To investigate the damping effect of the superstructure during a collision, oil dampers were installed to each story of the superstructure. Table 2 presents the specifications of the oil dampers used in the experiment. In cases without collision, the retaining wall was removed. In this study, even if there were multiple collisions, only the about the first collision was reported. During measurements, output signals from accelerometers, displacement transducers, and load cell were all treated with 100 Hz low-pass-filter (LPF). To assess the effects on the superstructure while varying the retaining wall rigidity, nitrile rubber (NBR) attached to the retaining wall was changed from hardness of 50°, 70°, 80°, and 90°. A compression test was performed on the rubber members based on the measurement method described in the JIS standard (JIS K6254; 2010 5.1 compression test method A). Compressive force-deformation curves were obtained. Table 3 presents the Young modulus and rigidities for each rubber member calculated from the material test results.

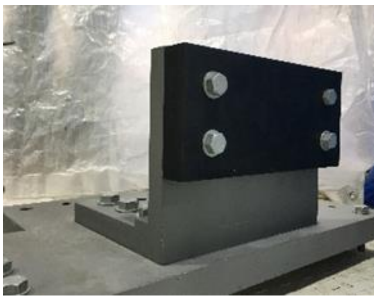


Fig. 2 – Photograph of the rubber member

Table 2 - The specifications of the oil dampers

	Maximum damping force	Designed damping coefficient	Stroke
Third story		2 kNs/m	
Second story	3 kN	3 kNs/m	±75mm
First Story		4 kNs/m	

Table 3 – Young's modulus and rigidity of rubber member

	Young's modulus : E (MPa)	Rigidity : K_w (kN/m)
Hardness 50°	3.69	292
Hardness 70°	6.82	540
Hardness 80°	18.53	1467
Hardness 90°	25.99	2058

3. Damping Effect of Superstructure by Oil Damper

3.1 Relations between the collision velocity and the response on the superstructure

Collision velocity was found by relative velocity of the base-isolated story at the time (=t_c) when the relative story displacement exceeded the length of the design clearance. Figure shows a schematic diagram of the calculation method of collision velocity. Figure 4 portray relations between the collision velocity and the maximum floor acceleration, maximum relative story displacement for all inputs. The maximum responses were observed from the first peak following the collision. Figure 5 portray relations between the collision velocity and the acceleration RMS value, relative story displacement RMS value for all inputs. The RMS value was in the range of the duration just until before the second collision.

Results show that the maximum responses and RMS values have a linear relation with the collision velocity. Furthermore, by installing the oil dampers, the maximum responses and RMS values were reduced. These results depend less on the difference of the retaining wall rigidity.

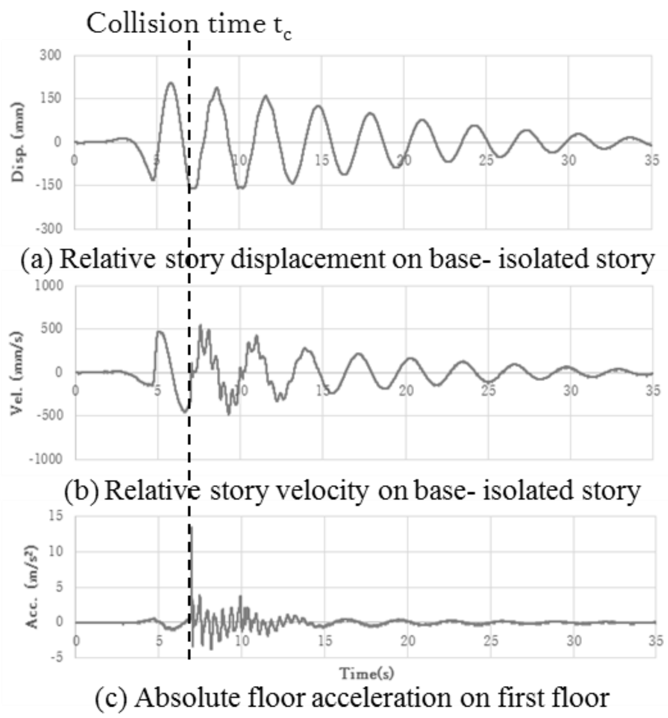
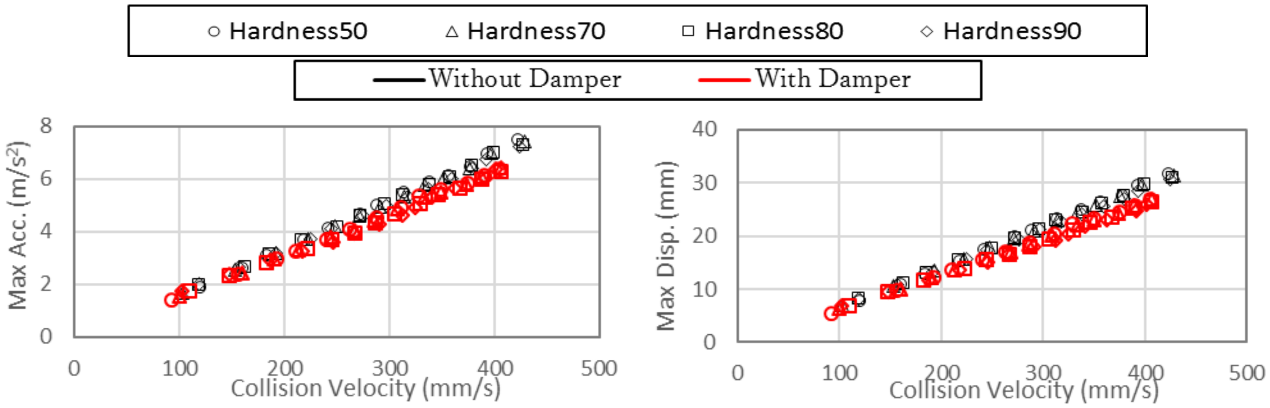


Fig.3 – Time-history of responses of base-isolated story and first floor

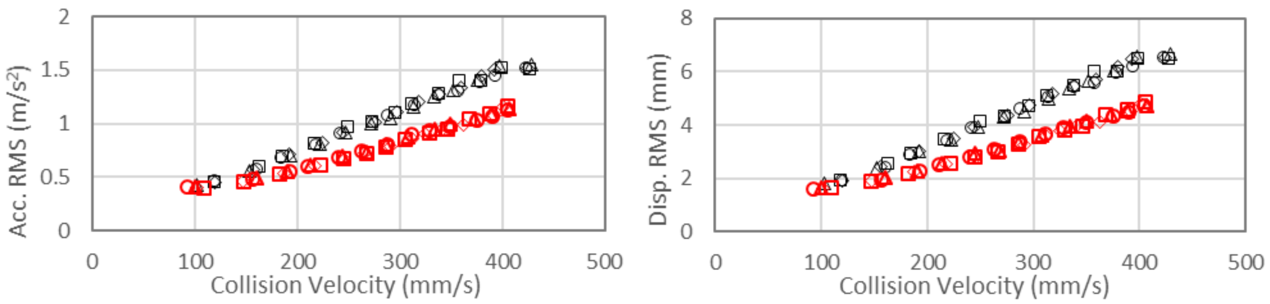
(Half-sine 30%; hardness 70°; with collision)



(a) Collision velocity vs. Maximum acceleration on roof

(b) Collision velocity vs. Maximum relative story displacement on third story

Fig.4 – Relations between the collision velocity and maximum responses



(a) Collision velocity vs. Acceleration RMS value on roof

(b) Collision velocity vs. Relative story displacement RMS value on third story

Fig.5 – Relations between the collision velocity and RMS values

3.2 Damping effect of superstructure by oil dampers

Damping effect on superstructure by oil dampers is evaluated based on the reduction rate, which is obtained by Equations (1) and (2).

$$\left(1-\frac{\text{Maximum response (with damper)}}{\text{Maximum response (without damper)}}\right)\times 100(\%) \tag{1}$$

$$\left(1-\frac{\text{RMS value (with damper)}}{\text{RMS value (without damper)}}\right)\times 100(\%) \tag{2}$$

Table 4 and 5 show the reduction rates of the maximum acceleration response and maximum relative story displacement of the superstructure. The reduction rate tended to be higher in the upper story. The average value was about 10%. Also, the difference in the reduction rate due to the difference in the hardness of the rubber member was hardly obsereved. Table 6 and 7 show the reduction rates of the RMS value of the superstructure. From table 6, it was found that the average value of the reduction rate of acceleration RMS value was about 20%, which was about 10% more than the reduction rate of the maximum acceleration. From table 7, it was found that the reduction rate of the relative story displacement RMS value was higher in the upper story, and the average value was about 16% to 19%. Also, it was confirmed that the values of the reduction rates depend less on the difference in hardness of the rubber members.

Table 4 – Reduction rate of maximum acceleration (%)

	2F	3F	Roof	Average
Hardness 50°	5.5	10.2	11.0	8.9
Hardness 70°	2.1	9.0	9.4	6.8
Hardness 80°	6.0	11.7	12.2	10.0
Hardness 90°	7.7	11.2	11.8	10.2

Table 5 – Reduction rate of maximum relative story displacement (%)

	First story	Second story	Third story	Average
Hardness 50°	7.5	8.2	12.5	9.4
Hardness 70°	6.5	7.5	11.6	8.5
Hardness 80°	8.5	9.1	13.8	10.5
Hardness 90°	7.1	9.5	14.2	10.3

Table 6 – Reduction rate of acceleration RMS value (%)

	2F	3F	Roof	Average
Hardness 50°	19.9	19.4	22.8	20.7
Hardness 70°	18.5	19.1	22.7	20.1
Hardness 80°	20.2	20.6	25.9	22.2
Hardness 90°	19.5	19.9	26.2	21.9

Table 7 – Reduction rate of relative story displacement RMS value (%)

	First story	Second story	Third story	Average
Hardness 50°	7.9	15.6	25.3	16.3
Hardness 70°	8.1	16.0	24.7	16.3
Hardness 80°	10.4	18.5	27.4	18.8
Hardness 90°	9.7	18.6	27.8	18.7

4. Validation of Analysis Model

4.1 Collision analysis model

A mass system model was created and analyzed using general-purpose analysis software Matlab. Figure 6 shows the analysis model. The analysis model is a 4-mass system model including the base-isolated story, and the mass of each floor, the stiffness of each layer and the damping coefficient are shown in Table 1. The collision is expressed by adding the rigidity of the retaining wall K_w to the rigidity of the base-isolated story when the clearance displacement is exceeded. The rigidity of the rubber member of each hardness is calculated from the Young's modulus (E), the rubber area at impact (A), and the rubber thickness (L) shown in Table 2, and the retaining wall rigidity K_w=EA/L (kN /m). The same value as the value set in the experiment is used for the clearance displacement. The analysis is performed at a sampling time of 1 kHz.

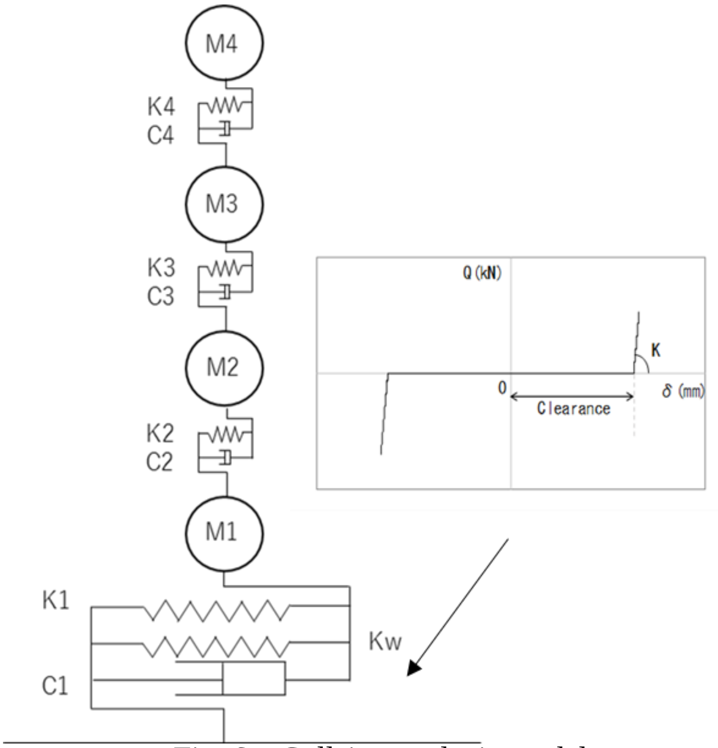


Fig. 6 – Collsion analysis model

4.2 Comparison of results found through experimentation and collision analysis

To verify the validity of the collision analysis model, the time history of responses obtained from the experiments and analysis were compared for the floor acceleration and relative story displacement. Figure 7 shows the time history response of the acceleration of each floor and the relative story displacement of each story during half-sine 30% without collision. From figure 7, it is considered that the analysis results of the acceleration of all floors and the relative story displacement of all stories accurately reproduce the experimental results. Figure 8 shows the time history response during half-sine 30% with collision(hardness 50°,without damper). It is confirmed from figure 8 that the maximum values of the relative story displacement of the experiment and the analysis were almost the same, and that the waveforms were also reproduced with high accuracy. However, in the case of the maximum acceleration, the value of the experiment and the analysis differed greatly especially in 1F, and the difference was more remarkable as the hardness increased. At a hardness of 90 °, there was a maximum relative error of about 70%, and the instantaneous increase in acceleration could not be reproduced with sufficient accuracy.

4.3 High-frequency component

Fourier spectrum analysis was applied to verify the effects of the high-frquency components included in the floor acceleration. Figure 9 presents a fourier spectrum of the floor acceleration on 1F during half-sine 30% with collision(hardness 50°,without damper). According to eigenvalue analysis, the natural frequencies of the testing model were 0.32 Hz (1st), 2.11 Hz (2nd), 3.70 Hz (3rd), and 5.32 Hz (4th). As Figure 9 shows, fourier spectrum had four predominant peaks around these four natural frequencies. However, it includes response components higher than about 10 Hz, which are frequencies higher than the highest order natural frequency of the test model. To investigate characteristics of these high-frequency response components in floor acceleration, the measured acceleration responses at each flooor are decomposed into two waveforms in high and low range frequencies at the cut-off frequency of 6 Hz. Considering that the highest natural frequency (4th mode) of the testing model was 5.32 Hz, the acceleration wave was decomposed into low- frequency components and high-frequency components by application of a low or high pass filter (LPF and HPF) with cut-off frequency of 6Hz.

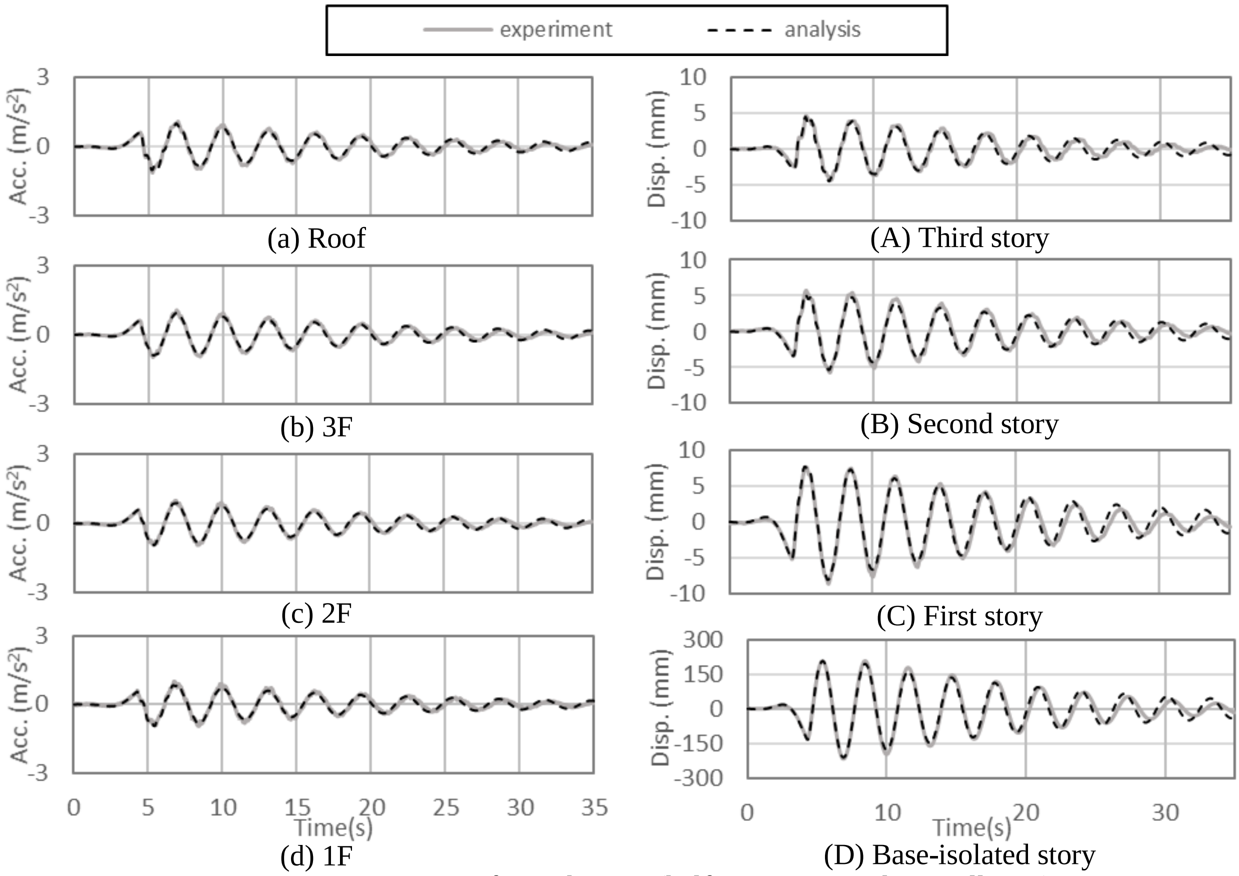


Fig. 7 – Comparison of time-history (half-sine 30%, without collision)

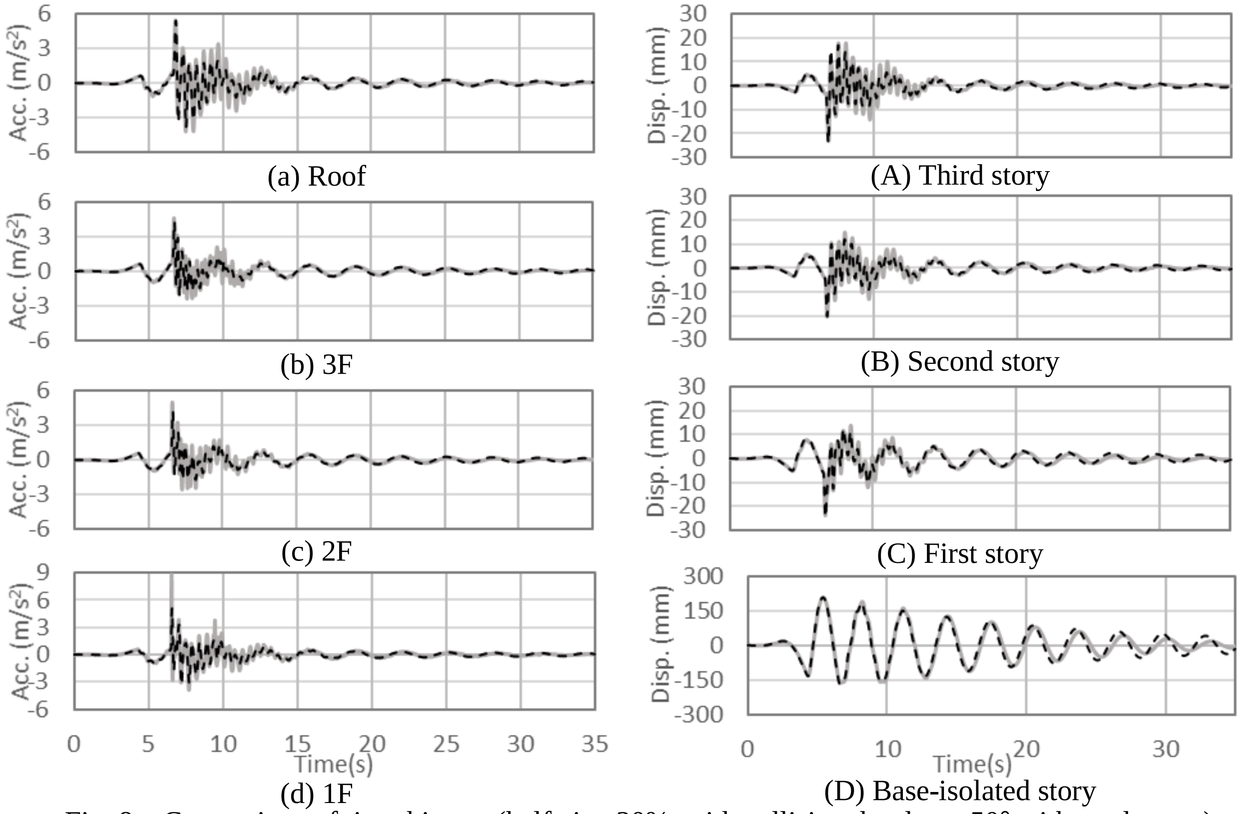
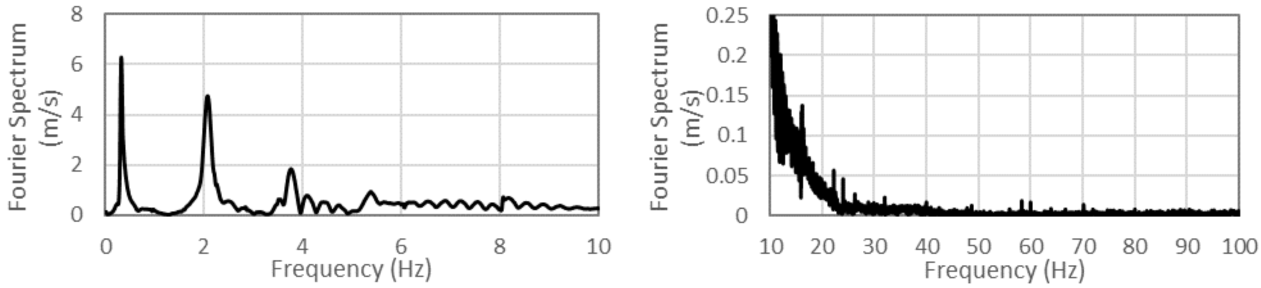


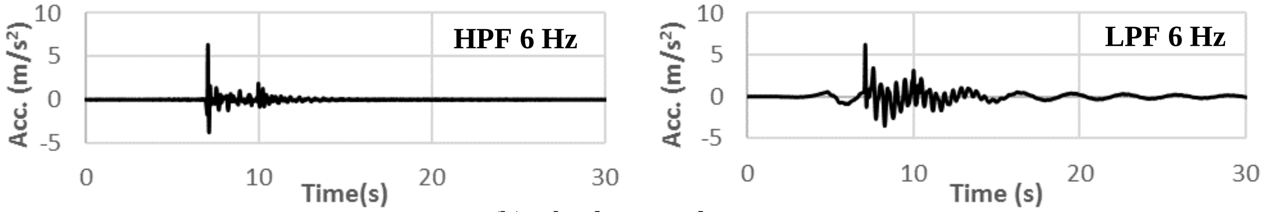
Fig. 8 – Comparison of time-history (half-sine 30%, with collision, hardness 50°,without damper)

Figures 10(a) and 10(b) respectively decipt time histories of floor acceleration responses decomposed into high and low ranges at the cutt-off frequency of 6Hz and time histories of relative story displacements by integrating the decomposed floor acceleration repsponses twice. From these figures, it was comfired that high-frquency components have no influence to the response displacement of the testing model during a collision. Figure 11 depicts a comparison of floor acceleration responses(LPF 6Hz) during half-sine 30% with collision(hardness 50°,without damper).

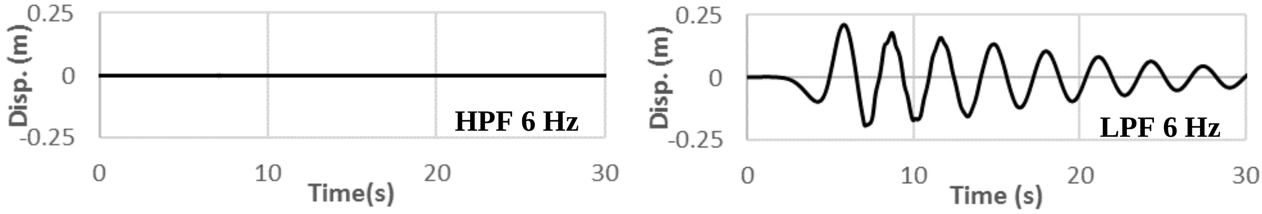


(a) Range of 0 Hz – 10 Hz (b) Range of 10 Hz – 100 Hz

Fig. 9 - Fourier spectrum of the floor acceleration on 1F (half-sine 30%, hardness 50°)

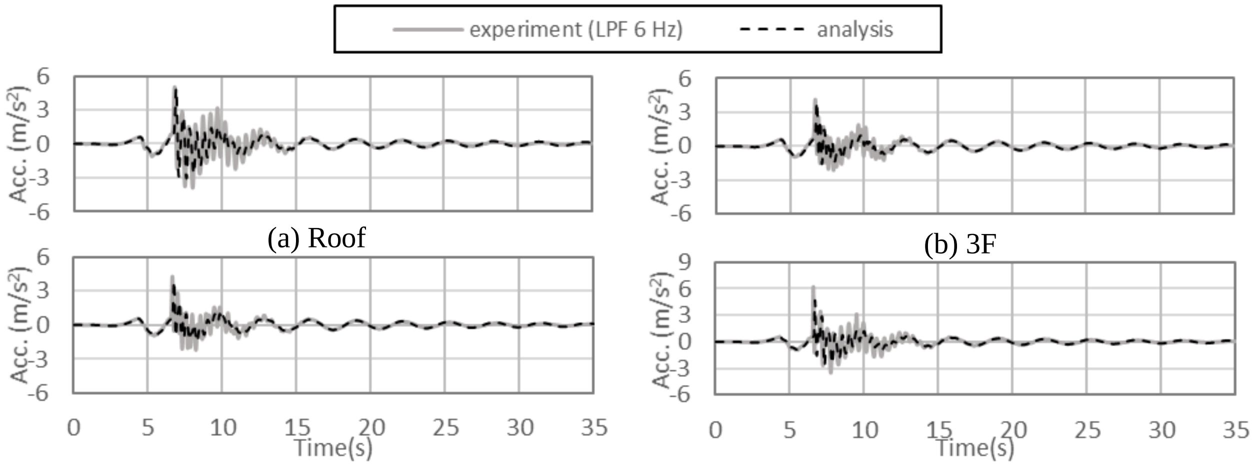


(b) Absolute acceleration



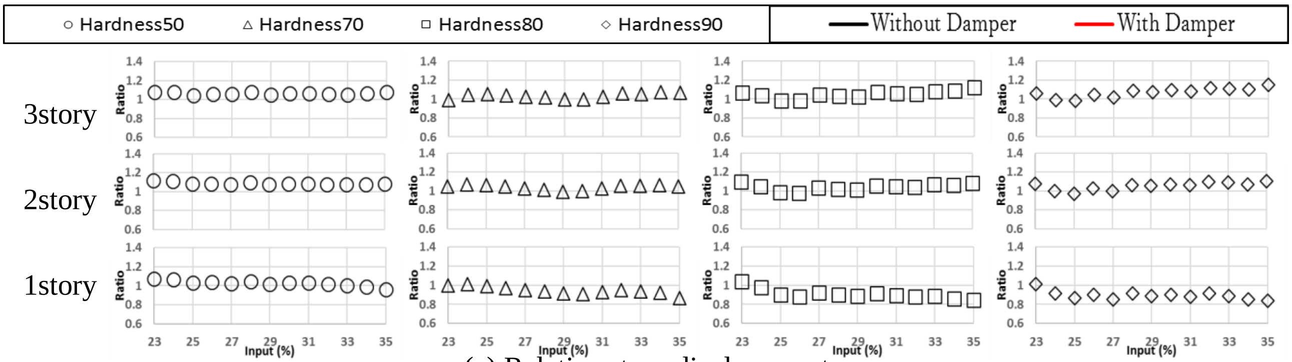
(b) Absolute displacement

Fig. 10 – Time-history of floor acceleration and displacement on the first story

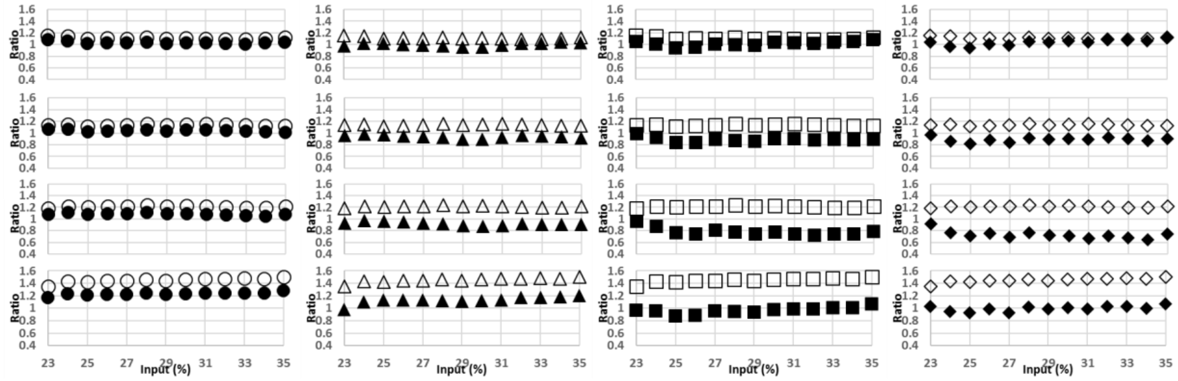


(a) Roof (b) 3F (c) 2F (d) 1F

Fig. 11 – Comparison of time-history (half-sine 30%, with collision, hardness 50°,without damper)

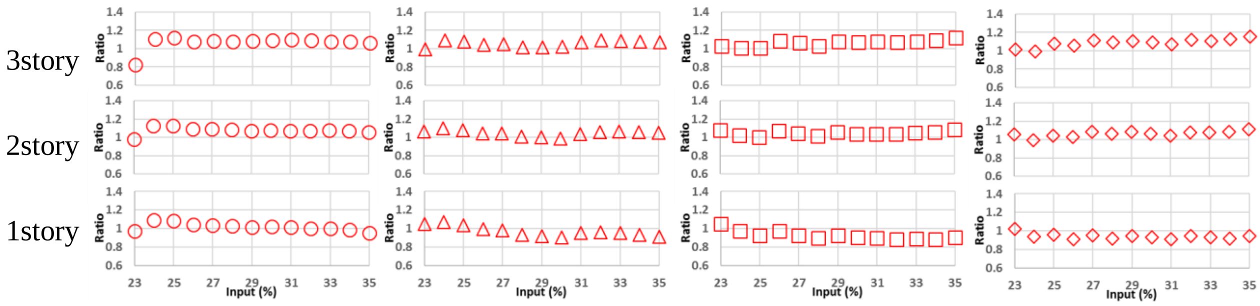


(a) Relative story displacement

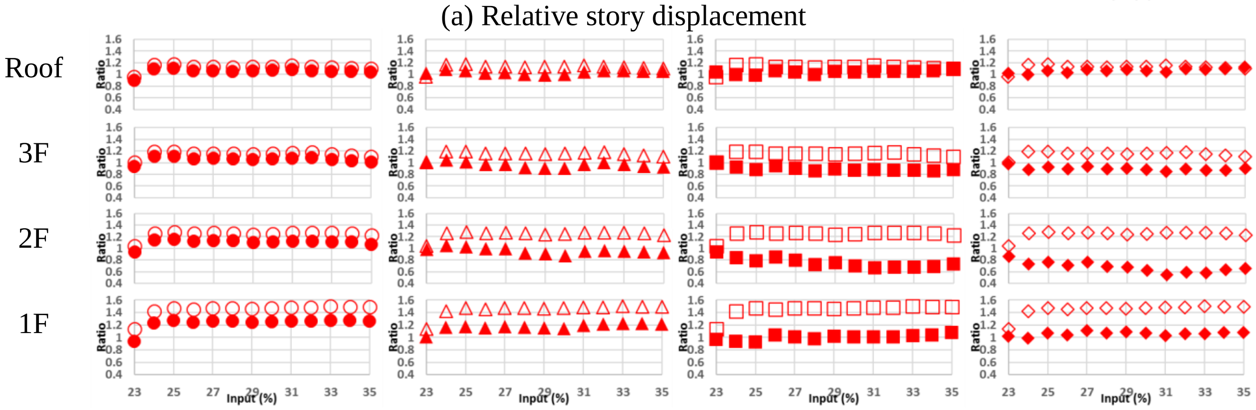


(b) Floor acceleration

Fig. 12 – Comparison of maximum response values using experiment and collision analysis



(a) Relative story displacement



(b) Floor acceleration

Fig. 13 – Comparison of maximum response values using experiment and collision analysis

From figure 11, it was confirmed that the maximum error rate of in the floor acceleration on the 1st floor was significantly reduced. Figure 12 and 13 show maximum values obtained as analysis results and experimentally obtained results for each floor acceleration and each relative story displacement. Figure 12 and 13 plots show the ratio of the maximum value of the analysis results divided by the maximum value of the experimentally obtained results. In the figures, experimental results treated by LPF are filled with color. The effect of the error rate on the other floors increases as the hardness increases. This is because the measurement part of the load cell has a curvature, but it was treated as a plane in the analysis, so that the evaluation of the rigidity was not sufficient. It is considered that the difference is smaller for a rubber member having a lower hardness having a large amount of indentation during collision. From the above, it was confirmed that the experimental response could be reproduced by analysis to some extent by removing the high-frequency components included in the floor acceleration of the experimental values. However, in order to reproduce acceleration with sufficient accuracy, it is necessary to consider accurate retaining wall rigidity and the effects of higher modes.

5. Conclusion

In this study, an extensive experimental study using a shaking table was conducted considering collision of a base-isolated model, installing oil dampers on the superstructure, with a retaining wall. Using the relative story displacement and the floor acceleration responses of the superstructure measured through the collision, the influence of impact on the superstructure response and the damping effect of superstructure by oil dampers were investigated. Findings are summarized as follows.

1. The relationships between the collision velocity of the base-isolated velocity and maximum response, RMS value were obtained. The relationships between the collision velocity of the base-isolated velocity and maximum response, RMS value were confirmed to be mostly linear for all stories. In this study, rubber members having various hardness values were used as stopper at the colliding interface. Variations in the rigidity of the retaining wall had no notable effect on the story shear force.

2. Damping effect on superstructure by oil dampers was evaluated based on the reduction rate. The reduction rates of the maximum acceleration response and maximum relative story displacement of the superstructure tended to be higher in the upper story and the average value was about 10%. The reduction rates of the RMS value of the superstructure was observed, and it was found that the average value of the reduction rate of acceleration RMS value was about 20%, which was about 10% more than the reduction rate of the maximum acceleration. The reduction rate of the relative story displacement RMS value was higher in the upper story, and the average value was about 16% to 19%.

3. Using a collision analysis model, the time history of responses obtained from the experiments and analysis were compared for the floor acceleration and relative story displacement. Without collision, it was considered that the analysis results of the acceleration of all floors and the relative story displacement of all stories accurately reproduce the experimental results. During collision, it was confirmed that the maximum values of the relative story displacement of the experiment and the analysis were almost the same, and that the waveforms were also reproduced with high accuracy. However, in the case of the maximum acceleration, the value of the experiment and the analysis differed greatly especially in 1F, and the difference was more remarkable as the hardness increased.

4. In the experimentally obtained results, high-frequency components that have no effect on the relative story displacements were found in the floor acceleration responses. By cutting off the high-frequency components considering the highest natural frequency of the testing model, it was confirmed that the experimental response could be reproduced by analysis to some extent. However, in order to reproduce acceleration with sufficient accuracy, it is necessary to consider accurate retaining wall rigidity and the effects of higher modes.

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