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Seismic performance of steel plate slit-friction hybrid dampers

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ABSTRACT

In this study a new hybrid energy dissipation device is developed by combining a steel slit damper and rotational friction dampers in parallel to be used for seismic retrofit of structures. Compared with the conventional slit dampers with the same yield strength, the hybrid damper has an advantage in that only friction dampers are activated for small earthquakes or strong wind, and both friction and slit damper work simultaneously for strong earthquakes. Cyclic loading tests of the friction, slit, and the combined hybrid dampers are carried out to evaluate their seismic energy dissipation capability. Finite element analyses of the test specimens are also carried out for comparison, which correspond well with the test results. The hybrid dampers are applied to seismic retrofit of an reinforced concrete analysis model structure, where it is observed that the dampers are effective in restraining the building performance within a given target performance level. The fragility analysis of the structure shows that the probabilities of reaching four limit states decrease significantly after the seismic retrofit. The effect is most significant in the reduction of the probability of reaching the complete damage state.

1. Introduction

After the Northridge earthquake in 1994 and Kobe earthquake in 1995, it was observed in many structures that, even though the collapse prevention or the life safety design objective was satisfied, significant economic loss occurred due to major damage in non-structural elements and minor damage in structural elements. To mitigate earthquake induced structural damage, various energy dissipation devices have been applied to structures. 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 [3,4]. Hu [5] investigated the effect of the slit damper made of shape memory alloy. Mualla and Belev [6] developed a rotational friction damper and showed that the hysteretic behavior of the friction damper was frequency-independent. Kim et al. [7] investigated the effect of rotational friction dampers on enhancing seismic and progressive collapse resisting capacity of structures. Patel and Jangid [8] investigated the dynamic response of adjacent structures connected by friction dampers. Kaur et al. [9] compared the seismic performance of a steel moment resisting frame with friction dampers with those of a moment frame and a braced frame. Recently Lee et al. [10] developed friction dampers utilizing friction between low-steel composite material and milled steel, and Kim and Kim [11] developed a seismic retrofit scheme for staggered truss frames using friction dampers.

Attempts have been made to utilize combined mechanism of multiple dampers. Pong et al. [12] investigated the seismic performance of TPEA (tapered-plate energy absorber) combined with fluid dampers or viscoelastic dampers. Uetani et al. [13] applied the gradient projection algorithm for optimum design of a real building structure with viscous and hysteretic dampers. Marshall and Charney [14] studied the concept of the hybrid passive control system with BRB and viscous fluid device by investigating the seismic response of steel frame structures. Murakami et al. [15] proposed a sensitivity-based practical optimization method for simultaneous use of viscous, hysteretic, and inertial mass dampers for earthquakes. Asadi et al. [16] developed a hybrid damper composed of viscous and electromagnetic subsystems, and Wang et al. [17] investigated the effect of tuned mass damper and viscous damper on the mitigation of wind-induced vibration in tall buildings. Lee and Kim [18] investigated the seismic energy dissipation capacity of a hybrid passive damper composed of a friction and a hysteretic slit damper, and compared the results with those of slit and friction dampers with the same yield strength. Kim and Shin [19] carried out seismic loss assessment of a structure retrofitted with slit-friction hybrid dampers, and found that the life cycle cost of a structure with the hybrid dampers is smaller than that of the structure with slit dampers with the same yield strength.

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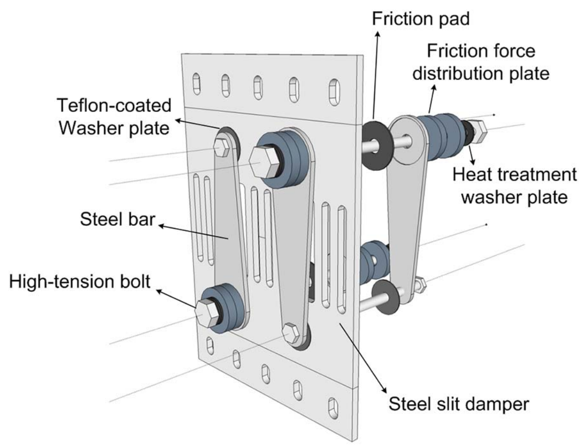

Fig. 1. Hybrid slit-friction damper.

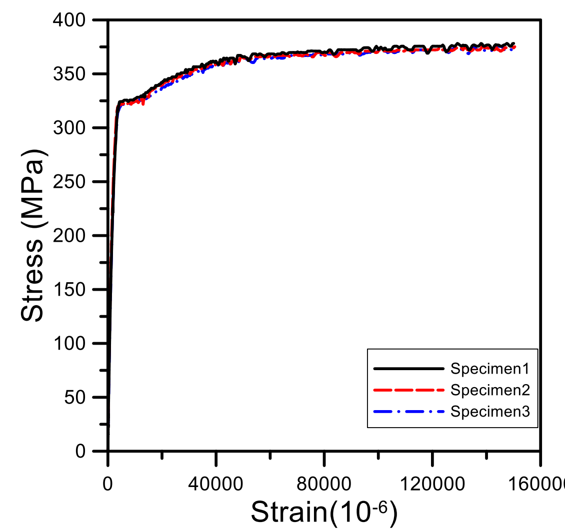

Fig. 3. Stress-strain curve of the steel.

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 and rotational 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 and slit dampers work simultaneously to dissipate seismic input energy. Compared with the conventional slit dampers with the same yield strength, the hybrid damper has an advantage in that only friction dampers are activated for small earthquakes or strong wind, and both friction and slit damper work simultaneously for strong earthquakes. 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, and the results are compared with the finite element analysis results of the test specimens. The hybrid dampers are applied to seismic retrofit of a reinforced concrete analysis model structure, and the effectiveness of the dampers are checked by nonlinear dynamic analyses using the seven earthquake records scaled to the design spectrum. Fragility analyses of the model structure before and after retrofit are also carried out to compare the probability of reaching damage limit states.

2. Analytical modeling of hybrid slit-friction dampers

A steel plate slit damper is composed of many vertical strips as shown in Fig. 1. Based on the assumption that each strip in the slit damper has fixed end condition, the stiffness and the yield strength of a slit damper can be derived as follows [3]:

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

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

where n = number of strips, t = thickness of strips, b = width of strips, and l_o = length of the vertical strip. A friction damper is activated when the applied load reaches the slip force. As the initial stiffness of a friction damper is very large, larger energy is dissipated compared with hysteretic dampers with similar yield force. The yield force of a rotational friction damper can be obtained as follows [20]:

$$P_{yf} = 2\mu\, NQ\,\frac{R_m}{L_0} \tag{2}$$

where L_0 is the length between the two slip pads, μ is the friction coefficient of the friction pad, N is the number of friction face, Q is the clamping force, and R_m is the effective area of the friction face. In case the slit damper and the friction damper are connected in parallel as shown in Fig. 1, the yield strength of the hybrid damper can be obtained as follows:

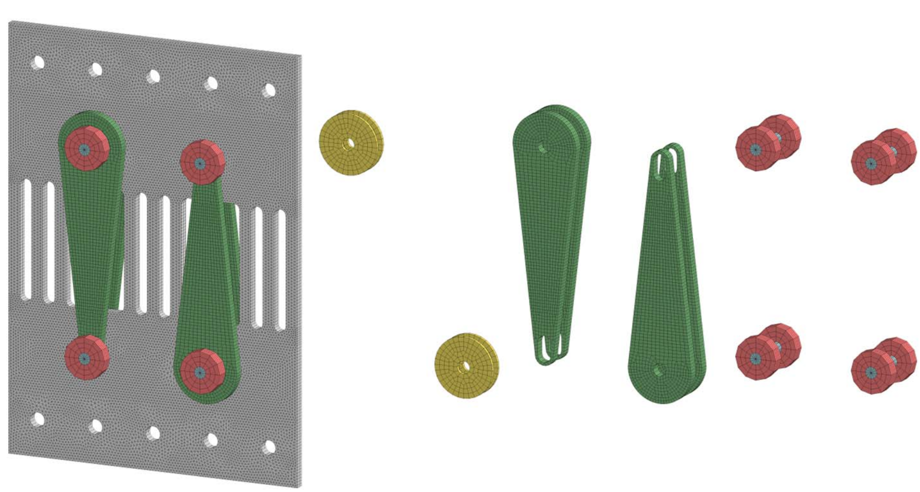

Fig. 2. Finite element model of all components of the hybrid damper.