BEHAVIOR OF REINFORCED CONCRETE COLUMNS UNDER DIFFERENT LOADING HISTORIES

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Abstract: Three reinforced concrete (RC) circular columns were tested under different reversed cyclic loading programs to investigate the seismic behavior of the columns in near-fault earthquakes. The ultimate capacity, ductility ratio, hysteretic curve and hoop strain in plastic hinge region were obtained through experimental study of the columns. The influence of displacement history sequence upon the hysteretic characteristics, stiffness and strength degradation, ability of energy dissipation and hoop strain distribution were analyzed. It is shown that the ductility of RC columns designed by Chinese design code is inadequate in near-fault earthquake region, and the sequence of maximum displacement in the loading history could lead to an earlier buckling of the longitudinal bars. The ultimate capacity and displacement of columns failed in flexural mode are controlled by fatigue fracture or compressive buckling of the longitudinal bars, concrete in plastic hinge region can be effectively confined by the steel hoops.

Keywords: Reinforced concrete column; seismic test; displacement history sequence; near-fault ground motion

1 INTRODUCTION

Near-fault ground motion records obtained during the recent years have provided clear evidence that the near-field earthquakes may lead a serious damage to the RC structures, and the impulsive property made it unique comparing with the far-fault earthquakes. The propagation of fault rupture toward a site at a velocity close to the shear wave velocity causes most of the seismic energy from the rupture to arrive in a single large long-period pulse of motion that occurs at the beginning of the record (Somerville *et al.* 1997), and the largest deformation demands in the shaking are associated with fewer reversed cycles of loading due to the impulse (Kalkan *et al.* 2006). The spectra of the near-fault earthquakes were different from the normal ground motions. The velocity-sensitive region of the near-fault motions in spectra is much narrower than the far-field motions and shifts to a longer period (Chopra *et al.* 2001).

During the past few decades, researchers have carried out a number of experimental researches on the seismic performance of RC columns considering the characteristics of the pulse-like ground motion. However, these tests did not achieve consistent results. Santigao *et al.* (2006) designed 16 RC columns with rectangular section, they found that the displacement history before the column yielded did not affect the drift capacity of the specimens, but the capacity of the columns was a function of the amplitude and number of the cycles exceeding the yield point. Hwang (1984) reported a contrary result as Hamilton *et al.* (2001) and Gibson *et al.* (2002), the impulsive loading has little effect on the displacement ductility capacity for flexural column. Loh *et al.* (2002) pointed out that the permanent displacement was not obvious in the experimental verification of the pseudo-dynamic test, and the hysteretic characteristics of the column correlate well with the improved Takeda model rather than the EPP model, but Kawashima *et al.*(1998), Phan *et al.*(2007) and Hoonchoi *et al.*(2010) found the near-fault ground motions could generate large residual displacement on one side of the columns. A study by Yi *et al.* (2012) found that both the axial load level and the loading path affect the length of the plastic region in the columns. However, Choi *et al.* (2010) reported that the ductility capacity and measured plastic hinge lengths for columns subjected to near-fault earthquakes were comparable to the columns of the same scale tested under far-field earthquake.

According to the characteristics of the near-fault seismic displacement demand, a unique loading pattern has been designed, which contains an impact of displacement demand caused by several peaks of cyclic loading in the early stage. Three RC circular columns have been tested under reversed cyclic loading to investigate the influence of different displacement history on seismic behavior of the columns.

2 EXPERIMENT PROCEDURE

2.1 Specimen Design

Three large-scale specimens were designed and tested at the Structural Laboratory of Hunan University. Each of the column had a circular cross section with a diameter of 370mm and a net height of 2400mm.The surface of the circular hoops were exposed to air for an easy installation and an accurate measurement of the strain gauges. Details of the reinforcement and material properties are summarized and shown in Table1 and Figure 1.

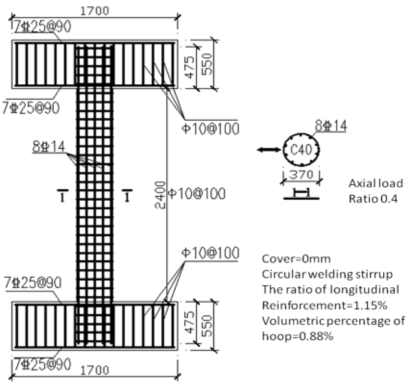


Figure 1. Model column details

Table 1. Specimen detail

Specimen	Transverse Reinforcement	Longitudinal Reinforcement	Concrete Strength (MPa)
L1	Circular Hoops	8×HRB400	48.08
L2	*D*=10mm	*D*=14mm	43.05
L3	f_y=468MPa f_u=615MPa	f_y=421MPa f_u=543MPa	52.44

2.2 Test Setup

The specimens were tested under displacement control. All the servo actuators have internal LVDTs and load cells, and the hysteretic curve data were auto-recorded by the data acquisition system of the MTS controller. An amendment was applied for vertical load by subtracting the contribution of the axial loads. The loading arm was designed as L-shaped for transferring the axis of the lateral actuator through the inflection point of the column to reduce the changing in vertical forces. The unbalanced moment caused by eccentric load of the beam itself was balanced by two vertical actuators. During the test, both sides of the specimen were mounted by the steel beams with two displacement transducers monitoring the lateral slip between the footing and the base. Two vertical actuators applied the constant axial force 1600kN on the loading arm and kept it parallel to the base by adjusting vertical displacements, as shown in Figure 2. In the potential plastic zone, strain gauges were installed along the circumferential direction of the hoops, as shown in Figure 3. At each peak point of the cyclic, the cracks were depicted by directions and the locations.

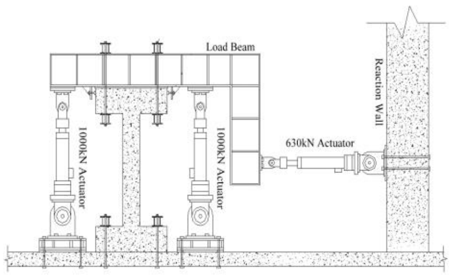


Figure 2. Test setup

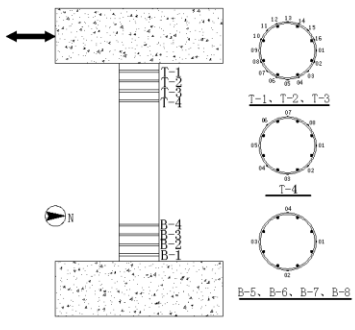
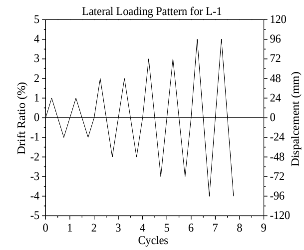


Figure 3. Strain gage details

2.3 Displacement History

L-1 was applied increased cyclic lateral loading to measure the ductility of the column designed under current seismic code. L-2 and L-3 were subjected to comparable loadings to study the behaviour of columns under different loading histories. The amplitude of the first 14 cycles in the loading pattern for L-2 was increased from 0.5% to 2%, but a reversed sequence was applied to L-3.

After implicating the contrary loading sequences, both of the specimens were subjected to cyclic lateral loading with a same drift ratio for measuring the rate of stiffness decrease and recording the distribution of the confining stress of hoops. Detail of loading patterns for each specimen was shown in Table 1 and Figure 4.



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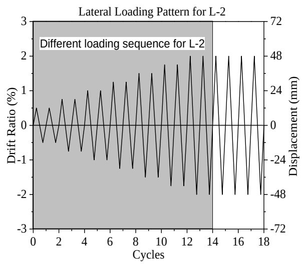

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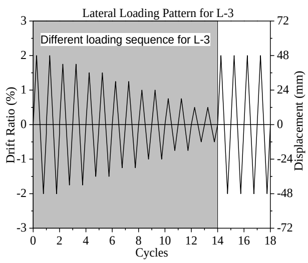


(c)

Figure 4. Lateral loading sequence (a) Column L-1; (b) Column L-2; (c) Column L-3

3 TEST RESULTS

3.1 Specimen L-1

During the drift ratio of 1% (24mm), several flexural cracks were observed in the tension region of the plastic hinge, and the concrete between stirrups was peeling. Slight buckling near the footing and more peeling of the concrete were found at the drift ratio of 2% (48mm). At the first peak of 3%(72mm), the lateral force decreased down to about 83 % of the maximum one, and the longitudinal reinforcement in the plastic hinge region had undergone a significant buckling with severe peeling of the core concrete. During the second cycle of 3%, the lateral strength dropped to 64% of the maximum lateral strength and the vertical carrying capacity was lost after the buckling of the longitudinal reinforcements. It was observed that the limit drift ratio for L-1 was 3%, and the displacement ductility ratio was around 4.5.

3.2 Specimen L-2

At the second cycle of drift ratio of 2.0%, the lateral strength in both directions dropped to 79% of the maximum strength in two directions. The loading was consisted along with the decrease of the lateral strength. At the seventh cycle of 2% (fifth cycle of 2% in the constant loading history), the lateral strength fell to 55.8% of the maximum strength, and the vertical capacity was achieved when the buckling of the longitudinal reinforcement occurred along with the direction of loading which led to abandonment of the test. The failure status of this member is basically the same as the L-1.

3.3 Specimen L-3

During the first cycle of the peak drift ratio 2% (48mm), peeling and crushing occurred at the outer compression concrete in plastic hinge region, after the first cycle, the lateral strength in both directions dropped to 75.6% of the maximum strength in two directions. The decreased loading sequence was subjected to the specimen after several peak cycles. In this sequence, the specimen performed reasonably well without new crack or peeling occurred. During the second constant cycle of 2% after the decreased loading sequence, the lateral strength dropped to 67.8% of the maximum strength, and the vertical capacity of the specimen was lost. The failure pattern was the buckling of the longitudinal reinforcement, basically the same as L-1 and L-2.

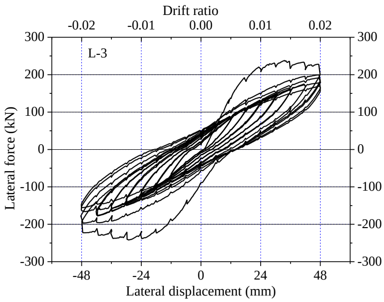
4 DISCUSSION AND ANALYSIS

4.1 Hysteretic curves, lateral capacity and

energy dissipation

Lateral force-displacement hysteresis loops were shown in Figure 5. The hoop spacing of L series columns was 7.14 times of the diameter of longitudinal bars, and the buckling of longitudinal bars and the crushing of the compression concrete were the major failure mode for them. A comparison study was made between L-1, L-2 and L-3 as following, the lateral capacity of L-1 was 220kN, while 200kN for L-2 and 230kN for L-3. All the specimens reached their lateral capacity during the cycle of 2%, but numbers of previous cycles before 2% were different for each of the specimens. It was indicated that the number of cycles had an obvious influence on the lateral capacity of the columns.

A comparison was also made between L-3 and L-2. Both of the specimens achieved their lateral capacity at the same drift ratio (1.5%) with different cycle sequences, and stiffness of the columns was basically the same at the end of the reversed sequence loading, but during the constant drift ratio cycles, the stiffness of L-3 failed much quickly, and the failure occurred only after 2 cycles of 2% drift ratio, while 5 cycles for L-2. This reflected that the sequences in loading history have an influence on lateral capacity of columns. It could be inferred that the peak loading in early stage of the loading history could lead to an earlier buckling of the longitudinal bars.



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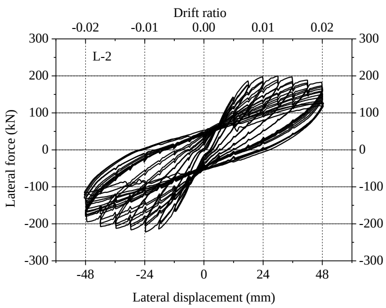

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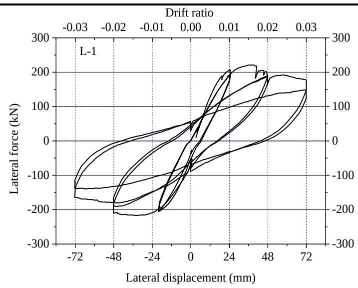

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Figure 5. Hysteretic curves of three specimens (a) Column L-1; (b) Column L-2; (c) Column L-3

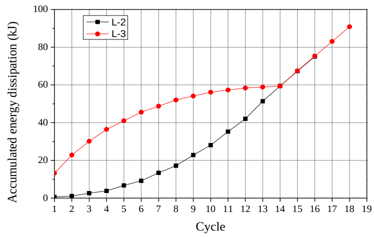


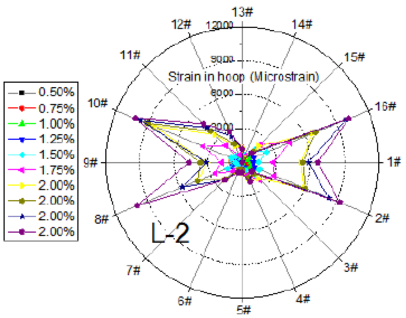
Figure 6. Accumulated energy dissipation of L-2 and L-3

The accumulated energy dissipation curves of L-2 and L-3 were shown in Figure 6, due to the different loading sequence of the first 14 cycles, the paths of the accumulated energy curves were different. At the 16th cycle, the curves of accumulated energy dissipation almost coincided, but the energy dissipation capacity for L-2 was better than L-3 in the following cycles. Because L-3 failed at the 16th cycle, while L-2 still kept its lateral capacity until the 19th cycle. So it could be inferred that the sequence of the loading history has an influence on the energy dissipation capacity.

5.2 Distribution of hoop strain

The distribution of maximum hoop strain along the height of the plastic hinge region in every cycle was shown in Figure 7. It was obvious that the maximum hoop strain located 180mm away from the ends, about half of the diameter of the cross-section. This phenomenon was also reported by Xiao *et al* (1998).

Hoop strains in L-2 increased with the increment of the drift ratio, while L-3 reached its maximum hoop strain at the first cycle. After the first two cycles of the 2.0% drift ratio, the strains of all of the hoops nearly remain the same value, the experimental observations had shown that the buckling of longitudinal reinforcement has a relationship with the hoop strains. When the hoop strain exceeded the yield point, the longitudinal bars began buckling. The different behavior of the variation law of the hoop strains indicted that the different loading sequence of the peak loading has an influence on the nature of confined stress for the core concrete, and on the buckling for the longitudinal bars.



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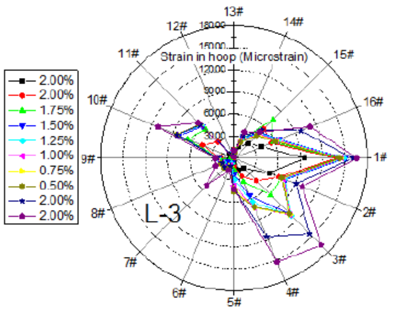

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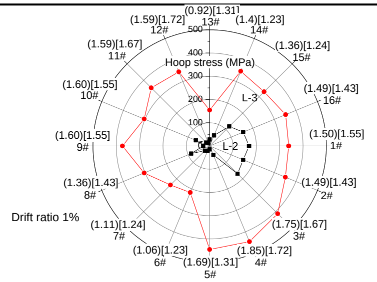
Figure 7. Circumferential distribution of T-2 hoop strain (a) Column L-2; (b) Column L-3

The circumferential distribution of hoop stress can be obtained by measuring the stress-strain curve in material test, but due to the lack of cyclic data, a numerical model which was proposed by Menegotto *et al.* (1973) was used. By substitution of the data obtained from monotonic loading test into the numerical model, the circumferential distribution of confining stress (only for L-3) was calculated and put into the Figure 8. Maximum confined stress and the average confined stress obtained by the equilibrium conditions were respectively recorded in parentheses and the brackets in Figure 8.



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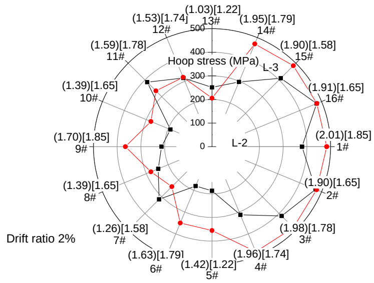

(b)

Figure 8. Circumferential distribution of hoop stress (a) 1% (b) 2%

5 CONCLUSIONS

Based on the experimental simulation of three specimens under cyclic loading, the effect of the pulse-like near-fault earthquake on the RC column was studied. It was found that not only the number of cycles but also the sequence of the peak value in the loading history had an important influence on the lateral capacity of the columns. The sequence of the loading history dominates the energy dissipation capacity, and the different behavior of the variation law of the hoop strains indicated that the different loading sequence of the peak loading had an influence both on the nature of confined stress for the core concrete and on the buckling for the longitudinal bars. The peak value in early stage of loading history could give rise to large strains in the hoop and lead to an earlier buckling of the longitudinal bars. Hoop rupture was not occurred during the tests and could confine the core concrete effectively. The effect of different sequence of the maximum loading cycles in the loading history was not obviously on the stiffness decrease in well confined columns.

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