International Journal of Concrete Structures and Materials
Vol.5, No.1, pp.49~55, June 2011
DOI 10.4334/IJCSM.2011.5.1.049

Size Effect of Axial Compressive Strength of CFRP Confined Concrete Cylinders

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(Received January 11, 2011, Revised March 8, 2011, Accepted May 31, 2011)

Abstract: The main objective of this investigation is to study size effect on compressive strength of CFRP confined concrete cylinders subjected to axial compressive loading. In total 24 concrete cylinders with different sizes were tested, small specimens with a diameter of 100 mm and a height of 200 mm, medium specimens with a diameter of 200 mm and a height of 400 mm, and big specimens with a diameter of 300 mm and a height of 600 mm. The lateral confining pressure of each specimen is the same and from that hypothesis the small specimens were confined with one layer of CFRP, medium and big specimens were performed by two and three layers of CFRP respectively. Test results indicate a significant enhancement in compressive strength for all confined specimens, and moreover, the compressive strengths of small and medium specimens are almost the same while a bit lower for big specimens. These results permit to conclude that there is no size effect on compressive strength of confined specimens regardless of cylinder dimension.

Keywords: size effect, compressive strength, CFRP, concrete cylinder, confinement.

1. Introduction

The use of Fiber Reinforced Polymer (FRP) wrapping instead of steel jackets has become more popular for external reinforcement, not only for its good resistance to corrosion and ease on-site handling, but also for its superior mechanical properties. Confinement of Reinforced Concrete (RC) columns by means of Fiber Reinforced Polymer (FRP) jackets is an effective technique by providing lateral confining pressure, which increase the compressive strength and deformability of the concrete column.

This technique has been extensively studied, in particular the behavior of confined elements of circular cross-section because the confinement of circular columns provides circumferentially uniform confining pressure to the radial expansion of the compression member. Some of investigations focused on size effect analysis of confined concrete cylinders have concluded that the scale of cylinders does not significantly affect the normalized axial stress-strain behavior.[1] Furthermore, the most of existing studies are based on small scale specimens and limited studies are found for the case of big scale specimens.[2]

Confinement by means of FRP wrapping has been of considerable interest for upgrading columns, piers, and chimneys in order to verify the effectiveness of FRP confinement with respect to real-scale axially loaded columns, to study the structural behavior of FRP-wrapped compression members, to investigate some specific aspects of the modeling of FRP-confined concrete, and several research programs have been conducted internationally. Matthys et al.[3] reported on axially loaded large-scale columns of 400 mm in diameter and with steel reinforcement confined with fiber reinforced polymer composites and found that available models based on small-size cylinders, seem to predict the ultimate strength of large-scale columns fairly accurately. Ongpeng et al.[4] examined the strength enhancement and common modes of failure by testing this concrete cylinders of size 180 mm diameter x 500 mm height by wrapping CFRP of 75 mm-strips, one-ply, two-ply with varying amount of steel bars present and found that concrete with no steel ties using CFRP strips produces 35% to 65% strength enhancement, same as when 1-ply of fully wrapped CFRP was used. Hamdy et al.[5] studied axial load capacity of concrete-filled FRP tubes (CFFT) of small and medium scale columns and revealed that the design equation of ACI 440.2R-08, CAN/CSA-S6-06 and CAN/CSA-S6-06-02 overestimate the factored axial load capacity of the short CFFT columns as compared to the yield and cracking load levels. The Canadian design code showed conservative predictions while the ACI 440.2R-08 was slightly less conservative. Scott et al.[6] also conducted research on behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders, which are found to correlate reasonably well with the ACI 440.2R-08 predictions for FRP confined concrete columns. Wu et al.[7] proposed a model for predicting the strength of FRP-jacketed concrete columns based on the Hoek-Brown failure criterion with a unified form for both square and circular cylinders. A comprehensive, updated database has been used to evaluate the performance of the proposed and existing models, demonstrating the advantages and enhanced accuracy of the proposed model.

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Extensive work in both the experimental and analytical areas has been conducted on small-scale plain concrete specimens of circular and non-circular cross-sections of considerable size, minimum dimension of 300 mm in diameter confined with FRP and subjected to pure axial compressive loading[8-16]. However, few studies have been investigated on size effect allowing different size of cylinders confined with the same lateral confining pressure of CFRP.

It has been found that there is no significant scale effect where jackets with similar confinement capacity were provided, by examining 8 full-scale, 508 mm diameter circular and 457 mm square reinforced concrete cylinders confined with unidirectional CFRP oriented in circumferential directional of the column under axial compression.[17] Miyauchi et al.[17] investigated size effect by comparing full and partial various layers (1, 2 and 3 layers) of FRP-confined specimens with sizes of 100 × 200 mm and 150 × 300 mm, strength enhancements from FRP confinement were reported to be independent of specimen size. Lorenzis et al.[1] came to a similar conclusion by testing specimens with diameter ranging from 55 to 150 mm, all of these specimens are actually small-scale cylinders and do not represent variation in size to evaluate the size effect. Carey et al.[2] also conducted tests on small-scale specimens (D = 152 mm), medium-scale specimens (D = 264 mm), and large-scale columns (D = 610 mm) confined with various layers of FRP, to explore the size effect and came to the same result.

The current investigation in difference of previous studies, took as test parameters different size of cylinders (100 × 200 mm, 200 × 400 mm, and 300 × 600 mm) confined with the same lateral confining pressure of CFRP in order to analyze the behavior of axially loaded concrete cylinders confined by means of CFRP wrapping and get more accurate results of size effect on confined concrete cylinders. From that hypothesis, if small specimen is confined with one layer of CFRP, medium and big specimens are confined with two and three layers of CFRP respectively. Four small cylinder specimens, four medium cylinder specimens and four big cylinder specimens are

confined with one, two and three layers of CFRP respectively to study the size effect on axial compressive strength of concrete cylinders by comparing experimental compressive strength results of specimens tested. Analysis and interpretation of each range of specimen have been done and comparison in stress-strain response between experimental results of each confined specimen is made to give conclusion of this work.

2. Experimental program

The main experimental parameters of this investigation take account of size of concrete cylinder and number of CFRP layer used to confine each specimen tested. The lateral confining pressure (f_l) of each manufactured specimen is the same, therefore it is found that relationship between the size of concrete cylinder and the number of confinement layer:

$$f_l = \frac{2f_{FRP}t}{D} = \frac{2f_{FRP}t_{100}}{D_{100}} = \frac{2f_{FRP}t_{200}}{D_{200}} = \frac{2f_{FRP}t_{300}}{D_{300}} \tag{1}$$

$$\frac{t_{100}}{D_{100}} = \frac{t_{200}}{D_{200}} = \frac{t_{300}}{D_{300}} \tag{2}$$

where, f_{FRP} is the tensile strength of FRP, t is the total thickness of the FRP jacket, D is the diameter of the confined cylinder.

From this relationship, if the specimen of 100 mm in diameter is confined with one layer of CFRP, other sizes of specimen 200 mm and 300 mm in diameter are confined with two and three layers of CFRP respectively, which illustrate our research idea. Table 1 shows the test program conducted for the specimens in this study. Carbon/epoxy jacket was used to confine the concrete cylinder.

2.1 Material properties

2.1.1 Concrete

A commercial concrete was used and the quantities of ingredients in the concrete mix are shown in Table 2. The design compressive strength of concrete used in this test is 20 MPa. However, the average value of compressive strength of a cubic specimen with side length of 150 mm is equal to 33.8 MPa and the modulus of elasticity of the concrete is 23.3 GPa. Fly ash admixture were used in the concrete and slump value of the concrete is 20.0 cm

2.1.2 CFRP laminate

Carbon fibers used in this study have mechanical properties of CFRP determined by tensile test on flat coupons ASTM D3039. The tensile strength f_{uj} and modulus $E_j$were equal to 3,248 MPa and 242 GPa, respectively. Ultimate strain was determined to be 0.0134**,** the nominal thickness of CFRP laminate and the ultimate strain are 0.167 mm; 0.015 respectively.

2.2 Specimen preparation

In total 24 concrete circular cylinders were tested. Small specimen of 10 0 × 200 mm in dimension, medium specimen of 200 × 400 mm in dimension, and big specimen of 300 × 600 mm in dimension. In each set, four unconfined specimens are tested without any strengthening, and other specimens are tested after externally confined by one, two and three layers of CFRP jackets respectively to small, medium and large specimen.

2.2.1 CFRP Jacketing

After 28 days of curing, the concrete specimens were carefully sandblasted. The two-part epoxy system used, consisting of epoxy primer (A:B = 100:45) and epoxy resin (A:B = 4:1), was thoroughly hand mixed for at least 5 min before used. The CFRP laminates were then applied directly onto the surface of the specimens

Table 1 Properties and dimensions of specimens.

Specimen	Diameter (mm)	Height (mm)	Number of layers	No. of specimens
PC	100	200	0	4
PC	200	400	0	4
PC	300	600	0	4
CC-100	100	200	1	4
CC-200	200	400	2	4
CC-300	300	600	3	4

Table 2 Proportions of ingredients used for concrete mix (kg/m^3).

Cement	Water	Sand	Stone power	Admixture
320	228	776	976	9.5

and were pressed with a roller brush in the fiber direction to remove entrapped air and extra epoxy to consolidate the jackets. In the case of small specimens, 60 mm overlap was used, while 120 mm and 180 mm overlaps were used for medium and big specimens respectively to avoid debonding of CFRP laminates. Figure 1 shows the specimens after jacketing with carbon fibers. All specimens were stored at room temperature for at least 10 days before testing. This was done to ensure that enough time had passed for the epoxy to cure. Prior to loading the specimens onto the test machine, the ends of the jacket were ground-smoothed to remove any uneven edges.

2.3 Instrumentation

All the specimens of 100 mm in diameter were instrumented by two strain gauges (one vertical and one horizontal) mounted at the mid height of each specimen, 180^o apart on the concrete and the jacket surface. For the specimens of 200 mm and 300 mm in diameter, two strain gauges (one vertical and one horizontal) were also mounted at the mid height of each specimens, 120^o apart on the concrete and the jacket surface to measure axial and lateral strains respectively. To measure axial strain, each specimen of 100 mm in diameter was fitted with two clip gauges that were mounted on two round sleeves at 180^o apart around the specimens and each specimen of 200 mm and 300 mm in diameter was fitted with three LVDTs that were mounted on three round sleeves at 120^{o}apart around the specimen. The sleeves were attached to the specimen with pin-type support that would not affect the dilation of the specimens. The wires for strain gauges, the load cell, and the LVDTs were connected to data acquisition system and checked for readings. Figure 2 shows a sketch of the instrumentation of circular specimens.

Fig. 1 Jacketed specimens with diameters of 100, 200, 300 mm.

2.4 Test procedure

All the specimens were tested using a high-stiffness, high-capacity compression testing machine at Structural Laboratory of Dalian University of Technology. This unique equipment has sufficient capacity and stiffness, required for conducting such tests. The machine is also equipped with sophisticated computer control and data acquisition system. The acquired data included the applied axial load P, axial deformation of concrete, and transverse and axial strains of the jacket. The test was conducted by first setting the specimen in test machine, centered under the machine spacer. The LVDTs were then zeroed out in preparation to start the test, and then the load was applied at a loading rate equal to 2 kN/s. The capacity of this machine in compression is 5,000 kN and the specimens were tested under pure axial compression. Figure 3 shows specimens at test preparation

3. Test results and discussions

All the plain concrete strength and strain (f'_{co} , ε_{co}) and confined concrete strength and strain (f'_{cc} , ε_{cc}) are shown in Table 3. As seen in this table, the confined strength value for the three series of specimen are approximate, this explains that the confinement is effective. The strength and strain enhancements are a little more significant for medium specimens than small and large specimen. The results show that the lateral confinement of; first, small

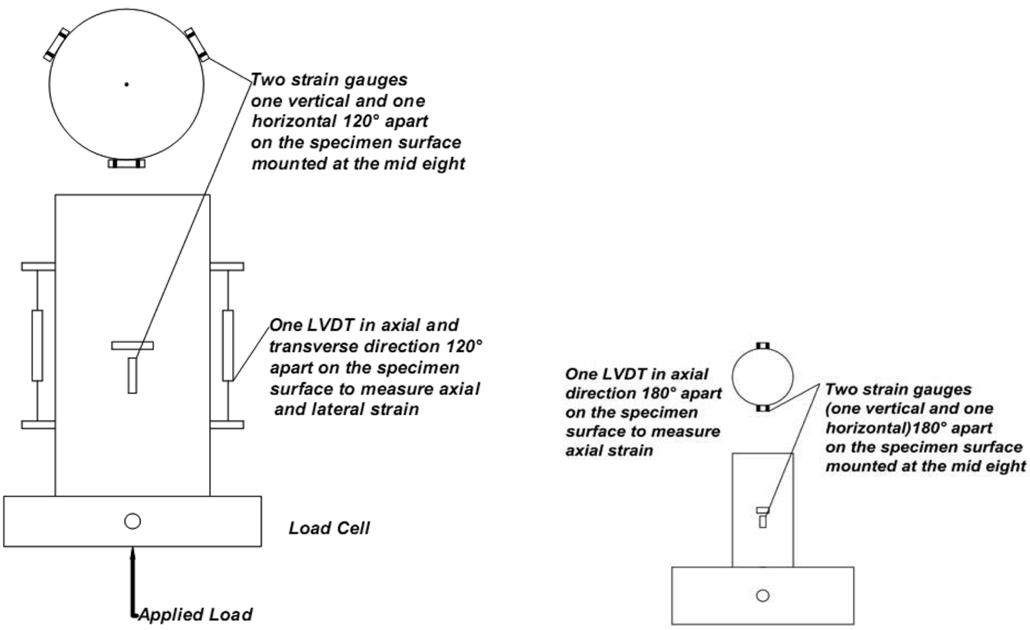


Fig. 2 Instrumentation of small, medium, and big specimens.

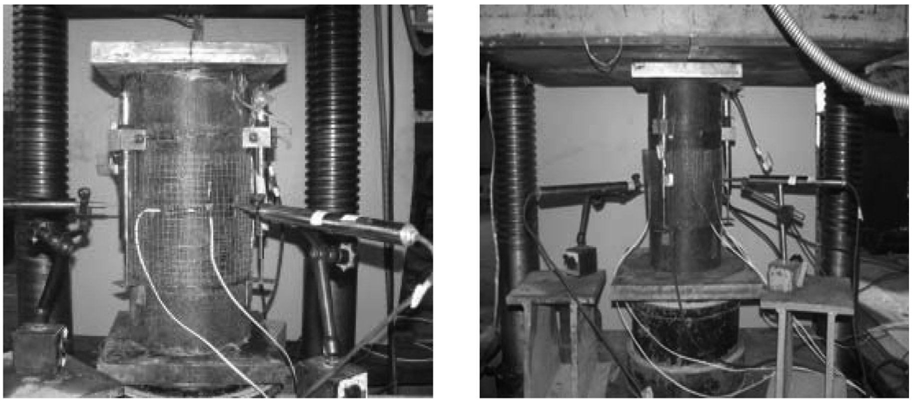


Fig. 3 Specimens at test preparation.

Table 3 Summary of experimental results for all specimens.

Specimen Diameter (mm)	f'_{co} (MPa)	ε_{co}	f'_{cc} (MPa)	ε_{cc}	$f_l\,(MPa)$	$\frac{f'_{cc}}{f'_{co}}$	$\frac{f_l}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$
D = 100	25.2	0.0031	64.3	0.0255	9.8	2.55	0.39	8.22
	25.9	0.0021	63.0	0.0218	9.8	2.43	0.38	10.38
	28.1	0.0033	66.4	0.0229	9.8	2.36	0.35	6.94
	26.8	0.0038	64.8	0.0248	9.8	2.42	0.36	6.53
Mean	26.5	0.0031	64.63	0.0238	9.8	2.44	0.37	8.02
S.D C.V	1.252 0.047	0.0007 0.226	1.406 0.022	0.002 0.084				
D=200	21.8	0.0026	64.3	0.0279	9.6	2.95	0.44	10.73
	20.6	0.0017	69.1	0.0269	9.6	3.35	0.47	15.82
	23.6	0.0021	60.1	0.0210	9.6	2.54	0.41	10.00
	20.6	0.0024	66.3	0.0254	9.6	3.22	0.47	10.58
Mean	21.65	0.0022	64.95	0.0253	9.6	3.01	0.45	11.78
S.D C.V	1.418 0.065	0.0004 0.182	3.785 0.058	0.003 0.118				
D = 300	25.3	0.0021	58.8	0.018	9.6	2.32	0.38	8.57
	24.0	0.0021	59.4	0.020	9.6	2.47	0.40	9.52
	23.7	0.0020	63.00	0.019	9.6	2.66	0.40	9.5
	25.0	0.0026	60.6	0.020	9.6	2.42	0.38	7.69
Mean	24.5	0.0022	60.45	0.0193	9.6	2.47	0.39	8.82
S.D C.V	0.77 0.031	0.0003 0.136	1.857 0.031	0.001 0.052				

specimen confined with one layer of CFRP increases the strength by 144% and the strain of plain concrete by 668%; second, medium specimen confined with two layers of CFRP increases the strength by 199% and the strain of plain concrete by 1050%; third, big specimen confined with three layers of CFRP increases the strength by 147% and the strain of plain concrete by 764%. Inequality of confined small, medium and big specimens stress-strain results can be initially explained by the difference in results of strength between small, medium and big unconfined specimens. Confinement effectiveness is 2.44; 3.01 and 2.47 and confinement ratio is 0.37; 0.45 and 0.39 for small; medium and big specimens respectively. The confinement is effective for all specimens as shown in Table 3. The relationship between the confined specimen strength and each category of specimen is shown in Fig. 4. As seen in this figure, the average strength of CC-100 and CC-200 is almost in the same line and the average strength of CC-300 is under this line that shows the scattering of plain concrete strength of small, medium, and big cylinder concrete. The strength and the strain of small, medium and big specimens confined to one, two, three layers of CFRP respectively would have been approximately the same if more specimens were tested and good care was taken for the concrete mixing and also a good care was taken to ensure the bond between the concrete core and CFRP material.

3.1 Failure mode

During the loading process of the specimens prior to the failure, cracking noises were heard, indicating the start of stress transfer from the dilated concrete to the CFRP jacket. The failure was gradual and was marked by fiber rupture at or near the mid-height

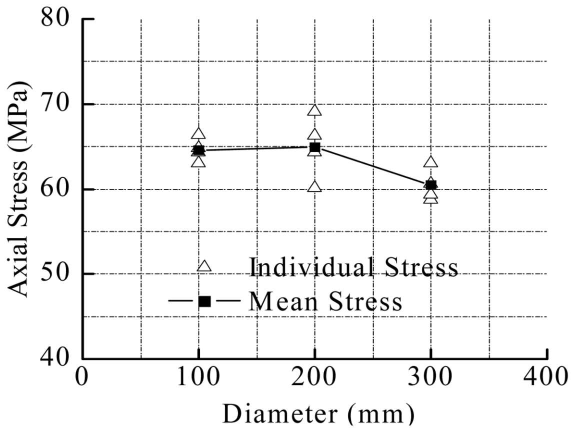


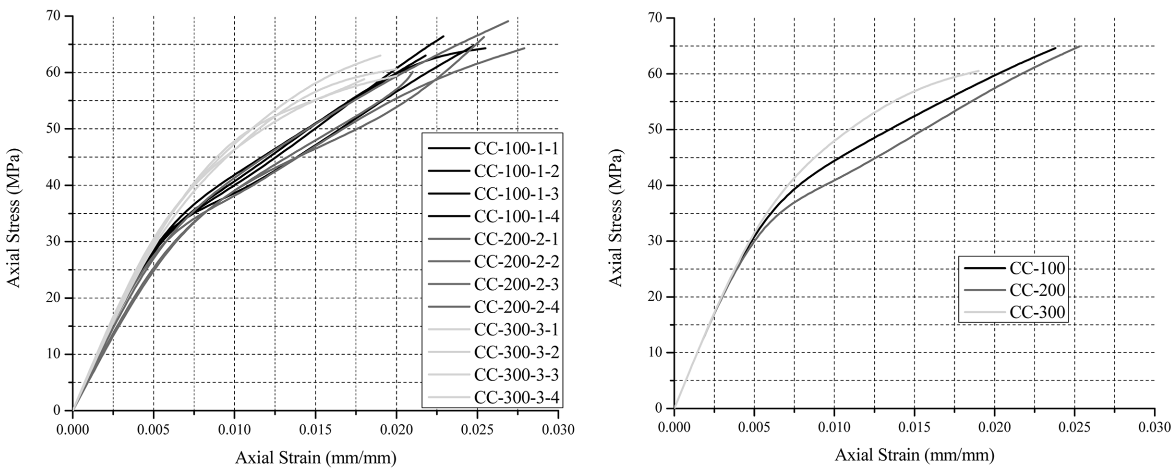
Fig. 4 Individual and mean compressive strengths of CFRP confined columns with100, 200, 300 mm in diameter.

of the specimens, ended with a sudden and explosive noise. The jacket rupture started at mid height and progressed to up and down of the specimen. The sudden and explosive nature of the failure indicates the release of tremendous amount of energy as a result of the uniform confining stress provided by the jacket. Inspection of the broken specimen showed that some of the specimens were crushing with delamination but the rupture of most of the specimens was characterized by crushing of concrete followed by cutting of CFRP laminates. Once the jacket was removed, it became clear that shear cones were formed at top and bottom of most specimens as shown in Fig. 6.

3.2 Comparisons and analysis

A comparative study between the experimental results of all confined tested specimen are presented in this chapter. The average value of strength f_{cc}' is 64.6 *MPa*, 64.9 *MPa* and 60.5 *MPa* for small; medium and large confined specimens respectively and the average value of strain ε_{cc}' is 0.0238, 0.0253 and 0.019 for small, medium and large confined specimens respectively. The results indicated that the deformation field is not uniform and the measured rupture strains of CFRP jackets exhibit diversity. Likewise, test results of the previous studies from other authors pointed out that even for the readings of LVDTs to measure axial deformation at a specified height, it is impossible to obtain a uniform deformation field and the reading of different LVDTs can show significant variations next to the maximum load.[18]

The axial stress and axial strain curves for small (CC-100), medium (CC-200) and big (CC-300) are shown in Fig. 5. As seen in this figure, it can be noticed that all the specimen curves, small specimen confined with one layer of CFRP, medium specimen confined with two layers of CFRP and big specimen confined with three layers of CFRP are almost overcome from 0 to 0.005 strain value and after this space of deformation the curves diverge, but the small confined specimen and medium confined specimen



(a) (b)

Fig. 5 Axial stress-strain relationships for all tested specimens in the first figure and average curve in second figure.

Fig. 6 Typical failure of carbon wrapped concrete specimens tested.

Table 4 Test results of previous and new investigation.

Reference	Type of fiber	Diameter(mm)	Number of layer	$f_l\,(MPa)$	$f'_{cc}\ (MPa)$	$\frac{f'_{cc}}{f'_{co}}$
Thériault et al.[19]	Carbon	152 304	2 4	14 15	64 66	1.78 1.83
Thériault et al.[19]	Glass	51 152	1 3	23.5 27	64 90	3.56 2.50
Youssef et al. [16,20,21]	Glass	152 406	3 8	9.5 5.8	65.5 55.2	2.22 1.58
This Test	Carbon	100 200 300	1 2 3	9.8 9.6 9.6	64.6 64.9 60.5	2.49 3.01 2.47

curves are adjacent, only the big confined specimen curves were stayed up to those adjacent curves because those curves are a little more concave than small and medium confined specimen curves. From 0.005 value of deformation, all the specimen curves converged at the same point of stress-strain value but did not reach this point, because different value of stress-strain at loading rupture was obtained. The same remark was observed for the average curve of all the specimens tested in difference that the curves are overcome from 0 to 0.005 deformation space. A significant difference between compressive strength of plain concrete cylinders was observed. However a correlation between small specimens of 100 mm in diameter and medium specimens of 200 mm in diameter and also a correlation between small specimens and big specimens was obtained from statistical analysis methods (Table 3).

In the case of plain concrete cylinders deformation, there is no significant difference between the deformation of medium specimens of 200 mm in diameter and big specimens of 300 mm in diameter, but a correlation between small, medium and big specimens was obtained (Table 3). It has been found, for confined concrete cylinders strength, that there is no significant difference between small specimens of 100 mm in diameter and medium specimens of 200 mm in diameter (Table 3). Statistical analysis for confined concrete cylinders deformation shows that there is no significant difference between deformation of small and medium confined concrete specimens. Therefore, the deviation is minimized for confined concrete cylinders strength and strain even if it has been a little significant in the case of plain concrete cylinders. As conclusion, the same interpretation of results has been found from both stress-strain curve comparison and statistical methods analysis.

The previous test data of confined concrete cylinders are presented in Table 4. As shown in this Table size effect is observed on confined concrete cylinders of 51 mm specimen in diameter confined with one layer of GFRP and 152 mm specimen in diameter confined with three layers of GFRP, and this because the specimen of 51 mm in diameter is too small and "wall effect" exists. [19] Also in the case of 152 mm specimen in diameter confined with three layers of GFRP and 406 mm specimen in diameter confined with eight layers of GFRP, size effect is observed, the hoop rupture strain in the GFRP jacket of 406 mm specimen in diameter confined with eight layers of GFRP is too small compared to the value of 152 mm specimen in diameter which has effect on the value of confined concrete strength.[20,21] There is not a significant difference between the lateral confining pressure (f_l) of 152 mm confined with two layers of CFRP and 304 mm of specimen in diameter confined with four layers of CFRP therefore the strength of each confined concrete is almost the same. [19]

4. Conclusions

This work was conducted to study size effect of compressive strength of CFRP confined circular concrete cylinder. The experiment included testing under pure axial load in which 24 concrete cylinders (small, medium and big) specimens were tested. The average value of strength is 64.6 *MPa*, 64.9 *MPa* and 60.5 *MPa* for small; medium and big confined specimens respectively and the average value of strain is 0.0238, 0.0253 and 0.019 for small, medium and big confined specimens respectively. The new investigation results in comparison to the previous test data results shows that size effect on confined concrete strength is not observed when the proportional relationship between the confinement layer and the size of the specimen is correctly defined. From stress-strain curve comparison analysis, it is noticed that the scattering of plain concrete strength evaluated between small, medium and big specimens explains why the curves are not totally overcome. The statistical analysis shows that the strength correlation of confined concrete cylinders between small, medium and big specimens is converging at the same value and there is no significant difference between them which is observed in the case of plain concrete cylinders. The same remark has been mentioned for the confined concrete strain. From all these analysis, it can be concluded that no size effect is observed on axial compressive strength of CFRP confined concrete cylinders, a bit lower strength obtained in the case of big confined specimens can be explained by scattered strength value of plain concrete specimens. However more investigations need to be done to get an accurate result useful in the concrete structures design.

Acknowledgements

This work described in this paper was fully supported by a grant from the National Natural Science Foundation of the People's Republic of China (Project No. 50578025).

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