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AXIAL COMPRESSIVE STRENGTH OF REINFORCED CONCRETE COLUMNS WRAPPED WITH FIBRE REINFORCED POLYMERS (FRP)

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Abstract This paper presents the results of a study on the axial compressive strength of columns strengthened with FRP wrap. The experimental part of the study included testing 6 reinforced concrete columns in two series. The first series comprised three similar circular reinforced concrete columns strengthened with FRP wrap. The second series consisted of three similar square columns, two with sharp corners, and the other with rounded corners. Axial load and displacement of columns were recorded during tests using a displacement control test set up. Test results are compared with the values calculated using CSA (Canadaian Standard Association) Code provisions and recent proposed equations. It is shown that the FRP wrap increases the strength and ductility of circular columns, significantly. The recent proposed equations correlate well with the test results of circular and square columns with rounded corners. According to the test results, the FRP wrap did not increase the strength of square columns with sharp corners. However, the square column with rounded corners exhibited a higher strength and ductility compared to those with sharp corners.

Key Words Column, Concrete, Fiber Reinforced Polymer, Wrap

چکیده در این مقاله رفتار و مقاومت فشاری ستونهای بتن آرمه تقویت شده با پلیمرهای مسلح الیافی بررسی می گردد. در بخش آزمایشگاهی پژوهش،شش عدد ستون بتن آرمه تقویت شده با پوشش های پلیمری ساخته و آزمایش شدند. سه عدد از این ستونها دایره ای و سه عدد مربع شکل بودند. یکی از ستونهای مربع شکل دارای گوشه های گرد شده بود. آزمایشها توسط دستگاهی با کنترل تغییر مکان انجام گردید و نتایج آنها توسط یک سیستم کامپیوتری ثبت شد. مقایسه بین نتایج آزمایش و مقادیر محاسباتی آیین نامه کانادایی A23.3-94 نشان میدهد که ورق های پلیمری مسلح الیافی (FRP) می توانند به مقدار زیادی مقاومت فشاری و شکل پذیری ستون های بتن آرمه با مقطع دایره ای را افزایش می دهند. استفاده از ورق های پوششی FRP ممکن است باعث افزایش مقاومت فشاری ستون های مربع شکل نگردد. در صورتی که گوشه های ستونهای مربع شکل گرد شوند مقاومت فشاری شکل پذیری ستونها تا حد زیادی افزایش می یابند. معادله پیشنهادی اخیر Theriault and Neale برای ستونهای دایره ای پوشش شده با ورق های FRP برای پیش بینی مقاومت فشاری این ستونها مناسب است. در عین حال معادله ارائه شده برای ستونهای مربع شکل مقاومت فشاری ستونها را دست بالا برآورد می کند مگر اینکه گوشه های ستونها به مقدار مناسبی گرد شوند.

1. INTRODUCTION

Many studies concerned with strengthening of existing reinforced concrete columns, especially in seismic regions, have focused on providing additional confinement to the core concrete by means of external reinforcement. From the studies that have been conducted over the past several years, the advantages of using FRP materials have become more apparent. Strengthening and increased durability against steel corrosion can be achieved in a column by wrapping the column with fiber reinforced polymer (FRP) (1-3).

The use of FRP wrapped reinforced concrete columns has been introduced into the earthquake repair industry, due to the efficiency of the repair methods. Research has shown that closely spaced transverse reinforcement in concrete bridge columns, particularly in the plastic hinge zone; substantially increase the compressive strength and ultimate compressive strain in the core concrete (4).

Due to the increase in the ultimate compressive strain, the ductility capacity and energy absorption capacity are also considerably improved. The use of FRP in this particular application is similar to that in the rehabilitation due to deteriorating infrastructure. The product is high in strength, light-weight, corrosion resistant, low in cost, and extremely versatile. When dealing particularly with earthquake damaged zones, the importance of avoiding the need for heavy equipment in the repair methods is particularly increased. It has been concluded through various tests of seismically deficient columns both before and after repair, that FRP composite wraps are effective in restoring the flexural strength and ductility capacity of earthquake-damaged concrete columns.

In all repaired specimens, the rate of stiffness deterioration under large reversed cyclic loading was lower than that of the corresponding original columns. It should be noted however, that the initial stiffness of the repaired columns was lower than that of the original (4). Although many research has been carried out to investigate the behavior of FRP wrapped concrete columns, the available results are not adequate to be able to reach an appropriate conclusion.

The post peak load behavior of reinforced concrete columns wrapped with FRP under axial compression has not been investigated properly. In the following, the test results of six concrete columns wrapped with FRP are presented and analyzed. The behavior of columns after maximum load is discussed. The results are compared with the provisions of CSA Code and recent proposed equations.

2. EXPERIMENTAL PROGRAM

2.1 Materials The concrete mix design of all specimens was based on the CSA code (5). The concrete mixture and properties are given in Table 1. The cylinder concrete compressive

TABLE 1. Concrete Mixture and Properties.

Material	Volume (m^3/m^3)	Mass (kg/m^3)	Concrete Properties
Water	0.164	164	Compressive Strength (f'_c)= 46.1 MPa
Cement	0.130	410	Slump=80 mm
Air	0.06	-	Water to Cement Ratio=0.4
Coarse Agg.	0.409	1084	Maximum Aggregate Size=20 mm
Fine Agg.	0.237	623	Air Volume= 6%
Total	1.000	2281	

TABLE 2. Tyfo SCH-41S System Properties.

Description	Ultimate Tensile Strength, f_{FRP}	Tensile Modulus E	Thickness
Primary Carbon Fiber 0° aramid fiber 90°	876 MPa	72.4 GPa	1.0 mm

TABLE 3. Epoxy Material Properties.

Tensile Strength	Tensile Modulus	Elongation Percent	Flexural Strength	Flexural Modulus
72.4 MPa	3.18 GPa	5.0 %	123.4 MPa	3.12 GPa

strength, f'_c, for all specimens was 46.1 MPa. The reinforcement material, which was applied horizontally to the columns, was the Tyfo SCH-41S Composite Fiber System. This system consists of Tyfo S Epoxy and Tyfo SCH-41S reinforcing fabrics. The Tyfo SCH-41S is a unidirectional carbon fabric with aramid cross fibers. It has been custom stitched, with the carbon material oriented in the 0° direction, and aramid fibers at 90°. The Tyfo S epoxy material used for bonding applications is a two-component epoxy matrix material. The system properties are summarized in Tables 2 and 3. The FRP was applied in accordance with the methods recommended by the manufacturer of Tyfo SCH-41A Composite Fiber Systems.

2.2 Test Specimens To determine the effect of FRP wraps on column strength, 3 circular and 3 square columns were manufactured and tested. The details of the column specimens are shown in Figures 1 and 2. The properties and dimensions of the circular columns were selected to be similar in order to obtain a reasonable mean value of the results. The square column specimens were also similar with the exception of Specimen C which had the corners removed to a depth of 12mm. the circular and square column properties were selected to yield similar theoretical load carrying capacity without considering the effect of FRP. All specimens were wrapped using two layers of FRP. The thickness of each layer of FRP was 1 mm.

3. TESTING PROCEDURES

The columns were axially loaded using a displacement control compression apparatus in the laboratory Figure 2. The first column (circular – Specimen A) was loaded at a rate of 0.2 mm/sec until failure. During the test it was observed that this rate was too fast, so it was reduced to 0.05 mm/sec for the remaining 5 columns. Displacement and ultimate strength were recorded throughout the entire tests. The mode of failure for each specimen was also observed Figure 3.

4. TEST OBSERVATIONS

4.1 Circle Specimens

Specimen A: Failure was sudden. It was observed through a crack which formed approximately 200 mm from the top of the columns. The FRP appeared to have burst due to the pressure or strain caused by the load.

Specimen B: Several signs of failure were evident

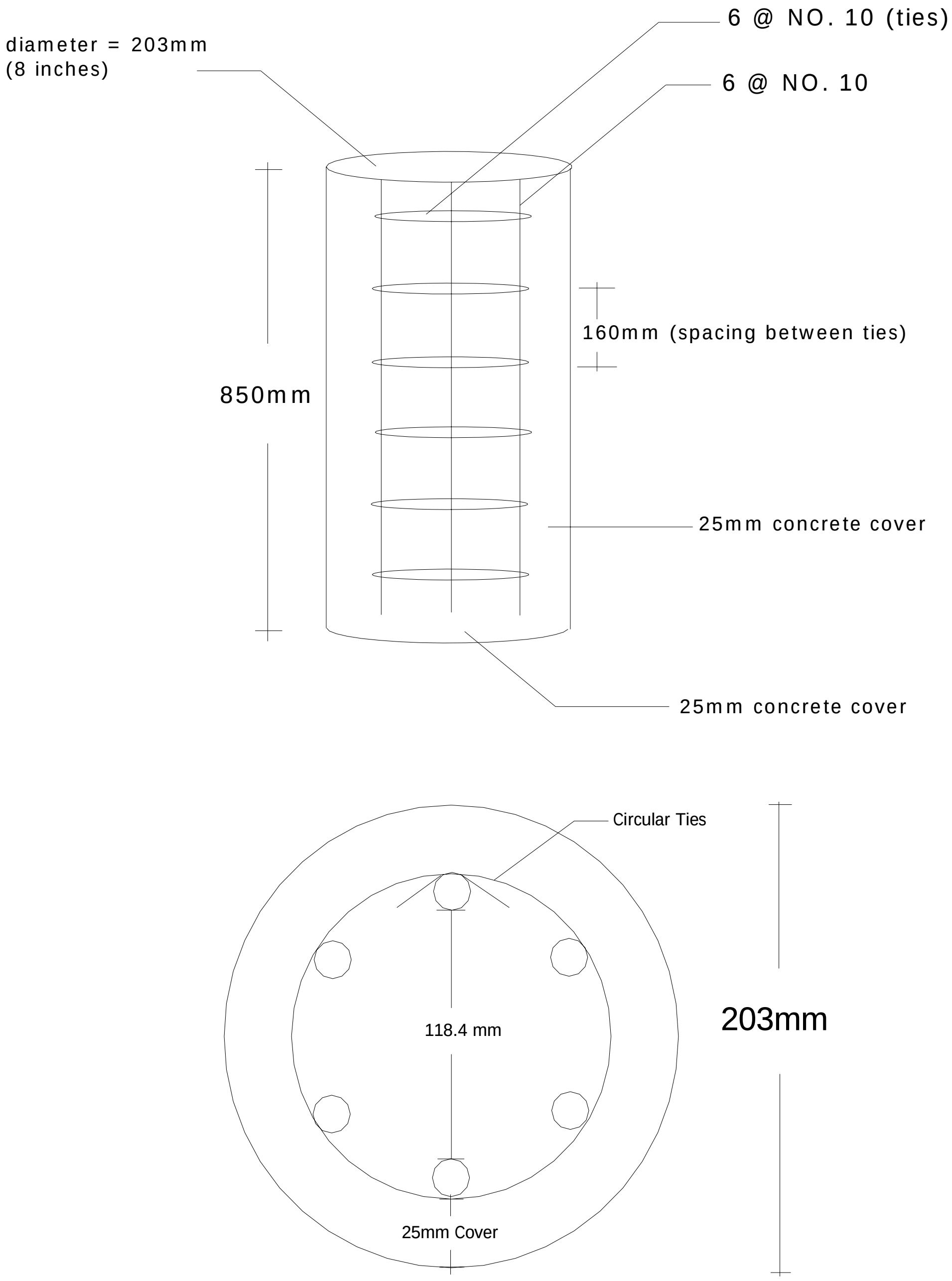

Figure 1. Circular columns.

during testing. Failure for this specimen was much slower that that for Specimen A. Failure occurred at a crack approximately 200mm from the top of the column in similar form to the previous.

Specimen C: Reacted to the loading the same as Specimen B, except that it failed at a lower loading value.

4.2 Square Specimens

Specimen A: As failure occurred, a slight bubble

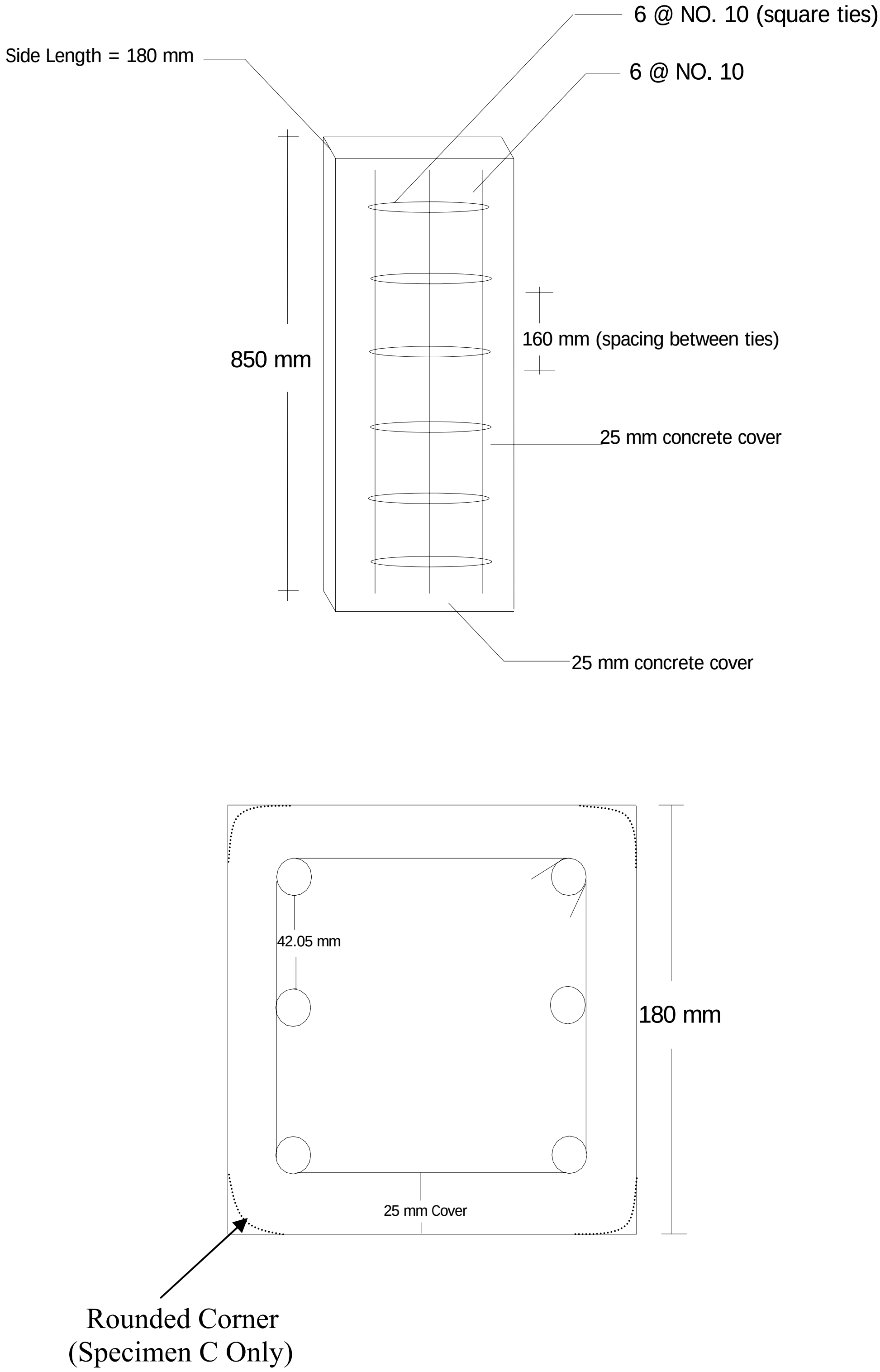

Figure 2. Square columns.

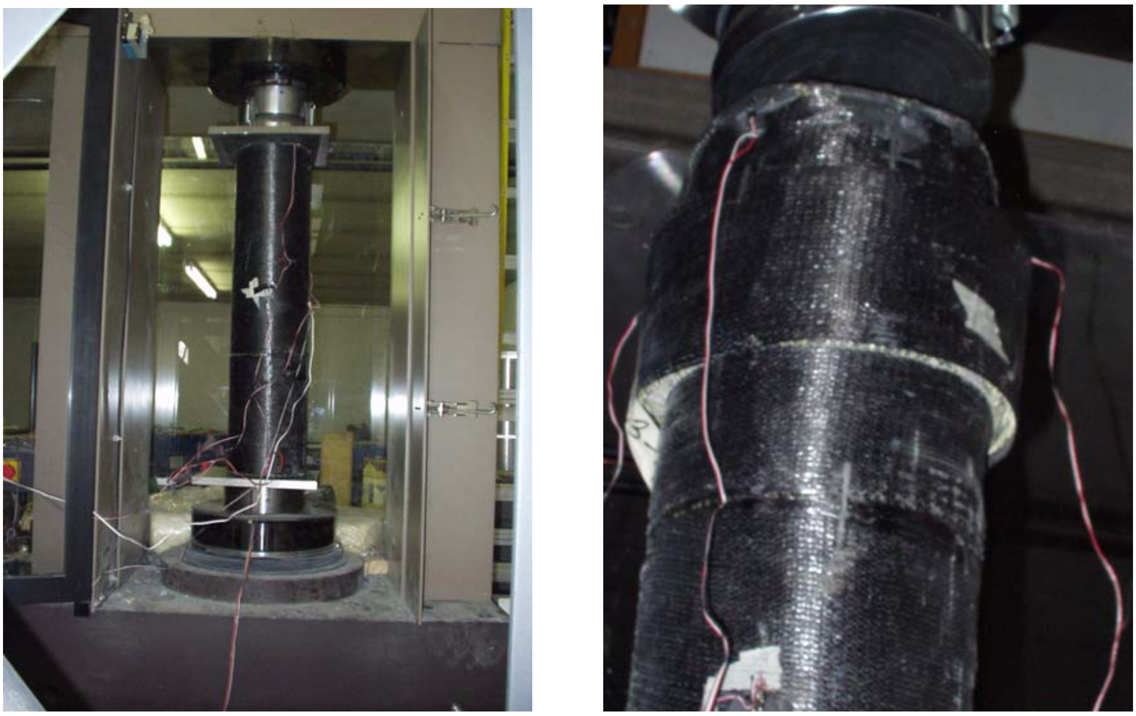

Figure 3. Test set up and shape of failure.

formed on the sides of the column approximately 200 mm from the top of the column. Failure was not sudden, yet not very many warning signs were evident.

Specimen B: The column showed very little warning signs of failure and cracked approximately 200 mm from the top of the column.

Specimen C (with rounded Corners): The columns showed warning signs of failure and cracked approximately 200 mm from the top of the column. There were visual signals of failure such as particle debris and crackling sounds.

5. TEST RESULTS

The ultimate axial strength and displacement of the columns in tests are summarized in Table 4.

The load-displacement relationships of specimens in tests are shown in Fig.3. Also, the values of P_r (compressive strength of an unwrapped column) are shown by a short horizontal line.

6. ANALYSIS OF THE RESULTS

To be able to determine the confining effect of FRP wrap on the behaviour of reinforced concrete columns, the axial compressive strength of concrete columns without FRP wrap are calculated. According to CSA Standard A23.3-94 (5), the axial strength of a reinforced concrete column is calculated by:

$$P_r = \phi_c \alpha_1 f'_c (A_g - A_{st}) + \phi_s f_y A_{st} \quad (1)$$

Where α_1=0.85-0.0015$f'_c \geq$0.67, f'_c is the specified compressive strength of concrete, A_g is the gross area of section, A_{st} is the total area of longitudinal reinforcement, f_y is the specified yield strength of reinforcement, ϕ_c and ϕ_s are the resistance factors for concrete and steel (=1 for laboratory conditions). Using Eq.1, the axial

TABLE 4. Ultimate Axial Strength and Displacement of Specimens.

Circular Specimen	Max. Load (kN)	Displacement (mm)		Square Specimen	Max. Load (kN)	Displacement (mm)	
		At Max. Load	Ultimate			At Max. Load	Ultimate
A	2798	12.3	12.7	A	1417	7.4	14.1
B	2488	11.6	18.7	B	1343	3.3	7.7
C	2324	10.6	12.4	C*	1618	10.9	11.9
Average (A, B, C)	2537	11.5	14.6	Average (A and B)	1380	5.4	10.9

* Square Specimen C had rounded corners.

compressive strengths of circular and square columns are calculated as follows:

Square Column: $P_r = (0.8)(46.1)\ [(180)\ (180) - (6)\ (100)] + (400)\ (600) = 1413$ kN

Circular Column: $P_r = (0.8)(46.1)[(\pi/4)(203)^2 - (6)(100)] + (400)(600) = 1411$ kN

The above values of P_r for different concrete columns are shown in Figure 4 using short horizontal lines. As seen in Figure 4, the measured strengths of circular wrapped columns are much larger than the value of P_r. Therefore the FRP wrap has increased the axial compressive strength of circular concrete columns, significantly. However, the strengths of square columns have not increased because of the application of the FRP wrap. The exception is the Square Column C with the increase of 15% in strength. The Square Column C had the corners removed to a depth of 12mm.

Figure 4 shows that for FRP circular columns, the load versus displacement relationship is almost linear up to the value of the axial compressive strength of an unwrapped concrete column, P_r.

After this value, the slopes of the load-displacement relationships decrease due to the reduction of the stiffness of the concrete columns. The stiffness of the columns has decreased because of the cracking and the expansion of the confined concrete. At this stage, the confining effect of FRP wraps starts to increase the compressive strength of the columns. The load-displacement relationships of the confined columns are still linear but with smaller slopes. This may be because of the linear behavior of the FRP wrap against the radial stresses in the confined concrete. The linear behavior of the confined columns continues, with a smaller stiffness, until failure. The failure is sudden without warning because of the fact that the materials in FRP wrap are brittle in behavior. Figure 4 also shows that the load-displacement relationships of square columns are almost linear until the value of P_r. There is no an apparent indication of the effect of the FRP wraps in increasing the compressive strengths of the square columns. In the case of Column C with rounded corners, the strength has increased approximately 15%. However, it seems that the ductility of the wrapped square columns has improved, especially in the column with rounded corners. Therefore, the application of FRP wrap on square columns can only improve the ductility of these columns.

Figure 5 shows the load versus axial strain relationship for all circular and square columns. It is seen that in all cases, the load-strain relationship is almost linear up to the strain of 0.0025. For the square columns, the maximum loads occur around the strain of 0.005. The maximum loads of square columns are close to the value of P_r as calculated by Eq.1. The value of P_r is shown in Figure 5 by a horizontal dashed line at load 1412 kN. Therefore, the FRP wrap may not increase the strength of the square columns. However, Figure 5 shows that the FRP wrap has improved the ductility of the square columns. For circular columns (solid lines in Figure 5), the FRP wrap has increased the axial strengths, approximately 80%. The ductility of FRP wrapped circular columns has also improved.

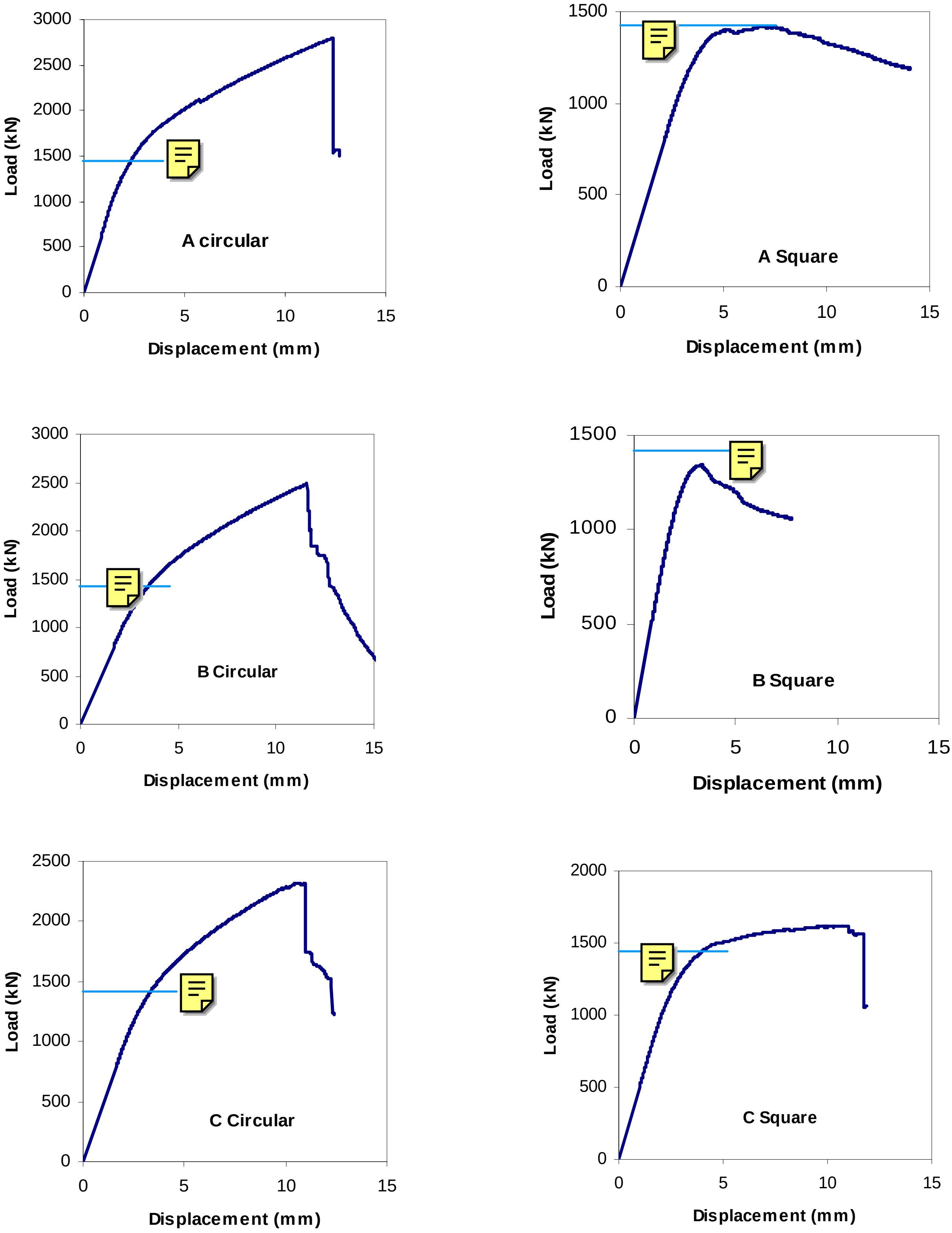

Figure 4. Load versus displacement relationships for different specimens.

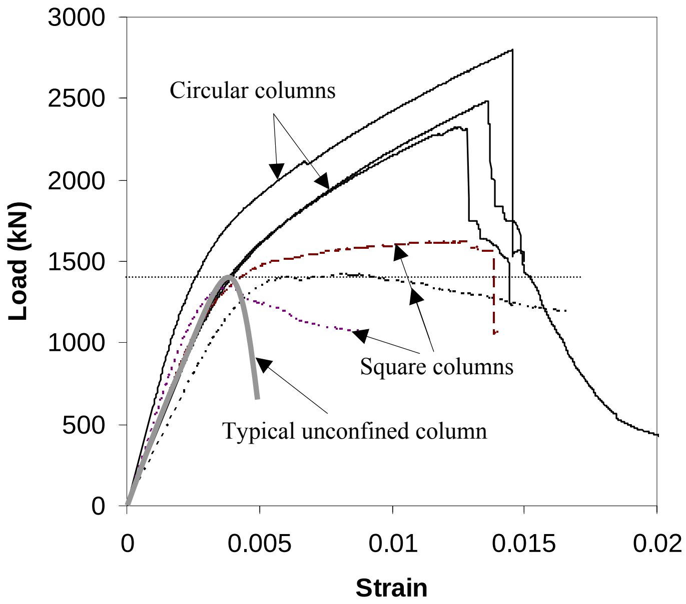

Figure 5. Load versus strain relationship for circular and square columns.

7. PREVIOUS MODELS FOR FRP WRAPPED COLUMNS

The axial strength P_{rc} of the columns wrapped with FRP can be calculated based on Eq.1 with the replacement of f'_c by the compressive strength of confined concrete f'_{cc}. To calculate the value of f'_{cc}, different models have been proposed. Theriault and Neale (6) presented the following equation for the strength of confined concrete:

$$P_{rc} = \phi_c \alpha_1 f'_{cc}(A_g - A_{st}) + \phi_s f_y A_{st} \qquad (2)$$

$$f'_{cc} = f'_c(1 + \alpha_{pc}\omega_w) \qquad (3)$$

where

$$\omega_w = 2f_{lfrp} / \phi_c f'_c \quad \text{(Circular Columns)} \qquad (4)$$

$$\omega_w = f_{lfrp} / \phi_c f'_c \quad \text{(Square Columns)} \qquad (5)$$

$$f_{lfrp} = 2N_b \phi_{frp} f_{frpu} t_{frp} / D_g \quad \text{(Circular Columns)} \qquad (6)$$

$$f_{lfrp} = 2N_b \phi_{frp} E_{frp} \varepsilon_{frp} t_{frp} (b+h) / (bh) \quad \text{(Square Columns)} \qquad (7)$$

The term α_{pc} is a performance coefficient for circular columns, ω_w is the ratio of ultimate confinement stress due to FRP to concrete strength, f_{lfrp} is the ultimate confinement pressure due to FRP reinforcement in MPa, N_b is the number of layers of FRP, ϕ_{frp} is the resistance factor for the FRP (=1 for laboratory conditions), f_{frpu} is the ultimate tensile strength of the FRP, t_{frp} is the thickness of the FRP, b, h, D_g are dimensions of square and circular columns, E_{frp} is the modulus of elasticity of FRP, and ε_{frp} is the strain in FRP reinforcement (0.003, conservatively).

Using the proposed equations for wrapped columns, the axial strengths of FRP wrapped circular and square columns are calculated as follows:

Circular Columns:

$f_{lfrp} = 2N_b f_{frpu} t_{frp} / D_g = 2(2)(876)(1) / 200 = 17.26$ MPa

$\omega_w = 2f_{lfrp} / f'_c = 2(17.26) / (46.1) = 0.75$

$f'_{cc} = f'_c(1 + \alpha_{pc}\omega_w) = (46.1)[1 + (1)(0.75)\ ] = 80.67$ MPa

$P_{rc} = [\alpha_1 f'_{cc}(A_g - A_{st}) + f_y A_{st}]$

$P_{rc} = [(0.8)\ (80.67)\ [(\pi/4)(203)^2 - (6)(100)] + (400)(600) = 2289$ kN

Square Columns:

$f_{lfrp} = 2N_b E_{frp}\varepsilon_{frp}t_{frp}\ (b + h) / (bh) = 2(2)(72400)(0.003)(1)(180 + 180) / (180)(180) = 9.65$ MPa

$\omega_w = f_{lfrp} / f'_c = 9.65 / 46.1 = 0.209$

$f'_{cc} = f'_c(1 + \alpha_{pr}\omega_w) = (46.1)[1 + (1)(0.209)] = 55.7$ MPa

$P_{rc} = [\alpha_1 f'_{cc}(A_g - A_{st}) + f_y A_{st}]$

$P_{rc} = [(0.8)(55.7)[(180)(180) - (6)(100)] + (400)(600) = 1657$ kN

Table 5 summarizes the calculated values of P_r, P_{rc} and the measured strengths of columns. Comparison between the calculated values of P_{rc} with the average measured strengths of columns in Table 5 shows that the proposed Equation 2 for circular columns underestimates the column strength by approximately 11% (i.e. The proposed equation for FRP wrapped circular columns can be used safely). It is also seen that the proposed equation for square columns overestimates the column strengths by approximately 20%. However, for the square column with rounded corners (Square Column C), the calculated strength is close to the measured strength of the column. Therefore, it seems that the proposed equation for FRP wrapped square columns can be used to predict the axial strength of square columns only if the corners of the columns are rounded appropriately.

8. CONCLUSIONS

The effect of the FRP wrap on the axial strength of reinforced concrete columns was studied in this paper. The study included testing six columns in two series. The first series comprised three similar circular columns wrapped with FRP sheets. The second series consisted of three similar square columns wrapped with FRP sheets. The corners of one of the square columns (Column C) were rounded in order to study the effect of corner shape of square columns on load resistance. The values of load and displacement of columns were recorded using a displacement control test set up. Test results were compared with available

TABLE 5. Summary of Column Strengths.

Specimen Type	P_r (kN)	P_{rc} (kN)	P_{rc} (test) (kN)
Circular	1411	2289	2537
Square	1413	1657	1380
Square (rounded corners)	1413	1657	1618

proposed equations. Based on the test results, the following conclusions are drawn:

1. Comparison between the test results of wrapped circular columns with the values calculated using A23.3-94 (CSA 1994) shows that the FRP wrap can increase the axial strength of circular columns significantly. The ductility of circular columns improves because of the application of the FRP wrap.

2. The application of FRP wrap may not increase the axial strength of square columns. However, if the corners of the square columns are rounded appropriately, the axial strength and ductility of columns increase considerably.

3. The recent proposed equations presented by Theriault and Neale (6) for the wrapped circular columns can be used to predict the axial strength of FRP wrapped circular columns. However, their proposed equations for square columns overestimate the axial strength of FRP wrapped square columns unless the corners of the square columns are rounded appropriately.

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