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NEW SEISMIC RESPONSE CONTROL SYSTEM USING BLOCK AND TACKLE

T. Saito[(1)], T. Maegawa[(2)], S. Denno[(3)], S. Sakai[(4)], M. Uchikawa[(5)], M. Kanagawa[(6)] and H. Ryujin[(7)]

[(1)] *Professor, Toyohashi University of Technology, tsaito@ace.tut.ac.jp*
[(2)] *General Manager, Technical Research & Development Institute, Kumagai Gumi Co. Ltd., tmaegawa@ku.kumagaigumi.co.jp*
[(3)] *Research Staff, Research and Development Center, Toda Corporation, satoshi.denno@toda.co.jp*
[(4)] *General Manager, Research Institute, Hazama Ando Corporation, sakai.shigeki@ad-hzm.co.jp*
[(5)] *Manager, Structural Design Division, Sato Kogyo Co., Ltd., Uchikawa@satokogyo.co.jp*
[(6)] *Senior Researcher, Research and Development Center, Nishimatsu Construction Co., Ltd., motoi_kanagawa@nishimatsu.co.jp*
[(7)] *Senior Researcher, Research Institute, Maeda Corporation, ryujinh@jcity.maeda.co.jp*

Abstract

This paper proposes a new seismic response control system using a block and tackle (hereinafter, referred to as a movable pulley damper system) developed especially for high-rise buildings. The proposed system has a configuration where a damper is installed on the track of the cable-stayed wire, amplifying the amount of movement of the wire by using a movable pulley that increases the damping effect in order to reduce the vibration of a building. Since the wire can be stretched across multiple stories of a building, this system is able to exert an effect on a large relative displacement. To examine its efficiency, a real scale structural test was conducted where a movable pulley damper system was installed in a beam-column frame. It was verified that the movement of the damper was amplified at around 10 times larger than that of the frame. On the contrary, the force of the frame was amplified at around 10 times larger than that of the damper. Also a shaking table test was conducted using a 1/20 scale specimen of a high-rise building to examine the efficiency of the new response control system. It was verified that the new system enabled reduction in the relative deformation of the building.

Keywords: Block and tackle system, Seismic control system, High-rise building, Long period ground motion

1. Introduction

After the 1995 Kobe Earthquake, it has become popular in Japan to install vibration control devices such as oil dampers in high-rise buildings to reduce building vibration during an earthquake. However, during the 2011 Great East Japan Earthquake, high-rise buildings in Tokyo, Nagoya and Osaka swayed significantly and caused damage to non-structural elements such as deformation of fire protection walls and the dropping of ceiling panels.

This paper proposes a new seismic response control system with a block and tackle (hereinafter, referred to as a movable pulley damper system) developed especially for high-rise buildings. The idea of a damping device to enhance the vibration reduction effect using wire and pulleys has been already studied as shown in Kawase et al. [1]. The basic configuration is to span the cable-stayed wire to building parts and install a damper connecting the wire. The structural system proposed in this study has a similar configuration; installing a damper on the track of the cable-stayed wire, except for amplifying the amount of movement of the wire by using a movable pulley and increasing the damping effect of the damper to reduce building vibration.

As a damping mechanism having an amplifier, devices using rotational inertial mass [2-4] and a toggle mechanism [5] have been developed. Such devices are generally installed in a beam-column frame and the damping effect is dependent on the relative displacement between the stories of the building. In contrast, the movable pulley damper system is able to exert an effect on a larger relative displacement by stretching the wire across multiple stories. In addition, the system can be realized by a simple and inexpensive mechanism. However, for practical use of this system, it is necessary to clarify the basic properties of the pulley damper by experiment and analysis.

Firstly, this paper explains the mechanism of the movable pulley damper and introduces the constitutive equation of the system. Then, the paper describes the real scale structural test results from installing a movable pulley damper system in a beam-column frame. Furthermore, the paper describes a shaking table test using a 1/20 scale specimen of a high-rise building to examine the efficiency of the new response control system.

2. Mechanism of the movable pulley damper system

Fig. 1 shows the principle of the damping mechanism. A stretched wire to reciprocate between pulleys groups A, B and the wire ends is fixed to either the ground or a building to connect the damper to the other end. Additionally, there is a wire and pulley in the same configuration located on the other side of the damper. When a building is moved, according to the movement of pulley group A, the amount of movement of the wire is amplified as the number of the wires back and forth through the pulleys. At the same time, the damping force of the damper acting on the pulley is amplified by an equal amount.

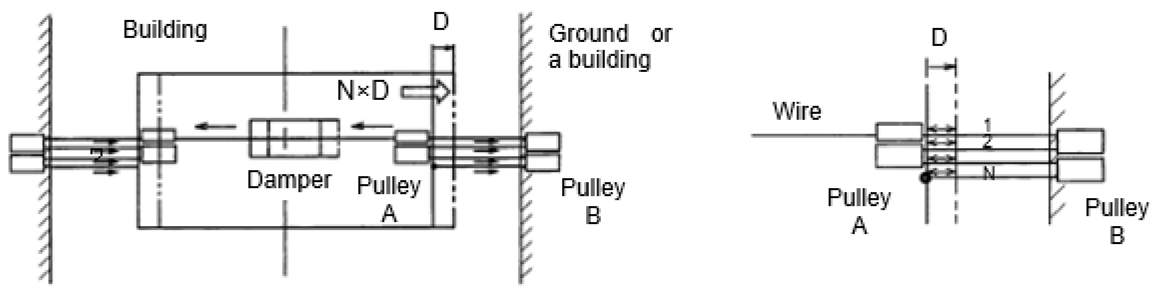


Fig. 1 – A principle of the mechanism of movable pulley damper system

Fig. 2 shows the configuration for the wires stretched between the building and ground, and the damper is placed on top of the building. It may be also possible to cross the wires in an X-shaped configuration and have the stretched wire set at an angle from the outside of the building. Fig. 3 shows another configuration for the wire stretched inside a beam-column frame of the building and the damper installed in the same frame. It may be also possible to install a pulley damper in the same configuration by stretching the wire over multiple spans or stories. Any types of damper such as a viscous damper, a friction damper and a hysteretic damper could be used for this system; however, it must be able to work with a large amount of movement. It is also necessary to add appropriate initial tension in the wire to prevent occurrence of wire loosening during operation.

3. Consitutive equation for the movable pulley damper system

For the movable pulley damper system, a force-deformation relationship considering elongation of the wire is derived below. Here, it is assumed that there is no friction between the wire and pulley, and stretching due to temperature change and deflection due to the mass of the wire are ignored in the derivation.

First, we consider the system where the wire has been stretched over the pulley between a wall and a rigid body rolling on the horizontal plane and a spring is installed at the end of the wire (Fig. 4). The following equation is established between the force and deformation acting on the wire.

$$f = K_w d, \quad K_w = \frac{EA}{nL_1 + L_2} \tag{1}$$

where, E: Young's modulus of the wire, A: cross sectional area of the wire, n: number of wires (hereinafter, referred to as a pulley magnification factor), K_w: axial stiffness of the wire.

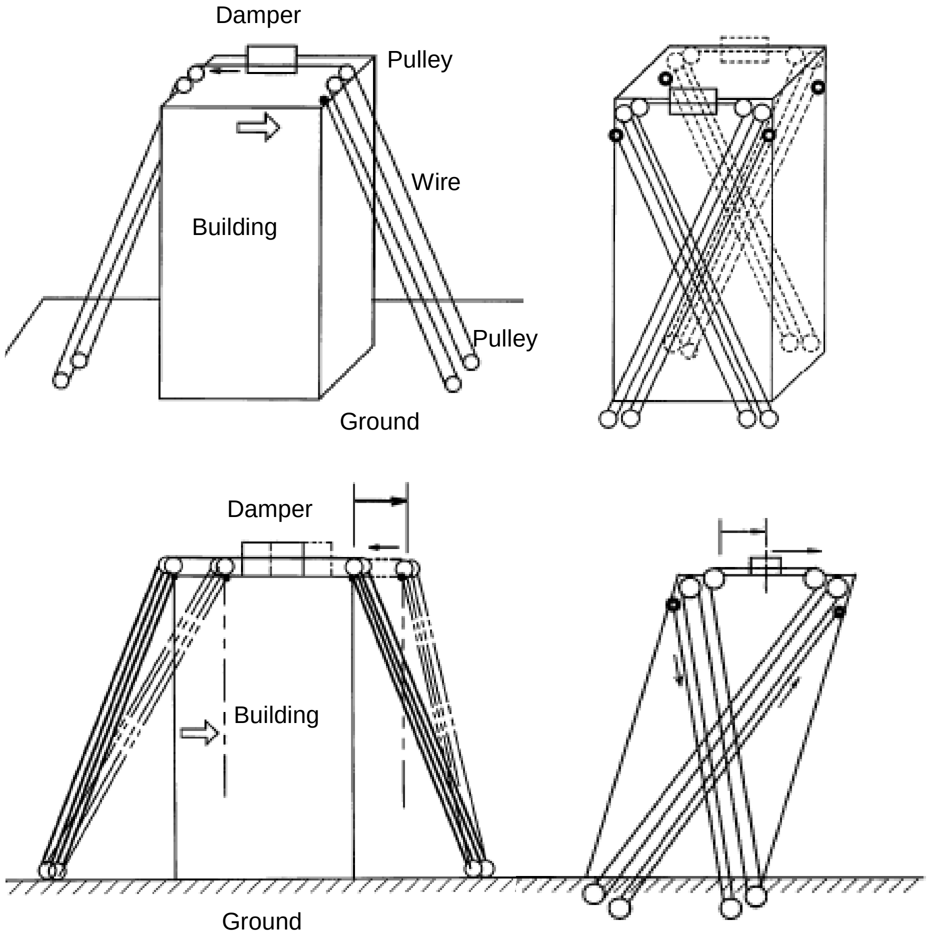


Fig. 2 – Configuration for the damping system mounted on the top

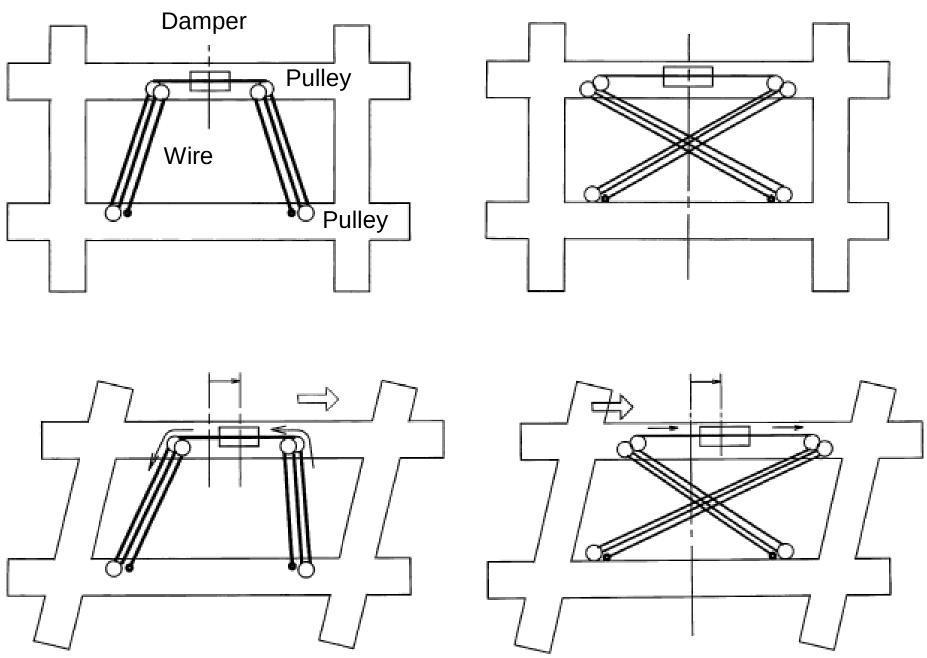


Fig. 3 – Configuration for the damping system inside a frame

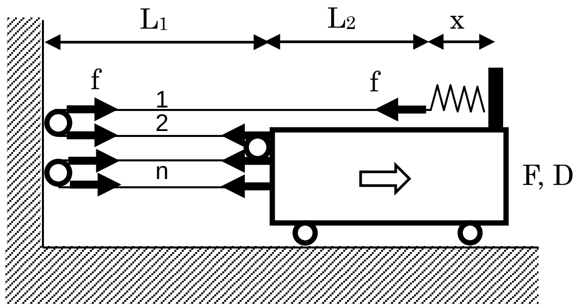


Fig. 4 – A model with wire stretched horizontally

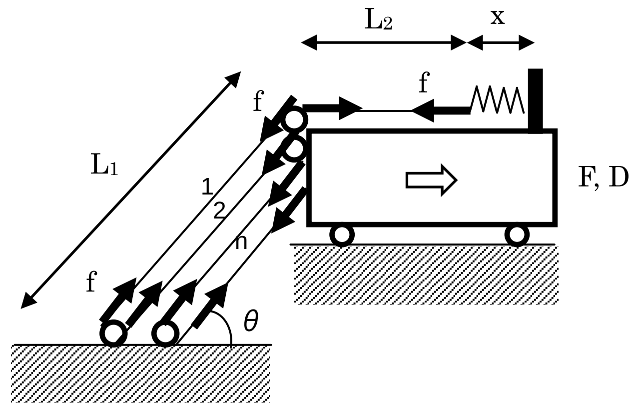


Fig. 5 – A model with wire stretched obliquely

The relationship between the deformation (x) and force (f) of the spring, is

$$f = K_d x \tag{2}$$

where, K_d : stiffness of the spring. The total force (F) acting on the rigid body is $F = nf$, and the amount of movement (D) of the rigid body is $D = \left(d + x\right)/n$. Therefore, the force-deformation relationship of the model is expressed by the following equation.

$$F = \left(\frac{n^2}{1/K_w + 1/K_d}\right)D \tag{3}$$

When the wire is stretched obliquely as shown in Fig. 5, a force-deformation relationship is divided into a diagonal portion, a horizontal portion and a spring part as,

$$f = \frac{K_{pw}}{n}d_1, \quad K_{pw} = \frac{EA}{L_1} \qquad \text{: diagonal portion} \tag{4}$$

$$f = K_{hw}d_2, \quad K_{hw} = \frac{EA}{L_2} \qquad \text{: horizontal portion} \tag{5}$$

$$f = K_d x \qquad \text{: spring part} \tag{6}$$

where, d_1: displacement of the wire of the diagonal part, d_2 : displacement of the wire of the horizontal part. Since the force (F) acting on the rigid body and the amount of movement (D) are obtained as $F = nf\cos\theta$ and $D = \left(d_1 + d_2 + x\right)/\left(n\cos\theta\right)$, respectively, the force-deformation relationship of the model is expressed by the following equation.

$$F = \left(\frac{2n^2\cos^2\theta}{n/K_{pw} + 1/K_{hw} + 1/k_d}\right)D \tag{7}$$

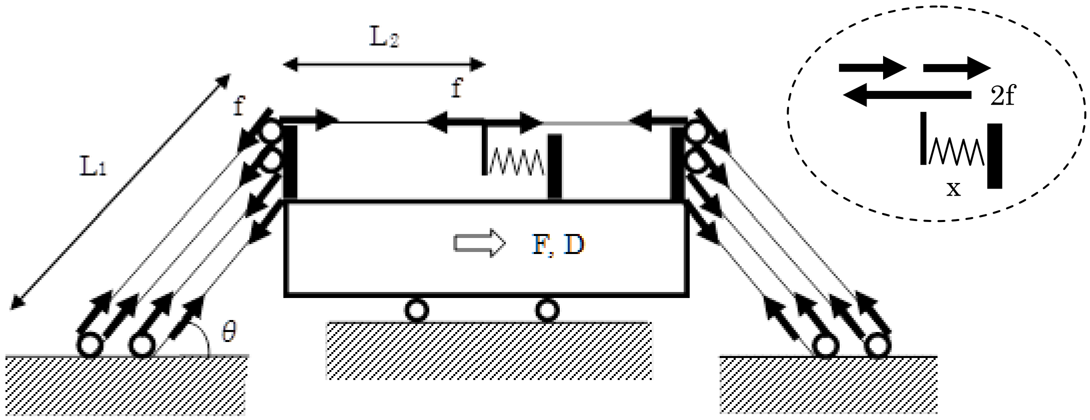


Fig. 6 – A model with wire stretched symmetrically

Finally, when the wire is stretched symmetrically as shown in Fig. 6, twice the amount of tension on the wire acts on the spring, therefore, the force-deformation relationship of the spring is,

$$f = (K_d / 2)x \tag{8}$$

and the force-deformation relationship of the model is expressed as,

$$F = \left(\frac{2n^2 \cos^2 \theta}{n / K_{pw} + 1 / K_{hw} + 2 / k_d} \right) D \tag{9}$$

4. Real scale structural test of the movable pulley damper

A real scale structural test was conducted for the movable pulley damper system installed in a beam-column frame. A view of the experimental apparatus is shown in Fig. 7.

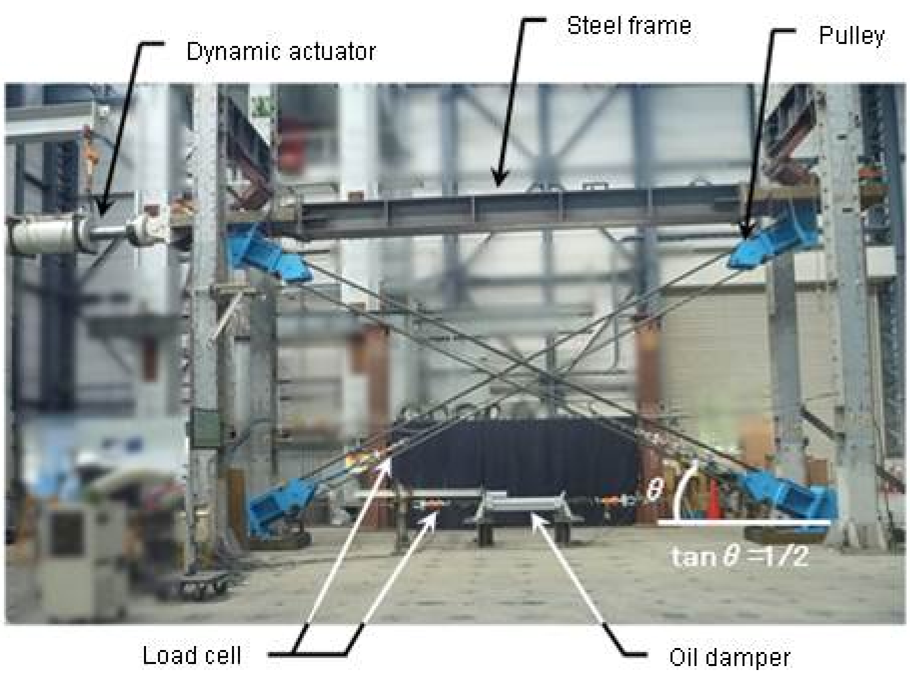


Fig. 7 – A model with wire stretched symmetrically

Fig. 8 – View of the pulley

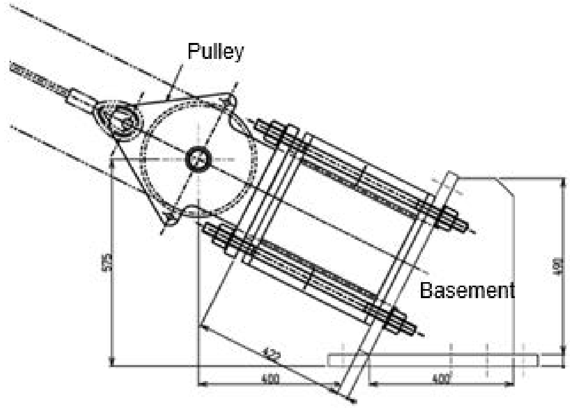
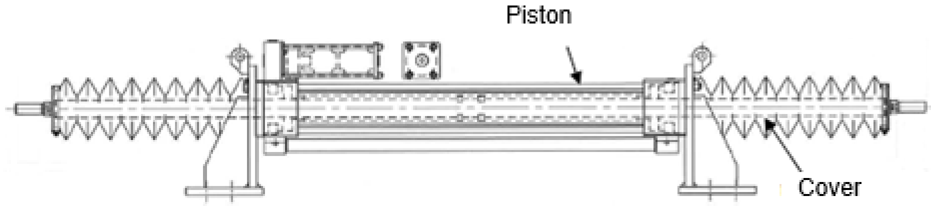
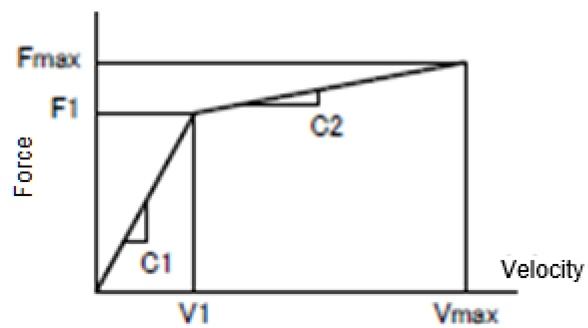


Fig. 9 –Detail of the pulley





Specification of the damper

Stroke	D (cm)	700 (±350)
1st damping coefficient	C1 (kNs/cm)	1.25
Release velocity	V1 (cm/s)	8
Release damping force	F1 (kN)	10
2nd damping coefficient	C2 (kNs/cm)	0.081
Maximum velocity	Vmax (cm/s)	70
Maximum damper force	Fmax (kN)	15

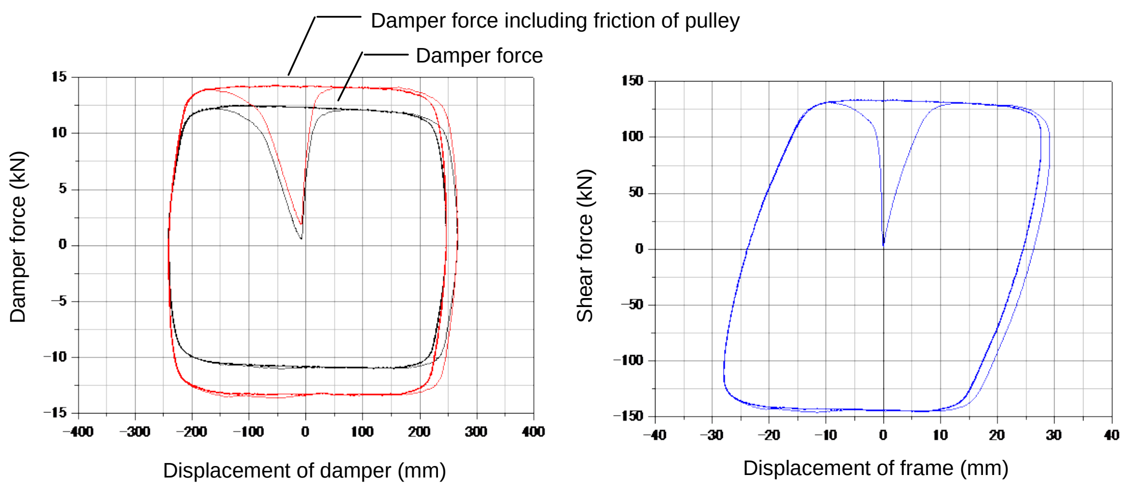
Fig. 10 –Oil damper and its specification

Four pulleys were fixed at the corners of a steel frame, and a wire was stretched six times back and forth between the diagonal pulleys. An oil damper was installed in the middle portion of the bottom connecting wires on both sides. The steel columns were designed to have pin connections at the ends. The lateral displacement of the frame is controlled by a dynamic actuator attached to the end of the beam. The size of the frame, measuring the distance from the center of the pulleys, is 6000mm in span and 3000mm in height. Figs. 8 and 9 show the six-series pulley used for the test. The diameter of the pulley is 300mm and the diameter of the wire is 18mm. The total length of the wire used for a single side is about 90m. Fig. 10 shows the configuration of the damper and its specifications. The piston rod moves to the left and right in the tie rod cylinder, and the maximum amplitude of the damper is designed to be ± 350mm.

The lateral force and the lateral displacement of the frame were measured by the signals of the hydraulic jack, the displacement of the oil damper is measured by a displacement meter and the force of the damper is measured from a load cell installed on the left and right sides of the damper. In addition, the tension of the wire is measured by a load cell located on the end portion of the wire rope.

Excitation is a sine wave with three types of velocity (1kine, 2kine, 3kine, kine=cm/s) and three types of amplitude (10mm, 20mm, 30mm). The duration of the excitation is 5 cycles. In order to suppress the slack of the wire, an initial tension of 10kN was given using a turnbuckle. Fig. 11 shows the force-displacement relationships of the damper and frame when the velocity of the frame is 3kine and the amplitude is 30mm. This figure also shows the force, including the friction force of the pulley, calculated from the tension force of the wire. As seen in this figure, the displacement of the frame reaches the target value of 30mm and the displacement of the damper is amplified to 270mm, about 9 times of the frame displacement. For loading, the maximum force of the damper is 12.5kN and the maximum horizontal force of the frame is 125kN, about 10 times of the damper force. Since the wire is stretched obliquely, the theoretical value of the amplification factor is 11.6. However, the amplification factor obtained from the measured value is around 10, which is slightly less than the theoretical value, probably because of the elastic deformation of the wire.

Fig. 12 shows the force-displacement relationship of the frame with different input velocities and displacement amplitudes. In case of a small input velocity, the loop shape became oval. To see the effect of repetition, the force-displacement relationships of 60 cycles under the conditions of 3kine and 30mm are shown in Fig. 13. There is no big difference in loop shape due to the repetitions and the dissipated energy is equivalent between the damper and the frame.



(a) Damper (b) Frame

Fig. 11 – Force-displacement relationship of the damper and the frame (3kine, 30mm)

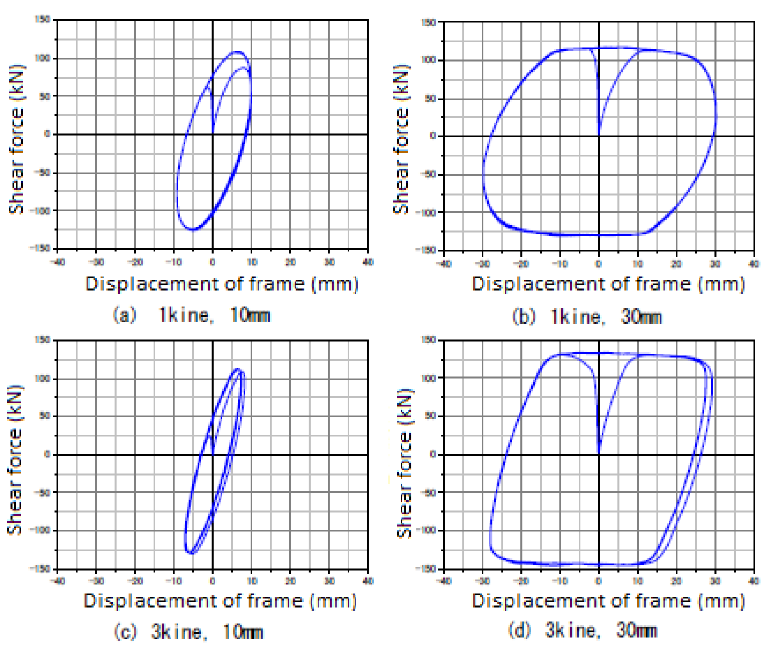


Fig. 12 –Force-displacement relationships of different inputs

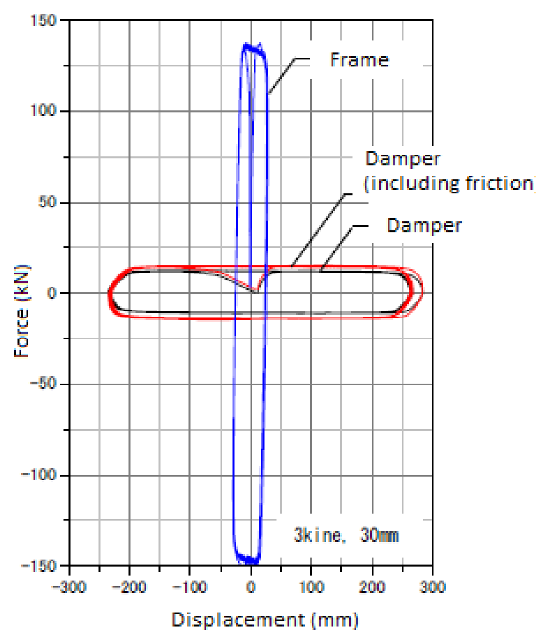


Fig. 13 –Hysteresis loops under 60 cycles

5. Shaking table test of the movable pulley damper

A 12-story reinforced concrete structure with the floor height of 3.2m and an aspect ratio of 3.0 is designed as shown in the left side of Fig. 14. The weight and stiffness of each floor are 1960kN and 525kN/mm, respectively. The first natural period of the building is 1.085sec. A damper is mounted at the top of the building and wires are stretched between the pulley at the top of the building and the pulley on the ground, placed symmetrically on the left and right sides of the building.

The specimen of the shaking table test is designed to be 1/20 scale of the building. The specimen is a 6-story model with a floor height of 320mm and a width of 400mm as shown in the right side of Fig. 14. A steel plate with a thickness of 6mm and a width of 100mm is used for the four columns in each story. The story weight is 0.49kN on the 1st to the 5th floor and 0.56kN on the top floor. The first natural period of the specimen is 0.256sec. The damper is a steel rod with a thickness of 3.2mm, a width of 6mm, a height of 100mm and a lateral strength of 0.051kN. The diameter of the wire is 1.2mm. Fig. 15 shows a photo of the specimen.

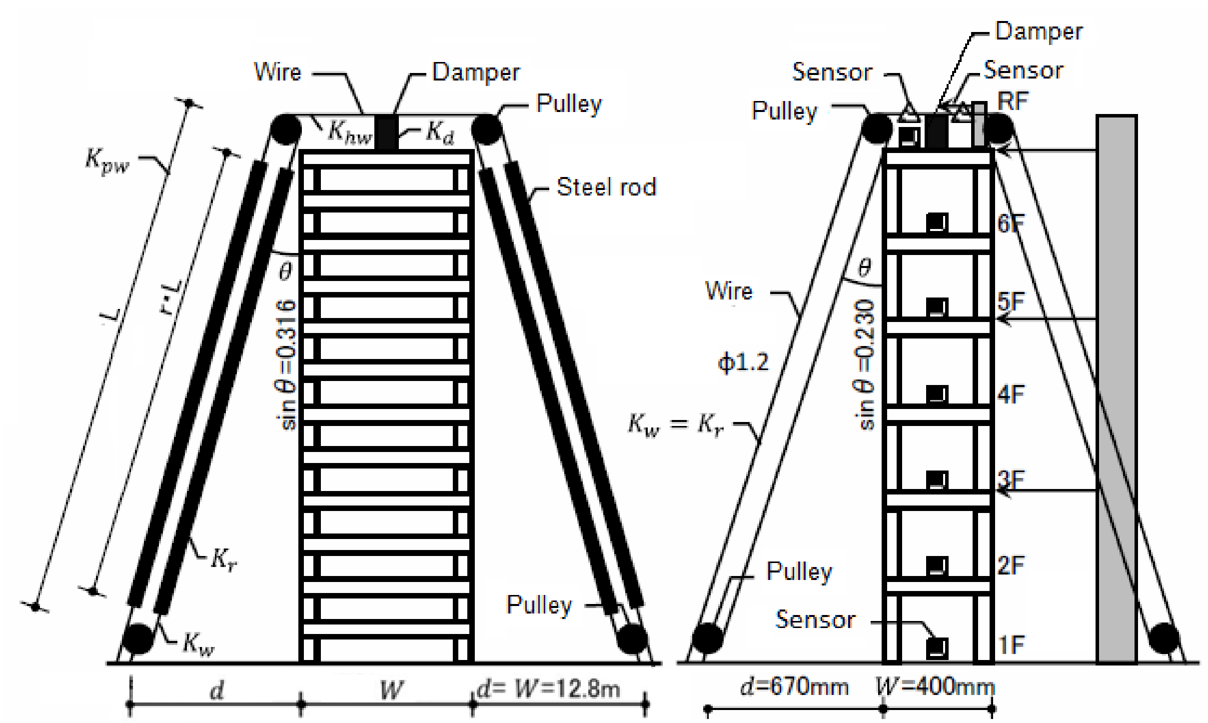


Fig. 14 –Real scale model (left) and test specimen (right) of the shaking table test

The shaking table test was conducted for the model without a damper and the model with a damper by changing the pulley magnification factor $n \times 1, 5, 9$. An initial tension of 100N was set to suppress the slack of the wire. The floor acceleration, damper force and damper displacement were measured by measuring instruments. This paper reports the test results under the BCJ-L2 input ground acceleration wave. Since the scale of the specimen is 1/20 of the real one, the time axis of the input acceleration wave is reduced to $1/\sqrt{20}$ using the similarity rule. Fig. 16 and Fig. 17 show the waveform and the response spectrum of the BCJ-L2 wave, respectively.

Fig. 18 shows the comparison of the maximum story responses of the model without a damper and those of the models with a damper at different pulley magnification factors $n \times 1, 5, 9$. More than 20% reduction for the maximum velocity and 30% reduction for the maximum displacement were achived at the top floor in case of $n \times 5$ and $n \times 9$. On the other hand, the acceleration response does not change significantly.

Fig. 15 – Test specimen of the shaking table test

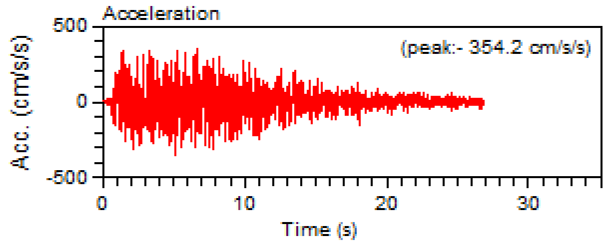


Fig. 16 – BCJ-L2 input acceleration wave

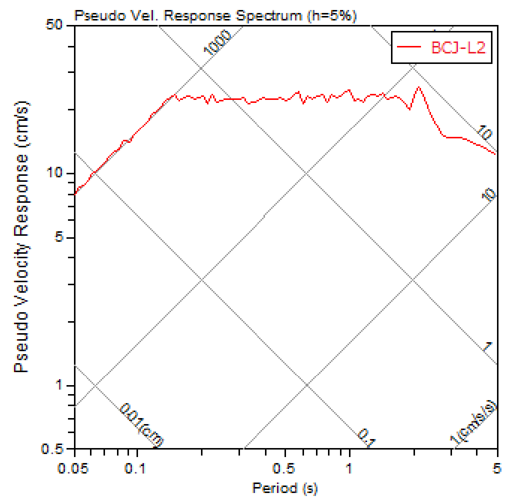


Fig. 17 – BCJ-L2 pseudo velocity response spectrum

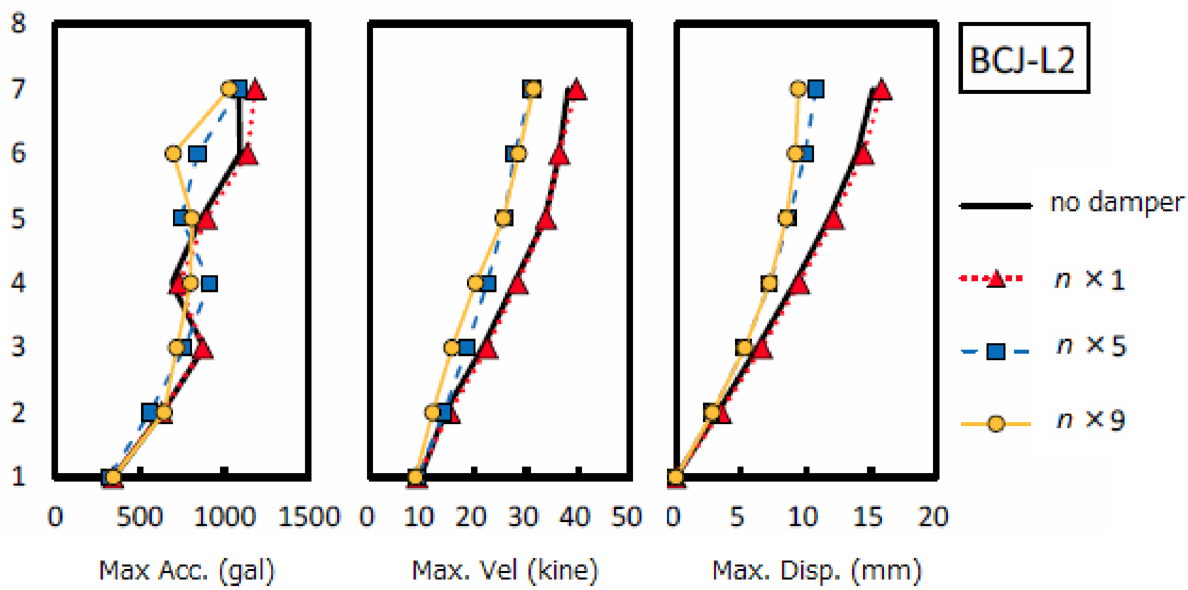


Fig. 18 –Comparison of maximum story responses (gal=cm/s^2, kine=cm/s)

A multi-story lumped mass model with a damper at the top, as shown in Fig. 19, is used to simulate the test results. The stiffness of shear spring in each floor and the Rayleigh damping factors of the model are determined from the results of a free vibration test of the specimen. The nonlinear force deformation relationship of the damper is assumed to be a bilinear hysteresis model with strain hardening as shown in Fig. 20. The initial stiffness and the yielding force of the damper with different pulley magnification factors $n \times 1, 5, 9$ are calculated using Eq. (9).

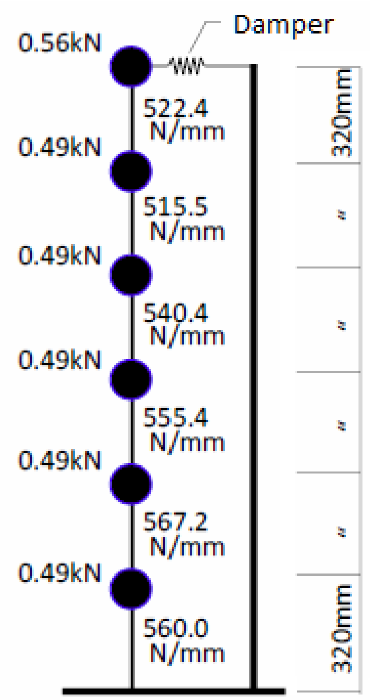


Fig. 19 –Analytical model

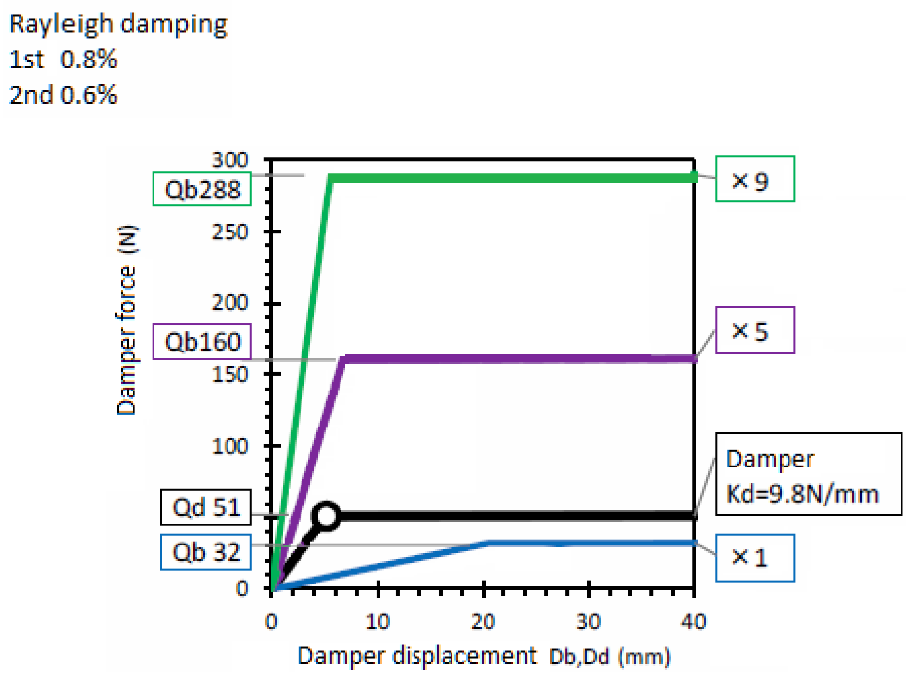


Fig. 20 –Force-deformation relationship of the damper

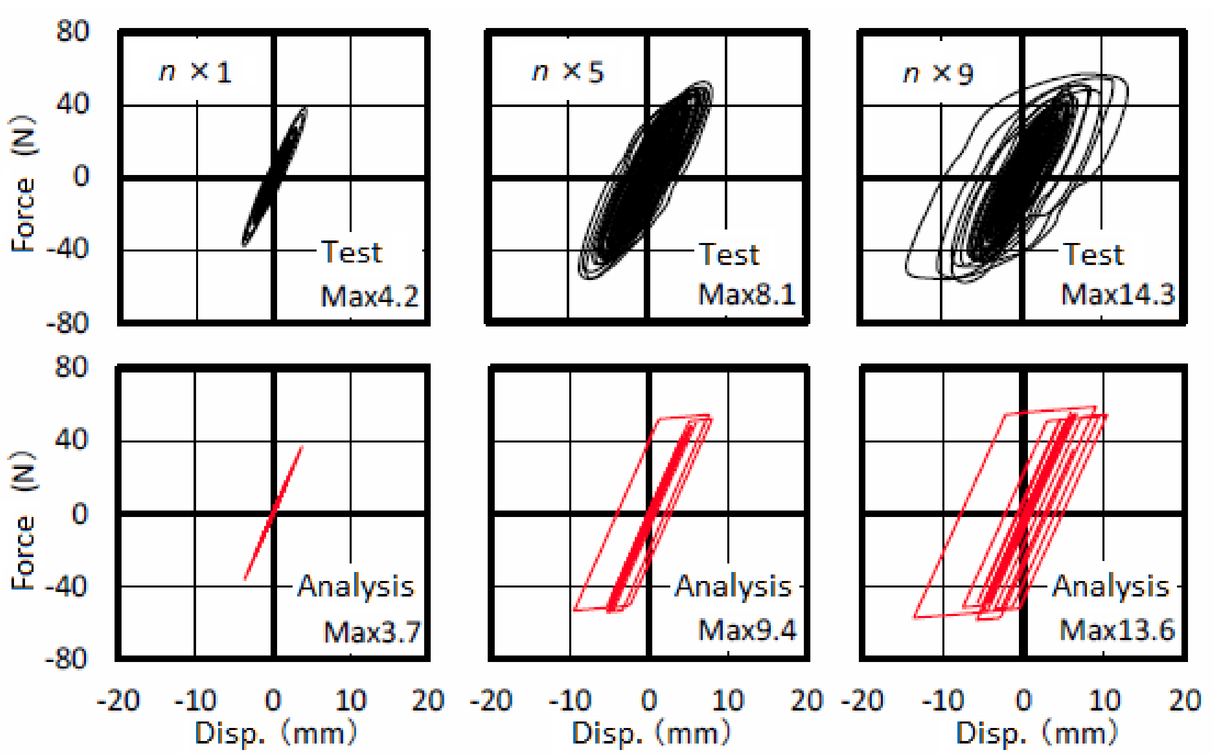
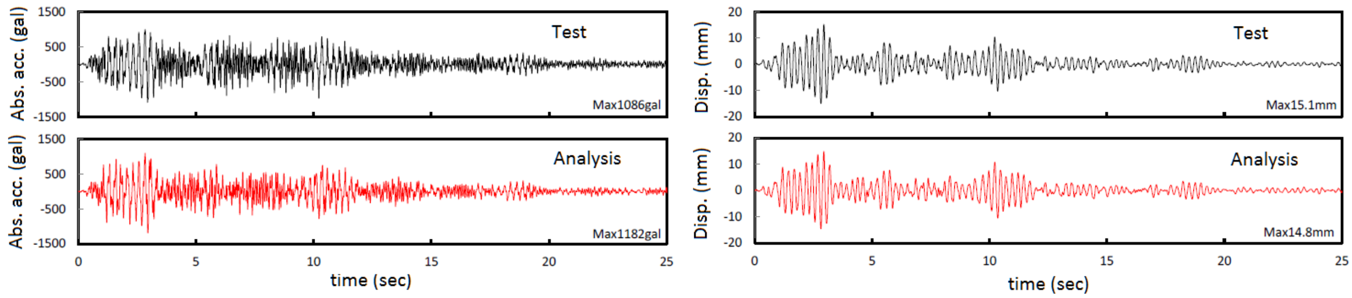
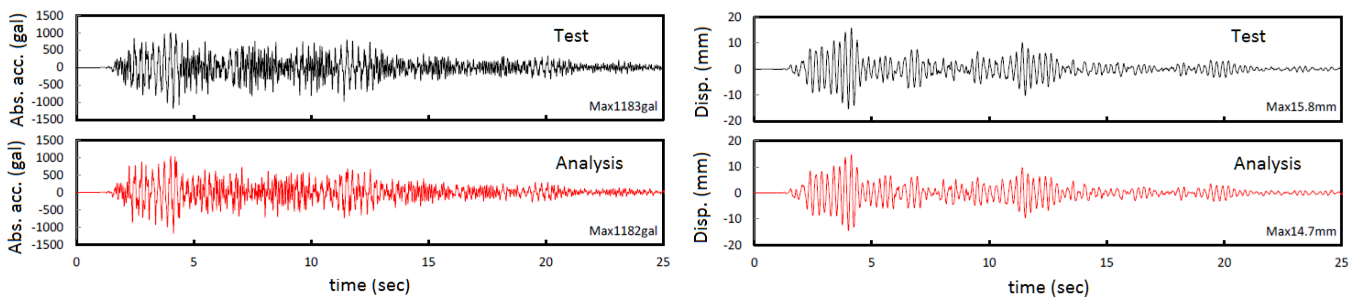


Fig. 21 –Comparison of force-deformation relationships of the damper at the top



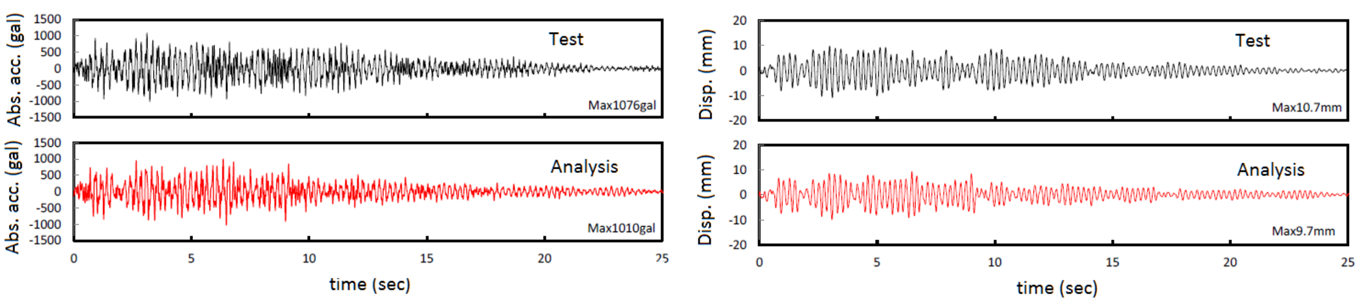
(a) Absolute acceleration response at the top floor
(b) Relative displacement response at the top floor

(c) without damper



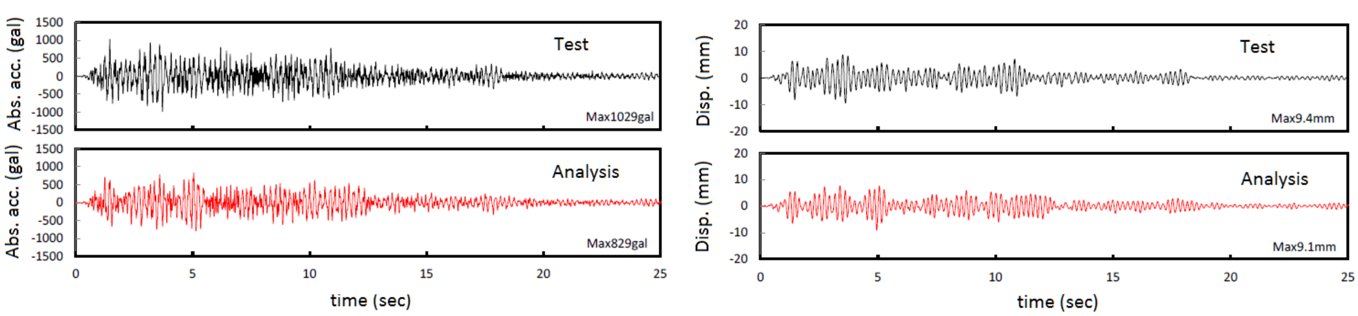
(a) Absolute acceleration response at the top floor
(b) Relative displacement response at the top floor

(a) with damper, $n \times 1$



(a) Absolute acceleration response at the top floor
(b) Relative displacement response at the top floor

(d) with damper, $n \times 5$



(a) Absolute acceleration response at the top floor
(b) Relative displacement response at the top floor

(b) with damper, $n \times 9$

Fig. 22 – Time history response of top floor (gal=cm/s^2)

Fig. 21 shows a comparison of the force-deformation relationships of the damper between the shaking table test and the analysis. Fig. 22 shows a comparison of the time history responses of the top floor between the shaking test and the analysis for the absolute acceleration response and the relative displacement response from the basement. In both cases, the analytical results provide a good estimation of the test results.

From Fig. 21, it is seen that when the value of the pulley magnification factor, *n*, becomes larger, the deformation of the damper also becomes larger and the damper dissipates more energy. On the contrary, as can be seen from Fig. 22, the top floor responses of the specimen are getting smaller. Therefore, this system succeeded in reducing the building response effectively under the input ground motion.

6. Conclusions

This paper proposed a new seismic response control system using a block and tackle, named as a movable pulley damper system. A real scale structural test was conducted where the system was installed in a beam-column frame. It was verified that the movement of the damper was amplified around 10 times larger than that of the frame and effectively absorbed a large amount of energy. Additionally, a shaking table test was conducted using a 1/20 scale specimen of a high-rise building to examine the efficiency of the new response control system. It was verified that the new system effectively enabled reduction in the relative deformation of the building by increasing the value of the pulley magnification factor. Furthermore, the analysis model using the constitutive formula developed in this study simulated the results successfully.

7. References

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