Soil Dynamics and Earthquake Engineering 112 (2018) 8–17

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Cyclic loading test for circular reinforced concrete columns subjected to near-fault ground motion

Wei-Jian Yi[a,b], Yun Zhou[a,b,*], Hyeon-Jong Hwang[a], Zhi-Jie Cheng[c], Xiang Hu[a]

[a] College of Civil Engineering, Hunan University, Changsha, Hunan Province 410082, China
[b] Hunan Provincial Key Lab on Damage Diagnosis for Engineering Structures, Hunan University, Changsha, Hunan 410082, China
[c] Capol International & Associates Group Shenzhen Branch, Shenzhen 518038, China

ARTICLE INFO

Keywords:
Reinforced concrete column
Near-fault ground motion
Shear failure
Seismic behavior
Quasi-static cyclic test

ABSTRACT

Near-fault earthquake load causes more serious damage in reinforced concrete (RC) structures when compared with far-field earthquake load. Particularly, a short column under the near-fault earthquake load is vulnerable to shear failure, which requires special design consideration to avoid the brittle failure under the near-fault ground motion. In the present study, quasi-static cyclic tests were conducted on four circular RC columns to investigate load-carrying capacity, deformation capacity, failure mode, stiffness degradation, energy dissipation capacity, and deformation components. For the test parameters, shear-span ratio, longitudinal bars diameter, and cyclic loading type were considered. The test results showed that under the cyclic loading to describe the near-fault ground motion, the RC columns were susceptible to premature concrete spalling and shear failure.

1. Introduction

Near-fault earthquake loads such as 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi earthquakes cause more serious damage in reinforced concrete (RC) structures than that by far-field earthquake load. Compared to the far-field ground motions considered in most of seismic design criteria, the near-fault ground motions show the distinctive response. Generally, the near-fault ground motions include a long period-high velocity pulse in the fault-normal direction and permanent ground displacement (e.g., [1]). The analytical simulation for typical steel moment frames shows that the near-fault ground motions cause large displacement demands at the arrival of the velocity pulse, which require the structure to dissipate considerable input energy in a single or relatively few plastic cycles. The large displacement demand induces significant damage in the structures with limited ductility capacity (e.g., [2]).

Existing studies have mainly focused on flexural behavior of RC bridge columns under near-fault earthquake load. Mayes et al. [3] evaluated the cyclic response of sixteen columns, which had heights of 6.1–15.2 m and periods of 0.7–3.8 s, subjected to several seismic events including near-fault ground motions. They reported that the near-fault ground records increased the displacement demand of columns, which was greater than the displacement capacity of several columns. Orozco et al. [4] tested three identical bridge columns with the shear span ratio of 2.25 to study the effect of near-fault ground motion on the bridge columns. Under a single pulse to describe the near-fault earthquake load according to standard cycles, the influence of the large velocity pulse on the structural performance of the bridge columns was not significant. Kazuhio and Park [5] tested five RC bridge columns to evaluate the effect of loading pattern on damage of the columns. Test results showed that the loading pattern was not critical to the maximum lateral load-carrying capacity of the columns, but the failure mode was affected by the loading pattern. Using the fatigue based damage model combined with energy dissipation, a simple procedure was proposed to predict the damage and failure of the RC columns subjected to an arbitrary seismic loading pattern. Chang et al. [6] performed pseudo dynamic test of two two-fifths scale bridge columns to investigate seismic responses of as-built and repaired RC bridge columns with the shear span ratio of 2.17 under near-fault ground motion. The test results showed that the significant pulse-like wave destroyed the columns without ductile behavior to dissipate seismic energy. Phan et al. [7] performed a shaking table test on two flexural-governed RC columns under near-fault ground motion, which showed the shear span ratio 2.26, and compared the test results with that of a similar column under far-field ground motion. They reported that the plastic hinge length in columns subjected to near-fault ground motion is comparable to that of columns subjected to far-field motion, but the near-fault earthquake records with forward directivity provided an asymmetric velocity pulse

* Corresponding author at: College of Civil Engineering, Hunan University, Changsha, Hunan Province 410082, China.
E-mail addresses: wjyi@hnu.edu.cn (W.-J. Yi), zhouyun05@hnu.edu.cn (Y. Zhou), hwanggun85@naver.com (H.-J. Hwang), zhijiecheng@163.com (Z.-J. Cheng), baren@hnu.edu.cn (X. Hu).

https://doi.org/10.1016/j.soildyn.2018.04.026
Received 29 November 2017; Received in revised form 12 March 2018; Accepted 20 April 2018
0267-7261/

with high amplitude, which caused the whip-like behavior of the columns and large residual displacement in one direction. Choi et al. [8] performed a shaking table test on four bridge columns with the shear span ratio of 2.25–3.88 under near-fault ground motion to evaluate the effect of near-fault earthquake load. High amplitude velocity pulse related to near-fault earthquake load caused large residual displacements of the columns, but the ductility capacity and plastic hinge lengths of the columns subjected to near-fault earthquake load were comparable to those of the columns under far-field earthquake load. Brown et al. [9] tested two cantilever columns with the shear span ratio of 1.94 on a shaking table subjected to near-fault and far-field ground motion records. They reported that significant damage occurred by the impulsive effect of near-fault ground record, and the near-fault ground motion increased the strains, curvatures, and drift ratios, compared to those of the far-field ground motion.

In the last few decades, near-fault earthquakes have become a hotspot in earthquake engineering field. Due to long period high velocity pulse of near-fault earthquake, structures would suffer more serious damage and permanent residual deformation than those under far-field earthquake. Thus, greater capacity and ductility are required in the structures under near-fault earthquake. For columns with a relatively small shear span ratio and poor seismic details, shear failure results in low ductility and energy dissipation of the columns. Though shear failure of RC columns has been often reported in recent earthquakes, the shear behavior of the RC columns under near-fault earthquake load has not been a critical issue compared to the flexural strength and ductility of the RC columns. Particularly, as more near-fault ground motions have been recorded, careful considerations are needed for structures located in near-fault ground.

As a fundamental study for RC columns subjected to near-fault ground motion, this study focused on the loading pattern effect on RC bridge columns that show shear failure. To investigate the effect of near-fault ground motion on RC bridge columns, four circular RC columns were tested under quasi-static cycle loadings on the basis of the near-fault and far-field ground motion records. The structural performance including load-carrying capacity, deformation capacity, failure mode, stiffness degradation, energy dissipation capacity, and deformation components were evaluated.

Table 1
Test parameters.

Specimens	C-1	C-2	C-3	C-4
Height (mm)	1900 (2.56)	1600 (2.16)	1600 (2.16)	1600 (2.16)
Longitudinal bars (steel ratio, %)	20-Φ16 (3.74)	20-Φ16 (3.74)	20-Φ16 (3.74)	12-Φ20 (3.51)
f_y / ε_y (MPa, mm/mm)	403 / 0.0020	403 / 0.0020	403 / 0.0020	529 / 0.0026
f_u (MPa)	566	566	566	652
Cyclic load[a]	Type 1	Type 1	Type 2	Type 2
f_c' (MPa)[b]	42.3	40.2	51.1	39.9
Axial load (kN)	1210	1180	1417	1120
Axial compression ratio	0.32	0.33	0.31	0.31

f_y: yield strength; ε_y: yield strain; f_u: tensile strength.

[a] Type 1 and type 2 describe far-field ground motion and near-fault ground motion, respectively.

[b] Cube compressive strength of concrete. On the basis of Chinese design code of concrete structures, the axial compressive strength of the concrete cylinder is approximately 80% of the cube compressive strength.

2. Test Program

2.1. Test Specimens

Fig. 1 and Table 1 show four RC column specimens in detail. The column specimens were designed according to Chinese codes and provisions [10–12]. The cross-section of the specimens was circular shape with 370 mm diameter and the hoops were Φ8 @ 100 mm. The specimens were subjected to uniform axial compression and cyclic lateral loading. The test parameters were the shear span ratios (i.e., 2.56 for C-1 or 2.16 for C-2, C-3, and C-4), longitudinal reinforcing bars (i.e., 20-Φ16 for C-1, C-2, and C-3 or 12-Φ20 for C-4). The cyclic lateral loading procedure was to investigate the shear behavior under two-typed cyclic loadings (far-field ground motion for C-1 and C-2 or near-fault ground motion for C-3 and C-4).

For specimen C-1, column height was 1900 mm, which shows the shear span ratio 2.56. On the basis of the design method of the existing three test results showing flexural failure by Liu [13] and Yi et al. [14], C-1 was designed to investigate the failure mode that changes from flexural failure to shear failure. Twenty HRB 400-D16 (GB50010-2010)

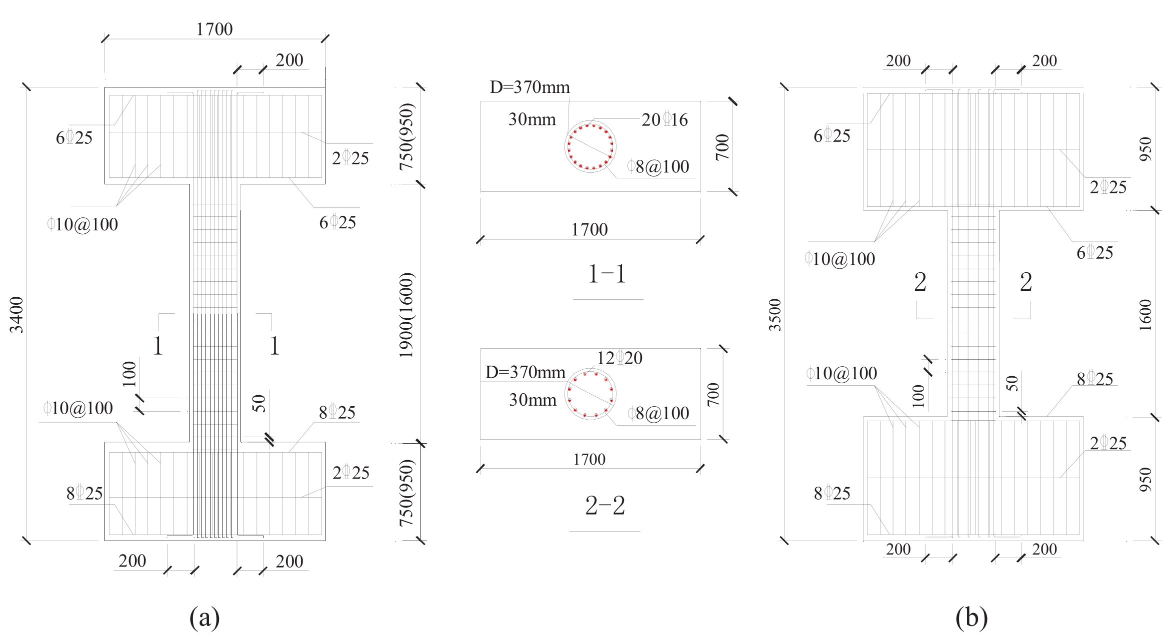

Fig. 1. Dimensions and detail of test specimens (dimension of C-2 to C-3 was denoted in brackets, mm).

bars (diameter Φ = 16 mm, cross-sectional area = 201.1 mm^2, and yield strength = 403 MPa) were used for longitudinal reinforcing bars. The rebar ratio was 3.74%. HRB 235-D8 bars (diameter Φ = 8 mm, cross-sectional area = 50.3 mm^2, and yield strength = 397 MPa) were used for hoops. The vertical spacing was s = 100 mm, in which the hoops ratio was 0.5%.

Specimens C-2 and C-3 had the same cross section and reinforcing bars as those of C-1. However, column height was decreased to 1600 mm, which shows the shear span ratio 2.16, to describe the short columns prescribed in Chinese provisions [12].

Specimen C-4 had the same cross section and column height as those of C-2 or C-3. However, twelve HRB 400-D20 bars (diameter Φ = 20 mm, cross-sectional area = 314.2 mm^2, and yield strength = 529 MPa) were used for longitudinal reinforcing bars to investigate the effect of rebar diameter. The rebar ratio was 3.51%.

2.2. Materials and Testing Setup

At the day of the cyclic loading tests, concrete cube strength were f_c' = 42.3 MPa for C-1, 40.2 MPa for C-2, 51.1 MPa for C-3, and 39.9 MPa for C-4 (refer to Table 1). The yield and tensile strengths of rebars were f_y = 403 MPa and f_u = 566 MPa for Φ16 bars, f_y = 529 MPa and f_u = 652 MPa for Φ20 bars, and f_y = 397 MPa and f_u = 504 MPa for Φ8 bars, respectively.

Fig. 2 shows the cyclic lateral loading test setup. The top and bottom footings of the column specimens were post-tensioned to an L-shaped loading beam and reaction floor by tie-down rods, respectively. Two vertical actuators were connected to the L-shaped loading beam to apply constant axial load of N = 1120–1417 kN (= 0.31–0.33 $f'_{c,cyl}A_g$, in which $f'_{c,cyl}$ = cylinder compressive strength of concrete and approximately 80% of the cube compressive strength f_c', A_g = gross-sectional area of column) to the column specimens. Cyclic lateral load was applied using a horizontal actuator connected to the mid-height of the L-shaped loading beam, which causes the inflection point at the mid-height of the column specimens. The unbalanced moment caused by the eccentric loading of the L-shaped loading beam was controlled by the two vertical actuators. At the beginning of each test, 20% of cracking loading was pre-loaded to verify the test facilities in proper working order. Deformations were measured by linear potentiometers at the loading point and the plastic hinge zones. Strains of reinforcing bars were measured by uniaxial strain gauges.

2.3. Loading Plan

Generally, near-fault ground motions include a long period high velocity pulse in the fault-normal direction and permanent ground displacement. In this study, large lateral displacement is applied to test specimens at the initial stage to generate damage. Thereafter the input displacement was gradually reduced to zero. Fig. 3 shows the two types of cyclic lateral loading applied to test specimens, which describe far-field ground motion (type 1) and near-fault ground motion (type 2). For better description of the near-fault ground motion, the cyclic lateral loading protocols were modified on the basis of the existing study by Orozco et al. [4]. Fig. 3(a) and (b) show the cyclic lateral loading type 1 applied to specimens C-1 and C-2, respectively. Two load cycles were applied at every 0.25% lateral drift ratio increase. Fig. 3(c) shows the cyclic lateral loading type 2 applied to specimens C-3 and C-4. Two load cycles were applied at initial 1% lateral drift ratio, and then two load cycles were applied at every 0.25% lateral drift ratio decrease. After the load cycles reached zero, ten load cycles were re-applied at 1% lateral drift ratio. Finally, two load cycles were applied at every 0.1% lateral drift ratio increase.

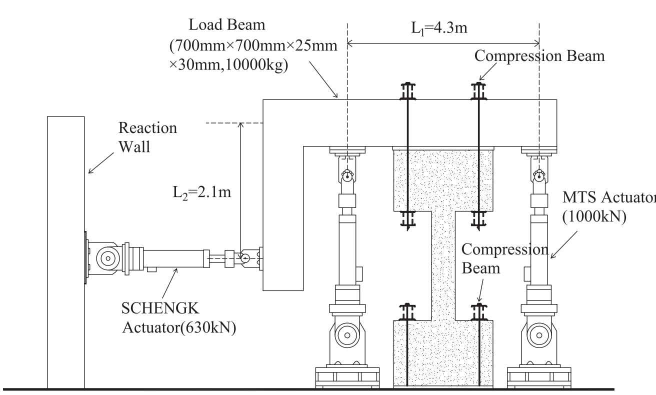

Fig. 2. Test setup.

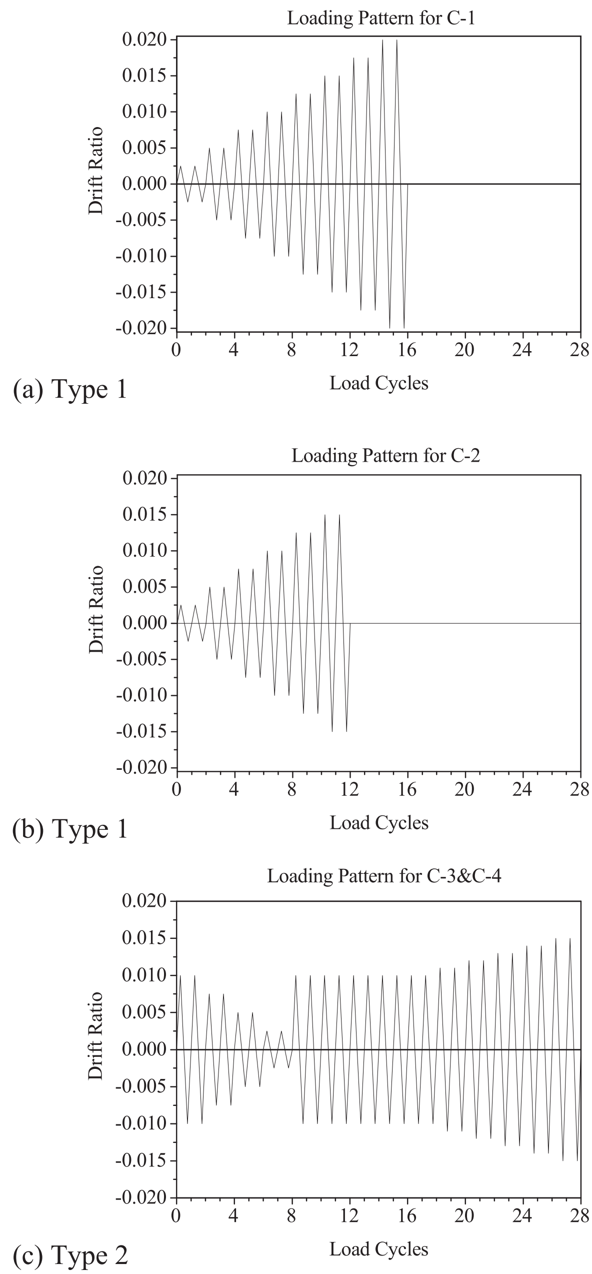

Fig. 3. Loading plans for test specimens.