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Response reduction methods for base isolated buildings with collision to retaining walls

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ABSTRACT

This paper proposes a new damper that can change the damping force depending on the response displacement and response velocity. The proposed damper reduces the damage of seismic-isolated structures which undergo excessive deformation during huge earthquakes, without lowering the performance of the seismic-isolation system during medium to small magnitude earthquakes. We investigate the effects of using the proposed attenuator on the responses of a superstructure model to seismic motion that causes collision with retaining walls. An experiment using a shaking table is conducted, and the results from the test are compared with those from numerical analyses. The test results agree approximately with the numerical analysis results except for the absolute acceleration results in collision cases.

Keywords: Seismic-Isolation Structures, Collision with Retaining Walls, On-Off Dampers

1. INTRODUCTION

In Japan, seismic isolation systems have been used increasingly to mitigate damage to building structures during earthquakes, especially after the Hyogo-ken Nanbu Earthquake of 1995. Excessive deformation of a building's isolation layer during a huge earthquake may cause the layer to collide against retaining walls if the clearance between the building and the retaining walls is insufficient. This phenomenon cannot be overlooked, especially in seismic-isolated buildings which are expected to be highly earthquake resistant. Hence, it is imperative to redesign the seismic isolation system to reduce the response displacement (deformation of the isolation layer) in newly constructed buildings as well as in already constructed buildings with insufficient clearance around the isolation layers. Passive dampers can be used to effectively restrict the response displacement of the isolation layer, because the damping force could be increased. This solution is effective during large earthquakes; however, they also increase the response acceleration during medium to small earthquakes and lower the performance of the seismic isolation structure. In this paper we propose a new damper called an on-off damper that can vary the damping force depending on the response displacement and response velocity^{1,2)} (Fig. 1). The on-off damper has an elongated hole at the support joint. Only when the response displacement exceeds a certain level, the joint comes in contact with the edge of the loose hole and pushes or pulls the cylinder to attenuate the earthquake force. The design involves a simple modification of the shape of the pin support in existing oil dampers and requires only slight modification of existing attenuators. A gap damper was proposed in previous work and its effectiveness was evaluated in a shaking test; however, the experiments did not include collision with retaining walls around the structure³⁻⁶⁾. We investigate the efficacy and the effects of using the proposed attenuator on the responses of a superstructure model under seismic forces that causes the isolation layer to collide with the retaining walls. An experiment using a shaking table is conducted, and the test results are compared with the numerical analysis results.

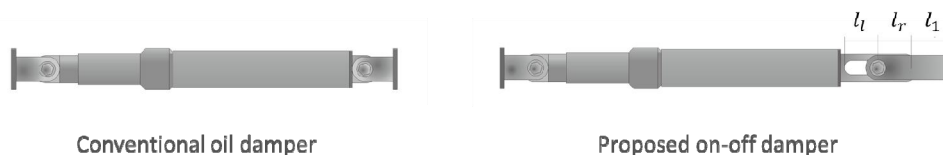


Figure 1. Schematic diagram of a conventional damper (left) and an on-off damper (right).

2. DAMPING DEVICE

2.1 Initial Damper

We use an magnetorheological fluid damper (MR damper) as an initial damper. The force of an MR damper can be controlled by changing the applied electric current. The MR damper was set to simulate a bilinear hysteresis of an oil damper with a valve relief, with the parameters shown in Table 1.

Table 1. Parameters of simulated bilinear hysteresis.

	UNIT	VALUE
Viscous damping coefficient (before relief)	kN/(m/s)	6.82
Post-relief viscous damping coefficient	kN/(m/s)	0.44
Relief force	kN	0.89
Velocity at relief	m/s	0.13
Maximum force	kN	1.27
Maximum velocity	m/s	1.00

2.2 On-Off Damper

Consider the actuated condition of an on-off damper (Fig.1) when the structure is connected to the right side support of the on-off damper and the shaking table is connected to the left side of the damper. The left and right clearance of the hole at the i -th step in the vibration are expressed as

$$l_{li} = l_{l(i-1)} + u_i$$

$$l_{ri} = l_{r(i-1)} - u_i$$

$$u_i = x_i - x_{i-1}$$

in which l_{li} and l_{ri} are the left and right clearances at the i -th step; x_i = the relative displacement of the isolation layer (the right direction is plus) at the i -th step. The on-off damper actuates when

$$l_{li} \leq 0 \quad \cap \quad V < 0$$

$$l_{ri} \leq 0 \quad \cap \quad V > 0$$

where $V = \frac{u_i}{\Delta t}$ (relative velocity of the isolation layer); Δt = time interval for 1 step.

3. SHAKING TABLE TEST

3.1 Experimental contents

We conducted an experiment using a shaking table to confirm the effect of the on-off damper. The test specimen is a four-story model with a base isolation layer (Fig. 2); its composition is shown in Table 2. Damping devices are installed on the base isolation layer. The initial damper is one MR damper described in subsection 2.1. The additional dampers were on-off dampers with three different damping coefficients ($c = 0.98, 1.96, \text{ and } 2.94$ [kN s/m], hereafter denoted as dp1, dp2, and dp3, respectively) and three initial clearance lengths ($l = 0, 25, \text{ and } 50$ [mm], hereafter denoted as L0, L25, and L50, respectively). The oil damper in the on-off dampers has linear viscous damping force characteristics, and two

on-off dampers are set at the base isolation layer. The input accelerations were the estimated pulse waveforms of earthquakes that are predicted to occur along Uemachi fault in Osaka, Japan (calling them level-3C earthquakes⁷⁾), and three observed earthquakes (El Centro 1940 NS, Hachinohe 1968 NS, JMA Kobe 1995 NS) normalized to the maximum velocity of 50 cm/s (level-2 earthquakes). Figure 3 shows the time history waveforms of the input accelerations. The level-3C pulse waves have three periods, 1, 2, and 3 s (hereafter denoted as Tp1, Tp2, and Tp3, respectively). The similarity ratio of length between a test and real model is 1:4, and time is condensed to half the original length of the signal. A stopper with a rubber pad represents the retaining wall (Fig. 2) and the stoppers are attached at both sides. The clearances between the test specimen and the stoppers are 100 mm and 150 mm (denoted as L_w100 and L_w150 , respectively).

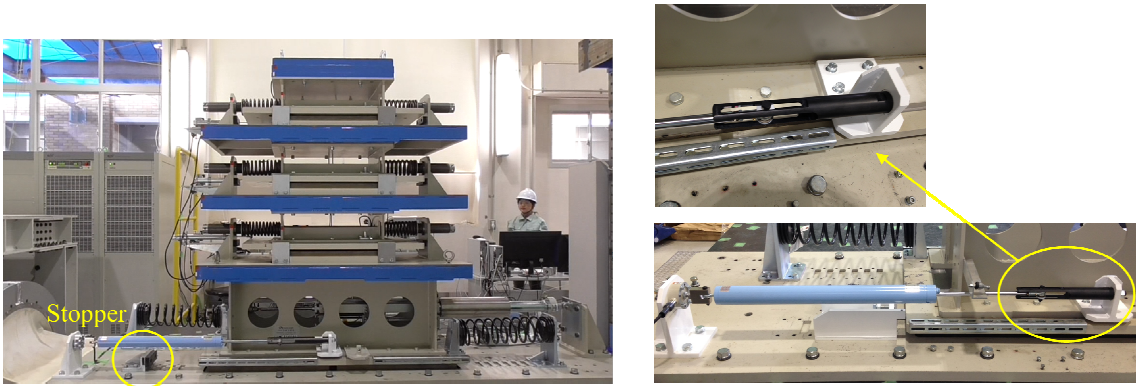


Figure 2. Experimental setup showing the test specimen (left panel) and on-off damper (right panels).

Table 2. Mass and stiffness parameters of four-storied test specimen.

STORY	MASS (kg)	STIFFNESS (kN/m)
4th	503.5	118.0
3rd	482.2	111.4
2nd	478.2	137.7
1st	713.2	18.8

First natural period of base isolation model	2.14 (s)
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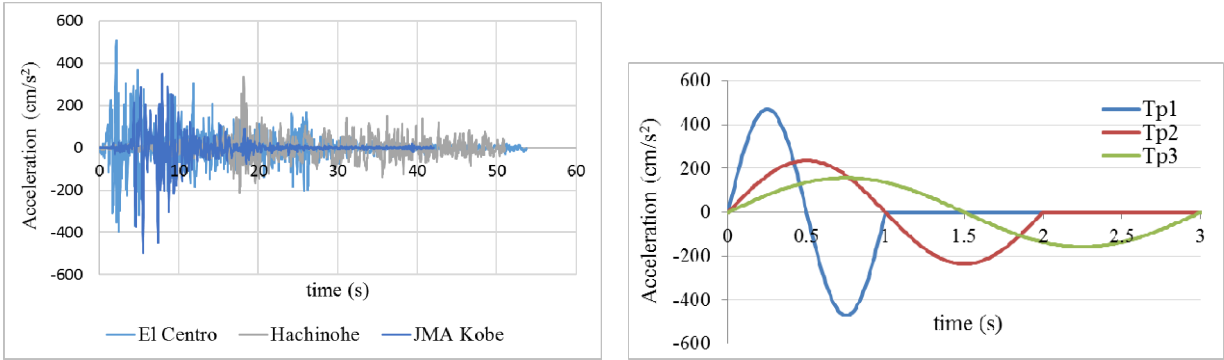


Figure 3. Time history waveforms of input accelerations from three observed earthquakes (El Centro 1940, Hachinohe 1968, and JMA Kobe 1995) and pulse waves of 1, 2, and 3 s (Tp1, Tp2, and Tp3, respectively).

3.2 MR damper characteristics

We control the MR damper to simulate an oil damper with bilinear hysteresis. Figure 4 shows the behavior of the MR damper superimposed on the target performance line. The blue line shows the MR damper's behavior in response to a Tp1 pulse wave without on-off dampers, while the green line shows the MR damper's behavior when a Tp1 pulse wave is input with dp2, L50 on-off dampers. The black line shows the target trajectory of damping force. The output damping force with the MR damper is close to the target within the relief velocity or the positive velocity, but moves away from the target when the negative velocity exceeds the relief velocity. This occurs when the damping force rises up from zero for the first time, and is observed in all cases.

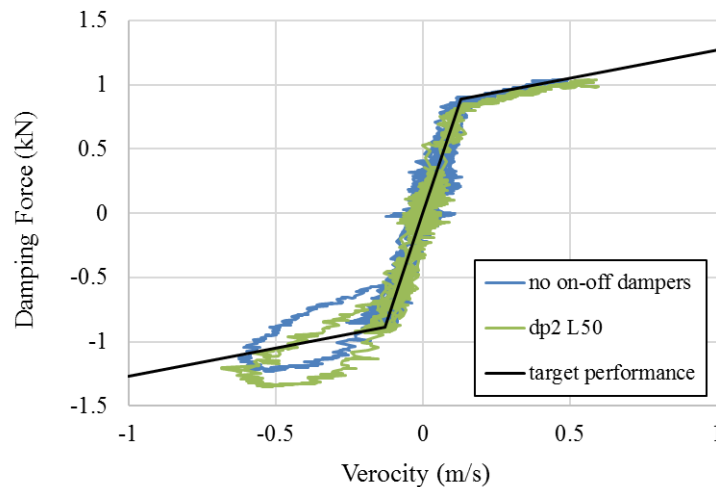


Figure 4. Damping force of MR dampers with and without additional damper (green and blue lines, respectively) and the target line (black line).

3.3 Test results

Figures 5 and 6 show the maximum relative story displacement and maximum absolute acceleration for each floor, respectively, in response to the El Centro and JMA Kobe earthquake waves and the Tp2 and Tp3 pulse waves. The solid lines are the test results when the stoppers (as retaining walls) were not set, and the dotted lines represent the collision cases. The green lines are the results with the dp1 on-off dampers, the blue lines are those with dp2, and the red lines are those with dp3. The gray lines are the results without on-off dampers. The results for each input type are shown for three cases of the initial clearance of the on-off damper: L0, L25, and L50. We can define the response ratio as follows.

$$\text{Response ratio} = \text{Maximum response with on-off dampers} / \text{Maximum response without on-off dampers}.$$

Table 3 and 4 show the response ratios of the relative story displacement and those of the absolute acceleration, respectively, for the level-2 observed earthquakes. Table 5 and 6 show the response ratios of the relative story displacement and those of the absolute acceleration, respectively, for the level-3C pulse waves when the retaining walls were set.

Response to level-2 earthquake waves with L0 on-off dampers (conventional dampers)

For the upper stories, the response ratios of the relative story displacement ranged from 1.13 to 1.47 and those of the absolute acceleration ranged from 1.13 to 1.55. When the additional dampers were changed to L25 on-off dampers, the maximum response ratio of the relative story displacement for the upper stories was 1.20 and that of the absolute acceleration was 1.33; in this case, the increase of the response caused by the on-off dampers was restrained to some degree. When the L50 on-off dampers were used as additional dampers, there was no change in the response. For the response to level-2 earthquake waves, L50 on-off dampers perform mostly the same as without on-off dampers.

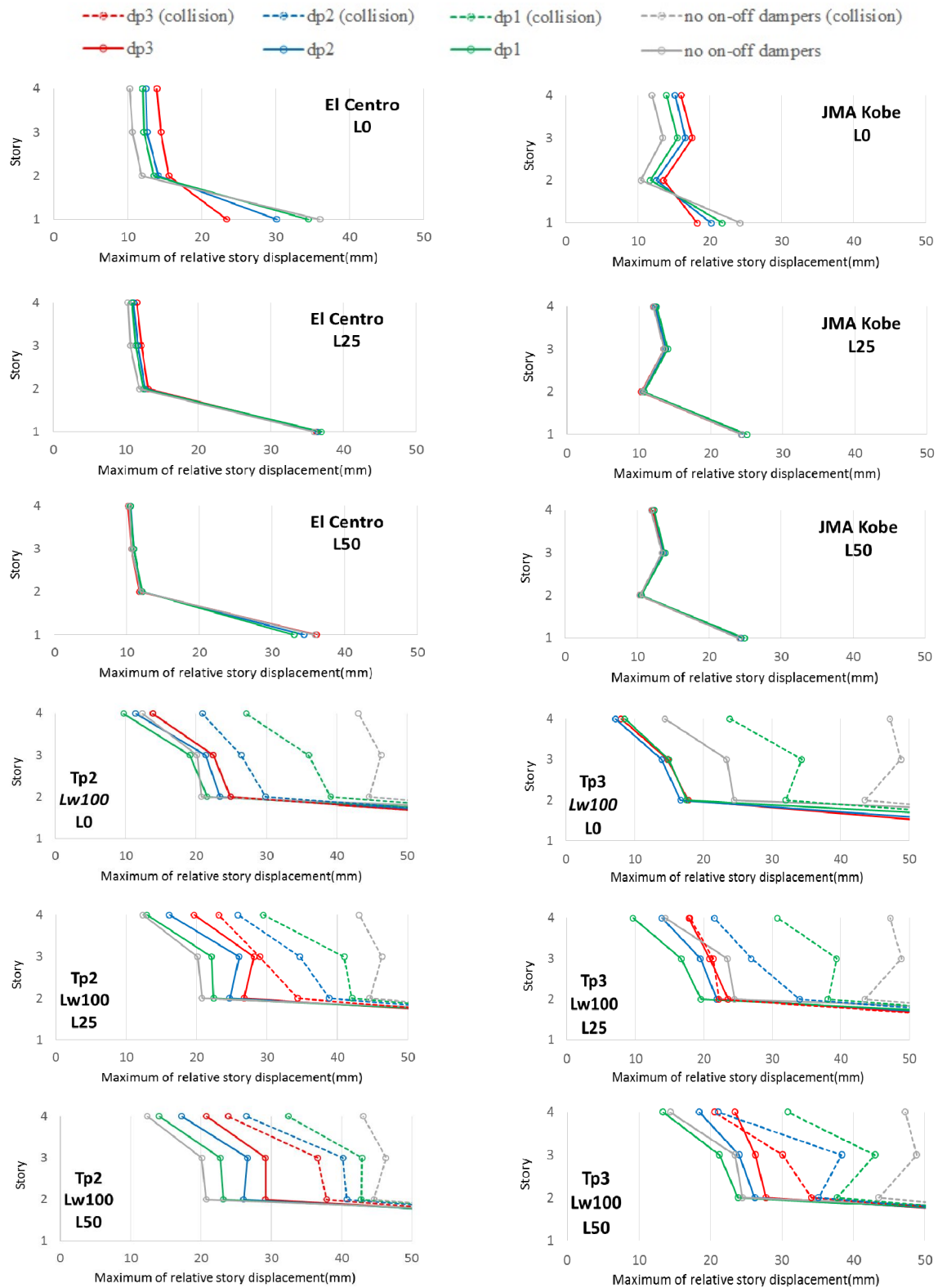


Figure 5. Maximum relative story displacement response to observed earthquakes and level-3C pulse wave input sources, with various dampers and collision cases.

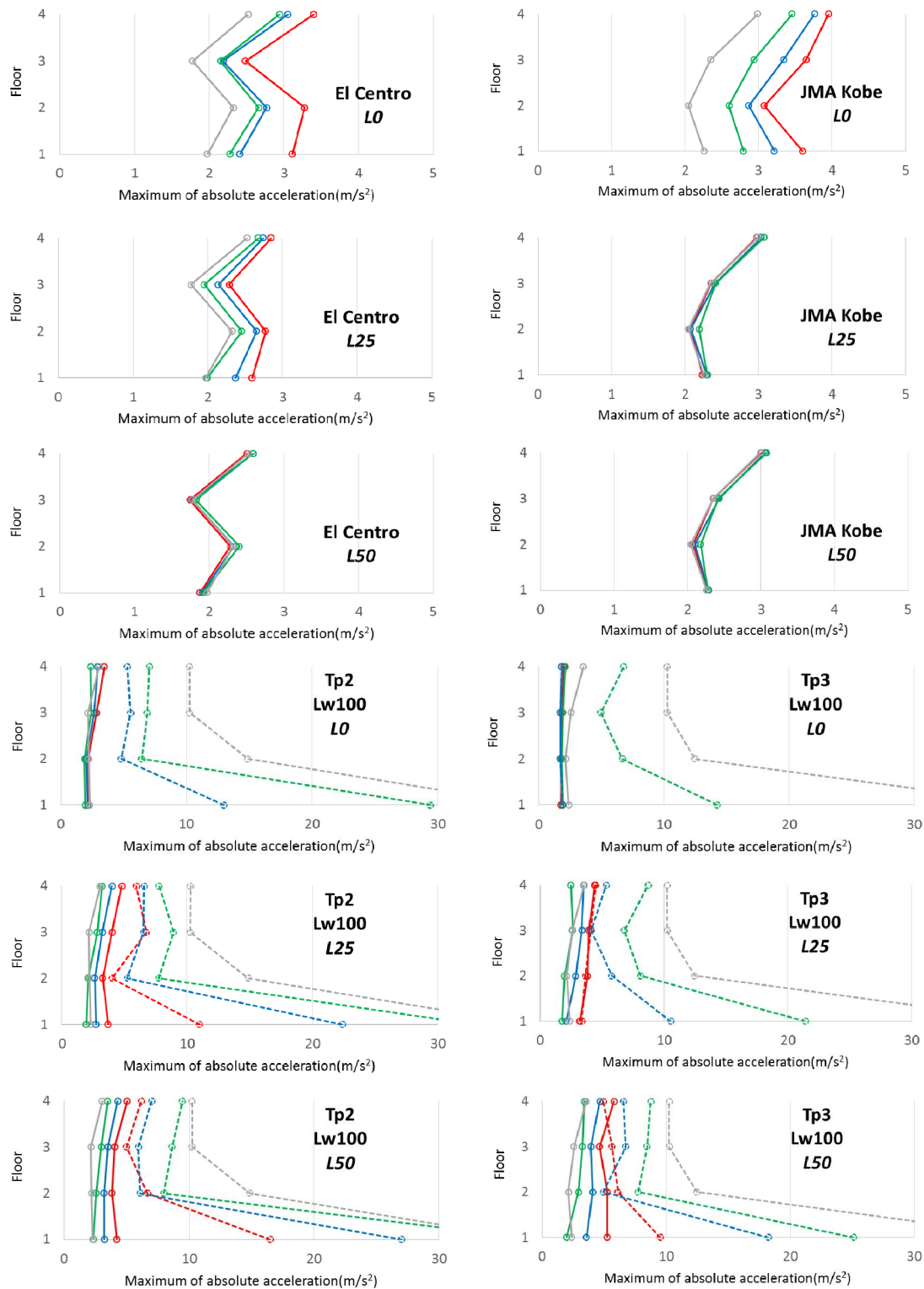


Figure 6. Maximum absolute acceleration response to observed earthquakes and level-3C pulse wave input sources, with various dampers and collision cases.

Table 3. Response ratios of relative story displacement for level-2 observed earthquakes.

		1st story			2nd story			3rd story			4th story		
		L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50
El Centro	dp1	0.96	1.03	0.92	1.14	1.05	1.02	1.14	1.07	1.03	1.17	1.06	1.02
	dp2	0.84	1.01	0.96	1.19	1.06	1.01	1.18	1.10	1.03	1.21	1.08	1.02
	dp3	0.65	1.01	1.01	1.31	1.10	0.99	1.36	1.14	1.00	1.36	1.13	0.99
Hachinohe	dp1	0.81	0.94	0.99	1.22	1.08	1.02	1.17	1.09	1.00	1.21	1.12	1.01
	dp2	0.72	0.90	0.98	1.34	1.12	1.02	1.30	1.15	1.02	1.28	1.15	1.04
	dp3	0.64	0.91	1.00	1.47	1.14	1.00	1.39	1.20	1.00	1.42	1.17	0.99
JMA Kobe	dp1	0.90	1.03	1.03	1.13	1.03	1.02	1.15	1.04	1.03	1.16	1.04	1.03
	dp2	0.83	1.00	1.01	1.21	1.01	1.01	1.23	1.02	1.01	1.27	1.02	1.03
	dp3	0.75	1.00	1.00	1.30	0.99	1.00	1.30	1.00	1.01	1.34	1.01	1.01

Table 4. Response ratios of absolute acceleration for level-2 observed earthquakes.

		1st floor			2nd floor			3rd floor			4th floor		
		L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50
El Centro	dp1	1.15	1.01	0.97	1.14	1.06	1.03	1.21	1.10	1.03	1.17	1.06	1.02
	dp2	1.22	1.20	0.97	1.19	1.14	1.00	1.23	1.21	1.00	1.21	1.09	1.03
	dp3	1.58	1.31	0.95	1.41	1.19	0.98	1.40	1.29	0.98	1.35	1.13	0.99
Hachinohe	dp1	1.17	1.15	1.04	1.16	1.07	0.99	1.13	1.04	0.97	1.19	1.12	1.01
	dp2	1.41	1.50	1.07	1.27	1.21	0.94	1.20	1.11	0.94	1.25	1.15	1.02
	dp3	1.63	1.58	1.00	1.36	1.33	0.98	1.35	1.15	0.97	1.40	1.17	0.98
JMA Kobe	dp1	1.24	1.02	1.01	1.27	1.07	1.06	1.25	1.03	1.03	1.16	1.03	1.03
	dp2	1.42	1.02	1.01	1.40	1.01	1.03	1.42	1.03	1.03	1.26	1.02	1.02
	dp3	1.59	0.99	1.01	1.50	1.01	1.01	1.55	1.00	1.00	1.32	1.00	1.00

Table 5. Response ratios of relative story displacement for level-3C pulse waves.

Retaining walls at L_w100		2nd story			3rd story			4th story		
		L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50
Tp1 pulse wave	dp1	0.71	0.74	0.74	0.80	0.85	0.87	0.64	0.66	0.60
	dp2	0.79	0.82	0.83	0.93	0.98	0.94	0.75	0.80	0.73
	dp3	0.86	0.91	0.92	1.00	1.09	1.06	0.84	0.94	0.85
Tp2 pulse wave	dp1	0.88	0.94	0.96	0.78	0.88	0.93	0.63	0.68	0.75
	dp2	0.67	0.87	0.91	0.57	0.75	0.87	0.48	0.60	0.61
	dp3	0.56	0.77	0.85	0.48	0.63	0.79	0.32	0.54	0.55
Tp3 pulse wave	dp1	0.74	0.88	0.87	0.70	0.81	0.88	0.51	0.65	0.65
	dp2	0.38	0.78	0.81	0.29	0.55	0.78	0.15	0.46	0.45
	dp3	0.41	0.51	0.78	0.30	0.44	0.62	0.17	0.38	0.44

Retaining walls at L_w150		2nd story			3rd story			4th story		
		L=0	L=25	L=50	L=0	L=25	L=50	L=0	L=25	L=50
Tp2 pulse wave	dp1	0.71	0.74	0.76	0.64	0.74	0.76	0.51	0.68	0.74
	dp2	0.77	0.81	0.86	0.72	0.88	0.90	0.60	0.85	0.91
	dp3	0.82	0.88	0.96	0.75	0.95	0.98	0.73	1.04	1.10
Tp3 pulse wave	dp1	0.50	0.56	0.68	0.44	0.49	0.62	0.40	0.45	0.63
	dp2	0.47	0.62	0.74	0.41	0.57	0.70	0.34	0.65	0.87
	dp3	0.51	0.67	0.79	0.43	0.61	0.77	0.38	0.84	1.10

Table 6. Response ratios of absolute acceleration for level-3C pulse waves.

Retaining walls at L_w100		2nd floor			3rd floor			4th floor		
		$L=0$	$L=25$	$L=50$	$L=0$	$L=25$	$L=50$	$L=0$	$L=25$	$L=50$
Tp1 pulse wave	dp1	0.47	0.53	0.52	0.46	0.54	0.54	0.62	0.63	0.61
	dp2	0.58	0.70	0.65	0.53	0.64	0.64	0.72	0.76	0.73
	dp3	0.65	0.88	0.83	0.60	0.75	0.77	0.81	0.90	0.84
Tp2 pulse wave	dp1	0.43	0.52	0.54	0.67	0.87	0.84	0.69	0.76	0.92
	dp2	0.32	0.35	0.41	0.54	0.64	0.58	0.52	0.64	0.68
	dp3	0.14	0.27	0.45	0.28	0.66	0.49	0.34	0.58	0.60
Tp3 pulse wave	dp1	0.53	0.65	0.62	0.48	0.66	0.82	0.66	0.85	0.86
	dp2	0.14	0.46	0.40	0.17	0.40	0.66	0.18	0.52	0.64
	dp3	0.15	0.29	0.49	0.18	0.40	0.55	0.19	0.44	0.48

Retaining walls at L_w150		2nd floor			3rd floor			4th floor		
		$L=0$	$L=25$	$L=50$	$L=0$	$L=25$	$L=50$	$L=0$	$L=25$	$L=50$
Tp2 pulse wave	dp1	0.22	0.24	0.29	0.50	0.59	0.62	0.52	0.69	0.76
	dp2	0.23	0.30	0.36	0.56	0.67	0.74	0.64	0.87	0.93
	dp3	0.24	0.37	0.44	0.59	0.84	0.85	0.75	1.04	1.09
Tp3 pulse wave	dp1	0.38	0.41	0.62	0.37	0.51	0.64	0.33	0.39	0.53
	dp2	0.36	0.60	0.86	0.34	0.66	0.77	0.28	0.55	0.73
	dp3	0.39	0.81	1.11	0.36	0.77	0.91	0.31	0.69	0.90

Response to level-3C pulse waves with on-off dampers as additional dampers and without retaining walls

The response ratios of the relative story displacement for the 1st story ranged from 0.60 to 0.95 and those of the absolute acceleration for the 1st floor ranged from 0.67 to 2.21; the increase and decrease tendencies of the responses varied depending on each case. When adding on-off dampers and the test specimen collided with the retaining walls, the response ratios of the relative story displacement for the upper floors ranged from 0.38 to 0.96 and those of the absolute acceleration were from 0.27 to 0.92; thus, the effect of the on-off dampers is clearly demonstrated when the collision with the retaining walls occurs. When the collision is avoided by adding on-off dampers, the response ratios of the relative story displacement for the upper stories range from 0.45 to 1.10, and those of the absolute acceleration for the upper floors are from 0.24 to 1.11; thus, the responses increase in some cases of slight collision without on-off dampers.

The relationship between the effects of on-off dampers and each parameter is as follows,

- 1) The results show that the proposed on-off dampers can reduce the displacement response of the isolated story and can make collision with a retaining wall hard to occur in cases of level-3C earthquakes. At the same time, the on-off dampers can avoid lowering performance of the seismic-isolation system in cases of level-2 earthquakes by adjusting the elongated hole to an appropriate clearance.
- 2) When collision with a retaining wall occurs in cases of level-3C earthquakes, the proposed on-off dampers with a larger damping coefficient can effectively restrain the increase of the upper structure's responses of the seismic-isolated structures.

4. NUMERICAL ANALYSIS

4.1 Time response analysis

We compare our analysis results with experimental results to review the effectiveness of the on-off damper from the analytical investigation. A four-mass shear model with a base-isolated story was provided (Fig. 7); the model parameters are shown in Table 2. A fixed damping factor of 3% was assumed for every story in the model. The damping devices

installed at the base isolation layer are those described in section 2. The stiffness of retaining walls k_w is determined by the size and composition of the rubber component; thus $k_w = 2495$ (N/mm).

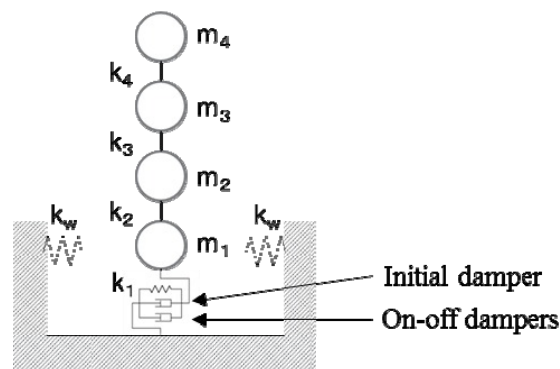


Figure 7. Analysis model, using parameters shown in Table 2.

4.2 Comparison of no-collision cases

Figure 8 shows a comparison between time history waveforms of the test results and those of the numerical analysis results when a Tp2 pulse wave is input with dp2, L50 on-off dampers, in case of no-collision. The left panels show the waveforms of the relative story displacement for each story, the right panels show those of the absolute acceleration for each floor. The waveforms of all the no-collision test results agree well with those of the analysis results.

4.3 Comparison of collision cases

Figure 9 shows a comparison between the time history waveforms of the test results and those of the numerical analysis results when a Tp2 pulse wave is input with dp2, and L50 on-off dampers, in case of collision $L_w 100$. The results are similar to those of the no-collision case. The relative story displacement waveforms of the test results agree with those of the analysis results. However, the absolute acceleration waveforms of the test results do not agree well with those of the analysis results, particularly at the upper floors. These results suggest that it is necessary to reconsider the modeling of the retaining wall's stiffness in other ways.

5. CONCLUSION

- 1) We proposed a new damper named the on-off damper that varies the damping force depending on the response displacement and response velocity, and investigated the effect and efficiency of the proposed damper. A shaking-table experiment was conducted, and the test results were compared with the numerical analysis results.
- 2) As results of the experiment, it was assured that the proposed on-off dampers could reduce the displacement response of the isolated story and could make collision with retaining walls hard to occur in cases of level-3C earthquakes. At the same time, the on-off dampers could avoid lowering performance of the seismic-isolation system in cases of level-2 earthquakes by adjusting the elongated hole to an appropriate clearance. When the collision with retaining walls occurs in cases of level-3C earthquakes, the on-off dampers with larger damping coefficient could effectively restrain the increase of the upper structure's responses of the seismic-isolated structures.
- 3) In no-collision cases, good agreement was found between the numerical analysis results and the test results. In collision cases, the test results for the relative story displacement agree with the analysis results; however, the absolute acceleration results do not agree well, particularly at the upper floors. These results suggest that the modeling of the retaining wall's stiffness should be reconsidered in other ways.

○ Timing when on-off damper starts to work

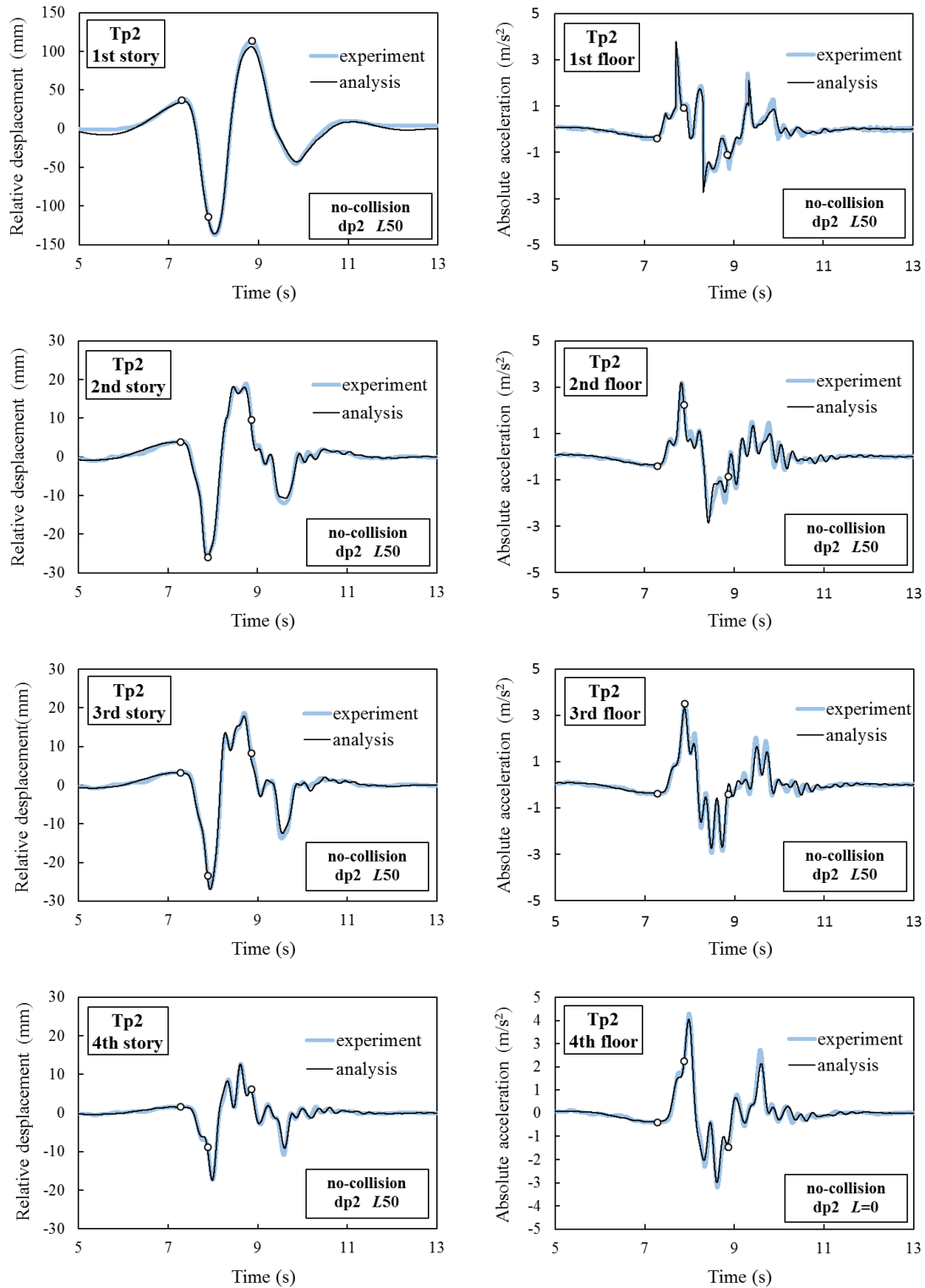


Figure 8. Time history waveforms of test results and numerical analysis results (Tp2, dp2, L50, in case of no-collision). Left panels: relative displacement; right panels: relative acceleration. Circles indicate the time when the on-off damper is activated.

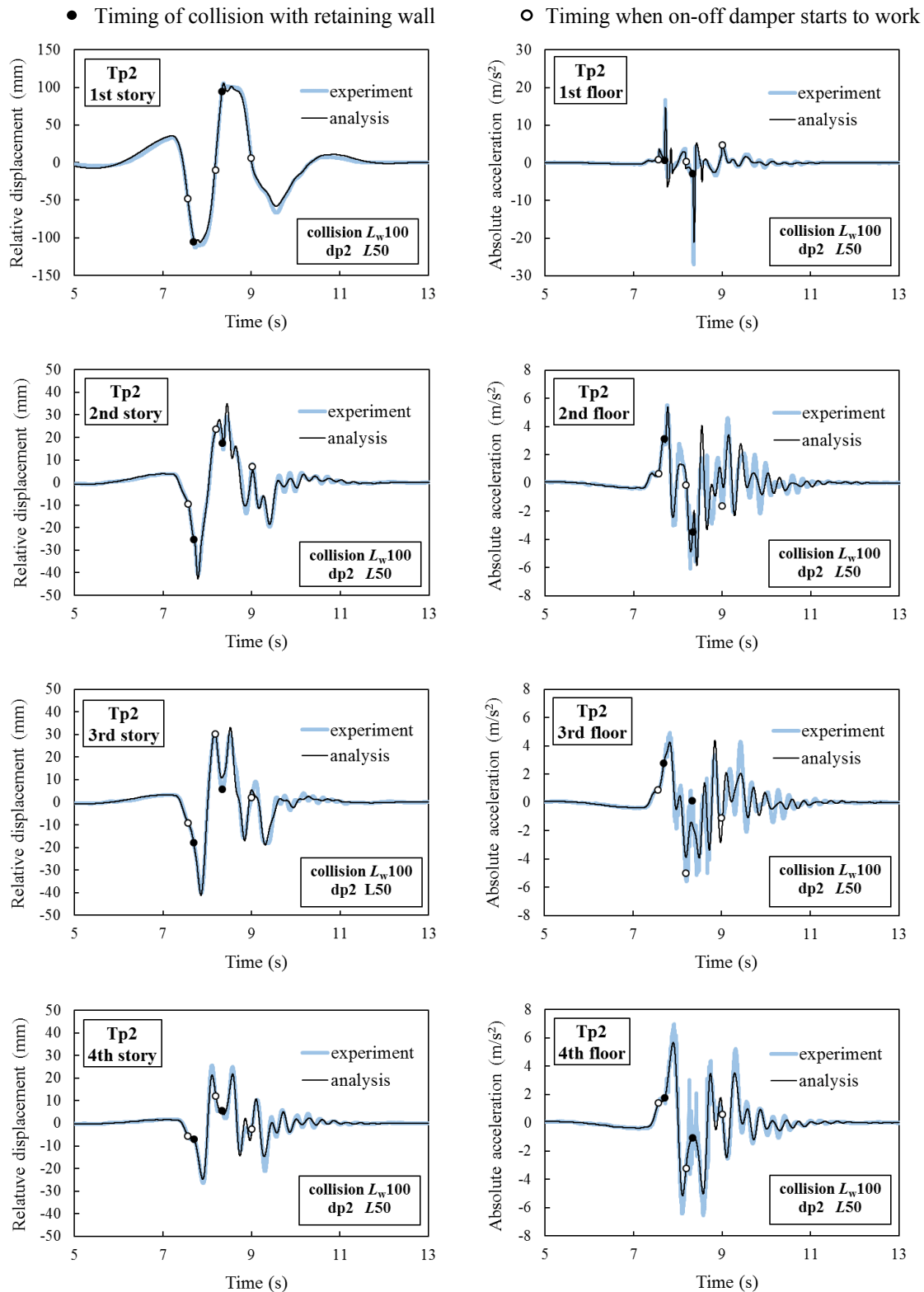


Figure 9. Time history waveforms of test results and analysis results (Tp2, dp2, L50, in case of collision L_w100 .) Left panels: relative displacement; right panels: relative acceleration. Black dots show the time of collision with the retaining wall, white circles indicate the time when the on-off damper is activated.

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