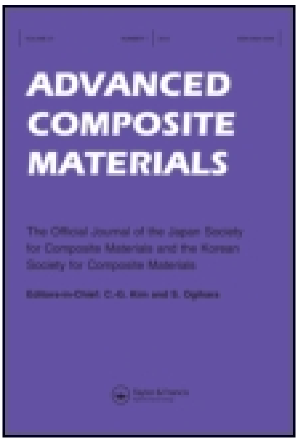

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Performance of concrete columns strengthened with fiber reinforced polymer composite sheets

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Abstract—The performance of concrete columns externally wrapped with carbon, glass, and aramid fiber reinforced polymer composite sheets is presented in this paper. The confined and unconfined (control) specimens were loaded in uniaxial compression. Axial load and axial and lateral strains were obtained in order to evaluate stress–strain behavior, ultimate strength, stiffness, and ductility of the wrapped specimens. Results show that external confinement of concrete by FRP composite sheets can significantly enhance strength, ductility and energy absorption capacity. An analytical model to predict the entire stress–strain relationship of concrete specimens wrapped with FRP composite sheets was developed. Comparison between the experimental results and those of analytical indicates that the model provides satisfactory predictions of the stress–strain response. The paper also presents the performance of the wrapped concrete specimens subjected to wet-dry environments. The specimens were exposed to 300 cycles of wetting and drying using salt water. Results show that the specimens wrapped with carbon and aramid fibers experienced no reduction in strength due to wet/dry exposure, whereas those wrapped with glass fiber experienced a significant reduction in strength.

Keywords: FRP composites; confinement; concrete columns; stress–strain; repair; strengthening; durability; wet-dry exposure.

1. INTRODUCTION

Post-strengthening of a structure becomes necessary when its safety and/or serviceability become compromised and can no longer be guaranteed. Steel has been utilized since 1967 to rehabilitate structures but it is heavy, difficult to handle and prone to corrosion. Problems with the deteriorated national infrastructure, and the urgent need for the development of novel and more reliable construction systems, have led to the development of advanced composite materials. Advanced composites promise to provide substantially improved mechanical, durability- and

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constructability-related properties, essential for successful long-term solutions to the problems of the deteriorated national infrastructure. FRP composites are light-weight, and exhibit high tensile strength and modulus, corrosion resistance, and durability. In addition, their low density is important because it adds less weight to the existing structures, and because the use of heavy equipment for repair with FRP composites is not necessary during rehabilitation.

Retrofitting of existing concrete columns by wrapping and bonding of fiber reinforced polymer (FRP) sheets, straps, or pultruded FRP shells around existing columns has gained great interest in the research community and construction industry. External confinement of existing concrete columns by means of high-strength fiber composites can significantly enhance their strength, ductility, and energy absorption capacity. A similar application for new construction is concrete-filled FRP tubes. The FRP tube works as a protective jacket for the concrete core and it increases the axial strength, ultimate strain and toughness of the concrete column. Despite their promising results in the laboratory, construction of traffic bridges, marine column systems and other load bearing applications built with fiber reinforced polymer composite tubes, have not been widely implemented due to high costs of materials and uncertain performance, including doubt about long term durability and maintenance.

It has been shown that wrapping FRP fabrics around the perimeter of both circular and rectangular concrete columns improves ductility and strength [1, 2]. It has also been shown that confinement with FRP improves the behavior of columns submitted to seismic loading [3, 4]. FRP fabric wraps consisting of carbon, aramid, or glass fibers bonded by an epoxy resin, have been successfully applied for seismic rehabilitation of bridge piers in the US and Japan [5, 6]. Other FRP confinement techniques have been shown to improve the behavior of normal and high-strength concrete [7]. Saadatmanesh *et al.* [8] used the stress–strain model proposed by Mander *et al.* [9], that analyzes the behavior of concrete columns externally wrapped with fiber composite straps.

The performance of concrete columns confined with FRP composite sheets including experimental and analytical work is presented in this paper. This paper should provide a framework for better understanding of the behavior of fiber-wrapped or FRP-confined concrete columns. The effect of wet/dry environments on the performance of FRP-wrapped concrete specimens is else evaluated.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

A total of forty 76 × 305 mm cylindrical specimens were tested, which included 32 FRP-wrapped concrete specimens and 8 plain concrete specimens. The concrete mix had a ratio of cement:sand:gravel:water of 1 : 2 : 3 : 0.5, respectively. The coarse aggregate consisted of crushed stone with a maximum size of 12.7 mm. The fine

Table 1.
Mechanical properties of FRP sheets and epoxy system

FRP sheets and epoxy	Tensile strength (MPa)	Elasticity modulus E_f (GPa)	Ultimate strain (%)	Thickness (mm)
AR	2059	118	1.75	0.286
GE	1518	72.6	2.1	0.118
C1	3485	230.5	1.5	0.110
C5	2940	372.8	0.8	0.165
Epoxy	55.9	2.35	2.4	—

aggregate composition was made of 50% river sand and 50% beach sand. All specimens were cured for 58 days at a temperature of +25°C and a relative humidity that exceeded 90%. The average 28-day compressive strength of the concrete was about 31 MPa. The concrete cylinders were confined by wrapping them in a continuous manner with two laps of unidirectional FRP sheets. Four types of FRP sheets were used: two carbons (C1 and C5), one glass (GE), and one aramid (AR), which were bonded to the concrete with one type of epoxy system. A summary of the properties of the FRP composite sheets and the resin epoxy system is presented in Table 1.

2.2. Specimen preparation

The epoxy system consists of two parts, resin and hardener, mixed in the ratio of 2 : 1. The epoxy system was thoroughly hand mixed for at least five minutes. The concrete cylinders were cleaned and completely dried before the epoxy was applied. A thin layer of epoxy (300 g/m^2) was applied to the concrete cylinder. A unidirectional FRP sheet was then applied directly on the surface. Special attention was taken to ensure that there were no voids between the FRP sheet and the concrete surface. After the application of the first lap of the FRP sheet, a second layer of epoxy was applied on the surface of the first layer to allow the impregnation of the second lap of the FRP sheet. Finally, a last layer of epoxy was applied on the surface of the wrapped cylinder. All specimens were confined at a configuration of 0° orientation. In all cases, the outside layer was extended by an overlap of 76 mm to ensure the development of full composite strength. All specimens were left at room temperature for at least 7 days before testing. This was done to ensure that enough time had passed for the epoxy system to cure.

All specimens were loaded in uniaxial compression until failure, using a hydraulic testing machine. Both ends of the cylinders were capped with sulfur to ensure parallel surfaces and to distribute the load uniformly. The applied load was measured using a load cell. Axial and lateral strains were measured using electronic strain gauges. The axial and lateral strain gauges were installed at the center point of the cylinders. A computerized data logger system was used to obtain the results of the load and strains during the test.

3. RESULTS

3.1. *Effect of confinement*

Table 2 presents the experimental results of the wrapped and unwrapped specimens. The compressive strength and the axial and lateral strain values are based on the average of four tested specimens. Results show that the compressive strength of the concrete specimens was improved by about 200% due to confinement with carbon fiber, by about 100% due to glass fiber, and by about 230% due to aramid fiber. The compressive strength of the specimens confined with carbon and aramid fibers is higher than that confined with glass fiber, because the lateral strength developed due to carbon and aramid fibers is much higher than that developed due to the glass fiber.

Figure 1 shows the stress–strain curves of the confined and unconfined concrete cylinders. The curves on the right side represent axial stress–axial strain curves and on the left side show axial stress–lateral strain curves. The stress–strain response of the FRP-wrapped concrete specimens can be divided into two regions. In the first region, the curve ascends rapidly slightly above the ultimate unconfined concrete strength, which is similar to the behavior of plain concrete. In this region, the stress and strain produced over the concrete, due to confinement, are very small. In the second region, the concrete is cracked and the FRP wrap is fully activated, improving the compressive strength, energy absorption capacity and ductility of the specimens. The response in this region seems mainly dependent on the stiffness of the composite sheets.

The stress–strain curves (Fig. 1) show that, at the same stress level, the axial strains for the confined cylinders with carbon and aramid fibers were always higher than the lateral strain, whereas with glass fiber, the axial and the lateral strains were approximately the same. This is due to the fact that the stiffness of confinement of glass fiber is lower than that of carbon or aramid fiber.

3.2. *Confinement modeling (stress–strain relationship)*

The proposed model in this study consists of two distinct regions. In the first region, the behavior is similar to that of plain concrete, since lateral expansion of the

Table 2.
Experimental results of concrete specimens confined with frp sheets

FRP sheets	Compressive strength (MPa)	Maximum axial strain (%)	Maximum lateral strain (%)	Lateral elastic modulus, E_ℓ (MPa)	Maximum lateral stress (MPa)
Plain	31.8	0.19	0.18	—	—
AR	140.89	2.05	1.55	1774	32.46
GE	60.82	1.53	1.63	449.7	7.33
C1	95.02	2.45	1.25	1331.2	16.64
C5	94.01	1.55	0.55	3228.8	17.76

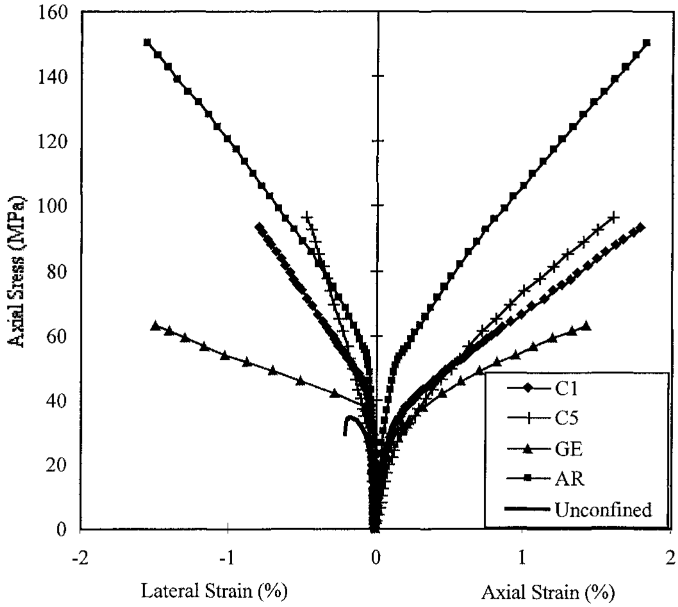

Figure 1. Stress–strain curves of confined and unconfined concrete.

confined concrete is insignificant. A second region is recognized in which the FRP wrap is fully activated, and the stiffness is generally stabilized around a constant rate. The response in this region is mainly dependent on the stiffness of the FRP composite. Boundary conditions are necessary to develop the equations for the first region. For simplicity, the stress–strain relationship equations are first developed for the second region.

The axial stress (f_a) in every point of the second region is calculated using the following relationship [10]

$$f_a = f_c' + k_1 f_\ell, \tag{1}$$

where, f_c' is the strength of the unconfined concrete, f_ℓ' is the lateral stress applied to the concrete by the FRP composite, and k_1 is the confinement effectiveness coefficient. The values of the coefficient k_1 can be obtained as a function of the ratio between the lateral stress and the concrete strength (f_ℓ/f_c'), as shown in equation (2) [11]

$$k_1 = 3.5\left(\frac{f_\ell}{f_c'}\right)^{-0.15}. \tag{2}$$

Substituting k_1 into equation (1), an expression to calculate the axial stress of FRP-confined concrete specimens in the second region is obtained.

$$f_a = f_c'\left[1 + 3.5\left(\frac{f_\ell}{f_c'}\right)^{0.85}\right]. \tag{3}$$

Mander *et al.* [9] have shown that the axial strain at maximum stress can be expressed as a function of the strength of confined concrete (f_{cc}).

$$\varepsilon_{ca} = \varepsilon_o\left[1 + 5\left(\frac{f_{cc}}{f'_c} - 1\right)\right]. \tag{4}$$

By changing the constant 5 for the variable k_2, f_{cc} for the axial stress (f_a) and ε_{ca} for the axial strain (ε_a), the expression in equation (4) becomes

$$\varepsilon_a = \varepsilon_o\left[1 + k_2\left(\frac{f_a}{f'_c} - 1\right)\right], \tag{5}$$

where ε_o is the axial strain in strength of unconfined concrete. The coefficient k_2 increases with increasing lateral strain (ε_ℓ). Using a regression analysis k_2 is calculated as [11]

$$k_2 = 310.57\varepsilon_\ell + 1.90. \tag{6}$$

Substituting k_2 into equation (5), an expression to calculate the axial strain in every point of the second region of confined concrete with FRP composites is obtained

$$\varepsilon_a = \varepsilon_o\left[1 + (310.57\varepsilon_\ell + 1.90)\left(\frac{f_a}{f'_c} - 1\right)\right]. \tag{7}$$

The meeting point between the first and the second regions is adopted when the lateral strain is equal to 0.002. The intersection point at strain of 0.002 seems to produce a good prediction of the experimental data of confined concrete with FRP composites.

To construct the first region of the stress–strain response, it is assumed that the intersection point between the first and the second regions occurs when the lateral strain is equal to 0.002. By substituting this value in equations (1), (3) and (7), the following expressions are obtained [12].

$$\varepsilon_{ul} = 0.002, \tag{8}$$

$$\varepsilon_{ua} = \varepsilon_o\left[1 + 0.0448\left(\frac{E_\ell}{f'_c}\right)^{0.85}\right], \tag{9}$$

$$f_{ua} = f'_c\left[1 + 0.0178\left(\frac{E_\ell}{f'_c}\right)^{0.85}\right], \tag{10}$$

$$E_{ul} = 7.557E_\ell\left(\frac{f'_c}{E_\ell}\right)^{0.15}, \tag{11}$$

$$E_{ua} = 0.3075\frac{f'_c}{\varepsilon_o}. \tag{12}$$

3.3. Comparison between experimental and analytical results

The experimental results obtained in this study are compared with those of analytical obtained by the proposed model, as seen in Fig. 2. To generate the stress–strain

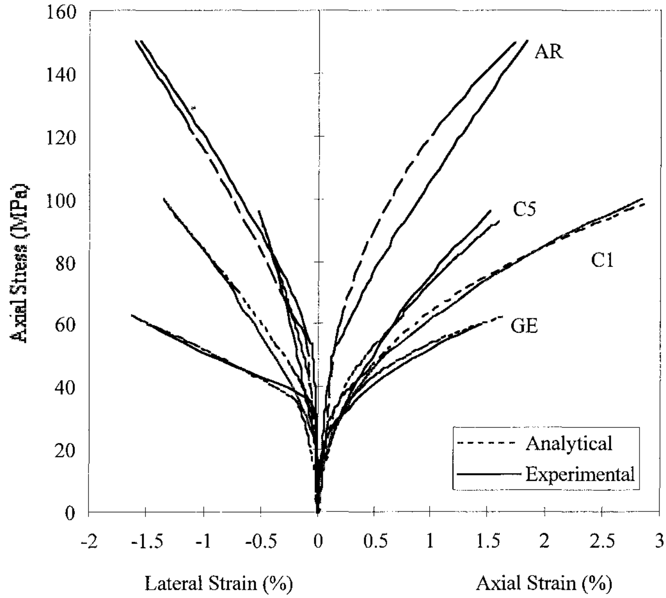

Figure 2. Comparison between experimental and analytical results.

Table 3.
Data for applying the analytical model

Size of the cylinders		Concrete strength, f'_c (MPa)	Type of fiber	Elasticity modulus of fiber, E_f (GPa)	Thickness of the fiber, t (mm)[a]	Lateral elastic modulus, E_ℓ (MPa)[b]
Radius (mm)	Length (mm)					
38	305	44	Aramid	118	0.572	1774
38	305	31	Glass	72.6	0.24	450
38	305	31	Carbon	230.5	0.22	1331
38	305	31	Carbon	372.8	0.33	3229

[a] Two layer of FRP wraps.
[b] Lateral elastic modulus of confined specimens (E_ℓ) is calculated as $E_f * t/R$.

analytical curves for concrete confined with FRP composites, it is necessary to know the ultimate unconfined compressive strength and its corresponding strain, the radius of the concrete cylinder, and the elastic modulus and thickness of the fiber sheet. Table 3 provides data necessary to use the developed model on the results obtained in this study. The ultimate strain of the unconfined concrete is assumed to equal to 0.002. A comparison between the experimental and the analytical curves indicates that the proposed model provides good predictions of stress–strain response of cylinders wrapped with FRP composites (see Fig. 2).

The proposed model was developed for cylinders wrapped with FRP composites, in which the fiber is bonded to the concrete with an epoxy system to ensure perfect union between the fiber and the concrete. However, in concrete-filled FRP tubes

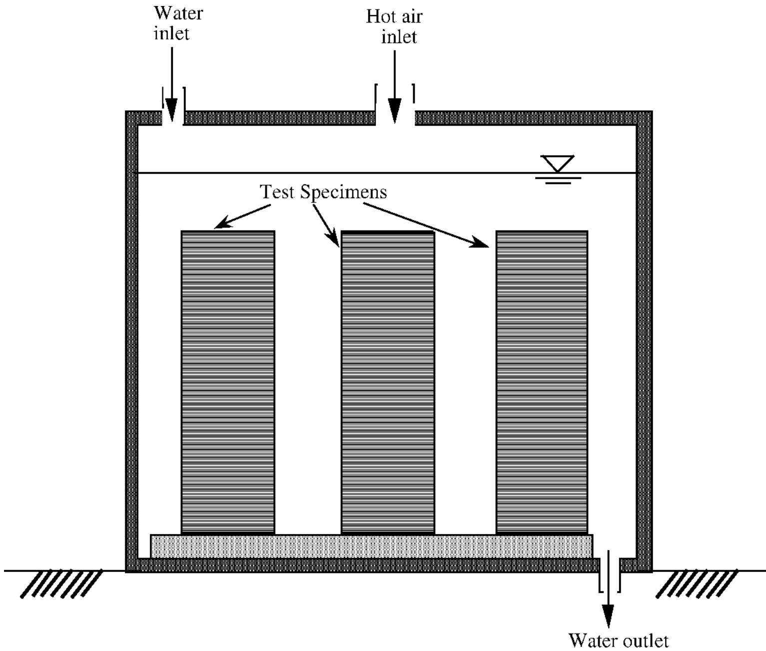

Figure 3. Schematic of the wet-dry exposure set-up.

there is a little bond between the concrete and the FRP tub. Thus, the proposed model overestimates the stress–strain curves of concrete-filled FRP tubes [12].

3.4. The effect of wet/dry exposure

To study the effect of wet/dry conditions on the FRP-confined concrete specimens; the specimens were placed in a specially constructed environmental chamber and were exposed to 300 cycles of wetting and drying. The wet/dry environmental chamber is schematically shown in Fig. 3. The specimens were subjected to salt water environments in which there were alternating wet and dry cycles (hot air at 35°C average and 90% humidity). Seawater was simulated using 35 grams of salt in a liter of water. This is the approximate content of salt found in the ocean. The duration of the wet cycle was four hours and that of the dry cycle, two hours; thus the specimens were exposed for a total of 75 days.

Table 4 presents the experimental results for unconditioned (i.e. room temperature specimens) and wet/dry conditioned specimens. The compressive strength f_c' is the average of four specimens and ε_a is the axial strain at failure. Due to wet/dry conditioning the glass wrapped concrete specimens exhibited a reduction in strength of as much as 10%, whereas carbon fiber and aramid fiber wrapped specimens showed no reduction in strength. In fact the aramid fiber wrapped specimens showed a slight increase in strength, as shown in Table 4.

The failure of both wet/dry and unexposed specimens was initiated from one-fourth to midway along the height of the column. Wet/dry exposure shows a little

Table 4.
Experimental results for conditioned and unconditioned specimens

Specimen	Room temperature		Wet/dry	
	f_c' (MPa)	ε_a (%)	f_c' (MPa)	ε_a (%)
Control	31.8	0.19	38.2	0.13
AR	140.9	2.05	150.9	3.17
GE	60.62	1.53	57.2	1.41
C1	95.02	2.45	94.6	1.56
C5	94.01	1.55	91.8	1.48

effect on the stiffness of the carbon fiber wrapped specimens (the slope of the second region of the stress–strain curve, Fig. 4), whereas it has significant effect on those wrapped with aramid and glass fibers (Figs 5 and 6). The slop of the second region of stress–strain curves of concrete specimens wrapped with aramid and glass fibers exhibited an increase in stiffness (increase in the slope) due to wet/dry exposure.

It should be noted that there was an increase in the strength of unwrapped cylinders due to wet/dry exposure. The compressive strength increased by as much as 20%, from 31.8 to 38.2 MPa. This increase in strength attributed to the longer period of moist curing of the wet/dry specimens.

4. CONCLUSIONS

Concrete cylinders confined with four different types of FRP composite sheets were tested in compression, and their stress–strain curves (compressive stress *vs.* axial and lateral strains) were determined. The confinement with FRP composite sheets constrains the lateral strain, producing a triaxial stress field in the concrete, which results in improving the compressive strength, maximum strain and ductility.

A model to predict the behavior of the axial stress *vs* axial strain and *vs* lateral strain curves of concrete columns confined with FRP composite sheets was developed. The model is limited to circular short columns with axial load; the columns are confined with fiber composite sheets at 0° fiber orientation. The proposed model consists of two distinct regions. In the first region, the behavior is similar to that of plain concrete, since lateral expansion of the confined concrete is insignificant. A second region, which is mainly dependent on the stiffness of the FRP composite, is recognized in which the FRP wrap is fully activated. In this region, the stiffness is generally stabilized around a constant rate. The developed model produces reliable results in predicting both the axial stress–axial strain and axial stress–lateral strain of FRP-wrapped concrete columns.

The durability test results of this study are in agreement with others which have shown that carbon fiber reinforced polymer is superior to glass when exposed to harsh environments. Exposure to wet/dry environments has little effect on the compressive strength of CFRP and AFRP wrapped specimens. The GFRP wrapped specimens exhibited a reduction in strength of 10%. Exposure to wet/dry environments produced no loss in ductility in specimens wrapped with CFRP or AFRP; however, specimens wrapped with GFRP sheets exhibited a reduction in ductility.

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REFERENCES

1. H. Katsumata and K. Kimura, Applications of retrofit method with carbon fiber for existing reinforced concrete structures, in: *The 22nd Joint UJNR Panel Meeting, US–Japan Workshop*, Galthersburg, MD, pp. 1–28 (1990).
2. F. Picher, P. Rochette and P. Labossiere, Confinement of concrete cylinders with CFRP, *Fiber Composites in Infrastructure*, in: *Proceedings of the First International Conference on Composites in Infrastructure*, pp. 829–841 (1996).
3. M. J. N. Priestley, F. Seible and E. Fyfe, Column seismic retrofit using fiber glass/epoxy jackets, in: *Proceedings of the First International Conference on Advanced Composite Material in Bridges and Structures*, Sherbrooke, Canada, pp. 287–298 (1992).
4. H. Katsumata, Y. Kobatale and T. Takeda, A study on the strengthening with carbon fiber for earthquake-resistance capacity of existing reinforced concrete columns, in: *Proceedings of the Seminar on Repair and Retrofit of Structures*, US–Japan Panel on Wired and Seismic Effects, UJNR, pp. 1816–1823 (1987).
5. A. A. Mufti, M. A. Erki and L. C. Jaeger, Advanced composite materials in bridges and structures in Japan, in: *Canadian Society of Civil Eng.*, Montreal, Canada (1992).
6. M. Kasei, *Carbon Fiber Reinforced Earthquake-Resistant Retrofitting.* Mitsubishi Kasei Corporation, Japan (1993).
7. T. Harmon, K. Slattery and S. Ramakrishnan, The effect of confinement stiffness on confined concrete, *Non-Metallic Reinforcement for Concrete Structures*, in: *Proceeding of the Second International RILEM Symposium*, (FRPRCS-2), pp. 584–592 (1995).
8. H. Saadatmanesh, M. R. Ehsani and M. W. Li, Strength and ductility of concrete columns externally reinforced with fiber composite straps, *ACI Structural Journal* **91** (4), 434–447 (1994).
9. J. B. Mander, J. N Priestley and R. Park, Theoretical stress–strain model for confined concrete, *ASCE Structural Journal* **114** (8), 1804–1826 (1988).
10. F. E. Richart, A. Brandtzaeg and R. L. Brown, The Failure of Plain and Spirally Reinforced Concrete in Compression, *Bulletin,* University of Illinois Engineering Experimental Station, Champaign IL (1990).
11. H. Toutanji, Stress–strain characteristics of concrete columns externally confined with advanced fiber composite sheets, *ACI Materials Journal* **96** (3), 397–404 (1999).
12. D. Cusson and P. Paultre, Stress–strain model for confined high-strength concrete, *ASCE Structural Journal* **121** (3), 468–477 (1995).