Seismic Performance of RC frame

Retrofitted by Epoxy Injection Technique

Tested on Shaking Table

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SUMMARY:
A 1/4-scale two-bay eight-storey reinforced concrete (RC) frame was tested on shaking table. Initial tests were carried out through a set of real seismic excitations to investigate the seismic behavior of the RC frame. Subsequently, the damaged frame was repaired using epoxy injection technique, and then subjected to tests with the same input accelerograms selected for the initial. This paper compares the responses between the initial and repaired frame in terms of dynamic characteristics, cracking pattern, failure mechanism, maximum responses of deformation and storey drift ratio. To further study the efficiency of epoxy injection technique, a series of wedge splitting tests on concrete specimens were carried out. The fracture energy and double-K fracture parameters of initial and repaired specimens were obtained and compared. The above tests indicate that epoxy injection technique is an adequate method for repairing earthquake-damaged structures.

Keywords: reinforced concrete frame model; shaking table test; epoxy injection technique; seismic performance; wedge splitting test

1. GENERAL INSTRUCTIONS

The design philosophy presented in *Chinese Code for Seismic Design of Buildings* (GB5011-2010) in China provides three structural performance levels for earthquake resistance: ①the structures should resist minor earthquakes whose intensity was lower than seismic precautionary intensity without damage; ②resist moderate earthquakes with some non-structure damage but without significant structure damage; and ③resist major earthquakes without collapse. Structures which have been exposed to the first two levels of damage are usually considered repairable. According to the field investigation after earthquake, reinforced concrete (RC) structure designed according to the new code when suffered major earthquake, except a few that are destroyed or collapse, are damaged slightly or moderately and still can be serviceable after repair.

Alternative retrofit and strengthening solutions for reinforced concrete structure have been studied in the past and adopted in practical applications, such as section enlargement, steel plates jacketing, pre-stressed method, FRPs strip, reinforcement layer. The seismic performance of damaged column-beam joints (YU Jiangtao,2010), beams (Myers, 2007) and frames (Balsamo,2005) can be restored or even largely elevated by employing appropriate reinforcing design and construction. Generally, for the cracked or crushed concrete of element or structure, it is mainly filled with high strength materials such as epoxy resin and then strengthened by high-performance composite. From the rehabilitation effect point of view, this method is effective in repairing and strengthening, but it fails to distinguish the contribution between resin-injection and composite strengthening. It is a fair question to define the effectiveness of epoxy-injection for concrete structures.

In the last several decades, as one of the repair techniques, epoxy-injection technique was extensively applied to repair the reinforced concrete structures with low or moderate level damage. But so far, only a few experimental research works have been published on the effectiveness of this technique. Moshe et al. (1993) carried out quasi-static tests to evaluate the cyclic behavior of reinforced concrete beam-column joints repaired by epoxy. The comparison between the response of the specimens before and after repair clearly indicated considerable increase in stiffness, general yield resistance, envelope stiffness, and ultimate resistance with energy-dissipation capacity. Karayannis et al. (2008) also tested the effectiveness of seventeen exterior RC beam-column connections repaired using epoxy resin infused under pressure into the crack system of the damaged joint body. The repaired specimens compared with the virgin ones exhibited equal or higher load-carrying capacities, loading stiffness of the same level and increased hysteretic energy absorption capability. The repaired specimens also sustained more full loading cycles without significant loss of strength or stiffness. Camille et al. (2007) adopted epoxy compounds to restore the integrity of cracked specimens by gravity filling of the crack. The test results indicated that, compared with control specimens, the compressive strength of cracked concrete test cubes and repaired cubes respectively decline 40.93% and 8.23%. Catherine et al. (1987) investigated the effectiveness of epoxy techniques to repair moderate earthquake damage. The specimens after the initial damage were repaired with one of the two epoxy repair techniques: pressure injection or vacuum impregnation and retested. Their experiment results indicated the epoxy repair techniques worked well in restoring the strength, stiffness, energy-dissipation capacity, and bond of the specimens.

The above researches illustrate that epoxy-injection technique is effective in repairing structures damaged in minor or medium earthquake. However, none of the above studies investigated the efficiency for epoxy-injection at repairing the seismic behavior of RC frames using shaking table tests. The purpose of this paper is to investigate experimentally the effectiveness of epoxy repair for RC structure. A 1/4-scale two-bay eight-storey reinforced concrete frame was tested on shaking table. Initial shaking table tests were carried out through a set of real seismic excitations for investigation of seismic behavior of the reinforced concrete frame. Subsequently, the damaged frame was repaired using epoxy-injection technique, and then subjected to the test with the same input accelerograms selected for the original.

The experimental program focuses on the comparison of experimental performance between initial and repaired frame to evaluate the effectiveness of epoxy repairs for concrete structures. The following contents are included:

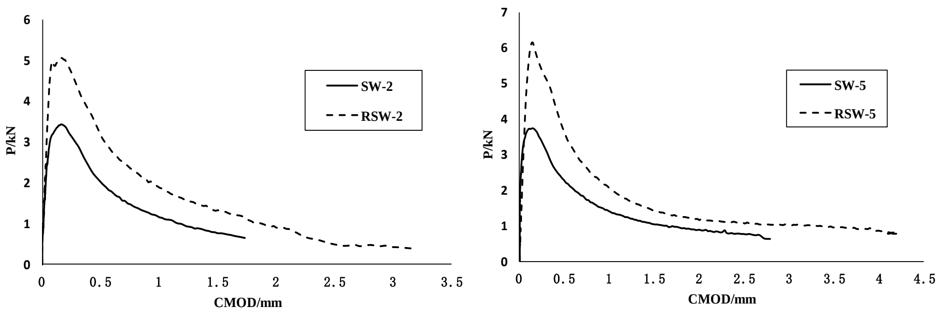
a) Wedge splitting tests were conducted on six specimens made of the concrete from the RC frame. After repairing by epoxy-injection, the specimens were retested. The effectiveness of repair was investigated by the comparison of fracture energy and double-K fracture parameters from the original

and repaired specimens.
b) The global behavior and damage pattern were observed.
c) The variations of dynamic characteristics (natural frequency, damping ratio) throughout the whole process were investigated.
d) The acceleration response, the displacement response and storey drift ratio of models were compared to evaluate the effectiveness of epoxy-injection technique.

2. REPAIRING TESTS OF CONCRETE SPECIMENS

To study the feasibility of restoring concrete with epoxy, wedge splitting tests (XU Shilang et al, 2003) were conducted on six specimens made of the same type of concrete as the RC frame. And then the splitting specimens (200 mm×200 mm×200 mm) were repaired with epoxy namely XH160A/B and retested after curing. The effectiveness of repair was illustrated by the comparison of fracture energy and double-K fracture parameters of the initial specimens (SW-1~6) and the repaired ones (RSW-1~6).

A closed-loop servo controlled hydraulic jack with a maximum capacity of 1,000 kN was employed to conduct the wedge splitting test. Two Clip-on Extensometers were suited at the mouth and the tip of the crack to measure the crack mouth opening displacement (CMOD) and the crack tip opening displacement (CTOD). To obtain the complete load-deflection curve (P-CMOD), the test rate was fixed at 0.2 mm/min, and it took approximately 40 min to complete a single test of specimens.



a) SW-2 b) SW-5

Figure 1. P-CMOD curves of specimens from initial test and retest

Table 1. Results from wedge splitting tests

Specimen	P_{ini} (kN)	P_{max} (kN)	K_{IC}^{ini} (MPa.m$^{1/2}$)	K_{IC}^{S} (MPa.m$^{1/2}$)	G_F (N/m)
SW	2.48	3.68	0.18	0.45	128.73
RSW	3.58	5.76	0.25	0.52	197.86
Growth(%)	42.14	49.7	40.71	24.34	61.66

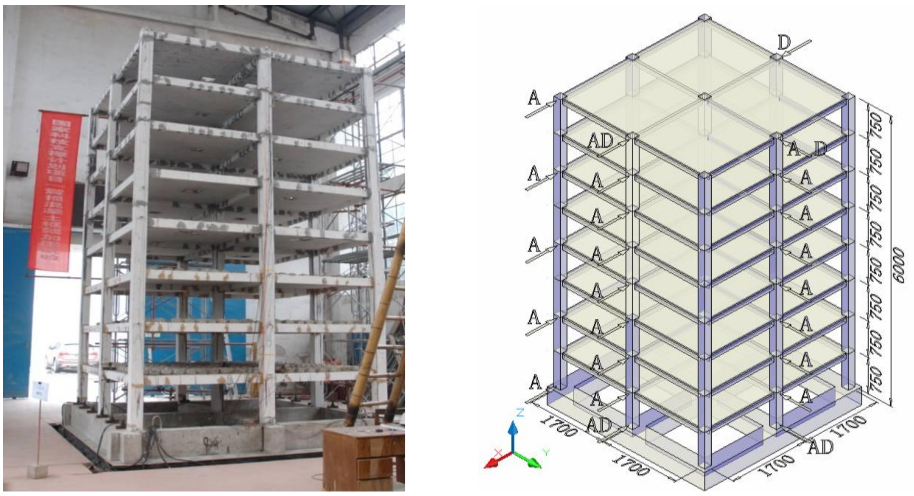
The P-CMOD curves of specimens SW-2 and SW-5 are presented in Figure 1. The comparison of the P-CMOD curves show that the peak loads and the embraced areas of the repaired specimens are higher than those of the initial ones, which indicates the improvement of load bearing capacity and fracture energy of the repaired specimens. The initial crack load (P_{ini}), the peak load (P_{max}), the initial fracture toughness (K_{IC}^{ini}), the unstable fracture toughness (K_{IC}^{s}) and fracture energy (G_F) can be calculated from the P-CMOD curves, and these data are presented in Table 1.

For the initial specimens, the average value of P_{ini}, P_{max} and G_F are 2.48 kN, 3.68 kN and 128.73 N/m, whereas for the repaired specimens, the corresponding terms achieve 3.58 kN, 5.76 kN and 197.86 N/m with an increase of 42.14％, 49.70％ and 61.66％, respectively. The average value of K_{IC}^{ini} is evidently increased from 0.18 MPa.m$^{1/2}$ to 0.25 MPa.m$^{1/2}$, while that of K_{IC}^{s} from 0.45 MPa.m$^{1/2}$ to 0.52 MPa.m$^{1/2}$, which show 40.7％ and 24.34％ increase, respectively.
On the basis of all the above tests and analysis, it is reasonable to infer that the properties of damaged concrete can be restored or even improved through epoxy injection technique.

3. SHAKING TABLE MODEL TEST OF RC FRAME MODEL

3.1 Model design

A 1/4-scale two-bay eight-storey RC frame (shown in Figure 2a) tested on shaking table had a rectangular plan of dimensions 3.4 m×3.4 m, a total structural height of 6 m and its typical storey height is 0.75 m. The cross sections of column and beam were 150 mm×150 mm and 125 mm×50 mm respectively, the thickness of slabs was 30 mm. Model concrete, with a ratio of 0.76:1:4.58:1.69 were made of regenerated aggregate served as course aggregate and fresh sand served as light aggregate. The total weight of the model was 23560 kg.



a) The repaired model frame b) The layout of displacement & acceleration transducers

Figure 2. Facade view of initial model frame and repaired model frame

3.2 Instrumentation and test program

The shaking table test was conducted in the State Key Laboratory for Disaster Reduction in Civil

Engineering at Tongji University. 12 displacement transducers, 28 accelerometers and 6 strain gauges were installed on the model to measure the lateral displacement and the angular rotations in the ends of beams and columns, acceleration at each story, and strain on the columns. Figure 2b shows the view of the experimental setup and instrumentations for the shaking table test, where letters A and D refer to accelerometer, displacement transducer respectively.

Four seismic ground motions were inputted to the shaking table in the test: a) El Centro record; b) Kobe record; c) Wenchuan record; and d) MYG013 record. These inputs were divided into 4 phases, i.e. frequently occurring (Frequent 8), basic (Basic 8), rarely occurring earthquakes of intensity 8 (Rare 8) and rarely occurring earthquake of intensity 8.5 (Rare 8.5). Wenchuan record, MYG013 record, El Centro record and Kobe record were subsequently inputted in the shaking table during each phase, in which the frame was subjected to 2D and 3D seismic excitation in turn. According to the similitude law, seismic records were varied as earthquake inputs. Before the inputs of each event, white noise tests were taken to acquire the model dynamic characteristics including frequency and damping ratio.

3.3 Epoxy injection procedure

The damaged frame was repaired with two kinds of epoxy, namely XH160A/B and XH111 Normal A/B applied by Araldite Company. XH160A/B is a two component, solvent-free, low viscosity liquid, based on high strength epoxy resins. It is used to fill and seal cavities and cracks in structural components such as bridges, industrial structures, columns, beams, foundations, walls and floor slabs. XH111 Normal A/B also is a bi-component room curing epoxy with thixotropic property and used to seal the cracks. It has some advantages such as high mechanical and adhesive strengths, watertightness, and high resistance to chemical attack. After the initial test, the width and quantity of cracks was statistically analyzed. All the cracks can be categorized into three levels by width and location, as is shown in Table 2.

Table 2. Quantity of cracks categorized by width and location

Location	Width(mm)			
	0.01~ 0.10	0.10~ 0.30	0.30~ 1.00	1.00~
Mid-span of beam	54	42	2	—
Beam end	45	60	18	12
Joint	—	—	—	131

According to the categorizations mentioned above, the following methods were employed.

1) For the cracks (at the mid-span of beams and in the columns), epoxy resin XH160A/B was injected to the cracks sealed by XH111 Normal A/B under constant low pressure.

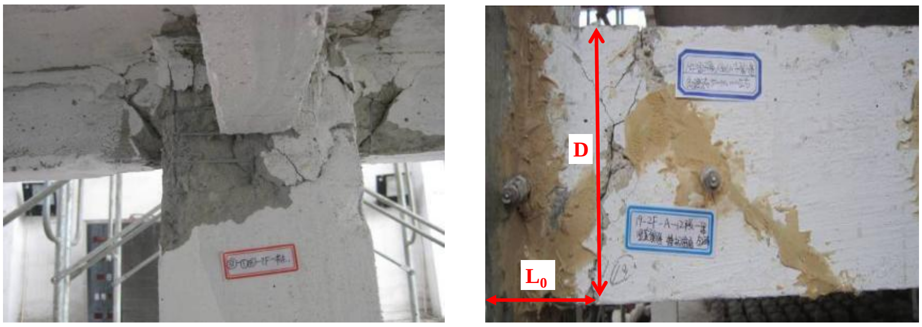
2) For the crushed or heavily cracked concrete (mainly at the interface between beam and column), such damaged concrete was removed and XH111 Normal A/B was put to the broken part and XH160A/B was injected too.

As the width of the crack was very small, general injection technique was not able to make the epoxy full of the crack under low pressure. So a special injection technique was adopted whose process is presented as follows (in Figure 3): a) drilling small holes in the beams and columns along the cracks; b) cleaning dusts and particles in the hole with blower; c) putting needles in the holes; d) sealing the cracks by XH111 Normal A/B; e) injection under pressure which can be varied according to the location and width of the crack. During the injection, appropriate pressure should be taken to avoid the rupture of the concrete. And cyclical injection was recommended to make sure that the crack was filled with epoxy. After repairing of the beams, columns and joints, the crack in the slabs was rehabilitated by epoxy grouting. Epoxy XH160 A/B was painted along the cracks.

When the retest finished, rock driller was used to take samples (diameter=60 mm) of model for examination of the effectiveness of epoxy-injection, as is shown in Figure 3c. It can be found that the epoxy whose location shown by the red line in the picture can permeate the concrete along the crack which demonstrate the favorable effect of such injection technique.

a) crack sealing b) pressure injection c) concrete sample

Figure 3. Process of epoxy-injection technique and concrete samples



a) Joints failure of the model in initial test b) Joints failure of the model in retest

(D denotes the height of the beam; L_0 denotes the distance between the new cracks and the column)

Figure 4. Comparison of the failure of models in the initial test and retest

4. TEST RESULTS AND ANALYSIS

4.1 Failure mode of the model

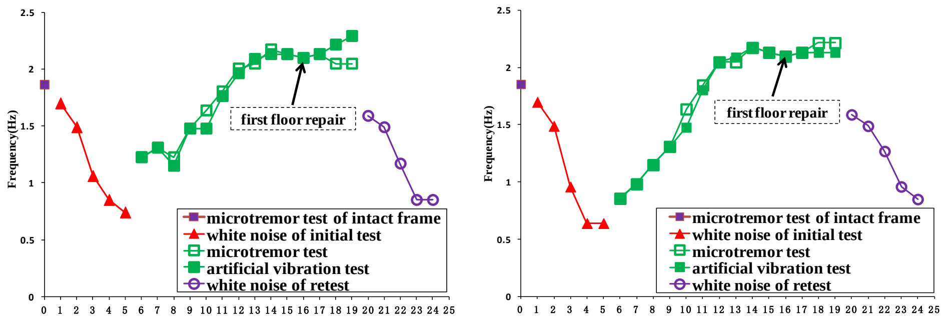
The initial test showed that cracks could be seen in beams and columns at each floor and a few columns ends were crushed. There are typically five crack-concentrated zones on the model structure: 1) the interface between beam and column with broad cracks (shown in Figure 4a); 2) some beams ends with cross diagonal crack stretching to joints and underneath concrete crushed; 3) the bottom of beam at mid-span with small cracks; 4) a few columns of the ground floor and most columns above the fifth floor, few columns ends above the fifth floor were crushed; and 5) the negative moment regions of slabs. Compared with the upper stories, damage in the lower structures was relatively slight. The retrofitted model exhibited the following difference with the initial model in failure pattern: 1) all cracks occurred in areas without restoration; 2) cracks of beams decreased dramatically in quality, as well as columns and slabs; 3) failure mode was changed from joint failure to beam end failure and the distance between new crack and juncture of beam and column was at the range of 0.5 to 1 times of beam height (shown in Figure 4b); 4) damage extend of the retrofitted model was similar to that of the initial in lower stories, while in upper stories, the former was apparently slighter than the latter.

4.2 Dynamic properties of the model

Figure 5 and 6 respectively show the variation of natural frequency and damping ratio throughout the whole process. The whole process can be divided into three stages: (1) the frequencies and damp ratios of the initial model at different phases of inputs were obtained from white noise tests; (2) the damaged model then was gradually repaired and subjected to micro-tremor tests and artificial vibration tests to study the vibration of natural frequency and damping ratio during repairing; (3) white noise tests were applied again to gain the frequencies and damp ratios of the repaired model at different phases. From these tests, the natural frequency and damping ratio were achieved by using the Fourier transform and logarithmic decrement method.

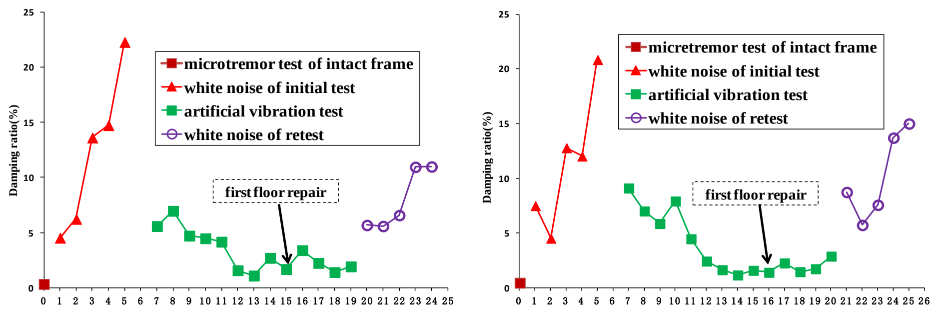
According to Figure 5 and 6, the following conclusions can be drawn: 1) the frequency of the model decreases with the increase of the peak value of acceleration inputs. In the four phases, the frequencies of the initial model in X direction and Y direction reduce respectively by 56.47% and 62.35%, while that of the retrofitted 46.54% and 46.54%. With reference to the interdependence of stiffness and frequency, the model is seriously damaged in both tests with its stiffness distinctly declining. In the meantime, the frequency of the retrofitted model decreases slower than that of the initial demonstrates that the repaired model has higher residual stiffness; 2) the damping ratio of the model increases with the peak value of acceleration inputs. The damping ratios of the initial model in X direction and Y direction are respectively 22.29% and 20.85%, while those of the retrofitted 10.99% and 15.00%. The damping ratios of the retrofitted model are similar to those of the initial when inputs lower peak value of acceleration, while are 49.30% times in X direction and 71.94% in Y direction higher than those of the initial when processing the fourth phase.

The variation of frequency and damping ratio during rehabilitation process are also illustrated in Figure 5 and 6. The changes of frequency and damping ratio show evident regularities as follows: the frequency increases gradually while the damping ratio decreases gradually when the cracks in beams, columns and joints are repaired; the frequency and the damping ratio almost keep constant when the cracks in floors are repaired. In general, the cracks repairing cause a increase in the frequency of the model in X direction and Y direction respectively up to 92.25% and 146.60%, namely from 1.42 Hz and 1.03 Hz to 2.73 Hz and 2.54 Hz. Besides, the repairing cause a decrease in the damping ratio of the model in X direction and Y direction respectively by 65.47% and 68.39%, namely from 5.59% and 9.11% to 1.93% and 2.88%. Accordingly, the variation of structure’s seismic performance under repairing and strengthening can be obtained by monitoring the changes of structure's frequency and damping ratio. It should be recommended as a feasible way to acquire the effect of rehabilitation technique during strengthening.



a） X-direction　　　　　　　　　　b） Y-direction

Figure 5. Variation of the natural frequency



a） X-direction　　　　　　　　　　b） Y-direction

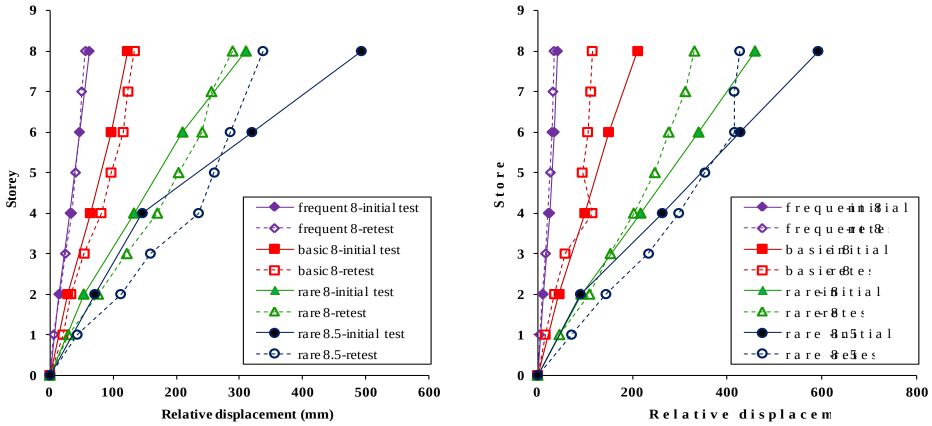
Figure 6. Variation of damping ratio

4.3 Displacement response of the prototype

In each phase, the inputting peak acceleration values (PGA) are adjusted in accordance with similarity law to simulate various seismic effects. Although the same levels of acceleration are designed to input, the measured inputs peak acceleration is not the same as designed, which leads to different measured peak acceleration between initial test and retest. Consequently, structure's responses are deduced to the prototype structure and compared in the prototype structure to study seismic performance of the original model and the retrofitted. Formulas (LU Xilin, 2007) are used to eliminate this error. Prototype calculated from the initial test and the retest is respectively termed as prototype 1 and prototype 2.

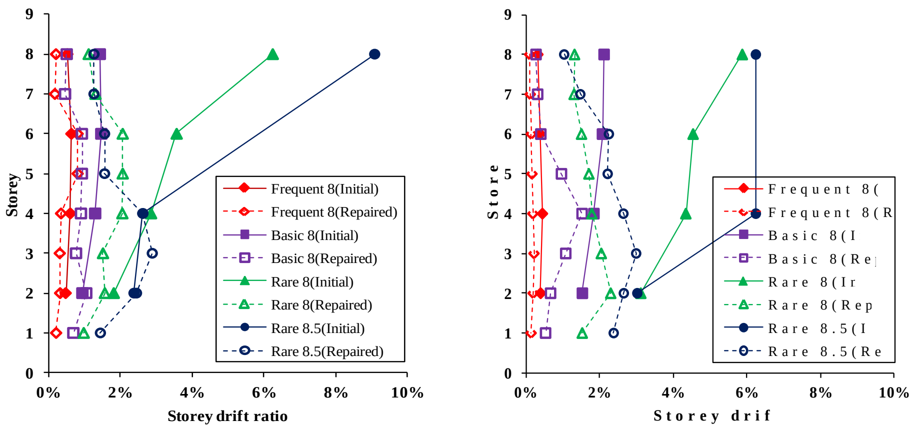
Comparisons of the maximum relative displacements of each storey of prototypes at different earthquake levels are shown in Figure 7. Displacement values of prototype 2 are a bit lower than those of prototype 1 in both X and Y direction during the first phase (PGA=0.084 g) and higher in X direction but lower in Y direction above sixth floor during the second phase (PGA=0.24 g). During the last two phases (PGA=0.48 g, 0.612 g), the prototype 2 has higher displacement in underneath floors but lower above sixth floor compared with prototype 1. In the last phase, the maximum relative displacements of the top storey of prototype 1 are 492.70 mm in X direction and 591.37 mm in Y direction, while those of prototype 2 are 337.02 mm and 426.08 mm. It can be discovered that the maximum relative displacements of prototype 1 are lower below sixth floor but higher above the sixth floor, which conforms to the results of the tests.

Comparisons of the maximum storey drift of prototypes at different earthquake levels are displaced in Figure 8, in which prototype 1 has lower maximum storey drifts during the first two phases and higher during the last two phases.



a） X-direction b） Y-direction

Figure 7. Comparisons of the maximum relative displacements of each storey of prototypes at different earthquake levels



a） X-direction b） Y-direction

Figure 8. Comparisons of the maximum storey drift ratios of prototypes at different earthquake level

5. CONCLUSIONS

In this paper, the seismic performance of a 1/4 scaled model was evaluated with the wedge splitting tests and shaking table tests to study the efficiency of the rehabilitation technique at repairing earthquake-damaged frame structures. According to the test results, the following conclusions are derived: 1) properties of splitting concrete can be restored or even improved through epoxy injection technique and that indicates the possibility of applying epoxy injection technique to repair concrete damaged by tension; 2) the extent of damage of the repaired frame is similar to that of the initial below the fifth floor and slighter above the fifth floor; 3) the repaired frame exhibits lower decreasing range of frequency and higher increasing range damping ratio, which also illustrate the efficiency of epoxy injection technique; 4) the comparisons of the prototype index such as displacement and story drift ratio demonstrate the efficiency of epoxy injection technique in repairing RC frame damaged in earthquake.

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