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SEISMIC PERFORMANCE INVESTIGATION OF THE FOLDED CANTILEVER SHEAR STRUCTURE: AN EXPERIMENTAL STUDY

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ABSTRACT

A newly designed structure named folded cantilever shear structure (FCSS) is proposed as an alternative seismic isolation approach incorporating coupling method and base isolation method in one structure for improving earthquake resistant ability and seismic performance of mid-rise buildings. The proposed structure consists of non-isolated and fully-isolated sub-frames of similar heights that are rigidly connected to each other at the top part. In this manner, it is aimed to extend the natural period of the structure and to decrease the overall seismic responses. A set of experiments were conducted to obtain dynamic parameters such as natural frequencies, damping ratios and mode shapes, and shaking table test were also carried out using 16-storey vibration model to explore seismic responses of the proposed structure under four exemplary ground motions, namely El-Centro, Hachinohe, Miyagi and Taft earthquakes. It was found that the proposed structure is capable of extending natural period and minimizing accelerations, displacements and base shear forces simultaneously. However, relative displacements of the proposed structure were relatively high with respect to base. Therefore, additional viscous dampers were added between adjacent beams to connect both sub-frames with the aim of avoiding excessive displacements and increasing the damping ratio as well. The experimental results were also compared and verified by analyzing vibration model by ABAQUS, well-known finite element software. In both studies, the proposed structure performed substantial improvement in reducing seismic responses when compared to ordinary structure of similar height

Keywords: Seismic performance, mid-rise building, folded cantilever shear structure, viscous damper, natural period, shaking table test.

I. INTRODUCTION

In the last decade, coupling method has received increasing attention by a significant amount of researchers dealing with structural responses and pounding issues of mid-rise structures due to seismic and wind excitations. One of the main aspects of this concept is that the method let researchers interconnect adjacent structures by incorporating various passive energy dissipation devices and base isolation systems in structures. Moreover, coupling method is also similar to base isolation method in that it can be implemented either in existing or newly designed structures not only for reducing pounding possibility but also increasing seismic performance.

For instance, Ohami *et al*. [1] tried to improve the seismic reliability of an existing structure built in accordance with old provisions of building codes of Japan before revisions were made in 1981. Different heights of buildings, one is 5-storey representing old building and the other is 10-storey building representing newly designed building, were selected to be idealized shear models for numerical analysis, and interconnections were made by using rigid connection elements and viscous dampers. The reason for choosing buildings of different heights was reported that responses of coupled buildings could not be reduced when similar heights of buildings was chosen, Azuma *et al*. [2] and Ohami *et al*. [1]. As a result, it was found that it is more effective to design new building to be connected to old one as stiff building instead of flexible building when rigid connection elements were used and rigid connection elements were insufficient to prevent the collapse of 5-storey old building when incorporated in flexible building. In another remarkable study, Ng and Xu [3] carried out an experimental investigation using 12-storey building model to be interconnected to 3-storey low-rise podium structure in 3 different configurations which are respectively fully-separated, rigidly connected and friction damped-linked. Results showed that passively controlled buildings provided most effective performance when compared to other cases. Interestingly, the rigidly connected buildings gave rise to increase in seismic responses. Xu *et al*. [4] also stated that fluid damper connected buildings are more effective in reducing seismic responses for lower adjacent buildings than of higher ones and fluid dampers are more favorable for buildings of same height than those of different heights. Some selected studies with similar configurations and outcomes can be seen in these references, Luco and Barros [5] and Cimellaro *et al*. [6]. As seen in these studies, it should be noted that most of researches aimed to buildings of different heights for studying coupling method, but it should also be taken into account that most of them used boundary conditions of each buildings to be fixed as well.

Aida *et al.* [7] used only one connecting member which consists of one spring and one damper element to connect adjacent structures of different heights, one structure is *n*-dof and the other is *m*-dof, for improving damping performance. Numerical results showed that the most effective position to place connecting member was near to the top part of the structures and the damping performance increased as long as first natural periods of the structures became different. Hysteretic dampers were also used as connecting element in another study between two *m*-dof structures by Basili and Angelis [8]. Three cases were considered for numerical studies, two 10-storey structures connected at their roofs, and as for structures of different heights, one flexible 20-storey structure connected to the roof of a stiff 10-storey structure and 4-storey structure connected to the roof of a stiff 2-storey structure. In all cases, single hysteretic damper element used as a connector element, and also same structures analyzed for non-connected and rigidly-connected cases to compare the responses of the structures for different type of connections. Example results show that the hysteretic damper connection was more effective in reducing seismic responses for the structures of similar heights when compared to rigidly-connected and non-connected structures. As for structures of different heights, it was pointed out that the rigid connection performed a negative effect on protection of lower structure. It is also stated that rigid connection device does not appear as a convenient solution for such adjacent structures.

Agarwal *et al*. [9] mentioned in their study that the most common foundation configuration is that with both buildings fixed since base isolation is a relatively new response modification technique. Therefore, they investigated pounding responses of two adjacent buildings of similar heights with friction varying base isolation. Three different configurations for these two buildings were used for this purpose namely, single base isolated building, and buildings with and without base isolation systems with varying coefficient of friction. According to the results, there was little or no interaction between buildings for the case of single base isolated building configuration. Besides, shared tuned mass damper was implemented as an alternative connection element to adjacent by Abdullah *et al*. [10] in reducing vibration and pounding in adjacent structures. Moreover coupling method can be used for special cases such as over-track buildings, Hayashi [11] and Iwasaki *et al*. [12] for better use of space in high density cities.

In the view of these studies, there are few common points to be underlined that can be summarized as:

(i) coupling method can be an effective solution to deal with the problem of not only pounding but also decreasing seismic responses of mid-rise buildings,

(ii) However, most researchers have used buildings of different heights configuration to be modeled with fixed boundary conditions,

(iii) rigid connections have not been preferred as connecting elements when coupling buildings of similar heights due to insufficient outcomes in reducing building responses. Therefore, viscous damping devices come up with more favorable results.

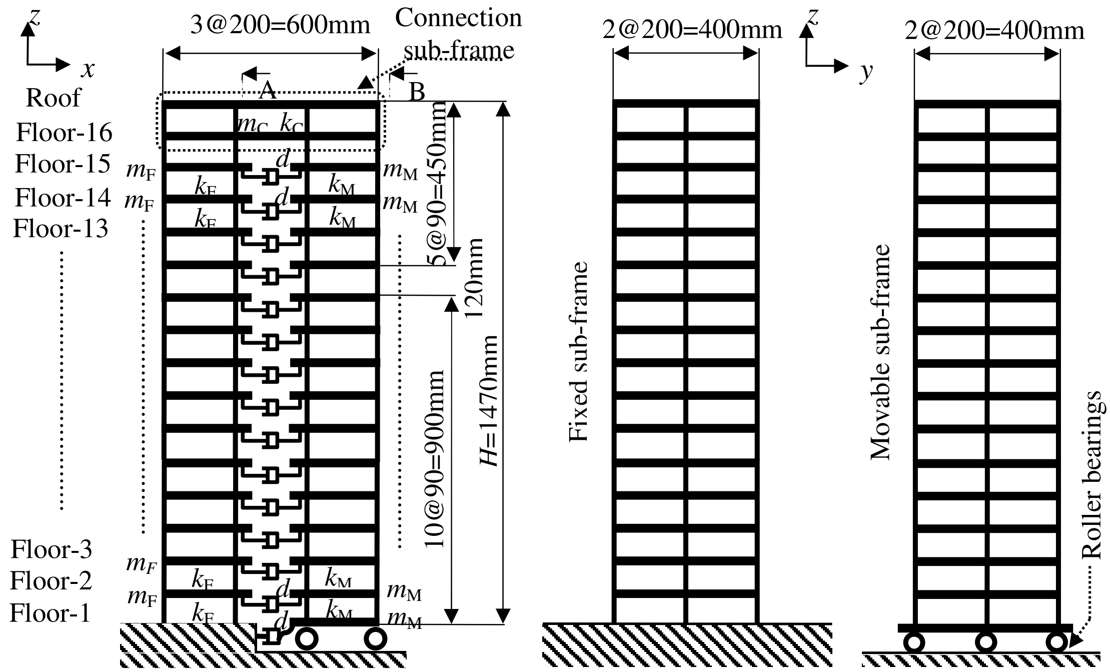
The main objective of this study is to propose an alternative seismic isolation approach incorporating base isolation system and coupling method into a mid-rise structure with the aim of increasing seismic performance and natural period. Therefore, a new configuration for buildings of similar heights were proposed and studied by connecting them at the roof part. Contrary to common configurations of above mentioned researches, the boundary conditions were selected to be one fixed supported building and the other to be base isolated building while using rigid connection at the top part, and buildings were also selected to be similar heights.

A set of experiments were conducted to obtain dynamic parameters and shaking table responses by using vibration model of the proposed structure with and without additional dampers. As for additional damper added structure, some studies offers practical and effective damper placement methods such as Garcia [13], Luco and Barros [5] and Takewaki [14]. And Whittle *et al*. [15] compared these methods in their study terms of effectiveness. Despite of these methods' benefits, these techniques are for advanced optimization, and the vibration model in this study, with additional dampers case, assumed to be uniformly distributed to clarify whether the newly designed structure is effective in reducing seismic responses.

II. EXPERIMENTAL MODEL

2.1 Vibration Model Configuration

The proposed structure consists of non-isolated and fully-isolated sub-frames of similar heights that are rigidly connected to each other at the top part by using connection sub-frame as in Fig. 1. That is, three sub-frames are combined in one structure which is able to move along x and y direction on the movable sub-frame side, Fig. 1 (a) and (b).



(a) Front view (b) side views of sub-frames

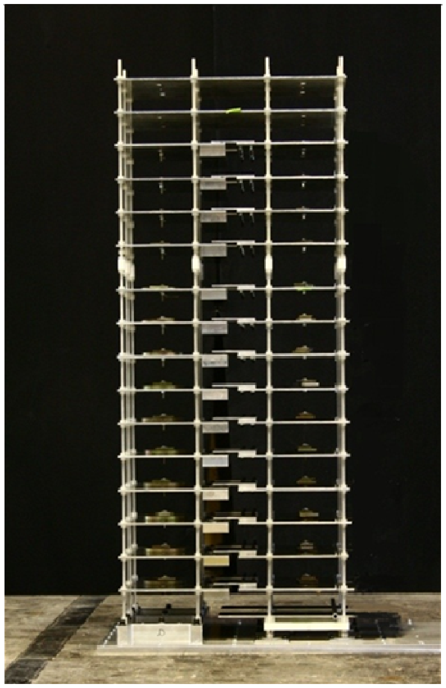
Fig.1. Front and side views of experimental vibration model

16-storey vibration model was constructed by using 230 mm × 5 mm × 430 mm and 630 mm × 5 mm × 430 mm sized rigid aluminum alloy (A5052) rectangular plates as beams for fixed - movable sub frames and connection sub-frame, respectively. Both sub-frames had 6 circular columns which were made of polycarbonate (PC) screw rods with M10 metric size, and aluminum plates were fixed to the screw rods at each column by tightening one plastic nut down of plate and the other on top of plate. The total height of vibration model was 1470 mm with 90 mm of floor height, Fig. 1 (a). Columns were set up by fastening two pieces of screw rods which were 1 m and 0.5 m in length. Therefore, the eleventh floor became 120 mm due to additional part of the rod connection. And these rods were fixed to the bottom plate which was 20 mm thick and including holes for mounting the plate on the shaking table. The clearance between columns was 200 mm along x and y direction that is, the vibration model was 600 mm in length and 400 mm in width. Fixed sub-frame had an encastre boundary condition at the foundation and movable sub-frame was supported by roller bearings. In order to prevent contact problems between sub-structures during any movement, gaps between dampers after installation to the sub-frames were arranged to be around 30 mm. Dampers of proposed model will be introduced in detail in the following section. According to the tension and bending tests of a polycarbonate rod of column, the axial stiffness (AE) were obtained around 1.10×10^5 N and flexural stiffness (EI) was 5.65×10^5 Nmm^2. In Fig. 1 (a), m_F, m_M and m_C stands for the floor mass of fixed, movable and connection sub-frames, respectively and k_F, k_M and k_C represents the lateral shear spring coefficients as well. The total mass of floors including beam, column and viscous damper device masses were arranged to be 3 kg for each side after installation of additional masses which were tightened to the plates at the mid-point. And total mass of connection floors and movable bottom floor were arranged to be 4.5 kg and 3.5 kg, respectively. The lateral shear coefficient tests of the columns were discussed in the following section.

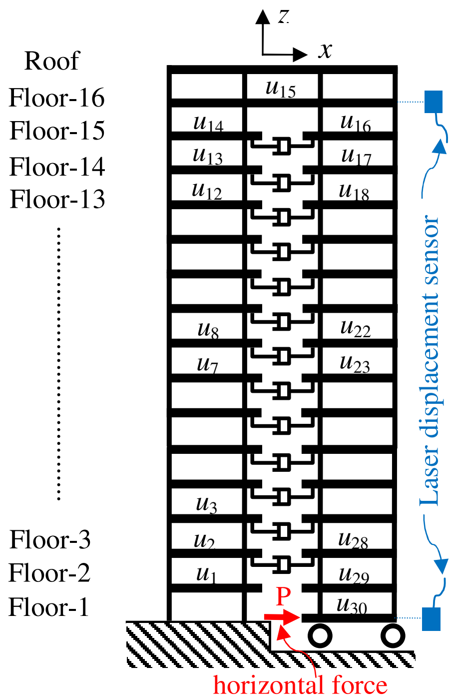
2.2 Vibration characteristics of the experiment model elements

2.2.1 Shear spring coefficient of model

Lateral shear spring coefficients of inter-storey columns, k_F and k_M of fixed and movable sub-frames, were investigated by conducting quasi-static loading test on the vibration test model which is illustrated in Fig. 2 (a).



(a)



(b)

Fig.2. (a) Experimental test model, (b) Quasi-static load test subjecting lateral force

The movable bottom floor was subjected to the lateral force of P, and the displacement of movable bottom floor, (u_{30}) and the top floor of connection sub-frame that is, Floor-16, (u_{15}) were obtained by using laser displacement sensors as illustrated in Fig. 2 (b). Besides u_1, u_2, u_3,…, u_{14} and u_{16}, u_{17}, u_{18},…, u_{29} represents the lateral displacements of each floors along x direction.

According to the quasi-static lading test results, the lateral force - displacement history curves were obtained as in Fig. 3 for Floor-16, (u_{15}), and for movable bottom floor, ($u_{15\text{-}30}$). The slope of history curve at Floor-16 was around 0.00382 N/m and estimated stiffness coefficient became 57.3 KN/m. As for movable bottom floor, the stiffness coefficient was obtained around 57.0 KN/m. The stiffness of columns to be used in simulations, eigenvalue analysis and elastic dynamic response analysis, was taken as the average of these obtained two values that was equal to 57.15 KN/m. And the force gap due to loading - unloading between parallel lines of history curve was obtained around 2.8 N, Fig. 3.

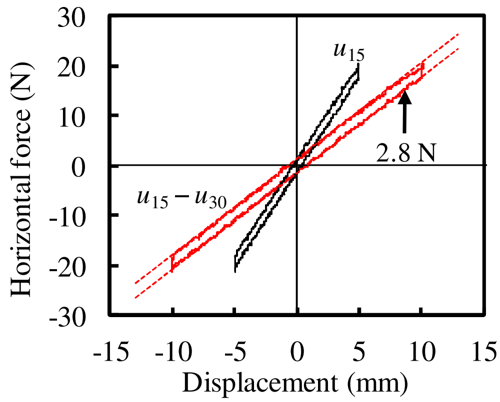


Fig.3. Quasi-static loading test result

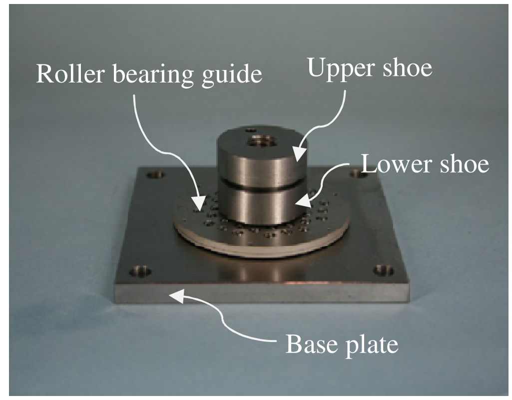


Fig.4. Roller bearing device

Roller bearing, designed and tested in the Structural Dynamics Laboratory of Sojo University, was chosen as the base isolation unit for the proposed structure. And the test mechanism of coefficient curve of roller bearing device is elaborated in the following section.

2.2.2 Roller Bearing Device

Roller bearing device components consist of 30 mm diameter of upper and lower shoes, 60 mm diameter of bearing guide and 6 mm thickness of base plate, Fig. 4. Upper shoe has a convex surface to place on the concave surface of lower shoe. Disc shaped roller bearing guide consists of 55 steel balls of 4 mm diameter, embedded within the bearing guides, for providing highly smooth surface in order to decouple the structure from the ground. Upper shoes, lower shoes and bearing guide were made of carbon steel (SC50C) and ball bearings were made of steel (SUJ2) material.

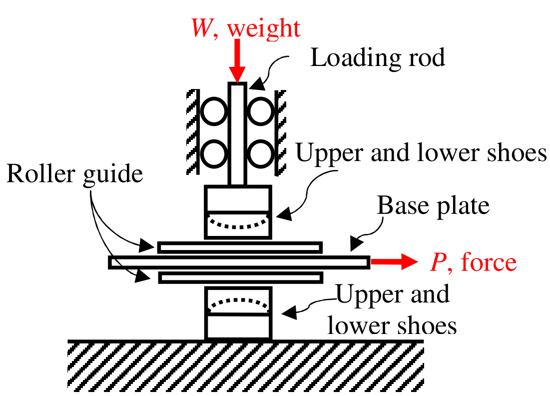


Fig.5. Friction test mechanism of roller bearings

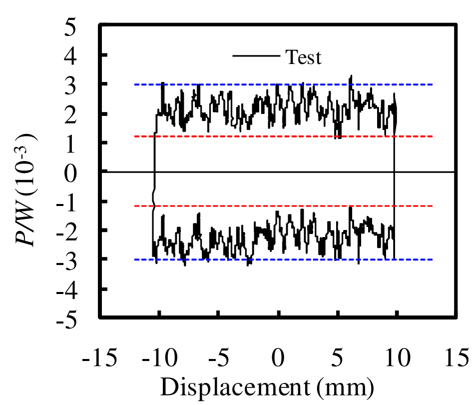


Fig.6. Frictional coefficient diagram

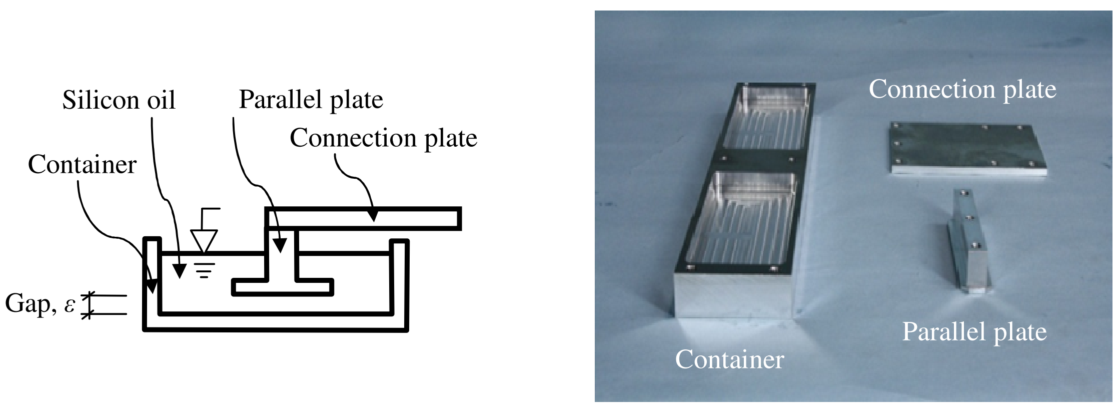
Fig. 5 illustrates the friction test mechanism of roller bearings in order to obtain the frictional coefficient of the roller bearing guide. Here, a pair of upper shoe - lower shoe - roller guide were placed upside and underside of the base plate. Then the base plate was forced to move back and forth through electric activator while the mechanism was under loading weight. The displacement of the base plate was measured through a laser measurer. The frictional coefficient diagram which obtained under 123 N vertical loads, Fig. 6, shows that the expected coefficient of the roller bearings was between 0.003 and 0.0012.

2.2.3 Viscous damping device

In order to come up with affordable damping solution for the experimental vibration model, a viscous damper device was designed that consists of container with two silicon oil pools, connection plates and parallel plates as shown in Fig. 7 (b). Containers were attached to the fixed sub-frame whereas two pieces of connection plates were fixed to the movable sub-frame. And the parallel plates which assembled with connection plates, Fig. 7 (a), were placed into the oil pools to make the connection between fixed and movable sub-structures. The dimensions of the container are 60 mm × 150 mm × 20 mm. The bottom surface of the parallel plates has 20 mm width and 110 mm length with 5 mm cut edge. So the bottom surface area of the parallel plates becomes a=2150 mm^2. Each of these three parts was made of aluminum alloy. The viscous damping coefficient of the damper device was estimated by given formula as follows:

$$d' = \frac{2\mu a}{\varepsilon} \qquad (1)$$

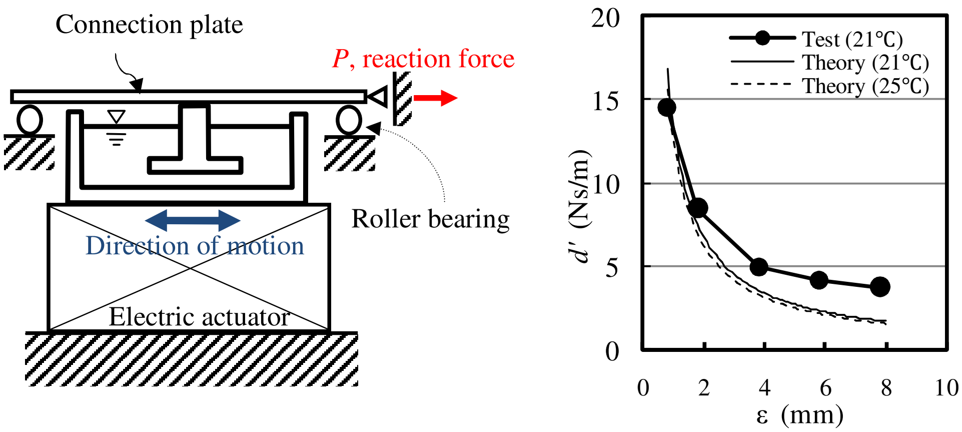
where ε is the gap between lower surface of the parallel plate and base surface of the container, a is the lower surface area of the parallel plate, υ is the dynamic viscosity of the silicon oil and d' is the viscous damping coefficient due to only one connection plate. Therefore the viscous damping coefficient becomes d=2d' for two connection plates.



(a) (b)

Fig.7. Viscous damper device: (a) cross sectional view, (b) components before assembly

The viscous damper was subjected to performance test to obtain the viscous damping coefficient. The container was forced to move back and forth in the vertical direction through electric activator and the reaction forces were obtained through load cell for different gaps as illustrated in Fig. 8 (a). The silicon oil has a ρ=3000 mm^2/s of viscosity and μ=970 kg/m^3 of density and $\upsilon_{25°C}$=2.91 Ns/m^2 of the viscosity coefficient for 25°C of room temperature. However the theoretical viscosity coefficient of the silicon oil was $\upsilon_{21°C}$=3.14 Ns/m^2 for 21°C of temperature. Fig. 8 (b) shows the diagram of damping coefficient versus gap.



(a) (b)

Fig.8. Viscous damping coefficient test: (a) test mechanism, (b) damping coefficient

Fig. 9 shows all the components of the vibration model at the bottom part after assembling. 6 pieces of roller bearing device were placed under each column, and additional dampers between fixed and movable sub-frames were aligned in 2 rows, and were connected by connection plates.

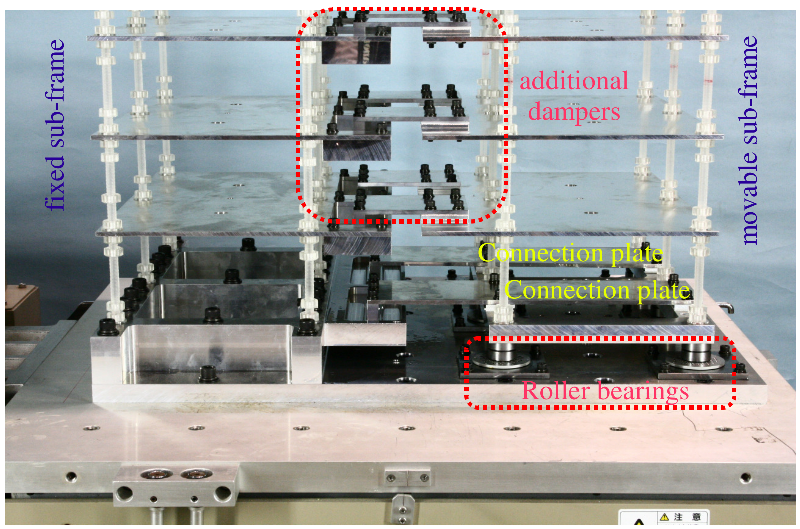


Fig.9. Vibration model components at the bottom: roller bearing and damper device

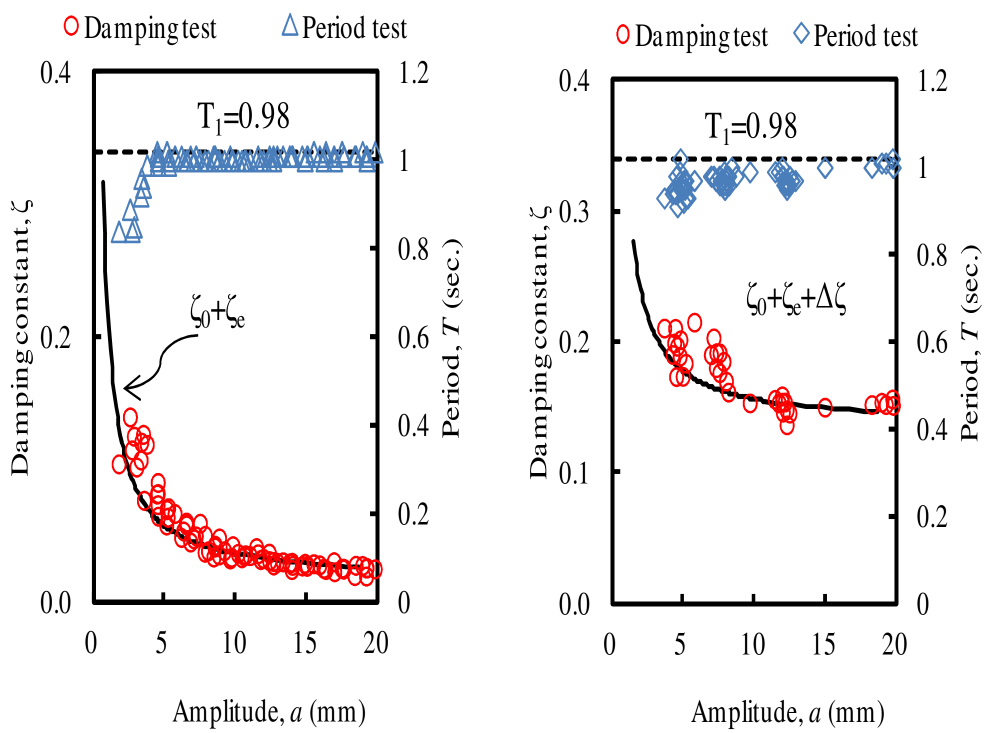
By this configuration, it is aimed to extend the natural period of the structure and to decrease the overall seismic responses. Numerical studies which include real-scale models were conducted to verify the theory of the proposed model, Kaya [16]. And it is seen that, the proposed configuration is able to extend the natural period by a factor of two for the proposed configuration when compared to ordinary building for the same building height. Moreover, these damping devices can be easily removed or added between the sub-frames, and since these sub-frames can move toward each other or away from each other, so it is an effective way placing damper devices in horizontal direction in increasing damping ratio.

III. EXPERIMENTAL STUDY OF FCSS MODEL

Since large additional dampers were added to the proposed structure for the case of vibration model with additional dampers, complex modes of experimental model due to obtained parameters in previous sections were calculated by using complex eigenvalue analysis, Foss Method [17]. Then a set of experiments to obtain dynamic parameters such as damping ratio and natural period, and elastic dynamic responses were conducted.

3.1 Free vibration analysis

Free vibration test is an essential way to obtain realistic values for natural period and damping ratios of a structure when compared to simulations due to assumptions to be made during the idealization of numerical model. For this purpose, the vibration model was mounted on the shaking table. Then, the vibration model was manually induced for a few times laterally. The displacements were recorded during oscillation until it came to rest. This process was repeated for 10 times to get the results precisely. This test was conducted two times for the proposed vibration model with and without additional damper systems.



(a) (b)

Fig.10. Natural period and damping tests of FCSS: (a) without damper, (b) with damper

The dynamic fictional force of the roller bearing system increases the damping of the structure. A frictional damping by a dynamic frictional force is evaluated so that the total energy dissipated per cycle is the same as for the viscous damping vibration during a steady state of motion. As the result this frictional damping can be evaluated by:

$$\zeta_e = \frac{2 f_b |\phi_b|}{\pi \theta \omega} x \frac{|\phi_i|}{a_i} \qquad (2)$$

where ζ_e is called the equivalent viscous damping constant of the i-th natural vibration mode, θ and a_j are the frequency and the amplitude at beam-j during a steady state of motion, respectively. Damping constant ζ, can be estimated by addition of structural damping constant and equivalent viscous damping constant of the roller bearing support, ζ_0+ ζ_e, due to friction forces. Equivalent viscous damping constant can be calculated by Eq. 2 where, f_b is the frictional force at the roller bearing, ϕ_b is the amplitude of the equivalent vibration mode of the roller bearing, ω is the natural frequency, ϕ_i is the amplitude of the natural vibration mode, θ is the (circular) shape frequency of the observed object, a is the observed amplitude and natural vibration modes. The total force and the friction coefficient at the roller bearing are 600N and 0.0012, respectively. Therefore the frictional force is equal to f_b = 0.0012 × 600N = 0.72N. As seen in Fig. 10, the damping constant decreased as long as the amplitude increased and in spite of the increasing amplitude value, the natural period changed in a small range. The structural damping constant of the vibration model was assumed as ζ_0=0.015. Besides, the viscous damping constant was d = 2 × 7.5Ns/m = 15 Ns/m corresponding to the gap of 2 mm as seen from Fig. 8 (b). The damping constant of the additional viscous dampers and the natural period were obtained ζ = 0.135 and T_{d1}= 0.98 sec, respectively.

3.2 Elastic dynamic response analysis

The vibration model of the proposed structure with and without additional dampers were tested through shaking table, Fig. 11, to verify the seismic response behavior due to El Centro, Taft, Hachinohe and Miyagi earthquakes with 50 gal of maximum acceleration.

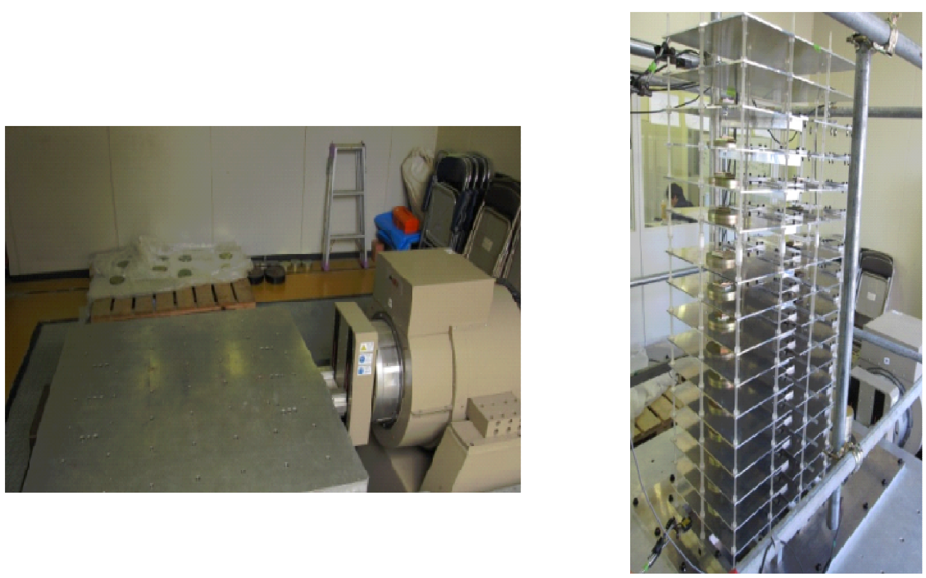


Fig.11. Shaking table and vibration model

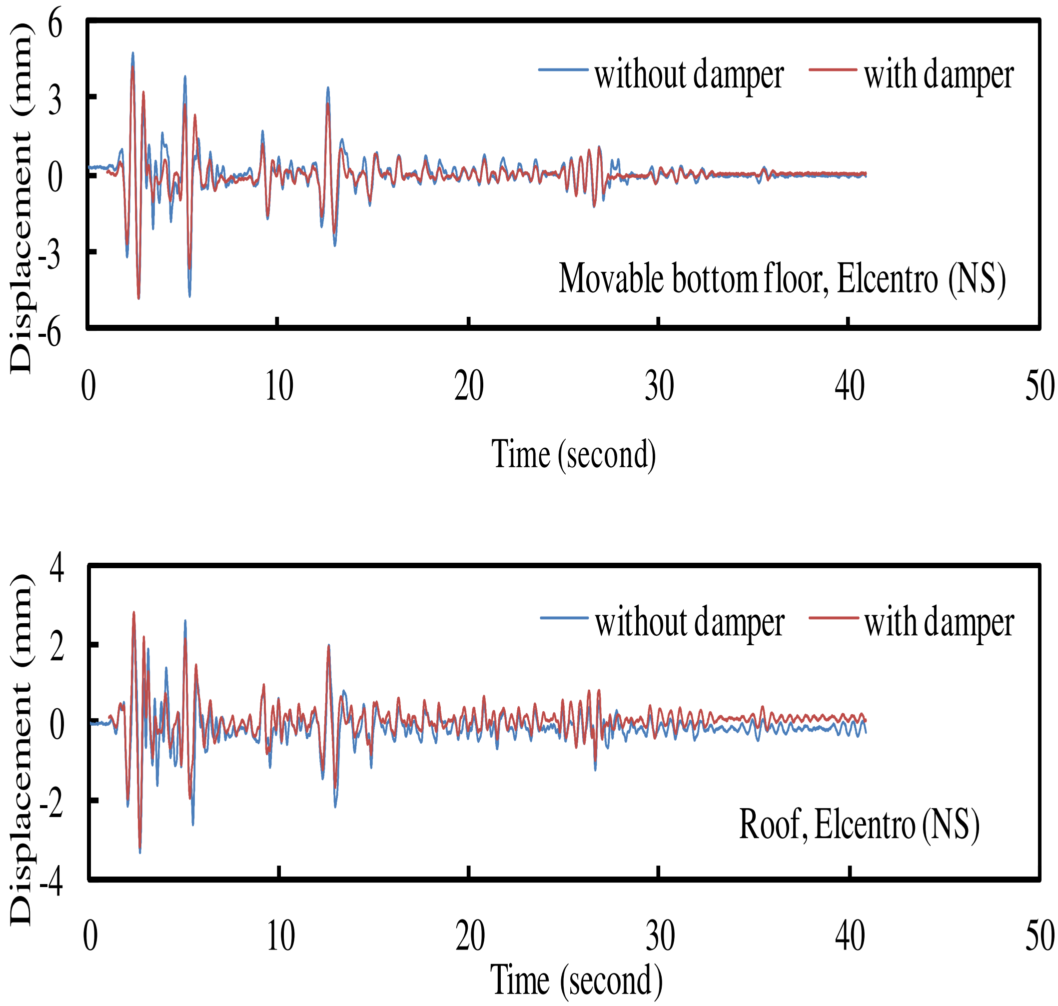


Fig.12. Shaking table responses of experimental model

Fig. 12 illustrates the relative displacement responses, with respect to shaking table, of the proposed model with and without additional dampers at the movable bottom floor and at the roof part.

Fig. 13 illustrates all relative displacement responses of the vibration model due to all above mentioned earthquake waves. The displacement responses can be relatively higher for the vibration model when no additional dampers were used. Therefore, it is important to use damper devices between sub-frames to minimize the displacement responses.

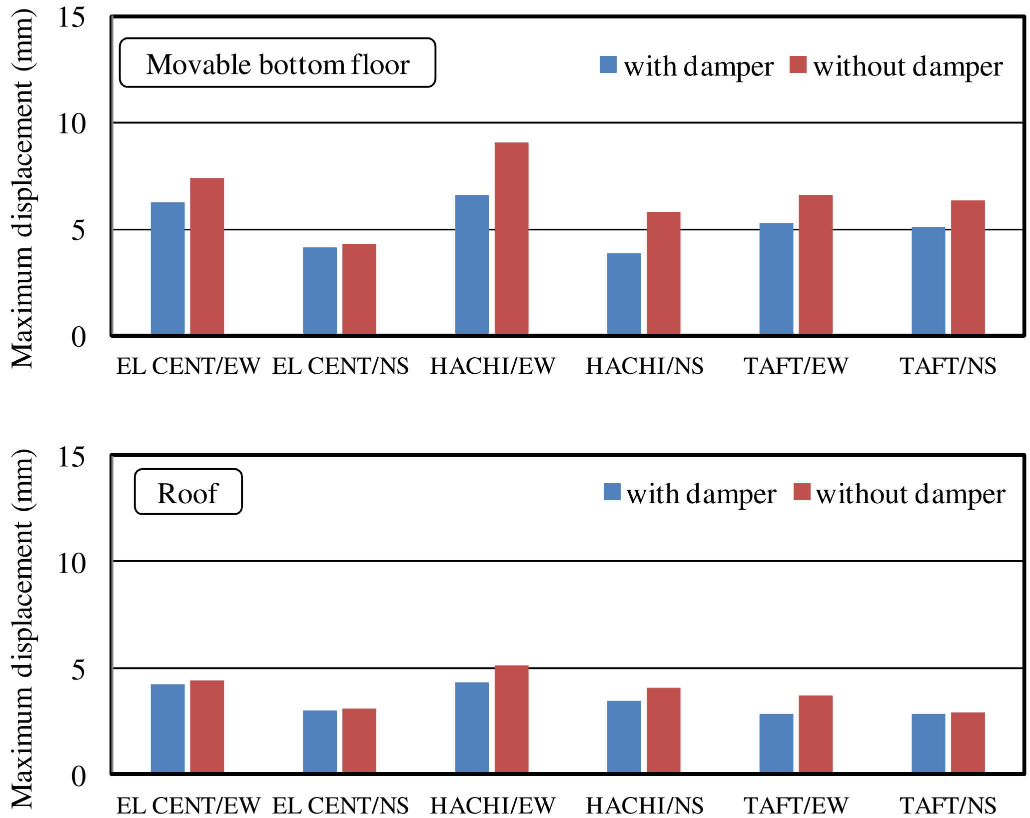


Fig.13. Shaking table responses of experimental model

The displacement responses were higher at the movable bottom part, when compared to roof part. The maximum values for relative displacements were obtained around 10 mm at the movable bottom and around 5 mm at the roof part.

IV. COMPUTATIONAL VERIFICATION OF EXPERIMENTAL MODEL

As it is mentioned before, the experimental vibration model is not a scaled model. It is needed to confirm that the behavior of the experimental vibration model is consistent and accurate. Therefore, ABAQUS software, well known and powerful finite element software, is chosen for the simulation studies of the proposed building especially for the dynamic analyze studies. If we have a brief look at literature on the studies using ABAQUS software, it is seen that the program have became increasingly used recently especially in the field of earthquake engineering including base isolation system analysis, and contact simulations to get the most accurate result before production.

On the other hand, since the program is so complicated the probability of making mistake is much bigger. Some studies using ABAQUS in the field of earthquake engineering are mentioned as follows. For example, Clarke *et al.* [18] used ABAQUS software to model a real scale FPBs for an structural platform of an offshore structure. Rubber bearings and roller bearings were studied as well by using ABAQUS software in complex structures with earthquake isolation systems, Amin [19] and Bushell [20]. It is also noted that the software is more complex for the users when compared to special purpose software aiming structural analyzing. To criticize how important is finite element methods with their strong calculation capacity, An *et al*. [21] summarizes major projects and their calculations especially in terms of elasto-plastic dynamic analysis.

4.1 Free vibration analysis

After modelling experimental vibration models in ABAQUS software, Fig. 14, eigenvalue analysis were conducted.

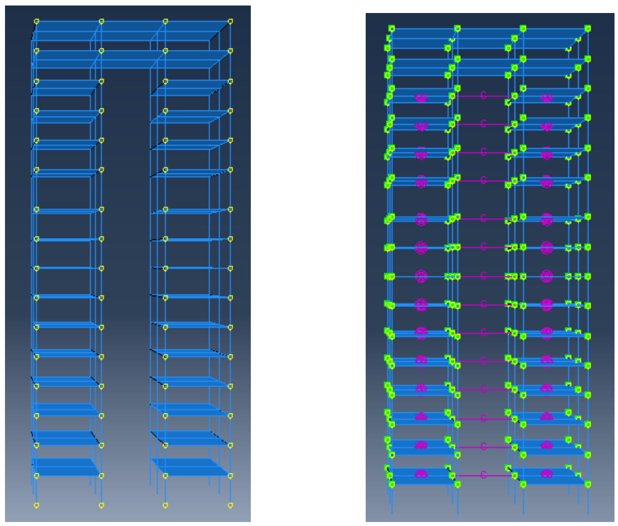


Fig.14. ABAQUS simulation models with and without additional dampers

Table 1 shows that the first natural period of experimental model obtained in free vibration analysis is T = 0.98 sec, whereas the result for ABAQUS simulation is T = 0.982 sec. Vibration modes are also illustrated in Fig. 15 that is obtained by ABAQUS software.

TABLE 1 Eigenvalues of the Experimental Model

	Experimental Model	ABAQUS Result		
	First	First	Second	Third
T(second)	0.98	0.982	0.308	0.181

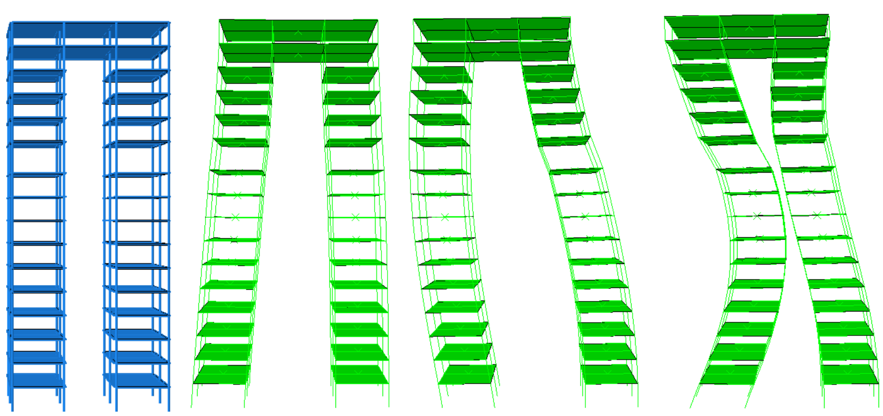


Fig.15. Vibration modes obtained by using ABAQUS

4.2 Elastic dynamic response analysis

The seismic responses of the modified vibration model are also tested through shaking table test due to same earthquake waves 50 gal of maximum acceleration. It is seen in Fig. 16 that the seismic responses for shaking table and computer simulations are in good match.

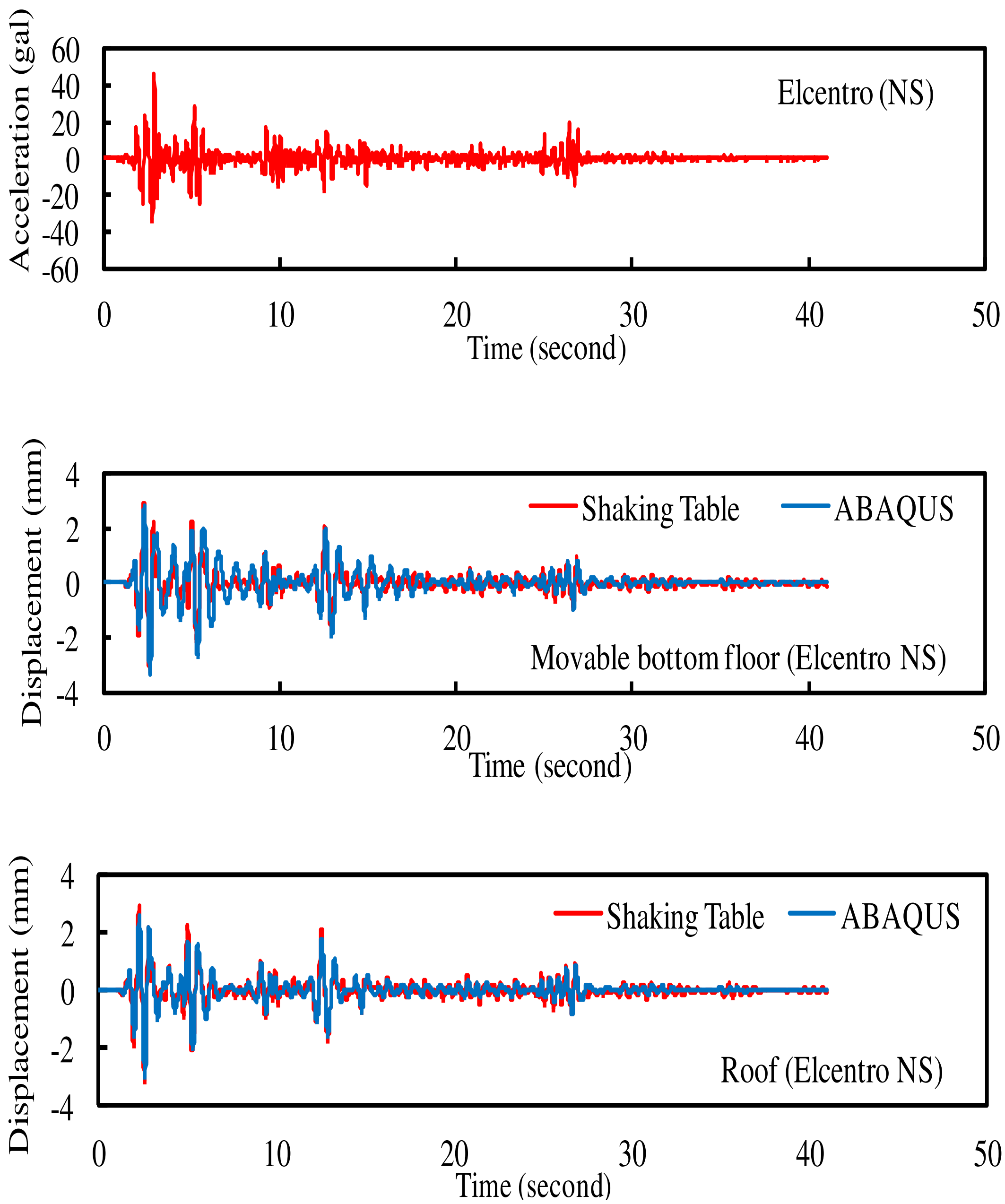


Fig.16. Comparison of shaking table test responses with ABAQUS

V. CONCLUSION

In this research, experimental studies using proposed folded cantilever shear structure, a newly designed structure, were conducted. The main idea of the proposed structure was that a new seismic isolation approach incorporating base isolation system and coupling method into a mid-rise structure might be effective in increasing seismic performance that consisted of coupled buildings of similar heights. Therefore, a new configuration for buildings of similar heights were proposed and studied by connecting them at the roof part. Contrary to common configurations, the boundary conditions were selected to be one fixed supported building and the other to be base isolated building while using rigid connection at the top. It was found that the proposed structure is capable of extending natural period and minimizing accelerations, displacements and base shear forces simultaneously. Contrary to ordinary idea, it is possible to increase the seismic performance of coupled structure consisting buildings of similar heights. And both experimental studies and the simulation results were obtained in good match. Besides, additional damping devices can be customized and easily removed or added between the sub-frames. And since these sub-frames can move toward each other or away from each other, it is an effective way placing damper devices in the horizontal direction for increasing damping ratio.

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