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Seismic-Resilient Steel Frame System Inspired by Ancient Timber Shaka Pagoda

Hong-Tai Zhang[1,2], Zuo-Shuai Sun[1,2], Yu-Ao Lin[1,2], and Si-Cheng Li[1,2], Ping Xiang[2], and Liang-Jiu Jia[1,2†]

[1]*State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China*
[2]*College of Civil Engineering, Tongji University, China*

Abstract Ancient timber structures represented by the Shaka Pagoda can maintain low damage after multiple strong earthquakes, which is credited to their unique seismic mitigation and rocking mechanism. Inspired by this fascinating phenomenon, an innovative steel multiple-rocking-column steel frame (MRCSF) system was proposed and investigated. It mainly consists of continuous beams, segmented columns and self-centering rocking friction connections. Self-centering forces are mainly provided by the gravity load. As a part of the RObust BUilding SysTem (ROBUST) collaborative China-New Zealand program, a series of full-scale shaking table tests were conducted to evaluate dynamic behaviors and seismic performance of the proposed MRCSF. Test results indicated that the proposed system presents excellent seismic resilience with negligible residual displacement and structural damage.

Keywords: ancient timber structures, multiple-rocking-column steel frame, shaking table test, low damage, resilient.

†Corresponding author:
Liang-Jiu Jia
E-mail:
lj_jia@tongji.edu.cn

1. Introduction

Rocking mechanisms allow structures or their members to uplift and pivot, effectively decoupling them from ground motions during earthquakes, thereby achieving low damage or concentrating damage on easily replaceable components. Coincidentally, the concept of multiple rocking in modern research has been employed thousands of years ago to Greek temples (Mouzakis et al. 2002) and ancient timber structures (Fang et al. 2001 and Wu et al. 2020). Ancient timber structures, such as the Shaka Pagoda in China, have withstood many strong earthquakes without collapsing, demonstrating their unique and superior seismic performance (Sha et al. 2021). In ancient timber structures, columns are simply supported by stone bases and are connected with beams by mortise-tenon connections (Sun-Mao in Chinese) (Sha et al. 2021) and Dou-Gong connections (Wu et al. 2020). The above connection details enable ancient timber pagodas to achieve superior seismic performance through column rocking, column base sliding, column uplift, and friction among members during earthquakes (Suzuki et al. 2006 and Sun et al. 2022). Meanwhile, self-weight functions as the restoring force, leading to excellent self-centering ability of timber pagodas, which coincides with the concept of rocking.

Inspired by the multiple rocking phenomena of ancient timber pagodas, the authors proposed a multiple-rocking-column steel frame (MRCSF) system (Xiang et al. 2022). It mainly consists of continuous beams, segmented columns and self-centering rocking friction connections. As a part of the RObust BUilding SysTem (ROBUST) collaborative China-New Zealand program, a series of full-scale shaking table tests were conducted to evaluate dynamic behaviors and seismic performance of the proposed MRCSF. Test results indicate that the proposed system presents excellent seismic resilience with negligible residual displacement and structural damage.

2. Seismic Resilience in Ancient Timber Pogada

The Shaka (Yingxian) Pagoda, as shown in Fig. 1(a), was built in 1056 A.D. with a height of 67.31 m and a base diameter of 30.27 m, which has 5 visible stories and 4 invisible ones. A 1:3.4 scaled typical timber frame was designed based on details of the Shaka Pagoda and tested. As shown in Fig. 1(b), a typical timber frame in the multi-story pagoda includes a column-frame layer and a paving layer, in which the column-frame layer includes 2 forked columns, a main Lan-e and a Pupai-Fang, the paving layer includes Dou-Gong brackets shown in Fig. 1(c) and multiple Zhutou-Fangs.

Quasi-static tests were conducted on this timber frame with forked columns, subjected to 3 varying axial ratios as shown in Fig. 2. During the initial loading as shown in

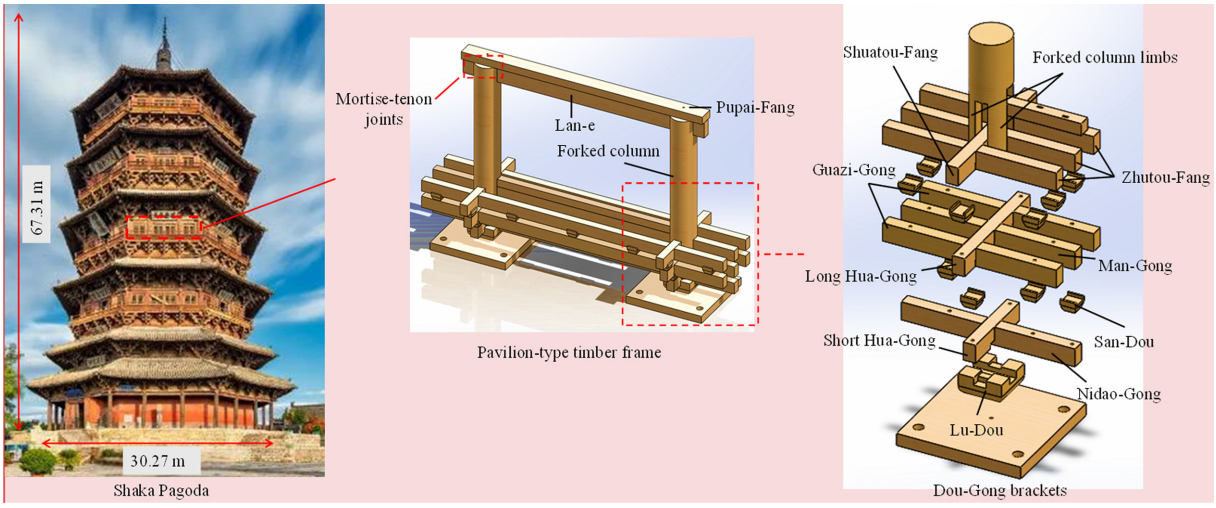


Figure 1. Composition of pavilion-type timber frame in Shaka Pagoda.

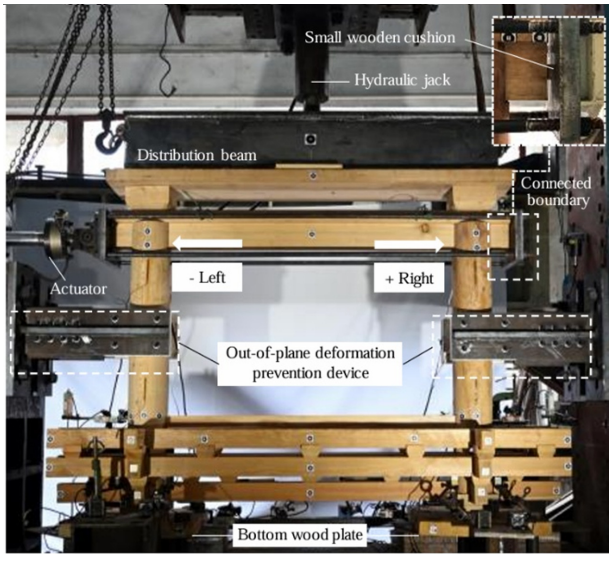


Figure 2. Test setup.

Fig. 2, the specimen was loaded from the inter-story drift of 1/2400 to 1/600, following by cyclic loading to 0.075Δ, 0.1Δ, 0.2Δ, 0.3Δ, 0.5Δ, 0.6Δ, and 1.0Δ.

During the loading process, similar deformation behaviors without significant damage of the 3 test cases were observed before the inter-story drift of 1/30, and compression plastic deformation as well as bending deformation of the components were the major deformation modes. A four-stage deformation process of the forked column limb was proposed as shown in Fig. 3. The initial state is that the bottom fork column limb is not in contact with the bottom Lu-Dou, and the horizontal displacement of the bottom forked column limbs is close to 0. As the inter-story drift achieved 1/150, the bottom of forked column limb is in contact with the bottom Lu-Dou. When loaded to an inter-story drift of 1/75, local compressive plastic deformation at the Lu-Dou occurred, and plastic deformation increases with an increasing inter-story drift, which generates negative horizontal displacement during

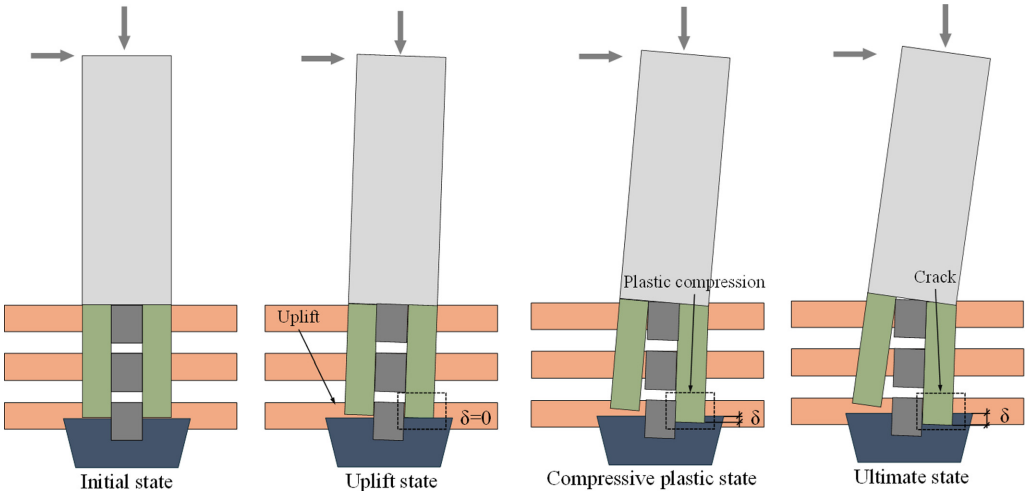


Figure 3. Deformation process of forked column limb.

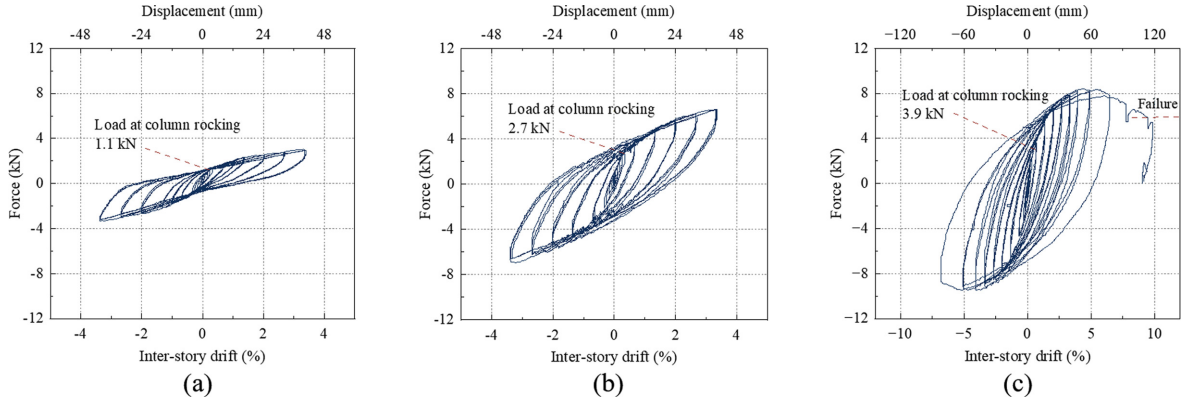


Figure 4. Hysteretic curves: (a) axial ratio of 0.006, (b) axial ratio of 0.023, (c) axial ratio of 0.034.

unloading with the inter-story drift exceeding 1/75. When loaded to an inter-story drift of 1/30, tension cracks perpendicular to grain at the free end of Lu-Dou occurs due to local compression of Lu-Dou from forked column limb.

As shown in Fig. 4, hysteretic curves of the cases with axial ratios of 0.023 and 0.034 exhibit relatively plump shapes, whereas that of an axial ratio of 0.006 shows slight pinching. This is due to reduction in the gap among components of the timber frame as the axial ratio increases. Moreover, due to strong correlation between the resisting force of the rocking timber column and axial loads, increasing axial loads also leads to a higher lateral force. In fact, the column has high compressive strength parallel to the grain, and no significant damage was observed in the 3 tests before an inter-story drift of 1/30. In summary, apparent damage and cracking of components started when the inter-story drift reached 1/20, and a decreasing trend in the bearing capacity can be observed from the hysteretic curve. Figure 4: Hysteretic curves: (a) axial ratio of 0.006, (b) axial ratio of 0.023, (c) axial ratio of 0.034.

3. Seismic Resilient Multiple-rocking-column Steel Frame (MRCSF)

The proposed MRCSF, mainly consisting of continuous beams, segmented columns and self-centering rocking friction connections, behaves as a rigidly connected frame under frequent earthquakes (FE). Under strong earthquakes, the column endplates of each story can rock to achieve multiple rocking along the structural height. Asymmetric friction connections (AFCs) were employed at the beam-column and column base joints to dissipate energy as shown in Fig. 5. It is rigid-plasticity hysteresis with a secondary stiffness. Energy dissipation is contributed by the friction connection at the column web with a rectangular hysteresis. Area of the hysteresis loop represents the capacity of energy dissipation. The hysteresis curve of the proposed rocking connection is obtained as shown in Fig. 5. Similar to the ancient timber pagoda, the columns are segmented and structural control can be achieved through

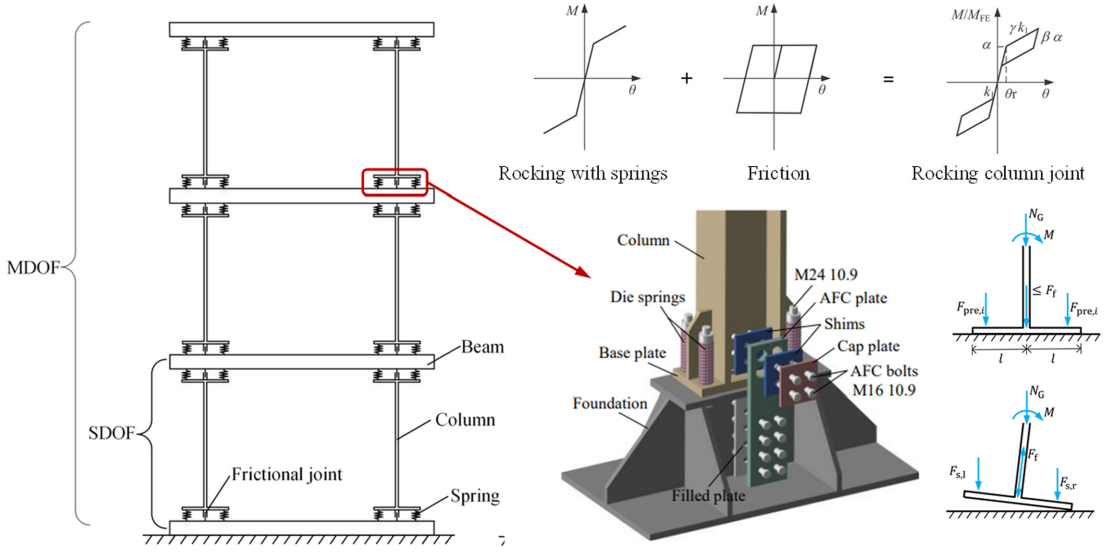


Figure 5. Schematic illustration of the MRCSF and rocking column joint.

column rocking, joint rotation and friction.

Here, the axial force causes a negative post-rocking *M-θ* stiffness while the springs provide an increasing restoring moment and contribute to the positive post-rocking *M-θ* stiffness. Based on previous studies by authors (Zhang et al.), the post-rocking stiffness of the rocking column can be changed by replacing the springs arranged at the connection if the axial force and member dimensions are determined.

4. Full-scale Shaking Table Tests on MRCSF

Shaking table tests of a full-scale three-story seismic resilient steel framed building system were conducted as part of the ROBUST collaborative China-New Zealand program. The purpose of this program was to explore several low damage structural systems through shaking table tests of a full-scale three-story steel structure (MacRae et al. 2020, Dhakal et al. 2020, and Yan et al. 2020). The steel frame building with 9 different interchangeable seismic resisting configurations was designed to dissipate energy by friction, including 8 different structural systems and 1 typical building non-skeletal elements (NSEs) system. The three-story MRCSF building with one gravity frame and 2 free-rocking frames in the loading direction for shaking table tests is shown in Fig. 6. The building design is based on existing design standards with considering the capacity of the shaking table of the International Joint Research Laboratory of Earthquake Engineering (ILEE) facilities, Tongji University, Shanghai Chin. The prototype building is assumed to be a typical office building located in Beijing, China. The structure has 2 bays in the longitudinal direction and 1 bay in the transverse direction with a plan view size of 7.25 m × 4.75 m. The total height is 9 m with an inter-story height of 3 m. The composite flooring system with trapezoidal steel deck and concrete topping is used and considered as the permanent load on the structure. The slab depth is 150 mm. Additional mass blocks were used to simulate the live load in different stories which imposed a uniform load of 3.5 kPa on the first and second stories and 4.7 kPa on the third story. The loading direction was designed along the transverse direction.

The typical ground motion Imperial Valley, El-Centro 1940, Array #9 station was selected. The level of excitations was designed to increase gradually, including frequent earthquake (FE) level, design earthquake (DE) level, and rare earthquake (RE) level. Before and after each set of earthquakes, the FSRS was subjected to low-amplitude white-noise (WN) excitation with 0.05g PGA to test its dynamic characteristics and ensure instrumentation was fully functioning.

As shown in Fig. 7(a), the maximum inter-story drift ratio was in the first story under excitations below DE level. When the peak ground acceleration (PGA) was larger than 0.40g, the maximum inter-story drift ratio was in the second story. In general, the maximum inter-story drift was satisfied the limit value of the current Chinese seismic code, i.e., 2% under the RE level. The dynamic

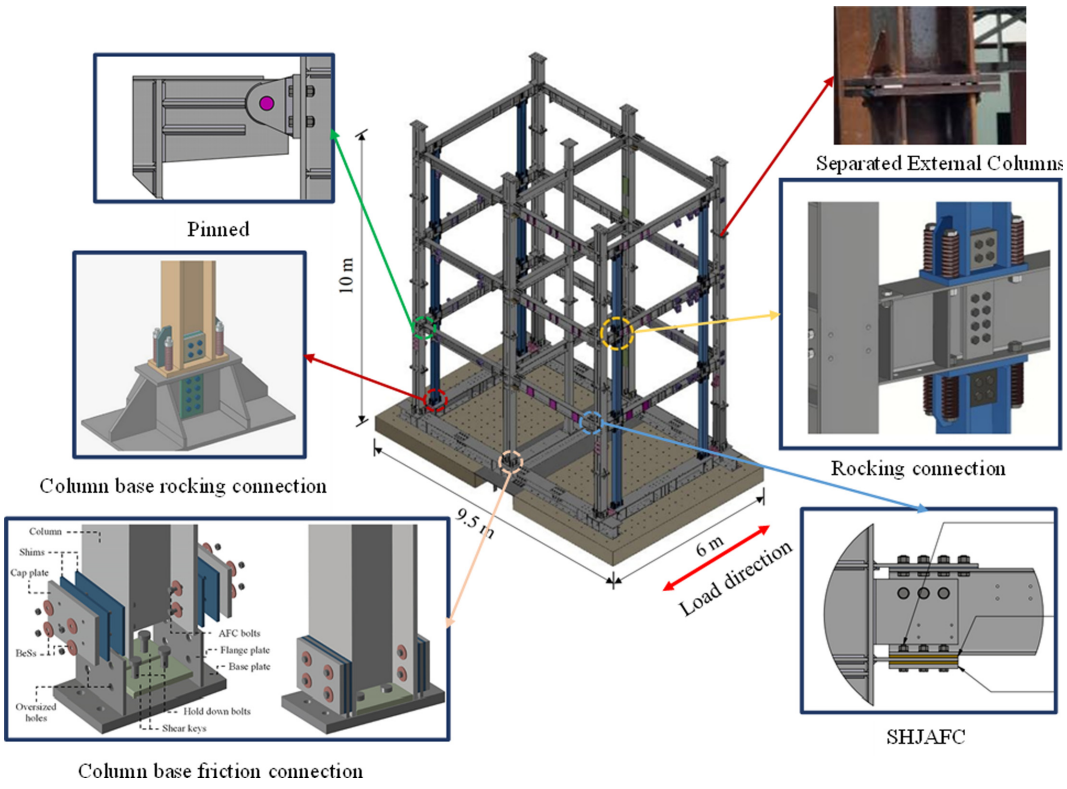


Figure 6. Schematic illustration of the MCRSF in the ROBUST program.

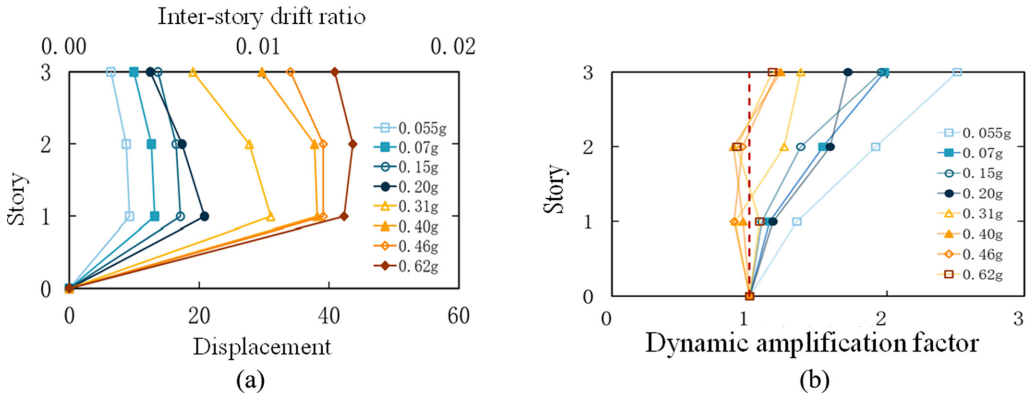


Figure 7. Horizontal response of the MRCSF: (a) maximum inter-story drift; (b) dynamic amplification factor.

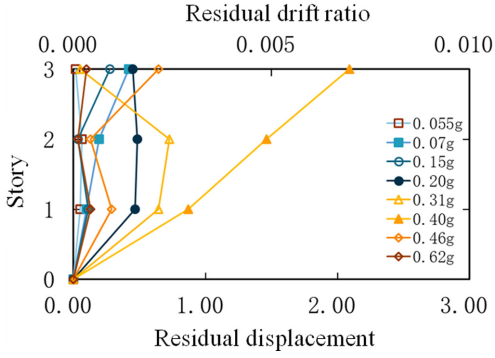


Figure 8. Maximum inter-story residual drift.

amplification factor, defined as the ratio of the horizontal peak floor acceleration (PFA_H) to that of the shaking table, was used to study the horizontal vibration control effect of the MRCSF. The dynamic amplification factor decreases with an increasing PGA as shown in Fig. 7(b). The multiple rocking effectively controls the horizontal acceleration, especially under strong earthquakes. Figure 7: Horizontal response of the MRCSF: (a) maximum inter-story drift; (b) dynamic amplification factor.

MRCSF shows good self-centering capability as shown in Fig. 8. In the beyond RE case, the inter-story residual drift is even smaller compared to the DE cases, i.e., the residual drift for the 0.62g case is smaller than that for the 0.40g case, which is close to the residual drift for the FE cases.

The inter-story hysteretic response of the MRCSF is given in Fig. 9. Before rocking, the MRCSF behaved as a linear structure as shown in Fig. 9(a), corresponding to the conventional fixed structure. When the MRSCF was subjected to an earthquake exceeding the DE level, 0.62g as shown in Fig. 9(b), the MRCSF exhibited a flag-shaped hysteretic curve.

5. Conclusions

Inspired by the multiple rocking phenomenon of ancient timber pagodas, a seismic resilient multiple-rocking-column steel frame (MRCSF) system was proposed and investigated experimentally. The main conclusion can be summarized as following:

1. Hysteretic curves of the timber frame with forked columns under different axial ratios are plump. No apparent damage is observed in the timber frame before an inter-story drift of 1/30. Through rotation

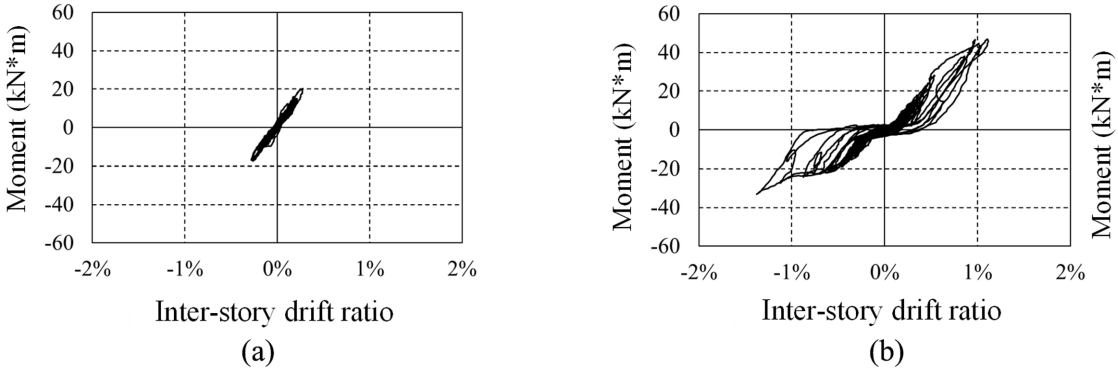


Figure 9. Inter-story hysteretic responses of the MRCSF: (a) PGA of 0.07g (before rocking); (b) PGA of 0.62g (after rocking)

and friction at the mortise-tenon joints, superior seismic resilience was achieved. With an increasing axial ratio, compressive plastic deformation of the bottom Lu-Dous and flexural stiffness of the forked column limbs increase significantly.

2. The proposed controlled multiple-rocking-column system frame (MRCSF) can achieve low damage while satisfying the drift limit of current Chinese seismic code, i.e., 2% under rare earthquakes. It also has good vibration mitigation performance along the horizontal direction, especially under strong earthquakes.
3. Gravity-dominated self-centering mechanism performs well in the full-scale shaking table tests, and the proposed steel system can achieve negligible residual drift after testing.

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