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SIZE EFFECT ON CONFINING STRESS OF CIRCULAR CONCRETE FILLED IN STEEL TUBE UNDER AXIAL COMPRESSION

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Abstract: Size effect is one of the principal mechanical properties of concrete under uniaxial compression. Size effect on compressive strength of concrete has been investigated and provided the corresponding rules of the size effect. However, size effect on confining action on concrete subjected from steel tube has been not sufficiently studied. To fill the gap, size effect on the confining stress of concrete filled in steel tubular under axial compression was discussed. 4 groups of circular short columns of concrete filled in steel tube were conducted under monotonic axial compression. The diameters of the specimens were 219mm, 426mm, 630mm, and 820mm respectively. The ratios of diameter to thickness of the specimens were 88. The grade of concrete was C30. Damage processes of the specimens with different sizes were described. The final failure modes of all specimens were shear failure. Based on the calculation method of steel tube stress derived by Gu's, horizontal and longitudinal strain of steel tube obtained from each measuring point on the specimen during the test was transformed into the corresponding horizontal and longitudinal stress on the surface of steel tube respectively. Then, the average of the steel stress of all measuring points arranged on one specimen was taken to behalf the stress of overall steel pipe in longitudinal and lateral directions. Therefore, the confining stress when the peak load was achieved was obtained based on the average lateral stress of the steel tube. The analysis results indicated that when the peak load was achieved, the ratio of the vertical stress to the yield strength of the steel tube was enlarged with the diameter of the specimen increased; the ratio of the transverse stress to the yield strength of the steel pipe decreased with increment of the diameter of the specimen; the confining force provided by steel tube to the core concrete also reduced with the enlargement of the size of the column. All the variation degree gradually slowed down when the size of the column enlarged. The confinement action to the concrete existed size effect. According to the test results, calculation model of confining force considering the

size effect was built, and results calculated by the model were in good agreement with experimental results.

1 INTRODUCTION

Concrete material exists size effect inevitably due to its quasi brittle anisotropic materials nature. The size effect of concrete compressive strength behaves that strength of concrete under uniaxial compression gradually reduces along with the rising of size of the concrete cross section, and the decreased degree slows down gradually along with the increase of the size. Blanks and Mcnamara[1]conducted axial compression experiment on concrete cylinders with different section sizes and grading of aggregate, then the results showed that the compressive strength of concrete cylinder existed size effect, and the reduction extent of concrete strength stabilized after the specimen diameter reached 609.6mm. Bazant[2] put forward an analytical model of compressive strength of concrete related to component dimensions according to the internal buckling theory, to explain the mechanism of size effect on concrete strength under axial compression. Kim[3] built a half experience and half theory formula of compressive strength of concrete considering size effect based on a large number of test data. Noguchi[4] provided a calculation formula of compressive strength of concrete considering section size, and the strength varied with the change of concrete volume to behave its size effect.

Size effect on concrete under uniaxial compression has been investigated and provided the corresponding rules of the size effect. Size effect on performance of confined concrete under axial compression also has been one of the main concern in the area of size effect on concrete. Among confined concrete, core concrete of concrete-filled in steel tube (CFT) is subject to tri-axial compression, because of the fully enclosed confinement by the surrounding steel tube. The confining force provided by steel tube to the core concrete is the most representative in all kinds of confined concrete, and some scholars have also made some exploratory research on size effect on circular CFT columns. Saknio[5] conducted 23 CFT short columns with different section sizes and wall thicknesses under axial compression, and all section diameters were smaller than 450mm, then the size effect correction coefficient $r_u = 1.67D^{-0.112}$ was fitted based on the test data of Blanks[1], in which D was the outer diameter of the specimen; the correction coefficient was used in the part of uniaxial compression strength in the formula of bearing capacity of CFT. Yamamoto[6] carried on experimental study on size effect on circular and square CFT columns complied with the principle of similarity, with the diameter-thick ratio of 31.8 for circular CFT column and 44.4 for square CFT columns, and the section size was below 300mm; the results showed that size effect on compressive strength of circular CFT column was not obvious, while size effect on the square column was significant; the given calculation formula of bearing capacity adopted the same correction coefficient of size effect provided by Sakino[5]. Chen[7] took the CFT column of arch bridge with diameter of 1200mm and steel tube thickness of 24mm as the prototype, to carry on scale experiment of CFT columns in the proportion of 1:2.4 (diameter was 500mm) and 1:4.8 (diameter was 250mm) under axial compression; the test results showed that there was not big difference on the ratio of test bearing capacity to the code value between large size specimen and the small size one. Caner and Bazant[8] conducted an axial compression test of circular CFT columns with a series of different wall thicknesses but the same diameter size of core concrete; the critical steel ratio of the CFT existing size effect was 4% - 8% derived based on the test result. Wu[9] processed 5 groups a total of 19 bearing strengths of circular CFT columns under axial compression; the results showed that the smaller the lateral restriction of core concrete, the more significant the size effect, and the size effect of circular CFT column under axial compression obeyed the Bazant's unified size law.

Current research for size effect on CFT showed that the size effect are covered when the confinement action was strong enough to change brittle failure of concrete into the plastic failure; when the lateral confining force was not big enough to cover the size effect, the calculation formula of bearing capacity of CFT under axial compression only considered size effect correction in the part of the concrete cylinder strength, but not evaluated the size effect on the strength part of confinement action provided by steel tube to concrete. To evaluate the above problems, referring to the engineering practice of CFT in China, this paper has carried on experiment research on axial compression performance of circular CFT short columns with the diameter to thickness ratio of 88 and with specimen size span of 219-820mm. The size effect on confining force provided by the steel tube on concrete was discussed, and the evaluation method of the size effect was proposed.

2 SPECIMEN DESIGN AND MECHANICS PERFORMANCE OF MATERIAL

There are 4 groups of 8 specimens as a total in the axial compression experiment of circular CFT columns. The ratio of height to diameter of specimen was 3. The nominal diameter-thickness ratio (D/t) was 88. The test parameter was outer diameter of specimen, the nominal size of which was 219, 426, 630 and 820mm respectively. The design details of specimens are given in Table 1. The numbers in Table 1 were measured values. In Table 1, the meaning of specimen number is as follows: C represents the circular columns; D is the diameter of specimen; the number 2, 4, 6 and 8 after D denotes that the diameter of specimen is 219, 426, 630 and 820mm respectively; the last number -1 or -2 denotes the first or the second specimen in the same group.

The concrete grade of specimens was C30, and the pumping concrete was used, with the maximum aggregate size of 25mm. Steel tube with the grade of Q235 was adopted in the specimens. The steel tube with the diameter of 219mm was straight seam pipe, and tubes with other diameters used spiral pipe. All specimens were cast vertically by layers in the same batch. The height of each cast layer was 30-50mm. Cube and prism concrete blocks were reserved in the casting process. Steam curing was used after the casting. Steel plates were set at the top and bottom of the specimen, and the bottom steel plate was welded with steel pipe before casting, and the top steel plate was welded on the tube after concrete curing and top surface plastering. The surface of steel pipe was painted white in order to proof rust in the process of specimen production and observe phenomena in the test. 3 steel samples were reserved for each type of steel tube vertically. The mechanical properties of steel and concrete are listed in Table 2 and Table 3, and the mechanical properties were obtained according to the Chinese Code GB-T228.1-2010 and GBT 50081-2002[10-11].

Table 1: Details of specimen design

Specimen No.	Diameter D/mm	Height H/mm	Thickness of steel tube t/mm	D/t
CD2-1	215.4	657	2.5	85.0
CD2-2	216.6	657	2.5	86.6
CD4-1	425.8	1278	5.2	82.4
CD4-2	427.1	1278	5.1	83.8
CD6-1	628.5	1890	6.9	91.1
CD6-2	628.0	1890	7.1	88.0
CD8-1	817.4	2460	9.0	90.8
CD8-2	820.8	2460	9.3	87.9

Table 2: The mechanical properties of steel tube

Specimen No.	Yield strength f_y [MPa]	Ultimate strength f_u [MPa]	Break elongation A [%]
CD2	590.4	619.5	3.7
CD4	259.8	418.4	24.4
CD6	276.0	437.9	29.1
CD8	278.8	416.2	30.9

3 LOADING SYSTEM AND MEASUREMENT ARRANGEMENT

The experiment was conducted in the Key Laboratory of Urban Security and Disaster Engineering of Education Ministry of Beijing

University of Technology. The 4000t of multifunction electro-hydraulic servo loading system was used to apply axial compression load on the specimens. The loading device and arrangement of measuring points are displayed in Figure 1.

Table 3: The mechanical properties and mixture ratio of concrete

Grade of concrete	C30
The prism compressive strength f_c [MPa]	41.24
The cube compressive strength f_{cu} [MPa]	51.51
Cement [kg•m^{-3}]	270
Water [kg•m^{-3}]	175
Sand [kg•m^{-3}]	865
Stone [kg•m^{-3}]	1015
Admixtures [kg•m^{-3}]	4.8
Fly ash [kg•m^{-3}]	67

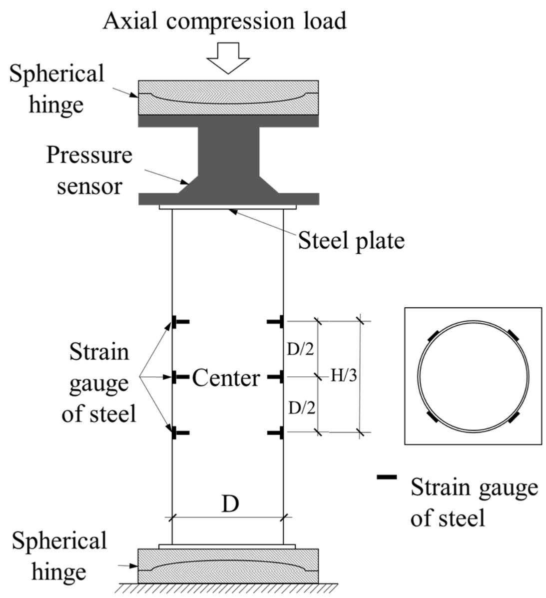

Figure 1: Test loading device and arrangement of measuring points.

The hybrid control of force and displacement was used as loading system. The loading process was as follows: firstly, 500kN was preloaded and then unloaded on the column, to examine whether all the instruments and data collection system worked normally; then, load system of force control was adopted to load continuous loading on the column; when the specimen nearly reached yield, the loading system switched into displacement control, and then the displacement control adopted uniform continuous loading method; until the total deformation reached 6% of the height of the specimen, the test loading ended. The load time of specimen was proportional to the specimen size.

In the test, the measurement data included the axial load of the specimens, steel strain, etc. All data were collected by the IMP static data acquisition system. The axial load on the specimen was measured by the force sensor. The strain of the steel tube was recorded by the steel strain gauge, which was arranged in the scope of 1/3 height of the specimen and distributed at four sides of the specimen. Each measuring point included a vertical strain gauge and a horizontal one. Therefore there was a total of 24 strain gauges for each specimen.

4 FAILURE MODE OF SPECIMEN

The destruction of the specimen was basically experienced the following process: with the increase of load, the axial deformation of specimen gradually added; then when the peak load reached, the development of axial deformation accelerated; after reaching the peak load, along with the improvement of axial deformation, the white paint on the surface of steel tube began peeling, and oblique fracture band gradually formed in the surface of steel tube; then the main oblique crack connected and got though the specimen gradually, and local buckling occurred in the surface of steel tube, along with the continuous falling of bearing capacity of the specimen; finally the inclined section formed, the specimen lost its bearing capacity and damaged.

All surfaces of specimen at the time of peak load are shown in Figure 2. It can be seen that the specimen performed axial deformation mainly, and the oblique fracture band was not formed. After the test, the failure modes of all specimens are displayed in Figure 3, and all the specimens occurred shear failure mode finally.

5 STRESS ANALYSIS OF STEEL TUBE

In order to obtain the confining action provided by steel tube to concrete, quantitative analysis on the stress state of the whole loading process was necessary to make. Therefore, measured strain field on the surface of the steel tube must be transformed into stress field, in order to obtain the lateral and longitudinal stress of the steel tube, then the confining stress subjected on concrete from steel tube can be derived by the lateral stress of steel tube.

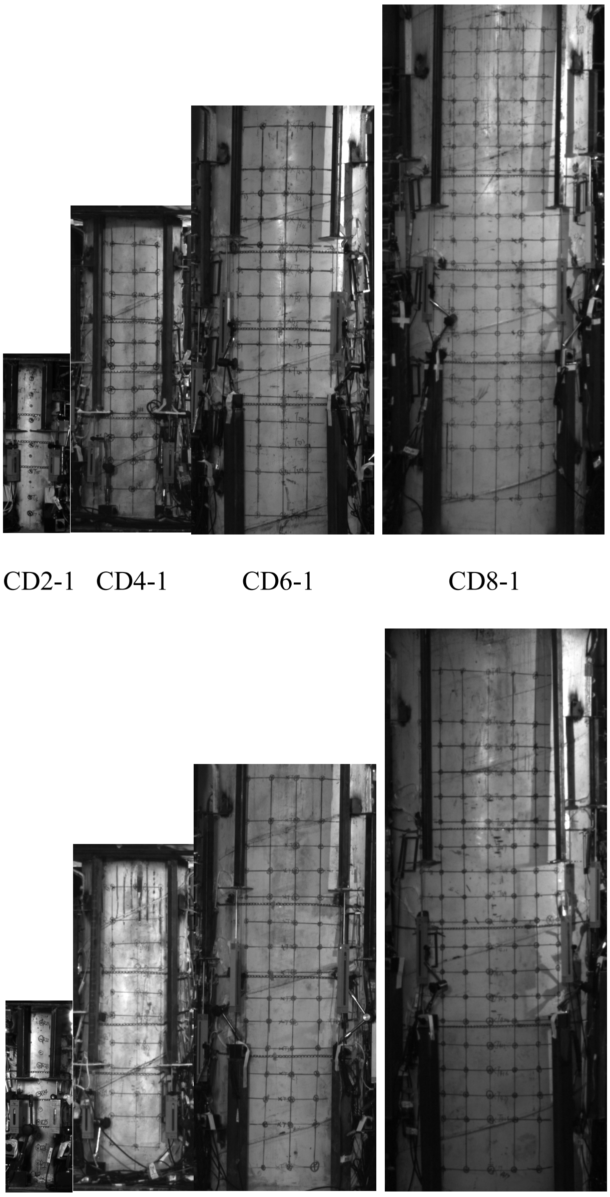

Figure 2: Specimen appearance at the peak load.

The steel tube stress of circular CFT column under axial compression conforms to the Von Mises yield criterion. Gu's[12] calculation method of steel tube stress used the generalized hooke's law in the elastic stage, and adopted total deformation theory and numerical iterative method to obtain the initial value which connected the elastic stage and the plastic stage. Then incremental theory was utilized after entering the plastic stage. The differential equations based on the Prandtl-Lester flow rule and the Von Mises yield criterion were solved simultaneously to obtain the lateral and longitudinal stress of steel tube. This paper Gu's method [12] was adopted to transform the transverse and longitudinal strain of each gauge points arranged on the surface of steel tube into the transverse and longitudinal stress of the steel tube.

Figure 2 shows that the oblique crack band was not formed at the moment of peak load, and all specimens performed axial deformation mainly. Also, Guo[13] described that when the peak load was reached, concrete under triaxial compression occurred axial splitting cracks, and the main oblique cracks formed after entering the load declining segment along with further development of deformation. Therefore, the mean value of horizontal and vertical stress of all gauge points on each specimen was regarded as a representative of transverse and longitudinal stress of steel tube of the specimen.

In order to analyze the size effect on stress distribution of the steel tube at the moment of the peak load, the influence of different steel yield strength of steel tube on transverse and longitudinal stress distribution should be removed. Therefore, the yield strength of the steel tube was divided by the representative transverse and longitudinal stress of steel tube of the specimen, namely transverse stress distributed ratio and longitudinal stress distributed ratio of steel tube respectively, which is given in Table 4 and Figure 4.

Table 4 and Figure 4 illustrates that the transverse distribution ratio of steel pipe decreased with increasing diameter, and the lateral stress ratio slightly increased when specimen diameter rase up to 820mm; however, the vertical stress distribution ratio of steel pipe increased with the size, and the longitudinal stress distribute ratio slightly reduced when the specimen diameter grew to 820mm. The transverse and longitudinal stress distribution ratio of steel pipe existed size effect.

CD2-1 CD4-1 CD6-1 CD8-1

CD2-2 CD4-2 CD6-2 CD8-2

Figure 3: Final failure mode of the specimen.

Fitting the data in Figure 4, the relation between transverse stress distribution ratio of steel tube and specimen diameter at the moment of peak bearing capacity can be derived, as shown in Equation (1), and the fitting curve is displayed in Figure 5.

$$G_\theta = 2.76D^{-0.29} \quad (1)$$

In Equation (1), G_θ is transverse stress distribution ratio of steel tube when the bearing capacity was reached; D is specimen diameter, the unit of which is mm.

Table 4: Horizontal and vertical stress distribution ratio of steel tube at peak load moment

Specimen No.	The ratio of lateral stress	Mean value	The ratio of vertical stress	Mean value
CD2-1	57.2%	60.7%	63.5%	58.4%
CD2-2	64.1%		53.4%	
CD4-1	45.0%	48.3%	67.0%	64.1%
CD4-2	51.5%		61.2%	
CD6-1	37.1%	38.4%	75.0%	73.6%
CD6-2	39.6%		72.3%	
CD8-1	43.8%	45.9%	69.2%	65.2%
CD8-2	48.0%		61.2%	

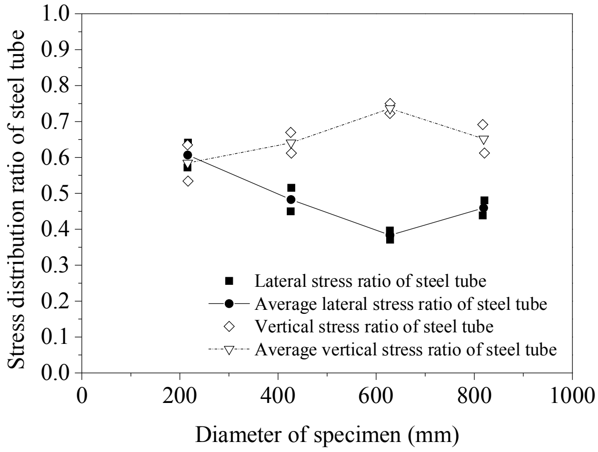

Figure 4: The relationship between distribution ratio of steel tube at peak load and specimen size.

6 LATERAL CONFINING STRESS

After the representative transverse stress of steel tube was got, according to the relationship of the force and reaction between steel tube and core concrete, then the lateral confining action provided by steel tube on core concrete, namely confining stress. The relationship between confining stress and the transverse stress of steel tube can be described as Equation (2) and (3). The direction of confining stress was along the direction of column diameter and pointed to the column center.

$$p = 2t/(D-2t)\ \sigma_\theta \tag{2}$$

$$\sigma_\theta = G_\theta f_y \tag{3}$$

In Equation (2) and (3), p is the confining stress from steel tube to core concrete; σ_θ is the representative transverse stress of steel tube.

The confining stress from steel tube to core concrete derived from experimental data at peak time is shown in Table 5 and Figure 6. It can be observed that the confining stress from steel tube to concrete reduced with enlargement of cross section diameter of specimen. When the diameter of specimen grew to 820mm, the confining force slightly increased but still smaller than that of the smallest size specimen. Therefore, the confining stress existed size effect.

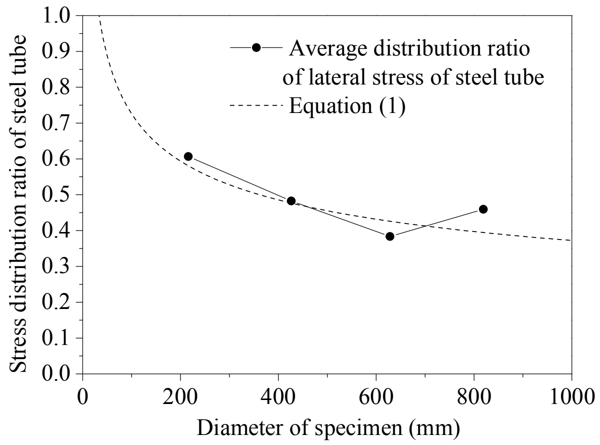

Figure 5: Model of lateral stress distribution ratio of steel tube at peak load.

Table 5: Confining stress at peak load

No.	Test value N_e [MPa]	Mean value [MPa]	Calculation value N_c [MPa]	N_c/N_e
CD2-1	8.13	8.53	8.18	0.96
CD2-2	8.94			
CD4-1	2.91	3.09	3.05	0.99
CD4-2	3.28			
CD6-1	2.30	2.42	2.69	1.11
CD6-2	2.54			
CD8-1	2.75	2.94	2.52	0.86
CD8-2	3.12			

Equation (1), (2) and (3) was brought together to build the calculation model of confining stress of the CFT short column under axial compression at peak load moment. The calculation results of confining stress are listed in Table 5. The calculated value and the test results of confining stress are displayed in Figure 6. Table 5 and Figure 6 indicates that the calculated results were in good agreement with the test value.

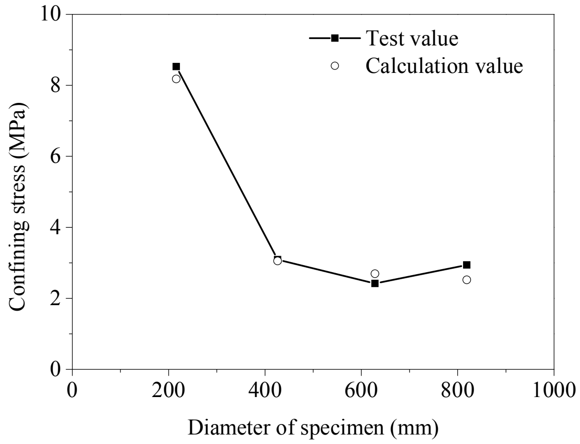

Figure 6: The relationship between confining stress of steel tube at peak load and specimen size.

7 CONCLUSIONS

In order to investigate the size effect on confined action on the core concrete provided by steel tube in CFT column, four groups of eight circular CFT short columns with different sizes were conducted under axial compression. The diameter to thickness ratio of the specimen was 88; concrete grade of the column was C30, and Q235 steel served as the material of steel tube of the specimen. The following conclusions can be generated based on the test result.

At the moment of peak bearing capacity, the columns developed axial deformation primarily, and the oblique crack has not been formed yet. Ultimately, the columns occurred shear failure.

The measured strain field of the steel tube was transformed into the stress field of the steel tube. The representative lateral stress of the steel tube of the column reduced when the section size of the column raised. The representative longitudinal stress of the steel tube of the column improved with the increase of section diameter of the specimen. When the diameter of specimen raised to 630mm, the reduction or improvement trend of stress of steel tube became slow down.

Based on the experimental values, the confining stress on core concrete from steel tube decreased with the increasing of specimen size. When the diameter raised more than 630mm, the decrease tendency became flat. The calculation model of the confining stress was built. The calculation results of the confining stress were well agreed with the test results.

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