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Experimental investigation of tri-axial self-centering reinforced concrete frame structures through shaking table tests

Ye Cui [a,*], Xilin Lu [b], Chun Jiang [a]

[a] Research Institute of Structural Engineering & Disaster Reduction, Tongji University, Shanghai 200092, China
[b] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

This paper presents an experimental study on the seismic performance of a tri-axial self-centering reinforced concrete (RC) frame structure. In such a structure, the column-base joints were free to uplift, and the beam-column joints were relaxed to open. Post-tensioned (PT) strands passed through the RC beams and columns to provide re-centering capability. In order to accommodate the gap openings in beam-column joints, rubber pads were placed underneath the floor slabs to provide a smooth sliding motion between the RC beams and the slab. A 1/2.5-scale model of a tri-axial three-story self-centering RC frame structure was designed and tested on a shaking table under a series of earthquake excitations with increasing amplitudes. The results showed that the self-centering RC frame structure had desirable seismic performance with little damage even under extreme earthquakes. The reduction in natural frequencies were quite small after the extreme earthquakes, indicating that the structure had remained almost elastic. The test model showed a desirable tri-axial re-centering capability with negligible residual deformation. The sliding of the slabs was also measured throughout the tests, and the data indicated that the slabs re-centered to their original positions after the tests.

1. Introduction

Recent earthquake events have highlighted the limitations of traditional seismic lateral load resisting systems, which can experience significant damage and large residual deformation that is difficult and costly to repair. As a current state-of-the-art branch of structural design to resist seismic loads, self-centering structures can protect a structure by concentrating the majority of the structural damage in replaceable energy-dissipation devices, while eliminating or minimizing the residual deformation.

Previous studies have validated that post-tensioned (PT) reinforced concrete (RC) frames and shear walls have excellent seismic performance and self-centering capability [1–6]. Ricles et al. [7], Rojas et al. [8], Iyama et al. [9] and Vasdravellis et al. [10] proposed self-centering steel beam-column connections with angle steel or friction devices. The connections had initial stiffness similar to that of a typical rigid connection under minor earthquakes. In larger earthquakes, a gap formed in the beam-column interface, and the energy-dissipation device was then activated. The self-centering capability of the joint was provided by the incremental force in the PT strand due the gap opening. The design objectives of post-tensioned frame systems are outlined by Garlock et al. [11,12], and a step-by-step design procedure was provided.

Christopoulos et al. [13] and Kim et al. [14] conducted experimental and analytical studies on a type of post-tensioned energy dissipating connection for steel frames, which was verified to undergo large inelastic deformations without any damage to the beam or column and without residual drifts. Guo et al. [15] and Song et al. [16] conducted a series of experimental and numerical research investigations on the seismic performance of a self-centering steel moment-resisting frame with web friction devices; and the frame subassembly performed well and remained damage free.

Researches have validated that the seismic behavior of rocking structural systems with column uplift was better than that of fixed-base systems through shaking table tests and numerical analyses by Midorikawa et al. [17]. A simplified analytical model for rocking columns has been developed by Roh and Reinhorn [18–20]. Computational tools were created to simulate structural behaviors, and global nonlinear static response of rocking structures was examined through experiments. Lu et al. [21] carried out an experimental and computational study on the seismic performance of a 1/2-scale model of a two-story bi-axial self-centering RC frame, with self-centering capability in X and Z directions. Test results indicated that the designed RC frame had desirable seismic

* Corresponding author.
E-mail address: 2010_yecui@tongji.edu.cn (Y. Cui).

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performance and bi-axial self-centering capability. Chou and Chen [22–24] conducted a series of shaking table tests on a two-by-two bay one-story self-centering steel frame with a slab that accommodated frame expansion, which comprised one PT frame and two gravitational frames. These tests confirmed the self-centering response of the PT frame and explored failure of the beam compression toe. Garlock et al. [25] conducted nonlinear analyses of several floor diaphragm designs, and examined the influence that the floor diaphragm stiffness, strength, and configuration have on the seismic response of SC-MRFs.

It is worthwhile noting few studies have examined the seismic performance of tri-axial self-centering RC frames with slabs accommodating the frame expansion. Therefore, the knowledge on the behavior of the entire tri-axial self-centering RC frame structures is still quite limited. This study further investigated the seismic performance of tri-axial self-centering RC frame structures through the construction of a 1/2.5-scale 3-story tri-axial self-centering RC frame and its subsequent testing on a shaking table.

2. Experimental setup and procedure

2.1. Tri-axial self-centering structure system

The tri-axial self-centering structure system is composed of the following components: the column-base joints that are free to uplift, the beam-column joints that are relaxed to open, and PT strands that ensure the self-centering of the structure. The beam-column joints (*X* and *Y* directions of the structure) will re-center to their initial position by the force of PT strands after an earthquake, while the self-centering of the column-base joints (*Z* direction of the structure) is provided by gravity and the PT strands.

Fig. 1 shows the configuration of column-base joints. The columns were fastened in the base pits by two high strength PT strands with a diameter of 15.2 mm. The strands were cast in each column. The bottom ends of the strands were anchored in the base before casting, and the other ends were post-tensioned to the steel plates on the tops of the columns before testing. To prevent local failures of concrete when the frame rocked, steel plates were embedded in the base pits and the column ends were armored with steel boots. The longitudinal reinforcement was welded to the steel boots at the ends of the columns. The interfaces between the steel plates in the base and the steel boots at the ends of the columns were expected to be able to separate from each other to ensure possible uplift of the columns. To protect the concrete from damage when the frame rocked, the interspaces between the columns and the base were filled with rubber [21].

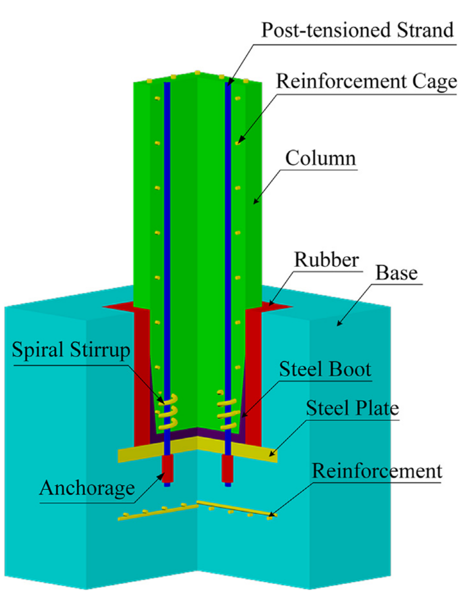

Fig. 1. Configuration of the column-base joints.

Fig. 2 presents the configuration of column-beam-slab joints. PT strands passed through the beams and were post-tensioned to the exterior columns. To prevent local failure of the concrete of the columns, steel plates were set at the ends of the beams, and columns were fitted with steel jackets. Top angle steel connections were used as energy dissipating devices after the joints opened. The shear resisting capability of these joints was increased due to the application of the brackets.

In the design phase, the self-centering of a beam-column or column-base joint can be checked by the moment contribution ratio, α, as follows:

$$\alpha = \frac{M_{pt} + M_N}{M_S} \geqslant 1.15 \qquad (1)$$

where M_{pt} is the flexural moment contributions of the PT strands, M_N is the flexural moment contributions of the axial force, and M_s is the flexural moment contributions of the non-prestressed components [26]. The non-prestressed components could be in many types. For example, angle steel, rubber blocks, and frictional dampers all can be considered as non-prestressed components.

The prestressed force in each strand are shown in Section 2.3. With this formula, the prestressed force in each strand can be checked.

When gaps open at the column-base and beam-column interfaces, the self-centering frame "expands", as shown, for a two-bay frame in Fig. 3 [11]. Obviously, the distance between the centerlines of the columns in the deformed configuration is larger than that in the original configuration. As a consequence, the concrete slabs will crack along the beams due to the gap opening of the self-centering joints, and will also restrain the connection gap opening.

To eliminate this restraint effect, modifications along the boundaries of the slabs were carried out to allow for gap opening. Fig. 4 shows a detailed illustration of the interface between the concrete slab and the self-centering frame that eliminates the restraining effect of slabs. Bolts were embedded in the beams to restrain the slabs. The diameter of the hole of the slabs is larger than the bolts, namely, there is a gap between the slab and the bolt, so that the slab can move with the expansion of the self-centering frame. To allow for the sliding of the slabs, rubber pads with a

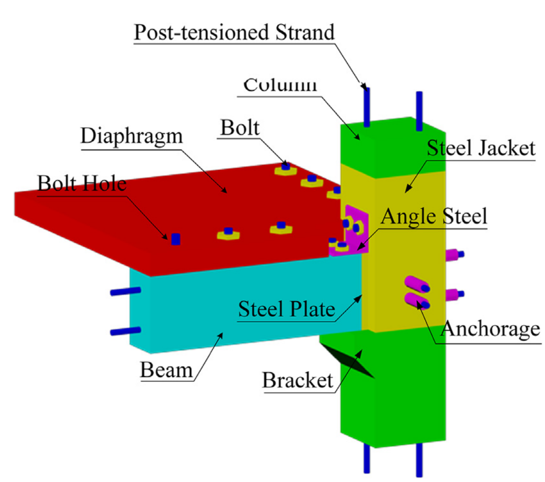

Fig. 2. Configuration of the column-beam-slab joints.