Experimental versus design guideline predictions for confined strength and axial load carrying capacity of circular concrete cylinders wrapped with CFRP

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Abstract: This study presents the results of the comparison of the experimental values with the theoretical values of strength predictive design guidelines for the circular concrete cylinders wrapped with carbon fiber reinforced polymer. The comparison was carried out in terms of confined strength and axial load carrying capacity. The experimental results were compared with the theoretical predictions of 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). This research identified the most and least conservative design guideline predictions for low, medium, normal and high strength concrete.

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1. Introduction

The confinement of concrete is a popular method for strengthening and repairing of concrete structures. The confinement by fiber reinforced polymer wraps, in particular, is a technique that is gaining to much popularity for increasing the load carrying capacity of the structural concrete members subjected to extreme loading. The demand to improve the strength of existing concrete structural members could be due to overloading, the change of usage of the existing structures or up gradation of existing code. The technique of using fiber reinforced polymer wraps for increasing the confined strength of circular members of concrete has been demonstrated (Seible et al. 1997). Different confinement models have been proposed and evaluated. (Fardis and Khalili 1982; Miyaushi et al. 1997; Monti and Spoelstra 1997; Kono et al. 1998; Samaan et al. 1998; Saafi et al. 1999; Spoelstra and Monti 1999). Extensive work has been published in experimental and analytical areas for fiber reinforced polymer confinement. Numerous other researches have been carried out to evaluate different confinement models that predict the confined compressive strength of concrete. (Bisby et al. 2005; Carey and Harries 2005; Challal et al. 2006). The design guidelines have also been compared with the experimental work carried out by various researches. (Hamdy M., and Radhouane M., 2010; Omar Challal, 2006, M. ASCE; Silvia Rocca, 2008).According to the knowledge of the authors very limited research has been conducted to evaluate the applicability of existing strength design guidelines for low, normal, medium and high strength concrete. The available published research data for the prediction of strength limited to 30 to 45 MPa concrete. There is a strong need to investigate the applicability of existing strength predictive 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 Technical Report (CS TR-55), fédération Internationale du béton *fib* Bulletin-14) for low, normal medium and high strength concrete.

2. Methodology

Circular concrete cylinders were prepared in the laboratory for low (8, 10, 13 and 17 MPa), normal (21 and 29 MPa), medium (37 and 49 MPa) and high strength (56 and 62 MPa) mixes. The specimens were wrapped using single layer of carbon fiber reinforced polymer (CFRP) in this study. The entire jacket was made of one continuous sheet that was cut to the proper required length. An additional 4in (100mm) overlap was provided in the transverse direction in order to prevent overlap failure. The carbon fabric (Sikawrap Hex 230 C) with adhesive Sikadur 330 was used as a jacketing material in this research work. The cured laminate properties of Sikawrap Hex-230 C and adhesive (Sikadur 330) provided by the supplier were shown in Table 2 (A). The top and bottom ends of all the specimens were capped with sulphur mortar in order to ensure the uniform loading during testing.

Figure 1(A): Casting of specimens in laboratory

Fig. 1 (B) Rupture of cylinder wrapped with FRP

Table 2 (A): Cured Laminate Properties with of Sikawrap Hex-230 C with Sikadur 330

Property	Value (psi)	Value (MPa)	ASTM Method
Tensile strength	129,800	894	D-3039
Tensile Modulus	9,492,300	65402	D-3039
Tensile Elongation	1.33	1.33	D-3039
Compressive strength	9,724,700	779	D-3039

Table 2 (B) shows the mix properties of the specimen.

Table 2 (B): Mix properties of specimen

Sr. No	Specimen Designation	Strength (MPa)	Slump (mm)	w/c	Mix Ratio
1	T-1	7.84	75	1.08	1:4:8
2	T-2	9.70	60	0.93	1:3:6
3	T-3	13.27	71	0.78	1:2.5:5
4	T-4	16.82	125	0.51	1:2.5:5
5	T-5	20.83	102	0.47	1:2:4
6	T-6	28.77	85	0.40	1:1.3:2.6
7	T-7	36.72	135	0.42	1:1:2
8	T-8	48.89	125	0.42	1:0.8:1.6
9	T-9	56.34	90	0.33	1:0.5:1
10	T-10	62.48	105	0.39	1:0.5:1

Review of Design Guidelines for predicting confined strength and axial load carrying capacity:

American Concrete Institute (ACI Committee 440.2R-2008)

The following design equations suggested by ACI Committee 440.2R-2008 were used to predict the CFRP confined compressive strength and axial load carrying capacity of low, medium, normal and high strength concrete circular cylinders

$$P_u = 0.85 f_{cc'}(A_g - A_{st}) + f_y A_{st}$$

Where

P_U = Axial load carrying capacity

$f_{cc'}$ = Compressive strength of confined concrete

A_g = Cross sectional area of the confined concrete

A_{st} = Longitudinal reinforcing steel area

f_y = Yield strength of longitudinal bars

Formula for confined strength is as follows

$f_{c'}$ = Unconfined concrete compressive strength

f_1 = Lateral confinement pressure

$$f_{cc'} = f_{c'} + 3.3 k_a f_1$$

$$f_1 = \frac{2 \in_{fe} E_f n t_f}{D}$$

where

n = number of FRP layers

t_f = Thickness of FRP layer

E_f = Modulus of Elasticity of FRP

$\in_{fe}$ = FRP effective strain

$\in_{fe}$ = FRP effective strain $= k_e \in_{fu}$

$k_\in = 0.55$

CSA-S806-02

According to Canadian Standard Association CSA-S806-02, the load carrying capacity and CFRP confined strength of circular cylinders were calculated for low, medium, normal and high strength concrete using the following equations.

$$f_{cc'} = 0.85 f_{c'} + k_1 k_s f_1$$

The factor k_1 is dependent on confinement pressure and can be solved using the following equation obtained from tests (CSA 2002)

$$k_1 = 6.7(f_1)^{-0.17}$$

Where k_s is the shape factor which is equal to 1 in circular cross sectional shapes. f_1 can be found out by the following formula: (CSA 2002)

$$f_1 = \frac{2 n t_f \in_{fe} E_f}{D}$$

$\in_{fe}$ will be least of the following values i.e, 0.004 E_f and 0.75* ultimate FRP strain. (CSA 2002)

Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001)

The confined strength of concrete can be calculated using the following design equations provided Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001):

$$f_{cc'} = f_{c'}(1+\alpha_{pc}\omega_w)$$

where

f'_{cc} = Compressive strength of concfined specimen

α_{pr} = Performance coefficient = 1 for circular columns

ω_w = Volumetric strength ratio

ω_w can be found out by (ISIS MO4 2001)

$$\omega_w = \frac{f_1}{f_{c'}}$$

where

f_1 = Lateral confinement pressure

f_l can be found out by the following equation: (ISIS MO4 2001)

$$f_1 = \frac{2N_b f_{frpu} t_{frp}}{D_g}$$

N_b = Number of layers of FRP

f_{frpu} = Ultimate strength of FRP

t_{frp} = Thickness per layeof FRP

D_g = Diameter of the member

ISIS imposes a limitation of minimum confining pressure for design purposes to be taken equal to 4 MPa. (ISIS MO4 2001; Hamdy M., 2010)

Concrete Society Technical Report (TR-55)

The Concrete Society suggested the following design guidelines to predict the confined strength of circular sections

$$\frac{2nt_f E_f}{D(f'_c)^2} > 0.183 \quad (mm^2/N)$$

$f_{cc'}$ is given by the equation: (CS TR-55)

$$f_{cc'} = f^*_{cu} + 0.05(\frac{2nt_f}{D})E_f$$

fc' = Unconfine d compressive concrete strength

$$f^*_{cu} = \frac{f_{c'}}{0.8}$$

$f_{c'}$ = unconfined strength specified

f^*_{cu} = unconfined concrete specified

n = number of FRP layers

t_f = Thickness of FRP layer

D = Diameter of section

***fib* Technical Report (Approximate and Exact Methods) (Bulletin 14)**

The *fib* design guidelines suggested the following two methods to predict the confined compressive strength of circular sections

Approximate Method

The following formulae were used to predict the confined compressive strength

$$f_{cc'} = f'_c(0.2 + 3\sqrt{\frac{f_1}{f_{c'}}})$$

$$f_1 = \frac{1}{2}k_e \rho_f E_f \in_{fu}$$

$k_e = 1$ for full wrap in circular sections

$\in_{fu}$ = Ultimate tensile strain of FRP

E_f = Tensile modulus of Elasticity of FRP

b_f = width of FRP strip in partial wrapping

s = Pitch in partial wrapping

t_f = Thickness of FRP wrap

n = Number of wraps of FRP

k_e = Confinement effectiveness coefficient

ρ_f = volumetric ratio of FRP reinforcement

$$\rho_f = \frac{4nt_f}{10}\left(\frac{b_f}{s}\right) \quad \text{for circular sections}$$

Exact Method

$$f_1 = \frac{1}{2}k_e \rho_f E_f \in_{fu}$$

$k_e = 1$ for full wrap in circular sections

$\in_{fu}$ = Ultimate tensile strain of FRP

E_f = Tensile modulus of Elasticity of FRP

k_e = Confinement effectiveness coefficient

ρ_f = volumetric ratio of FRP reinforcement

$$\rho_f = \frac{4nt_f}{10}\left(\frac{b_f}{s}\right) \quad \text{for circular sections}$$

$$E_c = 4730\sqrt{f'_c}$$

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

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

$$f^*_{cc'} = f'_c\left[2.254\sqrt{1+7.94\frac{f_l}{f'_c}} - 2\frac{f_l}{f'_c} - 1.254\right]$$

$$\in^*_{cc} = \in_c\left[1+5\left(\frac{f^*_{cc'}}{f'_c} - 1\right)\right]$$

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

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

$$f'_{cc} = E_{\sec,u} \text{ x} \in_{cc}$$

$E_{\sec,u}$ = Secant Modulus of elasticity of concrete at ultimate

f'_c = characteristic concrete compressive strength

b_f = width of FRP strip in partial wrapping

s = Pitch in partial wrapping

t_f = Thickness of FRP wrap

n = Number of wraps of FRP

(*fib* Bulletin-14)

3. Results and Discussions

The main focus of the current study is to investigate the applicability of existing design guidelines for prediction of confined strength and axial load carrying capacity of low, medium, normal and high strength concrete. The results are presented graphically in terms of theoretical versus experimental values based on the tested experimental data. The American Concrete Institute ACI 440.2R-2008, the Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001), Concrete Society Technical Report (TR-55), *fib* (Bulletin 14) design guidelines were used for the comparison of the results for low, medium, normal and high strength concrete.

3.1 Predicted versus measured confined strength

3.1.1 Predicted versus measured confined strength for low strength concrete cylinders

Fig.1 and Table.1 shows the results of CFRP confined compressive strength of low strength concrete cylinders. It is evident from Fig.1 and Table.1 that the American Concrete Institute ACI 440.2R-2008 guidelines predict the confined compressive strength of low strength concrete cylinders very close to the experimental results. However, the Canadian Standard Association (CSA-S806-02) and Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001 underestimate the confined compressive strength of the low strength concrete cylinders. However, the *fib* exact, *fib* approximate and Concrete Society Technical Report (TR-55) overestimate the confined compressive strength (refer to Fig.2 and Table.2). The increase in the experimental confined compressive strength of the cylinders with respect to the theoretical confined compressive strength of Canadian Standard Association (CSA-S806-02) and Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001 was 8 and 18 %. However, the Concrete Society Technical Report (TR-55), the *fib* exact and approximate methods overestimate the CFRP confined compressive strength by 31, 36 and 17 percent respectively.

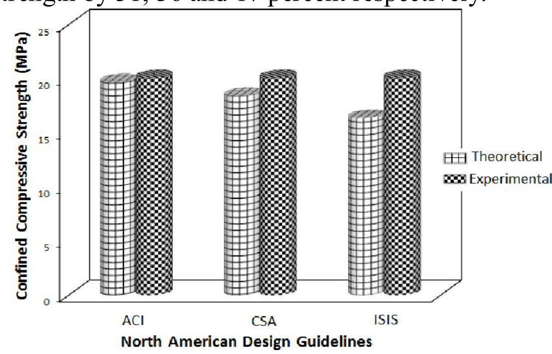

Figure 1: Comparison of Confined Compressive Strength Predicted by North American Strength Design Guidelines and Experimental Test Results for low strength concrete cylinders

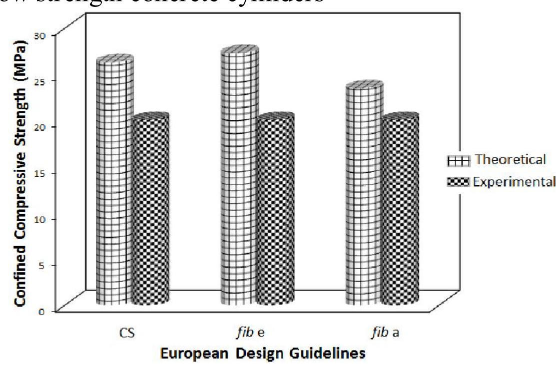

Figure 2: Comparison of Confined Compressive Strength Predicted by Concrete Society (CS), *fib* exact, approximate and Experimental Test Results for low strength concrete cylinders

Table 1: Performance of North American Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Low Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)} - f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
ACI	T-1	15.37	16.71	1.96	2.13	8.02
	T-2	17.55	17.54	1.81	1.80	-0.06
	T-3	21.15	21.65	1.59	1.63	2.31
	T-4	24.70	24.38	1.47	1.45	-1.31
	Avg	19.69	20.07	1.65	1.69	1.88
CSA	T-1	14.89	16.71	1.90	2.13	10.89
	T-2	16.56	17.54	1.71	1.81	5.59
	T-3	19.60	21.65	1.48	1.63	9.47
	T-4	22.61	24.38	1.34	1.45	7.26
	Avg	18.42	20.07	1.55	1.69	8.25
ISIS	T-1	12.30	16.71	1.57	2.13	26.39
	T-2	14.16	17.54	1.46	1.81	19.27
	T-3	17.74	21.65	1.34	1.63	18.06
	T-4	21.27	24.38	1.26	1.45	12.76
	Avg	16.37	20.07	1.37	1.69	18.45

Table 2: Performance of Concrete Society and European Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Low Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
CS	T-1	22.92	16.71	2.92	2.13	-37.16
	T-2	24.48	17.54	2.52	1.81	-39.57
	T-3	27.47	21.65	2.07	1.63	-26.88
	T-4	30.44	24.38	1.81	1.45	-24.86
	Avg	26.33	20.07	2.21	1.69	-31.18
fib e	T-1	21.41	16.71	2.73	2.13	-28.13
	T-2	24.82	17.54	2.56	1.81	-41.51
	T-3	29.38	21.65	2.21	1.63	-35.70
	T-4	33.65	24.38	2.00	1.45	-38.02
	Avg	27.31	20.07	2.29	1.69	-36.10
fib a	T-1	19.09	16.71	2.43	2.13	-14.24
	T-2	21.43	17.54	2.21	1.81	-22.18
	T-3	24.45	21.65	1.84	1.63	-12.93
	T-4	29.03	24.38	1.73	1.45	-19.07
	Avg	23.50	20.07	1.97	1.69	-17.09

3.1.2 Predicted versus measured confined strength for normal strength concrete cylinders

Fig.3 and 4 shows the comparison of theoretical values of CFRP confined normal strength concrete predicted by three North American design guidelines, Concrete Society and European *fib* design guidelines with the experimental results. It can be seen from Figs.3, 4 and Tables.3, 4 that the Canadian Standard Association (CSA-S806-02) and Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) prediction was very close to the experimental results. However, the American Concrete Institute ACI 440.2R-2008, Concrete Society Technical Report (TR-55) and *fib* exact and approximate overestimate the CFRP confined normal strength concrete cylinders. It is evident from Table.4 and Fig.4 that the Concrete Society (CS) and *fib* exact guidelines predict the similar results for CFRP confined normal strength concrete cylinders. It is worth to highlight that the American Concrete Institute ACI 440.2R-2008 and *fib* approximate design guidelines overestimate the CFRP confined compressive strength by 9 and 20 percent respectively. The CFRP confined normal strength concrete predicted by Concrete Society and *fib* exact guidelines were 37 percent less when compared to the experimental data.

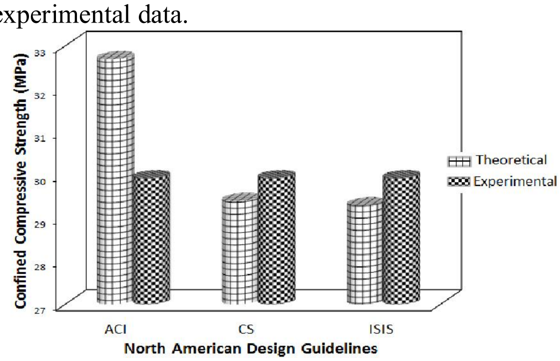

Figure 3: Comparison of Confined Compressive Strength Predicted by North American Strength Design Guidelines and Experimental Test Results for normal strength concrete cylinders

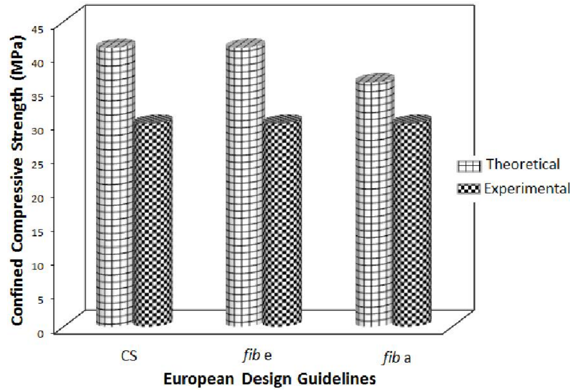

Figure 4: Comparison of Confined Compressive Strength Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for normal strength concrete cylinders

Table 3: Performance of North American Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Normal Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
ACI	T-5	28.71	25.32	1.38	1.22	-13.39
	T-6	36.66	34.53	1.27	1.20	-6.17
	Avg	32.69	29.93	1.32	1.21	-9.22
CSA	T-5	26.03	25.32	1.25	1.22	-2.80
	T-6	32.77	34.53	1.14	1.20	5.10
	Avg	29.40	29.93	1.19	1.21	1.75
ISIS	T-5	25.38	25.32	1.22	1.22	-0.24
	T-6	33.22	34.53	1.15	1.20	3.79
	Avg	29.30	29.93	1.18	1.21	2.09

Table 4: Performance of Concrete Society and European Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Normal Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
CS	T-5	33.80	25.32	1.62	1.22	-33.49
	T-6	48.44	34.53	1.68	1.20	-40.28
	Avg	41.12	29.93	1.66	1.21	-37.41
fib e	T-5	38.07	25.32	1.83	1.22	-50.36
	T-6	44.21	34.53	1.54	1.20	-28.03
	Avg	41.14	29.93	1.66	1.21	-37.48
fib a	T-5	32.71	25.32	1.57	1.22	-29.19
	T-6	39.31	34.53	1.37	1.20	-13.84
	Avg	36.01	29.93	1.45	1.21	-20.33

3.1.3 Predicted versus measured confined strength for medium strength concrete cylinders

Fig.5 presents the comparison of the theoretical results of North American strength predictive and the experimental results for the medium strength CFRP confined compressive strength of concrete cylinders. Fig.5 and Table.5 clearly shows that The Canadian Standard Association (CSA-S806-02), and Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) design guidelines slightly underestimate the CFRP confined compressive strength for medium strength concrete cylinders. However, the American

Concrete Institute ACI 440.2R-2008 design guidelines slightly overestimate the results of the CFRP confined compressive strength for medium strength concrete cylinders. Fig.6 and Table.6 compares the results of theoretical CFRP confined compressive strength predicted by the Concrete Society Technical Report (TR-55), *fib* exact and *fib* approximate with the experimental tested data. It is noteworthy to mention here that the results of confined compressive strength predicted by *fib* approximate and Concrete Society were approximately close to the experimental results. The Concrete Society slightly overestimates while *fib* approximate slightly underestimates the CFRP confined compressive strength for medium strength concrete cylinders. It can be seen from Fig.5 that the Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) underestimate the CFRP confined compressive strength for medium strength concrete cylinders by 10 and 5 percent respectively. The *fib* exact overestimates the confined compressive strength by 15 percent (refer to Fig.6 and Table.6)

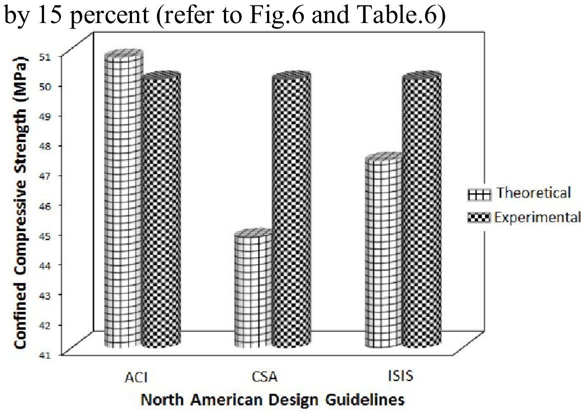

Figure 5: Comparison of Confined Compressive Strength Predicted by North American Strength Design Guidelines and Experimental Test Results for medium strength concrete cylinders

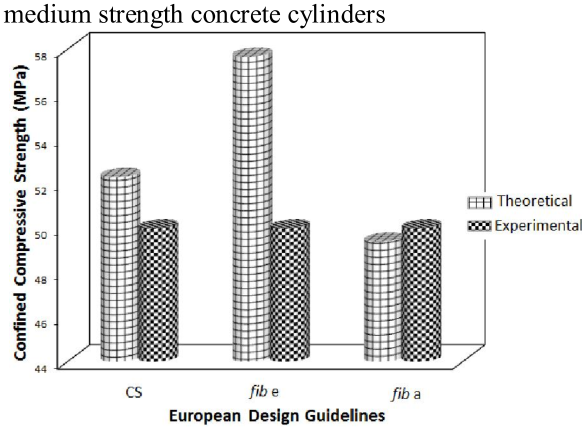

Figure 6: Comparison of Confined Compressive Strength Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for medium strength concrete cylinders

Table 5: Performance of North American Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Medium Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
ACI	T-7	44.61	44.66	1.21	1.22	0.11
	T-8	56.78	55.25	1.61	1.13	-2.77
	Avg	50.70	49.96	1.18	1.17	-1.48
CSA	T-7	39.53	44.66	1.07	1.22	11.49
	T-8	49.88	55.25	1.02	1.13	9.72
	Avg	44.71	49.96	1.04	1.17	10.51
ISIS	T-7	41.16	44.66	1.12	1.22	7.84
	T-8	53.34	55.25	1.09	1.13	3.46
	Avg	47.25	49.96	1.10	1.17	5.41

Table 6: Performance of Concrete Society and European Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (Medium Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
CS	T-7	47.25	44.66	1.29	1.22	-5.79
	T-8	57.29	55.25	1.17	1.13	-3.69
	Avg	52.27	49.96	1.22	1.17	-4.63
fib e	T-7	52.60	44.66	1.43	1.22	-17.78
	T-8	62.73	55.25	1.28	1.13	-13.54
	Avg	57.67	49.96	1.35	1.17	-15.43
fib a	T-7	45.22	44.66	1.23	1.22	-1.25
	T-8	53.53	55.25	1.09	1.13	3.11
	Avg	49.38	49.96	1.15	1.17	1.16

3.1.4 Predicted versus measured confined strength for high strength concrete cylinders

Fig.7 and 8 shows the comparison of the theoretical results predicted by North American, Concrete Society and European (*fib* Bulletin-14) design guidelines with the experimental tested data. Fig.7 and Table.7 clearly shows that the American Concrete Institute ACI 440.2R-2008 and the Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) design guidelines predicts the CFRP confined compressive strength very close to the experimental results for CFRP confined high strength concrete cylinders. However, the American Concrete Institute ACI 440.2R-2008 slightly overestimates while the Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) design guidelines slightly underestimates the results for CFRP confined high strength concrete cylinders. It is worth to mention here that the Canadian Standard Association (CSA-S806-02) underestimates the CFRP confined compressive strength by 10% when compared with the experimental tested data (refer to Table.7). It can be seen from Fig.8 and Table.8 that the Concrete Society predicts the CFRP confined compressive strength very close to the experimental results for high strength concrete cylinders. However, the *fib exact* and approximate design guidelines overestimate and underestimate the CFRP confined compressive strength for high strength concrete cylinders by 10 and 7 percent respectively.

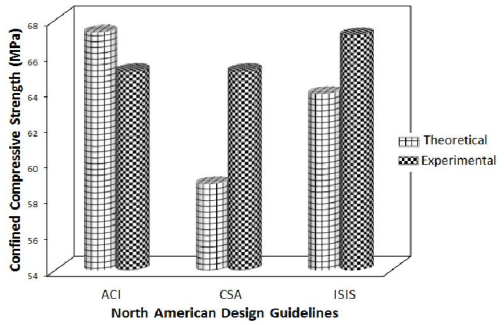

Figure 7: Comparison of Confined Compressive Strength Predicted by North American Strength Design Guidelines and Experimental Test Results for high strength concrete cylinders

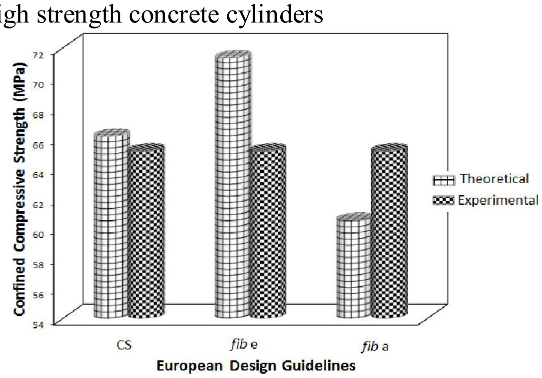

Figure 8: Comparison of Confined Compressive Strength Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for high strength concrete cylinders

Table 7: Performance of North American Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (High Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
ACI	T-9	64.23	62.76	1.14	1.11	-2.34
	T-10	70.37	67.52	1.13	1.08	-4.22
	Avg	67.3	65.14	1.13	1.10	-3.32
CSA	T-9	56.21	62.76	1.00	1.11	10.44
	T-10	61.43	67.52	0.98	1.08	9.02
	Avg	58.82	65.14	0.99	1.10	9.70
ISIS	T-9	60.79	62.76	1.08	1.11	3.14
	T-10	66.92	67.52	1.07	1.08	0.89
	Avg	63.86	67.14	1.07	1.10	1.97

Table 8: Performance of Concrete Society and European Design Guidelines in Terms of Compressive Strength Enhancement of circular concrete cylinders (High Strength)

Guidelines	Test. No	$f'_{cc(Model)}$ (MPa)	$f'_{cc(Exp)}$ (MPa)	$\frac{f'_{cc(Model)}}{f'_c}$	$\frac{f'_{cc(Exp)}}{f'_c}$	$\frac{f'_{cc(Exp)}-f'_{cc(Model)}}{f'_{cc(Exp)}}$ (%)
CS	T-9	63.54	62.76	1.13	1.11	-1.24
	T-10	68.68	67.52	1.10	1.08	-1.72
	Avg	66.11	65.14	1.11	1.10	-1.49
fib e	T-9	68.78	62.76	1.22	1.11	-9.59
	T-10	73.89	67.52	1.18	1.08	-9.43
	Avg	71.34	65.14	1.20	1.10	-9.51
fib a	T-9	58.18	62.76	1.03	1.11	7.30
	T-10	62.89	67.52	1.01	1.08	6.86
	Avg	60.54	65.14	1.02	1.10	7.07

3.2 Predicted versus measured axial load carrying capacity

3.2.1 Predicted versus measured axial load carrying capacity for low strength concrete cylinders

Fig.9 and 10 presents the comparison of results for the theoretical axial load carrying capacity predicted by North American, Concrete Society and European design guidelines with the experimental tested data.Fig.9 and Table.9 clearly shows that the North American design guidelines (ACI 440.2R-2008, CSA-S806-02, ISIS MO4 2001) underestimate the axial load carrying capacity for CFRP confined low strength concrete cylinders. However, it can be seen from Fig.10 and Table.10 that the Concrete Society Technical Report (TR-55), *fib* exact and *fib* approximate overestimate the axial load carrying capacity for the CFRP confined low strength concrete cylinders. The gain in the experimental axial load carrying capacity of the cylinders with respect to the theoretical axial load carrying capacity for American Concrete Institute ACI 440.2R-2008, the Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001 was 17, 25 and 33 percent respectively (Refer to Fig.9 and Table.9). However, the decrease in the experimental axial load carrying capacity of the cylinders with respect to the theoretical axial load carrying capacity was found to be 29 and 8 percent for Concrete Society and *fib* exact respectively (refer to Fig.10 and Table.10). It is interesting to note that the *fib* approximate method underestimates the load carrying capacity by 8 percent for low strength CFRP concrete cylinders.

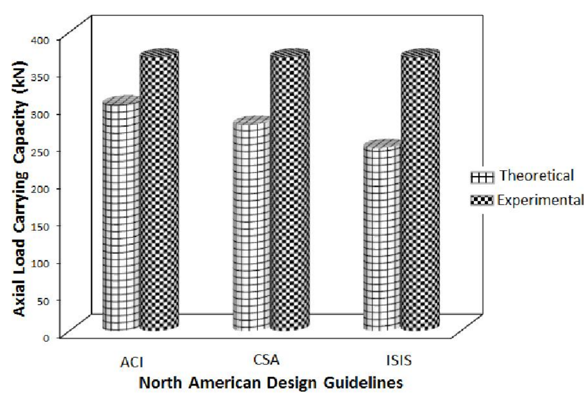

Figure 9: Comparison of Axial load carrying capacity Predicted by North American Design Guidelines and Experimental Test Results for low strength concrete cylinders

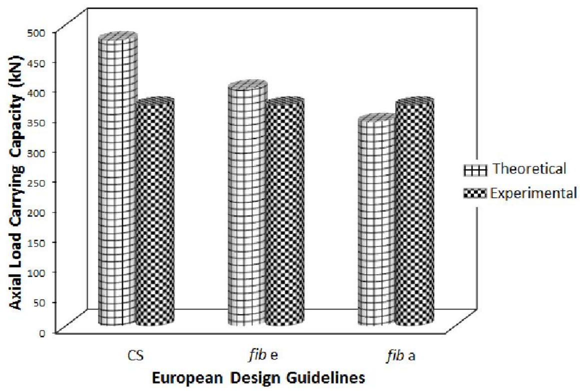

Figure 10: Comparison of Axial load carrying capacity Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for low strength concrete cylinders

Table 9: Performance of North American Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Low strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Exp)}}$ (%)
ACI	T-1	241	305	0.79	20.98
	T-2	269	320	0.84	15.94
	T-3	324	395	0.82	17.97
	T-4	378	445	0.85	15.06
	Avg	303	366	0.83	17.27
CSA	T-1	226	305	0.74	25.90
	T-2	249	320	0.78	22.19
	T-3	293	395	0.74	25.82
	T-4	336	445	0.76	24.49
	Avg	276	366	0.75	24.64
ISIS	T-1	186	305	0.61	39.02
	T-2	213	320	0.67	33.44
	T-3	265	395	0.67	32.91
	T-4	316	445	0.71	29.99
	Avg	245	366	0.67	33.11

Table 10: Performance of Concrete Society and European Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Low strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Exp)}}$ (%)
CS	T-1	413	305	1.35	-35.41
	T-2	441	320	1.38	-37.81
	T-3	494	395	1.25	-25.06
	T-4	548	445	1.23	-23.15
	Avg	474	366	1.29	-29.42
fib e	T-1	308	305	1.01	-0.98
	T-2	357	320	1.12	-11.56
	T-3	427	395	1.08	-8.10
	T-4	485	445	1.09	-8.99
	Avg	394	366	1.08	-7.65
fib a	T-1	275	305	0.90	9.84
	T-2	309	320	0.97	3.44
	T-3	352	395	0.89	10.89
	T-4	418	445	0.94	6.07
	Avg	339	366	0.92	7.58

3.2.2 Predicted versus measured axial load carrying capacity for normal strength concrete cylinders

Fig.11 and Table 11 shows the experimental and theoretical axial load carrying capacity predicted by North American design guidelines for CFRP confined normal strength concrete cylinders. It can be seen from Fig.11 and Table 11 that the ACI 440.2R-2008, CSA-S806-02 and ISIS MO4 2001design guidelines predicted the conservative values for CFRP confined axial load carrying capacity for normal strength concrete cylinders. However Concrete Society Technical Report (TR-55) and *fib* exact overestimate the axial load carrying capacity for CFRP confined normal strength concrete cylinders. It is worth to mention here that the *fib* approximate also predicts the conservative axial load carrying capacity for the CFRP confined normal strength concrete cylinders. It was found from the results (refer Fig.11 and Table.11) that the American Concrete Institute (ACI 440.2R-2008), Canadian Standard Association (CSA-S806-02) and Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001) design guidelines were conservative by 9, 36 and 38 percent respectively for the prediction of CFRP Confined normal strength concrete cylinders in terms of gain in axial load carrying capacity. However, *fib* approximate design equations were conservative by 5 percent in terms of gain in axial load carrying capacity (refer to Fig.12 and Table.12). The Concrete Society Technical Report (TR-55) and *fib* exact overestimate the axial load carrying capacity by 18 and 8 percent respectively (refer to Fig.12 and Table.12).

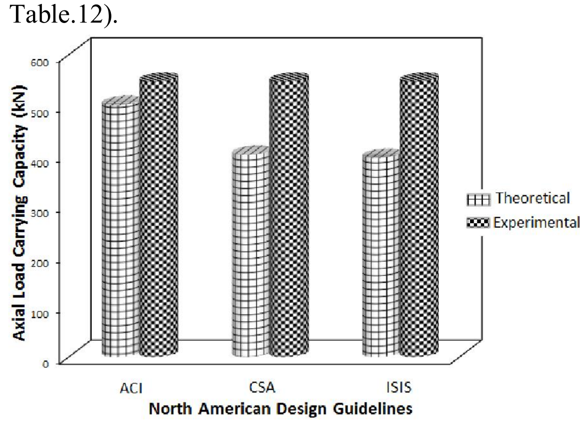

Figure 11: Comparison of Axial load carrying capacity Predicted by North American Design Guidelines and Experimental Test Results for normal strength concrete cylinders

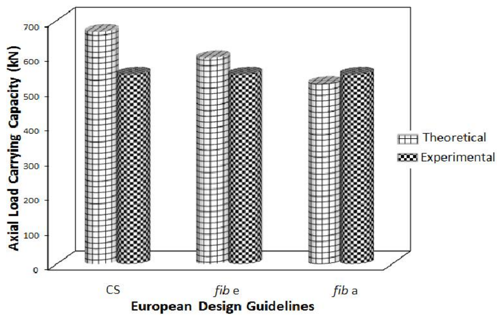

Figure 12: Comparison of Axial load carrying capacity Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for normal strength concrete cylinders

Table 11: Performance of North American Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Normal strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)} - P_{u(Model)}}{P_{u(Exp)}}$ (%)
ACI	T-5	439	462	0.95	5.24
	T-6	561	630	0.89	12.30
	Avg	500	546	0.92	9.20
CSA	T-5	384	462	0.83	20.31
	T-6	418	630	0.66	50.72
	Avg	401	546	0.73	36.16
ISIS	T-5	373	462	0.81	23.86
	T-6	417	630	0.66	51.08
	Avg	395	546	0.72	38.23

Table 12: Performance of Concrete Society and European Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Normal strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)} - P_{u(Model)}}{P_{u(Exp)}}$ (%)
CS	T-5	608	462	1.32	-24.01
	T-6	728	630	1.16	-13.47
	Avg	668	546	1.22	-18.26
fib e	T-5	548	462	1.86	-15.69
	T-6	637	630	1.01	-1.10
	Avg	593	546	1.09	-7.85
fib a	T-5	471	462	1.02	-1.91
	T-6	566	630	0.90	11.31
	Avg	519	546	0.95	5.30

3.2.3 Predicted versus measured axial load carrying capacity for medium strength concrete cylinders

For the medium strength CFRP confined cylinders (refer to Figs,13 and 14) it was found that all the five existing guidelines, three North American, Concrete Society and the European *fib* design guidelines predicted the conservative values in terms of gain in axial load carrying capacity. It was noted from Figs.13, 14 and Tables 13,14 that American Concrete Institute ACI 440.2R-2008, Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001), *fib* exact and *fib* approximate design guidelines were conservative by 17, 46, 37, 10 and 28 percent for predicting the axial load carrying capacity of CFRP confined medium strength concrete cylinders. The Concrete Society Technical Report (TR-55 overestimate the axial load carrying capacity by 3 percent (refer to Fig.14 and Table.14).

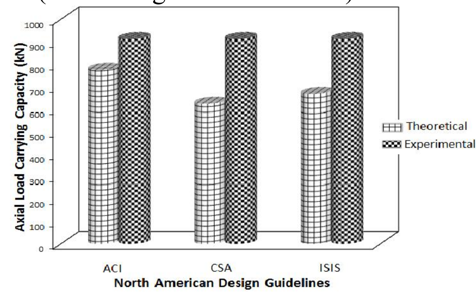

Figure 13: Comparison of Axial load carrying capacity Predicted by North American Design Guidelines and Experimental Test Results for medium strength concrete cylinders

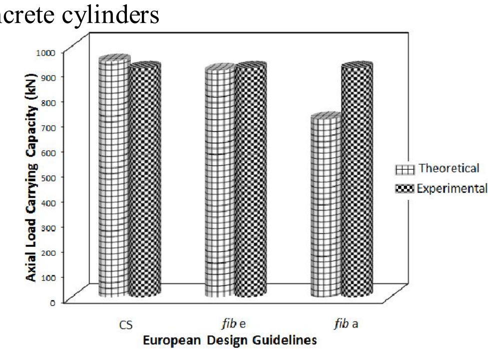

Figure 14: Comparison of Axial load carrying capacity Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for medium strength concrete cylinders

Table 13: Performance of North American Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Medium strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)} - P_{u(Model)}}{P_{u(Exp)}}$ (%)
ACI	T-7	683	815	0.84	19.33
	T-8	869	1008	0.86	16.00
	Avg	776	912	0.85	17.46
CSA	T-7	566	815	0.69	43.99
	T-8	682	1008	0.68	47.80
	Avg	624	912	0.72	46.07
ISIS	T-7	589	815	0.74	38.37
	T-8	746	1008	0.74	35.12
	Avg	668	912	0.73	36.55

Table 14: Performance of European Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (Medium strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)} - P_{u(Model)}}{P_{u(Exp)}}$ (%)
CS	T-7	850	815	1.04	-4.12
	T-8	1031	1008	1.02	-2.23
	Avg	941	912	1.03	-3.08
fib e	T-7	758	815	0.93	7.52
	T-8	903	1008	0.90	11.63
	Avg	903	912	0.91	9.75
fib a	T-7	651	815	0.80	25.19
	T-8	771	1008	0.76	30.74
	Avg	711	912	0.78	28.20

3.2.4 Predicted versus measured axial load carrying capacity for high strength concrete cylinders

Figs.15, 16 and Tables 15, 16 illustrate the comparison of the theoretical results predicted by the North American, Concrete Society and *fib* Bulletin-14 with the experimental tested data. From comparison of theoretical and experimental results it was found that The American Concrete Institute ACI 440.2R-2008, Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001), *fib* exact and *fib* approximate all predict the conservative values for axial load carrying capacity of CFRP confined high strength concrete cylinders (refer to Figs 15,16 and Tables 15, 16). However, the Concrete Society Technical Report (TR-55) predicted the best result for the axial load carrying capacity of CFRP confined high strength cylinders. The results predicted by the Concrete Society Technical Report (TR-55) were close to the experimental results (refer Fig.16 and Table 16). The results predicted by American Concrete Institute ACI 440.2R-2008, Canadian Standard Association (CSA-S806-02), Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001), *fib* exact and *fib* approximate were conservative by 5, 34, 24, 16 and 36 percent in terms of axial load carrying capacity of CFRP Confined high strength concrete cylinders

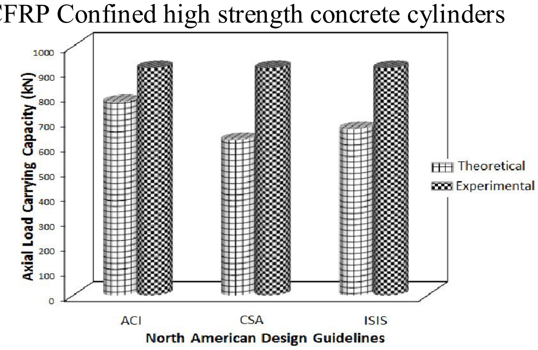

Figure 15: Comparison of Axial load carrying capacity Predicted by North American Design Guidelines and Experimental Test Results for high strength concrete cylinders

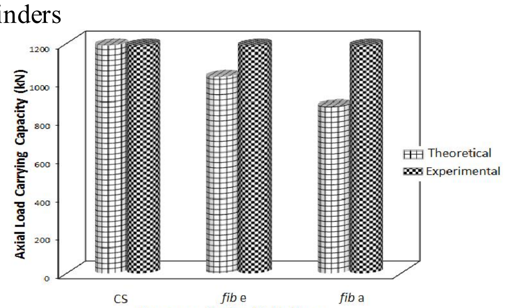

Figure 16: Comparison of Axial load carrying capacity Predicted by Concrete Society, European Design Guidelines and Experimental Test Results for high strength concrete cylinders

Table 15: Performance of North American Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (High strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Exp)}}$ (%)
ACI	T-9	983	1028	0.96	4.58
	T-10	1077	1140	0.94	5.85
	Avg	1030	1084	0.95	5.24
CSA	T-9	776	1028	0.75	32.47
	T-10	837	1140	0.73	36.20
	Avg	807	1084	0.74	34.41
ISIS	T-9	837	1028	0.81	22.82
	T-10	911	1140	0.80	25.14
	Avg	874	1084	0.81	24.03

Table 16: Performance of Concrete Society and European Design Guidelines in Terms of Enhancement of Axial Load Capacity for circular concrete cylinders (High strength)

Guidelines	Test. No	$P_{u(Model)}$ (kN)	$P_{u(Exp)}$ (kN)	$\frac{P_{u(Model)}}{P_{u(Exp)}}$	$\frac{P_{u(Exp)}-P_{u(Model)}}{P_{u(Exp)}}$ (%)
CS	T-9	1144	1145	1.00	0.09
	T-10	1236	1232	1.00	-0.32
	Avg	1190	1189	1.00	-0.13
fib e	T-9	990	1145	0.86	15.66
	T-10	1064	1232	0.86	15.79
	Avg	1027	1189	0.86	15.73
fib a	T-9	838	1145	0.73	36.63
	T-10	906	1232	0.74	35.98
	Avg	872	1189	0.73	36.30

4. Conclusions

- A comparative study on various compressive concrete strengths ranging from low to high strength was conducted using the available well known international design guidelines approaches (ACI 440.2R-2008, CSA-S806-02, ISIS MO4 2001 CS TR-55, *fib* exact and *fib* approximate). Based on research study the following conclusions were drawn from this investigation.
- The North American design guidelines (CSA-S806-02 and ISIS MO4 2001) underestimate the confined compressive strength by 8% and 18% respectively for low strength CFRP confined concrete. .However, ACI 440.2R-2008 better predicts the confined compressive strength of CFRP confined low strength concrete cylinders. The North American design guidelines (ACI 440.2R-2008, CSA-S806-02 and ISIS MO4 2001) underestimate the CFRP confined low strength concrete in terms of gain in axial load carrying capacity by 17%, 25% and 33% respectively The European design guidelines (*fib* exact and *fib* approximate) and CS TR-55 overestimate the results for low strength CFRP confined concrete in

terms of confined compressive strength by 31%, 36% and 17% respectively. CS TR-55 and *fib* exact overestimate the axial load carrying capacity for low strength CFRP confined concrete by 29% and 8% respectively. However, the *fib* approximate underestimate the axial load carrying capacity by 8% for low strength CFRP confined concrete.

- The North American design guidelines ACI 440.2R-2008, CSA-S806-02 and ISIS MO4 2001 better predict the confined compressive strength for normal strength CFRP confined concrete. However, the North American design guidelines ACI 440.2R-2008, CSA-S806-02 and ISIS MO4 2001 underestimate the axial load carrying capacity for CFRP confined normal strength concrete by 9%, 36% and 38% respectively.
- CS TR-55, *fib* exact overestimate the CFRP confined compressive strength for normal strength concrete by 37%. In term of axial load carrying capacity CS TR-55, *fib* exact overestimate by 18 and 8% for normal strength concrete. However, *fib* approximate overestimate the CFRP confined compressive strength by 20% for normal strength concrete and predict the reasonable value in terms of axial load carrying capacity by 5% for the same strength of concrete.
- The design guidelines of ACI 440.2R-2008, ISIS MO4 2001 CS TR-55 and *fib* approximate predict the reasonable value for CFRP confined compressive strength for medium strength concrete. However, CSA-S806-02 and *fib* exact underestimate and overestimate by 11% and 15% respectively in term of CFRP confined compressive strength for medium strength concrete. The North American design guidelines ACI 440.2R-2008, CSA-S806-02 and ISIS MO4 2001 and European design guidelines (*fib* approximate and *fib* exact) underestimate the axial load carrying capacity for medium strength CFRP confined concrete by 17%, 46% , 37%, 28% and 10% respectively. However, CS TR-55 overestimates the axial load carrying capacity by 3%. .
- The North American design guidelines (ACI 440.2R-2008 and ISIS MO4 2001) and the Concrete Society CS TR-55 better predict the CFRP confined compressive strength for high strength concrete. .However, the North American design guidelines, CSA-S806-02 overestimate the CFRP confined compressive strength by 10% for high strength concrete. The *fib* exact and *fib* approximate overestimate and underestimate by 10 % and 7% respectively for CFRP confined compressive strength for high strength concrete.
- The North American design guidelines ACI 440.2R-2008 and the Concrete Society CS TR-55 better predict the axial load carrying capacity for high strength concrete. However, the North American design guidelines CSA-S806-02, ISIS MO4 2001 and European design guidelines *fib* exact and *fib* approximate underestimate the axial load carrying capacity by 34%, 24%, 16% and 36% respectively for high strength concrete.

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