Seismic Performance of RPC Hollow Rectangular Bridge Columns

G.Y. Zhao[1], G.P. Yan[2] and W.X. Hao[3,4]

[1] *Lecturer, School of Civil Engineering, Beijing Jiaotong University, Beijing. China*
[2] *Professor, School of Civil Engineering, Beijing Jiaotong University, Beijing. China*
[3] *Ph.D Candidate, School of Civil Engineering, Beijing Jiaotong University, Beijing. China*
[4] *Lecturer, College of Urban and Rural Construction, Agricultural University of Hebei, Baoding. China*
Email: gyzhao@bjtu.edu.cn

ABSTRACT :
Two hollow rectangular bridge columns with Reactive powder concrete (RPC) were tested under a cyclically reversed horizontal load. Based on the test results, the seismic behavior of such columns was presented. An analytical model was developed to predict the force-displacement relationship of specimens. The test results were also compared to the proposed analytical model. It was found that the ductility factors of the specimens are over 4.0, and the proposed analytical model can predict the force-displacement relationship of such columns with acceptable accuracy.

KEYWORDS:
Seismic performance, Reactive Powder Concrete, ductility, columns, bridges

1. INTRODUCTION

Reactive powder concrete (RPC) is a new generation cementitious composite material with ultra-high performance (Richard and Cheyrez 1995). It's characterized by extremely superior physical properties, particularly its ultra-high strength and good ductility. Enhanced properties of RPC are obtained though grain size optimization, incorporation of micro-silica and post-set heat-treating. Compressive strength of RPC can range from 200MPa to 800MPa. By introducing fine steel fibers, RPC can achieve remarkable flexural strength up to 50MPa. The material exhibits high ductility, more than 250 times greater than that of conventional concrete (Cheyrezy et al. 1998).

It's feasible to apply RPC to the construction of bridge columns for better seismic performance. RPC columns may become lighter due to ultra-high strength of RPC and seismic inertia loads may be reduced. Ductility of RPC columns can be improved because of high flexural strength and fracture energy absorption capacity of RPC. Consequently, the amount of lateral reinforcement for confinement in columns can be reduced greatly.

In this paper seismic performance of RPC hollow rectangular bridge columns were investigated. Two specimens were tested under a cyclically reversed horizontal load. An analytical model was also developed to predict the force-displacement relationship of columns. The Analytical model was verified by experimental results.

2. EXPERIMENTAL PROGRAM

Two rectangular hollow columns were made from RPC with modified mix design. Compressive strength of RPC is 140MPa and tensile strength is 20MPa. This type of mix can efficiently make costs lower and construction easier. The columns were tested under a cyclically reversed horizontal load. The tests belong to preliminary investigation of seismic performance of RPC columns, so axial force was not applied in the tests for simplicity.

2.1. Specimens

Dimensions of the specimens are shown in Figure 1. The cross section of both specimens is 400 mm. The wall thickness of both specimens is 60 mm. The distance between the lateral loading point and the the top of the foundation is 1.4m. COL1 and COL2 are dedicated to name the two specimens. Table 2.1 includes details of the test specimens. Each specimen contains $16\phi16$ longitudinal rebars providing a reinforcement ratio of 3.94% of the gross sectional area of the column. Yielding strength of the longitudinal steel was 370 MPa. The volumetric ratio of transverse reinforcement to RPC core, measured out-to-out of perimeter ties, are 0.73% and 1.46% respectively, and spacing of the hoops are 100mm and 50 mm respectively.

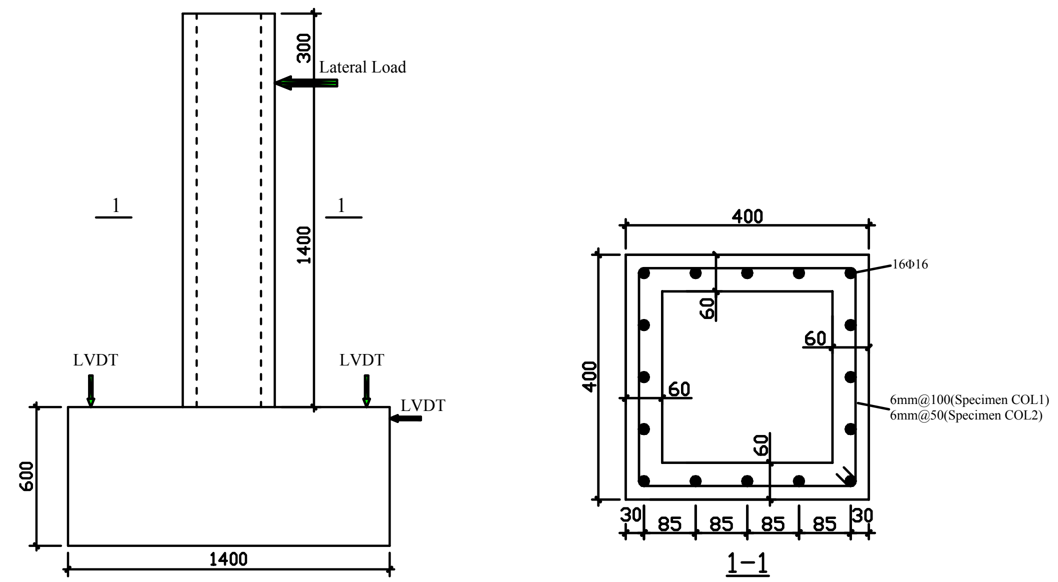


Figure 1 Detail of specimens

Table 2.1 Properties of specimens

Specimen	Length L (m)	f_c' (MPa)	Longitudinal reinforcement			Transverse reinforcement			
			d_s (mm)	f_y (MP)	ρ_l (%)	d_{st} (mm)	s (mm)	f_{yh} (MP)	ρ_s (%)
COL1	1.4	140	16	370	3.94	6	100	235	0.73
COL2	1.4	140	16	370	3.94	6	50	235	1.46

2.2. Materials

Modified mix of RPC with 140MPa compressive strength and 20MPa tensile strength was used. Although both the compressive strength and tensile strength of RPC for specimens are less than that developed by Richard and Cheyrez (1995), costs and construction difficulty may be reduced greatly. That's important for the application of RPC to engineering practice.

2.3. Test Setup and Loading Sequence

The lateral load was applied with a 1000 kN MTS actuator. The applied lateral force and the tip displacement were measured and recorded by the MTS software system. Three linear variable displacement transducers (LVDTs) are placed to monitor the slippage and rotation of the foundation. The specimens were tested under displacement control following a predetermined displacement history. The displacement routines for the specimens consist of several cycles up to failure (Figure 2). The displacement cycles were repeated five times to measure the strength degradation.

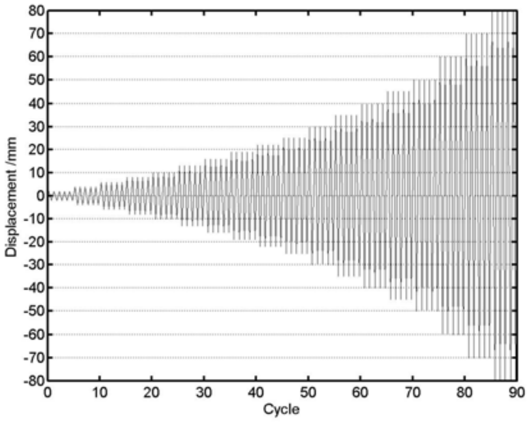


Figure 2 Lateral displacement sequence

3. TEST RESULTS

3.1. General Observations

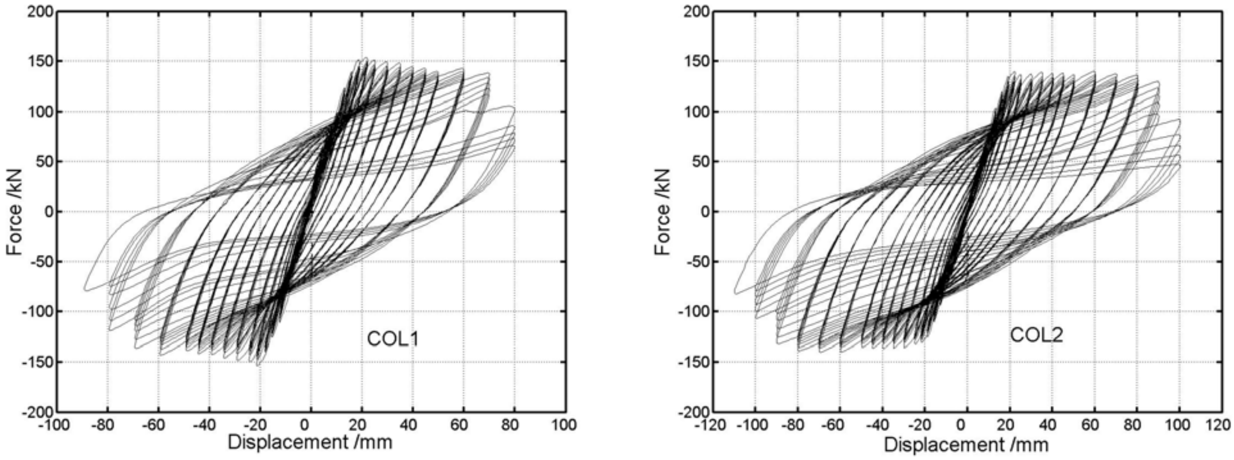
In both specimens, the first crack occurred in the direction perpendicular to the column axis in the plastic hinge region. As lateral force increased, flexural cracking spread. Afterwards, the longitudinal rebars yielded in tension. During the last cycle, buckling of the longitudinal bars was observed after yielding of the perimeter ties (Figure 3), which was an indication of the commencement of failure. The failure mode for both specimens was dominated by flexural effects.

(a) (b)

Figure 3 Specimens at the end of testing. (a) COL1; (b) COL2.

3.2. Hysteretic Loops

Lateral force–displacement hysteretic loops for both columns are shown in Figure 4. The response for the specimen COL2, with 50% higher amounts of transverse reinforcement than the specimen COL2, shows a more stable response. This is a result of the high transverse reinforcement, which enabled transverse steel to effectively confine the core concrete, thus reducing the drastic degradation of lateral strength. The maximum lateral force are 152.8kN and 40.1kN for COL1 and COL2 respectively.



(a) (b)

Figure 4 Hysteretic loops of specimens. (a) COL1; (b) COL2.

3.3. Ductility Factor and Energy Dissipation

Ductility factor and energy dissipation capacity are important indices to quantify the response of columns in seismic design. Both types of indicators are computed in this paper to compare seismic performance of columns. From the response of RPC columns, it's obvious to define an elastic branch and yielding point. The failure of RPC columns is conventionally defined where the remaining capacity of the column has dropped to 85% of the maximum load. It can be seen from Table 3.1 that the ductility factors for both specimens are 4.0 and 4.8 respectively.

Table 3.1 Experimental results

Specimen number	Yielding displacement (mm)	Yielding force (kN)	Ultimate displacement (mm)	Maximum force (kN)	Ductility factor	Energy dissipation (kN.mm)
COL1	18.5	146.6	74.2	152.8	4.0	3.8×10^5
COL2	18.8	130.1	89.6	140.1	4.8	5.3×10^5

3.4. Effect of Amount of Transverse Reinforcement

.

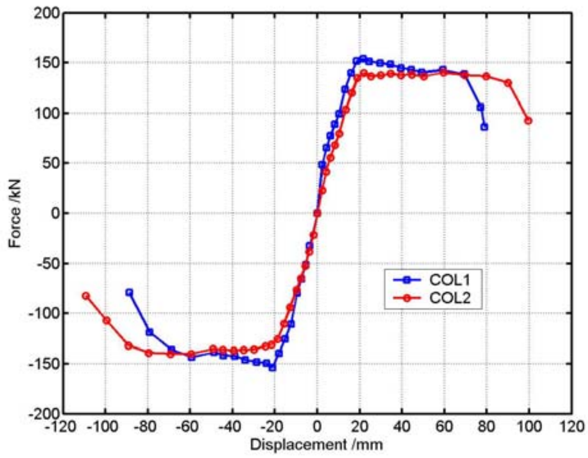


Figure 5 Lateral force-displacement relationships

The volumetric ratio of confinement steel in COL2 is two times that in COL1. Figure 5 illustrates that specimen COL2 can sustain larger inelastic cyclic displacement than specimen COL1. The results presented in Table 3.1 indicate that specimen COL2 has a displacement ductility level 1.2 times that of specimen COL1. The dissipated energy of specimen COL2 is 40% higher than that for specimen COL1. It should be noted that yielding force and maximum force of specimen COL2 is a little lower than that of specimen COL1. Test results show that the volumetric ratio of confinement steel can improve ductility level of RPC columns, but the effect on the strength improvement of columns is not obvious

4. ANALYTICAL RESULTS

4.1. Constitutive Models of Materials

The response of a structure under load depends to a large extent on the stress–strain relation of the constituent materials and the magnitude of stress. In this research the stress–strain relation of RPC in compression is of primary interest.

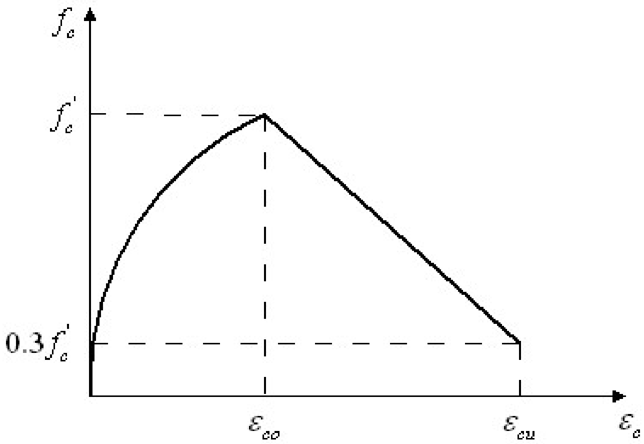


Figure 6 Stress-strain relationship of RPC

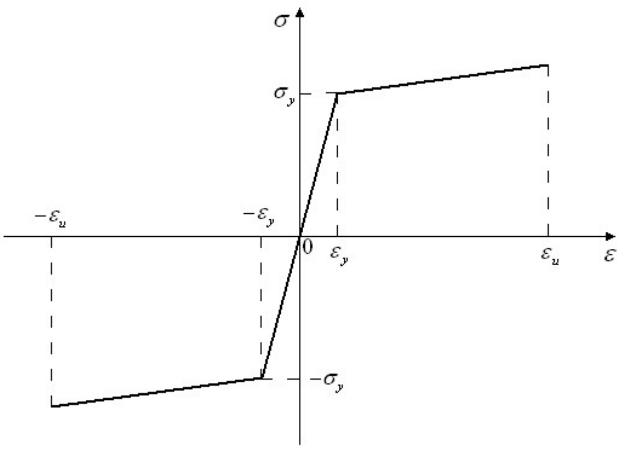


Figure 7 Stress-strain relationship of steel

4.1.1 Stress-strain relationship of RPC

Because research on the failure mechanisms of RPC under biaxial and triaxial loads is under way, a stress-strain relationship proposed from uniaxial compression tests is used to describe behaviour of both unconfined and confined RPC. In this model, as shown in Figure 6, the monotonic concrete stress–strain relation in compression is described by two regions:

$$f_c = f_c'\left[2\frac{\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right], \qquad \varepsilon_c \le \varepsilon_{co} \tag{4.1}$$

$$f_c = f_c'\left[1 - 0.7\left(\frac{\varepsilon_c - \varepsilon_{co}}{\varepsilon_{cu} - \varepsilon_{co}}\right)\right], \qquad \varepsilon_{co} < \varepsilon_c \le \varepsilon_{cu} \tag{4.2}$$

Where, f_c' is the compressive strength of RPC cylinder; ε_{co} is the RPC strain at maximum stress and equals to 0.003; ε_{cu} is the strain where the stress drops to 30% of peak stress and equals to 0.0055.

4.1.2 Stress-strain relationship of longitudinal rebars

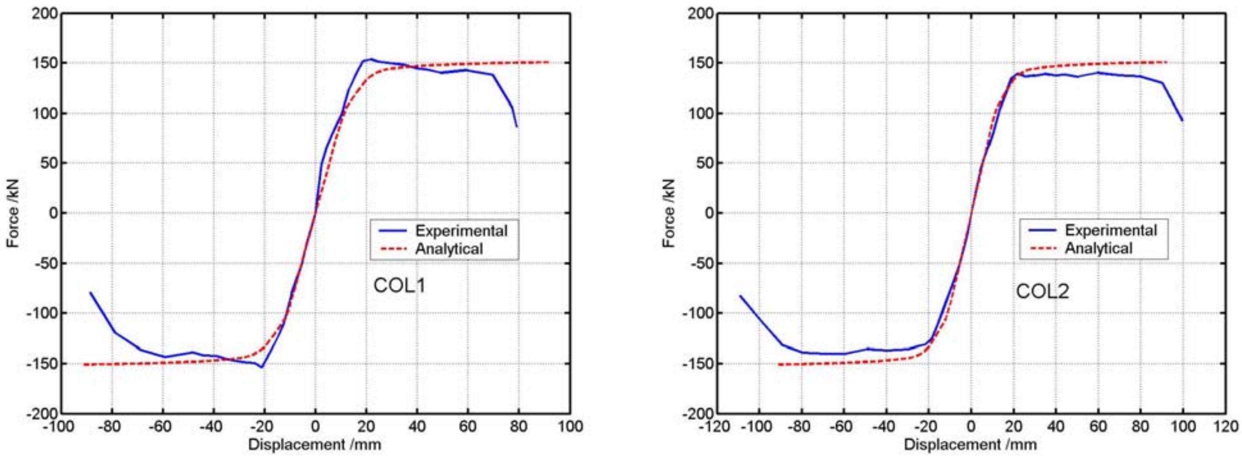
Longitudinal rebar is modeled as a linear elastic, linear strain hardening material with yielding stress σ_y as shown in Figure 7.

4.2. Flexibility-based Fiber Beam-column Element

Many beam-column element models to analyze R/C structures under monotonic and cyclic loads have been proposed to date. Recent studies (Taucer et al. 1991; Spacone et al. 1996a; Spacone et al. 1996b; Neuenhofer and Filippou 1997; Neuenhofer and Filippou 1998) have shown flexibility-based fiber beam-column element model is the most promising one. Flexibility-based fiber beam-element model is based on force interpolation functions within elements. The advantage of this model stems from the realization that the force interpolation functions satisfy the element equilibrium in a strict sense irrespective of the state of the element. Element states are decided by the integration of section responses computed using fiber models. Flexibility-based fiber beam-column element has been included in a Matlab toolbox named as NonlinSim for nonlinear static and dynamic analysis of structures developed by Zhao (2006). Analytical investigations of RPC specimens were carried out using NonlinSim. Constitutive laws proposed for RPC and longitudinal reinforcement aforementioned were used.

4.3. Comparison of Test Data with Analytical Result

Figure 8 shows a comparison of the force-displacement relationships for both tests and analytical models. It can be seen from Figure 8 that the analytical models can predict the test results with reasonable accuracy.



(a) (b)

Figure 8 Experimental and analytical force–displacement diagrams. (a) COL; (b) COL2.

5. CONCLUSIONS

Based on the studies presented in this paper the following conclusions can be made.

(1) The tested RPC hollow bridge columns have acceptable seismic performance because ductility factors for both columns are over 4.0.

(2) Test results show that the volumetric ratio of transverse reinforcement can improve ductility level of RPC columns, but the effect on the strength improvement of columns is not obvious.

(3) The analytical model proposed predicts the force-displacement relationship of RPC hollow bridge columns with acceptable accuracy.

6. ACKNOWLEDGEMENTS

The research has been funded by the National Natural Science Foundation of China (NSFC) through Grant No. 50778017. Construction and testing of the specimens were conducted by the third author as one part of his Ph.D research work.

REFERENCES

Richard, P., Cheyrez, M. (1995). Composition of reactive powder concretes. *Cement and Concrete Research* **25:7**, 1501–1511.
Cheyrezy, M., Behloul,M., Dowd, W.M., Dauriac, C.E.(1998). Reactive Powder Concrete (RPC) application for seismic design. American Concrete Institute Convention.
Taucer, F.F., Spacone, E. and Filippou, F.C. (1991). A fiber beam-column element for seismic response of reinforced concrete structures. *EERC Report* **No. 91/17**, Earthquake Engineering Research Center, University of California, Berkeley.
Spacone, E., Ciampi, V.and Filippou F.C. (1996a). Mixed formulation of nonlinear beam finite element. *Computer & Structures* **58:1**, 71-83.
Spacone, E., Filippou, F.C. and Taucer, F.F. (1996b). Fibre beam-column model for nonlinear analysis of R/C frames: formulation. *Earthquake Engineering & Structural Dynamics* **25**, 711-725.
Neuenhofer, A. and Filippou F.C. (1997). Evaluation of nonlinear frame finite-element models. *Journal of Structural Engineering* **123:7**, 958-965.
Neuenhofer, A. and Fillippou, F. (1998). Geometrically nonlinear flexibility-based frame finite element. *Journal of Structural Engineering* **124:6**, 704-711.
Zhao, G.Y. (2006). Nonlinear analysis and performance-based seismic design of reinforced concrete bridges. *Ph.D thesis*, Beijing Jiaotong University.