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INVESTIGATION OF SEISMIC PERFORMANCE OF TRI-AXIAL REINFORCED CONCRETE FRAMES WITH SELF-CENTERING CAPACITY

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Abstract

The goal of this study was to investigate the behavior of reinforced concrete frame structures with self-centering beam-column and column-base connections and to confirm the ability to model these systems with a state-of-the-art computer model that would be useful to engineers. To these ends, a three-story tri-axial reinforced concrete frame with self-centering capacity was designed and constructed for testing on a shake table. The beam-column and column-base joints of the self-centering frame are allowed to open at beam ends and uplift at column bases by releasing the constraints, while prestressed tendons are introduced to ensure the self-centering of the structure. The frame specimen was subjected to significant earthquakes during the tests. Test results indicate that the designed reinforced concrete frame has excellent seismic performance and self-centering capacity subjected to strong earthquakes with minor residual drifts in the frame, as designed. Analytical models of the entire frame with the beam-column connections and the column-base connections were constructed to study the seismic performance of the self-centering frames using OpenSEES, and a series of nonlinear time history analyses are carried out in this study. The results indicate that the self-centering technique is quite effective on reducing the residual deformation for the RC frame structure under strong earthquakes, which may therefore protect the main structure from being damaged.

Keywords: self-centering; reinforced concrete frame; seismic performance.

1. Introduction

Following the current design standard, conventional moment-resisting frames are designed to yield and expected to form plastic hinges with damage in beam-column joints and column-base joints, as shown in Fig. 1. This damage can result in significant post-earthquake residual drift and repair costs [1]. As a consequence, scientists and engineers have become increasingly interested in the post-earthquake performance of structures [2]. To prevent the damage and residual drift following an earthquake, post-earthquake resilient structures were developed, including self-centering structures, member-replaceable structures, and rocking structures [3].

The self-centering structures generally include three components: (1) connections that will remain elastic and develop gap opening-closing behavior at the interfaces between the members; (2) prestressed tendons that provide self-centering forces to close the gap; and (3) replaceable energy-dissipation devices that dissipate input energy. Beam-column connections were developed and studied by Ricles et al. [4], Christopoulos et al. [5], Rojas et al. [6], and Kim and Christopoulos [7]. Column-base connections were studied by Roh and Reinhorn [8] and Spieth et al. [9]. Midorikawa et al. [10] carried out a series of three-dimensional shaking table tests on seismic behavior of steel rocking frames. Lu et al. [11] have done a shaking table test and numerical study on bi-axial self-centering reinforced concrete frames. The tested frame had the self-centering capability in both the *X* and *Z* directions. It should be noted that a building structure is normally subjected to tri-directional excitations under an earthquake. Few researches on the tri-axial self-centering frame system have been generated by far, especially for the tri-axial self-centering reinforced concrete frames with slabs accommodating frame expansion. Therefore, a tri-axial self-centering reinforced concrete frames with the self-centering capability in the *X*, *Y* and *Z* directions and with slabs accommodating frame expansion was constructed and tested on a shaking table and modeled using OpenSEES.

(a) (b)

Fig. 1 – Damage of concrete frames after Wenchuan earthquake in 2008

This paper presents an experimental and numerical research on the behavior of reinforced concrete frame structures with self-centering beam-column and column-base connections. Comparisons were made to confirm the ability to model these systems with a state-of-the-art computer model that would be useful to practicing engineers. To these ends, a 1/2.5-scale three-story tri-axial reinforced concrete frame with self-centering capacity was designed and constructed for testing on a shaking table. Analytical models of the entire frame with the beam-column connections and the column-base connections were constructed to study the seismic performance of the self-centering frames using OpenSEES, and a series of nonlinear time history analyses are involved in this study.

2. Shaking table test

2.1 Test model

To study the seismic performance of tri-axial self-centering RC frames, a 1/2.5 scale model of a three-story tri-axial self-centering RC frame was designed and tested on the shaking table in State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University.

The plan dimensions were 2.8 m × 2.4 m and the story height was 1.2 m. Fig. 2(a) shows the elevation of the test model, while Fig. 2(b) shows the plan of the test model. The total height of the test model was 4.5 m while the total weight was 12.6 t. Fine aggregate concrete C40 was selected. HRB400 and HPB300 were selected for the longitudinal bars and stirrups, respectively. Prestressed tendons Φ15.2 were used. The characteristic strength of the angle steel was 345MPa. Fig. 2(c) shows a photo of the test model. Table 1 shows the similitude scale factors of the test model.

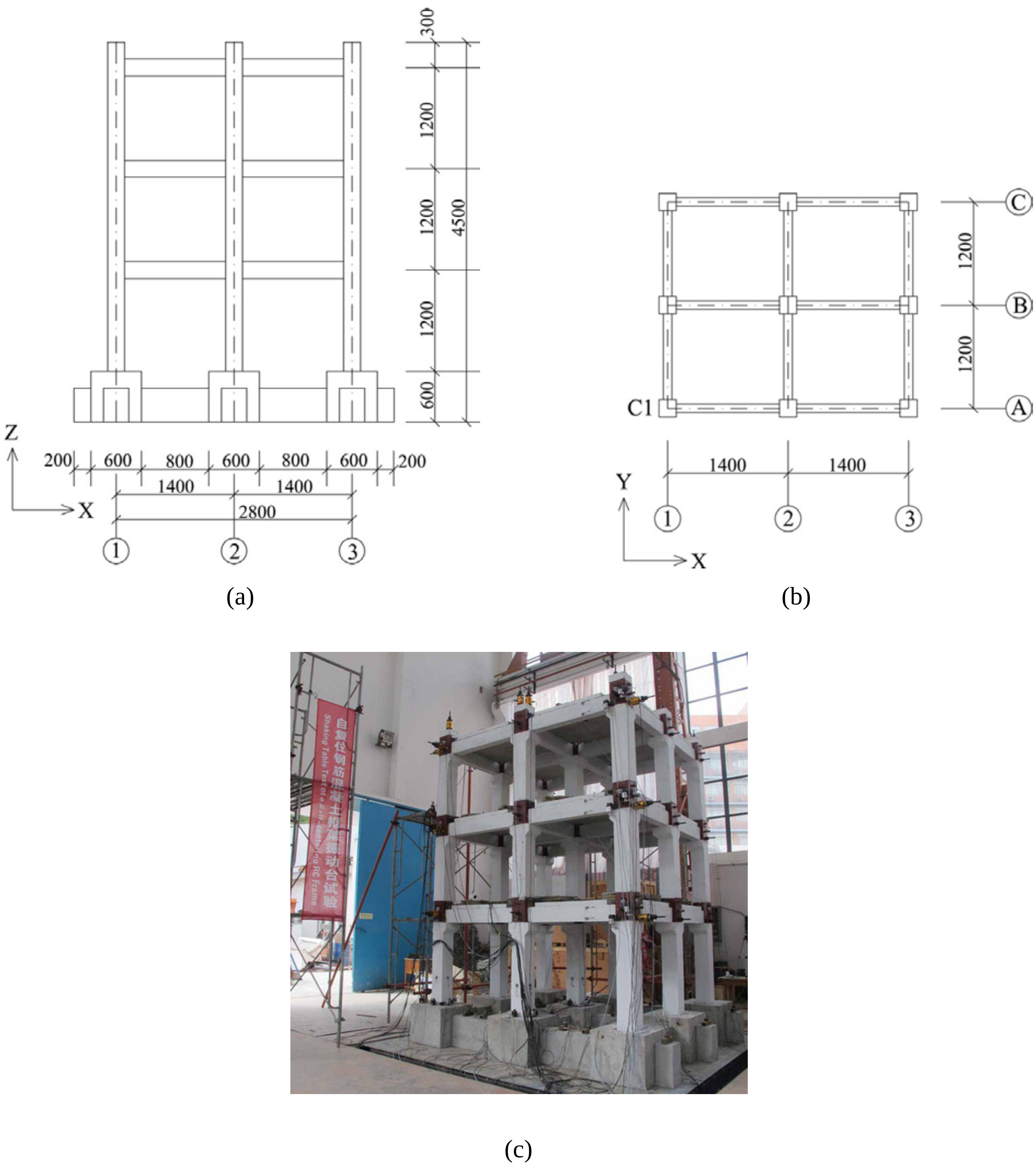


Fig. 2 – Test model: (a) elevation; (b) plan; (c) photo

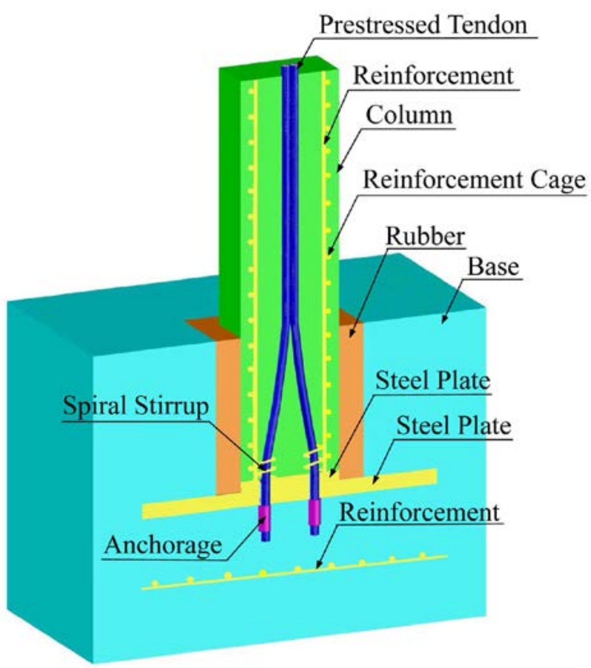
Table 1 –Similitude scale factors

S_ε	S_σ	S_E	S_l	S_ρ	S_a	S_t	S_m	S_K	S_F
Strain	Stress	Young's modulus	Length	Density	Acceleration	Time	Mass	Rigidity	Force
1.000	1.000	1.000	0.400	1.250	2.000	0.447	0.080	0.400	0.160

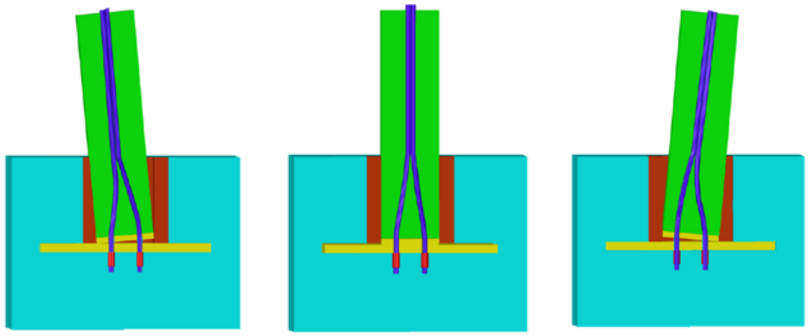
2.2 Self-centering connections

Fig. 3(a) shows the details of the column-base connection. This kind of self-centering column-base connection develops gap opening behavior at the beam-column interfaces, which means the column will uplift under earthquake loading. And after the earthquake excitation, the prestressed force closes the gap, and the connection will self-center to its initial position. To prevent local failures of concrete, steel plates were cast at the end of the columns and in the base, respectively. Rubber was placed in between column and base. Fig. 3(b) shows the uplifting mechanism of the connections under earthquake loading.

Fig. 4(a) shows the details of the column-beam connection. This type of self-centering beam-column connection develops gap opening behavior at the beam-column interfaces in the beams and uses prestressed tendons to precompress the beams to the columns and to close the gaps that develop under earthquake loading, returning the frame to its initial position after the earthquake excitation. Energy is dissipated by angle steel in the beam-column connection regions. To allow for the gap opening behavior at the beam-column interfaces, the slabs were not cast together with the beams but restrained by bolts embedded in the beams. The slab can slide smoothly and re-center to its initial position.

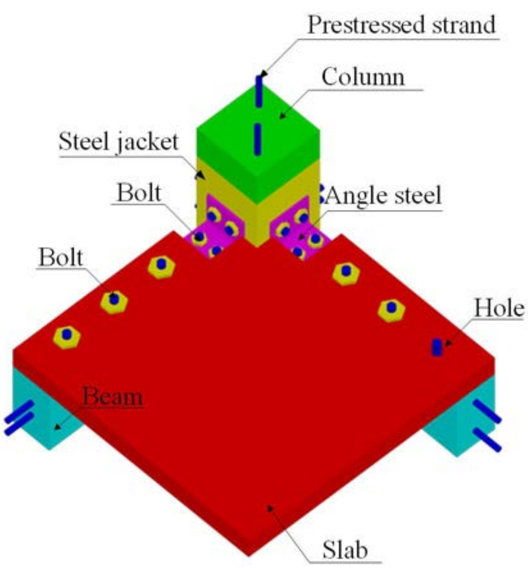


(a)

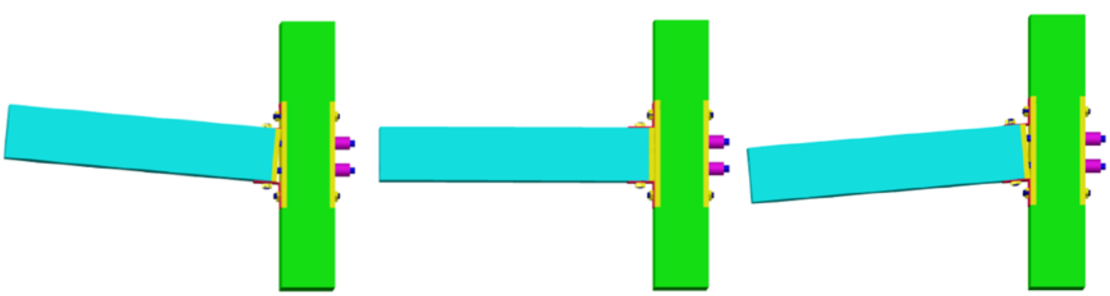


(b)

Fig. 3 – Column-base connection: (a) detail; (b) uplifting



(a)



(b)

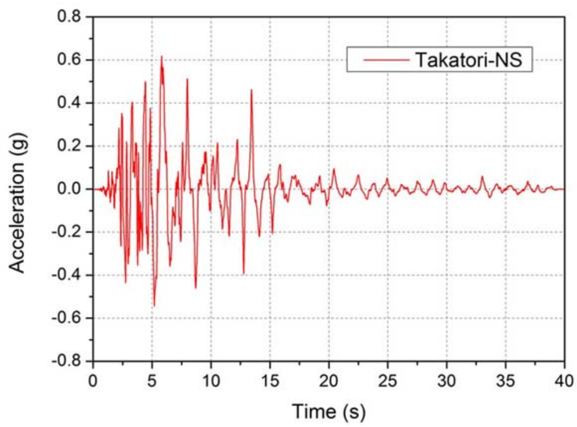
Fig. 4 – Column-beam connection: (a) detail; (b) opening

2.3 Seismic input and instrumentation

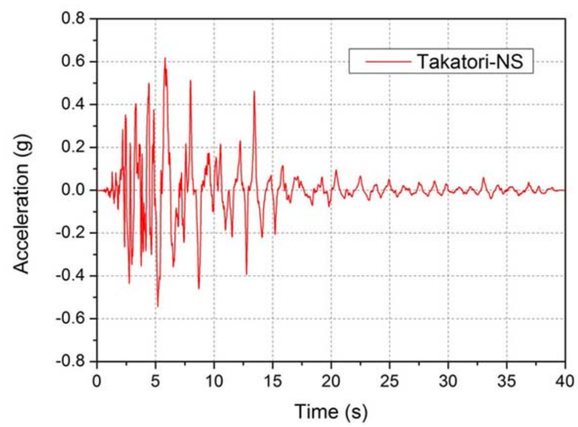
Earthquake excitations were input to the shaking table in the test. Takatori earthquake record (1995 Kobe earthquake, Takatori Station) were selected as the input ground motion. The input excitations were loaded at increments of peak ground acceleration (PGA) by 0.1-0.2g starting from 0.1g. The maximum level test was the

Takatori 1.60g test. Fig. 5(a) and (b) show the time history of Takatori wave (the NS and EW directions, respectively). Fig. 5(c) shows the response spectrum of Takatori wave.

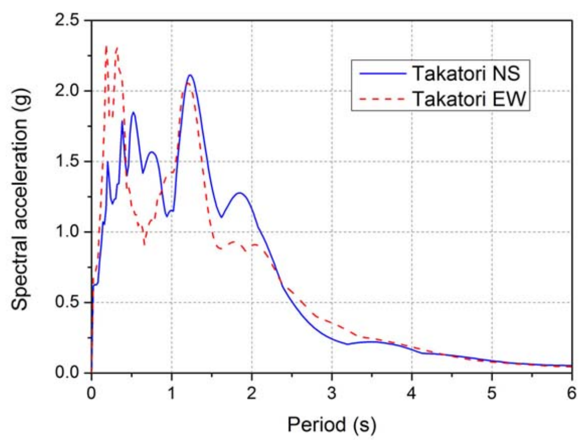
Sensors were used to record the response of the model: (a) accelerometers, measuring the horizontal and vertical acceleration at each floor; (b) LVDTs, measuring the displacement of each floor of the model, the sliding of slabs and the joint response to assess the opening and uplift of the joints; (c) load cells, measuring the axial force of the prestressed tendons in the beams and columns; (d) strain gauges, measuring the strain of the reinforcement and angle steel.



(a)



(b)



(c)

Fig. 5 – Takatori wave: (a) time history of NS direction; (b) time history of EW direction; (c) response spectrum

3. Results and discussion

3.1 Dynamic characteristics

Fig. 6 shows the change in the first and second frequencies obtained from each white noise test. The initial first frequency was 8.13 Hz. After the tests, the first frequency fell to 6.13 Hz. No crack was observed on columns and beams.

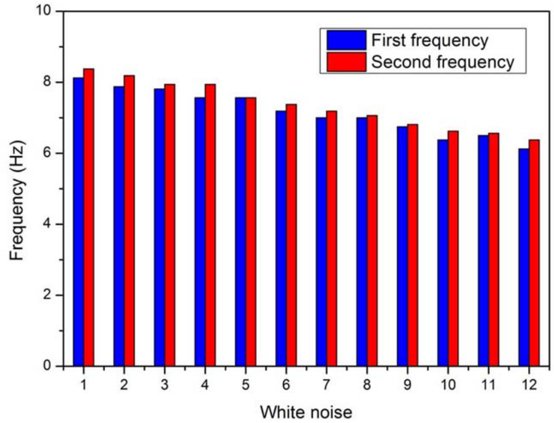


Fig. 6 – Change in frequency

3.2 Global response

Fig. 7 shows the change in maximum displacement with or without angle steel under Takatori earthquake excitations at each floor of the test frame. The maximum displacement obtained from the test was 32.023 mm under the Takatori 1.6g test. The displacement with angle steel was smaller than without angle steel under same excitations.

The designed reinforced concrete frame has excellent seismic performance and self-centering capacity subjected to earthquakes, and minor residual drifts in the frame. The amplification factor of acceleration decreases slightly after the basis earthquake, probably due to the gap-opening of the self-centering connections. The structure kept in good condition without structural damage throughout the test.

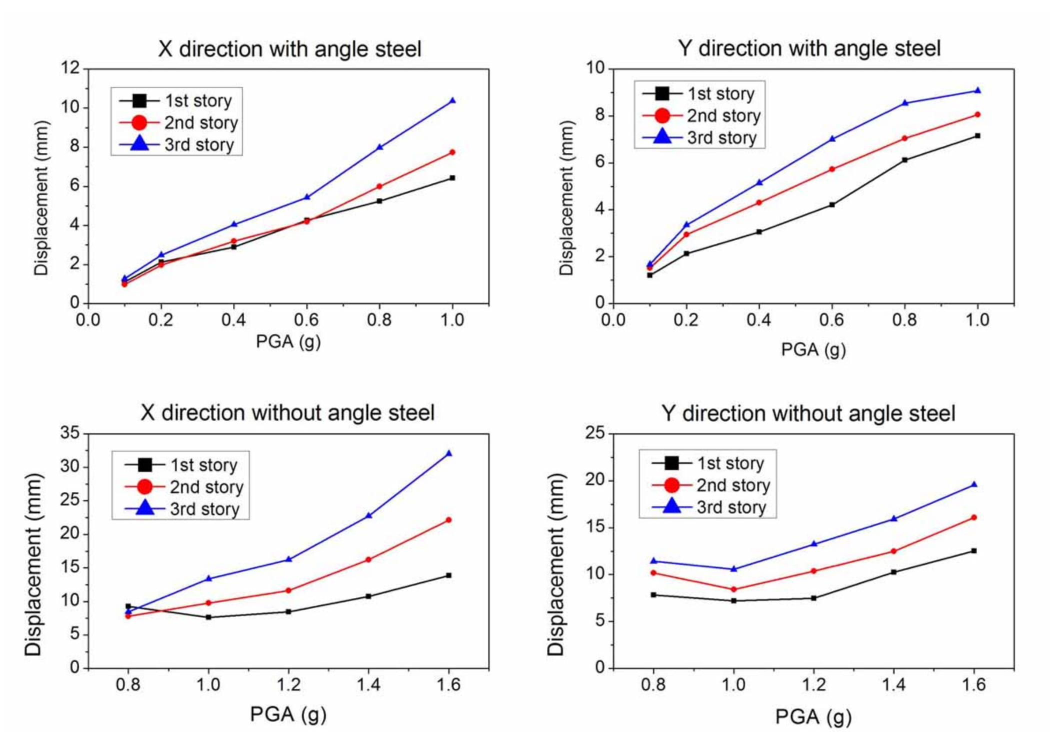
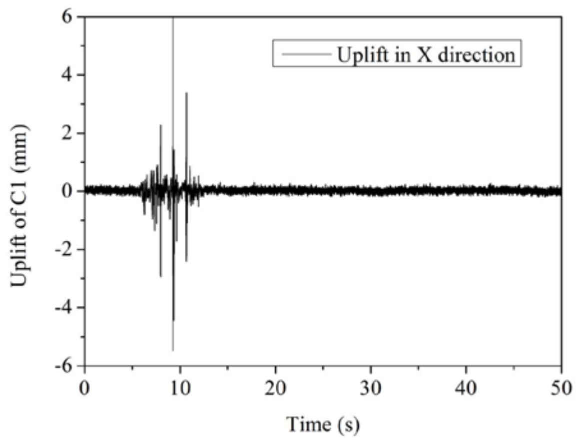
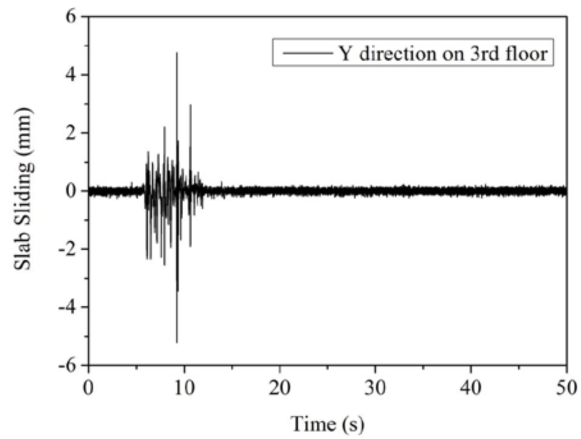


Fig. 7 – Change in displacement under Takatori wave

3.3 Self-centering behavior

Gap opening at the beam-column and column-base interfaces is a specific behavior of a self-centering connection under earthquake loading. Gap openings and slab slidings were captured in the test. Fig. 8(a) shows the time history curve of the uplifting of column under Takatori 1.6g test. Fig. 8(b) shows the time history curve of the slab sliding in Y direction on the third floor under Takatori 1.60g test. The structure went back to its initial position with negligible residual deformation. Test results indicate that the self-centering technique is quite effective on reducing the residual deformation for the RC frame structure, which may therefore protect the main structure from being damaged.





(a) (b)

Fig. 8 –Time history curve under Takatori 1.60 g test:

(a) uplifting of the corner column (C1), and (b) slab sliding in the Y direction on the 3rd floor

4. Numerical simulation

To describe and investigate the seismic behavior of the self-centering frames, analytical models of the entire frame with the beam-column connections and the column-base connections were constructed using OpenSEES.

Truss elements were used to model the prestressed tendons. Steel02 material was selected as the constitutive law assigned to truss elements and steel reinforcement bar. Rigid links were used at the end of columns or beams to consider the influence of the column and beam depths. Concrete beams and columns were modelled by using elements with fiber sections.

Gap opening at the beam-column and column-base interfaces is a specific behavior of a self-centering connection under earthquake loading. The interfaces can take no tension. Since there would be no tensile stresses in the interface, the ends of the columns and beams were under nonlinear stress distribution [9]. The deformation of compressive zone when the beam-column interface is no longer fully contacted has to be taken into account in the simulation of self-centering structures [8]. To these ends, parameters L_b and L_c (Fig. 9) to take the deformation of compressive zone of the beam ends and the column bases into account. Concrete and reinforcement fibers at the ends of the beams were modeled with compressive capacity but no tensile capacity which is achieved by connecting the conventional material with the Elastic-No-Tension (ENT) material in series.

The force-based beam-column element with fiber sections was selected to reflect the property of the rubber blocks between the column and base. Fibers of the rubber block were characterized with the compression-only stress-strain relationship using ENT material. Interaction between beams and slabs are taking into consideration by calculating axial and shearing behaviors of rubber pads.

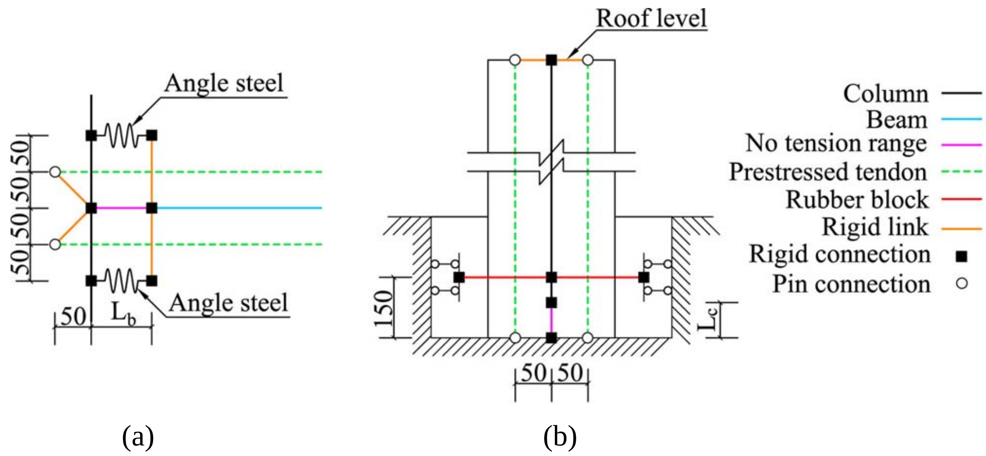


Fig. 9 – Computational models: (a) beam-column joints, and (b) column-base joints

A series of nonlinear dynamic time history analyses of the shaking table test were conducted to validate the accuracy of the proposed numerical model. The same ground motions used in the experiment were applied to the numerical model. According to previous research, the damping ratio was assumed to be 2%.

Fig. 10 shows the time history of the displacement at roof level of the test frame under Takatori 1.0 g test. The simulation results presented a sound agreement compared with the test results. The agreement between the simulation and the test results proved that the proposed analytical methodology could also be applied in further studies of tri-axial self-centering reinforced concrete frames.

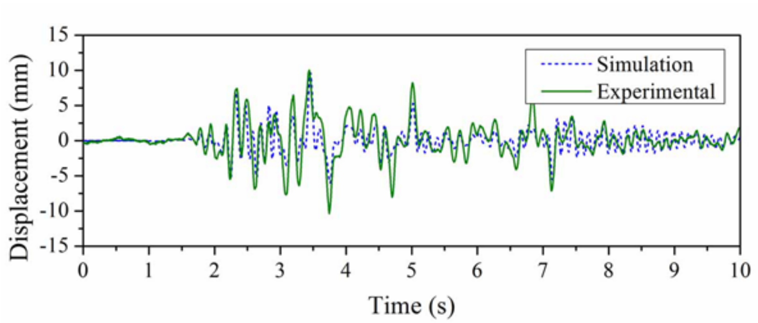


Fig. 10 –Response time history of displacement at roof level of the test frame under Takatori 1.0 g test

5. Conclusions

To investigate the behavior of tri-axial reinforced concrete frame structures with self-centering beam-column and column-base connections, a 1/2.5-scale 3-story tri-axial reinforced concrete frame with self-centering capacity was constructed for testing on a shake table. A series of nonlinear time history analyses are involved in this study. Below are the conclusions obtained from this research:

(1) The designed reinforced concrete frame has excellent seismic performance and self-centering capacity subjected to strong earthquakes with minor residual drifts in the frame. No crack was observed on columns and beams. The natural frequencies decrease very slightly during the test. The structure kept in good condition without structural damage throughout the test.

(2) Gap opening and slab sliding were captured in the test. The structure went back to its initial position with negligible residual deformation. The self-centering technique is quite effective on reducing the residual deformation for the RC frame structure, which may therefore protect the main structure from being damaged.

(3) Analytical models of the entire frame with the beam-column connections and the column-base connections were constructed to study the seismic performance of the self-centering frames using OpenSEES. The agreement between the simulation and the test results proved that the proposed analytical methodology could also be applied in further studies of self-centering reinforced concrete frames.

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