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Shaking Table Tests of a Novel Three-Story Re-Centering Steel Braced Frame with Sliding Slab for Earthquake Force Reduction

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ABSTRACT

Reducing earthquake force and residual deformation on the frame structure can enhance its seismic performance during ground motions. This study explores a novel system that uses a self-centering brace to provide the re-centering capability of the frame and a sliding slab to reduce the system's acceleration. The floors are allowed to slide with respect to the frame, while various horizontal energy dissipating devices are used to enhance the seismic response. A self-centering disc-spring device is added to re-center the slab after sliding in Phase 1. In addition to the spring device, a friction device in Phase 2 or a steel-only sandwiched buckling-restrained brace in Phase 3 is incorporated. The floor is "rigidly" connected to the frame in Phase 4, simulating a typical frame. Four phases, comprising 32 shaking table tests, were conducted on the specimen. Phase 1 tests demonstrated that the self-centering brace and horizontal disc-spring device re-center both the frame and sliding slab at the maximum-considered earthquake level. Compared to Phase 4, sliding slab caused a roof drift reduction of 23% and 18%, and a base shear reduction of 15% and 5%, in Phases 2 and 3, respectively.

Introduction

Slab in a conventional steel structure is rigidly connected to the lateral force-resisting system (LFRS) using shear studs, and no relative movement between the slab and the frame is expected during earthquakes. This research explores the potential of a sliding slab system in a re-centering steel braced frame. The combination of the sliding slab and self-centering brace aims to reduce the floor acceleration (i.e., inertial force) and minimize residual deformation of the frame during large earthquakes. A post-tensioned self-centering brace (SCB), developed based on the past research work [1], was adopted in this study to provide the re-centering capability of the steel LFRS under earthquake motion. A steel-only sandwiched buckling-restrained brace (SBRB) was also included for enhancing the energy dissipation of the frame [2, 3]. The slab was designed to

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decouple from the steel braced frame by using Teflon sheets at all precast concrete slab and steel beam interfaces to minimize friction during slab movement. Different energy dissipation devices were horizontally connected between the slab and the steel beam in the LFRS to limit the inertial force transferred to the LFRS.

A force-limiting connection between the gravity and LFRS has been investigated to a rigid connection [4, 5]. Zhang et al. [6] further validated the effectiveness of deformable connections through shaking table tests on a four-story reinforced concrete shear wall building. Paronesso and Lignos [7] incorporated sliding friction dampers and low-damping rubber bearings, showing significant reductions in floor accelerations and drifts in buildings with concentrically braced frames. By conducting shaking table tests and time history analyses of a three-story steel BRBF with sliding and rigidly-connected slabs, the effect of sliding slab on the floor acceleration and inertial force reduction was explored [8, 9]. The research was to evaluate the seismic performance of the re-centering steel braced frame with sliding slabs and energy dissipation devices used to connect the slab and the frame. Three different horizontal energy dissipation devices were used in this frame specimen in the first three test phases, including self-centering spring devices (SCSD) in Phase 1, friction devices (FD) in Phase 2, and horizontal all-steel sandwiched buckling-restrained braces (H-SBRB) in Phase 3. The “rigid” connection was provided between the slab and the frame in Phase 4 to study a typical braced frame in the same ground motion. The study highlights results of 32 shaking table tests and the effectiveness of slab sliding and self-centering brace in enhancing the seismic resilience of steel structures.

Re-Centering Steel Braced Frame with Sliding Slab and Energy Dissipation Device

The specimen is a full-scale, three-story re-centering braced frame and uni-directional shake table tests were conducted on the frame (Figure 1). This frame was designed according to a seismic zone III in Taipei, Taiwan [10]. The LFRS is a braced frame, consisting of stiffness-adjustable SCBs [1] at the bottom two stories and an all-steel SBRB [2, 3] at the third story with cross sections in Figure 1. Each story has a precast 15 cm-thick concrete slab and two concrete blocks. The total concrete weight is 340 kN, 369 kN, and 413 kN for the second floor, third floor and roof, respectively. All beams and columns in the LFRS are made of SN490B steel with a nominal yield stress of 325 MPa. Two SCBs are made of SN490B steel, and the SBRB is made of SN400 steel with a nominal yield stress of 235 MPa. Since no design guideline of the re-centering steel braced frame is specified in AISC 341-22 [11], all members in the LFRS were designed according to the BRBF provisions in AISC 341-22 and AISC 360-22 [12]. Table 1 lists dimensions of the beams and columns in the LFRS. The design and configuration of the gravity force-resisting system (GFRS) in Figure 1 followed the same scheme as in Chou et al. [8].

Four test phases were conducted on the frame specimen [13]. From Phase 1 to Phase 3, the precast slab was disconnected from all steel beams, and 2 mm-thick Teflon sheets were placed underneath the slab at all slab-to-beam interfaces to minimize friction force during the slab sliding. Additionally, horizontal devices were installed between the slab and the steel beam to mitigate the seismic response of the specimen. The horizontal devices were installed in pairs per slab, one on each side of the steel beam to avoid force eccentricity to the beam. In Phase 1, only a SCSD composed of two sets of disc spring stacks as shown in Figure 2(a) was used at each story as a horizontal device to provide the re-centering capability of the sliding slab. In Phase 2, a FD was added to the frame to provide the energy dissipation in addition to the Teflon frictional energy, as shown in Figure 2(b). In this case, the slab can move relative to the beam with the capability of SCSD self-centering and additional FD energy dissipation. In Phase 3, the FD was replaced by the horizontal all-steel H-SBRB at each story, as shown in Figure 2(c). In Phase 4, all horizontal devices were replaced by a high-strength and high-stiffness structural tee member to simulate a rigidly-connected floor in a typical steel

Shaking Table Test Results

Shaking table tests were conducted at the Tainan laboratory, National Center for Research on Earthquake Engineering (NCREE). The selected ground motion was obtained from the September 18, 2022, Guanshan and Chihshang Earthquake, recorded in East-West direction at National Yuli Senior High School (Station code

EYUL), close to a collapsed building [14]. A total of 32 tests in Phases 1-4 were conducted on the frame with the earthquake intensity ranging from 0.06×DBE to 1.9×MCE level, where the DBE and MCE represent the design-based earthquake and maximum considered earthquake levels in seismic design.

Table 1 Dimensions of Beams and Columns

Element	Frame	Section
Column	LFRS (1st-3rd story)	NC: box 235×235×8 (0.9)
		SC: box 235×235×8 (0.8)
	GFRS (1st-3rd story)	HC: H400×200×8×12
Beam	LFRS (2FL-RFL)	B1: H350×175×7×11 (0.7, 1.0, 1.0)
	GFRS (2FL-RFL)	B2: H400×200×8×12
		B3: H200×100×5.5×8

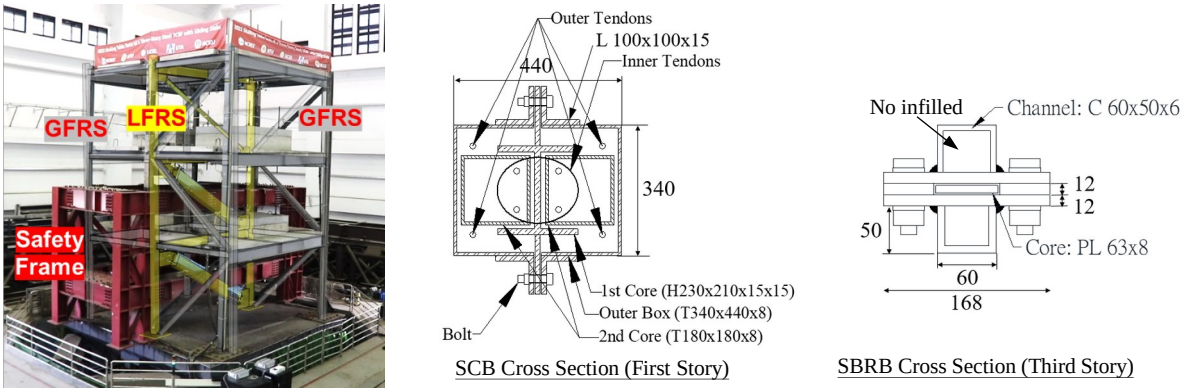
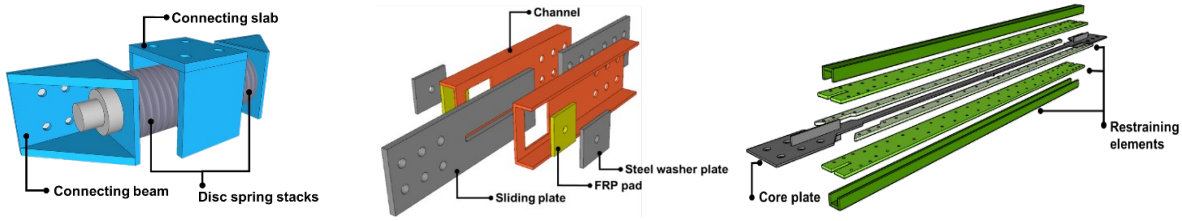


Figure 1 Three-Story Re-centering Steel Frame with Diagonal Braces (unit: mm)



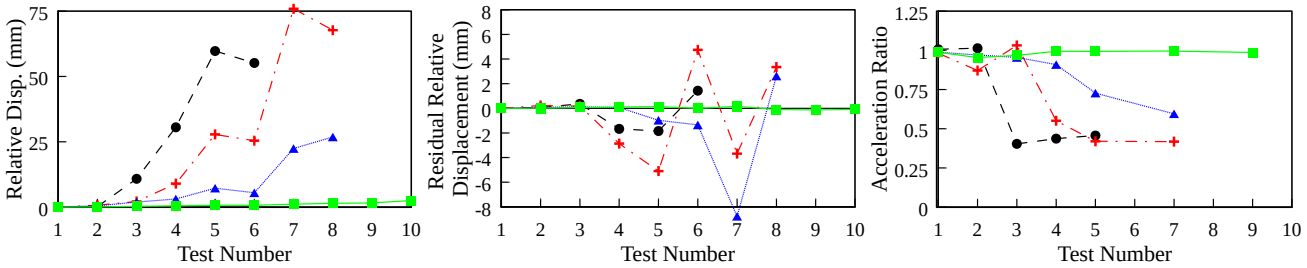
(a) SCSD (b) FD (c) H-SBRB

Figure 2 Horizontal Devices to Connect the Slab and the LFRS

Figure 3(a) shows the peak roof relative displacement of the slab in each test. The slab was activated to slide in Test 3, Phase 1, with a peak relative displacement of 11 mm. When the energy dissipating device was installed with the SCSD in Phases 2 and 3, the slab sliding was activated in Test 4 (DBE level) with a peak relative displacement of 9 and 3 mm in Phases 2 and 3, respectively. At the MCE level (Test 5), the maximum roof relative displacement was 60 mm in Phase 1, much larger than 28 and 7 mm in Phases 2 and 3. Therefore, the addition of energy dissipation devices, such as the FD or H-SBRB, significantly reduce the slab sliding. The slab relative displacement is further decreased for the frame specimen with H-SBRB than with FD due to the post-yield stiffness of H-SBRB, unlike FD, in the hysteretic response [13]. In Phases 2 and 3, the combined resistance of the H-SBRB (or FD) with SCSDs is larger than that of the SCSDs alone in Phase 1, causing more forces to be transferred to the frame and resulting in a larger drift. Figure 3(b) shows the roof residual relative displacement of the slab after each test. No residual displacement of the slab is observed throughout tests in Phase 4. When the slab is connected to the beam with only SCSD in Phase 1 tests, the maximum residual relative displacement of the slab is 2 mm after sliding 60 mm in Tests 5 or 6 (MCE level), demonstrating the

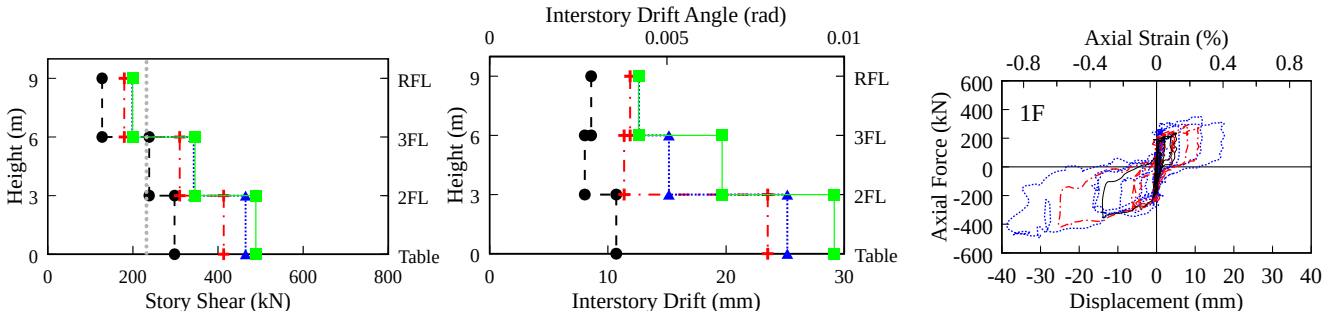
re-centering capability of the slab with SCSDs. Figure 3(c) shows the slab acceleration normalized with respect to the frame acceleration at the roof. As expected, the acceleration ratio in Phase 4 is about a value of 1.0 in all tests. In Phase 1, the slab acceleration is about 0.5 times the frame acceleration when the slab sliding is activated. In Phases 2 and 3, the acceleration ratio decreases from Test 4 with the increase of slab sliding; a larger relative displacement of the slab in Phase 2 than in Phase 3 results in a larger acceleration reduction. In Test 7 (1.4-1.7 times MCE level), the acceleration ratio is 0.4 and 0.6 in Phases 2 and 3, respectively.

Figure 4(a) shows the story shear distribution along the frame height in Test 5 (MCE level), computed based on the measured acceleration and the floor and frame weight. The shear at the first story was reduced by 39%, 15% and 5% in Phases 1, 2 and 3, when compared to Phase 4 test result. Figure 4(b) shows the interstory drift of the frame, where the maximum interstory drift was observed at the first story in all phases. The frame in Phase 1 showed the lowest interstory drift compared to that in Phases 2-4. The peak interstory drift at the first story was reduced by 63%, 19%, and 14% in Phases 1, 2 and 3, respectively, when compared to Phase 4 test result in Test 5 (MCE level). Figure 4(c) shows the hysteretic responses of the first-story SCB in Tests 5, 7 and 9 (Phase 4). The SCB shows the expected flag-shaped hysteretic behavior up to Test 9 (1.9×MCE), which minimized the frame residual drift at the end of each test. No damage of the frame, including the beam, column, or diagonal brace (SCB and SBRB), or horizontal energy dissipation devices was observed after 32 tests.



(a) Peak relative displacement (b) Residual relative displacement (c) Slab-to-Frame Acceleration

Figure 3 Peak Roof Slab Relative Displacement, Residual Displacement, and Acceleration Reduction



(a) Story Shear (Test 5, MCE level) (b) Interstory Drift (Test 5, MCE level) (c) SCB Response (Phase 4)

Figure 4 Story Shear, Interstory Drift, and SCB Response

Conclusions

The research aimed to evaluate the effect of sliding slab on a three-story, steel re-centering braced frame in shaking table tests. A significant reduction in the slab acceleration was clearly observed in Phases 1, 2, and 3 tests, when compared to Phase 4 test with a rigidly connected slab to the frame, started at DBE level due to the slab movement (Figure 3). More floor acceleration was reduced at MCE level (Test 5) or higher earthquake intensity levels. This led to a reduction of base shear and frame interstory drift in Phases 2 and 3 tests (Figure 4); the SCBs re-center the frame in Phase 4 tests up to 1.9×MCE level. The strategy, incorporating a sliding slab with force-limiting devices, reduces floor acceleration, story shear, and interstory drift of the frame,

thereby limiting damage to nonstructural components and supporting the objective of achieving functional recovery after a major earthquake.

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