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Development of Seismic Retrofit Devices for Building Structures

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Abstract

In this paper passive seismic retrofit devices for building structures developed by the author in recent years are introduced. The proposed damping devices were developed by slightly modifying the configuration of conventional devices and enhancing their effectiveness. First a seismic retrofit system consisting of a pin-jointed steel frame and rotational friction dampers installed at each corner of the steel frame was developed. Then two types of steel slit dampers were developed; box-type slit damper and multi-slit damper. In addition, hybrid dampers were developed by combining a slit damper and a friction damper connected in parallel. Finally a self-centering system was developed by using preloaded tendons and viscous dampers connected in series. For each retrofit system developed, an appropriate analytical model was developed, and the seismic performance was verified by loading test and earthquake analysis of case study structures. The experimental and analysis results show that the proposed systems can be used efficiently to enhance the seismic performance of building structures.

Keywords: Seismic retrofit; Slit dampers; Friction dampers; Viscous dampers; Self-centering

1. Introduction

In 2016 an earthquake with magnitude of 5.8 occurred near *Gyeongju*, southern city of Korea, and one year later another earthquake with magnitude of 5.4 occurred in *Pohang*. They were the largest earthquakes ever recorded in Korean peninsular. Even though the magnitude of the *Pohang* earthquake was smaller than that of the *Gyeongju* earthquake, the structural damage caused by the Pohang earthquake was significantly larger due mainly to the fact that it occurred in more densely populated area. More than one thousand building damages were reported after the *Pohang* earthquake. Especially many low-rise residential buildings with soft-first story were severely damaged during the Pohang earthquake. As can be seen in Fig. 1 which was taken in the aftermath of the Pohang earthquake, shear failure of columns and shear walls at the first story was the most common structural failure mechanism of buildings.

Energy dissipation devices have been applied in buildings for mitigation of vibration induced by both wind and earthquakes (Omika et al. 2016). In Korea the seismic design code was enforced in 1989, and there still remain a lot of buildings not designed for seismic load. After the two earthquakes, there have been huge demands for seismic retrofit of existing buildings. This paper presents passive seismic retrofit devices recently developed by the author for seismic retrofit of building structures. The seismic performance of each device was verified by appropriate loading test and structural analysis.

The proposed devices were developed by modifying conventional damping devices such as rotational friction dampers, steel plate slit dampers, damped cable system, etc. Rotational friction dampers are versatile energy dissipation devices which are applied in various schemes. Previously, Martinelli and Mulas (2010) presented a rotational friction damper which is installed at beam-column joints in precast concrete structures. Lee and Kim (2015) used rotational friction dampers in conjunction with steel plate slit dampers for seismic retrofit of moment framed structures. It was also applied to industrial portal frames with an additional re-centering device developed by Belleri et al. (2017). The seismic performances of hysteretic passive energy dissipative devices have been investigated such as ADAS device (Bergman and Goel, 1987), slit dampers (Chan and Albermani 2008), and friction dampers (Kim et al. 2011). Some researchers investigated simultaneous application of multiple devices to maximize the energy dissipation mechanism. Tsai et al. (1998) and Chen et al. (2002) studied combined displacement-dependent and velocity-dependent devices for seismic mitigation of structures to minimize the shortcomings of individual dampers, and proposed the most economical solution for seismic mitigation. Marshall and Charney (2012) studied the concept of the hybrid passive control system with BRB and viscous fluid device by investigating the seismic response of steel frame structures.

Self-centering systems have potential for seismic retrofit of structures due to their capability to minimize residual displacement and interstory drift after the structure is

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(a) Soft first story building (b) School building

Figure 1. Building damage during 2017 Pohang earthquake.

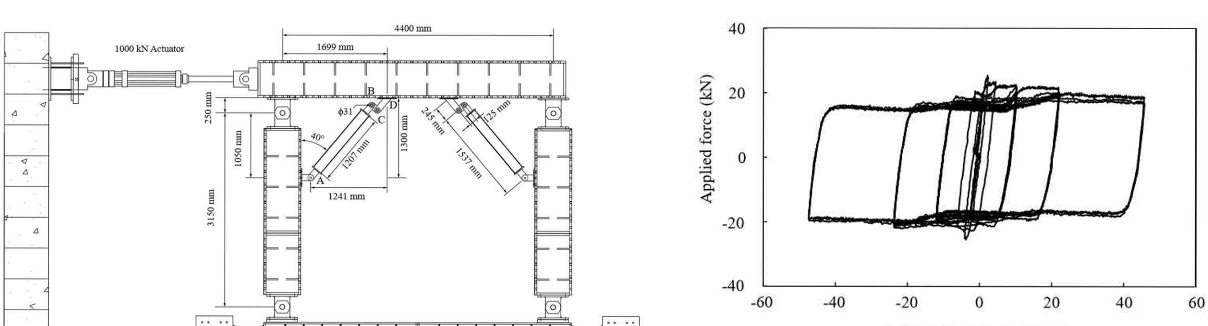
shaken by an earthquake. In order to reduce or eliminate residual deformation in structures subjected to seismic loads, many researchers have investigated various self-centering schemes. For example, bracing systems providing stable energy dissipation capacity and a restoring force have been developed (Christopoulos et al. 2008, Miller 2012, Chou et al. 2016). Post-tensioned tendons have been used in prestressed precast shear walls (Ruiz et al. 2012), RC moment frames (Rahman and Sritharan 2007), and steel braced frames (Roke et al. 2012, Dyanati et al. 2014, Eatherton et al. 2014) to provide both stiffness and restoring force. Pekcan et al. (2000) and Sorace and Terenzi (2001, 2012) proposed a criterion for estimating the preliminary size of the damped cable system. The superelastic property of the shape memory alloy has been applied to produce damping devices having both energy dissipation and self-centering capacity (Dolce and Cardone 2006, Ingalkar and Rameshwar 2014). The hybrid slit damper with shape memory alloy and life cycle cost analysis of the hybrid damper is presented elsewhere (Naeem et al. 2017, NourEldin et al. 2018).

2. Corner rotational friction dampers

In this study, rotational friction dampers were developed for seismic retrofit of soft-first story structures. As the relative displacement imposed on a damper located at the corner is not large, an amplification mechanism is applied to achieve an acceptable energy dissipation capacity. A pin-jointed steel frame is attached to the considered bay of the structure in parallel to the existing columns, and the rotational friction dampers are installed at corners like knee braces. Since the steel frame is pin-jointed, connecting the dampers to the steel frame provides enough relative displacement to dissipate energy.

As the proposed damper is a displacement-dependent device, its energy dissipation capability is evaluated using cyclic loading tests. Details of the dampers and the installation jig are shown in The test setup is shown in Fig. 2(a). Fig. 2 (b) shows the force-displacement curve of the test structure, where it can be observed that the damper have a stable behavior and the capacity is approximately 25 kN as estimated by the formulation.

The test results of the damping system showed that the dampers were suitable for seismic retrofit of structures in which diagonal bracing-type dampers cannot be applied. The seismic retrofit design of an analysis model structure with a soft first story and plan asymmetry showed that the proposed retrofit system could be used efficiently to prevent collapse of the structure and reduce inter-story



(a) Test setup (b) Hysteresis curve

Figure 2. Cyclic loading test of the corner rotational friction dampers.

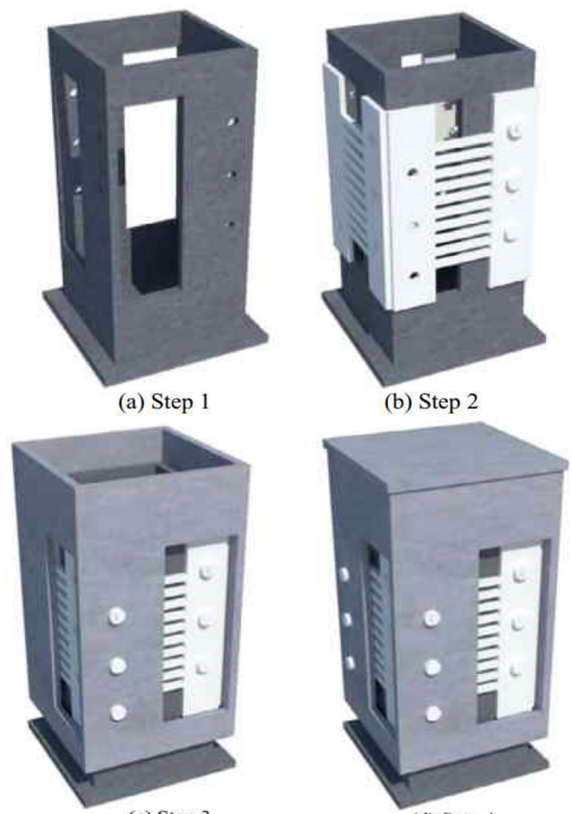
drift ratios below the code-stipulated limit states. More detailed information of this system can be found in Javidan and Kim (2019).

3. Steel slit dampers

3.1. Box type slit dampers

Metallic dampers are considered to be efficient and reliable energy dissipative devices for mitigating earthquake-induced damage in structures. They can be easily implemented in practice as no special fabrication technique or expansive material is involved. They are generally placed between stories where inter-story drifts are relatively large, and dissipate seismic energy by hysteretic behavior of vertical steel strips.

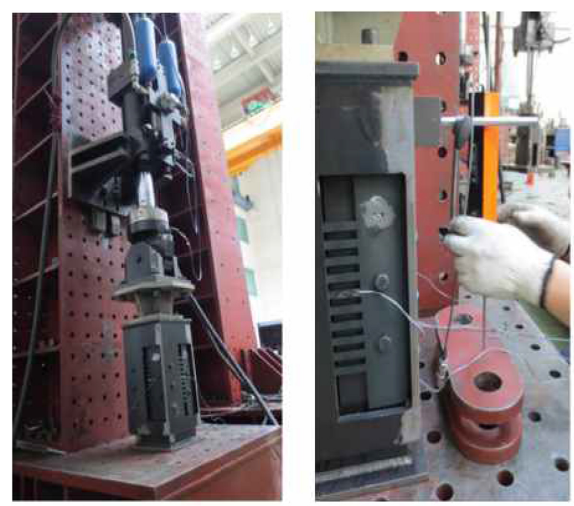
In this study a steel slit damper is developed by combining four steel slit plates into a box shape, as shown in Fig. 3, to be used for seismic retrofit of structures. They are designed to be installed as knee or diagonal braces between stories. The proposed damper with four slit plates integrated into relatively small size can produce larger damping force compared with the conventional slit plate dampers composed of single slit plate. Cyclic loading tests of the dampers are carried out to evaluate their seismic energy dissipation capability. Fig. 4 depicts the test setup



(a) Step 1 (b) Step 2

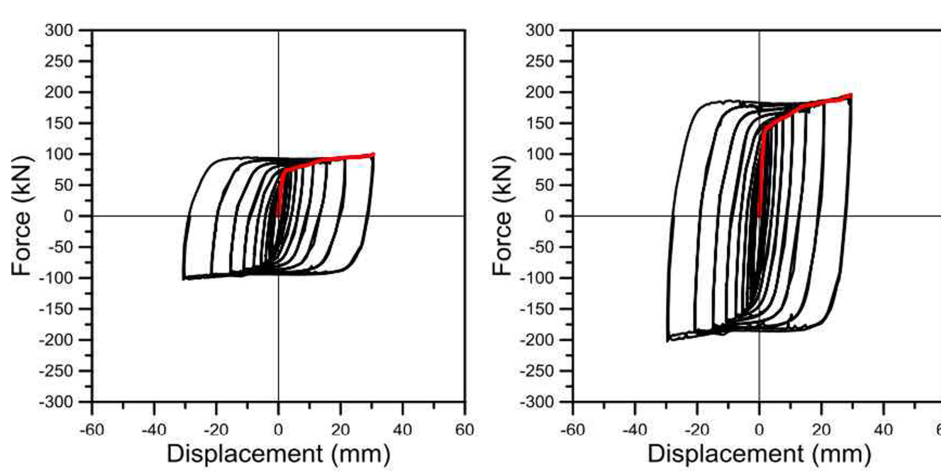
(c) Step 3 (d) Step 4

Figure 3. Assembly of the damper.



(a) Test setup (b) LVDT

Figure 4. Test setup.



(a) BS-T1 (b) BS-T2

Figure 5. Hysteresis curves of the test specimens.

of the dampers.

Two LVDTs (Linear variable differential transformers) are attached to the exterior casing to measure displacement. Fig. 5 shows the hysteresis curves of the two specimens obtained from the loading tests. The test results show that the dampers act stably during the cyclic loading test dissipating significant amount of seismic energy. No local buckling or out-of-plain buckling was observed in the slit plates and the internal and external casings. More detailed information of this system can be found in Lee and Kim (2017).

3.2. Double slit dampers

The proposed damper consists of steel slit dampers with two different stiffnesses and yield strengths. During low to medium earthquakes, the weak slit damper is activated while the strong slit damper remains elastic. For severe earthquakes, both the weak and strong dampers act together to dissipate large seismic energy. When the displacement of the weak slit damper reaches near the fracture point, further displacement in the weak slit part is prevented by a stopping mechanism and the force is transferred to the strong slit damper. A simplified analytical model of the proposed damping devices is developed (Fig. 7), verified, and calibrated by cyclic loading test and detailed finite element analysis in the ANSYS workbench.

It was observed in the cyclic loading test of the multi-slit damper that two distinct yield points existed as designed and that the damper showed stable hysteretic behavior at the lateral displacement larger than 4% of the story height. The force-displacement relationship of the test specimen obtained from finite element analysis matched well with the test results. The analysis model made by a combination of three nonlinear link elements turned out to simulate the test result quite well in a general purpose structural analysis software. More detailed information of this device can be found in Naeem and Kim (2018).

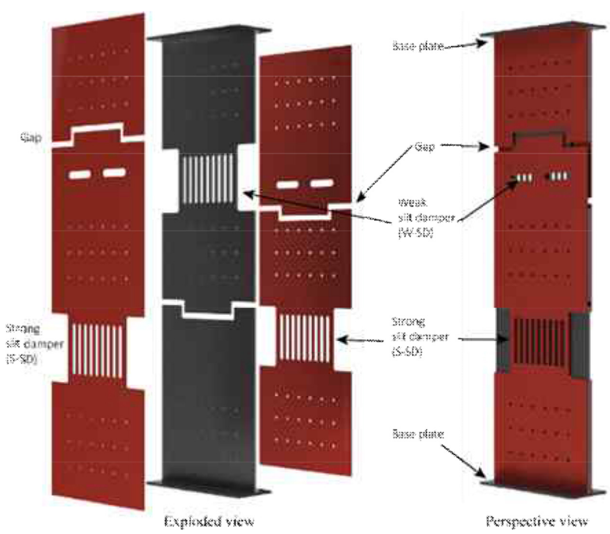


Figure 6. Multi-slit damper.

4. Slit-friction Hybrid Dampers

The purpose of this study is to develop a hybrid damper which works for both major and minor earthquakes. To this end the hybrid damper is made of a steel slit damper

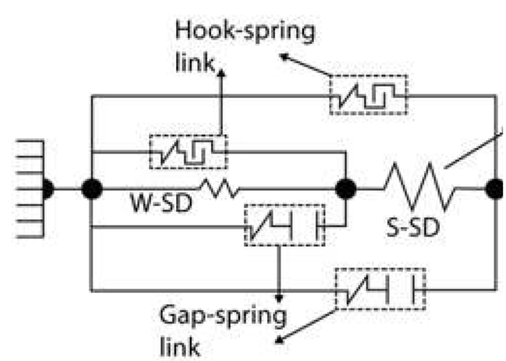
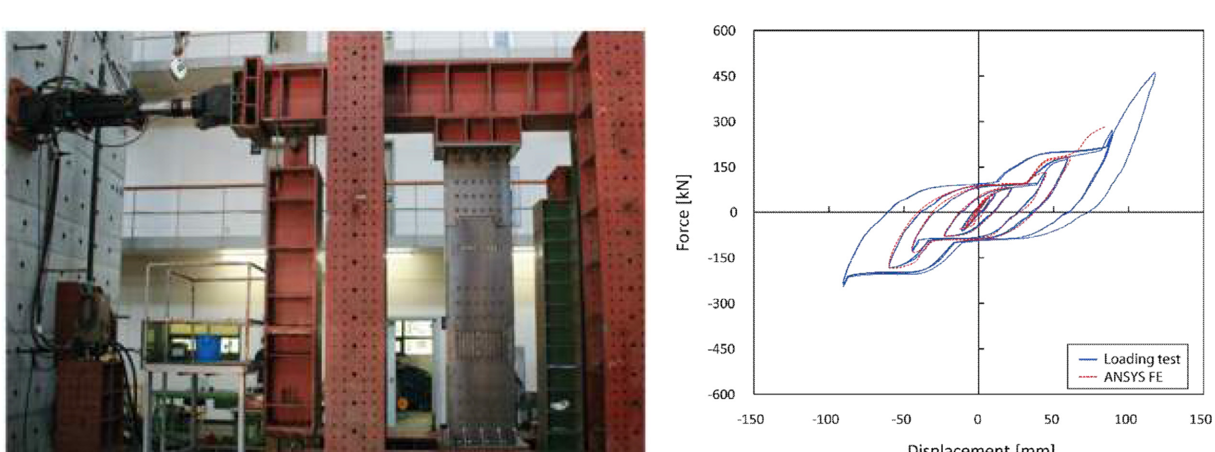


Figure 7. Analysis model.



(a) Test setup (b) Hysteresis curve

Figure 8. Loading test of multislit damper.

and rotational friction dampers connected in parallel (Fig. 9). For minor earthquakes or strong winds, the slit damper remains elastic and only the friction damper is activated to dissipate vibration energy, while for strong earthquakes both the friction and slit dampers work simultaneously to dissipate seismic input energy. Compared with friction dampers the hybrid dampers can be made smaller in size with the same energy dissipation capacity. Cyclic loading tests of the friction, slit, and the combined hybrid dampers are carried out to evaluate their seismic energy dissipation capability (Fig. 10), and the results are compared with the finite element analysis results of the test specimens.

The test results showed that the hybrid dampers were effective in dissipating seismic energy through stable hysteretic behavior throughout the given loading history. It was noticed that when vertical deflection of the specimen was restrained the post-yield stiffness increased due to the generation of tension field at large displacement. Similar behavior was observed in the finite element analysis results. More detailed information of this system can be found in Lee and Kim (2015) and Lee et al. (2017).

5. Viscous Damper-cable System

Self-centering retrofitting systems can restore the structure back to its original position, hence eliminating or reducing the residual deformation in a structure after an earthquake. This study investigates the seismic performance of the spring viscous damper cable (SVDC) system, which consists of a viscous damper with external spring and a prestressed high strength steel cable. One end of the spring viscous damper is attached to the bottom of a structure, and the other end is connected to a pre-stressed steel cable which is fixed to an upper part of the structure. A silicon gel type viscous damper with an external spring is manufactured and is tested using a dynamic actuator to obtain its dynamic characteristics at different loading frequencies (Fig. 11). Due to the interaction between the external spring and the

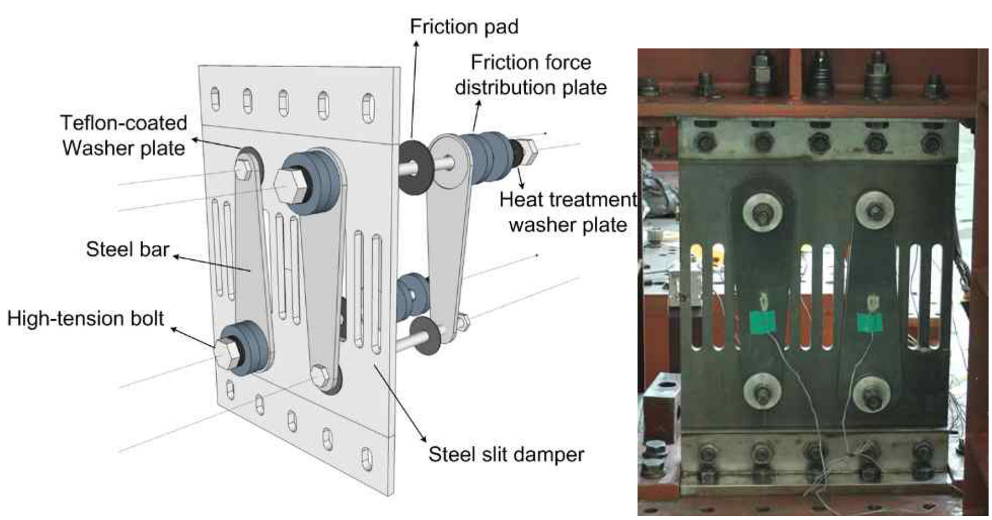
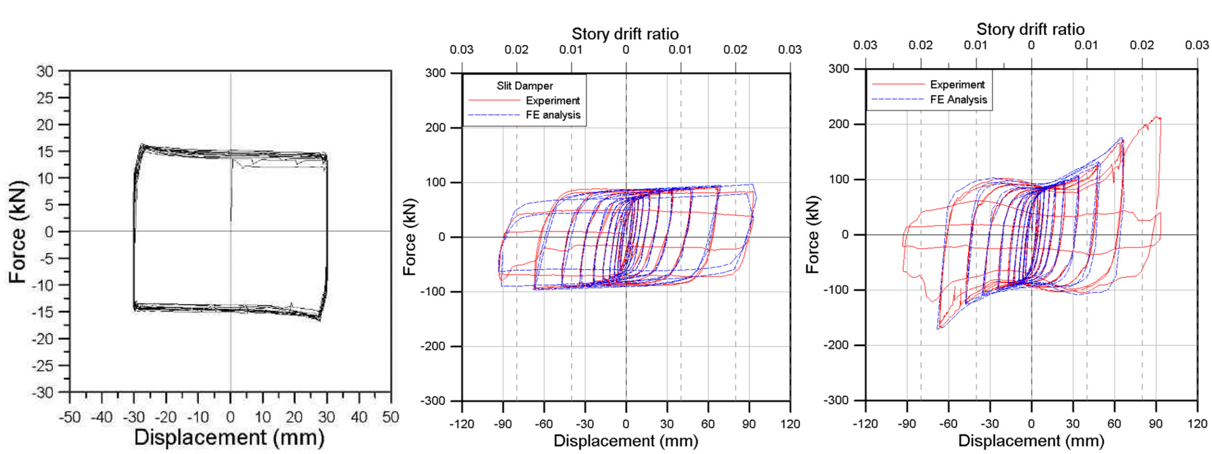
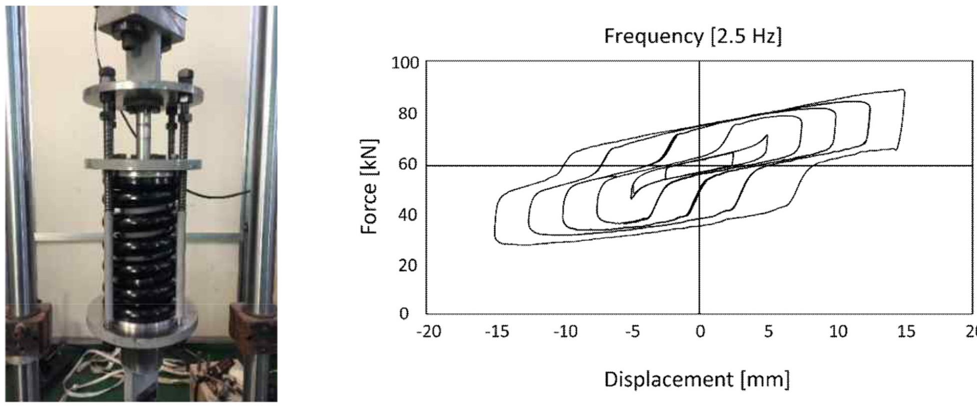


Figure 9. Hybrid slit-friction damper.



(a) Friction dampers (b) Slit damper (c) Hybrid

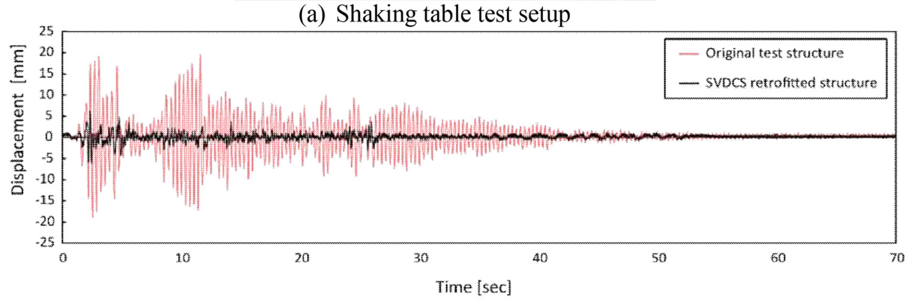
Figure 10. Hysteresis curves of the damper obtained from cyclic loading test.



(a) Test setup (b) Hysteresis curve

Figure 11. Loading test of the spring-viscous damper.

(a) Shaking table test setup



(b) El Centro earthquake (1940)

Figure 12. Shaking table test of the spring-viscous damper cable system.

prestressed tendons, the system has self-centering capability. The shaking table tests of a two-story steel frame installed with the proposed damping system are carried out using five different earthquake records (Fig. 12).

The results obtained from the experiments and numerical simulations demonstrate that the proposed damping system with added stiffness and self-centering capability is effective in reducing earthquake-induced displacement and member forces. More detailed information of this system can be found in Naeem and Kim (2018).

6. Concluding remarks

In this paper passive seismic retrofit devices for building structures developed recently by the author were introduced. For each retrofit system developed, an appropriate analytical model was developed, and the seismic performance was verified by loading test and earthquake analysis of case study structures. The experimental and analysis results showed that the proposed systems can be used efficiently to enhance the seismic performance of building structures.

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