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Seismic loss assessment of a structure retrofitted with slit-friction hybrid dampers

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ABSTRACT

In this study a hybrid energy dissipation device is developed by combining a steel slit plate and friction pads to be used for seismic retrofit of structures, and its effectiveness is investigated by comparing the life cycle costs of the structure before and after the retrofit. A hybrid damper is manufactured and is tested under cyclic loading. It is observed that the damper shows stable hysteretic behavior throughout the loading history, and that the cumulative ductility ratio obtained from the experiment far exceeds the limit value required by the AISC Seismic Provisions. The probabilities of reaching various damage states are obtained by fragility analysis to evaluate the margin for safety against earthquakes, and the life cycle costs of the model structures are computed using the PACT (Performance Assessment Calculation Tool). According to the analysis results the slit-friction hybrid damper shows superior performance to the slit damper with the same yield strength for seismic retrofit of structures. The analysis results also show that the probabilities of reaching the limit states are minimized by the seismic retrofit with hybrid dampers combined with increasing column size. The combined seismic retrofit method also results in the lowest repair cost and shortest repair time.

1. Introduction

Currently two of the most widely used seismic energy dissipation devices in building structures are metallic yield dampers and friction dampers. The metallic energy dissipative devices have been developed in many forms such as ADAS [1], buckling restrained braces [2], and slit dampers [3]. Among the metallic dampers, steel plate slit dampers have advantage in that they are relatively easy to design and manufacture [4–8]. Friction dampers have also been applied in various forms as presented in Pall and Pall [9] and Mualla and Belev [10]. Recently Lee et al. [11] developed friction dampers utilizing friction between low-steel composite material and milled steel.

Recently various energy dissipation devices or passive dampers have been widely applied for seismic retrofit of existing structures. Some researchers investigated simultaneous application of multiple devices to maximize the energy dissipation mechanism. For example, Tsai et al. [12], Chen et al. [13], and Uetani et al. [14] studied combined displacement-dependent and velocity-dependent devices for seismic mitigation of structures to minimize the shortcomings of individual dampers. Marko et al. [15] studied the effect of combined friction-viscoelastic damping devices strategically located within shear walls and demonstrated the feasibility of mitigating the seismic response of building structures by using embedded dampers. Marshall and Charney [16] studied a hybrid system with buckling restrained braces and viscous fluid device by investigating the seismic response of steel frame structures. Optimum design procedures for hybrid or multiple dampers have been developed by Murakami et al. [17]. Lee and Kim [18] investigated the effectiveness of a hybrid damper consisting of steel slit plate and rotational friction devices to be used effectively both for small and large earthquakes. Lee et al. [19] investigated the combined behavior of shear-type friction damper and non-uniform strip damper for multi-level seismic protection. The results of the previous studies demonstrated the capability of hybrid passive systems to improve structural response compared with conventional lateral systems. The hybrid configuration improved some aspect of structural response providing benefits for multiple damage measures.

The purpose of this study is to develop a hybrid slit-friction damper which works for both major and minor earthquakes, and to investigate its validity by evaluating the life cycle cost of a structure before and after retrofit with the dampers. The hybrid damper is made of a steel slit damper and friction dampers connected in parallel. For minor earthquakes or strong winds, the slit damper remain elastic and only the friction damper yields to dissipate vibration energy, while for strong earthquakes both the friction

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and slit dampers work simultaneously to dissipate seismic input energy. Cyclic loading tests of the hybrid dampers are carried out to evaluate their seismic energy dissipation capability. The hybrid dampers are applied to seismic retrofit of an analysis model structure, and the effectiveness of the dampers is checked using fragility analyses to obtain the probability of four limit states being reached. Finally, loss estimation is carried out using the PACT (Performance Assessment Calculation Tool) program developed based on FEMA P-58 [20] methodology.

2. Development of a slit-friction hybrid damper

2.1. Property of the damper

The hybrid damper developed in this study consists of a steel slit damper to resist strong earthquakes and friction dampers to dissipate vibration energy caused by small earthquakes or strong winds connected in parallel as shown in Fig. 1(a). The friction pads are attached on both surfaces of the steel slit plate, and two side plates are placed at both sides of the slit plate. The two side plates are fastened together by high-tension bolts which go through the slotted holes in the slit plate so that the slit plate does not contact with the bolts. In practice the slit plate is connected to the structure at both the top and bottom so that it deforms to the inter-story drift, and the two side plates are only connected to the structure at the bottom so that friction force is generated by the relative movement between the slit plate and the side plates. A 1.0 mm-deep engraving is made on the surface of the slit plate where the friction pads are attached to prevent lateral movement of the friction pads and to restrain radial elongation of the pads due to the large clamping force applied by the high-tension bolts. To evenly distribute the clamping force on the surface of the friction pads, the rectangular plates are inserted between the bolt head or the nut and the steel side plates. The overall width and height of the steel plate are 500 mm and 700 mm, respectively. The plate has nine slit columns: the width (b), thickness (t), and the height (l_o) of each slit column are 20 mm, 15 mm, and 200 mm respectively, as depicted in Fig. 1(b). The stiffness and yield strength of a slit damper can be derived based on elementary mechanics of materials as follows [3]:

$$k_s = n\frac{12EI}{l_o^3} = n\frac{Etb^3}{l_o^3} \tag{1a}$$

$$P_y = \frac{2nM_p}{l_0} = \frac{n\sigma_y tb^2}{2l_0} \tag{1b}$$

where n = number of strips, M_p is the plastic moment of a strip, σ_y is the yield stress of the plate, t = thickness of strips, b = width of strips, and l_o = length of the vertical strip.

The yield force of the friction dampers is proportional to the clamping force N and the friction coefficient μ as follows:

$$P_{yf} = \mu \times N \tag{2}$$

In the case the slit damper and the friction damper are connected in parallel, the yield strength of the hybrid damper can be calculated as follows:

$$P_y = \left(\frac{n\,\sigma_y t\, b^2}{2\, l_o}\right) + \mu N \tag{3}$$

The hybrid damper is basically a displacement-dependent device which dissipates seismic energy by yielding of steel slits (slit dampers) and slip of friction pads (friction dampers). The slip of friction pads occurs at small lateral displacement, which makes it effective in resisting small earthquakes and strong wind loads. The slit dampers remain elastic during small earthquakes and are activated at major earthquakes.

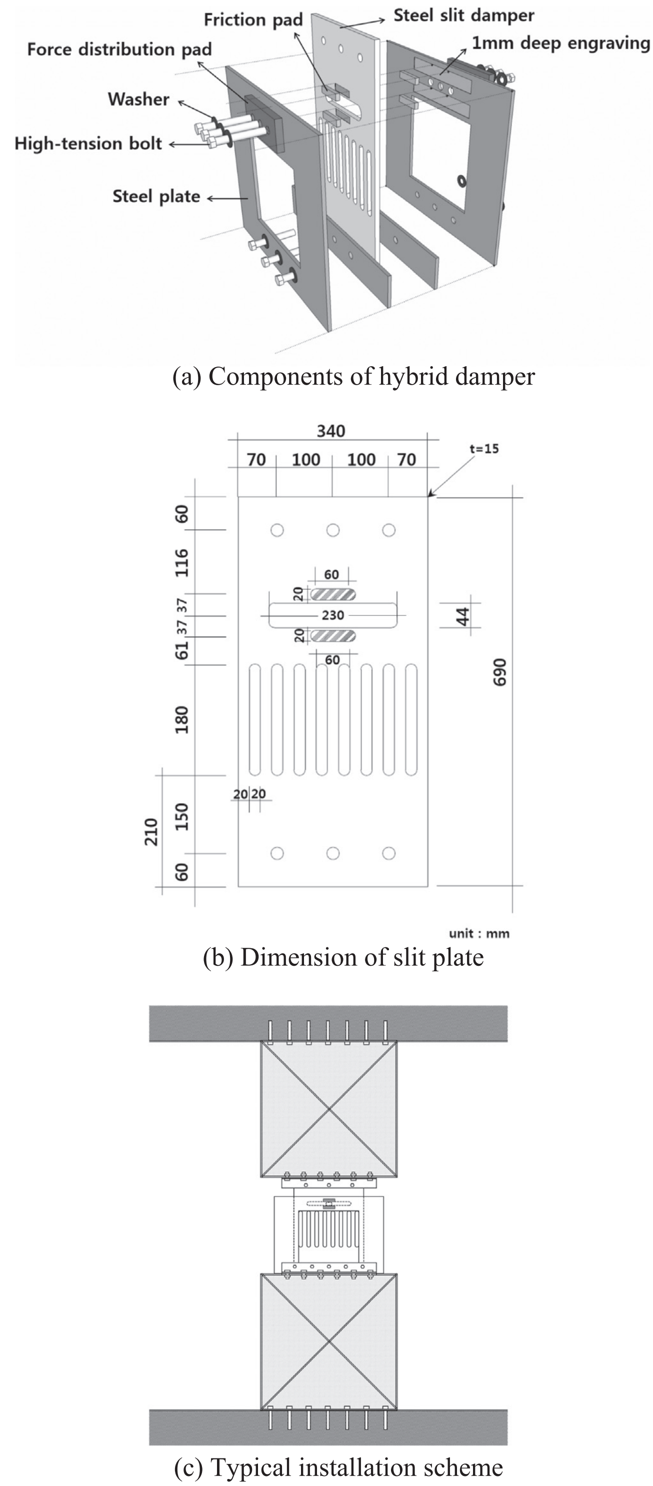

Fig. 1. Configuration of the proposed slit-friction hybrid damper.

Such dampers are generally located inside of partition walls. The damper unit is placed between two strong frames as shown in Fig. 1(c); the upper strong frame is fixed to the upper beam and the lower one is fixed to the lower beam. The strong frame can be made of rectangular steel plate with diagonal stiffener or rectangular frame with diagonal or X-shaped steel bracing, which