SEISMIC BEHAVIOR OF CONCRETE AND STEEL COMPOSITE COLUMNS UNDER CYCLIC LOADING

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SUMMARY

An investigation of the seismic behaviour of 12 CFRT column specimens subjected to reversed cyclic loading and constant axial load is reported. The nonlinear full range analysis of these composite columns was carried out to simulate the test results and to do parametric study. The effects of varying width-thickness ratio of the steel plate, axial compression ratio, and different strengths of infilled concrete on the seismic behaviour of CFRT columns were studied as wall.

INTRODUCTION

The use of concrete-filled rectangular tubular columns in buildings is a new trend in high-rise composite construction. During construction, the flange plate acts as both erection steel and forming for the composite column, decreasing the labor and materials required for construction and, consequently, lowering the construction cost. Structurally, the flange plate acts as longitudinal and transverse reinforcement. The shell also improves the structural behaviour of the column, and efficiently to provide confinement to inside concrete and increase the resistance to bending moment, shear force, and column buckling. On the other hand the flange plate is stiffened by the concrete core, while the ductility of the concrete core is enhanced by the flange plate. The enhanced behaviour of concrete-filled rectangular tubular columns allows the use of smaller sections than required for conventionally reinforced concrete columns with similar loading. The configuration of concrete-filled rectangular tubular columns promotes ductile behaviour of the concrete and yielding of the flange plate, but to what degree is uncertain. Questions exist regarding the bond strength between the concrete core and flange plate, and the onset of local buckling in the flange plate, both of which affect the ductility and strength of column. A better understanding of the behaviour of concrete-filled rectangular tubular columns under seismic loading is necessary to recognise and take advantage of the benefits offered by this form of construction.

The purpose of the experimental study presented in this paper is to investigate the seismic behaviour of concrete-filled rectangular tubular columns. An investigation of the seismic behaviour of 12 CFRT column specimens subjected to reversed cyclic loading and constant axial load is reported. The effects of varying width-thickness ratio of the steel plate, axial compression ratio, and different strengths of infilled concrete on the seismic behaviour of CFRT columns were studied as wall.

OUTLINE OF EXPERIMENT

Test specimens and material property

The tests were carried out at the State Key Laboratory for Disaster Reduction in Civil Engineering in Tongji University. It was conducted on eleven composite column specimens subjected to cycled lateral load, and one specimen subjected to monotonic lateral load. The column specimens were designed in accordance with the column part between the inflection point of top and bottom column.

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In examining earthquake-resistant capability of composite columns, parameters that must be considered include cross-sectional shape, steel grade, structural configuration, welding method of the flange-web connection, width-thickness ratio, slenderness ratio, stiffener rigidity, axial load, and lateral-load history. These parameters are also the main parameters considered on practical design. In this study, based upon typical industry applications in buildings and testing equipment limitations, the main selected parameters were the flange plate width-thickness ratio (Rf=D/t), axial compression force ratio (n=N/N0), and strength of the concrete cores (fc). A schematic illustration of test specimens is show in Fig. 1 and ranges of various parameters of the test specimens are listed in Table 1.

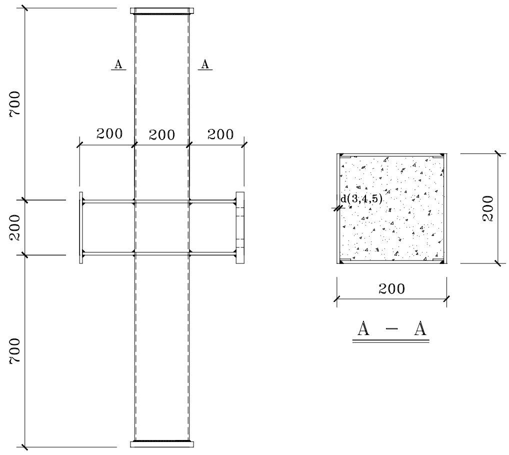

Fig.1 --Test specimens

Table 1—List of Test Specimens

Specimen	D (mm)	t (mm)	Rf	Concrete strength	n	Axial load (kN)	Concrete strain transducers
R4M3	200	4	50	C50	0.3	650	Yes
R4M5	200	4	50	C50	0.5	1100	Yes
R4M7	200	4	50	C50	0.7	1550	Yes
R4M5m	200	4	50	C50	0.5	1100	Yes
R4L5	200	4	50	C40	0.5	1050	No
R4L7	200	4	50	C40	0.7	1450	No
R4H5	200	4	50	C60	0.5	1150	No
R4H7	200	4	50	C60	0.7	1600	No
R5M5	200	5	40	C50	0.5	1200	No
R5M7	200	5	40	C50	0.7	1680	No
R3M5	200	3	67	C50	0.5	950	No
R3M7	200	3	67	C50	0.7	1350	No

The steel used was mild steel of grade 16Mn (nominal yield stress fy=315 MPa), and the nominal thickness of test specimens were 3 mm, 4 mm, and 5 mm. The material properties, which were determined from the tension test on six coupons in each series, are 283Mpa, 311Mpa, and 314Mpa, respectively.

The concrete used for columns consisted of coarse aggregate, medium sand, and ordinary Portland cement. To determine the mechanical properties of concrete, compression tests were carried out on three cubes and three prisms. The measured average values of concrete are given in Table 2.

Table 2—Material Properties of Concrete

Nominal strength	fcu (MPa)	fc (MPa)	Ec (GPa)
C40	39.48	31.00	35.36
C50	44.86	38.50	35.31
C60	48.07	39.34	38.84

Test setup

Fig. 2 shows the test setup. The specimen is supported by cylinder hinged support at top and bottom ends. Axial load was first applied to the bottom of the specimen using a 3200 kN hydraulic jack operated in load control. Lateral load was then applied in the middle of the specimen using a 500 kN servo-controlled hydraulic actuator operated in load control before yield of the stell plate and in displacement control after the yield.

The behaviour of the specimens was monitored during testing by load cell, LVDT, and electrical resistance foil strain gages. All data was recorded intermittently on a personal computer. The self-made concrete strain transducers are embedded in concrete core to measure its strain in longitudinal direction.

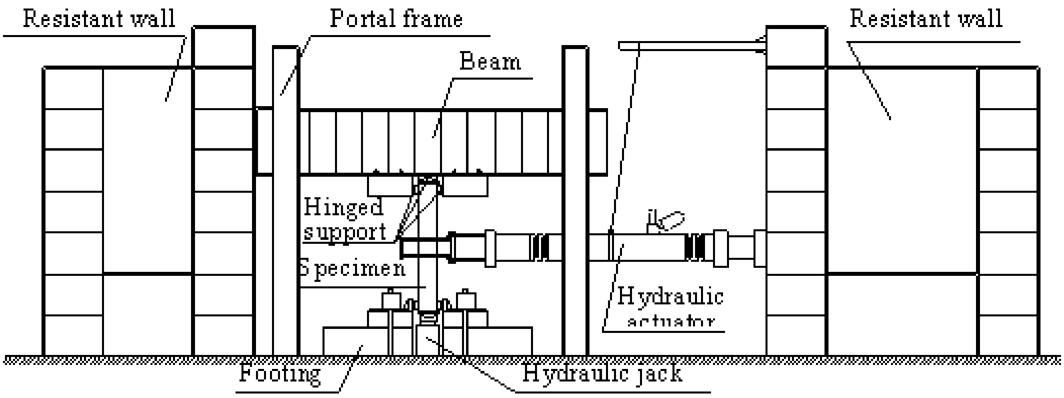

Fig. 2—Test setup

Load Sequence

Each specimen, excluding specimen R4M5m, was subjected to a prescribed horizontal-displacement history under a constant axial load. The horizontal-displacement history consists of sequences of fully reversed displacement cycles as shown in Fig. 3, namely, the peak displacements were increased stepwise after three successive cycles at each displacement level.

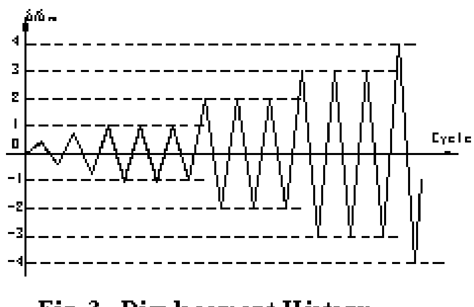

Fig. 3--Displacement History

TEST RESULTS AND DISCUSSION

Collapse Modes

For the test specimens subjected to cycled lateral load, the collapse mode was similar: Slight local buckling deformations were first observed in the flange plates of the column during cycling to $\mu = \pm 2\sim3$, and then observed in the opposite flange plate during reversed loading. After that, the buckling waves progressively grew, and eventually the specimen lost its lateral resistance after vertical cracking in the weld material of flange-web junctions became considerable. There was also some diffident in these specimens: the specimens with 3 mm plate have several obvious buckling waves but the specimens with 4, 5 mm plate only one; the local buckling was observed earlier in specimens with higher compression force ratio than specimens with lower compression force ratio. Fig. 4 shows the specimen R3M7 after failure.

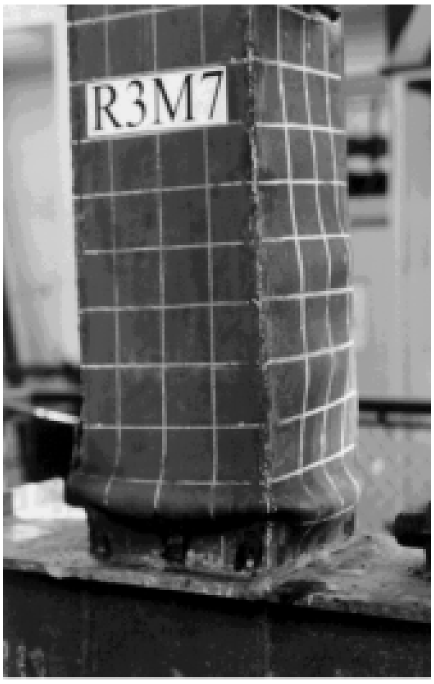

Fig.4 R3M7 after failure Failure

Fig.5 Typical concrete failure Appearances of Filled-in Concrete

The specimen R4M5m was subjected to monotonic lateral load under constant axial load. It was terminated before its lateral resistance decreased considerably because of the limitation of stroke of the horizontal actuator. Local buckling deformations were observed only in the compressive flange plates of the column and no vertical cracking in the weld material of flange-web junctions.

The flange plates of some specimens were removed after failure by gas-cutting, it was observed that concrete behind the portions of plates that buckled was seriously crushed and meshy crack was observed in both sides of buckled plates. Shown in Fig. 5 is a typical failure appearance of filled-in concrete.

Horizontal Load versus Horizontal Displacement Hysteretic Curves

The typical horizontal load versus horizontal displacement hysteretic curves for the test specimens is shown in Fig. 6.

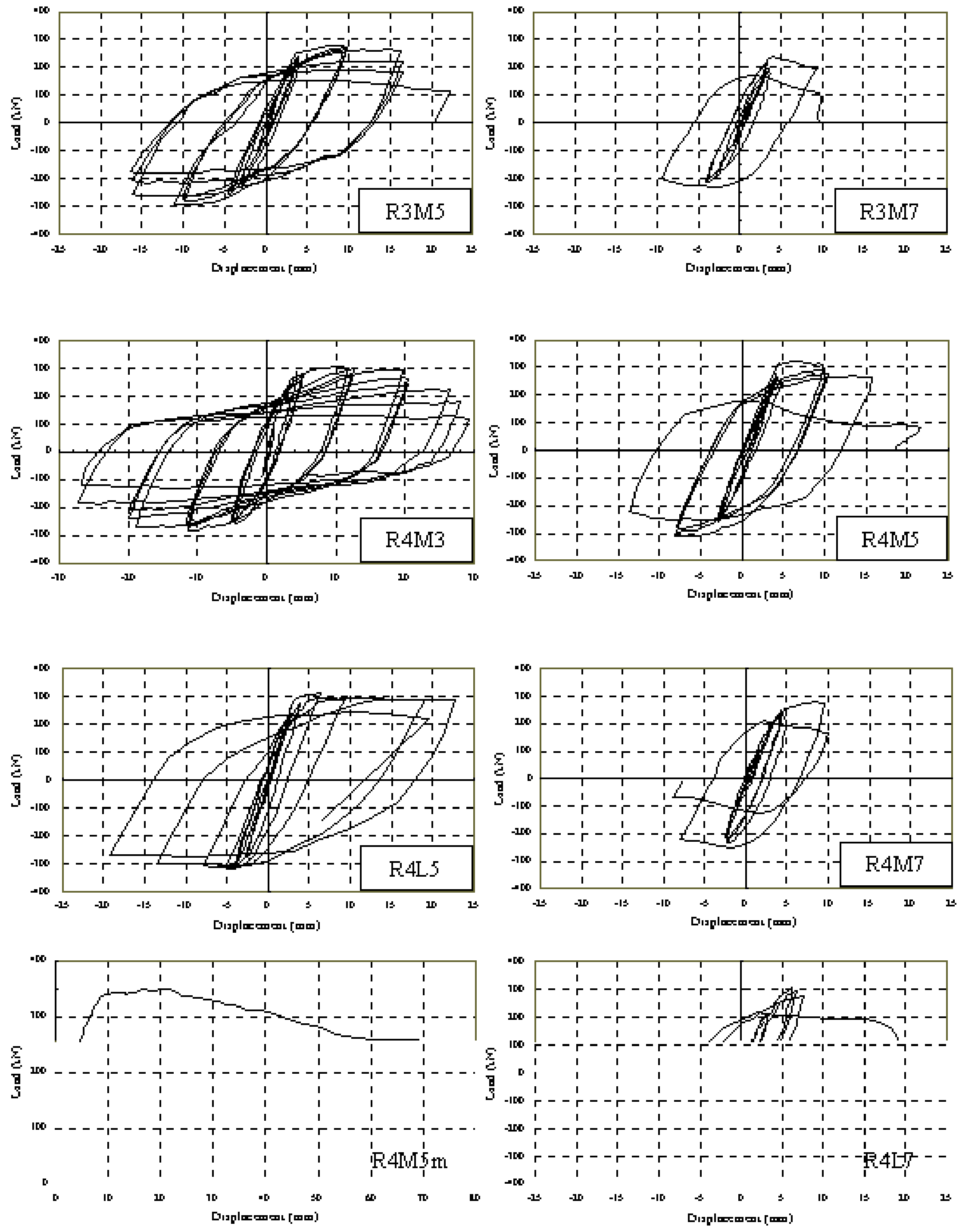

Fig.6 Horizontal load versus horizontal displacement hysteretic curves

Test Data

The original test results are given in Table 3. The notation used in Table 4 is as follows: N0=fcAc+fyAt is the nominal collapse load of the specimen; n=N/N0 is the compression force ratio; Qul and Qur are the lateral load when specimen reaching ultimate load in positive cycles and negative cycles, respectively; Xu is the displacement when the bearing capacity of the specimen descended to 0.85Qu; Xy is the yield displacement of the specimen; μ is the ductility factor of the specimen.

Table 3 Test Result

No.	Specimen	D (m)	t (mm)	fcu (MPa)	fy (MPa)	N/N0	N (kN)	Qul (kN)	Qur (kN)	Xy (mm)	Xu (mm)	μ
1	R3M5	200	3.030	44.9	283.4	0.5	950	-292.9	280.4	3.52	17.01	4.83
2	R3M7	200	3.041	44.9	283.4	0.7	1350	-230.4	238.9	2.98	8.63	2.90
3	R5M5	200	4.908	44.9	314.1	0.5	1200	-353.1	375.3	3.52	15.27	4.34
4	R5M7	200	4.955	44.9	314.1	0.7	1680	-340.5	321.7	3.01	9.66	3.21
5	R4L5	200	4.054	39.5	311.0	0.5	1050	-316.8	313.1	2.83	--•	--
6	R4L7	200	4.068	39.5	311.0	0.7	1450	-284.5	305.1	3.32	10.14	3.05
7	R4H5	200	4.075	48.1	311.0	0.5	1150	-385.8	366.8	2.39	12.37	5.17
8	R4H7	200	4.074	48.1	311.0	0.7	1600	-346.6	337.1	3.17	12.10	3.82
9	R4M3	200	4.073	44.9	311.0	0.3	650	-283.6	305.2	3.05	22.99	7.54
10	R4M5	200	4.071	44.9	311.0	0.5	1100	-309.7	321.0	2.96	15.09	5.10
11	R4M7	200	4.066	44.9	311.0	0.7	1550	-250.2	277.8	3.52	9.71	2.76
12	R4M5m	200	4.078	44.9	311.0	0.5	1100	-	349.7	5.73	43.70	7.63

The envelope of load-displacement hysteretic curves doesn't descended to 0.85Qu.

Effect of width-Thickness Ratio

The width-thickness ratio (D/t) is the reflection of the steel ratio of the section. So the specimens with larger width-thickness ratio got higher ultimate strength.

In this study, the test results show that the ductility of the specimens with small width-thickness ratio is not greater than the specimens with large width-thickness ratio (Fig. 7). It possibility has two causes: First, the width-thickness ratio of the specimens in this study is very large when compared with it used in pure steel tubular structure, so the concrete confinement provided by the flange plate is very small. Second, the concept of the axial compression ratio used in this study is different from it used in conventionally reinforced concrete structure. It based on the "nominal collapse load" which include the compression strength of the steel flange plates.

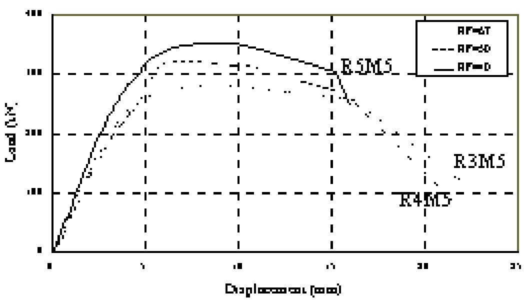

Fig.7—Load-Displacement Envelope Curves with Different D/t

Effect of concrete core strength

The effect of the concrete core strength is shown on only in the ultimate strength but also in the ductility. High-strength concrete in the column core resulted in higher ultimate strength but greater strength degradation and lower energy dissipation when compared to columns with normal strength concrete core. The load-displacement envelope curves of specimens R4L5, R4M5, R4H5 are shown in Fig. 8.

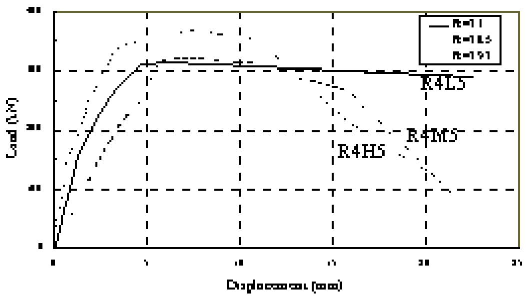

Fig.8—Load-Displacement Envelope Curves with Different f_c

Effect of axial compression force ratio

As it found in reinforced concrete structure and steel structure, axial compression force ratio has large effect for structure aseismatic behavior. The test result shown that higher axial compression force ratio resulted in lower energy dissipation and greater strength degradation. The load-displacement envelope curves of specimens R4M7, R4M5, R4M3 are shown in Fig. 9.

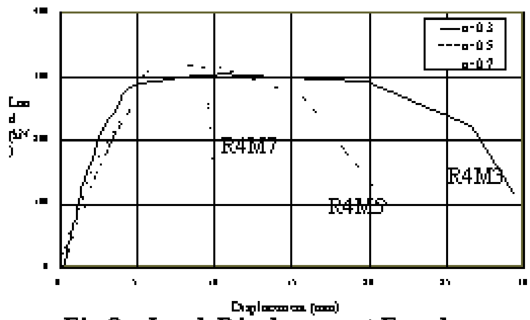

Fig.9—Load-Displacement Envelope Curves with Different n

Effect of Load Sequence

Specimen R4M5 and R4M5m has the same test parameters except the load sequence. Before the buckling of flange plates, the specimen R4M5 and R4M5m have same behavior – their load-displacement curves are superposition, then the specimen R4M5 which subjected cyclic lateral loading shown greater strength degradation than the specimen R4M5m which subjected monotonic lateral loading. The load-displacement envelope curves of specimens R4M5 and R4M5m are shown in Fig. 10.

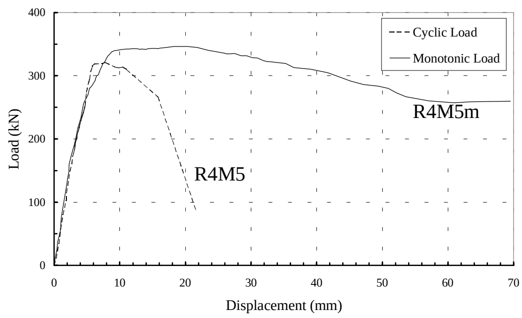

Fig.10—Load-Displacement Envelope Curves with Different Load Sequence

Comparison of Experimental and Computational P-Δ Curves

The comparison of tested and calculated P-Δ curves are shown in Fig. 11 which indicate that the calculated results agree well with the test results.

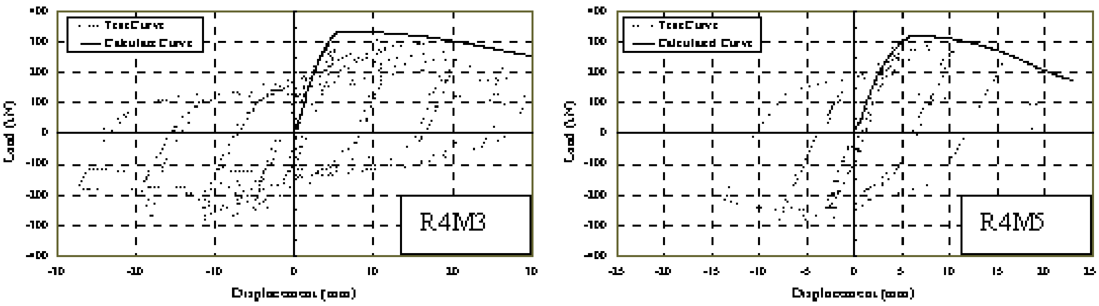

Fig.11 Comparison of Experimental and Computational P- ΔCurves

CONCLUSIONS

The seismic behavior of CFRT column under cyclic loading is good. Compared to steel tubular columns, the CFRT columns exhibited better behavior of resisting local buckling; Compared to conventionally reinforced concrete columns the CFRT columns exhibited greater energy-dissipation characteristics.

The test results show that the use of a thicker steel tube can increase the strength. Higher concrete strength will result in higher ultimate strength but larger strength degradation and lower energy dissipation compared to columns with normal strength concrete. It was also found that higher axial compression force resulted in low energy dissipation and larger strength degradation.

The numerical method proposed in this paper can not only simulate the load-displacement relationship but also calculate the ultimate strength of CFRT columns, and it can replace the experiment to a certain degree.

REFERENCES

Lu, W, “Research on Seismic Behavior of Concrete-Filled Rectangular Steel Tubular Columns under Cyclic Loading”, Master degree dissertation, Research Institute of Engineering Structures, Tongji University, P. R. China. (in Chinese)

Zhang, Z., “Research on Basic Behavior of concrete Filled Square Steel Tubular Stub under Eccentric Load”, *Journal of Building Structures*, Vol. 10, No. 6, 1989. (in Chinese)

Lu, X., Jin, G, and Wu, X., “Nonlinear Finite Element Analysis and Application of Reinforced Concrete Structures”, Publisher of Tongji University, China. (in Chinese)

Li, S., Huo, D., and Wang, Q., “Ultimate Strength of Concrete Filled Square Steel Tubular Columns under Eccentric Compression”, *Journal of Building Structures*, Vol.19, No. 1, 1998. (in Chinese)

Hajjar, J. F., and Gourley, B. C., “Representation of Concrete-Filled Steel Tube Cross-SectionStrength”, *Journal of Structural Engineering*, ASCE, V.122, No.11, November 1996.

Knowles, R.B., and Park, R.•Strength of Concrete-Filled Tubular Columns, *Journal of Structural Division*, ASCE, V.95, No.12, December 1969.

Matsui, C., Tsuda, K., Ozaki, I., and Ishibashi, Y., “Strength of Slender Concrete Filled Steel Tubular Columns”, *J. Struct. Cnstr. Eng.*, AIJ, No. 494, 1997. (in Japanese)

Furlong, R. W., “Strength of Steel-Encased Bean-Columns”, *Journal of Structural Division*, ASCE, V.93, No.5, May 1967.