NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

Shaking Table Tests on RC Frames Strengthened with Simplified Friction Damper

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ABSTRACT

This study investigates the behaviour of two reinforced concrete (RC) frames retrofitted with a simplified friction damper subjected to dynamic loading conditions. The simplified damper was designed with intent to achieve an economical and easy-to-fabricate and install damping device with minimum technical complexities. The damper was first tested under reversed cyclic loading conditions and later, used in retrofitting RC frames, mimicking the design of existing old structures in Korea. The damper was developed by converting the splice of a steel diagonal brace. The shaking table tests were carried out using an artificial seismic wave representing the characteristics of the recent Korean earthquake records. The shaking table test results showed that the proposed friction damper effectively dissipated the seismic energy and reduced the seismic drift demands even for higher excitation levels than those of Korean earthquakes.

1 INTRODUCTION

Historically, the Korean peninsula has been considered less prone to earthquakes. However, the recent events of Gyeong-ju and Pohang have increased the demand for retrofitting the existing buildings. Active research efforts have been made afterwards, to develop domestically the efficient and economical retrofitting schemes for existing non-seismically designed structures. The use of friction dampers for seismic retrofitting has been widely recognised due to their simple but efficient energy dissipation mechanism. The friction dampers dissipate seismic energy through sliding of the friction interfaces i.e. slotted bolted connection (Grigorian et al., 1993; Khoo et al., 2014) and Pall friction dampers (Pall and Pall, 1996, 2004), etc. These dampers are typically used with diagonal or chevron steel braces, and are developed in a variety of forms from basic bolted splice connections. A bracing system with U-shaped steel strips which could be classified as a bending dissipative brace was proposed which showed stable hysteretic behaviour under cyclic tests (Taiyari et al., 2015, 2019a). A friction damper proposed using steel pad and a new clamping set-up equipped with a high strength bolt (Sui et al., 2021). Eldin et al. aligned a friction damper the in corner of RC frame (Eldin et al., 2020). To avoid the implementation complexity and cost of installation, a friction damper using position-controlled semi-active system was developed and tested by shaking table for verifying its feasibility (Lu et al., 2018). The traditional friction damper system has the optimum behaviour with symmetric response in both tension and compression as well as a rectangular hysteresis loop. Several numerical simulations showed that the friction dampers effectively reduce the earthquake-induced responses of structure if the slip force of the dampers is appropriately selected (Bhaskararao and Jangid, 2006). Also, the probabilistic approaches were adopted to predict the friction coefficient of the pads equipping the damper and the randomness of the bolts preload (Lauro et al., 2019). A bracing system was introduced by using a probability-based design methodology in multi-story frame (Taiyari et al., 2019b). For seismic design using the friction damper, Jarrahi et al. (2020) proposed an optimal design of a rotational friction dampers using ibarra krawinkler deterioration model.

Although the studies mentioned above show that the existing friction damper approaches provide effective retrofitting solutions but in pursuit of economy and ease in fabrication and installation, a simplified friction damper was proposed in this study. A friction damper with long slotted holes and gap between the braces was developed and tested under reversed cyclic loading for evaluating the slip load and hysteretic behaviour. Later, two RC frames retrofitted with the diagonal brace and the proposed friction damper were evaluated under dynamic loading conditions and results were compared with the response of a bare frame.

2 CYCLIC TEST

The proposed friction damper was so designed that it fits as a conventional splice of steel brace. Figure 1 presents the concept of the proposed friction damper which has long slot holes on both braces and splice plates, high strength bolts (M20, A490M), and washers. In addition, a gap between braces (H-beams), hereafter, called “the stroke of damper”, was designed in accordance with the allowable drift limit of 1% for ordinary moment frames as per ASCE 41-17. The long slot holes allow the sliding displacement of the damper which helps to dissipate seismic energy through friction. A total of eight bolts were used in dampers to avoid any out-of-plane movement of splice plates during loading. Four loadcells and four bolt strain gauges were installed to measure the bolt tension forces during the test. The friction surfaces were unpainted clean mill scale steel and a slip coefficient could be determined as the value of 0.3 (AISC, 2016).

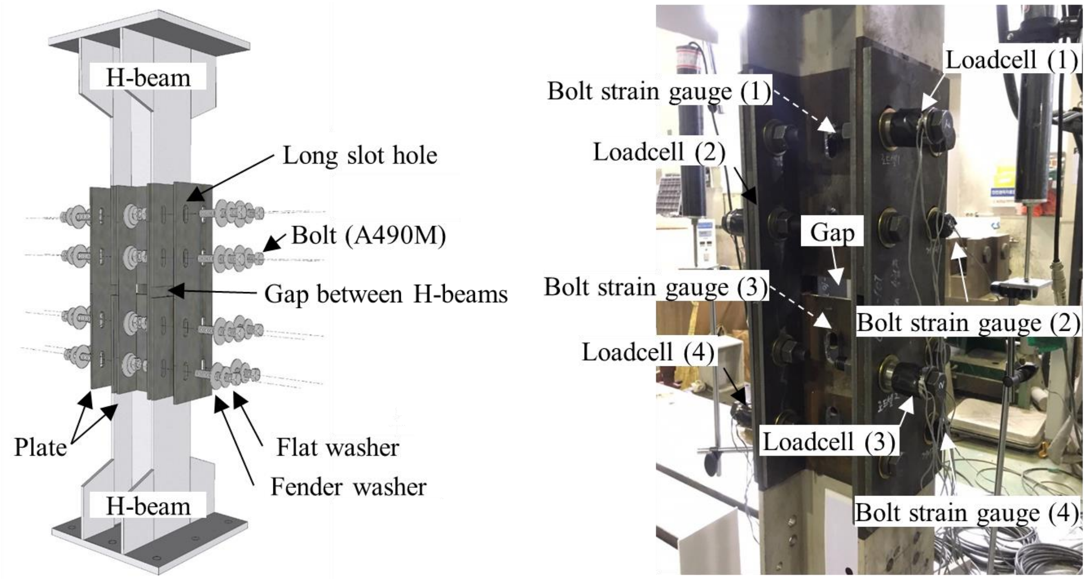
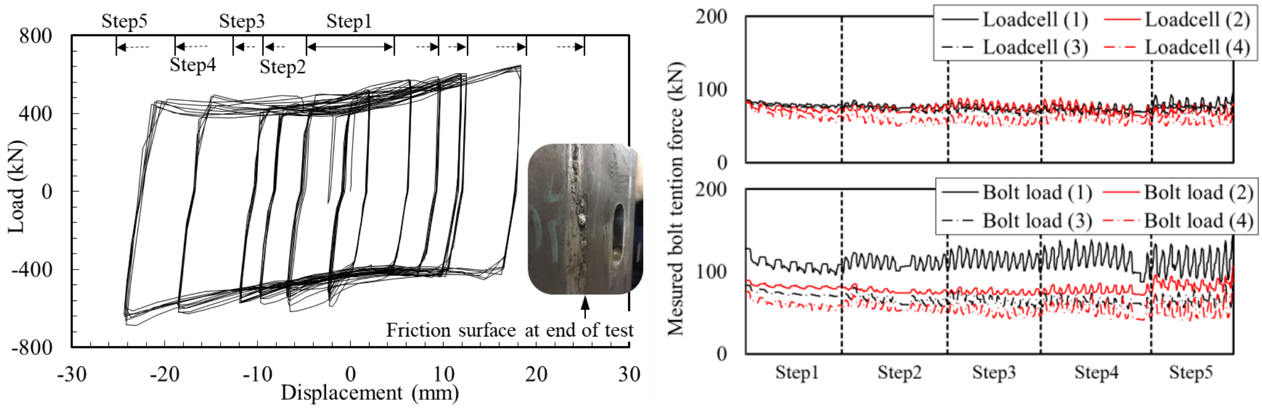


Figure 1: Concept and detail of simplified friction damper.

Figure 2a shows the hysteresis loop of the friction damper under cyclic tests. A five steps loading protocol was adopted. The load and displacement relationships show a stable behaviour. As the loading step increases the slip load tends to gradually increase, which indicates the increasing roughness of the surface due to friction. Nevertheless, the simplified friction damper used in this study shows a rectangular hysteresis loop of a typical friction damper. Figure 2b shows the change in the initial bolt tension force during tests. The initial bolt tension forces were about 80kN, which was 45% of the minimum fastener tension force of M20 bolt (AISC, 2016). The bolt tension forces were gradually decreased with repeated friction, but maintained until the end of the test. Based on the measured bolt tension forces, the friction coefficient of the simplified friction damper was determined to be as 0.451.



(a) (b)

Figure 2: (a) Load-displacement relationship and (b) bolt tension force measured by loadcell and bolt gauge.

3 SHAKING TABLE TEST

Three RC frames were tested under shaking table test as shown in Table 1. The tested RC frame without friction damper (bare frame, presented as “BF”) was non-seismically designed to simulated with behaviour of existing buildings. The compressive strength of concrete used in this study was 16.9MPa, and the yield strength of flexural reinforcement of columns and beams were 512.2MPa and 503.3MPa, respectively. The RC frame was designed with a strong-beam and weak-column philosophy, the cross-sectional dimensions and clear height of columns were 400mm×400mm and 2.75m, while the cross-sectional dimensions and clear length of beams were 350mm×550mm and 2.9m, respectively. The RC frames retrofitted with simplified friction damper are shown in Figure 3. The friction dampers were installed in the left-side corner of conventional diagonal H-beam brace (200×200×8×12). The dampers were designed with design slip loads of 50% (BF-0.5) and 80% (BF-0.8) of the maximum lateral strength of bare frame. The initial bolt tension forces of 0.22T_0 and 0.36T_0 were provided in the bolts of the friction damper. To install the friction damper and brace H-beam, the box shaped connection were anchored at the left-bottom and right-top corners of the frame using the anchor bolts (M16×160mm).

Table 1: List of shaking table test specimens.

Specimen	**Bolt (minimum fastener tension force, T_0)**	**Initial bolt tension force (T_i)**	**T_i / T_0**	**Slip force (kN)**
BF-0.0	-	-	-	-
BF-0.5	A490M (179 kN)	40 kN	0.22	204.2
BF-0.8		65kN	0.36	331.8

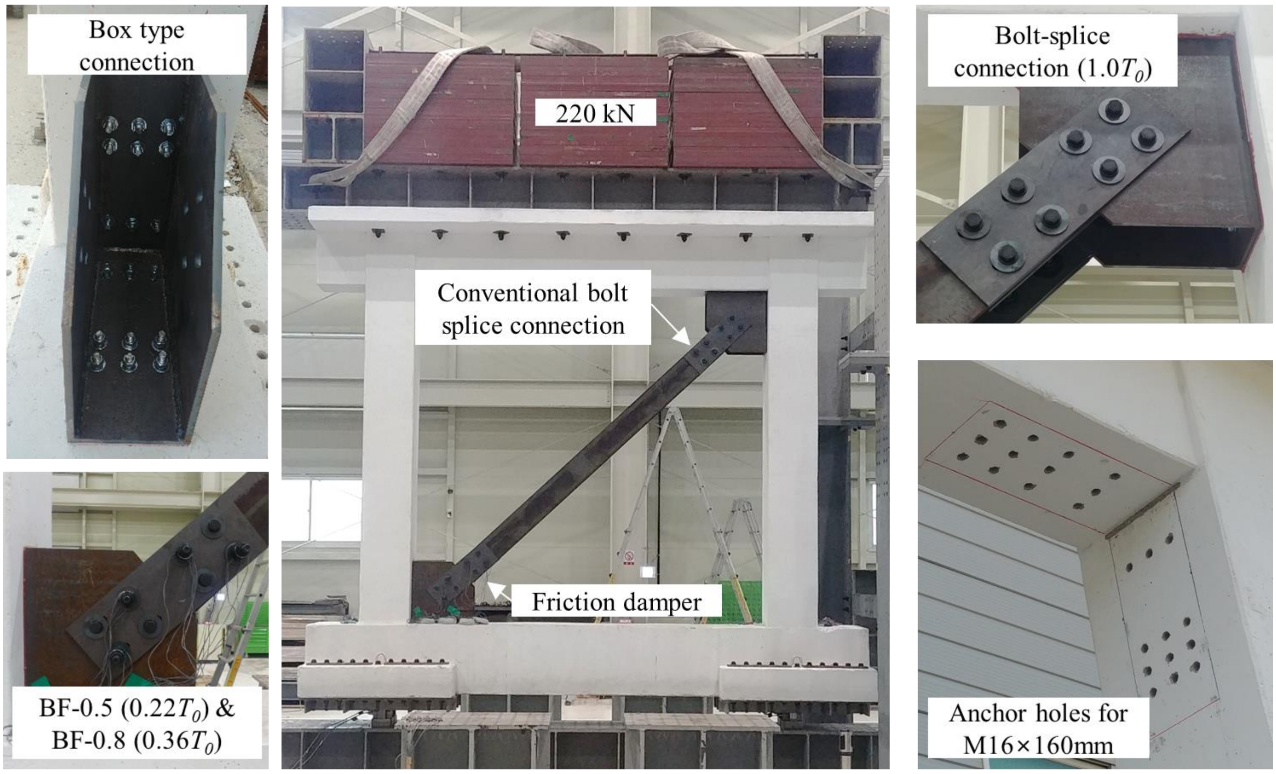
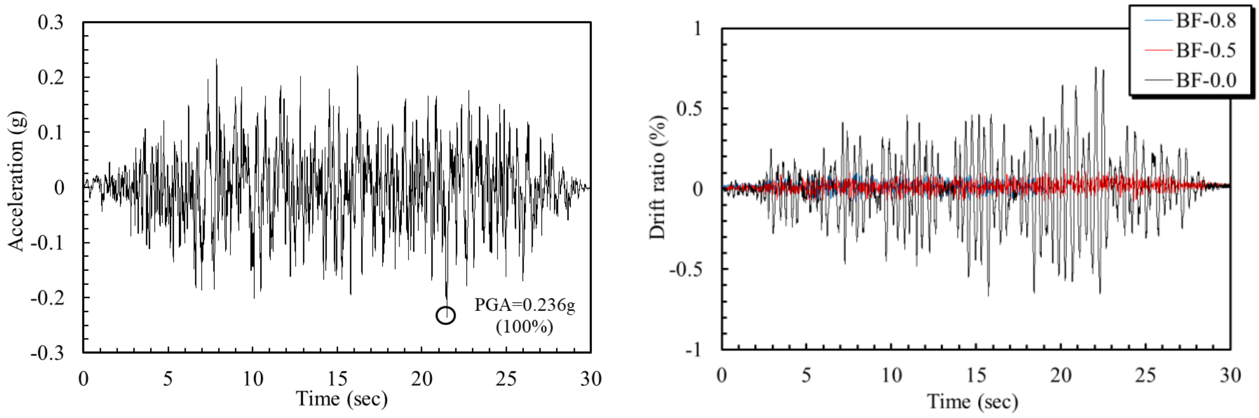


Figure 3: Installation of friction damper on RC frame.



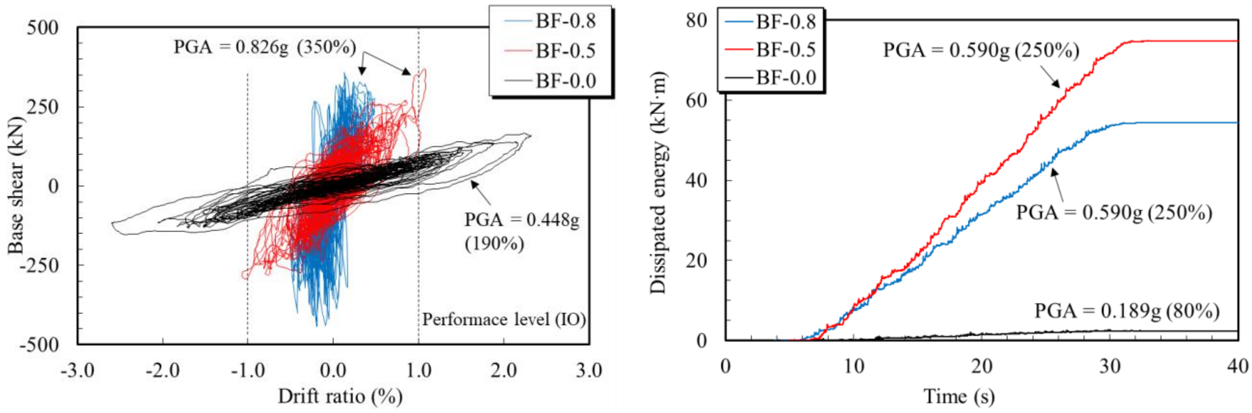
(a) (b)

Figure 4: (a) artificial seismic wave and (b) Time history of drift ratio under the seismic excitation (100% of PGA).

Figure 4a shows an artificial seismic wave used in this study. It was designed based on the response spectrum in according with the KDS 41 17 (2019) guidelines assuming S4 soil type, seismic grade-1, and a damping ratio of 5%. The peak-ground acceleration (PGA) was 0.236g (100%). The seismic wave on shaking table test was applied in a gradually increasing way from 0.118g (50% of PGA) to 0.826g (350% of PGA).

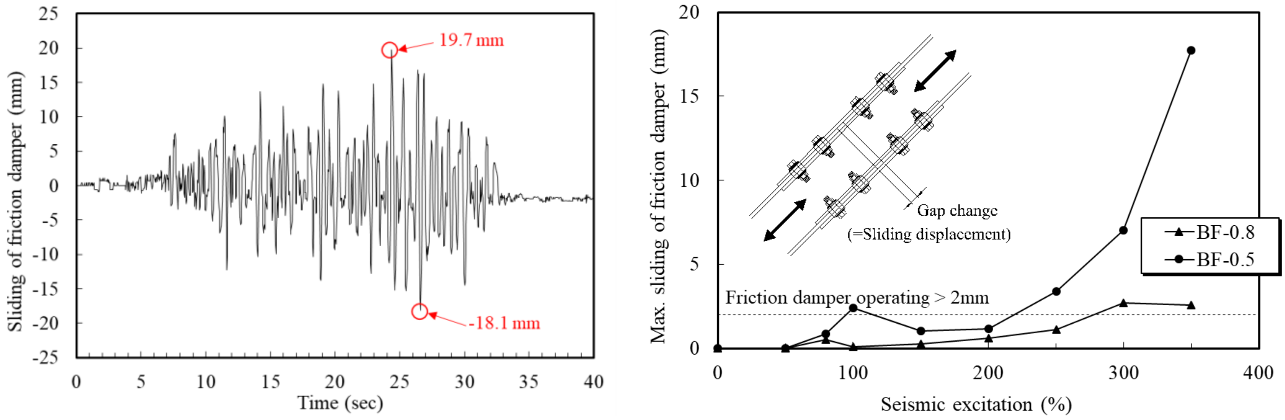
At the PGA of 0.236g (100% of PGA), the dynamic responses of tested specimens were shown in figure 4b. The shaking table test of the bare frame (BF-0.0) was stopped at the PGA of 0.448g (190% of PGA) with a large drift ratio. The two specimens retrofitted with 50% (BF-0.5) and 80% (BF-0.8) of the bare frame's strength were stopped at the PGA of 0.826g (350% of PGA) because of the capacity of the shaking table. The response of retrofitted specimens (BF-0.5 and 0.8) showed that the drift ratio was significantly reduced. Figure 5a shows the base shear and drift ratio at the end of the shaking table test. Considering the drift ratio of 1% as the seismic performance indicator (Immediate Occupancy, IO of RC frame), the two specimens retrofitted with the simplified friction damper satisfied well this limit even for the PGA of 0.826g (350% of PGA). Figure 5b presents the energy dissipation of the specimens at 0.4% drift ratio. The 0.4% drift was selected for fair comparison of energy dissipation at the same drift level. Two retrofitted specimens (BF-0.5 and 0.8) reached the 0.4% drift ratio at the PGA of 0.590g (250% of PGA), and the bare frame (BF-0.0) at 0.189g (80% of PGA). The energy dissipation capacity BF-0.0 was measured to be 2.4kN·m. The specimen BF-0.5 and BF-0.8 demonstrated the energy dissipation capacity of 74.8kN·m and 54.4kN·m, respectively. In general, two retrofitted specimens dissipated more seismic energy compared to BF-0.0. In specimen BF-0.5, the damper started to slip and dissipate sufficient energy at the PGA of 0.590g (250% of PGA), while damper in BF-0.8 did not show large slip at the same seismic excitation (see Figure 6b), therefore energy dissipation was lower than BF-0.5.

Figure 6a shows the sliding displacement of the friction damper for BF-0.5 measured at PGA=0.826g (350% of PGA). The sliding displacement was measured as the change in the gap between the brace components, which indicates the operation of the damper. Even a very small sliding displacement can confirm the operation of the friction damper, but in this study for the sake of precision in the measured record, it was assumed that the damper starts operation if the sliding displacement becomes at least 2mm or more. For the last seismic excitation (350% of PGA), the friction damper of BF-0.5 showed to slip and dissipate energy throughout the time history of excitation. Figure 6b presents the maximum sliding displacement of dampers at each seismic excitation. Considering the 2mm mark of sliding displacement, it can be said that the dampers of specimens BF-0.5 and BF-0.8 operated at the seismic excitation of 250% and 300% of PGA, respectively.



(a) (b)

Figure 5: (a) Base shear-drift ratio at the end of the test and (b) Dissipated energy at drift ratio of 0.4%.



(a) (b)

Figure 6: Sliding displacement of the friction damper (a) for BF-0.5 at the PGA=0.826g (350% of PGA) and (b) maximum values at each seismic excitation.

4 CONCLUSION

This paper presents the dynamic tests results of RC frames retrofitted with a simplified friction damper proposed in this study. The energy dissipation behaviour of the proposed damper was evaluated through cyclic tests, which showed a stable rectangular hysteresis loop similar to a conventional friction damper. The damper provides ease in fabrication and installation with sufficient energy dissipation. The dynamic response of the retrofitted RC frame showed that the damper dissipated the seismic energy effectively with slip starting at 250% and 300% of PGA. The results showed that the seismic drift demand was significantly decreased in retrofitted structures. The proposed damper is expected to simplify the retrofitting process with effective energy dissipation behaviour.

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