COMPRESSIVE BEHAVIOR OF CFRP-CONFINED SQUARE CONCRETE COLUMNS

Edmunds Zīle [1], Vitauts Tamužs [1] and Ralejs Tepfers [2]

[1] Institute of Polymer Mechanics
University of Latvia
Aizkraukles iela 23, Riga, LV-1006, Latvia

[2] Department of Structural Engineering and Mechanics
Chalmers University of Technology
Göteborg, SE-412 96, Sweden

ABSTRACT

Jacketing of the concrete leads to the increase of the strength and ductility of jacketed columns. A significant amount of research has been devoted to round columns that have been retrofitted with fiber-reinforced polymer (FRP), but much less is known about FRP-confined rectangular/square columns in which the concrete is non-uniformly confined and the effectiveness of confinement is much reduced. Results of an experimental investigation of the compressive behavior of square concrete columns confined by carbon FRP are presented. It was found that a simple formula which involves the definition of the equivalent round column and the shape factor can well estimate the compressive strength of the confined square columns.

1. INTRODUCTION

Fiber-reinforced polymers (FRP) are being increasingly used for strengthening and rehabilitation of concrete structures. One of the most attractive applications of FRP is the confinement of concrete columns to enhance both strength and ductility. Many researches have shown than confined round concrete columns exhibit a significant increase in strength and ductility. In the case of confined square concrete columns, the effectiveness of the confinement is much reduced because concrete is nonuniformly confined. Relatively small number of studies has been reported on these types of columns.

This paper presents the results form the experimental study of the compressive behaviour square concrete columns confined by the carbon FRP. By introducing the modifications to a simple formula used to predict the compressive strength of confined round concrete columns [1, 2] we obtain formula that can well estimate the compressive strength of the confined square columns. Applied modifications include the definition of the equivalent round column and use of the shape factor. The performance of different definitions [3-6] of these factors is investigated in this paper.

2. EXPERIMENTAL PROGRAM

2.1 Concrete specimens

Twenty-four FRP-confined square concrete specimens were prepared and tested in this experimental program. The concrete was prepared in the laboratory and the specimens were cast in plywood forms with a corner radius of r=15 mm or r=30 mm. All confined specimens had a cross section of 150×150 mm and height of 450 mm.

Twelve plain concrete columns were tested in monotonic uniaxial compression to estimate the unwrapped column strength. These included six round specimens of 150 mm in diameter and six square specimens of 150×150 mm in cross section. All plain concrete columns had a height of 450 mm. The results are summarized in Table 1.

Table 1: Concrete properties.

Concrete bach	Column cross section	Compressive strength f_{co} [MPa]	Elastic modulus E_o [GPa]
I	Round	18.4	25.6
	Square	18.6	21.5
Average		18.5	23.6
II	Round	38.7	32.1
	Square	42.7	30.5
Average		40.7	31.3

2.2. Composite confinement

Concrete columns were confined by wrapping continuous CFRP (carbon fiber fabric SikaWrap-230C) tape impregnated with epoxy resin around the column with the fibers oriented in the hoop direction, forming two and four layers of the CFRP, with each layer containing a single lap of the fiber fabric sheet. The properties of the tape, as given by the manufacturer, are shown in Table 2.

Table 2: Confinement properties given by the manufacturer.

Tensile strength [MPa]	Elastic modulus [GPa]	Elongation [%]	Thickness [mm]	Density [g/cm^3]
4300	238	1.8	0.131	1.76

After the wrapping of each lap of the CFRP sheet, a layer of the epoxy resin was applied and a roller was used to remove air voids and to allow a better impregnation of the resin. The finishing end of the each sheet overlapped the starting end of the sheet by 150 mm.

2.3. Instrumentation

The confined specimens were subjected to a monotonic uniaxial compression loading up to failure. Loading machine with a capacity of 500 tons was used. To capture possible softening behavior, all specimens were loaded under displacement control with the loading rate of 1 mm/min.

Three linear variable displacement transducers (LVDT) were used to measure the axial displacement and only one averaged signal was recorded to indicate the averaged value. To measure the lateral strains, one strain gauge was glued at the middle of the side face, one was glued near the curvature changing point. Another two strain gauges were positioned at exactly the opposite locations to the previous two gauges (Figure 1). Additional set of four strain gauges having the same arrangement in the hoop direction were glued at the vertical distance of 100 mm from the column end.

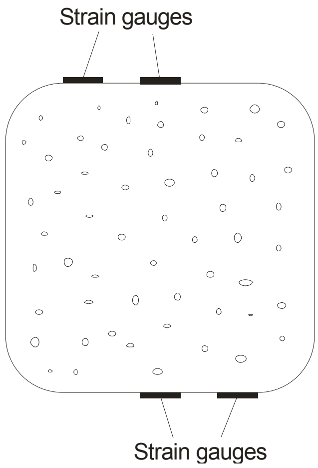

Figure 1: Arrangement of the strain gauges in the hoop direction.

2.4. Experimental results

Test results are shown in Table 3. Table 3 reports the plain concrete strength f_{co}, confinement thickness *h*, corner radius *r*, compressive strength of the confined concrete f_{cc}, ultimate axial strain ε_{cc}, ultimate lateral strain at the middle of the side face ε'_{lu} and ultimate lateral strain at the curvature changing point ε''_{lu}. Lateral strains are average values from the gauges placed at the appropriate location at the mid-height and at the vertical distance of 100 mm from the column end. Compressive strength and the ultimate strains of the confined concrete for the given plain concrete strength, confinement thickness and corner radius are obtained from three identical specimens. The confined specimens mostly failed near the mid-height.

Table 3: Summary of test results of the confined square concrete columns.

f_{co} [MPa]	h [mm]	r [mm]	f_{cc} [MPa]	ε_{cc} [%]	ε'_{lu} [%]	ε''_{lu} [%]
18.5	0.26	15	30.0	2.82	0.87	0.53
	0.52	15	42.7	4.11	0.93	0.44
	0.26	30	36.7	2.56	1.04	0.64
	0.52	30	56.8	4.13	1.24	0.76
40.7	0.26	15	47.1	1.11	0.64	0.43
	0.52	15	57.3	1.71	0.71	0.45
	0.26	30	55.1	0.81	0.63	0.57
	0.52	30	79.4	2.33	1.15	0.70

Averaged axial stress-strain curves are shown in Figures 2 and 3. Due to the nonuniformity of the confining stresses in the square section, for a given axial strain, the axial stress in the concrete varies over the cross section. Therefore axial stress in this paper is defined as the average axial stress (load divided by the cross sectional area). It is seen from the Table 3, that the lateral strain in the middle of the side face is considerably higher than the strain at the curvature changing point. A possible explanation for this effect is that large fraction of the lateral strain recorded in the middle of the side face is due to the outwards bending of the CFRP sheet in response to the dilating pressure of the encased core.

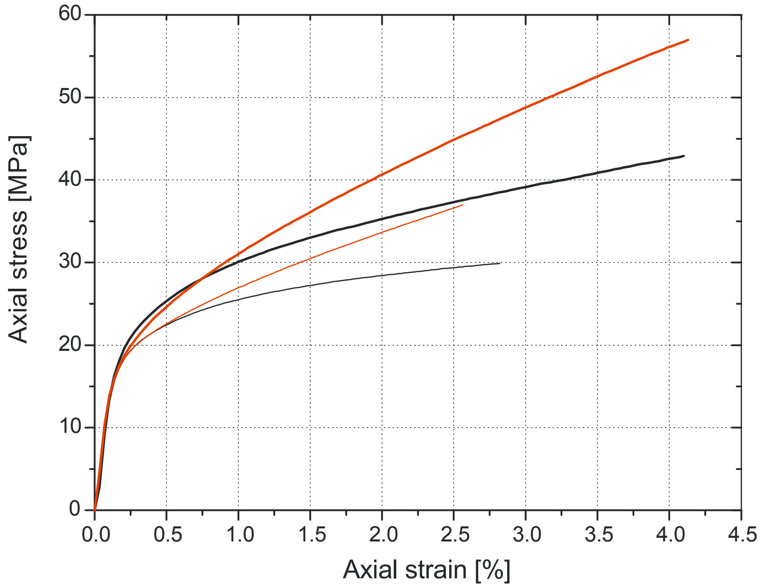

Figure 2: Axial stress-strain curves of the confined square concrete columns (concrete batch I). Thin line – 2 layers of the CFRP, thick line – 4 layers of the CFRP. Black line – *r*=15 mm, red line – *r*=30 mm.

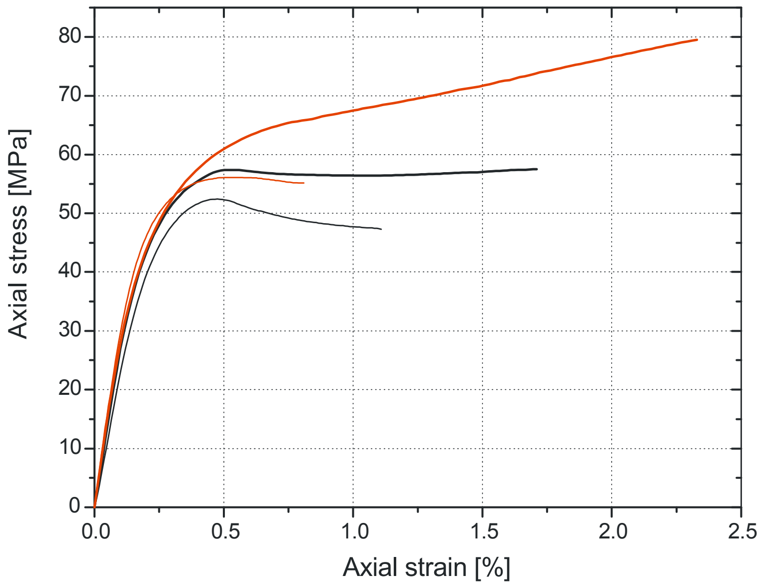

Figure 3: Axial stress-strain curves of the confined square concrete columns (concrete batch II). Thin line – 2 layers of the CFRP, thick line – 4 layers of the CFRP. Black line – *r*=15 mm, red line – *r*=30 mm.

3. STRENGTH OF THE CONFINED SQUARE CONCRETE COLUMNS

A rectangular column with rounded corners is shown in Figure 4, where side length is denoted by *a*.

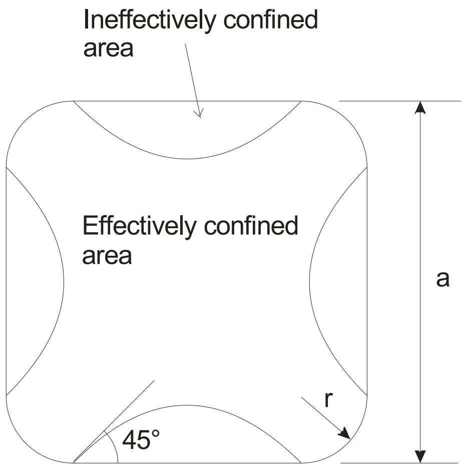

Figure 4: Cross-section of the square concrete column.

It is generally assumed that only the concrete contained by four second-degree parabolas as shown in Figure 4 is fully confined. These parabolas intersect the edges at 45˚. The confinement action is biaxial in the effectively confined area, but uniaxial in the ineffectively confined area. The smaller is the corner radius, the less is the effectively confined area which in turn leads to the decrease of the strength. This effect can be clearly seen in Figures 2 and 3.
It was shown in [1] that the following simple formula well estimates compressive the strength f_{cc} of confined round columns:

$$\frac{f_{cc}}{f_{co}} = 1 + 4 \cdot \frac{f_l}{f_{co}}, \qquad (1)$$

where and f_l is the maximum lateral pressure. To use Eq. (1) for the confined square columns, f_l should be replaced by the effective maximum lateral pressure f_l' which is defined as:

$$f_l' = k_s f_l^e, \qquad (2)$$

where k_s is the shape factor which accounts for the effect of non-uniform confinement and f_l^e is the equivalent maximum lateral pressure provided by the FRP to an equivalent round column defined. The equivalent maximum lateral pressure f_l^e can be written as:

$$f_l^e = \frac{2hE_j \varepsilon_{ju}}{D}, \qquad (3)$$

where D is the diameter of the equivalent round column, ε_{ju} is the hoop rupture strain of the composite jacket and h, E_j - thickness and modulus of composite jacket. For round columns wrapped with CFRP, it was found that $\varepsilon_{ju} = 0.36 \cdot \varepsilon_{ju}^m$, where ε_{ju}^m is the rupture strain given by the manufacturer [2]. Once the shape factor k_s, the equivalent column diameter D and the hoop rupture strain ε_{ju}^m are defined, the compressive strength of the confined square columns can be estimated by using the Eq. (1).
Mirmiran et al. [3] defined shape factor as:

$$k_s = \frac{2r}{D}, \quad (4)$$

where D is taken equal to the side length a of the square column: $D=a$.

In the *ACI Committee 440* report [4] the shape factor is defined as the ratio of the effectively confined area A_e to the total area of the concrete cross-section A:

$$k_s = \frac{A_e}{A}. \quad (5)$$

For square concrete columns the effectively confined area which is contained by the four parabolas can be written as:

$$A_e = \frac{1}{3}\left(a^2 + 8ar + \left(3\pi - 20\right)r^2\right) \quad (6)$$

The total area of the square concrete cross-section A is given by:

$$A = a^2 - \left(4 - \pi\right)r^2 \quad (7)$$

Then for square columns we have:

$$k_s = 1 - \frac{2\left(a - 2r\right)^2}{3\left(a^2 - \left(4 - \pi\right)r^2\right)} \quad (8)$$

and $D=a$.

Lam and Teng [5] defined the diameter D being equal to the diagonal length of the square cross-section: $D = a\sqrt{2}$. In the case of the square columns the shape factor proposed by Lam and Teng coincides with the Eq. (8).

Al-Salloum [6] defined D as the diagonal length of the square cross-section with rounded corners (Figure 5). That is:

$$D = a\sqrt{2} - 2r(\sqrt{2} - 1) \quad (9)$$

It is suggested in [6] that the effect of the non-uniformity of the confining pressure can be corrected by introducing additional parameter a / D ($a / D = 1$ for circular columns), where D is defined by Eq. (9).

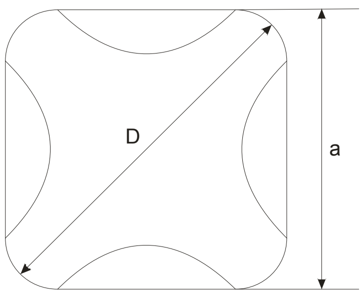

Figure 5: Definition of D in [6].

Then for the shape factor we have:

$$k_s = \left[1 - \frac{2\left(a - 2r\right)^2}{3\left(a^2 - \left(4 - \pi\right)r^2\right)}\right]\frac{a}{D} \quad (10)$$

Summary of the k_s and D definitions are shown in the Table 4. Estimation results are shown in the Figure 6.

Table 4: Summary of the k_s and D definitions for square concrete columns.

	k_s	D
Mirmiran et al. [3]	$\frac{2r}{D}$	a
ACI 440 [4]	$1-\frac{2(a-2r)^2}{3(a^2-(4-\pi)r^2)}$	a
Lam and Teng [5]	$1-\frac{2(a-2r)^2}{3(a^2-(4-\pi)r^2)}$	$a\sqrt{2}$
Al-Salloum [6]	$\left[1-\frac{2(a-2r)^2}{3(a^2-(4-\pi)r^2)}\right]\frac{a}{D}$	$a\sqrt{2}-2r(\sqrt{2}-1)$

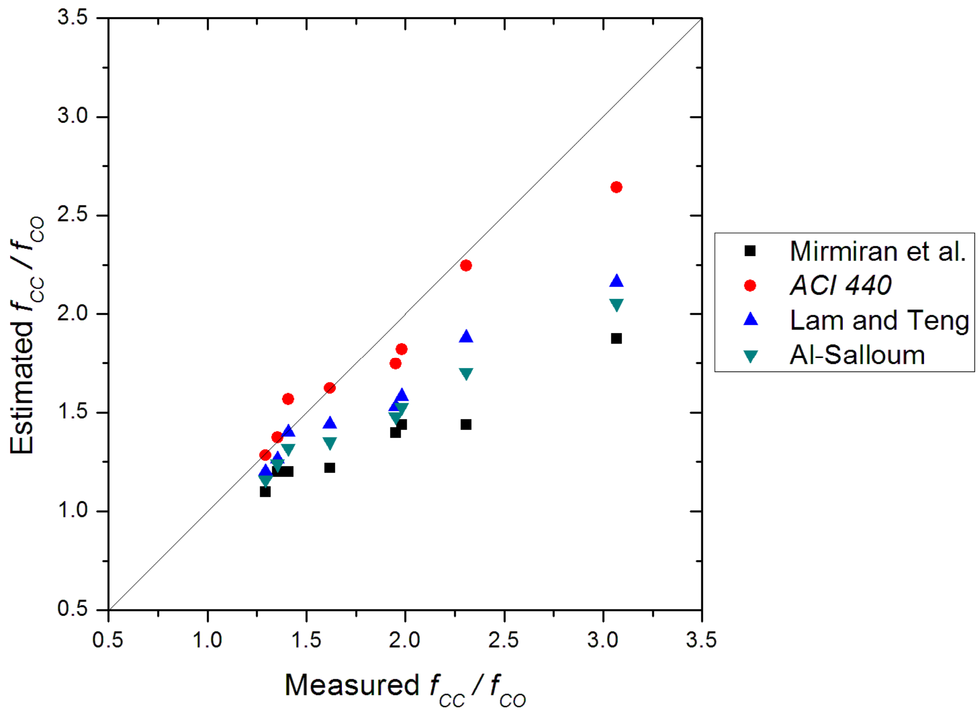

Figure 6: Comparison of the measured and estimated values of the normalized compressive strength of the confined square concrete specimens. Solid line – ideal correspondence.

The best estimation results are achieved when the shape factor is defined as the ratio of the effectively confined area to the total area of the concrete cross-section (Eq. (8)) and equivalent column diameter is taken equal to the side length of the square column: $D=a$.

4. CONCLUSIONS

1. The compressive strength of the confined square column increases as the corner radius increases.

2. The least estimation error of the compressive strength is achieved by using the shape factor defined by Eq. (8) and taking the equivalent column diameter equal to the side length of the square column.

ACKNOWLEDGEMENTS

This work was supported by the *European Social Fund*.

REFERENCES

1- Tamužs, V., Tepfers, R. and Spārniņš, E., “Behavior of concrete cylinders confined by a carbon composite. 2. Prediction of strength”, *Mechanics of Composite Materials*, 2006;42;2:109-118.

2- Tamužs, V., Tepfers, R., Zīle, E. and Ladnova, O., ”Behavior of concrete cylinders confined by a carbon composite 3. Deformability and the ultimate axial strain”, *Mechanics of Composite Materials*, 2006;42;4:303-314.

3- Mirmiran, A., Shahawy, M., Samaan, M. and El Echary, H., “Effect of Column Parameters on FRP-confined Concrete”, *J. of Composite for Construction ASCE*, 1998;2;4:175-185.

4- ACI Committee 440 Report. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.* ACI Committee 440, Technical Committee Document 440.2R-02, 2002.

5- Lam, L. and Teng, J.G., “Design-oriented stress-strain model for FRP-confined concrete in rectangular columns”, *J. of Reinforced Plastics and Composites*, 2003;22;13:1149-1186.

6- Al-Salloum, Y.A., “Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates”, *Composites: Part B*, 2007;38:640-650.