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SHAKING TABLE TEST TO FIND OPTIMAL WIRE ROUTES OF DYNAMIC PULLEY DAMPER SYSTEM

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Abstract

This paper presents a new seismic response control system using a block and tackle (hereinafter, referred to as Dynamic Pulley Damper System, DPDS) developed for the high-rise buildings. The dynamic pulley damping mechanism connects a wire to a damper and reciprocates the wire using pulleys to amplify the amount of the damper movement. Therefore, even a small deformation of the building can increase the movement of the damper and its energy dissipation. In this study, to examine the effectiveness of the DPDS, a small building specimen is designed, and its performance is evaluated by the shaking table test. The specimen is designed to have the scale of 1/10 times of the real scale of a high-rise building with 2.8 second natural period. The natural period of the specimen without the wire and the damper is 0.9 second. The specimen consists of a core structure (internal parking tower) and a surrounding frame (condominium). The core structure is designed to be rigid enough made of steel plates, with one third height of the surrounding frame. The surrounding frame is made of steel plates at floors and ultra-duralumin plates at columns. Pulleys are installed at the second and third stories of the surrounding frame, and on the top of the core structure. There are three cases of specimen by changing the arrangement of wire and damper. Case F is the specimen without a wire and a damper, Case FW is the specimen with a wire only without a damper, and Case FWD is the specimen with a wire and a damper. There are two types of wire routes; the first type is Single Type connecting a wire from the core to pulleys on the 3rd story, the second type is Double Type connected a wire from the core to pulleys on the 2nd and the 3rd story. The shaking table test was conducted using three earthquake waves; 1940 El Centro, 1968 Hachinohe, and 1995 JMA Kobe waves. After standardizing at the maximum velocity of 50 cm/s, the amplitude of the input waves was increased by 10% up to 100%. As with the result of Single Type, it was found that Case FWD successfully reduced the maximum displacement of the surrounding frame in case of El Centro and Hachinohe waves. However, in case of JMA Kobe wave, there was little difference among the cases. To overcome this problem, a test with Double Type was conducted and the result was examined. It was found that Double Type succeeded to reduce the displacement.

Keywords: Block and tackle; High-rise-building; Response control; Earthquake; Wire routes

1. Introduction

In 2011 during the Tohoku Earthquake, high-rise buildings in Tokyo, Nagoya and Osaka swayed significantly and caused damage to non-structural elements, such as fire protection walls and ceiling panels. In recent seismic design of high-rise buildings in Japan, it is common to install damping devices such as oil dampers to reduce the earthquake response of the building. Since the bending deformation component dominates in the upper part of the high-rise buildings, generally the installed dampers can reduce the response acceleration during earthquake for only 10% to 20%.

A new seismic response control system with a block and tackle and wire (hereinafter, referred to as a Dynamic Pulley Damper System, DPDS) has been proposed by the author, and the tests have already been carried out with the DPDS, using reduced specimens to verify its effectiveness [1][2]. These tests have shown that the proposed DPDS significantly reduced the building displacement. The coefficient of friction that occurs when a wire is placed on a pulley has been examined by Faisal et al [3].

This paper describes a shaking table test using a scaled down sample of a high-rise building by changing the different wire routes for the dynamic pulley damper to test the efficiency of the DPDS.

2. SHAKING TABLE TEST

2.1 Outline of the test specimen

The outline of the test specimen of the shaking table test is shown in Figure 1. The specimen consists of two parts; a four-story frame part and a core part in the center. The floors of the specimen are made of steel plate and the columns are made of ultra-duralumin plate. A steel plate with 150 mm length and 2 mm thickness is used as a hysteresis damper. The damper is placed at the ceiling of the third floor, and the wire is connected at the top of the damper. The yield strength of the damper is about 14N. The initial tension of the wire is 30 N. The left side of Figure 1 represents the stationary state, and the right side represents the deformed state. A photo of the specimen is shown in Figure 2. The first fundamental period of the small-scale specimen is 0.90 second which corresponds to the 1/10 scale of a high-rise building of 2.85 second first natural period.

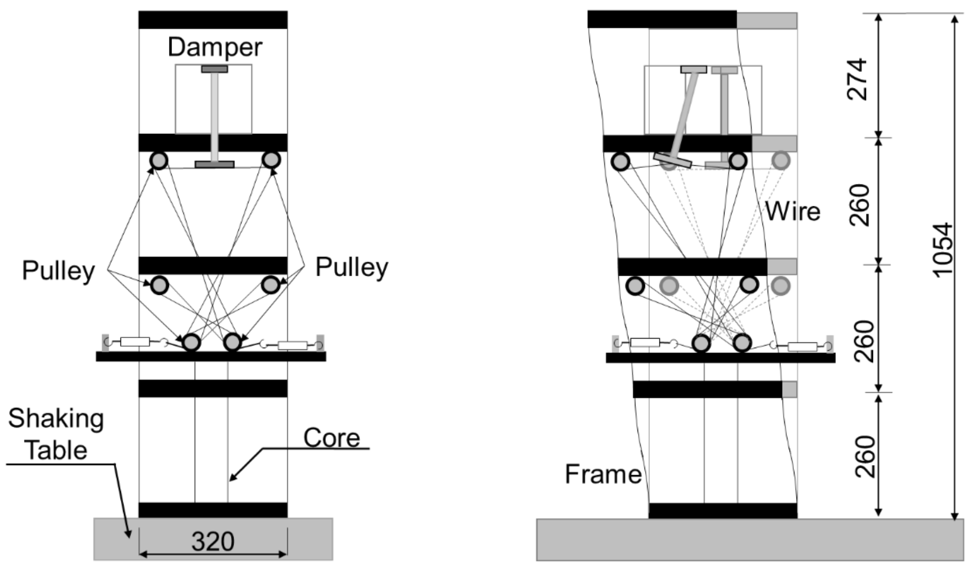


Fig. 1 – Outline of the test specimen of the shaking table (unit:mm)

Table 1 – The weight of test specimen each story

1st Story	2nd Story	3rd Story	4th Story
184 N	106 N	106 N	94 N

2.2 Input wave and test cases

Figure 2 shows the test cases changing the wire and damper arrangement. Case F is a non-damping model in which the frame part and the core part are not connected by wire. Case FW is a model in which the frame part and the core part are connected by wire and pulleys, however the damper is not introduced. Case FWD is a model in which the wire and the damper is introduced. In Case FW and Case FWD, the route of the wire is changed as Single Type and Double Type. In Single Type, the wire is stretched between the core and the pulleys at the third story. In Double Type, the wire is stretched between the core and the pulleys at the second and third stories.

The detail of the test setup is shown in Figure 3 for Double Type. The measurement system of building displacement is shown in Figure 3 (a) where *LD1* to *LD7* represent the displacement being measured, and the red arrows represent the rays of laser displacement sensors. The location of the accelerometer is shown in Figure 3 (b). A1 to A7 are the locations of accelerometers. Figure 3 (c) illustrates an enlarged view around the steel damper. W1 to W4 are the wires of Double Type. P1 to P4 are the pulleys. G1 to G4 are the strain gauges.

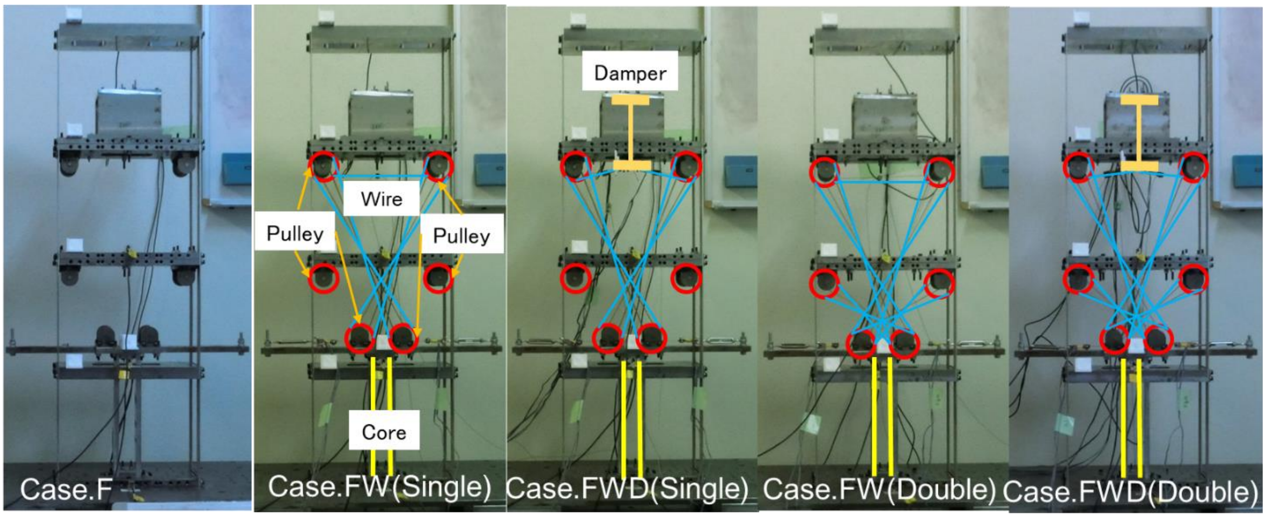
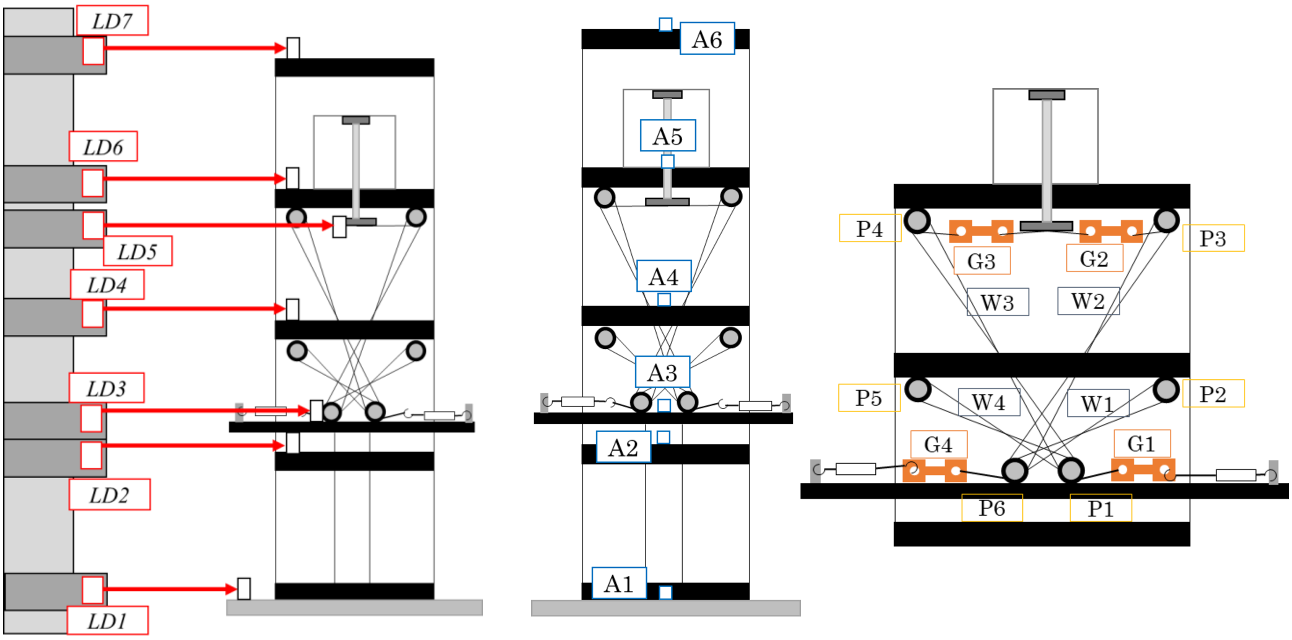


Fig. 2 – Test cases changing the wire and damper arrangement



(a) Laser Displacement measuring (b) Acceration measuiring (c) Details of the test specimen

Fig. 3 – Details of the test specimen

Figure 4 shows three input earthquake waves used for the shaking table test; 1940 El Centro wave, 1968 Hachinohe wave, and 1995 JMA Kobe wave, scaled to have the maximum velocity of 50 cm/s. The time step of each wave is multiplied by $1/\sqrt{10}$ to correspond to the scale of the specimen. In the shaking table test, the maximum velocity was gradually increased every 5 cm/s, and the test was terminated when the maximum deformation angle of the frame exceeded 1/25.

Table 2 shows the measurement locations of relative displacement. The relative displacements are obtained by subtracting the value of the LD1 displacement meter from each displacement sensor value.

Table 2 - Measurement location of relative displacement

1st Story	2nd Story	3rd Story	4th Story
LD2-LD1	*LD4-LD1*	*LD6-LD1*	*LD7-LD1*

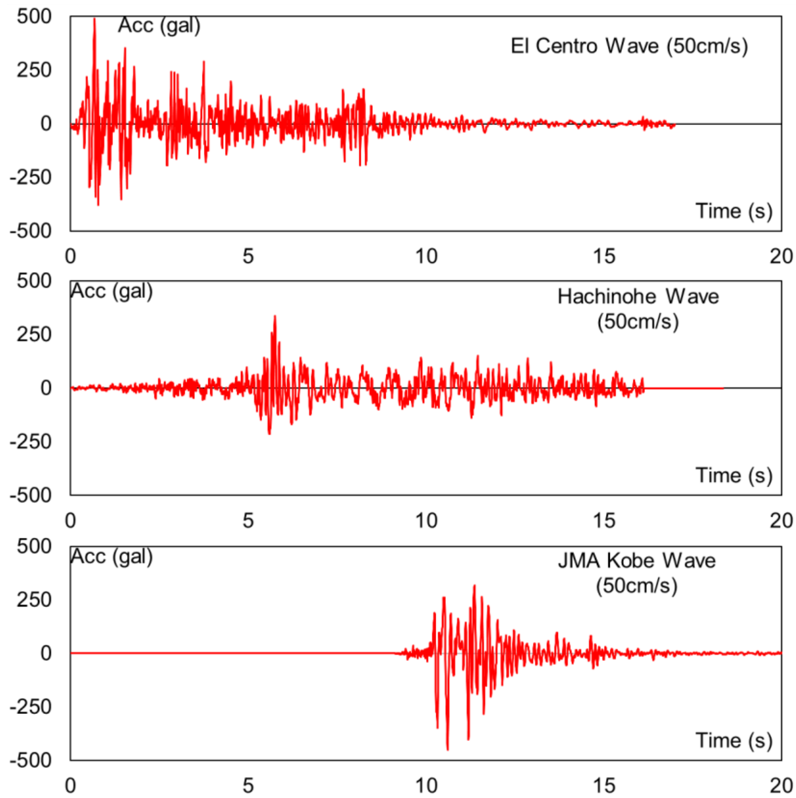
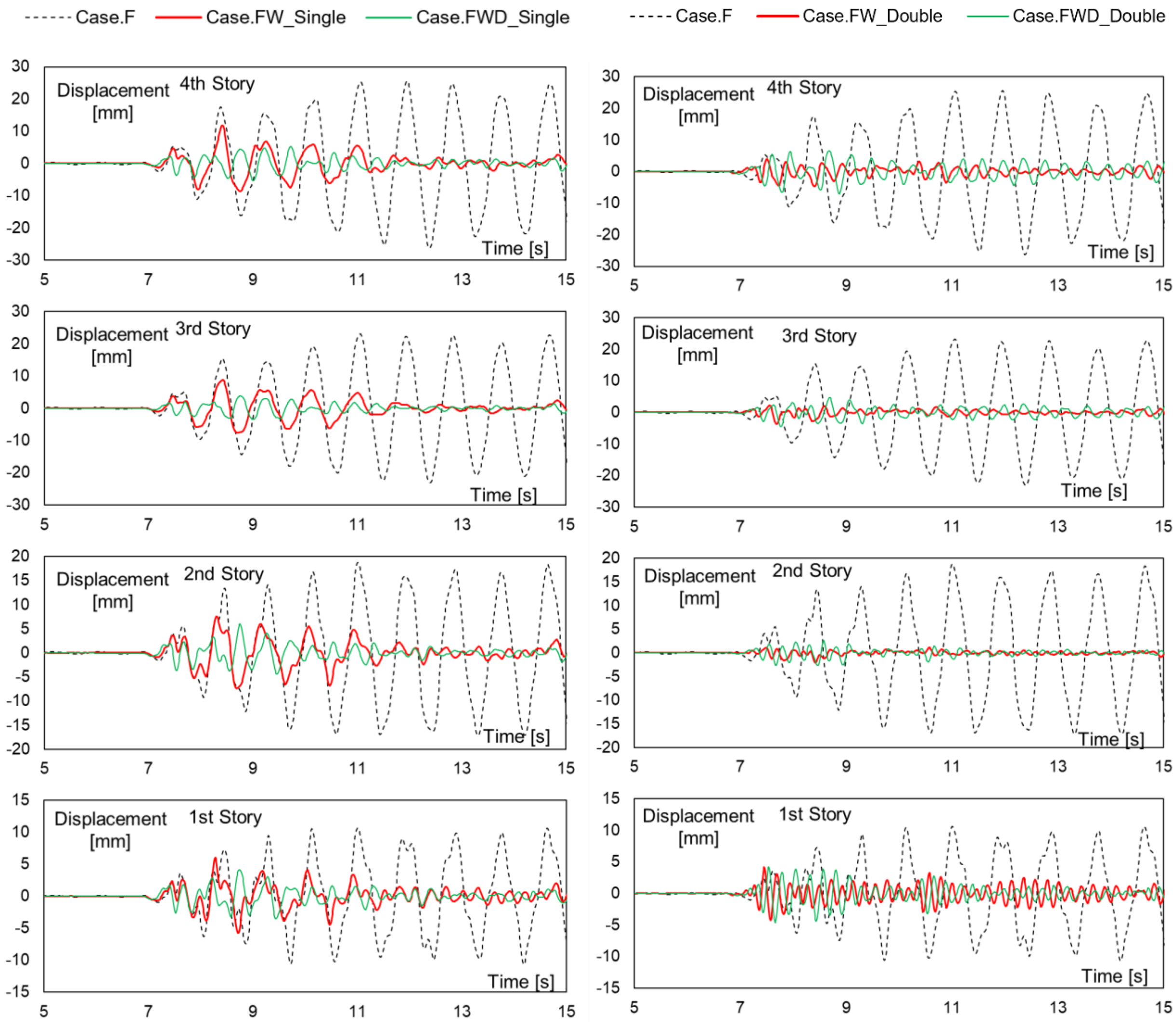


Fig. 4 – Input waves normalized to the maximum velocity of 50 cm/s

2.3 Test results

Figure 5 shows the time history of displacement of each story under El Centro wave magnified 30% of the original wave. It is seen that Case FW (red line) and Case FWD (green line) reduced the deformation effectively more than Case F (black dashed line) in both Single Type and Double Type. The displacements of Case FW and Case FWD in Double Type in Figure 5 (b) were smaller than those of Single Type in Figure 5 (a). Since the wire is stretched between the core and the pulleys at the second and third stories in Double Type, the displacement of the second and third stories reduced largely in Double Type and the displacement wave of Double Type contained higher frequency components compared to Single Type.



(a) Single Type

(b) Double Type

Fig. 5 – Time history response of displacement under the El Centro wave (magnification as 30%)

The relationships between the maximum input acceleration and the maximum relative displacement in case of El Centro, Hachinohe and JMA Kobe waves are shown in Figure 6 to 8.

In the case of El Centro wave in Figure 6, when the maximum relative displacement of the 4th story under Case F was 26 mm at the input acceleration of 140 gal, the displacement of Case FW in Single Type is 15 mm (43% reduction), the displacement of Case FWD in Single Type is 5.3 mm (67% reduction), the displacement of Case FW in Double Type is 4.7 mm (82% reduction) and the displacement of Case FWD in Double Type is 7.1 mm (77% reduction). When the input acceleration is higher than 200 gal, the reduction of displacement of Case FWD in Double Type is prominent. In the case of Hachinohe wave in Figure 7, Case F and Case FW in Single Type have the similar maximum displacement. In Case FWD, which introduced a damper, the displacement is reduced in both in Single Type and Double Type. However, in the case of JMA Kobe wave, as shown in Figure 8, the difference of the maximum displacement in each test condition is not large.

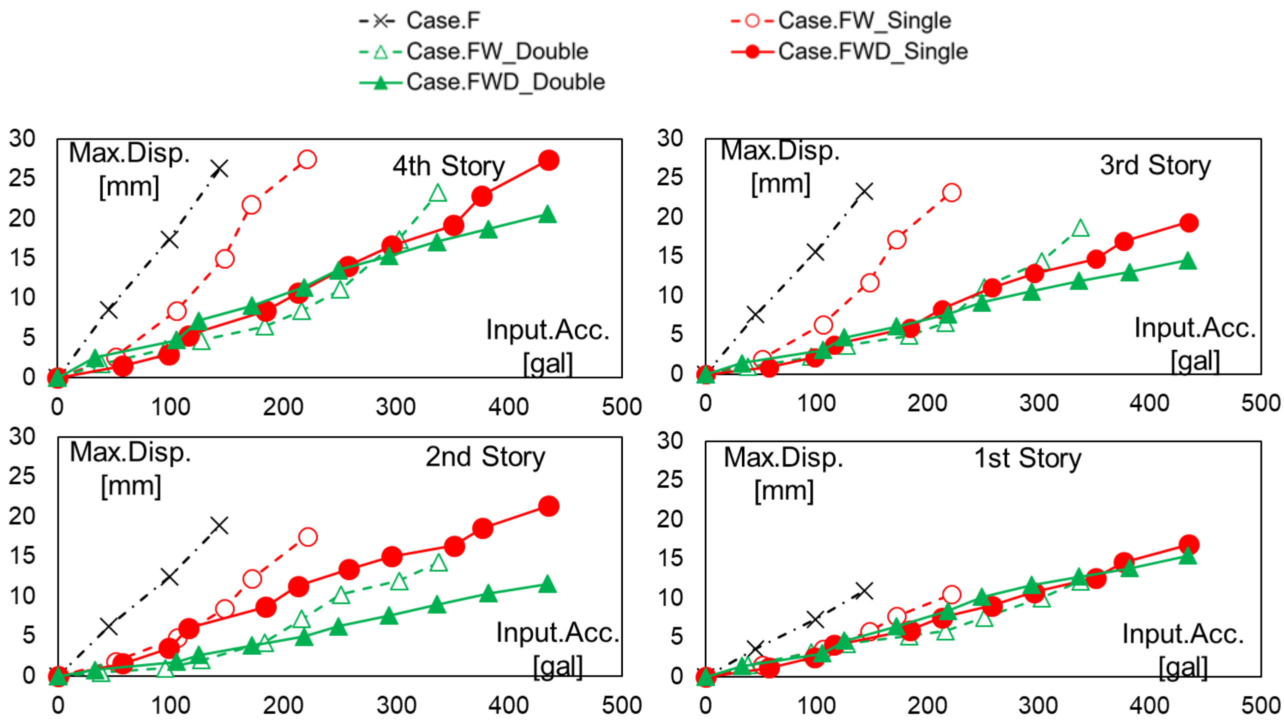


Fig. 6 – Maximum Floor Displacement under El Centro wave

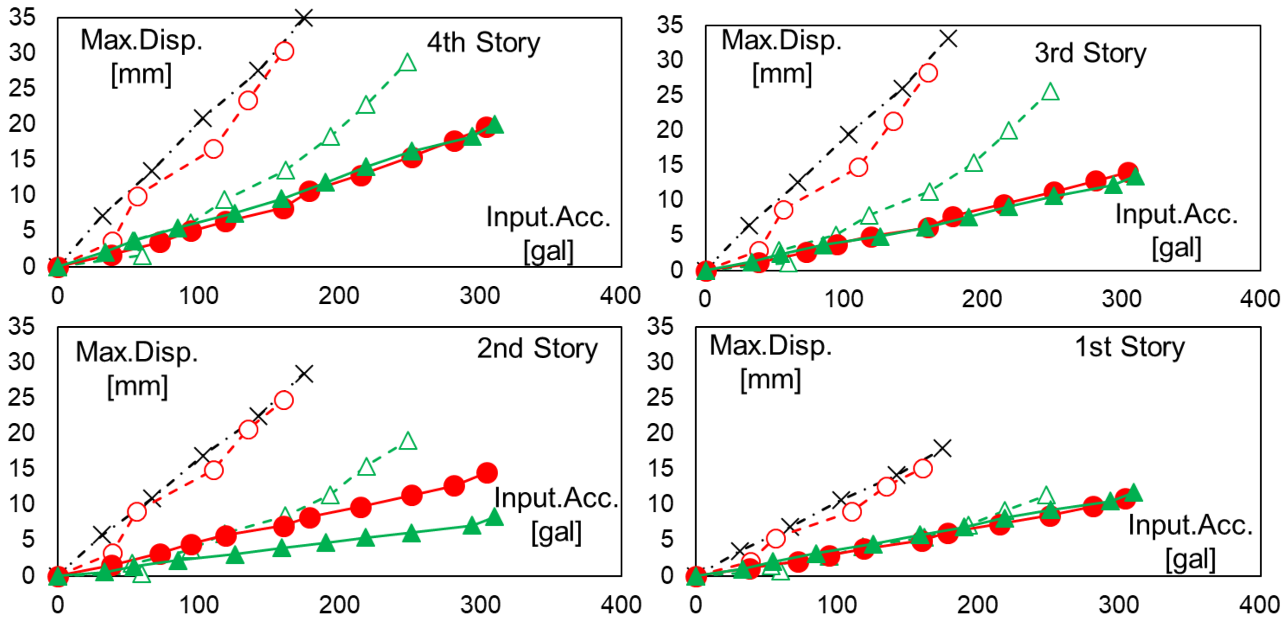


Fig. 7 – Maximum Floor Displacement under Hachinohe wave

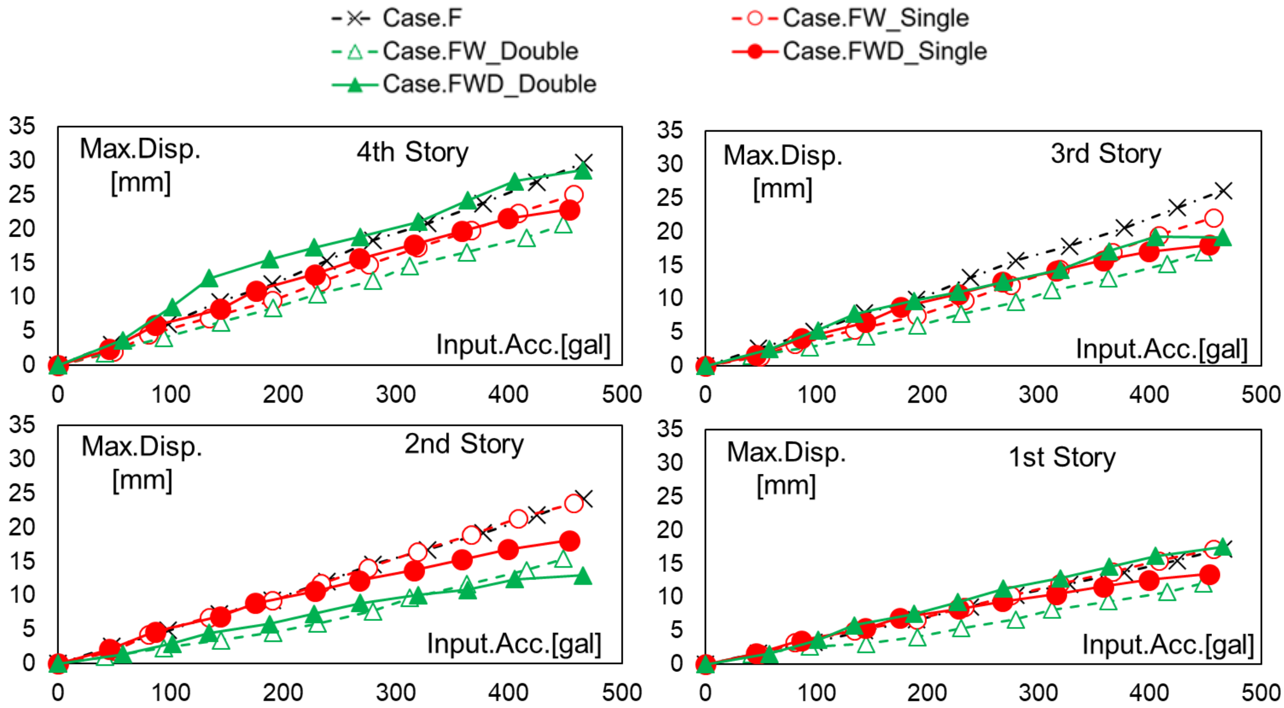


Fig. 8 – Maximum Floor Displacement under JMA Kobe wave

Figure 9 shows the maximum relative displacement of each story. The input acceleration is 140 gal for El Centro wave, 180 gal for Hachinohe wave, and 450 gal for JMA Kobe wave. Comparing with Case F, the introduction of the wire (Case FW) showed a remarkable reduction of displacement in case of El Centro and Hachinohe waves. However, in case of JMA Kobe wave, there is no large reduction of the displacement. Although further investigation is necessary in this regard, the pulse-shape input of Kobe wave generated the higher mode vibration of buildings and it made difficult to reduce the displacement.

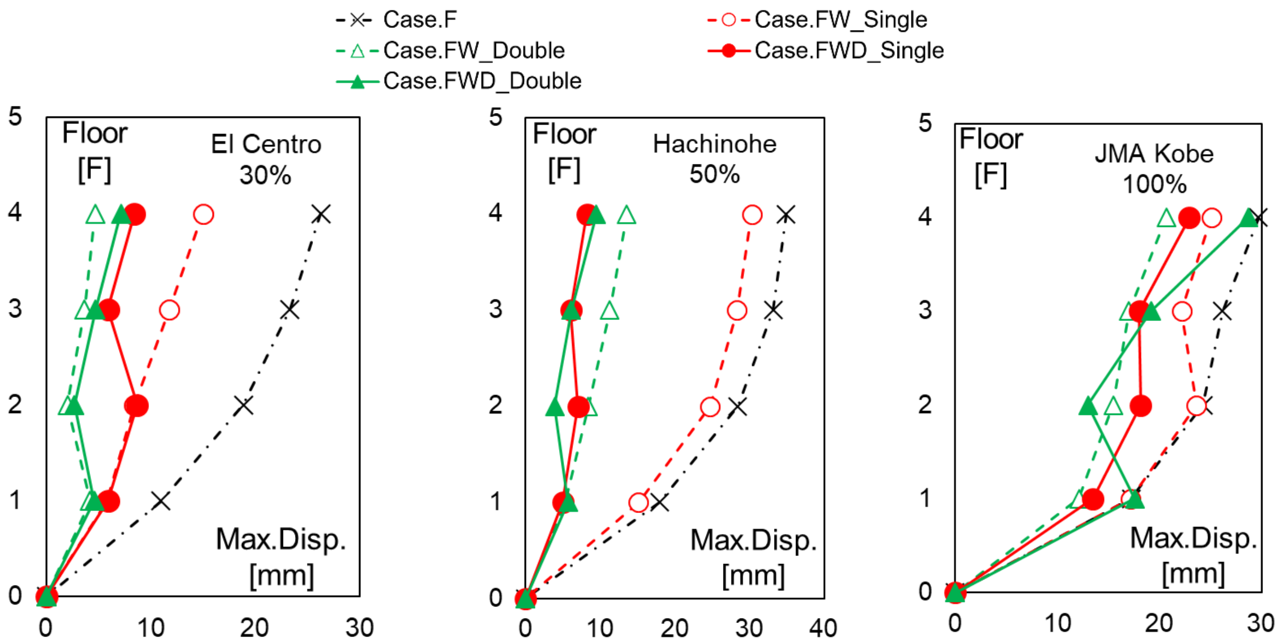
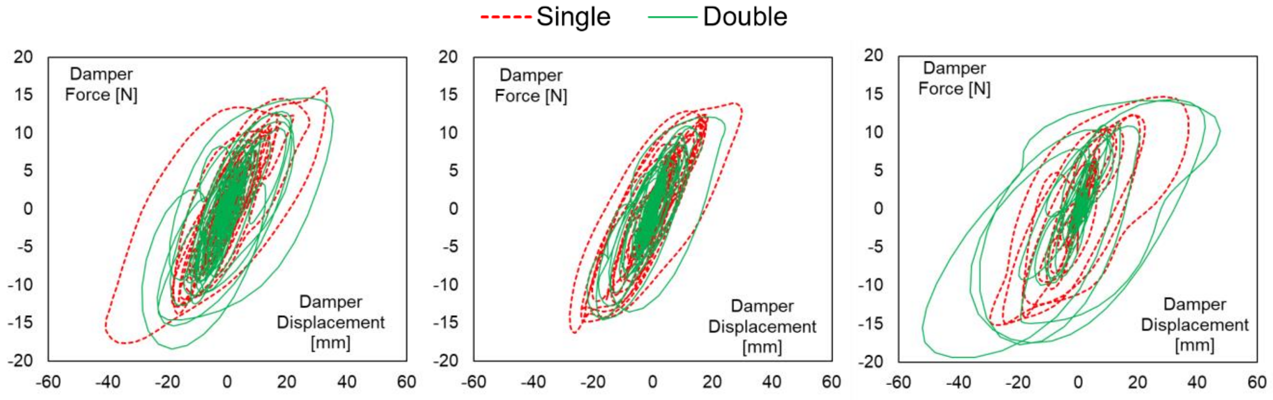


Fig. 9 – Maximum displacement of each floor



(a) El Centro (b) Hachinohe (c) JMA Kobe

Fig. 10 – Force-displacement relationships of the damper

Figure 10 shows the comparison of the force-displacement relations of the steel damper in Case FWD Single Type and Double Type. Although the difference of damper displacement between Single Type and Double Type is small under El Centro and Hachinohe waves, the displacement of Double Type under Kobe wave is larger than that of Single Type.

3. Conclusion

This paper presents the new seismic response control system using a block and tackle named as the Dynamic Pulley Damper System (DPDS) and its application to a high-rise condominium building with a parking tower in the middle. The small-scale test specimen with a surrounding frame (condominium) and a core (parking tower) was tested to verify the DPDS. There were three cases of specimen by changing the arrangement of wire and damper. The shaking table test was conducted using three earthquake waves; 1940 El Centro, 1968 Hachinohe, and 1995 JMA Kobe waves.

From the results of shaking table tests, it was found that the DPDS successfully reduced the displacement response of the specimen in case of El Centro and Hachinohe waves. However, in case of JMA Kobe wave, there was little difference among the cases probably because of higher mode vibration of the specimen.

4. Acknowledgements

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5. References

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