A Genetic–Programming–Based Formulation for the Strength Enhancement of Fiber–Reinforced–Polymer–Confined Concrete Cylinders

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ABSTRACT: This study addresses the availability of the genetic programming (GP) approach for the formulation of strength enhancement of FRP (fiber-reinforced polymer) confined concrete cylinders. The GP formulation is based on experimental results collected from the literature. The accuracy of the proposed GP formulation was satisfactory compared to the experimental results. Moreover, the results of the proposed GP formulation were compared with 10 models from the literature proposed by various researchers so far and were found to be more accurate. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 3087–3095, 2008

Key words: fibers; mechanical properties

INTRODUCTION

The use of fiber-reinforced polymer (FRP) composites in structural engineering applications has opened a new era in civil engineering. FRP composites have been successfully used in various construction applications, such as the repair and rehabilitation of existing structures and in new construction applications, for a few decades. External strengthening, repair, and ductility enhancement of reinforced concrete columns are major application areas in this field that are of significant importance.[1] Therefore, the effect the effect of FRP confinement on the strength and deformation capacity of concrete columns has been extensively studied, and several empirical and theoretical models have been proposed.[2] In this article, we propose a new approach for the formulation of the strength enhancement of FRP-confined concrete cylinders with a genetic programming (GP) approach, which has not been applied in this field so far.

FRP-CONFINED CONCRETE

The main types of FRP composites used in the external strengthening and repair of concrete structures are glass-fiber-reinforced polymers (GFRPs), carbon-fiber-reinforced polymers (CFRPs), and aramid-fiber-reinforced polymers (AFRPs). The types of FRPs confinement can be spiral, wrapped, and tube. FRP composites offer several advantages because of their extremely high strength-to-weight ratio, good corrosion behavior, and electromagnetic neutrality. The most widely used FRP type for strengthening applications in civil engineering applications is carbon fiber. There is a wide range of applications of FRPs in concrete structures. For example, the confinement of concrete columns with FRPs for strengthening purposes offer several advantages compared to steel,[3] including continuous confining action to the entire cross section, ease and speed of application, a lack of change in the shape and size of the strengthened elements, and corrosive resistance.[2] A typical response of FRP-confined concrete is shown in Figure 1,[4] where the normalized axial stress is plotted against the axial, lateral, and volumetric strains. The stress is normalized with respect to the unconfined strength of the concrete core. Figure 1 shows that both the axial and lateral responses are bilinear with a transition zone at or near the peak strength of the unconfined concrete core.[4] Considerable experimental research has been performed on the behavior of FRP-confined concrete cylinders.[5–21] Several models[10,11,22–28] that have been proposed in the literature for the strength enhancement of the FRP confinement effect on concrete cylinders are shown in Table I. A comparative study of the models of the confinement of concrete cylinders with FRP composites can be found in ref. 2.

GP

GP, proposed by Koza,[29] is an extension of genetic algorithms (GAs). Koza defined GP as a domain-independent, problem-solving approach in which computer programs are evolved to solve, or approximately solve, problems based on the Darwinian principle of reproduction and survival of the fittest and

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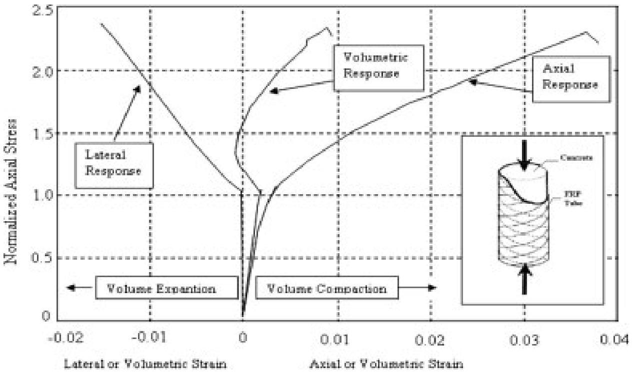

Figure 1 Typical response of FRP-confined concrete.

analogs of naturally occurring genetic operations such as crossover (sexual recombination) and mutation.

Gene expression programming (GEP) software, which was used in this study, is an extension of GP that evolves computer programs of different sizes and shapes encoded in linear chromosomes of fixed length. The chromosomes are composed of multiple genes, with each gene encoding a smaller subprogram. Furthermore, the structural and functional organization of the linear chromosomes allows the unconstrained operation of important genetic operators, such as mutation, transposition, and recombination.[30–32] APS 3.0,[33] a GEP software developed by Candida Ferreira (London, UK), was used in this study.

TABLE I
Models for the Strength Enhancement of FRP-Confined Concrete Cylinders

Model	Expression (f_{cc}/f_{co})
Fardis and Khalili, 1981[22]	$\frac{f_{cc}}{f_{co}} = 1 + 4.1\frac{p_u}{f_{co}}$ (3)
	$\frac{f_{cc}}{f_{co}} = 1 + 3.7\left(\frac{p_u}{f_{co}}\right)^{0.86}$ (4)
Saadatmanesh et al., 1994[23]	$\frac{f_{cc}}{f_{co}} = 2.254\sqrt{1 + 7.94\frac{p_u}{f_{co}}} - 2\frac{p_u}{f_{co}} - 1.254$ (5)
Miyauchi et al., 1997[10]	$\frac{f_{cc}}{f_{co}} = 1 + 3.485\frac{p_u}{f_{co}}$ (6)
Kono et al., 1998[11]	$\frac{f_{cc}}{f_{co}} = 1 + 0.0572p_u$ (7)
Saaman et al., 1998[24]	$\frac{f_{cc}}{f_{co}} = 1 + 6.0\frac{p_u^{0.7}}{f_{co}}$ (8)
Tountanji, 1999[25]	$\frac{f_{cc}}{f_{co}} = 1 + 3.5\left(\frac{p_u}{f_{co}}\right)^{0.85}$ (9)
Saafi et al., 1999[26]	$\frac{f_{cc}}{f_{co}} = 1 + 2.2\left(\frac{p_u}{f_{co}}\right)^{0.84}$ (10)
Spoelstra and Monti, 1999[27]	$\frac{f_{cc}}{f_{co}} = 0.2 + 3\left(\frac{p_u}{f_{co}}\right)^{0.5}$ (11)
Xiao and Wu, 2000[28]	$\frac{f_{cc}}{f_{co}} = 1.1 + \left(4.1 - 0.75\frac{f_{co}^2}{E_1}\right)\frac{p_u}{f_{co}}$ (12)

TABLE II
GEP Formulations Obtained for Various Gene and Head Sizes

Head size	Gene size	GP formulation	R	RMSE	MAE	COV
1	2	$e^{\sqrt{\frac{p_u}{f_{co}}+\frac{1}{f_{co}}}}$	0.89	0.36	0.27	15.6
1	3	$2 \times \sqrt[3]{\sqrt{p_u/f_{co}}} + \frac{p_u}{f_{co}} - \frac{1}{p_u^2}$	0.89	0.34	0.26	15.1
1	4	$\frac{p_u}{f_{co}} + \frac{1}{p_u^2} + \sqrt[3]{\frac{1}{\sqrt{p_u}}} + \sqrt[3]{\frac{p_u}{f_{co}}}$	0.89	0.34	0.26	15.1
1	5	$\frac{p_u}{f_{co}} \times \sqrt{\frac{f_{co}}{p_u}} + 2 \times \frac{1/p_u}{\sqrt{f_{co}/p_u}} + \frac{p_u \times \sqrt{p_u}}{f_{co}} + \frac{\ln(f_{co}/p_u)}{\sqrt{f_{co}/p_u}}$	0.90	0.33	0.25	14.8
1	6	$e^{\sqrt{p_u/f_{co}}} + \frac{1}{f_{co}} - \frac{1}{p_u} + \sqrt{\frac{1}{f_{co}}} + \ln\left(\frac{f_{co}}{p_u}\right) \times \frac{1}{f_{co}} + 2 \times \frac{1}{f_{co}} \times \ln\left(\frac{f_{co}}{p_u}\right)$	0.89	0.34	0.26	15.1
2	1	$e^{\sqrt{p_u/f_{co}}}$	0.89	0.37	0.28	15.6
2	2	$e^{\sqrt{p_u/f_{co}}} + \left(\frac{1}{p_u^2}\right)^{3/4}$	0.89	0.34	0.27	15.7
2	3	$0.226 \times \frac{1}{\sqrt{p_u}} + \frac{p_u}{f_{co}} + \sqrt[16]{\frac{1}{f_{co}}}$	0.89	0.34	0.26	15.2
2	4	$\sqrt[8]{\frac{p_u}{f_{co}}} - \frac{\sqrt{p_u}}{56.1} + \sqrt[4]{\frac{p_u}{f_{co}}} + \frac{p_u}{f_{co}}$	0.89	0.34	0.25	15.0
2	6	$\frac{\ln(f_{co})}{f_{co}} + \sqrt[5]{\frac{p_u^2}{f_{co}/p_u}} + \frac{\ln(f_{co}/p_u)}{f_{co}} + e^{\sqrt{p_u/f_{co}}-\sqrt{f_{cu}/p_u}} + 2 \times \frac{1}{p_u^2}$	0.90	0.33	0.25	15.0
3	1	$\frac{1}{f_{co}} + e^{\sqrt{p_u/f_{co}}}$	0.89	0.36	0.27	15.6
3	2	$e^{\sqrt{p_u/f_{co}}} + \sqrt{\frac{1}{f_{co}}} \times \sqrt[3]{\frac{p_u}{f_{co}}}$	0.89	0.34	0.26	15.5
3	3	$\sqrt[4]{\sqrt{\frac{p_u}{f_{co}}} - \frac{1}{p_u^2}} + \sqrt[4]{\frac{p_u}{f_{co}}} + \frac{p_u}{f_{co}} + \left(\frac{1}{p_u}\right)^3$	0.89	0.34	0.26	15.0
3	4	$e^{\sqrt{p_u/f_{co}}} + \sqrt{\frac{1}{f_{co}}} + \frac{1}{p_u^2} - \frac{1}{p_u} + \frac{1/p_u^2}{\ln(f_{co}/p_u) \times p_u^2}$	0.90	0.34	0.25	14.9
4	1	$e^{\sqrt{p_u/f_{co}}} - \frac{1}{p_u^3}$	0.89	0.37	0.28	15.6
4	2	$\sqrt[4]{\sqrt{\frac{p_u}{f_{co}}}} + \sqrt[4]{\frac{p_u}{f_{co}}} + \frac{p_u}{f_{co}}$	0.89	0.34	0.26	15.0
4	3	$e^{\frac{p_u^2 \times \ln(p_u/f_{co})}{12}} + \sqrt[3]{\frac{\sqrt{p_u/f_{co}}}{(p_u)^{1/10}}} + \sqrt[6]{\frac{p_u}{f_{co}}}$	0.90	0.33	0.25	14.8
5	1	$e^{\sqrt{p_u/f_{co}}} + \frac{1}{f_{co}}$	0.89	0.36	0.27	15.6

RMSE = root mean square error; MAE = mean absolute error; COV = coefficient of variation.

TABLE III
Parameters of the GEP Models

P1	Function set	+, −, ×, /, $\sqrt{}$, ln (x)
P2	Chromosomes	30–60
P3	Head size	6–8–10
P4	Number of genes	3
P5	Linking function	Addition, multiplication
P6	Fitness function error type	Mean absolute error, custom fitness function
P7	Mutation rate	0.044
P8	Inversion rate	0.1
P9	One-point recombination rate	0.3
P10	Two-point recombination rate	0.3
P11	Gene recombination rate	0.1
P12	Gene transposition rate	0.1

The fundamental difference between GAs, GP, and GEP is due to the nature of the individuals: in GAs, the individuals are linear strings of fixed length (chromosomes); in GP, the individuals are nonlinear entities of different sizes and shapes (parse trees); and in GEP, the individuals are encoded as linear strings of fixed length (the genome or chromosomes) that are afterward expressed as nonlinear entities of different sizes and shapes (i.e., simple diagram representations or expression trees). Thus, the two main parameters GEP are the chromosomes and expression trees.[30–32] Two languages are used in GEP: the language of the genes and the language of the expression trees. A significant advantage of GEP is that it enables one to infer exactly the phenotype given the sequence of a gene and vice versa, which is termed *Karva* language.

For each problem, the type of linking function, the number of genes, and the length of each gene are *a priori* chosen for each problem. While attempting to solve a problem, one can always start by using a single-gene chromosome and then proceed by increasing the length of the head. If it becomes very large, one can increase the number of genes and obviously choose a function to link the sub-expression trees. One can start with addition for algebraic expressions or for Boolean expressions, but in some cases, another linking function might be more appropriate (e.g., multiplication or IF). The idea, of course, is to find a good solution, and GEP provides the means of finding one very efficiently.[33]

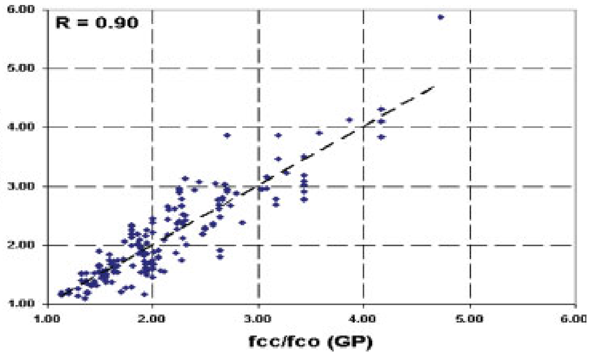

Figure 2 Performance of the GP formulation versus the experimental results. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

NUMERICAL APPLICATION

Our main aim in this study was to obtain an empirical formulation for the strength enhancement factor (f_{cc}/f_{co}), where f_{cc} is the compressive strength of the confined concrete cylinder and f_{co} is the compressive strength of the unconfined concrete cylinder, for FRP-confined concrete cylinders on the basis of the test results available in literature as a function of f_{co} and ultimate confinement pressure (p_u):

$$f_{cc}/f_{co} = f(f_{co}, p_u) \tag{1}$$

Therefore, an extensive literature review on experimental studies related to the strength enhancement of FRP-confined concrete cylinders was carried out, and an experimental database was gathered. A total of 180 specimens from 17 separate studies with the ranges of variables were included in the database, which is shown with further details in the appendix.[2]

The proposed GP formulation is the best one selected from among a set of formulations obtained for various numbers of genes and head sizes, as presented in Table II. The results of the proposed GP formulation versus actual the experimental values and

TABLE IV
Statistics of the Performance and Accuracy of f_{cc}/f_{co} of the Proposed GP Formulation and Existing Models Compared to the Experimental Results

	Test										
Model	GP	Eq. (3)	Eq. (4)	Eq. (5)	Eq. (6)	Eq. (7)	Eq. (8)	Eq. (9)	Eq. (10)	Eq. (11)	Eq. (12)
Mean	1.00	0.79	0.78	0.84	0.86	1.09	0.98	0.71	1.00	1.03	1.22
Standard deviation	0.15	0.19	0.16	0.13	0.19	0.22	0.15	0.11	0.16	0.18	0.91
R	0.90	0.84	0.88	0.89	0.86	0.88	0.90	0.91	0.91	0.90	0.64
MAPE (%)	0.12	0.23	0.23	0.17	0.19	0.19	0.12	0.29	0.13	0.15	0.48
COV	0.15	0.24	0.20	0.16	0.22	0.20	0.16	0.16	0.16	0.17	0.74

MAPE = mean absolute percentage error; COV = coefficient of variation.

their comparison with current design codes are given in the appendix. The GP formulation obtained from APS 3.0 corresponds to the following equation:

$$f_{cc}/f_{co} = \sqrt{\frac{p_u}{f_{co}}} + \frac{2}{\sqrt{p_u f_{co}}} + \frac{p_u\sqrt{p_u}}{f_{co}} + \frac{\ln(f_{co}/p_u)}{\sqrt{f_{co}/p_u}} \qquad (2)$$

Related parameters for the training of the GP models are given in Table III. The performance of the proposed GP formulation versus the experimental results are given in Figure 2, and the accuracy of the formulation was observed to be quite good with a standard deviation of 0.15 and a correlation coefficient (*R*) of 0.90.

The statistical parameters of the proposed GP formulation compared with the existing models are presented in Table IV. As shown in Table IV, the proposed GP formulation performed better than the existing equations found in the literature. The proposed GP formulation presented previously is valid only for the ranges of variables of the experimental database given in the appendix.

CONCLUSIONS

This article presents a novel application, GP, for the formulation of f_{cc}/f_{co} for FRP-confined concrete cylinders. The proposed GP formulation is actually an empirical formulation based on a wide range of experimental database collected from the literature. The GP formulation proposed in this article was quite accurate and performed very well with experimental results. For comparative analysis, numerical results of the same experimental database were obtained by existing models, and the proposed GP formula and GP formulation were found to be more accurate. The empirical formulations in structural engineering are mostly based on predefined functions, where regression analyses of these functions are later performed. However, in the case of the GP approach, there is no predefined function to be considered; that is, GP adds or deletes various combinations of parameters to be considered for the formulation that best fits the experimental results on the basis of the lowest mean square error. The findings of this study may lead to further GP-based formulations for structural engineering problems in the future.

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APPENDIX: RESULTS OF THE GP FORMULATION VERSUS THE EXPERIMENTAL AND THEORETICAL RESULTS

Reference	Code	Specimen type	Fiber type	D (mm)	H (mm)	nt (mm)	E_f (MPa)	f_{co} (MPa)	E_l (MPa)	p_u (MPa)	f_{cc} test (MPa)	f_{cc}/f_{co} (test)	f_{cc}/f_{co} (GP)	Test GP
Ahmad et al., 1991[5]	AH1	Fil. wound	GFRP	102	203	1	48,300	38.99	951	40.75	115.3	2.96	3.03	0.98
	AH2			102	203	1	48,300	50.51	951	40.75	135.1	2.67	2.73	0.98
	AH3			102	203	1	48,300	64.20	951	40.75	145.59	2.27	2.49	0.91
Nanni and Bradford, 1995[6]	NB1	Fil. wound	GFRP	150	300	0.3	52,000	36.30	208	2.33	46.00	1.27	1.29	0.98
	NB2			150	300	0.3	52,000	36.30	208	2.33	41.20	1.13	1.29	0.88
	NB3			150	300	0.6	52,000	36.30	416	4.67	60.52	1.67	1.49	1.12
	NB4			150	300	0.6	52,000	36.30	416	4.67	59.23	1.63	1.49	1.09
	NB5			150	300	0.6	52,000	36.30	416	4.67	59.77	1.65	1.49	1.10
	NB6			150	300	0.6	52,000	36.30	416	4.67	60.16	1.66	1.49	1.11
	NB7			150	300	0.6	52,000	36.30	416	4.67	69.02	1.90	1.49	1.27
	NB8			150	300	0.6	52,000	36.30	416	4.67	55.75	1.54	1.49	1.03
	NB9			150	300	0.6	52,000	36.30	416	4.67	56.41	1.55	1.49	1.04
	NB10			150	300	1.2	52,000	36.30	832	9.33	84.88	2.34	1.79	1.31
	NB11			150	300	1.2	52,000	36.30	832	9.33	84.33	2.32	1.79	1.30
	NB12			150	300	1.2	52,000	36.30	832	9.33	79.64	2.19	1.79	1.22
	NB13			150	300	2.4	52,000	36.30	1664	18.67	106.87	2.94	2.25	1.31
	NB14			150	300	2.4	52,000	36.30	1664	18.67	104.94	2.89	2.25	1.29
	NB15			150	300	2.4	52,000	36.30	1664	18.67	107.91	2.97	2.25	1.32
Harmon and Slattery, 1992[7]	HA1	Wrap	CFRP	51	102	0.089	235,000	41.00	820	12.22	86.00	2.10	1.87	1.12
	HA2			51	102	0.179	235,000	41.00	1650	24.57	120.50	2.94	2.39	1.23
	HA3			51	102	0.344	235,000	41.00	3170	47.22	158.40	3.86	3.19	1.21
	HA4			51	102	0.689	235,000	41.00	6350	94.57	241.00	5.88	4.73	1.24
	HA5			51	102	0.179	235,000	103.00	1650	24.57	131.10	1.27	1.74	0.73
	HA6			51	102	0.344	235,000	103.00	3170	47.22	193.20	1.88	2.22	0.84
	HA7			51	102	0.689	235,000	103.00	6350	94.57	303.60	2.95	3.04	0.97
Picher et al., 1996[8]	PI1	Wrap	CFRP	153	305	0.36	83,000	39.70	392	5.98	55.98	1.41	1.54	0.91
Watanabe et al., 1997[9]	WA1	Wrap	CFRP	100	200	0.1675	223,400	30.20	748	9.14	46.60	1.54	1.89	0.82
	WA2			100	200	0.5025	223,400	30.20	2245	27.42	87.20	2.89	2.79	1.03
	WA3			100	200	0.67	223,400	30.20	2994	36.56	104.60	3.46	3.18	1.09
	WA4			100	200	0.14	611,600	30.20	1712	4.38	41.70	1.38	1.56	0.89
	WA5			100	200	0.28	611,600	30.20	3425	8.75	56.00	1.85	1.86	1.00
	WA6			100	200	0.42	611,600	30.20	5137	13.13	63.30	2.10	2.11	0.99
	WA7		AFRP	100	200	0.145	90,600	30.20	263	7.70	39.00	1.29	1.80	0.72
	WA8			100	200	0.29	90,600	30.20	525	15.39	68.50	2.27	2.23	1.02
	WA9			100	200	0.435	90,600	30.20	788	23.09	92.10	3.05	2.60	1.17
Miyauchi et al., 1997[10]	MI1	Wrap	CFRP	150	300	0.11	230,500	45.20	338	5.11	59.40	1.31	1.42	0.92
	MI2			150	300	0.22	230,500	45.20	676	10.21	79.40	1.76	1.72	1.02
	MI3			150	300	0.11	230,500	31.20	338	5.11	52.40	1.68	1.60	1.05
	MI4			150	300	0.22	230,500	31.20	676	10.21	67.40	2.16	1.93	1.12
	MI5			150	300	0.33	230,500	31.20	1014	15.32	81.70	2.62	2.20	1.19
	MI6			100	200	0.11	230,500	51.90	507	7.66	75.20	1.45	1.51	0.96
	MI7			100	200	0.22	230,500	51.90	1014	15.32	104.60	2.02	1.86	1.08
	MI8			100	200	0.11	230,500	33.70	507	7.66	69.60	2.07	1.73	1.19
	MI9			100	200	0.22	230,500	33.70	1014	15.32	88.00	2.61	2.15	1.22

	MI10			150	300	0.11	230,500	45.20	338	5.11	59.40	1.31	1.42	0.92
Kono et al., 1998[11]	KO1	Wrap	CFRP	100	200	0.167	235,000	34.30	785	12.76	57.40	1.67	2.01	0.83
	KO2			100	200	0.167	235,000	34.30	785	12.76	64.90	1.89	2.01	0.94
	KO3			100	200	0.167	235,000	32.30	785	12.76	58.20	1.80	2.05	0.88
	KO4			100	200	0.167	235,000	32.30	785	12.76	61.80	1.91	2.05	0.93
	KO5			100	200	0.167	235,000	32.30	785	12.76	57.70	1.79	2.05	0.87
	KO6			100	200	0.334	235,000	32.30	1570	25.52	58.20	1.80	2.64	0.68
	KO7			100	200	0.334	235,000	32.30	1570	25.52	61.80	1.91	2.64	0.72
	KO8			100	200	0.334	235,000	32.30	1570	25.52	80.20	2.48	2.64	0.94
	KO9			100	200	0.501	235,000	32.30	2355	38.28	86.90	2.69	3.17	0.85
	KO10			100	200	0.501	235,000	32.30	2355	38.28	90.10	2.79	3.17	0.88
	KO11			100	200	0.167	235,000	34.80	785	12.76	57.80	1.66	2.00	0.83
	KO12			100	200	0.167	235,000	34.80	785	12.76	55.60	1.60	2.00	0.80
	KO13			100	200	0.167	235,000	34.80	785	12.76	50.70	1.46	2.00	0.73
	KO14			100	200	0.334	235,000	34.80	1570	25.52	82.70	2.38	2.57	0.92
	KO15			100	200	0.334	235,000	34.80	1570	25.52	81.40	2.34	2.57	0.91
	KO16			100	200	0.501	235,000	34.80	2355	38.28	103.30	2.97	3.08	0.96
	KO17			100	200	0.501	235,000	34.80	2355	38.28	110.10	3.16	3.08	1.03
Toutanji, 1999[12]	TO1	Wrap	GFRP	76	305	0.236	72,600	30.93	451	9.43	60.82	1.97	1.89	1.04
	TO2		CFRP	76	305	0.22	230,500	30.93	1334	20.18	95.02	3.07	2.44	1.26
	TO3			76	305	0.33	372,800	30.93	3237	25.53	94.01	3.04	2.68	1.13
Matthys et al., 1999[13]	MA1	Wrap	CFRP	150	300	0.117	220,000	34.90	343	4.06	46.10	1.32	1.46	0.90
	MA2			150	300	0.235	500,000	34.90	1567	3.45	45.80	1.31	1.41	0.93
Shahawy et al., 2000[14]	SH1	Wrap	CFRP	153	305	0.36	82,700	19.40	390	10.74	33.80	1.74	2.28	0.77
	SH2			153	305	0.66	82,700	19.40	716	19.69	46.40	2.39	2.84	0.84
	SH3			153	305	0.9	82,700	19.40	976	26.85	62.6	3.23	3.27	0.99
	SH4			153	305	1.08	82,700	19.40	1171	32.22	75.70	3.90	3.57	1.09
	SH5	Wrap	CFRP	153	305	1.25	82,700	19.40	1356	37.30	80.20	4.13	3.87	1.07
	SH6			153	305	0.36	82,700	49.00	390	10.74	59.10	1.21	1.70	0.71
	SH7			153	305	0.66	82,700	49.00	716	19.69	76.50	1.56	2.07	0.75
	SH8			153	305	0.9	82,700	49.00	976	26.85	98.80	2.02	2.32	0.87
	SH9			153	305	1.08	82,700	49.00	1171	32.22	112.70	2.30	2.50	0.92
Rochette and Labossiére, 2000[15]	RL1	Wrap	CFRP	100	200	0.6	82,700	42.00	992	15.18	73.50	1.75	1.99	0.88
	RL2			100	200	0.6	82,700	42.00	992	15.18	73.50	1.75	1.99	0.88
	RL3			100	200	0.6	82,700	42.00	992	15.18	67.62	1.61	1.99	0.81
	RL4		AFRP	150	300	1.26	13,600	43.00	228	3.86	47.30	1.10	1.35	0.81
	RL5			150	300	2.52	13,600	43.00	457	7.73	58.91	1.37	1.61	0.85
	RL6			150	300	3.78	13,600	43.00	685	11.59	70.95	1.65	1.81	0.91
	RL7			150	300	5.04	13,600	43.00	914	15.46	74.39	1.73	1.99	0.87
Micelli et al., 2001[16]	MC1	Wrap	GFRP	100	200	0.35	72,400	32.00	507	10.64	54.00	1.69	1.94	0.87
	MC2			100	200	0.35	72,400	32.00	507	10.64	48.00	1.50	1.94	0.77
	MC3			100	200	0.35	72,400	32.00	507	10.64	54.00	1.69	1.94	0.87
	MC4			100	200	0.35	72,400	32.00	507	10.64	50.00	1.56	1.94	0.81
	MC5		CFRP	100	200	0.16	227,000	37.00	726	12.13	60.00	1.62	1.93	0.84
	MC6			100	200	0.16	227,000	37.00	726	12.13	62.00	1.68	1.93	0.87
	MC7			100	200	0.16	227,000	37.00	726	12.13	59.00	1.59	1.93	0.83
	MC8			100	200	0.16	227,000	37.00	726	12.13	57.00	1.54	1.93	0.80
Rousakis, 2001[17]	RO1	Wrap	CFRP	150	300	0.169	118,340	25.15	267	4.56	44.13	1.75	1.67	1.05
	RO2			150	300	0.169	118,340	25.15	267	4.56	41.56	1.65	1.67	0.99
	RO3			150	300	0.169	118,340	25.15	267	4.56	38.75	1.54	1.67	0.93

APPENDIX *Continued*

Reference	Code	Specimen type	Fiber type	D (mm)	H (mm)	nt (mm)	E_f (MPa)	f_{co} (MPa)	E_l (MPa)	p_u (MPa)	f_{cc} test (MPa)	f_{cc}/f_{co} (test)	f_{cc}/f_{co} (GP)	Test GP
	RO4	Wrap	CFRP	150	300	0.338	118,340	25.15	533	9.12	60.09	2.39	2.00	1.20
	RO5			150	300	0.338	118,340	25.15	533	9.12	55.93	2.22	2.00	1.11
	RO6			150	300	0.338	118,340	25.15	533	9.12	61.61	2.45	2.00	1.23
	RO7			150	300	0.507	118,340	25.15	800	13.68	67	2.66	2.27	1.17
	RO8			150	300	0.507	118,340	25.15	800	13.68	67.27	2.67	2.27	1.18
	RO9			150	300	0.507	118,340	25.15	800	13.68	70.18	2.79	2.27	1.23
	RO10			150	300	0.169	118,340	47.44	267	4.56	72.26	1.52	1.36	1.12
	RO11			150	300	0.169	118,340	47.44	267	4.56	64.4	1.36	1.36	1.00
	RO12			150	300	0.169	118,340	47.44	267	4.56	66.19	1.40	1.36	1.03
	RO13			150	300	0.338	118,340	47.44	533	9.12	82.36	1.74	1.64	1.06
	RO14			150	300	0.338	118,340	47.44	533	9.12	82.35	1.74	1.64	1.06
	RO15			150	300	0.338	118,340	47.44	533	9.12	79.11	1.67	1.64	1.02
	RO16			150	300	0.507	118,340	47.44	800	13.68	96.29	2.03	1.85	1.10
	RO17			150	300	0.507	118,340	47.44	800	13.68	95.22	2.01	1.85	1.09
	RO18			150	300	0.507	118,340	47.44	800	13.68	103.97	2.19	1.85	1.18
	RO19			150	300	0.169	118,340	51.84	267	4.56	78.65	1.52	1.32	1.15
	RO20			150	300	0.169	118,340	51.84	267	4.56	79.18	1.53	1.32	1.16
	RO21			150	300	0.169	118,340	51.84	267	4.56	72.76	1.40	1.32	1.06
	RO22			150	300	0.338	118,340	51.84	533	9.12	95.4	1.84	1.59	1.16
	RO23			150	300	0.338	118,340	51.84	533	9.12	90.3	1.74	1.59	1.10
	RO24			150	300	0.338	118,340	51.84	533	9.12	90.65	1.75	1.59	1.10
	RO25			150	300	0.507	118,340	51.84	800	13.68	110.54	2.13	1.80	1.19
	RO26			150	300	0.507	118,340	51.84	800	13.68	103.62	2.00	1.80	1.11
	RO27			150	300	0.507	118,340	51.84	800	13.68	117.23	2.26	1.80	1.26
	RO28			150	300	0.845	118,340	51.84	1333	22.80	112.66	2.17	2.14	1.02
	RO29			150	300	0.845	118,340	51.84	1333	22.80	126.69	2.44	2.14	1.14
	RO30			150	300	0.845	118,340	51.84	1333	22.80	137.93	2.66	2.14	1.24
	RO31			150	300	0.169	118,340	70.48	267	4.56	87.29	1.24	1.20	1.04
	RO32			150	300	0.169	118,340	70.48	267	4.56	84.03	1.19	1.20	1.00
	RO33			150	300	0.169	118,340	70.48	267	4.56	83.22	1.18	1.20	0.99
	RO34			150	300	0.338	118,340	70.48	533	9.12	94.06	1.33	1.44	0.93
	RO35			150	300	0.338	118,340	70.48	533	9.12	98.13	1.39	1.44	0.97
	RO36			150	300	0.338	118,340	70.48	533	9.12	107.2	1.52	1.44	1.06
	RO37			150	300	0.507	118,340	70.48	800	13.68	114.12	1.62	1.63	0.99
	RO38			150	300	0.507	118,340	70.48	800	13.68	108.07	1.53	1.63	0.94
	RO39			150	300	0.507	118,340	70.48	800	13.68	110.38	1.57	1.63	0.96
	RO40			150	300	0.169	118,340	82.13	267	4.56	94.08	1.15	1.14	1.01
	RO41			150	300	0.169	118,340	82.13	267	4.56	97.6	1.19	1.14	1.05
	RO42			150	300	0.169	118,340	82.13	267	4.56	95.83	1.17	1.14	1.03
	RO43			150	300	0.338	118,340	82.13	533	9.12	97.43	1.19	1.37	0.86
	RO44			150	300	0.338	118,340	82.13	533	9.12	98.85	1.20	1.37	0.88
	RO45			150	300	0.338	118,340	82.13	533	9.12	98.24	1.20	1.37	0.87
	RO46			150	300	0.507	118,340	82.13	800	13.68	124.2	1.51	1.55	0.98
	RO47			150	300	0.507	118,340	82.13	800	13.68	129.58	1.58	1.55	1.02
	RO48			150	300	0.507	118,340	82.13	800	13.68	120.36	1.47	1.55	0.95

Saafi and Toutanji, 1999[18]	SA1	Tube	GFRP	152	435	0.8	32,000	35.00	336	4.72	52.80	1.51	1.51	1.00
	SA2			152	435	1.6	34,000	35.00	714	10.60	66.00	1.89	1.88	1.00
	SA3			152	435	2.4	36,000	35.00	1134	17.64	83.00	2.37	2.23	1.06
	SA4		CFRP	152	435	0.11	367,000	35.00	530	4.76	55.00	1.57	1.52	1.04
	SA5			152	435	0.23	390,000	35.00	1177	10.72	68.00	1.94	1.89	1.03
	SA6			152	435	0.55	415,000	35.00	2995	26.71	97.00	2.77	2.61	1.06
Mirmiran and Shahawy, 1997[19]	MS1	Tube	GFRP	153	305	1.44	37,233	30.86	703	9.90	53.66	1.74	1.92	0.91
	MS2			153	305	1.44	37,233	30.86	703	9.90	56.50	1.83	1.92	0.95
	MS3			153	305	1.44	37,233	29.64	703	9.90	67.12	2.26	1.94	1.17
	MS4			153	305	1.44	37,233	29.64	703	9.90	55.29	1.87	1.94	0.96
	MS5			153	305	1.44	37,233	29.64	703	9.90	60.23	2.03	1.94	1.05
	MS6			153	305	1.44	37,233	31.97	703	9.90	59.06	1.85	1.90	0.97
	MS7			153	305	1.44	37,233	31.97	703	9.90	60.79	1.90	1.90	1.00
	MS8			153	305	2.2	40,336	30.86	1164	16.71	72.92	2.36	2.28	1.04
	MS9			153	305	2.2	40,336	30.86	1164	16.71	65.67	2.13	2.28	0.93
	MS10			153	305	2.2	40,336	30.86	1164	16.71	77.99	2.53	2.28	1.11
	MS11			153	305	2.2	40,336	29.64	1164	16.71	74.56	2.52	2.31	1.09
	MS12			153	305	2.2	40,336	29.64	1164	16.71	93.02	3.14	2.31	1.36
	MS13			153	305	2.2	40,336	29.64	1164	16.71	71.74	2.42	2.31	1.05
	MS 14			153	305	2.2	40,336	31.97	1164	16.71	77.35	2.42	2.25	1.07
	MS15			153	305	2.2	40,336	31.97	1164	16.71	77.08	2.41	2.25	1.07
	MS16			153	305	2.97	40,749	30.86	1587	24.97	85.72	2.78	2.66	1.04
	MS17			153	305	2.97	40,749	30.86	1587	24.97	86.76	2.81	2.66	1.06
	MS18			153	305	2.97	40,749	29.64	1587	24.97	86.22	2.91	2.70	1.08
	MS19			153	305	2.97	40,749	29.64	1587	24.97	114.66	3.87	2.70	1.43
	MS20			153	305	2.97	40,749	29.64	1587	24.97	87.44	2.95	2.70	1.09
	MS21			153	305	2.97	40,749	31.97	1587	24.97	86.11	2.69	2.63	1.03
	MS22			153	305	2.97	40,749	31.97	1587	24.97	83.99	2.63	2.63	1.00
La Tegola and Manni, 1999[20]	LM1	Tube	GFRP	150	300	4.28	25,250	25.61	1441	37.21	71.00	2.77	3.44	0.81
	LM2			150	300	4.28	25,250	25.61	1441	37.21	71.30	2.78	3.44	0.81
	LM3			150	300	4.28	25,250	25.61	1441	37.21	74.70	2.92	3.44	0.85
	LM4			150	300	4.28	25,250	25.61	1441	37.21	79.20	3.09	3.44	0.90
	LM5			150	300	4.28	25,250	25.61	1441	37.21	81.50	3.18	3.44	0.93
	LM6			150	300	4.28	25,250	25.61	1441	37.21	77.50	3.03	3.44	0.88
	LM7			150	300	4.28	25,250	25.61	1441	37.21	89.90	3.51	3.44	1.02
	LM8			150	300	5.9	25,450	25.61	2002	52.71	98.50	3.85	4.16	0.92
	LM9			150	300	5.9	25,450	25.61	2002	52.71	110.30	4.31	4.16	1.04
	LM10			150	300	5.9	25,450	25.61	2002	52.71	105.20	4.11	4.16	0.99
Famand Rizkalla, 2000[21]	FR1	Tube	GFRP	168	336	3.73	33,400	58.00	1483	24.33	90.00	1.55	2.11	0.74
	FR2			219	438	3.7	33,400	58.00	1129	18.52	68.00	1.17	1.91	0.61
	FR3			100	200	3.08	23,000	37.00	1417	24.52	81.00	2.19	2.47	0.88
										Coefficient of variation				0.148
										Mean				1.00
										R				0.90

D = diameter of the concrete cylinder; nt = total thickness of the FRP layer; E_f = modulus of elasticity of the FRP laminate; E_l = confinement modulus or lateral modulus; H = height of concrete specimen; Fil. = filament.