Design Guidelines Review for CFRP Confinement of Plain and Reinforced Concrete Square Columns

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Abstract: The results of the five well known international design guidelines were reviewed for the plain and reinforced concrete square columns wrapped with a single layer of carbon fibre reinforced polymer (CFRP). The experimental results were compared with the values obtained using North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001), Concrete Society (TR-55) and European design guidelines, (fédération Internationale du béton fib Bulletin-14) in terms of confined compressive strength and the gain in axial load carrying capacity for the plain and reinforced concrete square columns. The results of this study indicated that for the plain concrete square columns, all the design guidelines were more conservative compared to the reinforced concrete square columns both in terms of CFRP confined compressive strength and the gain in axial load carrying capacity.

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1. Introduction:

Fibre reinforced polymer wrapping around the structural members for rehabilitation and strengthening of structures becomes the most popular methodology in the field of civil engineering. The performance of fibre reinforced polymer as a confining material is considered excellent among the engineering community especially for the retrofitting and strengthening of deficient bridge piers and building columns. It is well known fact that the fibre reinforced polymer jacketing increases the load carrying capacity and ductility of concrete columns. Considerable research has been carried out and numerous models have been developed in order to investigate the effectiveness of fibre reinforced polymer for the retrofitting and repairing of concrete columns [1-28]. In the literature a lot of research has been carried out on small scale fibre reinforced polymer wrapped concrete cylinders without using longitudinal reinforcement. A limited research was carried out on medium scale square columns with internal longitudinal reinforcement.

A number of design guidelines and models have been developed in the past to predict the confined compressive strength and axial load carrying capacity of columns [1-28]. The current existing well known international North American design guidelines; American Concrete Institute ACI 440.2R-2008 [1], Canadian Standard Association CSA-S806-02m[2], Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 [3], Concrete Society (TR-55) [4] and European design guidelines, (fédération Internationale du béton fib Bulletin-14) [6] provide design equations for columns retrofitted or strengthened with fibre reinforced polymer. Unfortunately, all the existing well known international design guidelines mentioned above were developed to repair or strengthen the columns having the existing internal longitudinal reinforcement. However, they are based on the confined concrete compressive strength resulting from FRP wrapping neglecting the effect of internal existing longitudinal and transverse reinforcement. According to authors knowledge no research has been carried out to date to evaluate the mentioned above existing well known international design guidelines to predict the confined compressive strength and ultimate load carrying capacities of columns considering the existing internal reinforcement and without considering the existing internal reinforcement. The main objective of the present study is to evaluate the values of CFRP confined compressive

Table 1. Certain Concrete Properties

Avg. Compressive Strength (fc')	24.51 MPa
Slump	75mm
Concrete Mix Ratio Water to Cement Ratio Lab Temperature	1:3:6 0.6 27^{O} C

Table 2. Properties of Reinforcing Steel

Test conditions	Size (mm)	Yield strength
Lab Temperature	10 mm	414 MPa
	12.5 mm	414 MPa

strength and the gain in axial load carrying capacities predicted by the design guidelines mentioned above and the experimental tested data for plain and reinforced concrete square columns.

2. Specimen Casting, Instrumentation and Testing Procedure

A total of eight square concrete columns were cast into the following two groups:

1) Plain concrete square columns (P.C); Four columns were cast without any internal reinforcement and they were called plain concrete (P.C) square columns

2) Reinforced concrete square columns (R.C); Four columns were cast with internal reinforcement and they were called reinforced concrete (R.C) square columns

All the specimens of the above mentioned groups were cast from the same concrete mix ratio (1:3:6) using sand, siliceous (gravel) aggregate (maximum size of 20 mm) and Ordinary Portland Cement (OPC) with the maximum water cement ratio 0.6 (w/c). The longitudinal reinforcement ratio used in the reinforced concrete (R.C) square columns was 1.6% with No.3 (10mm Ø) deformed bars used as the tie (square shape) bars spaced at 100 mm centers throughout the length of columns as shown in Fig.1. The concrete compressive strength and yield strength of reinforcing bars used in this study is shown in Tables 1 and 2.

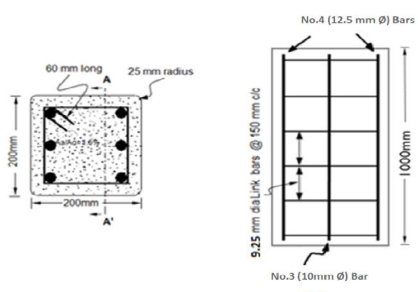

Fig.1 Cross-sectional dimensions and detail of reinforcing bars

A single layer of commercially available unidirectional carbon fibre reinforced polymer (CFRP) Sika Wrap Hex-230C sheets with adhesive Sikadur-330 was applied around the square columns according to the procedures specified by the manufacturers. The properties of Sika Wrap Hex-230C, Sikadur-330 epoxy resin and their laminate properties provided by the supplier are shown in Tables 3, 4 and 5. All the specimens before the application of carbon fibre reinforced polymer (CFRP) were kept for curing up to fourteen days and then left in the laboratory environment for one month. After one month, in each group of columns mentioned above, two columns of each group were wrapped with unidirectional carbon fibre reinforced polymer (CFRP) Sika Wrap Hex-230C sheets and cured for one month and then left in the laboratory environment until the day of testing.

Axial and transverse deformations of the columns were measured manually using dial gauges with a gauge length of 30 mm. Two dial gauges were used to measure vertical (axial) deformations while two dial gauges were used to measure horizontal deformations. All the columns were tested under axial compression loading using load control method. The load was applied using 3000 kN capacity hydraulic jack at an average rate of loading 1 kN/minute until failure. All the data was monitored and measured through the testing of all specimens.

Table 3. Typical dry fiber properties of Sika Wrap Hex-230C

Tensile Strength	3,450 MPa
Tensile Modulus	230,000 MPa
Tensile Elongation	1.5 %
Density	1.8 g/cc

Table 4. Epoxy Material Properties of Sikadur-330

Tensile Strength	30 MPa
Tensile Modulus	4,500 MPa
Elongation Percent	0.9 %
Density	1.3 Kg/Ltr

Table 5. Laminate Properties (after standard curing) of Sika Wrap Hex-230C with Sikadur-330 Epoxy

Tensile Strength	894 MPa
Tensile Modulus	65,402 MPa
Tensile Elongation	1.33 %
Ply thickness	0.381mm

3. Review of Design Guidelines

3.1 American Concrete Institute (ACI Committee 440.2R-2008)

According to ACI Committee 440.2R-08 [1], Eq.1 & Eq.2 are used to predict the axial load carrying capacity and the confined compressive strength of plain and reinforced concrete square columns.

$$P_u = 0.85 f'_{cc}(A_g - A_{st}) + f_y A_{st} \quad (1)$$

The maximum confined compressive f'_{cc} strength is based on a model proposed by Lam and Teng [21] as described in Eq.2

$$f'_{cc} = f'_c + 3.3 k_a f_l \quad (2)$$

The lateral confinement pressure f_l can be calculated by using the Eq.3

$$f_l = \frac{2\varepsilon_{fe} E_f n t_f}{D} \quad (3)$$

For non-circular section *D* can be calculated from Eq.4

$$D = \sqrt{(b)^2 + (h)^2} \quad (4)$$

For pure axial loading

ε_{fe} = FRP effective strain $= k_\varepsilon \varepsilon_{fu}$

$k_\varepsilon = 0.55$ (recommended value to take into account premature failure strain of FRP).

k_a and k_b are then defined based on the aspect ratio (b/h) and the effective confinement area versus the total area of concrete.

k_a and k_b can be calculated by Eq.5 & 6 respectively

$$k_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \quad (5)$$

$$k_b = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^{0.5} \quad (6)$$

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\frac{b}{h}\right)(h-2r)^2 + \left(\frac{h}{b}\right)(b-2r)^2\right]}{3A_g} - \rho_g}{1 - \rho_g}$$

The value k_a can be obtained by substituting the value of $\frac{A_e}{A_c}$ into Eq. 5 and 6.

$$k_a = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-\rho_g)} \quad (7)$$

It is important to note that the ratio of the confining pressure to the unconfined compressive strength should be greater than 0.08 based on tests by Lam and Teng [21]. This is the minimum level of confinement required to assure a non-descending second branch in the stress-strain behaviour [21]. It should be noted that in order to prevent the excessive cracking and resulting loss of concrete integrity, the maximum ultimate strain is limited to 0.01. When this limit is applicable the corresponding maximum value of confined compressive strength should be recalculated using the Eq. 8 based on stress-strain curve provided by the Concrete Society [1]

$$\varepsilon_{ccu} = \varepsilon'_c\left(1.50 + 12k_b \frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right) \quad (8)$$

$$\varepsilon_{ccu} \le 0.01 \quad (9)$$

3.2 Canadian Standard Association (CSA- S806-02)

According to the Canadian Standard Association S806-02(CSA 2002) [2], the confined compressive strength and the axial load carrying capacity of the CFRP strengthened plain and reinforced columns can be calculated using the Eq. 10 & 12 respectively.

$$P_u = \alpha f'_{cc}(A_g - A_{st}) + A_{st} f_y \quad (10)$$

Where

$$\alpha = 0.85 - 0.0015 f'_c \ge 0.67 \quad (11)$$

The compressive strength of confined concrete f'_{cc} can be calculated using Eq.12

$$f'_{cc} = 0.85 f'_c + k_l k_s f_l \quad (12)$$

Where $k_l = 6.7(k_s f_l)^{-0.17}$

k_s can be taken as 0.25 for non-circular section.

The lateral confinement pressure for non-circular sections f_l can be calculated by using Eq.13

$$f_l = \frac{2nt_f \varepsilon_{fe} E_f}{D} \quad (13)$$

3.3 Intelligent Sensing for Innovative Structures Canada (ISIS MO4-2001)

According to the intelligent sensing for innovative structures Canada Network of Centres of Excellence [3], the confined compressive strength of CFRP wrapped plain and reinforced concrete square columns can be calculated using Eq.14.

$$f'_{cc} = f'_c(1 + \alpha_{pr} w_w) \quad (14)$$

α_{pr} can be taken as equal to 1.0

w_w be calculated using Eq. 15

$$w_w = \frac{f_l}{f'_c} \quad (15)$$

f_l can be calculated using Eq.16

$$f_l = \frac{2nt_f \varepsilon_{fe} E_f (b+h)}{bh} \quad (16)$$

3.4 Concrete Society Technical Report (TR-55)
The confined compressive strength and the axial load carrying capacity of CFRP strengthened plain and reinforced square columns according to the Concrete Society confinement model [4] can be calculated using Eq.17

$$P_u = f'_{cc} A_c + f_y A_{st} \quad (17)$$

Where For non-circular sections

$$f_{cc}' = f_{co} + 2k_s f_l \quad (18)$$

$$f_{co} = 0.67 f_{cu} \quad (19)$$

$$k_s = \frac{b}{h}\frac{A_e}{A_g} \quad (20)$$

$$\frac{A_e}{A_g} = \frac{1 - \left[(h-2r)^2 + (b-2r)^2 - 3A_{ol}\right]/3A_g - \rho_g}{1-\rho_g}$$

$$A_{ol} = 0 \text{ if } 2b \geq (h-2r)$$

$$= \frac{4l_{ol}^{\ 3}}{3(h-2r)} + l_{ol}\left(2b - (h-2r)\right) \text{ if } 2b < (h-2r)$$

Where

$$l_{ol} = \sqrt{\frac{(h-2r)}{4} - \frac{b(h-2r)}{2}} \quad (21)$$

The lateral confinement pressure f_l can be calculated by using Eq.22

$$f_l = \frac{2 f_f t_f}{\sqrt{b^2 + h^2}} \quad (22)$$

3.5 *fib* Technical Report (Bulletin 14)
The ultimate axial load resistance of the FRP strengthened column according to Eurocode [5] can be calculated using Eq.23

$$P_u = \lambda \eta f'_{cc} A_c + f_y A_{st} \quad (23)$$

Where

$$\eta = 1 \quad \text{for } f'_c \leq 50 \text{ MPa}$$

$$\lambda = 0.8 \text{ for } f'_c \leq 50 \text{ MPa}$$

The European fédération internationale du béton (*fib* Bulletin-14) design guidelines [6] provide the following two equations for the value of maximum confined concrete compressive strength f'_{cc}.

3.5.1 *Exact Predictive Equation*

$$f'^{*}_{cc} = f'_c\left[2.25\sqrt{1 + 7.9\frac{f_l}{f_c'}} - 2\frac{f_l}{f_c'} - 1.25\right] \quad (24)$$

$$f_{lx} = \frac{2t_f k_a E_f \varepsilon_{fu}}{h} \quad (25)$$

$$f_{ly} = \frac{2t_f k_a E_f \varepsilon_{fu}}{b} \quad (26)$$

$$k_a = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-\rho_g)} \quad (27)$$

ρ_f for non-circular sections can be calculated by using Eq. 28

$$\rho_f = \frac{2nt_f(b+h)}{bh} \quad (28)$$

$$\varepsilon^*_{cc} = \varepsilon_c\left[1 + 5\left(\frac{f'^{\,*}_{cc}}{f'_c} - 1\right)\right] \quad (29)$$

The secant modulus $E_{\sec,u}$ is:

$$E_{\sec,u} = \frac{E_c}{1 + 2\beta\varepsilon_{fu}}$$

$$\beta = \frac{5700}{\sqrt{f'_c}} - 500$$

$$E_c = 4730\sqrt{f'_c} \text{ (MPa)}$$

$$\varepsilon_{cc} = \varepsilon^*_{cc}\left[\frac{E^*_{cc}(E_c - E_{\sec,u})}{E_{\sec,u}(E_c - E^*_{cc})}\right]^{1-\frac{E^*_{cc}}{E_c}}$$

$$E^*_{cc} = \frac{f'^{\,*}_{cc}}{\varepsilon^*_{cc}}$$

$$f'_{cc} = E_{\sec,u} \times \varepsilon_{cc}$$

3.5.2 *Approximate Predictive Equation*

The ultimate confined concrete strength is calculated using Eq.30

$$f'_{cc} = f'_c\left(0.2 + 3\sqrt{\frac{f_l}{f'_c}}\right) \quad (30)$$

$$f_{lx} = \frac{2t_f k_a E_f \varepsilon_{fu}}{h} \quad (31)$$

$$f_{ly} = \frac{2t_f k_a E_f \varepsilon_{fu}}{b} \quad (32)$$

The experimental un-confined and FRP confined compressive strengths were obtained by using the Eq. 33 and 34 respectively.

$$f'_{co(Exp)} = \frac{P_{uo} - f_y A_{st}}{A_g - A_{st}} \quad (33)$$

$$f'_{cc(Exp)} = \frac{P_{ucc} - f_y A_{s_t}}{A_g - A_{s_t}} \quad (34)$$

4. Results and discussions

The confined compressive strength and axial load carrying capacity predicted by the existing design guidelines: North American design guidelines (1) American Concrete Institute ACI 440.2R-2008, (2) Canadian Standard Association CSA-S806-02, (3) Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001,(4) Concrete Society (TR-55), (5) European design guidelines (fib bulliten-14) and their comparison with the experimental tested data for plain concrete (P.C) and reinforced concrete (R.C) square columns was discussed in the following sections.

4.1 Experimental versus predicted (North American design guidelines) CFRP confined compressive strength of plain and reinforced concrete square columns

Figs.2 to 4 and Table 6 shows the predicted and experimental results of confined compressive strength of plain concrete square columns wrapped with a single layer of carbon fibre reinforced polymer. From Figs.2 to 4 and Table 6 it is evident that the North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001) underestimate the confined compressive strength of plain concrete (P.C) square columns when wrapped with a single layer of carbon fibre reinforced polymer (CFRP). However, for the same number of carbon fibre reinforced polymer layer (CFRP), American Concrete Institute ACI 440.2R-2008 and the Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 predict the confined compressive strength very close to the experimental results. It is worth to mention here that for the both plain concrete (P.C) and reinforced concrete (R.C) square columns when wrapped with a single layer of CFRP jacket, Canadian Standard Association CSA-S806-02 predict more conservative values compared to other two North American design guidelines(American Concrete Institute ACI 440.2R-2008, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001).

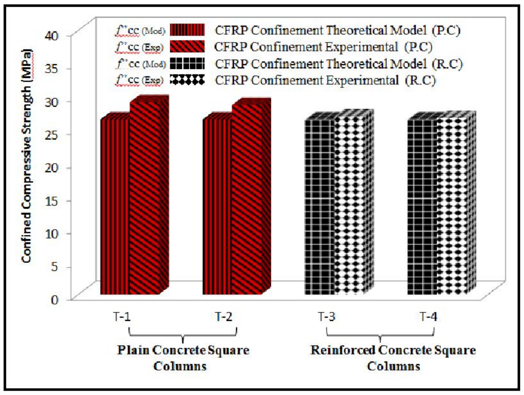

Fig.2: Comparison of Experimental Test Results with the American Concrete Institute (ACI-440 Committee 2008) Design Guidelines for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

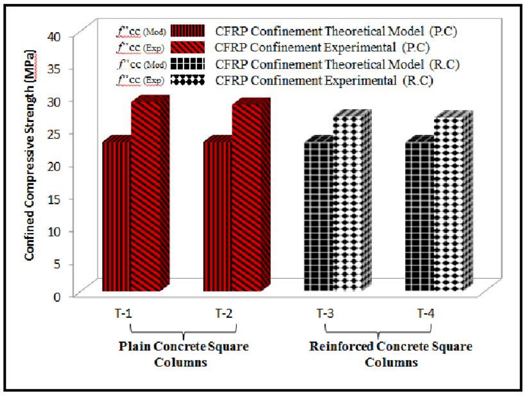

Fig.3: Comparison of Experimental Test Results with the Canadian Standard Association (CSA-S806-02 2002) Design Guidelines for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

Table 6. Performance of North American Design Guidelines in Terms of Compressive Strength Enhancement of P.C and R.C square columns

Guidelines	Test No.	Specimen Type	$f'cc$(Model) (MPa)	$f'cc$(Experimental) (MPa)	$\frac{f'_{cc(Exp)} - f'_{cc(Model)}}{f'_{cc(Model)}}$ %
ACI	T-1	P.C	26.51	29.09	9.73
	T-2		26.51	28.69	8.22
	T-3	R.C	26.5	26.93	1.62
	T-4		26.5	26.7	0.75
CSA	T-1	P.C	22.95	29.09	26.75
	T-2		22.95	28.69	25.01
	T-3	R.C	22.95	26.93	17.34
	T-4		22.95	26.7	16.34
ISIS	T-1	P.C	25.51	29.09	14.03
	T-2		25.51	28.69	12.47
	T-3	R.C	25.51	26.93	5.57
	T-4		25.51	26.7	4.66

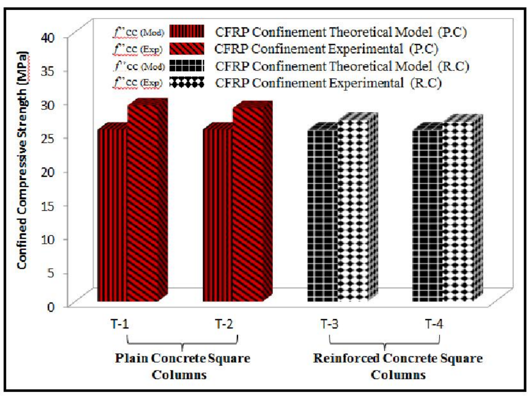

Fig.4 Comparison of Experimental Test Results with the Intelligent Sensing for Innovative Structures (ISIS MO4 2001) Design Guidelines for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

4.2 *Experimental versus predicted (Concrete Society and European design guidelines) CFRP confined compressive strength of plain and reinforced concrete square columns*

Fig.5 compares the theoretical CFRP confined compressive strength predicted by the Concrete Society (CS) technical report TR-55 and the experimental tested vales for plain concrete (P.C) and reinforced concrete (R.C) square columns. It is noteworthy to mention here that the Concrete Society (CS) technical report TR-55 underestimate the confined compressive strength both for plain and reinforced concrete square columns. However, for reinforced concrete square columns the predicted values are less conservative compared to the reinforced concrete (R.C) square columns when wrapped with a single layer of CFRP jacket (refer to Table.7).

Figs.6 and 7 presents results of predicted CFRP confined compressive strength calculated based on the European design guidelines, (fédération Internationale du béton *fib* Bulletin-14) *fib approximate and fib exact methods* both for the plain and reinforced concrete square columns. It is worth to highlight that *fib approximate* predicts the CFRP confined compressive strength more conservative for plain concrete (P.C) square columns compared to reinforced concrete square columns. However, the *fib approximate* prediction of CFRP confined compressive strength for reinforced concrete square columns was very close to the experimental results. It is interesting to note that the *fib exact method* overestimate the CFRP confined compressive strength both for plain and reinforced concrete square columns when compared with the experimental results. However, the *fib exact* prediction of CFRP confined compressive strength for plain concrete (P.C) square columns was close to the experimental results.

From Fig.5 and Table 7 it can be seen that the results of the Concrete Society (CS) technical report TR-55 for the CFRP confined compressive strength of plain concrete (P.C) square columns were conservative by 23% when compared to the experimental results. However, it is interesting to highlight that the Concrete Society (CS) technical report TR-55 results for the CFRP confined compressive strength of reinforced concrete (R.C) square columns were conservative by 14% when compared to the experimental results.

It is also evident from Figs.6 to 7 and Table 6 that *fib approximate* underestimate the CFRP confined compressive strength by 10% for plain concrete (P.C) square columns when compared to the experimental results. However, the *fib exact* overestimate the CFRP confined compressive strength by 6% for plain concrete (P.C) and by13% for reinforced concrete square columns when compared with the experimental results.

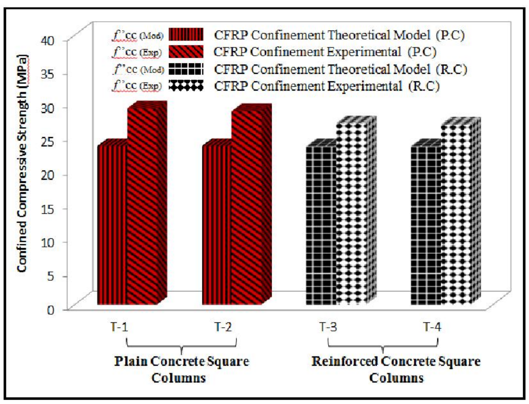

Fig. 5: Comparison of Experimental Test Results with the Concrete Society (CS) Technical Report TR-55 Design Guidelines for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

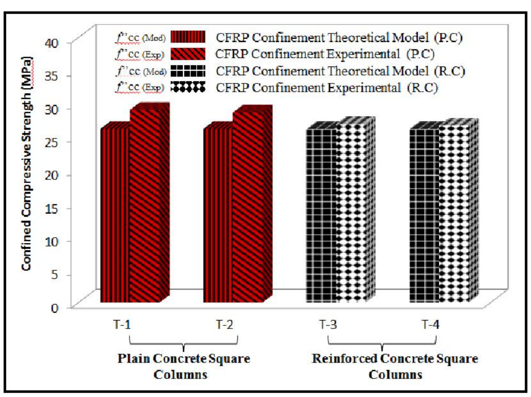

Fig.6: Comparison of Experimental Test Results with the fib Technical Report Design Guidelines (Approximate) for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

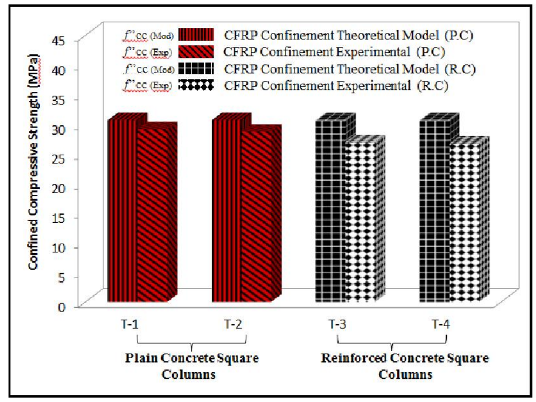

Fig.7: Comparison of Experimental Test Results with the fib Technical Report Design Guidelines (Exact) for the Confined Compressive Strength of Plain and Reinforced Concrete Square Columns.

4.3 Experimental versus predicted (North American design guidelines) CFRP confined axial load carrying capacity of plain and reinforced concrete square columns

This section addresses the predicted and experimentally tested data in terms of gain in axial load carrying capacity of plain and reinforced concrete square columns wrapped with a single layer of carbon fibre reinforced polymer (CFRP). The numbers on x-axis in Figs.8 to 13 refers to:

1) Comparison of predicted and tested axial load carrying capacities of plain concrete (P.C) square columns (Tests T1&T2)

2) Comparison of predicted and tested axial load carrying capacities of reinforced concrete (R.C) square columns (Tests T3 &T4)

Figs.8 to 10 show the comparison of results of axial load carrying capacities predicted by the three North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001) and tested data of the plain and reinforced concrete square columns. It can be seen from Figs.8 to 10 and Table.8 that all the three existing North American design guidelines underestimate the axial failure load capacity both for the plain and reinforced concrete square columns. Table 8 clearly shows that CSA-S806-02 prediction was more conservative while ACI 440.2R-2008 prediction was least conservative in terms of gain in axial load carrying capacity both for plain and reinforced concrete square columns.

It is worth mentioning here that the results of three North American design guidelines (refers to Table.8) were more conservative for plain concrete (P.C) square columns compared to reinforced concrete (R.C) square columns. This could be due to the fact that under axial compressive loading plain concrete displayed more lateral expansion compared to the reinforced concrete square columns. Consequently, the carbon fibre reinforced polymer (CFRP) provides more restraining effect for plain concrete compared to reinforced concrete square columns. Since the restraining action of CFRP jacket depends on the lateral expansion of concrete. Therefore, gain in the ultimate failure load was enhanced for plain concrete square columns compared to reinforced concrete square columns.

Table 7: Performance of European Design Guidelines (Concrete Society and fib) for Compressive Strength Enhancement of P.C and R.C square columns confined with CFRP.

Guidelines	Test. No	Specimen Type	$f'cc$(Model) (MPa)	$f'cc$(Experimental) (MPa)	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Model)}}$ %
Concrete Society TR-55 (UK)	T-1	P.C	23.54	29.09	23.58
	T-2		23.54	28.69	21.87
	T-3	R.C	23.52	26.93	14.50
	T-4		23.52	26.7	13.52
fib bulletin-14 Approximate European	T-1	P.C	26.32	29.09	10.52
	T-2		26.32	28.69	9.01
	T-3	R.C	26.22	26.93	2.71
	T-4		26.22	26.7	1.83
fib bulletin-14 Exact European	T-1	P.C	30.78	29.09	-5.49
	T-2		30.78	28.69	-6.79
	T-3	R.C	30.66	26.93	-12.17
	T-4		30.66	26.7	-12.92

Table 8: Performance of North American Design Guidelines in Terms of Enhancement of Axial Load Capacity of P.C and R.C square columns

Guidelines	Test. No	Specimen Type	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Model)}}$ %
ACI	T-1	P.C	889	1148	29.1
	T-2		889	1132	27.3
	T-3	R.C	1134	1305	15.1
	T-4		1134	1296	14.3
CSA	T-1	P.C	736	1148	56.0
	T-2		736	1132	53.8
	T-3	R.C	983	1305	32.8
	T-4		983	1296	31.8
ISIS	T-1	P.C	819	1148	40.2
	T-2		819	1132	38.2
	T-3	R.C	1064	1305	22.7
	T-4		1064	1296	21.8

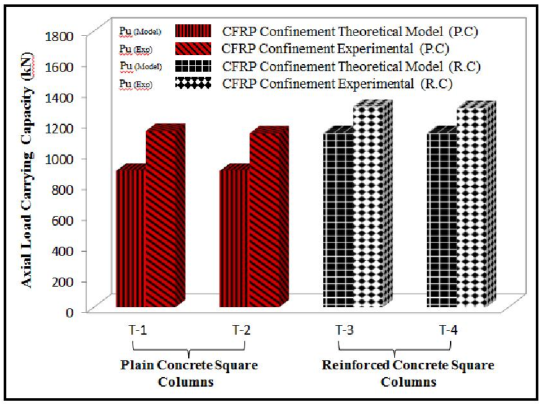

Fig.8: Comparison of Experimental Test Results with the American Concrete Institute (ACI-440 Committee 2008) Design Guidelines for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Columns.

From Figs.8 to 10 and Table 8 it can be seen that the American Concrete Institute ACI 440.2R-2008 predictions were conservative by 28% and 15% in terms of gain in axial load carrying capacity for the plain concrete (P.C) and reinforced concrete (R.C) square columns respectively. The Canadian Standard Association CSA-S806-02 predictions were conservative by 55% and 32% for plain and reinforced concrete square columns respectively. However, the axial load carrying capacity predicted by the Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 was 39% and 22% conservative for the plain concrete (P.C) and reinforced concrete (R.C) square columns respectively.

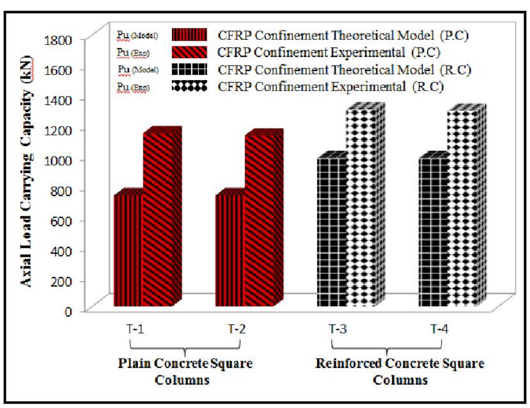

Fig.9: Comparison of Experimental Test Results with the Canadian Standard Association (CSA-S806-02 2002) Design Guidelines for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Column

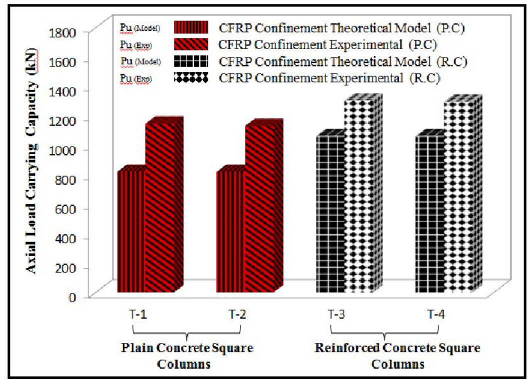

Fig.10: Comparison of Experimental Test Results with the Intelligent Sensing for Innovative Structures (ISIS MO4 2001) Design Guidelines for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Columns.

4.4 *Experimental versus predicted (Concrete Society and European design guidelines) CFRP confined axial load carrying capacity of plain and reinforced concrete square columns*

This section compares the experimental tested data with the theoretical results predicted by Concrete Society and European design guidelines in terms of gain in axial load carrying capacity for plain and reinforced concrete square columns wrapped with a single layer of carbon fibre reinforced polymer (CFRP). Figs.11 to 13 and Table.9 provide the information regarding the comparison of the experimental tested data and the theoretical axial load carrying capacity predicted by the Concrete Society (TR-55) and European design guidelines (*fib approximate and fib exact)*.It is evident from Figs.11 to 13 and Table.9 that the Concrete Society (TR-55) and the European design guidelines also predict the conservative results in terms of gain in axial load carrying capacity for both the CFRP wrapped plain concrete (P.C) and the reinforced concrete (R.C) square columns. However, the prediction of the Concrete Society (TR-55) and the European design guidelines were more conservative for plain concrete (P.C) square columns compared to the reinforced concrete square columns when wrapped with a single layer of carbon fibre reinforced polymer (CFRP).This is attributed to the fact that the presence of reinforcement could provide more restraining action against an inclined shear failure as compared to the plain concrete. Due to the more lateral expansion in plain concrete square columns under axial loading, the CFRP confinement effect was more pronounced in plain concrete square columns compared to reinforced concrete square columns.

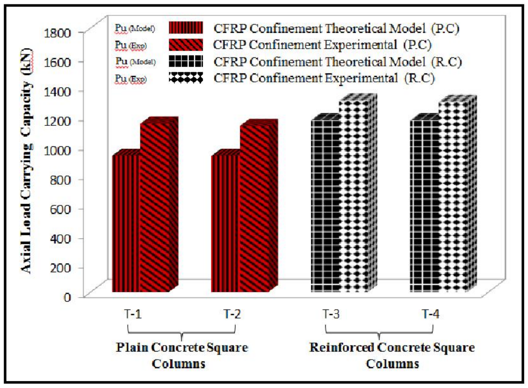

Fig.11 Comparison of Experimental Test Results with the Concrete Society (CS) Technical Report TR-55 Design Guidelines for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Columns.

Figs.11 to 13 and Table.9 clearly show that the axial load carrying capacity predicted by the Concrete Society (TR-55) was 23% and 11% conservative when compared with the experimental results for CFRP confined plain concrete (P.C) and reinforced concrete (R.C) square columns respectively. However, the *fib approximate* method predicts 38% and 21% conservative axial load carrying capacity for CFRP confined plain concrete (P.C) and reinforced concrete (R.C) square columns when compared with the experimental tested data (refers to Table.9).

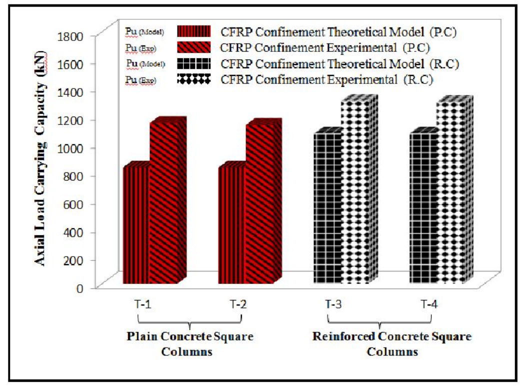

Fig.12 Comparison of Experimental Test Results with the fib Technical Report Design Guidelines (Approximate) for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Columns.

It is interesting to note that the *fib exact* method predicts the better results in terms of axial load carrying capacity for the CFRP confined reinforced concrete square columns compared to the CFRP confined plain concrete (P.C) concrete square columns. It is evident from Fig.13 and Table.9 that *fib exact* method predicts the axial load carrying capacity of CFRP confined plain concrete (P.C) square columns by 18% conservative. However, *fib exact* method predicts the axial load carrying capacity of CFRP confined reinforced concrete (R.C) square columns by 7% conservative which is approximately close to the experimental results.

Table 9. Performance of European Design Guidelines (Concrete Society and fib) in Terms of Enhancement of Axial Load Capacity of P.C and R.C square columns

Guidelines	Test. No	Specimen Type	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Model)}}$ %
Concrete Society TR-55 (UK)	T-1	P.C	929	1148	23.6
	T-2		929	1132	21.9
	T-3	R.C	1172	1305	11.3
	T-4		1172	1296	10.6
fib bulletin-14 Approximate European	T-1	P.C	831	1148	38.1
	T-2		831	1132	36.2
	T-3	R.C	1073	1305	21.6
	T-4		1073	1296	20.8
fib bulletin-14 Exact European	T-1	P.C	972	1148	18.1
	T-2		972	1132	16.5
	T-3	R.C	1211	1305	7.8
	T-4		1211	1296	7.0

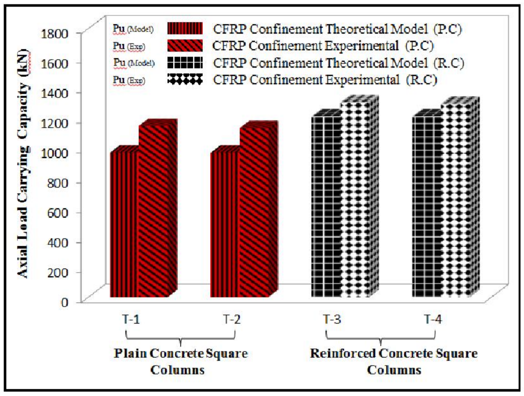

Fig.13 Comparison of Experimental Test Results with the fib Technical Report Design Guidelines (Exact) for the Confined Axial Load Carrying Capacity of Plain and Reinforced Concrete Square Columns.

5. Conclusions

The main objective of the present study is to evaluate the performance of existing North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001), Concrete Society (TR-55) and European design guidelines in terms of confined compressive strength and ultimate load carrying capacities for the plain concrete (P.C) and reinforced concrete (R.C) square columns. The following conclusions were drawn from this investigation.

1. The North American design guidelines; American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 underestimate the confined compressive strength for CFRP confined plain concrete (P.C) square columns by 9%,26% and 13%. For the CFRP confined reinforced concrete (R.C) square columns, the American Concrete Institute ACI 440.2R-2008 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 design guidelines predict the better results for the CFRP confined compressive strength (close to the experimental data). However, the Canadian Standard Association CSA-S806-02 underestimate the CFRP confined compressive strength by 17% for the reinforced concrete square columns when compared with the experimental results.
2. The Concrete Society technical report (TR-55) underestimates the CFRP confined compressive strength by 23% and 14% for the plain and reinforced concrete square columns respectively when compared to the respective experimental tested data. However, the *fib approximate* predicts the CFRP confined compressive strength by 10% conservative for the plain concrete (P.C) square columns and predicts the results very close to the experimental tested data for the reinforced concrete square columns. However, the *fib exact* overestimate the CFRP confined compressive strength by 6% for plain concrete (P.C) and 13% for reinforced concrete square columns when compared to the experimental results.
3. The three North American design guidelines; American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02, Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001 underestimate the gain in axial load carrying capacity by 28%,55%,39% and 15%, 32% 22% for CFRP confined plain and reinforced concrete square columns respectively.
4. The results in terms of gain in axial load carrying capacity predicted by the Concrete Society (TR-55), the *fib approximate* and *fib exact* were 23%, 38% and 18% conservative for the CFRP confined plain concrete (P.C) square columns respectively. However, for the CFRP confined reinforced concrete square columns, the results were 11%, 21% and 7% conservative in terms of gain in axial load carrying capacity predicted by the Concrete Society (TR-55), the *fib approximate* and *fib exact* respectively.

6. Notations:

P_u = axial load carrying capacity

f'_{cc} = compressive strength of FRP confined concrete

A_g = gross cross-sectional area of the confined concrete

A_{st} = longitudinal reinforcing steel area

f_y = yield strength of longitudinal reinforcing bars

f'_c = unconfined compressive concrete strength

A_c = net Cross-sectional area of concrete

f_l = lateral confinement pressure

f_{co} = unconfined concrete compressive strength

n = number of FRP layers

t_f = thickness of FRP layer

E_f = modulus of elasticity of FRP

ε_{fe} = FRP effective strain

b = side of column

h = side of column

k_ε = strain efficiency factor

ε_{fu} = the ultimate FRP strain.

k_a = shape factor

k_b = shape factor

k_a = Efficiency reduction factor

r = radius of the edges of the section

k_s = shape factor

α_{pr} = performance coefficient

w_w =volumetric strength ratio

ε_{ccu} = maximum ultimate strain

A_{ol} = area of overlap of the parabolas

l_{ol} =length of overlap region

f_f =ultimate tensile capacity of FRP

ρ_g = longitudinal reinforcement ratio

ρ_f = volumetric ratio of FRP reinforcement

$E_{\sec,u}$ = Secant modulus

$f'_{co(Exp)}$ = experimental un-confined compressive strength

$f'_{cc\,(Exp)}$ = experimental FRP confined compressive strength

P_{uo} = experimental ultimate maximum un-confined axial load

P_{ucc} = experimental ultimate maximum FRP confined axial load

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References:

1. American Concrete Institute (ACI).Guide for the design and construction of externally bonded FRP systems for strengthening of concrete structures 2008; ACI 440.2R-08, Farmington Hills (MI, USA):American Concrete Institute:2008.
2. Canadian Standards Association (CSA). Design and Construction of building components with fibre-reinforced polymers 2002; CSA-S806, Rexdale, Ontorio, Canada.
3. ISIS Canada, Design Manual No. 4: Strengthening Reinforced Concrete Structures with Externally Bonded Fiber Reinforced Polymers, Intelligent Sensing for Innovative Structures (ISIS) Canada, Winnipeg, 2001.
4. The Concrete Society. Design guidance for strengthening concrete structures using fibre composite material 2004.Technical Report No.55, Crowthorne, UK.
5. Euro Code 2: BS EN 1992-1-1:2004: Design of concrete structures.Part-1-1: General rules and rules for buildings
6. Fédération internationale du Béton fib. Externally bonded FRP Reinforcement for RC structures 2001; Bulletin No. 14, Technical Report. Lausanne, Switzerland.
7. Pellegrino. C and Modena.C.Analytical model for FRP confinement of concrete columns with and without internal steel reinforcement. Journal of Composites for Construction 2010; 14(6):693-705.
8. Xiao.Q.G,Teng.J.G and Yu.T. Behaviour and modelling of confined high-strength concrete. Journal of Composites for Construction 2010; 14(3):249-259.
9. Toutanji.H,Han.M,Gilbert.J and Matthys.S. Behaviour of large-scale rectangular columns confined with FRP composites. Journal of composites for construction 2010; 14(1):62-71.
10. Wu.Y.F and Zhou.Y.W.Unified strength model based on Hoek-Brown failure criterion for circular and square concrete columns confined by FRP. Journal of Composites for Construction 2010; 14(2):175-184.
11. Teng.J.G,Jiang.T,Lam.L and Luo.Y.Z. Reifinement of a design-oriented stress-strain

model for FRP-confined concrete. Journal of Composites for Construction 2009; 13(4):269-278.
12. Rocca.S, Galati.N and Nanni.A.Review of design guidelines for FRP confinement of reinforced concrete columns of noncircular cross-sections 2008; 12(1):80-92.
13. Shamim A. Sheikh, Yimin Li. Design of FRP confinement for square concrete columns 2007; 29(6):1074-1083.
14. Jiang.T and Teng.J.G. Analysis-oriented stress-strain models for FRP-confined concrete. Journal of Engineering Structures 2007; 29(11):2968-2986.
15. Yousaf.M.N,Feng.M.Q and Mosallam.A.S. Stress-strain model for concrete confined by FRP composites. Composites Part B: Engineering 2007; 38(5-6):614-628.
16. Hassan.M and Chaallal.O. Fibre reinforced polymer confined rectangular columns: Assessment of models and design guidelines. ACI Structural Journal 2007; 104(6):693-702.
17. Hadi.M.N.S. Behaviour of FRP wrapped normal strength concrete columns under eccentric loading. Composite structures 2006; 72(4): 503-511.
18. Chaallal.O, Hassan.M and LeBlanc.M. Circular columns confined with FRP: Experimental versus predictions of models and guidelines. Journal of Composites for Construction 2006; 10(1):4-12.
19. Esfahani.M.R and Kianoush.M.R.Axial compressive strength of reinforced concrete columns wrapped with fibre reinforced polymers. International Journal of Engineering transactions B: Application 2005; 18(1):9-19.
20. Bisby.L.A,Dent A.J.S and Green.M.F. Comparison of confinement models for fibre-reinforced polymer-wrapped concrete. ACI Structural Journal 2005; 102(1):62-72.
21. Teng.J.G and Lam.L. Behaviour and modelling of fibre reinforced polymer confined concrete. Journal of Structural Engineering 2004; 130(11):1713-1723.
22. Lam.L and Teng.J.G. Design-oriented stress-strain model for FRP-confined concrete in rectangular columns. Journal of reinforced plastics and composites 2003; 22(13):1149-1186.
23. Becque.J,Patnaik.A.K and Rizkalla.S.H. Analytical models for concrete confined with FRP Tubes. Journal of Composites for Construction 2003; 7(1):31-38.
24. Fam, A. Z., and Rizkalla, S. H. Confinement model for axially Loaded concrete confined by circular fibre-reinforced polymer tubes. ACI Structural Journal 2001; 98(4): 451-461.
25. M.Demers and Neale.K.W. Confinement of reinforced concrete columns with fibre reinforced composite Sheets (FRP)-An Experimental study. Canadian Journal of civil engineering 1999; 26:226-241.
26. Spoelsstra.M.R and Monti.G. FRP-confined concrete model. Journal of Composite for Construction 1999; 3(3):143-150.
27. Wu.F.Y and Zhou.W.Y.Unified strength model based on Hoek-Brown failure criterion for circular and square concrete columns confined by FRP. Journal of Composite for construction 2010;14(2):175-183.
28. Benzaid R, Chikh NE, Mesbah H. Behaviour of square concrete column confined with GFRP composite warp. J Civ Eng Manage 2008; 14(2):115-20.

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