Seismic Performance Improvement of the Existing High-rise Building by Connecting to its High-rise Extension Using Viscous Dampers

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SUMMARY:
This paper describes a method of improving the seismic performance of the existing high-rise building by utilizing its high-rise extension and discusses a case in which the method was actually adopted in two adjacent buildings. This method uses viscous dampers by which the adjacent buildings are connected to each other. Firstly, the effects of the arrangement of viscous dampers used for connecting elements to its high-rise extension are parametrically studied with the coefficient of damping of the dampers. Secondly, the case where this connecting system was applied to the actual buildings is numerically examined. The maximum responses of the existing building and the maximum responses of relative deformation between two adjacent buildings are reduced as compared to the case of the independent system.

Keywords: Seismic Retrofit, Existing High-rise Building and its Extension, Connecting System, Viscous Damper

1. INTRODUCTION

To improve the seismic performance of existing buildings during earthquakes, it is necessary to perform sufficient reinforcement in spaces that are already used. In many cases, such spaces are very limited and are not sufficient. Furthermore, in high-rise buildings, seismic retrofit is much more difficult not only for the above reasons but also because of the difficulties of the construction work and changes in the structural system due to the structural reinforcements. This paper describes a method for improving the seismic performance of existing high-rise buildings by utilizing their high-rise extensions, and discusses a case in which this method was actually adopted in two adjacent buildings. This method does not simply rigidly connect the structures of two buildings, but uses viscous dampers for vibration control that can efficiently dissipate earthquake input energy by using the differences in vibration behaviors of the adjacent buildings.

2. OUTLINE OF THE BUILDING

The buildings discussed in this paper are located on the south side of Osaka Station, a symbolic and important part of Osaka City in Japan. A retrofit of an existing high-rise building and its extension was planned with the aim of creating a new face on the south side of Osaka Station. The existing building and its extension are now collectively called “South-Gate Building.” The existing high-rise building (hereafter referred to as “Existing building”) has a height of about 120 m (28 stories above ground), and was designed and completed in 1983 according to the Building Standard Law of Japan at that time. The standard floor plan has an almost rectangular shape of 120 m × 35 m. The extension of the building (hereafter referred to as “Extension building”) is about 70 m in height (16 stories above ground), and it also has a rectangular standard floor plan with a large side length ratio, 120 m × 21 m. The main structure of Existing building was a rigid steel frame (1st floor and below: steel-reinforced concrete frame). Extension building also had a rigid frame comprised of steel beams and CFT columns with viscous dampers (1st basement floor and below: Steel-reinforced concrete structure). Table 2.1 presents the outlines of Existing building and Extension building, and Fig. 2.1 shows the standard floor plan.

Photo. 2.1. Appearance of the buildings

Table 2.1. Outline of the Buildings

Building name:	South-Gate Building (Osaka City, Japan)
Number of floors:	
(Existing building)	28 floors above ground 4 floors below ground 2 floors as the pent-house
(Extension building)	16 floors above ground 2 floors below ground 2 floors as the pent-house
Total floor area:	170,059.19 m^2
Building height:	
(Existing building)	122.4 m
(Extension building)	74.6 m
Major applications:	department store, hotel, station concourse
Structure type:	
(Existing building)	2nd floor and above: Steel structure 1st floor and below: Steel-reinforced concrete structure (reinforced concrete structure partially)
(Extension building)	1st floor and above: Steel structure (column: CFT) 1st basement floor and below: Steel-reinforced concrete structure (reinforced concrete structure partially)

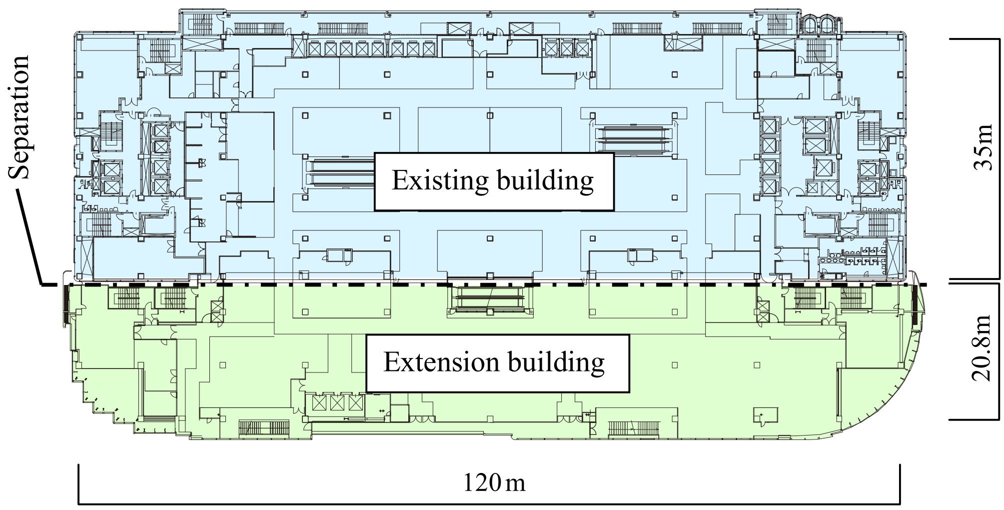


Figure 2.1. Standard floor plan

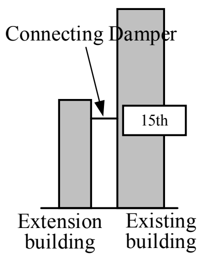
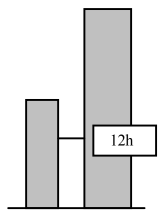
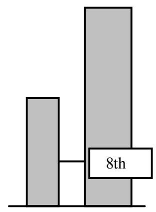
3. EFFICIENT ARRANGEMENT OF CONNECTING DAMPER

3.1. Study of Planning of Connecting Dampers

Before applying the connecting system to actual buildings, the following points were studied to decide on which floors to install the connecting dampers and how many are required.

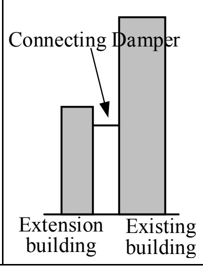
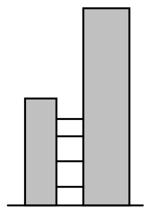
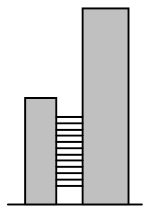
Investigation 1: Effects of differences in connecting floor
In this investigation, the different effects on seismic responses as a result of placing the connecting dampers on different floors were examined. As shown in Table 3.1, three models were examined: one with connection at the 15th floor level (CASE 1-1), another at the 12th floor level (CASE 1-2), and another at the 8th floor level (CASE 1-3).

Table 3.1. Investigation 1

Case name	CASE 1-1 Connection type of upper floor	CASE 1-2 Connection type of middle floor	CASE 1-3 Connection type of lower floor
Connecting floor	15	12	8
Model			

Investigation 2: Effects of the degree of distribution of the connecting dampers
The effects of the connecting dampers on degree of distribution in the direction of height were examined with three analysis models shown in Table 3.2. The coefficients of damping of the connecting dampers placed on different floors, when multiple dampers were used, were assumed to be the same. The model of CASE 2-1 is equivalent to CASE 1-1 mentioned above as the intensive arrangement at one floor of the connecting dampers. Both investigations focused on the effects on the responses of Existing building.

Table 3.2. Investigation 2

Case name	CASE 2-1 Intensive arrangement at one floor	CASE 2-2 Distributed arrangement at multi-floors	CASE 2-3 Distributed arrangement at all floors
Connecting floor	15	4, 8, 12, 15	4 – 15
Model			

3.2. Analysis Model and Input Seismic Waves

The vibration models used for time history response analysis were the equivalent-bending-shear type models with 31 and 17 lumped mass for Existing and Extension building, respectively. The connecting dampers were modeled according to the Maxwell model in which elastic spring and dashpot are installed in series. It was assumed that the damping properties were liner. The analysis model of longitudinal direction (short side direction) in CASE 1-1 is shown in Fig. 3.1.

The input seismic waves that satisfied the design spectrum of the current Japanese codes were selected for the analysis (Table 3.3).

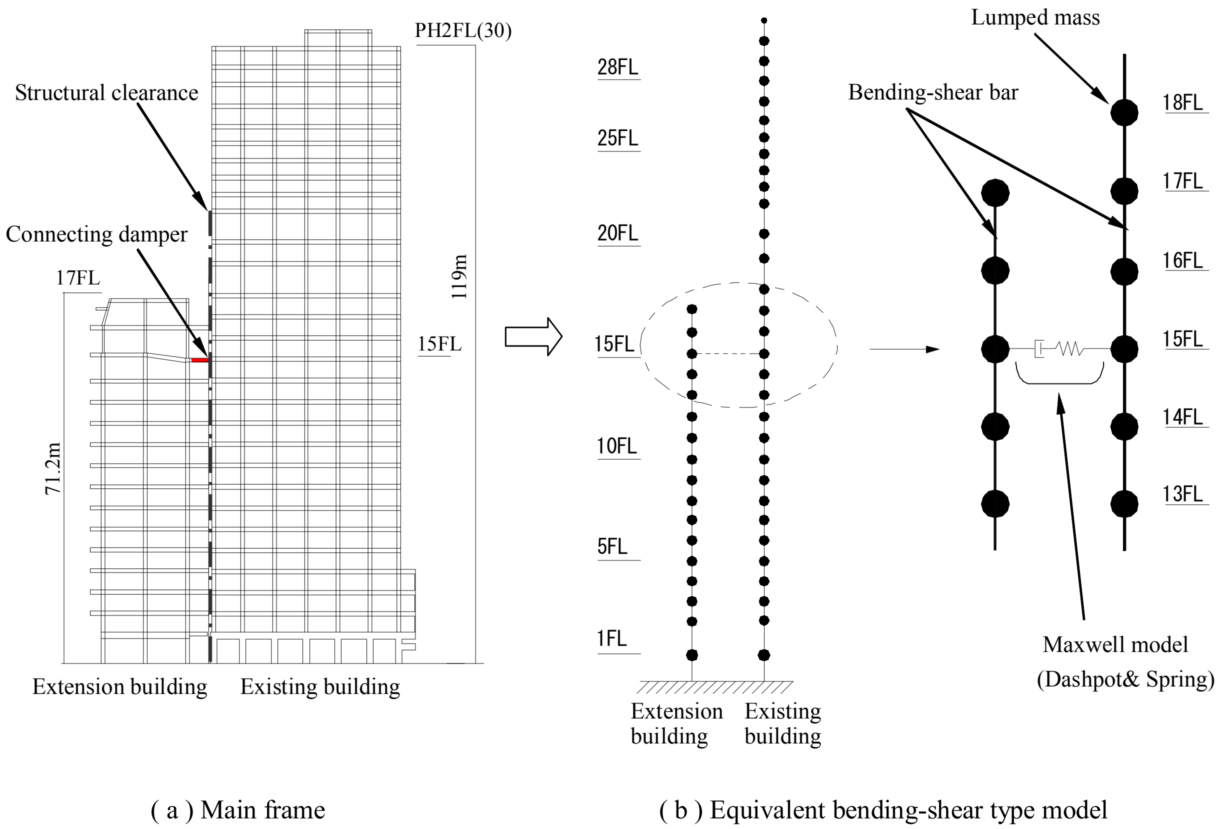


Figure 3.1. Analysis Model (short side direction)

Table 3.3. Input seismic waves

Name	Max Velocity (cm/s)	Max Acceleration (cm/s^2)	During (s)
WAVE-H	58.6	369.8	120
WAVE-R	82.4	350.5	120

3.3. Analytical Results

(Investigation 1)
The relation of the maximum base shear force coefficient of Existing building and the coefficient of damping of the connecting dampers by seismic analysis are shown in Fig. 3.2. The maximum base shear force coefficient was normalized by the coefficient of Existing building's response in the independent system. The connection of adjacent buildings with the connecting dampers caused a reduction in the maximum base shear force coefficient by approximately 20% in this study, but the effect became smaller with increases in the coefficient of damping. The energy dissipation ratio is defined as the ratio of dissipation energy of the connecting dampers to input energy during seismic analysis, and is shown in Fig. 3.3 as the relation to the coefficient of damping of the connecting dampers. The energy dissipation ratio of the connecting dampers has the local maximum value irrespective of the connecting floor, and the local maximum of energy dissipation ratio was shown as the coefficient of damping at about 300 kNs/cm for CASE 1-1 (15th floor level), about 400 kNs/cm for CASE 1-2 (12th floor level), and about 600 kNs/cm for CASE 1-3 (8th floor level). Thus, the considered connecting system will dissipate earthquake input energy more efficiently when the connecting dampers are installed at higher floor levels.

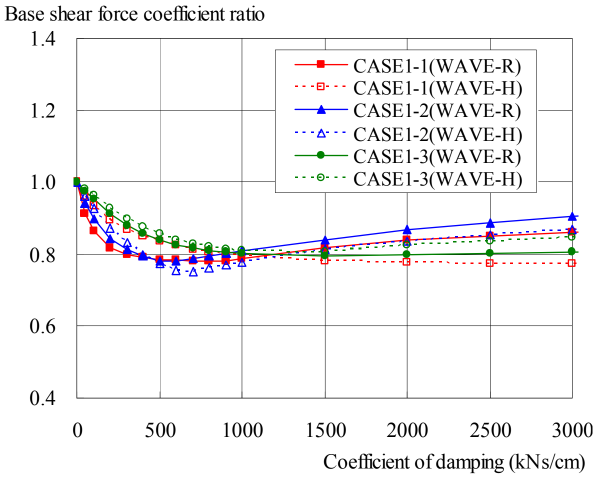


Figure 3.2. Results (1) of Investigation 1

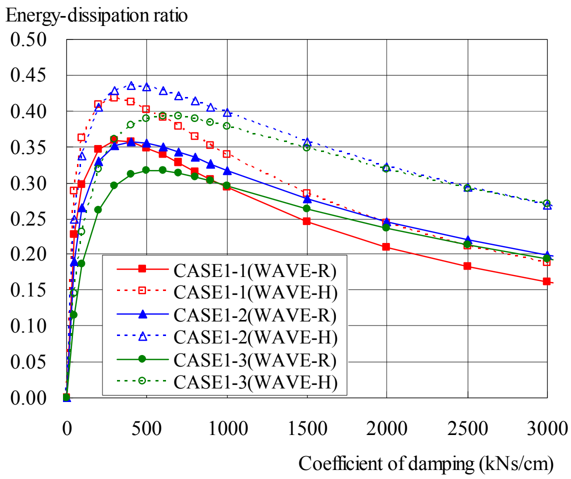


Figure 3.3. Results (2) of Investigation 1

(Investigation 2)
The relation between the coefficient of damping of the connecting dampers and the energy dissipation ratio is shown in Fig. 3.4. The coefficients of damping for CASE 2-2 and CASE 2-3 are indicated as the sum of the connecting dampers installed at multiple floor levels. The dispersed arrangement of the connecting dampers at multiple floor levels caused the coefficient of damping at the local maximum of energy dissipation ratio to shift slightly to a larger value. The distribution of maximum responses of story shear force coefficient of Existing building, the distribution of maximum responses of story drift of Existing building, and the distribution of maximum responses of relative deformation between two buildings, which were obtained using the coefficient of damping at the local maximum of energy dissipation ratio in each model (here, the coefficients are 300 kNs /cm in CASE 2-1, 600 kNs /cm in CASE 2-2 and CASE 2-3), are shown in Fig.3.5 along with the results for the independent system. Compared with the response of the independent system, all responses of CASE 2-1, CASE 2-2, and CASE 2-3 were decreased. With the exception of a slight difference in response around the 15th floor, there were no significant differences between the cases. Within the scope of this study, if the coefficient of damping at the local maximum of energy dissipation ratio will be adopted, it is estimated that the arrangement of dampers has little effect on response. As the coefficient of damping of CASE 2-1 was half those of CASE 2-2 and CASE 2-3, the intensive arrangement at the 15th floor level was predominant in the efficiency of reduction of earthquake responses with the connecting dampers.

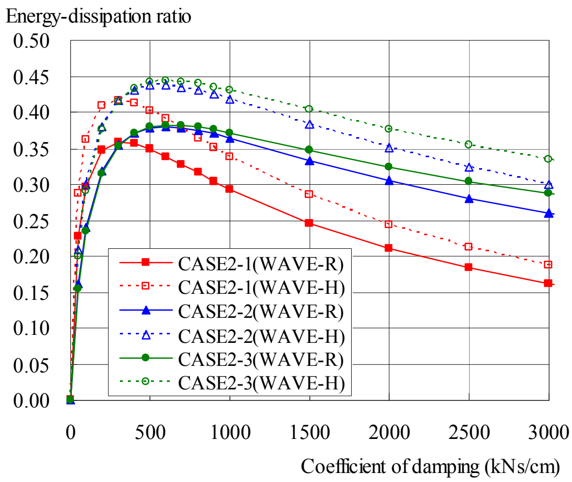


Figure 3.4. Results (1) of Investigation 2

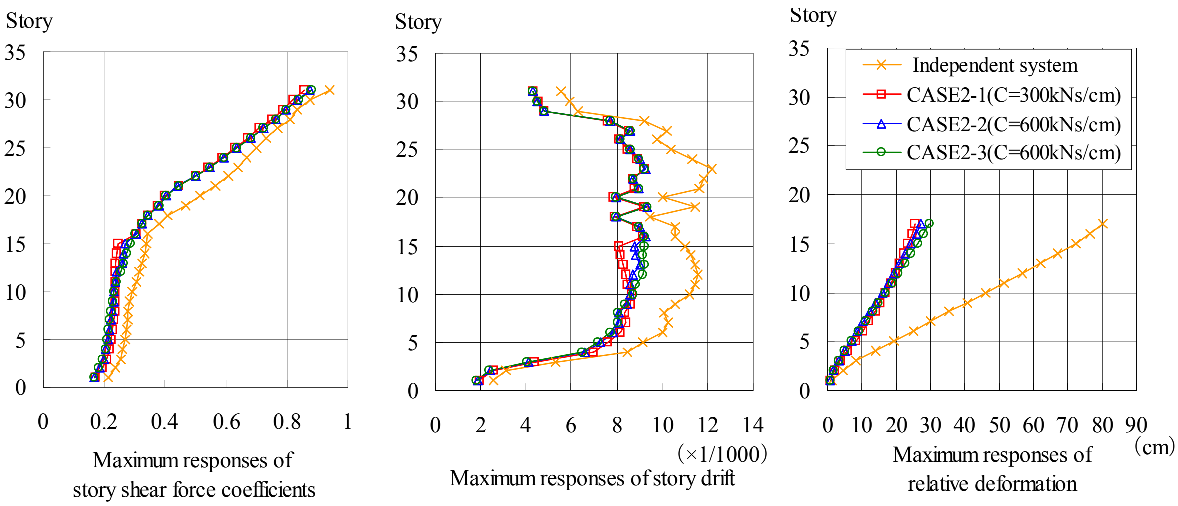


Figure 3.5. Results (2) of Investigation 2

4. APPLICATION OF THE CONNECTING SYSTEM TO ACTUAL BUILDINGS

4.1. Arrangement of Connecting Dampers

The specifications and arrangement of the connecting dampers would be decided based on the following to minimize reinforcement at the site of installation of the connecting dampers in the Existing building.

① The installation position of Existing building is the connection of beams to columns. The maximum damping force of the connecting dampers is 1000 kN and the damping force-velocity relation is bi-linear, which has a relief mechanism (Fig. 4.1).
② The connecting dampers were concentrated on the upper two floor levels, with 12 dampers installed per floor on the 14th and 15th floor level. The sum coefficient of damping was approximately 300 kNs/cm to optimize the energy dissipation ratio.
③ The connecting dampers were installed horizontally in the plenum above the suspended ceiling and located at an angle of 45° to the principal axes of the building to set the same ability for all directions.

The installation of the connecting dampers is illustrated in Fig. 4.2. This installation above the ceiling led to an improvement in seismic performance of Existing building without requiring space for reinforcement in the store area or hotel area.

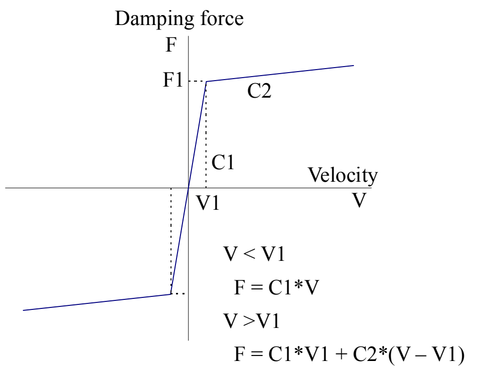
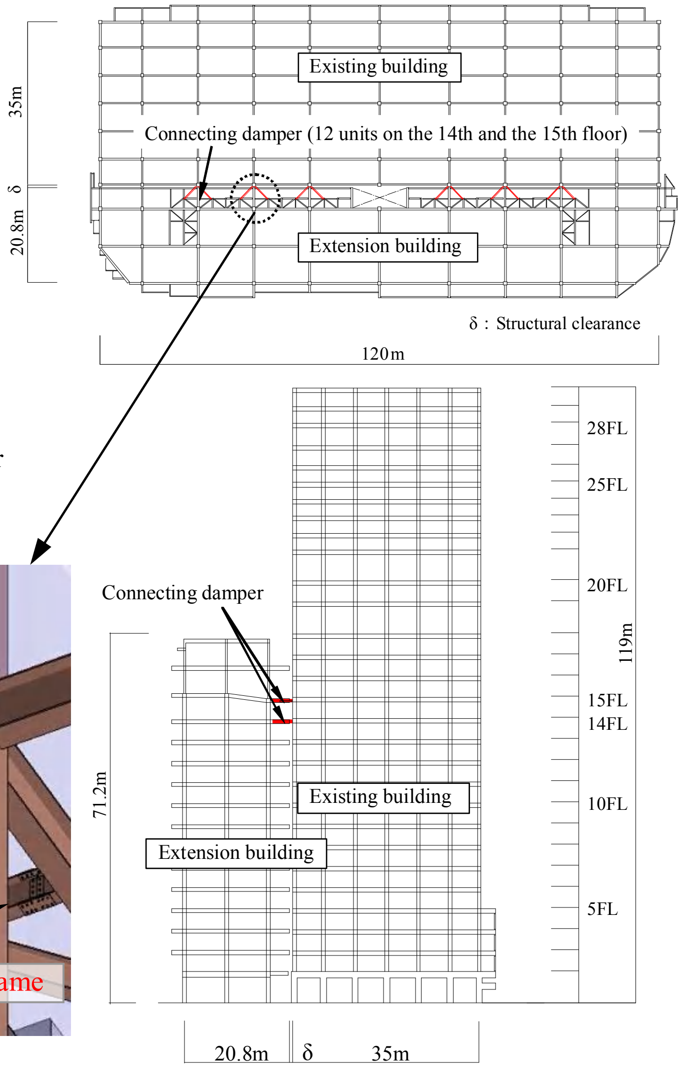


Figure 4.1. Bi-Linear Model of Viscous Damper



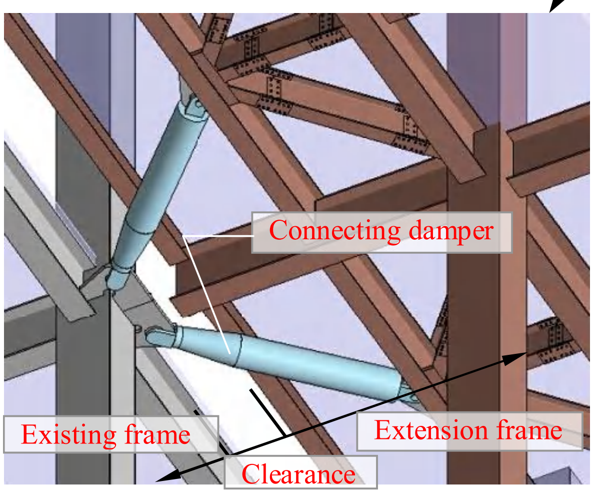


Figure 4.2. Arrangement of Connecting Damper

4.2. Confirmation of the Effects on Reduction of Earthquake Responses by Time History Response Analysis

The earthquake responses of the two actual buildings described in the preceding section were confirmed by time history response analysis. The model used for the analysis was the same as described in the preceding section, and the connecting dampers were installed on the 14th and 15th floor levels. The results of eigenvalue analysis in this model are shown in Table 4.1. Due to the differences in dynamic properties, such as mass and stiffness, the natural periods of the two buildings were very different, and therefore this system was expected to be effective. In the following, there is shown only the results of short side direction, similar results have been obtained for the long side direction.

As the results of time history response analysis, the maximum responses of story drift of Existing building are shown in Fig. 4.3(a) and the maximum responses of story shear force are shown in Fig. 4.3(b). The same figures also show the results for Existing building of the independent system. The maximum responses of story drift of Existing building were reduced to less than 1/100 which is one of the criteria for seismic performance of high-rise buildings in Japan, and the maximum responses of story shear force were 70% – 80% of those in the independent case. The maximum responses of relative deformation between two buildings as shown in Fig. 4.3(c) were also reduced by approximately 50% compared to the independent case. These observations indicated that this connecting system was successful in minimizing the structural clearance between the two buildings to maximize floor space usage.

Table 4.1. Natural Periods (s)

Direction	Building	1st	2nd	3rd
Transverse direction (Long side)	Existing building	3.16	1.16	0.72
	Extension building	2.16	0.74	0.52
Longitudinal direction (Short side)	Existing building	3.01	1.07	0.63
	Extension building	2.34	0.78	0.46

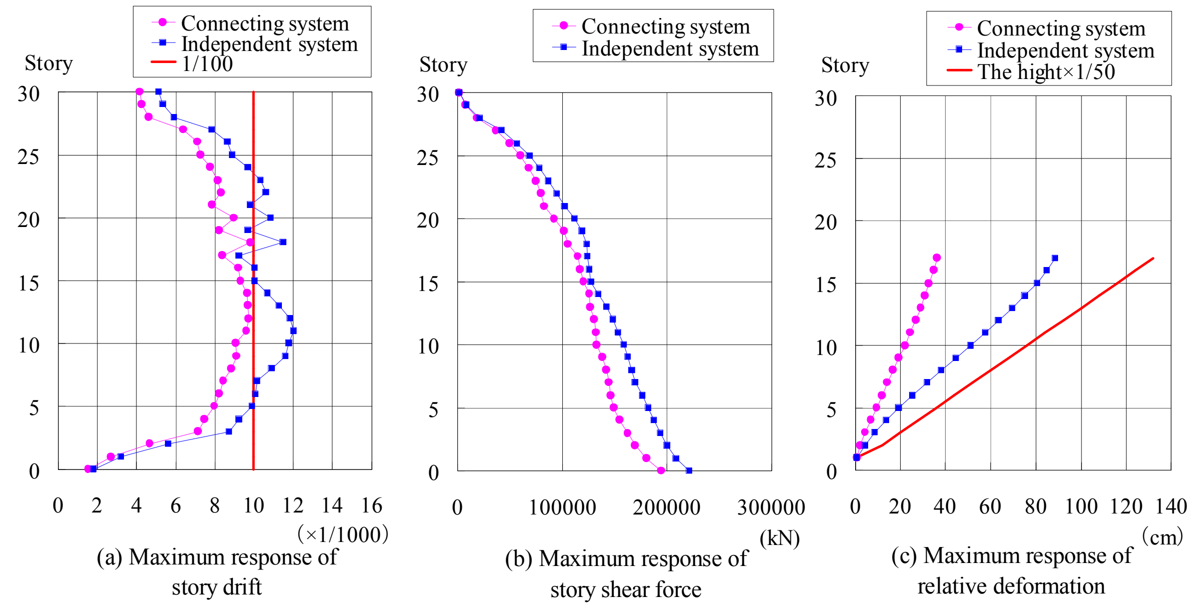


Figure 4.3. Maximum responses

4.3. Visual Confirmation of Seismic Behaviors of the Two Buildings

To visually confirm the differences in seismic behaviors of Existing and Extension buildings, deformation figures of the two buildings around the time period when the relative deformation between the two buildings reached the maximum (41.4 – 44.4 s) are shown in Fig. 4.4, expressed in deformation figures of lumped-mass-model in 0.2-s increments. White lines connecting the two buildings represent the connecting dampers. The scale of horizontal deformation is enlarged so that the differences in deformation of the two buildings can be visually confirmed. These figures visually indicate that the differences in the seismic behaviors of the two buildings create large deformation in the connecting dampers. This enables the connecting dampers to efficiently dissipate earthquake input energy.

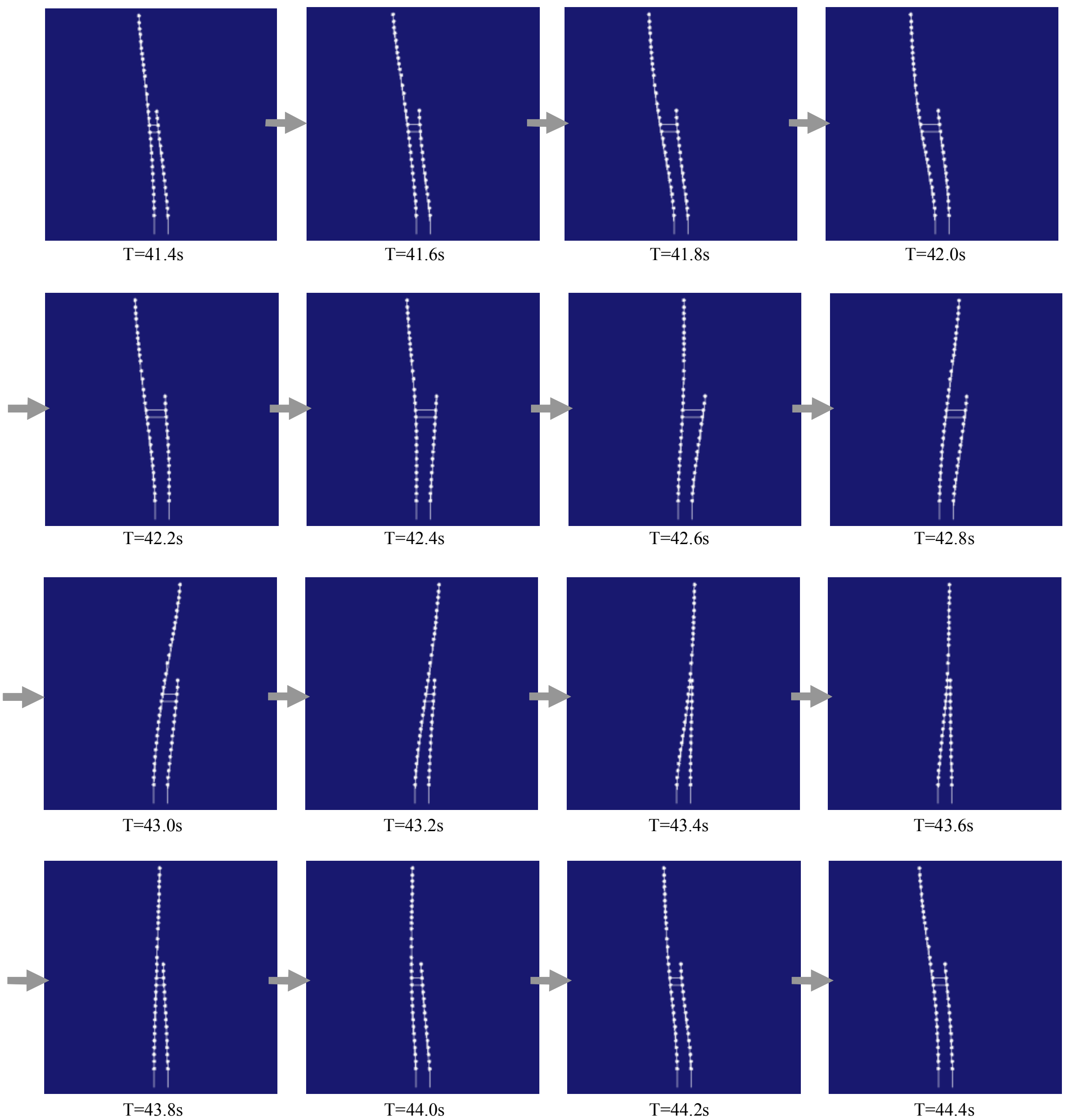


Figure 4.4. Behavior of the Adjacent Building during Strong Motion

5. CONCLUSIONS

For connecting damping structure through viscous dampers connecting existing high-rise building and high-rise extension, the effects of the arrangement of the connecting dampers were studied analytically using the coefficient of damping on the connecting dampers as an analytical parameter. The results were reflected in the case with actual buildings. Obtained results are mentioned as follow.

① The efficiency of reduction of earthquake responses with the connecting dampers is optimal when their installation is concentrated in the upper levels.
② Maximum response of story drift of Existing building is reduced to less than 1/100 and maximum response of story shear force became 70% – 80% of the independent case. These observations indicated improvement in seismic safety of Existing building.
③ Maximum responses of relative deformation between two buildings were reduced by approximately 50% compared to the independent case. The system proposed here was successful in increasing the utilizable floor area by minimizing the structural clearance between Existing and Extension buildings.

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