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EARTHQUAKE RESPONSE OF MODIFIED FOLDED CANTILEVER SHEAR STRUCTURE WITH FIXED-MOVABLE-FIXEDSUB-FRAMES

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ABSTRACT

Seismic performances of sixteen-storey folded cantilever shear structure (FCSS) with roller bearing and additional viscous damper have been studied using a shake table. The structures consist of fixed-movable-fixed supported shear sub-frames and connection rigid sub-frame which connect their sub-frames at the top. The movable sub-frame is supported by roller bearings and additional viscous damper are attached laterally between beams. Experimental and numerical analyses were conducted to identify dynamic responses of model with and without additional viscous damper. In order to observe the efficiency of the additional viscous damper and the effect of earthquake ground motion under three different strong ground motions, namely El-Centro, Hachinohe, and Taft earthquakes, both numerical analysis and shaking table test of the model with and without additional viscous damper were conducted. The maximum displacements, for top fixed floor and bottom movable floor were significantly reduced with the addition of viscous damper system of structure. A reasonable agreement between results obtained from numerical analysis and shaking table test were also obtained.

Keywords: Seismic performance, folded cantilever shear structure, viscous damper, damping ratio, shaking table test.

I. INTRODUCTION

In recent years, earthquake is one the most important issue of structural engineering problem. It has caused significant loss of life and severe damage to structures. Many seismic construction designs and technology have been developed over the years in attempts to mitigate the effects of earthquake on buildings. Some protective systems have been used to enhance safety and reduce damage of structures during earthquakes. The most practical and reliable method of reducing seismic structural response are seismic base isolation and passive energy dissipation system such us fluid and friction dampers. Recently, many researchers have been studied about seismic isolation systems.

N. Torunbalci [1] was studied seismic isolation and energy dissipating systems for improving the seismic performance of structures. These techniques reduce the seismic forces by changing the stiffness and/or damping in the structures. The research and development work of passive, active, and hybrid devices are ongoing intensively.Y.M Wu and B. Samali[2] investigated of five-storey benchmark model isolated with rubber bearing. Numerical analysis and shake table testing of model with and without the isolation system were studied under four different strong ground motions. It was found, from both numerical analysis and shake table testing, that the isolation effectiveness offered by the rubber bearings to earthquake inputs is strongly dependent on the type of earthquake motion. The displacement for all floors was significantly reduced with the addition of a rubber isolation system, regardless of ground motion input. N. Torunbalci and G. Ozpalanlar [3] were evaluated of earthquake response for base isolated building. The most important characteristic of the structural system, in terms of determining its response against the earthquake, is its natural period. The natural period depends on the mass, horizontal rigidity and damping of structure. One of the important things the seismic isolation actualizes on the structure is the prevention of coincidence with the fundamental period of the earthquake by increasing the natural period of the structure. Accordingly, the using of seismic isolation provides approximately seventy five percent decreases in the base shear forces on the structure. N. Torunbalci and G. Ozpalanlar [4] also studied earthquake responses of building with various seismic isolation techniques. The model building is analyzed in the nonlinear time domain both for fixed base situation and also by using various seismic isolation and earthquake protection alternatives such us rubber bearing, friction pendulum bearing, additional isolated story and viscous damper. It shows that acceleration and story drift in all various alternatives, is significantly reduced especially in the fixed-base alternative. The other hand, Azuma *et al.* [5] is discussed the seismic response control of a building by connecting to an adjacent building with coupling energy dissipating devices. Ten-storey and five-storey structures were investigated under artificial ground motion. Those structures were connected with rigid or bilinear hysteretic or viscous damping elements. The coupling showed that story drift and floor acceleration can be reduced. And also, Ohami*et al.* [6] studied about retrofitting seismically vulnerable buildings by externally inter-connecting to an adjacent building. The rigid element and viscous damper connecting element are used to connect between old five-storey building and new ten-storey building.The collapse of an old building can be prevented by connecting to a new stiff building using rigid elements, if viscous damper connecting elements are used, damage of the old building concentrated in a specific story.Limazie .T *et al.*[7]proposed structure is called mega-sub controlled structure system. This structure are designed as modulated sub-structures and fixed to the mega-beams structures, additional columns are introduced between mega-frame and the top-level of substructures. Structural parameters are examined and compared to the mega-sub structures. The results show that mega-sub controlled structure as proposed structure obviously improves the structures safety under seismic action, reduces displacement, velocity, and acceleration responses when subjected to random load, and also improves the comfort of the structure.

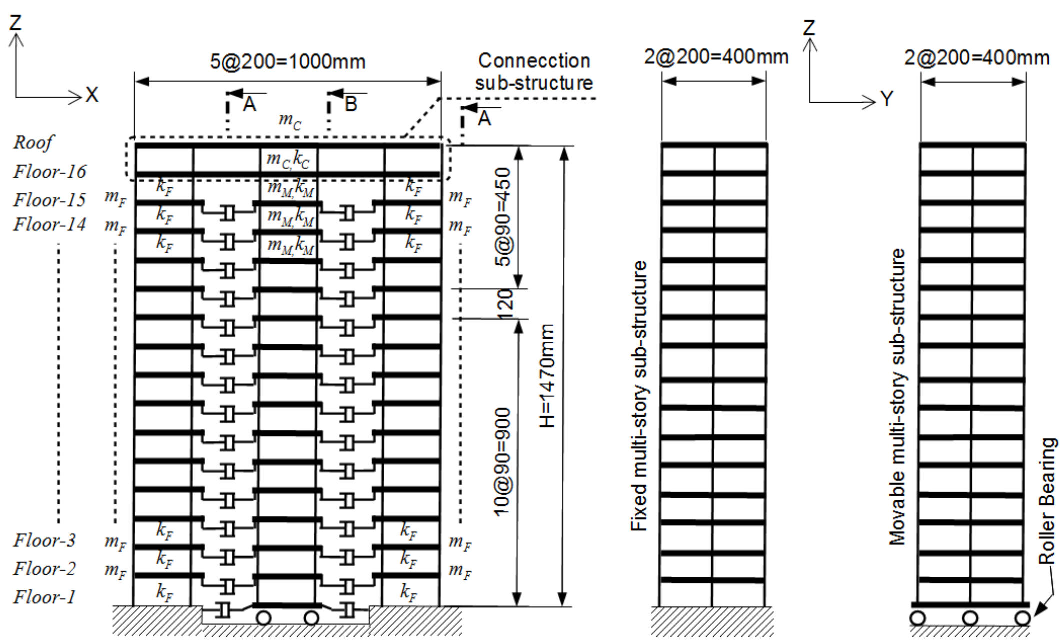
On the basis of those studies, some alternative seismic isolation was offered. It summarized that combination of seismic isolation can reduce seismic responses of buildings. Kaya *et al.* [8] were proposed a newly designed structure named Folded Cantilever Shear Structure (FCSS). It is proposed an alternative seismic isolation approach that combines roller bearing as base isolation and viscous damper as connection between inter-stories to improve seismic performance and increase natural period.The proposed folded cantilever shear structure is designed consisting of mainly two parts, fixed shear sub-structure and movable shear sub-structure. These sub-structures are interconnected by a rigid connection beam at the top of the sub-structures. Besides, additional viscous dampers are supplemented to connect fixed and movable shear sub-structures with each other horizontally on the base of stories. The analytical study was carried out to examine FCSS structure, also compare with ordinary cantilever shear structure (OCSS) and FCSS without additional damper. From the results show the proposed model FCSS is capable of extending the natural period two times compared to ordinary structure and also can decrease the displacement responses due to earthquake.

In this study, Folded Cantilever Shear Structure (FCSS) is modified to acquire symmetrical structural regularity. The proposed modified structure is designed consisting of fixed-movable-fixed shear sub-structures.At the top roof, rigid beam is used as a connection between fixed and movable parts. The purpose of this study are improving seismic performance of building structure and investigate the efficiency of additional viscous damper by modifying the FCSS model from previous study under different earthquake motion using shaking table test. To compare results of shake table testing, numerical analyses is conducted to verify of analytical methods.

II. STRUCTURAL AND GEOMETRIC FEATURES

2.1 Model of FCSS

As shown in Fig. 1 is structure plan view of the vibration model. The proposed structure model is arranged symmetrically, fixed sub-frames on the both edge sides and movable sub-frames at middle of structure. Rigid beam is used to connect the fixed-movable-fixed sub frames at the top of structure (Floor-16). The assembled structure of front view in x-z direction shown in Fig. 1 (a) and side view in y-z direction shown in Fig. 1 (b) and (c). The fixed sub frames are clamped at the base of structure. The movable sub frame (Floor-1) is supported by roller bearing and can move horizontal. Z-axis direction is fixed, moving condition of the movable sub frame in the x and y direction. The total floor of structure is 16-stories. Total height of structure is 1470 mm.



(a) Front view (b) Side view

Fig.1.Geometric of experimental vibration model

Between fixed sub frame and movable sub frame is connected by using viscous damping device for each floor horizontally. Viscous damping device is operated in the x-y horizontal plane. The detail of viscous damping device will describe in next section. Polycarbonate (PC) screw rods with M10 are used to all the columns of the model. Since the maximum length of the available polycarbonate is about 1000 mm, set up a column joints with plastic nut at the 11^{th} floor. And 120 mm height for 11^{th} floor, and 90 mm height for the other floors typically. According to the tension and bending test of polycarbonate rod of column, the axial stiffness (AE) was obtained around 1.10×10^5 N and flexural stiffness (EI) was 5.65×10^5 N.mm^2. Aluminum alloy (A5052) rectangular plates with 5 mm thickness are used as beams for each floor. Shown in Fig. 1, the mass floor of fixed sub frame, movable sub frame, and connection sub frame are represented m_F, m_M, m_C, respectively. k_F, k_M, k_C, are column stiffness of fixed, movable, and connection sub frame, respectively. The total mas for each floor are 2.5 kg of fixed sub frame floor, 3.8 kg of movable sub frame floor, and 6.1 kg of connection floor at the top.

2.2 Mechanical properties of elements

2.2.1 Shear spring coefficient of model

In order to determine the inter-storey shear spring coefficient of the movable sub frame and fixed sub frame, the quasi-static loading test on the vibration test model was conducted. Shown in Fig.2, the horizontal force P is applied at 1^{st} floor of the movable sub frame and the horizontal displacement $u_{29}$and u_{44} were measured by using laser displacement sensor. u_1, u_2, u_3… u_{14}andu_{15}, u_{16}, u_{17}… u_{28} are horizontal displacement in x direction of the floor-2 to floor-15 at the fixed sub frame of the left and right side, respectively. And also u_{29}, u_{30}, u_{31}… u_{43} for movable sub frame.

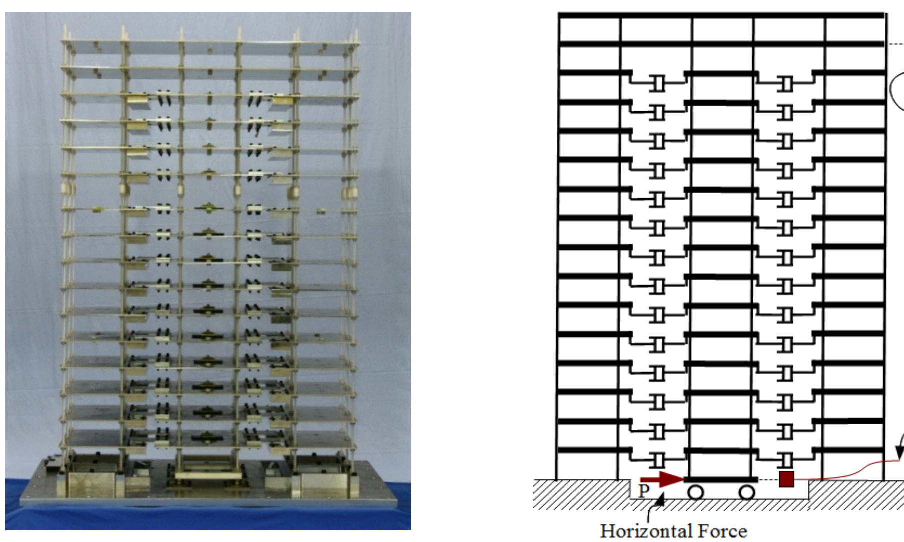


Fig.2. Experimental vibration model

Fig. 3 represents the horizontal force-displacement due to loading test. The slope of force-displacement history curve at top floor $u_{44}$is about 7.4 N/mm; inter-storey shear spring coefficient from this value is 56 KN/m. Slope at movable bottom floor, the force-relative displacement (u_{29} - u_{44}) is 3.8 N/mm, shear spring coefficients is 57 KN/m. The average of both these value is 56.5 KN/m was used as shear spring coefficient for the elastic dynamic response analysis, eigenvalue analysis and also simulation. The gap between unloading and loading from the graph is around 2.9 N. It considered that the half of this valueis the maximum static friction force of the roller bearing, is about 1.45 N. The total mass of movable sub frame without connection beam at the top floor is about 57.0 kg. Assumed that the movable structures are support one third of the connection beam at the top floor, is 4.1 kg. Therefore, the total mass of movable part of structure is 61.1 kg, approximately. And the total vertical force is about 600 N due to gravity. Static friction coefficient of roller bearing can be estimated from the ratio of friction force and vertical force about 0.0024.

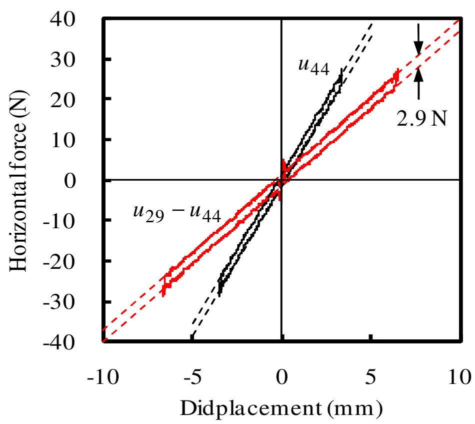


Fig.3. Quasi-static loading tests

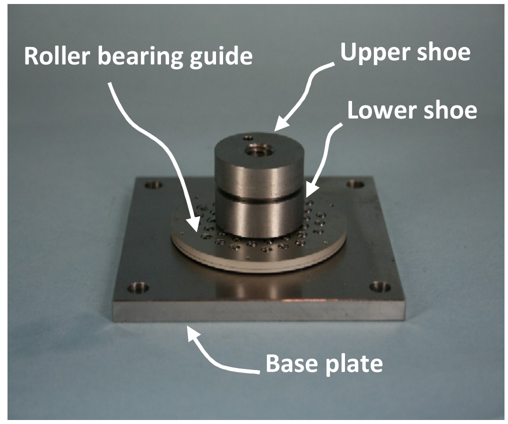


Fig.4.Roller bearing device

2.2.2 Roller Bearing Device

The set of roller bearing components are shown in Fig. 4. Roller bearing consist of upper and lower shoes with 30 mm of diameter, 60 mm diameter of bearing guide and 6 mm thickness of base plate. 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 presents the friction test procedure to determine the friction characteristics of roller bearing. 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.

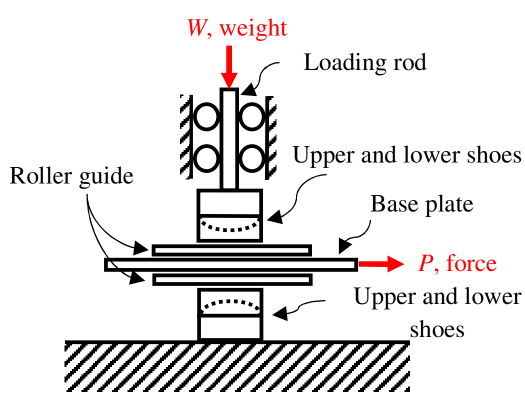


Fig.5. Friction test of roller bearing

The history of a horizontal displacement and horizontal force is shown in Fig.6. It was applied the vertical force of 123 N. Vertical axis is represent the ratio of horizontal and vertical force. Maximum static friction coefficient was estimated from quasi-static loading test in previous section is about 0.0024, it is half between 0.003 and 0.0012.

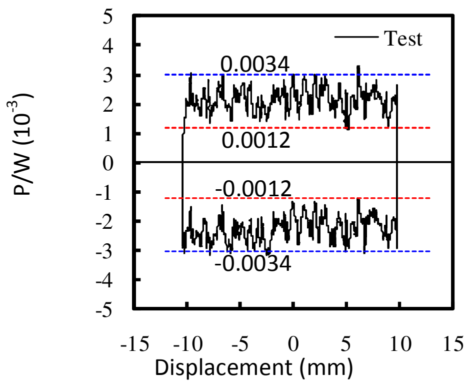


Fig.6. Friction coefficient of roller bearing

2.2.3 Viscous damping device

The components and cross section of viscous damping device are shown in Fig. 7. It was designed that consist of container with two silicon oil pools, connection plates and parallel plates.The dimensions of the container are 60 × 150 × 20 mm (width × length × depth). 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 calculation of viscous damping coefficient of damper device can be estimated as:

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

Where $\varepsilon$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, μ 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 $d = 2\ d'$for two connection plates.

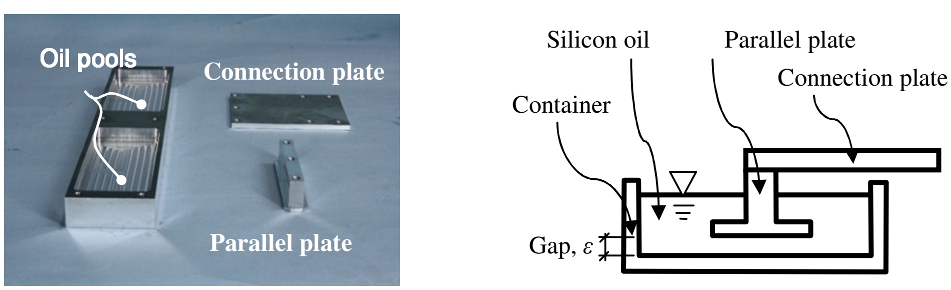
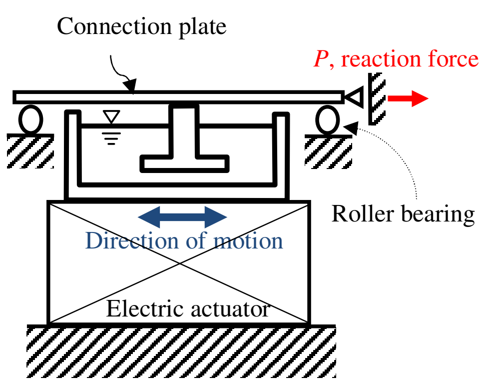


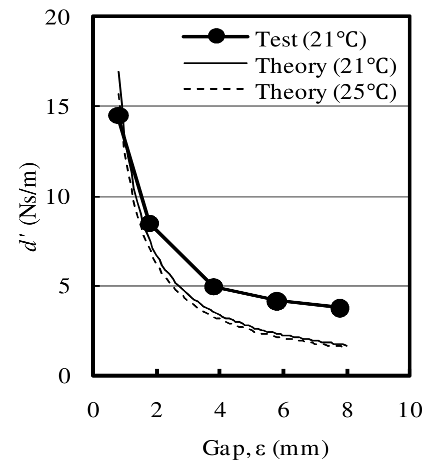
Fig.7. Cross section of viscous damping device

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 relationship of the viscous damping coefficient d' and the gap $\varepsilon$are shown in Fig. 8 (b). The kinetic viscosity 25 ^{0}C of silicon oil υ = 3000 mm^2/s and the density = 970 kg/m^3 were used in the experiment. Therefore, the dynamic viscosity μ_{25^0C} = 2.91 Ns/m^2. The temperature of the silicone oil during the experiment is 21^0C and the viscosity change rate by temperature is 1.08. Then the dynamic viscosity $\mu_{21^0C} = 3.14$ Ns/m^2.

The assembled structure can be seen in Fig. 9. The roller bearing and viscous damping device was constructed for whole structure to conduct the experiment study.



(a) Test of viscous damping device



(b) Coefficient of viscous damping device

Fig.8. Performance test of viscous damping device

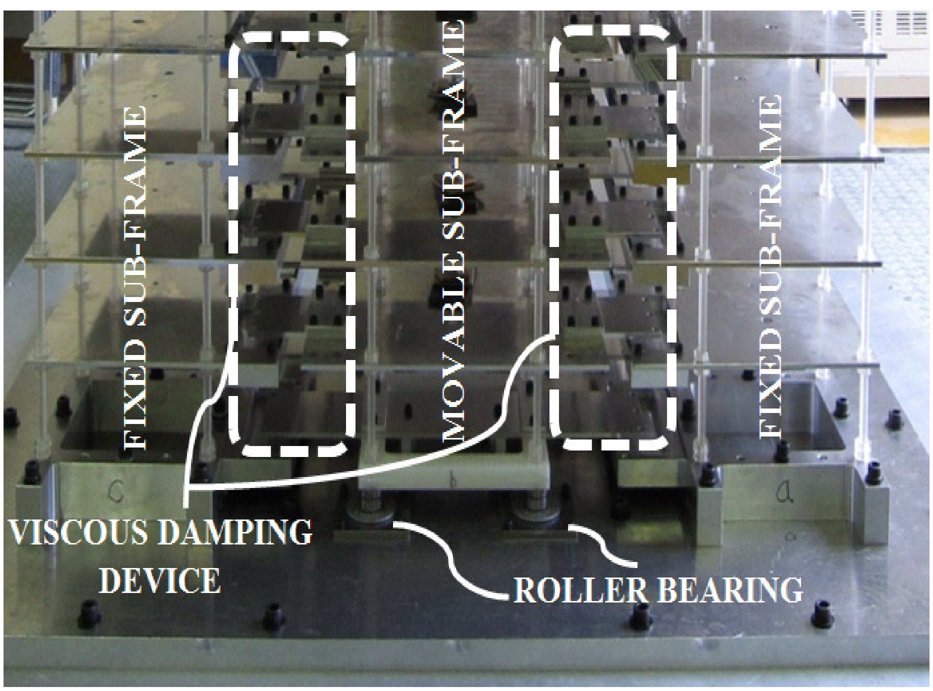
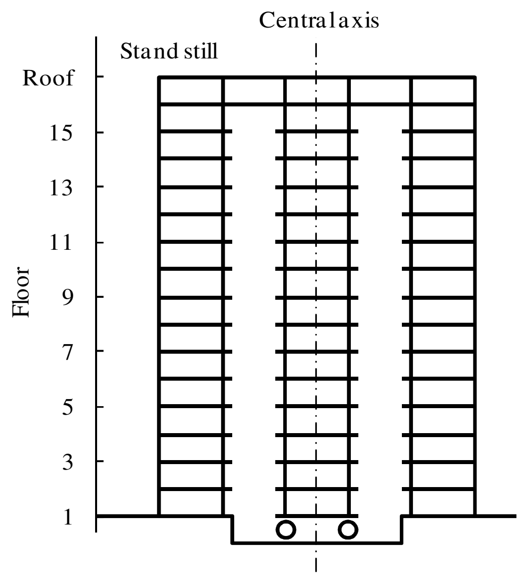


Fig.9. Component of experimental model

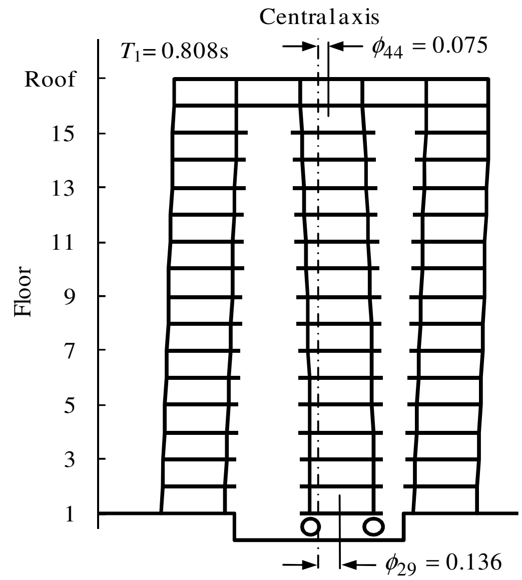
III. EXPERIMENTAL STUDY OF FCSS MODEL

3.1 Complex eigenvalue analysis

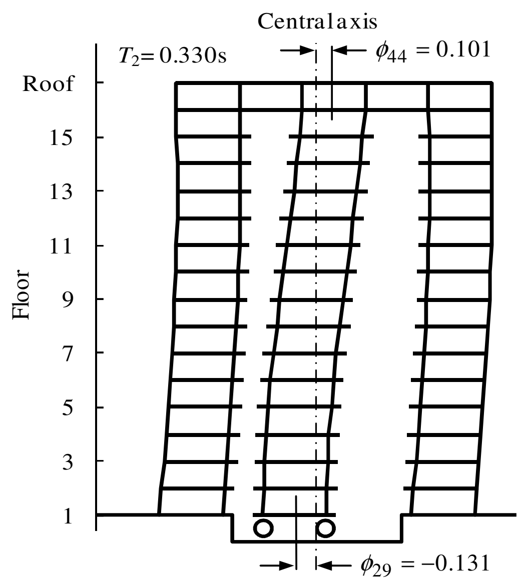
The eigenvalue and eigenvector analysis of experimental model were calculated by using complex eigenvalue analysis [8] and [9] to obtain the natural vibration mode and natural period theoretically. Fig. 10 shows the natural vibration mode. The first, second, and third modes were obtained with natural period and also amplitude of vibration mode. Fig. 11 show the relationship between additional damping constant $\Delta\zeta$, damped period T_d and viscous damping constant. The additional damping constant is increase by improving the viscous damping constant.



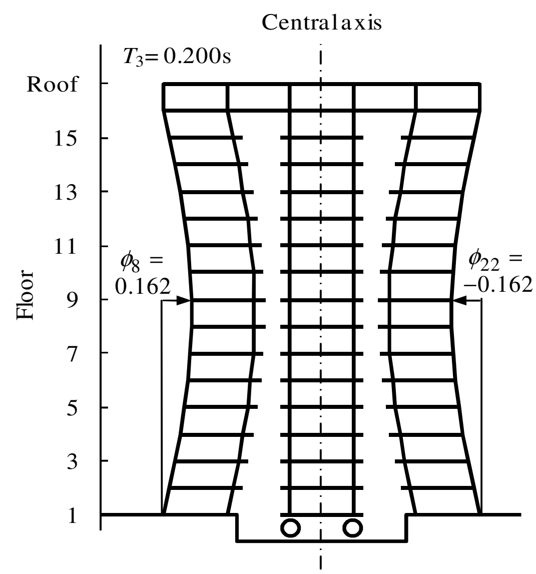
(a) Stand still



(b) First natural vibration mode



(c) Second natural vibration mode



(d) Third natural vibration mode

Fig.10. Natural vibration mode of experimental model

From the analytically, the first natural period of the model is T_1 = 0.808s for the model without additional viscous damping device, the additional damping constant and first natural period with viscous damping constant$d$ =15 Ns/m are $\Delta\zeta$=0.233 and T_1 = 0.796 s, respectively.

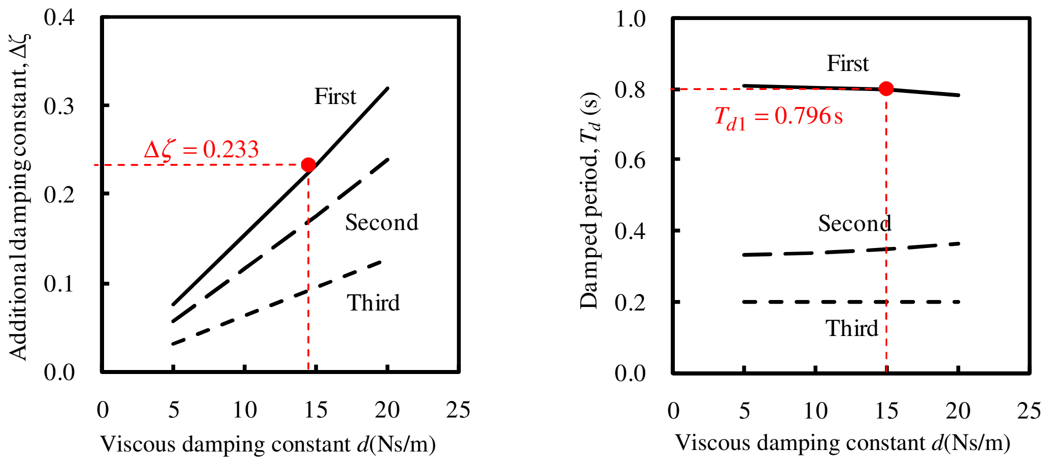
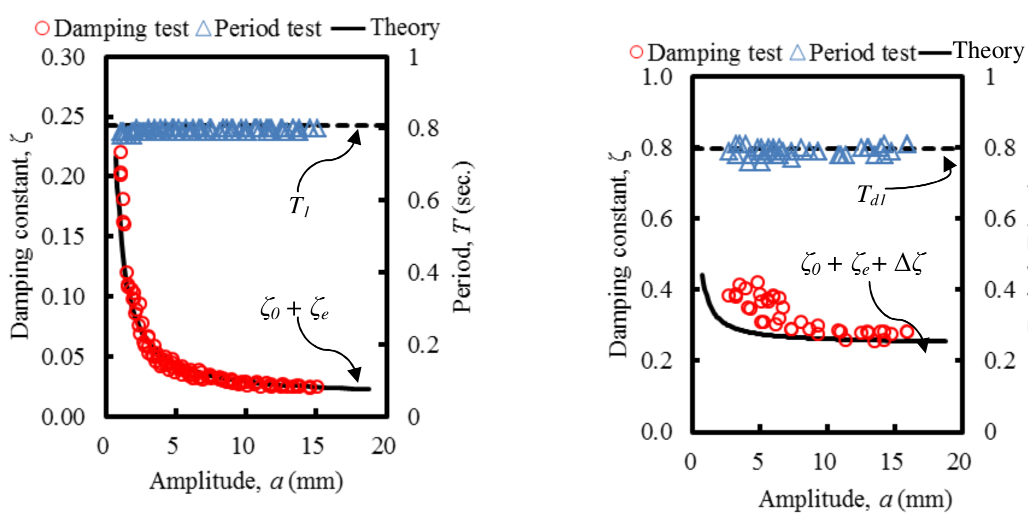


Fig.11.Additional damping constant and damped period

3.2 Free vibration test

Free vibration experiments provide one means of determining the natural period and damping ratio of the structure. It is useful for comparing simulation model during the theoretical and numerical study. The free vibration test was conducted manually. The model is induced for few times laterally. The displacements were recorded during oscillation until it came to rest. This process was repeated for 10 times to get results precisely. The free vibration test was carried out for vibration model with and without additional damping system. Theoretical and experimental of periods and damping ratio are calculated and plotted in the Fig. 12. The first period of the FCSS without additional damper is around T_1 = 0.808 s and the FCSS with damper is T_{d1} = 0.796 s.



(a) FCSS without additional damper (b) FCSS with additional damper

Fig.12. Natural period and damping test of FCSS

As shown above, ζ_0 is constant structural damping; ζ_e is equivalent damping constant due to frictional force obtained from Eq. (2), $\Delta\zeta$ is additional viscous damping constant and a is displacement amplitude.

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

where, f_b is friction force of the roller bearing, ϕ_b is the amplitude of natural vibration mode at movable base, ϕ_i is the amplitude of natural vibration mode at observation point, θ is frequency during a steady state motion, ω is natural frequency, a_i is displacement amplitude of observation point, Katayama *et al.*[10]. The total force of the movable sub frame is around 600 N and the friction coefficient of roller bearing is 0.0012. Therefore, the friction force of roller bearing is 0.72 N. The structural damping of vibration model is assumed, $\zeta_0 = 0.015$.In Fig. 12 (a), the total damping ratio is sum of structural damping and friction damping, while in Fig. 12 (b) it will be added by additional viscous damping. In here, the additional viscous damping device was used by 2 mm gap and as shown in Fig. 8 (b), the viscous damping is around $d' = 7.5$ Ns/m. For two connection plate of damping device is $d = 2d' = 15$ Ns/m. The additional viscous damping constant can be estimated from Fig. 11, $\Delta\zeta = 0.233$. And also in Fig 11, from complex eigenvalue analysis the first damped period $T_{d1} = 0.796$s.

3.3 Shaking table test

The shake table test is carried out to observe the seismic response of proposed model with and without additional damper under the earthquake data wave. As the input excitation to the shake table, three earthquake wave records: El Centro (1940), Hachinohe (1968) and Taft (1952) were used. Maximum acceleration for each earthquake is 50 gal scaled.

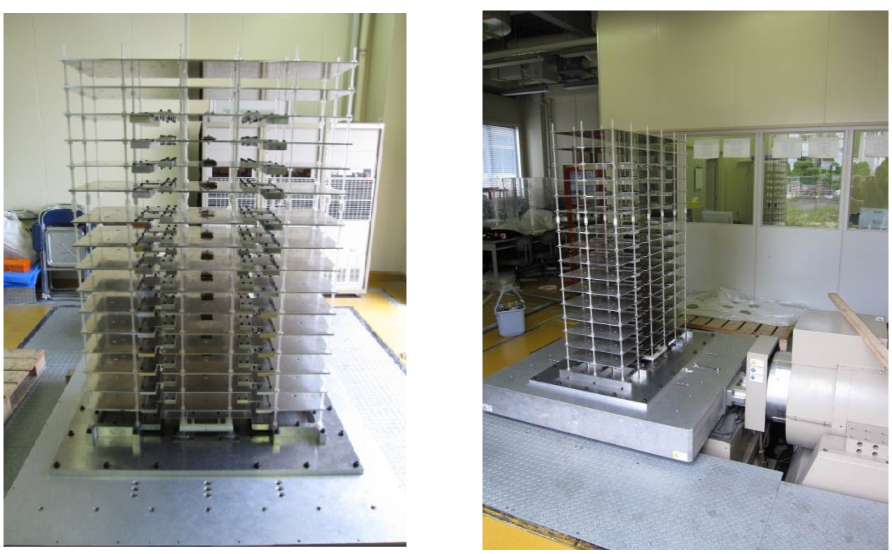
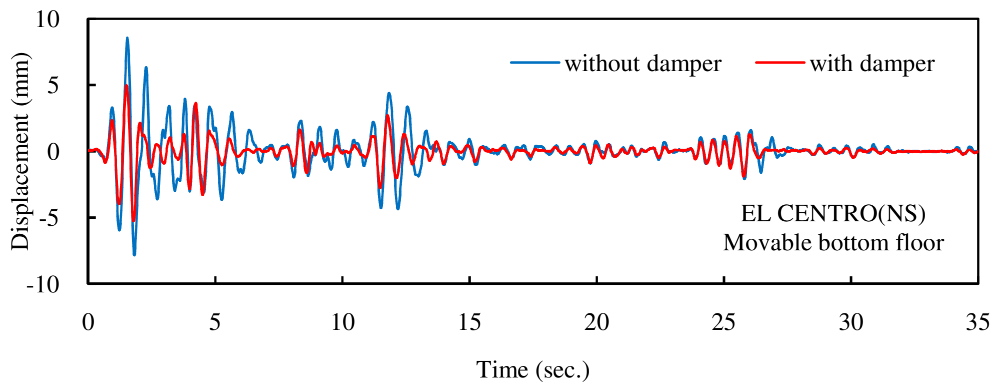
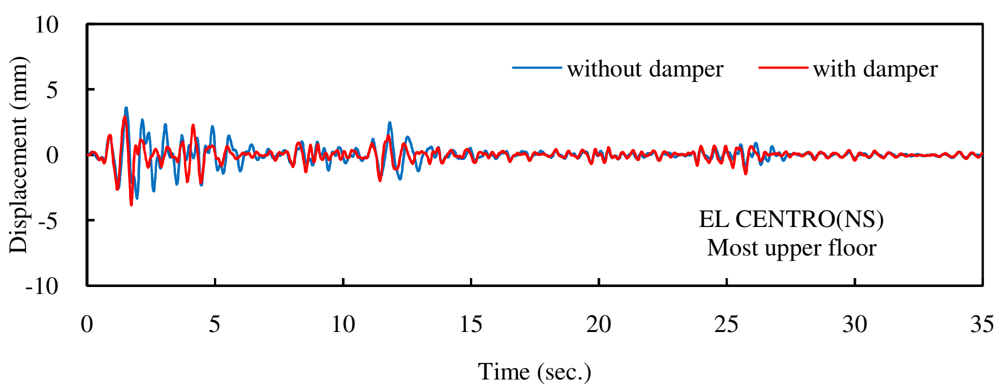


Fig.13. Shaking table test of sixteen-storey FCSS model

Fig. 13 shows the sixteen-storey of FCSS model on the shake table, and ready to be tested. The displacements floor of the test model was measured using laser displacement at the top floor and movable bottom floor.To set an example, only displacement history responses due to El Centro NS earthquake are given in Fig. 14. Then the maximum displacement responses of the others are summarized graphically of bar chart in Figure 15.



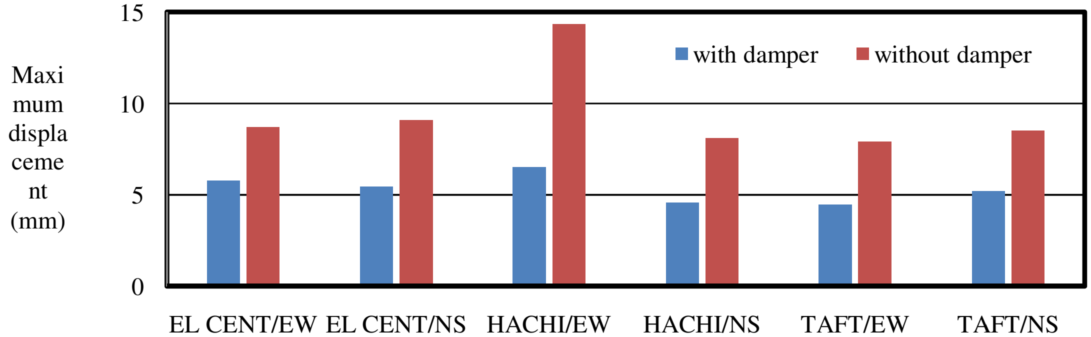
(a) Movable bottom floor



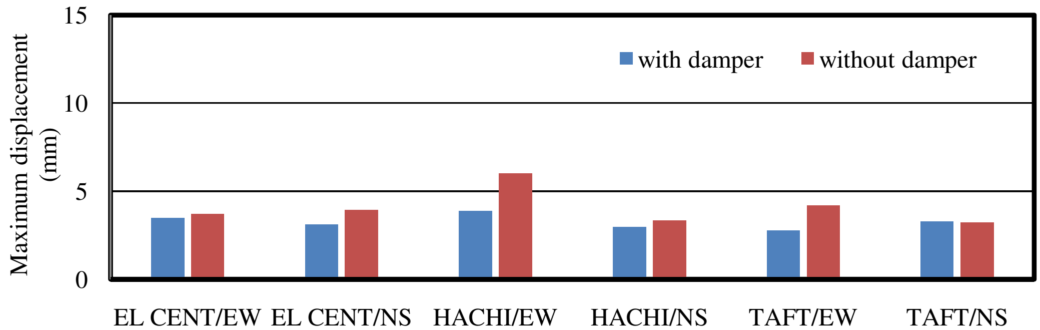
(b) Most upper floor

Fig.14. Time histories of displacement responses of FCSS model

Fig.14 show the displacement responses of proposed FCSS model at the bottom floor. In here, the displacement responses decrease significantly when the additional damper is attached in structure. In the other side at the most upper floor, effect of additional damper is not significant than at the bottom, however it still can reduce the displacement responses. Fig.15 show maximum displacement responses for all earthquake data waves. As mentioned above, the additional damper gives effect significantly to reduce the maximum displacement at the bottom floor than the most upper floor. It is shown when the additional damper attached in model; the maximum displacement is decrease, generally. For instance in Fig. 15 (a), a dramatic reduction in maximum model displacement is seen for FCSS with damper, which demonstrates the capability of viscous damping device in protecting the structure against the earthquake.



(a) Movable bottom floor

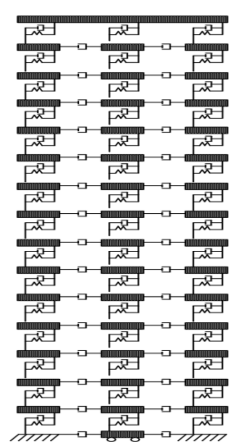


(b) Most upper floor

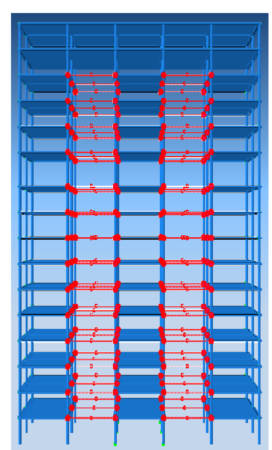
Fig.15. Maximum displacement responses of FCSS model

Besides, the confirming of experimental model was conducted to verify the results with numerical analysis. The experimental model was modeled by simplified model as spring – mass model and 3D model by used commercial software Abaqus. As shown in Fig. 16 is simulation model of experimental.

(a) Experimental model



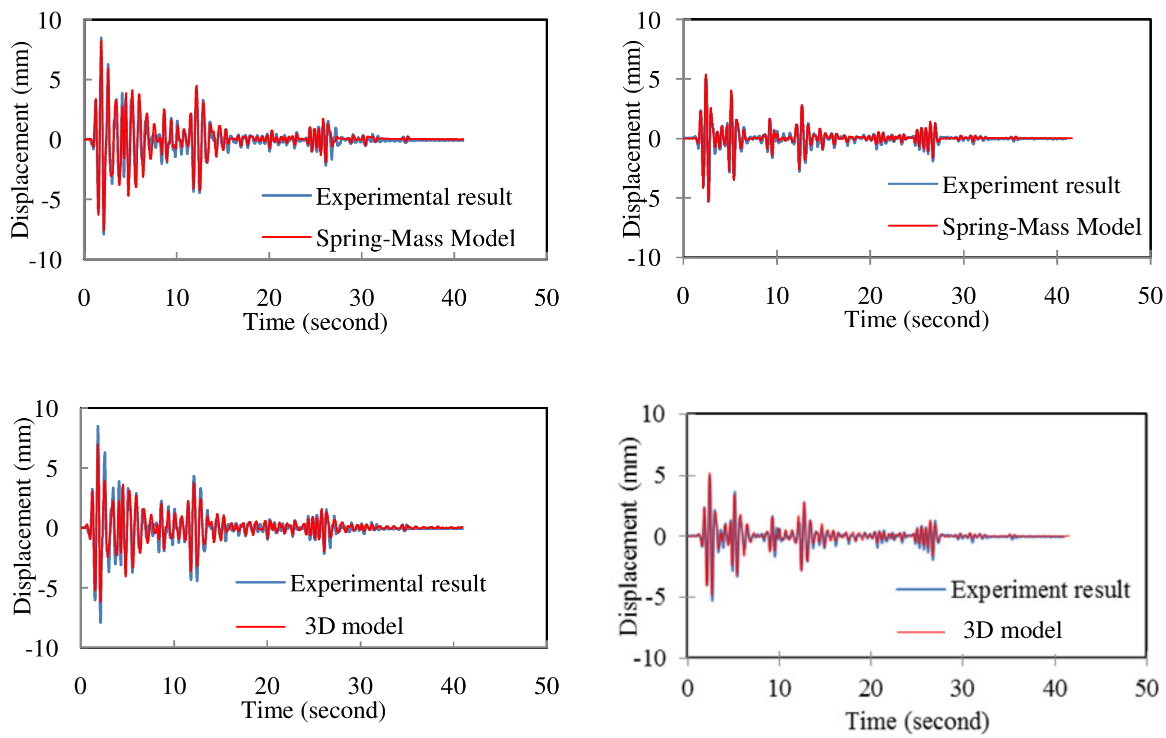
(b) Simplified model (spring-mass)



(c) 3D model

Fig.16. Experimental model and numerical model

Comparison of displacement time history record between experimental and numerical results is shown in Fig. 17. This figure depicts the displacement responses of FCSS with and without additional viscous damping device model at bottom movable floor with respect to ground motion under the El Centro NS earthquake. It can be seen that the values of time history displacement responses obtained from numerical analysis are very close to those from shake table testing.



(a) Without additional damper (b) With additional damper

Fig.17. Comparisons of FCSS model displacement responses at bottom movable floor

IV. CONCLUSION

In the present study, experimental model of folded cantilever shear structure (FCSS) was conducted. This model is modified from the previous study. New model is consisting of fixed – movable – fixed sub frames. According to the free vibration test, shake table testing and numerical analysis, it is found that:

1. The new proposed FCSS model is also capable of increasing natural period and decreasing seismic responses.
2. Based on shake table testing of model, it is important to use additional damping device to reduce the displacement responses.
3. A good agreement between the results of shake table testing and those of numerical analysis was obtained.
4. The effectiveness damper device of structure is also influenced by the type of earthquake. However, proposed FCSS model has seismic responses stability of the different earthquake ground motion.

V. ACKNOWLEDGMENTS

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