Response of retrofitted 3D RC frames under dynamic loading conditions

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ABSTRACT

In this study, the response of 3D double story reinforced concrete (RC) frames retrofitted through a diagonal friction damper under dynamic loading conditions, was evaluated using shaking table tests. A friction damper having a simplified energy dissipation mechanism was designed, fabricated, tested under cyclic loads, and used to strengthen the RC frames. The proposed damping device had a simple working mechanism and limited technical expertise were needed to fabricate and install. The damper was used as a joint region of a diagonal steel brace. The tested RC frames mimicked the non-seismic design of existing old structures in Korea. An artificial seismic ground motion record showing the characteristics similar to the Korean Earthquake histories, was used in the shaking table tests. The shaking table tests results demonstrated that the strengthened frames showed improved dynamic responses with reduced inter-story and residual drift ratios. The friction damping was effective in dissipating earthquake-induced energy and reduce the seismic demands.

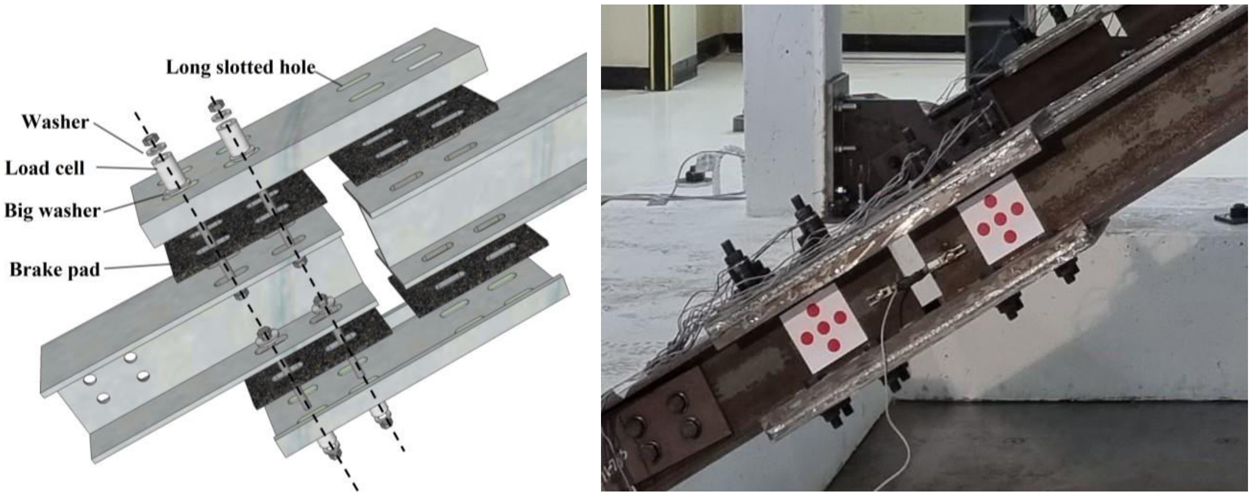
1 INTRODUCTION

The recent Korean earthquakes have increased the need for retrofitting the existing old structures with suitable strengthening scheme. Several public and residential buildings exist in Korea which were built prior to the introduction of the modern seismic design codes. A common piloti type structures with soft first story, are quite common in Korea. These soft story building demonstrate limited ductility because the lower story columns show shear failure in brittle. Among many strengthening schemes, the friction dampers are quite common in practice. This is because the working mechanism of friction damper is simple and cost effective compared to the other damping devices. Under seismic loads, the friction dampers convert the kinetic energy into the heat and sound through friction of contact surface. The friction material between the sliding surfaces is quite important for stable energy dissipation behaviour. Several researchers introduced friction dampers with several different friction materials such as steel-steel surface in mill scales and others used material like brake-lining pads etc. (Pall and Marsh, 1982; Lee et al., 2016). These studies demonstrated that with brake pads, the friction dampers showed stable hysteresis loop. Lee et al. (2016) proposed a new low-steel composite material for friction and verified its effectiveness by dynamic responses. Kiadarbandsari et al. (2022) investigated steel friction damper with horizontal brake pad.

In this study, a new friction with simplified geometric composition is proposed which requires limited technical expertise in its fabrication and installation. The performance of the proposed damper was investigated through cyclic load tests and later used to retrofit as diagonal aligned friction damped-brace through shaking table tests. The results of this study may helpful for developing an effective retrofitting schemes for existing old structures in Korea.

2 DESIGN OF FRICTION DAMPER

A friction damper was proposed in this study by converting a conventional bolted-splice steel connection requiring with a simple working mechanism. Fig. 1 presents the detailed drawings and photograph of the proposed damper. The main elements of the damper are the splice plates, braking pads as friction material, bolts, washers, and nuts fitted with conventional braces. The splice plates are designed with long slot holes which allow the inline movement of the braces and produces friction between the steel plates and brace elements. To avoid stick-slip phenomena between the steel-steel surfaces the braking pads are used between the splice plates and the brace elements. The braces elements are provided with a gap called, "stroke of damper" designed based on the maximum story drift ratio of 1%, as recommended by the ASCE 41 (ASCE-41 2017). Since the dampers is part of the conventional steel brace and works together with the brace, a three-stage load-displacement behaviour can be expected. The brace will initially absorb seismic energy until the load reaches slip load which is defined as the load required to initiate the splice between the splice plates and brace members. Then, at slip load the friction damper starts to dissipate the seismic energy which will avoids increasing in the base shear demand. The damper will dissipate energy until the slip becomes equal to the designed stroke of damper. After that the bearing of brace elements are expected and the brace starts to carry the load. Figure 1 presents the details of the proposed friction damper.



(a) Schematic view *(b) Actual photograph*

Figure 1: The proposed friction-damped in diagonal brace.

2.1 Prototype test

Two prototype damper specimens were tested under cyclic loading conditions to evaluate their energy dissipation capacity. Table 1 summarized the details of the test specimens. The brace elements were made with I-200×200×8×12 and SM355. Specimens were named with "FD-25 and FD-50, where "FD" presents the friction damper and numbers "25" and "50" present the initial bolt pretension force in percentage of tensile strength of bolts. The slip load (R_n) was calculated using Eq.(1) of Korean Design Code (Center 2016), by assuming the friction coefficient (μ) of 0.4 and taking the initial bolt pretension force as 25% and 50% of tensile strength of bolts. The tests were performed using a 3000kN Universal Testing Machine (UTM). A cyclic loading protocol was used as suggested by AISC (AISC 341-16, 2016) as shown in Figure 2.

$$R_n = \mu T_0 N_s N_b \quad (1)$$

where “R_n” shows the friction force, “μ” is the coefficient of friction which was initially assumed to be 0.4 for steel-to-steel surfaces, “T_o”, “N_s”, and “N_b” show the tensile strength of bolt, the number of slip planes and the number of bolts.

Figure 3 shows the cyclic hysteresis of the damper test results. The slip displacement of the test specimens was converted into drift ratio. The hysteresis loops of the tested dampers specimens showed a very stable behavior under axial cyclic loads and dissipated seismic energy without any stiffness degradation. The results showed some initial stiffens until it reached the design slip load, after that the showed a stable behavior without any further increase in stiffness.

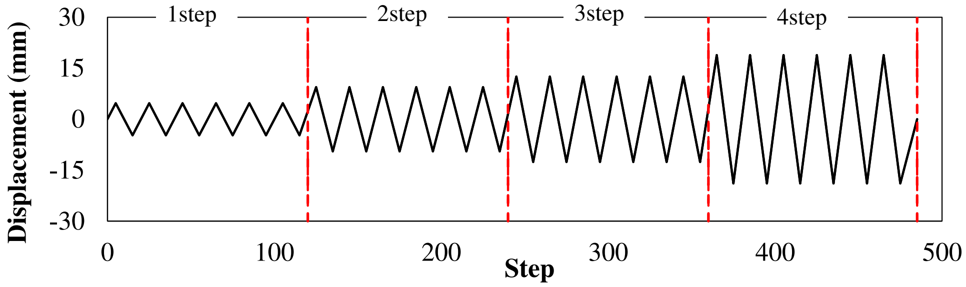
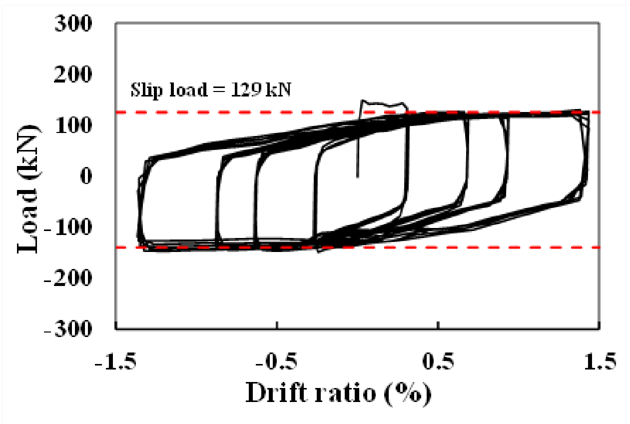


Figure 2: Cyclic loading protocol as per AISC 341-16.

Table 1: Summary of the prototype tests.

Specimen	Minimum fastener tension force (kN)	Bolt pretension force (kN)	Design Slip load (kN)
FD-25	165	41.25	132
FD-50		82.5	264



(a) FD-25 *(b) FD-50*

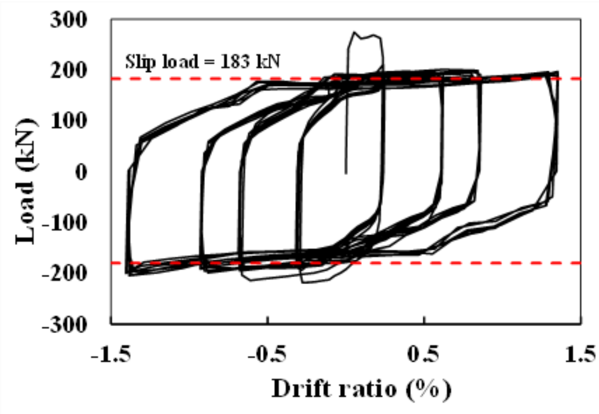


Figure 3: Load-slip behaviour of dampers under cyclic loading.

3 SHAKING TABLE TEST

3.1 Test set-up

The shaking table tests were performed on two double story RC frames simulating the non-seismic design of existing structures in Korea. The response of one RC frame retrofitted with proposed friction damper was compared with the behaviour of a bare frame. The two RC frames were half-scaled double story 3D structures. The dimensions of RC frames were 3.8m × 3.8m× 0.4m. The total height was 4.18m and each story height was 1.53m. Also, measured f_c' was 42.3MPa and f_y of rebar was 423 MPa. The cross-sections of beams and columns were 200mm × 200mm and 200mm × 300mm, respectively. The members were reinforced with 4-D13 main rebars and D6 stirrups. The masses of 9.6 tons were fixed on each story which presented the gravity load. In the case of retrofitted frame, the steel brace with friction damper was designed with steel section I-150 × 150 × 7 × 10 with 8-M16 high-tension bolts (F10T). Brake-lining pads were used as a friction material. The initial bolt pretension force of M16 bolts was 106kN which was nearly 15% of bolt tensile strength. The linear variable distance transducer (LVDT) and accelerations were installed at each story to measure the response of structures. Six accelerometers were attached to the top of columns on each story and six LVDTs were located at the right side of the RC frames. The specimens were named "NF" for non-retrofitted frame and "RF" for retrofitted RC frame. The tests were conducted using an artificial seismic wave with characteristics of Korean earthquake, having short period and a peak-ground acceleration (PGA) of 0.24g as shown in figure 4. The artificial wave was generated using the Korea Design Standard (KDS 41 17 00). For the shaking table test, the excitations with different scales starting from 0.07g to 0.24g were used as input ground motions in terms of friction of PGA, as shown in Table 2.

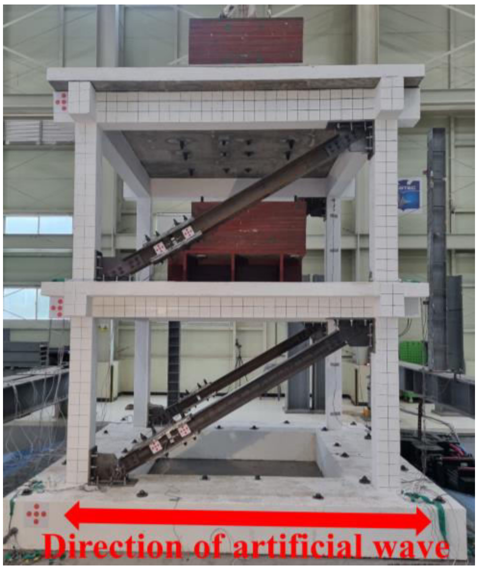


Figure 4: The RC frame with friction-damped diagonal brace. (RF)

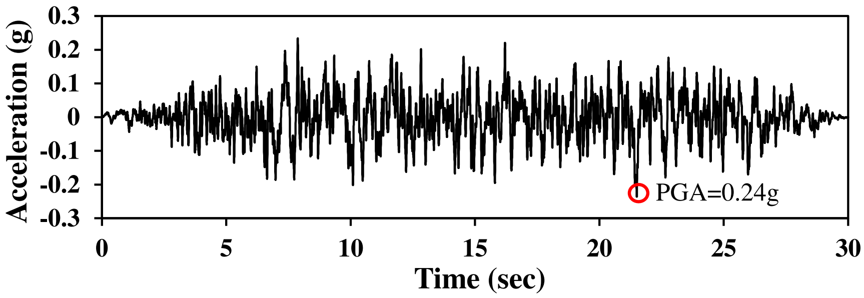


Figure 5: Generated artificial wave for shaking table test. (RF)

3.2 Shaking table test results

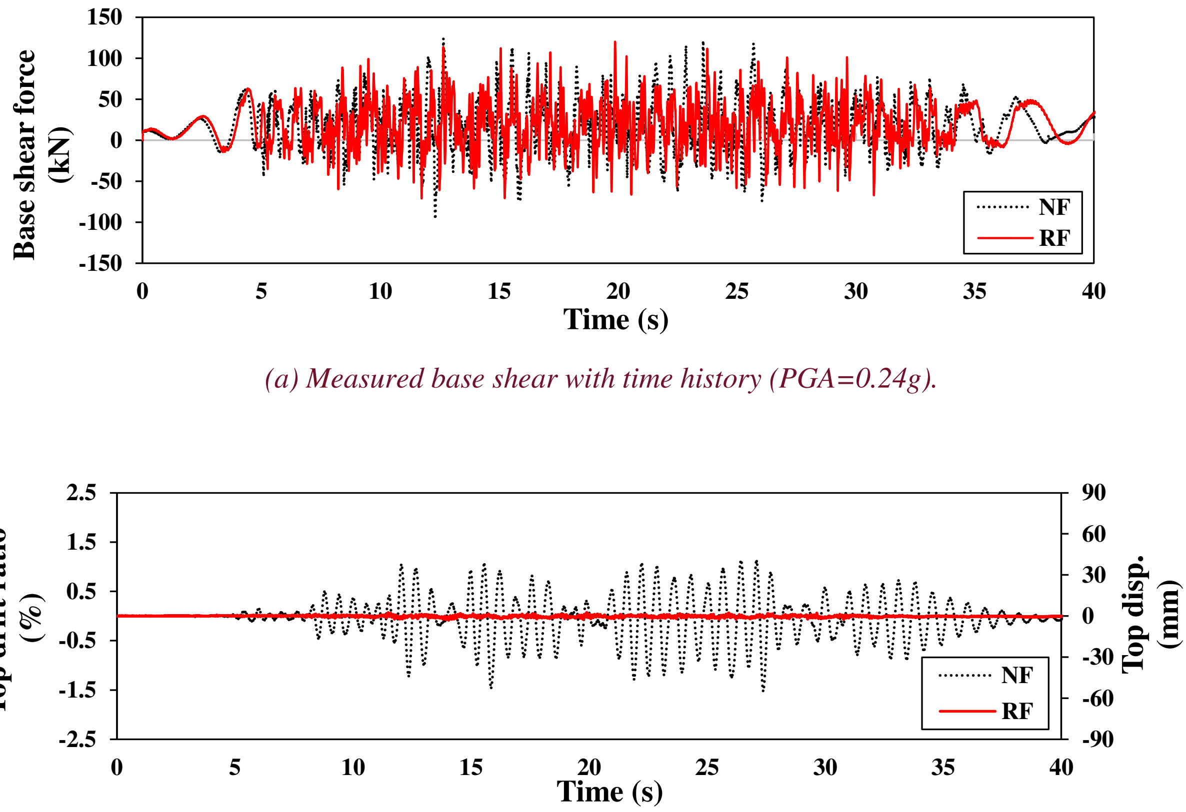
Figure 6 presents the measured the base shear and drift ratio of two frames with respect the time history corresponding to PGA of 0.24g. The drift ratio was determined by dividing the top roof displacement by the total height. The results show that, both the base shear and story drift in the retrofitted structure were significantly reduced compared to the bare frame which demonstrates the effectiveness of the proposed friction damper.

Table 2 summarises the shaking table test results of the RC frame with and without the friction damper corresponding to each scale of PGA. The maximum base shear and top drift ratio for NF specimen were 124.1kN and 1.52%, respectively. While for RF specimen, the two indexes were measured to be 120.3kN and 0.09%. Table also shows the measured axial force of brace, transformed from the measured based shear force. Until the excitation of PGA 0.17g, the axial brace load nearly similar to each other, but it started was increased when PGA 0.24g.

Table 2: Summary of the shaking table test results.

Specimen	PGA scale (g)	Base shear (kN)	Drift ratio (%)	Measured axial brace load (kN)

NF	0.07	68.1	0.19	-
	0.12	80.3	0.43	
	0.17	107.7	0.89	
	0.24	124.1	1.52	
RF	0.07	84.6	0.04	48.9
	0.12	95.2	0.05	54.9
	0.17	92.3	0.07	53.3
	0.24	120.3	0.09	69.5



(a) Measured base shear with time history (PGA=0.24g).

(b) Drift ratio with respect to time history (PGA=0.24g).

Figure 6: Dynamic responses for the RC frame by shaking table test.

4 CONCLUSION

In this paper, the friction damper was proposed and shaking table test was performed to investigate the dynamic responses of non-seismic RC frame with the brace. The test results showed that the base shear was not increased but the top drift ratios were reduced by 94.2%. The shaking table test results show that the proposed friction damper improved dynamic responses with reduced inter-story and residual drift ratios. The friction damping was in dissipating earthquake-induced energy and reduced the bases shear and drift demands.

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