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Design equations for concrete columns confined with hybrid composite materials

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Abstract—Retrofitting of existing concrete columns by wrapping them by fiber reinforced polymer (FRP) sheets, straps, or pultruded FRP shells has been gaining great interest in the research community and in industry. New hybrid concrete columns are developed in this study for new constructions. The basic structure of the proposed hybrid column consists of an exterior PVC-FRP shell with a concrete core. The exterior shell is commercially available cylindrical PVC pipe externally reinforced with impregnated continuous fiber in the form of hoops at different spacing. This paper presents the results of experimental and analytical studies of the performance of axially loaded concrete columns confined with PVC-FRP tubes. Test variables include type of confinement, volume of fiber and FRP hoop spacing. The results indicate that the new hybrid columns exhibited high strength and ductility. A new design procedure for concrete confined with PVC-FRP is proposed. Comparisons between experimental and theoretical results showed good agreement.

Keywords: PVC pipe; FRP composites; confinement; concrete columns; axial load; stress–strain.

1. INTRODUCTION

Past research was targeted at developing new reinforcing methods using less FRP in concrete structures to reduce cost. Shitindi [1] proposed FRP spirals to confine concrete instead of FRP tubes. Aramid, glass and carbon spirals were used. The spacing between the FRP spirals ranged between 30 and 80 mm. It was found that the stress–strain behavior of concrete confined with FRP spirals was similar to that confined with steel spirals with ascending and descending branches. Moreover, the ultimate compressive strength of columns was slightly affected by the volume and the type of fiber used. This is due to the fact that the concrete covers the FRP spiral cracks, resulting in little increase in strength.

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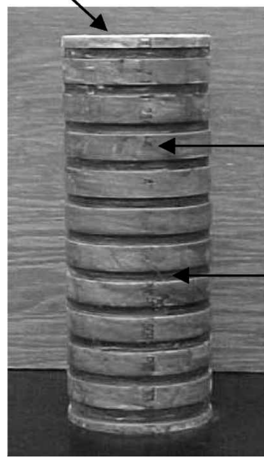

Figure 1. Proposed hybrid column system.

The proposed hybrid columns, cast in place, consist of PVC tubes reinforced with fiber reinforced polymer (FRP) hoops. The basic structure includes an exterior PVC-FRP shell with a concrete core. The exterior shell is commercially available cylindrical PVC pipe externally reinforced with impregnated continuous fiber in the form of hoops at different spacing as shown in Fig. 1. In the proposed system, the discrete confining pressures provided by the FRP hoops were distributed uniformly over the entire length of the column through the PVC tube. Moreover, the PVC tube has sufficient stiffness to prevent the spalling and cracking of the concrete core before the FRP hoops are activated. In addition, the PVC shell acts as formwork and protects the concrete and the internal reinforcements from environmental effects such as chloride and corrosion, while the FRP provides confinement to the concrete. The volume of fiber, in this reinforcing scheme, is very small compared with other existing confinement methods such as FRP tubes and FRP jackets [2]. The spacing of the FRP hoops is dependent on the strength and ductility requirement of the system. The proposed system does not need reinforcing cages or longitudinal reinforcement unless extra reinforcements are required.

The objective of this paper is to present new hybrid columns which can be used in highway bridge structure supports or as columns in marine and other construction applications. The experimental performance and theoretical analyses of axially loaded concrete-filled PVC-FRP tubes are presented in this paper.

2. EXPERIMENTAL PROGRAM

Thirty-eight short concrete columns were tested under a uniaxial compression load. Thirty-six concrete columns confined with PVC-FRP tubes and 2 control concrete

Table 1.
Mechanical properties of FRP hoops

Specimen	Thickness[a] (mm)	Hoop strength[a] (MPa)	Modulus of elasticity[a] (GPa)
GFRP	0.71	1500	74
AFRP	0.68	2100	120
CFRP	0.99	3000	400
PVC	6	42	3

[a] Excluding resin.

columns (concrete encased in PVC tubes) were used. All specimens measured 102 mm in diameter, 305 mm in length, and 6 mm in thickness. The PVC-FRP tubes used in this study were made of glass, aramid and carbon fiber reinforced polymers. The mechanical properties of the fibers, obtained from the manufacturer, are summarized in Table 1. The FRP hoops consisted of 75% fiber and 25% polyester resin and have a cross-section of approximately 12 mm^2, including the resin. The selected spacings of FRP hoops were 30 mm, 38 mm, 40 mm, 50 mm, 60 mm, and 78 mm. The average compressive strength of the concrete was 45 MPa.

The FRP strands were continuously wrapped around the PVC tube through grooves that were notched in the tubes. The process was repeated until the proper number of tows had been wound through the grooves. The winding procedure was repeated 6 times for glass and carbon fibers, producing 6 tows, and 3 times for aramid fibers producing 3 tows. After winding, the PVC-FRP tubes were left at room temperature until the resin hardened. The concrete-filled PVC-FRP tubes and concrete-filled PVC tubes (control specimens) were tested in compression. Four strain gauges were used, two to measure axial strain and two to measure lateral strain.

3. TEST RESULTS

3.1. Effect of confinement

The results of strength and deformation at failure are given in Table 2. Results show that the strength of PVC-FRP confined concrete increases with the increase of fiber volume. Lateral confinement by the PVC-FRP tubes causes the development of a triaxial stress field within the confined concrete, constraining it during dilation and thereby increasing the load carrying capacity. Figures 2, 3 and 4 show the axial stress plotted as a function of both axial strain and lateral strain for PVC-GFRP, PVC-AFRP and PVC-CFRP specimens, respectively. The figures show that the stress–strain curves of all concrete-filled PVC-FRP tubes are generally bilinear in nature with a small transition zone. The behavior of PVC-FRP tubes confined concrete columns under axial loading can be divided into three regions. In the first region, the behavior of confined concrete is similar to that of plain concrete: this

Table 2.
Summary of test results

Specimen	s^a (mm)	$\rho_{com}{}^b$ (%)	$f_{cu}{}^c$ (MPa)	$(f_{cu} - f_{co})/f_{co}$	$\varepsilon_{cu}{}^d$ (%)	$(\varepsilon_{cu} - \varepsilon_{co})/\varepsilon_{co}$	$\varepsilon_1{}^e$ (%)
Plain	—	—	33	0	0.2	0	0.2
As30	30	0.5	71.35	1.160	1.26	5.30	1.45
As38	38	0.42	64.2	0.945	1.48	6.40	1.42
As40	40	0.4	61.13	0.852	1.57	6.85	1.44
As50	50	0.32	54.8	0.661	1.16	4.80	1.3
As60	60	0.27	48.88	0.480	0.75	2.75	1.2
As78	78	0.002	44.3	0.342	0.63	2.15	0.89
Gs30	30	0.56	62.6	0.896	1.8	8.00	1.52
Gs38	38	0.44	58.9	0.785	1.35	5.75	1.65
Gs40	40	0.42	55.6	0.685	1.29	5.45	1.54
Gs50	50	0.34	52.1	0.579	0.97	3.85	1.06
Gs60	60	0.28	48.2	0.461	0.58	1.90	1.11
Gs78	78	0.22	43.5	0.318	0.31	0.55	0.24
Cs30	30	0.78	93	1.818	1.1	4.50	1.27
Cs38	38	0.62	91	1.758	1.6	7.00	1.23
Cs40	40	0.58	89	1.697	1.77	7.85	1.27
Cs50	50	0.47	78.4	1.376	1.8	8.00	1.25
Cs60	60	0.39	68	1.061	1.43	6.15	1.35
Cs78	78	0.3	62.6	0.897	1.18	4.90	1.06

[a] FRP hoop spacing.
[b] FRP volumetric ratio.
[c] Ultimate strength.
[d] Ultimate axial strain.
[e] Ultimate lateral strain.

is due to the fact that the confining effect of PVC-FRP tube is still not activated by the lateral expansion of the concrete core. In the vicinity of the peak stress of unconfined concrete, the confined concrete reaches a state of unstable volumetric growth caused by excessive cracking. At this point, the confining PVC-FRP tube is activated and starts to gradually restrain the rapid growth of the lateral strains. This region of response is characterized by a transitional curve in the vicinity of the unconfined strength. Finally, a third region is recognized in which the confining PVC-FRP tube is fully activated, and the stiffness is generally stabilized around a constant rate.

The results also show that in each case, the composite hoops failed when the radial strain reached the ultimate strain of composite. This was the case regardless of the magnitude of axial strain and the spacing of FRP hoops. Figure 5 shows a typical failure for PVC-GFRP, PVC-AFRP and PVC-CFRP tubes confined specimens. Snapping of PVC and FRP hoops could be heard near the end of the loading. In specimens with spacings of 60 and 78 mm, the failure occurred by shear failure of the concrete core and the PVC shell followed by the failure of the FRP hoops.

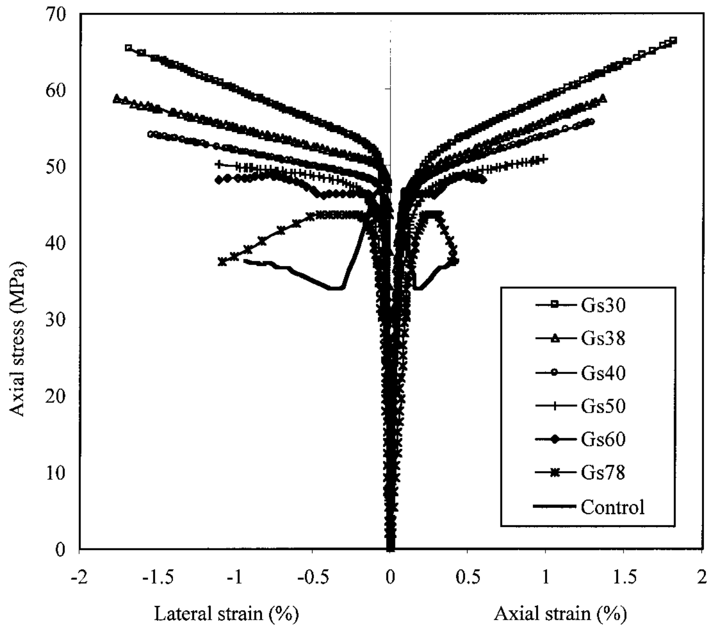

Figure 2. Stress–strain curves of PVC-GFRP confined concrete.

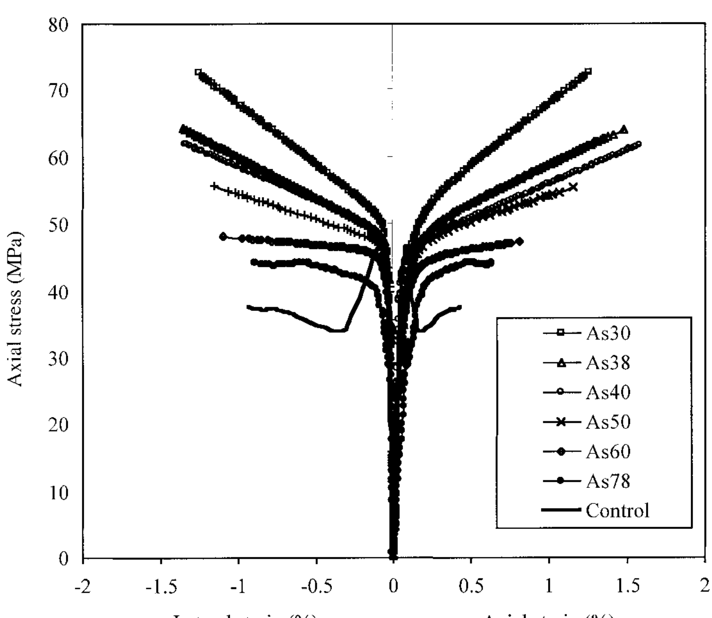

Figure 3. Stress–strain of PVC-AFRP confined concrete.

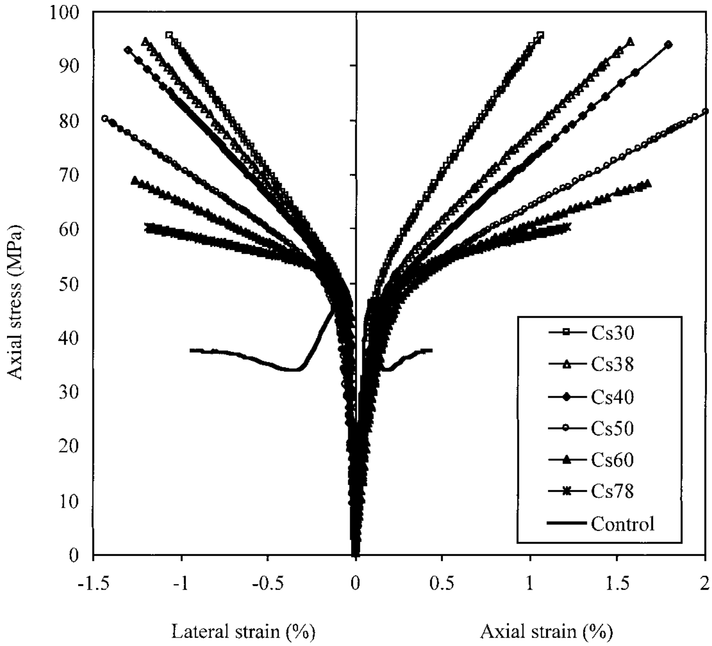

Figure 4. Stress–strain of PVC-CFRP confined concrete.

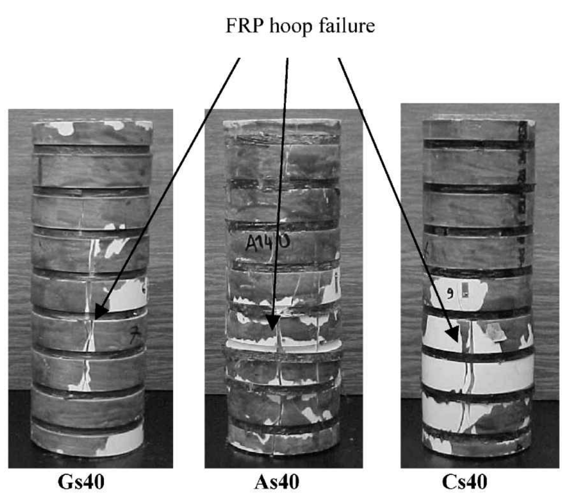

Figure 5. Typical failure mode of PVC-FRP confined concrete specimens.

This occurred due to the low volume of fiber confinement as well as the large hoop spacings.

3.2. Design equations for PVC-FRP confined concrete

Based on ACI 318 [3], the volumetric ratio of lateral spiral reinforcement is given by the following equation

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f_c'}{f_y}, \tag{1}$$

where A_g is the gross area of the section, A_c is the area of the concrete core measured to the outside diameter of the spiral, f_c' is the compressive strength of concrete, and f_y is the yield strength of lateral steel. The volumetric ratio of lateral steel ρ_s is given in equation (1) with a lower limit provided by the following equation

$$\rho_s = 0.12\frac{f_c'}{f_y}. \tag{2}$$

Equation (1) can be used only for concrete column with cover. Thus, equation (2) was used to generate a design procedure for PVC-FRP confined concrete.

The relationship between the amount of lateral FRP reinforcement obtained in equation (2) and the amount of lateral FRP reinforcement used in this study is taken as

$$\rho_{FRP} = \frac{0.12 f_c'}{f_{FRP}} Y, \tag{3}$$

where ρ_{FRP} is the volumetric ratio of lateral FRP reinforcement, f_{FRP} is the ultimate tensile strength of lateral FRP reinforcement and Y is a factor expressed as

$$Y = \beta Y_P Y \mu \tag{4}$$

where β is the parameter that accounts for the confinement efficiency. Due to the high confinement effect of FRP, the parameter β was assumed to be equal to 1. However, in concrete confined with steel spirals or ties, the parameter β depends on the configuration of lateral steel reinforcements, and this factor is expected to be greater than unity. Parameters Y_P and Y_μ take into account the effect of the axial load level and section ductility demand, respectively.

By substituting equation (4) into (3), the parameters $Y_P Y_\mu$ can be estimated as follows

$$Y_P Y_\mu = \frac{\rho_{com} f_{com}}{0.12 f_c'}. \tag{5}$$

The volumetric ratio of lateral FRP reinforcement can be calculated by the following equation

$$\rho_{com} = \frac{4A_{com}}{d_c s}, \tag{6}$$

where A_{com} is the cross-section of FRP hoops, d_c is the diameter of the concrete core, and s is the spacing of the FRP hoops. By substituting equation (6) into equation (5), the parameters $Y_P Y_\mu$ can be estimated by

$$Y_P Y_\mu = \frac{f_{com}}{0.12 f'_c}\left(\frac{4A_{com}}{d_c s}\right). \tag{7}$$

After investigating several possible forms of expressions for Y_P and Y_μ, based on experimental results, the following expressions were obtained

$$Y_P = \alpha_1 + \alpha_2\left(\frac{P}{P_o}\right)^{\alpha_3}, \tag{8}$$

$$Y_\mu = \beta_1\left(D_\mu\right)^{\beta_2}, \tag{9}$$

where α_1, α_2, α_3, β_1 and β_2 are constants to be determined empirically, and D_μ is the ductility index of tested specimens. The ductility index D_μ was obtained from the experimental results by dividing the area under the stress–strain curves of PVC-FRP confined concrete by the area under the stress–strain curve of unconfined concrete. Using the results from tested specimens, a least squares analysis was performed to find constants α_1, α_2 for selected values of α_3 that ranged from 1 to 5. Corresponding to each chosen value of α_3, and consequently obtained values for α_1, α_2, the constants β_1 and β_2 in the expression for Y_μ (equation (9)) were determined using the experimental results.

The expressions for parameters Y_P and Y_μ are evaluated by the best-fit curves from the analysis shown in Figs 6 and 7.

$$Y_P = 0.6 + 0.4\left(\frac{P}{P_o}\right)^3, \tag{10}$$

$$Y_P = 0.3 D_\mu^{0.65}. \tag{11}$$

Thus, the volumetric ratio of lateral FRP reinforcement in PVC-FRP columns may be calculated using the following equation

$$\rho_{com} = \frac{0.036 f'_c}{f_{com}}\left[0.6 + 0.4\left(\frac{P}{A_c f'_c}\right)^3\right] D_\mu^{0.65}, \tag{12}$$

where A_c is the area of the concrete core, P is the applied axial load and P_o is the maximum strength of unconfined concrete ($P_o = A_c f'_c$), and D_μ is the ductility index of tested specimens.

For concrete confined with PVC-FRP tubes, the ductility requirement depends on the category used in the design. Based on our experimental results, three categories were adopted. Category I for low ductility ($D_\mu < 1$), category II for moderate ductility ($1 < D_\mu < 10$), and category III for high ductility ($D_\mu > 10$).

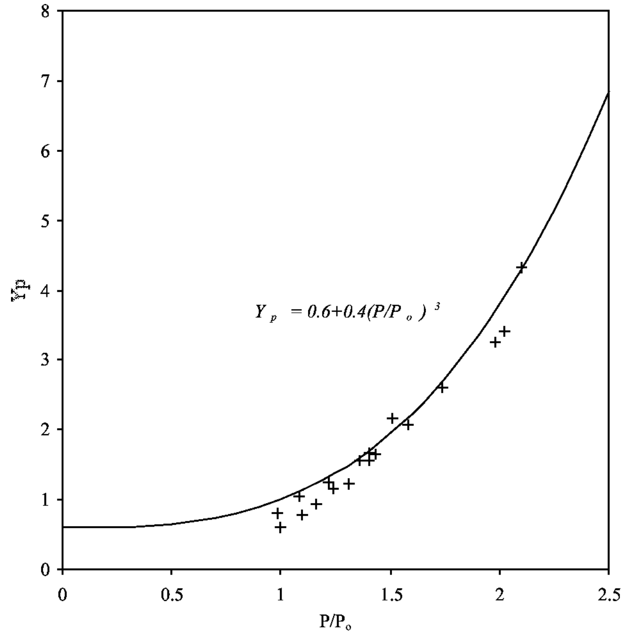

Figure 6. Required amount of FRP hoops as affected by axial load.

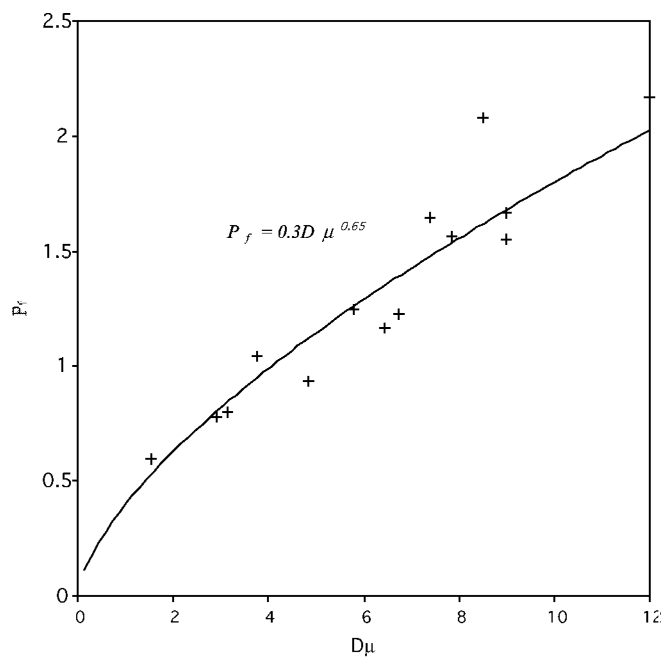

Figure 7. Required amount of FRP hoops as affected by ductility index.

3.3. Design load of PVC-FRP confined concrete

For axially loaded concrete columns, the ACI code requires that

$$\phi P_n \geqslant \sum \psi_i L_i, \tag{13}$$

where ϕ = strength reduction factor, P_n = ultimate nominal load, L_i = the i-th of various service loads acting simultaneously on the member, e.g. dead, live and wind, and ψ_i = load factor pertinent to degree of uncertainty of L_i.

By using equation (13) and introducing a capacity-reduction factor, the ultimate nominal load of concrete confined with FRP can be estimated by

$$\phi_{\mathrm{FRP}} P_n = \phi_{\mathrm{FRP}} \left[\frac{69.5 f_{\mathrm{com}} \rho_{\mathrm{com}}}{f_{\mathrm{c}}' D_{\mathrm{u}}^{0.65}} - 1.5 \right]^{1/3} A_{\mathrm{c}} f_{\mathrm{c}}' \tag{14}$$

where ϕ_{FRP} is the strength reduction factor of concrete confined with FRP.

For concrete confined with steel spirals, the ACI code recommends a value of 0.75 for ϕ. However, the assignment of specific values to ϕ_{FRP} factors for FRP confined concrete is an ambiguous task. Karbhari and Sieble [4] proposed a procedure for determining the ϕ_{FRP} factors associated with the FRP material properties alone (not including the application type, governing failure mode, etc.):

$$\phi_{\mathrm{FRP}} = \phi_{\mathrm{MAT}} \phi_{\mathrm{PROC}} \left[\frac{\phi_{\mathrm{CURE}} + \phi_{\mathrm{LOC}}}{2} \right] \phi_{\mathrm{DEGR}}, \tag{15}$$

where ϕ_{MAT} is a factor that accounts for the deviation and/or level of uncertainty of material properties from the specified characteristic values, ϕ_{PROC} is a factor that accounts for variation due to the processing method used, ϕ_{CURE} is a factor that accounts for variation due to degree of cure achieved, ϕ_{LOC} is a factor to account for the uncertainty in performance level due the location of processing, and ϕ_{DEGR} is a factor that accounts for changes in material properties over time and due to environmental effects.

Until further research provides more complete data concerning the FRP system types, the ϕ_{FRP} factors for concrete confined with FRP can be assumed as 0.6 for CFRP, 0.45 for AFRP and 0.25 for GFRP [5, 6].

Once the required percentage of FRP confining materials is determined, the FRP hoop spacing may be selected using the following expression

$$s = \frac{4A_{\mathrm{com}}}{\rho_{\mathrm{com}} d_{\mathrm{c}}}. \tag{16}$$

One can assume a cross-section for the FRP hoop and solve for the pitch required. It was found that when the volume of confining fiber increases beyond a certain limit, the ductility of PVC-FRP decreases. Based on this finding, a conservative limitation on fiber volume ratio ρ_{com} was adopted for all three confining materials used in this investigation.

$$\rho_{\mathrm{com}_{\min}} = 0.2\%, \tag{17a}$$

$$\rho_{\text{com}_{\max}} = 0.8\%. \tag{17b}$$

When the fiber volume ratio ρ_{com}, obtained from equation (12), is greater than $\rho_{\text{com}_{\max}}$, this indicates that longitudinal reinforcement such as steel or FRP bars is needed; therefore, the fiber volume ratio ρ_{com} can be estimated as

$$\rho_{\text{com}} = \frac{0.036 f_c'}{f_{\text{com}}}\left[0.6 + 0.4\left(\frac{P - f_y A_{\text{st}}}{A_c f_c'}\right)^3\right] D_\mu^{0.65}, \tag{19}$$

where A_{st} is the cross sectional area of the longitudinal reinforcement and f_y is the compressive strength of the longitudinal reinforcement.

3.4. Verification of the proposed design equation

The proposed design approach was used to estimate the ultimate compressive load of concrete columns confined with PVC-FRP tubes. At failure, the specimens exhibited moderate ductility; thus, the ductility index in equation (14) was assumed to be 5. The ultimate load of the specimens was calculated using equation (14) based on the mechanical properties of the FRP hoops and the concrete core. Table 3 shows a comparison between the experimental and predicted ultimate loads. As can be seen from Table 3, good agreement with the test data was obtained.

Table 3.
Comparison between experimental and theoretical ultimate load values

Specimen	Volume of fiber (%)	Experimental P_{uexp} (kN)	Predicted P_{upred} (kN)	$P_{\text{uexp}}/P_{\text{upred}}$
As30	0.5	578.15	588.28	0.98
As38	0.42	520.21	541.28	0.96
As40	0.4	495.33	526.5	0.95
As50	0.32	444.04	486.81	0.91
As60	0.27	396.17	424.11	0.94
As78	0.2	358.96	340.33	1.05
Gs30	0.56	507.25	529.00	0.96
Gs38	0.44	477.27	465.27	1.02
Gs40	0.42	450.52	452.15	0.99
Gs50	0.34	422.17	397.10	1.06
Gs60	0.28	390.56	340.33	1.14
Cs30	0.78	753.58	815.18	0.93
Cs38	0.62	737.37	746.61	0.99
Cs40	0.58	721.17	727.24	0.99
Cs50	0.47	635.27	667.85	0.95
Cs60	0.39	551.00	616.65	0.90
Cs78	0.3	507.25	547.56	0.93

4. CONCLUSIONS

Tests were performed to study the behavior of axially loaded concrete columns confined with PVC-FRP tubes. The influence on column strength and axial and lateral strains of FRP volumetric ratio, the type of FRP composite material, and the spacing between the FRP strips were evaluated. The hybrid tubes can provide an effective lateral confinement to the concrete core by increasing the strength and ductility of concrete. The confinement effectiveness diminishes, however, as the hoop spacing, s, increases. The stress–strain response of PVC-FRP tubes confined concrete is bilinear in both the axial and lateral directions. The first slope of the response depends on the concrete core, whereas the stiffness and the spacing control the second slope. The bend between the two slopes takes place at a stress level slightly higher than unconfined strength of the concrete core. The proposed design equation for concrete confined with PVC-FRP tubes depends on the ductility performance of the columns and the axial load. The proposed design equation produces good comparison with the experimental results.

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REFERENCES

1. R. V. Shitindi, Behavior of concrete cylinders confined with FRP spirals, PhD thesis, Kyoto University, Japan (1999).
2. H. Toutanji and M. Saafi, Behavior of concrete columns encased in PVC-FRP composite tubes, in: *Advanced Materials in Bridges and Structures* (*ACMBS-III*), J. Humar and A. G. Razaqpur (Eds), pp. 809–817, Ottawa, Canada (2000).
3. ACI Committee 318, *Building Code Requirement for Reinforced Concrete*, ACI 319-95, American Concrete Institute, Detroit (1995).
4. V. M. Karbhari and F. Sieble, Design considerations for the use of fiber-reinforced polymeric composites in the rehabilitation of concrete structures, in: *Proceedings International Concrete Repair Institute Symposium on FRP and Strengthening of Concrete*, Pleasanton, California (1998).
5. P. L. Kelley and M. L. Brainerd, Engineering guidelines for the use of Sika CarbDur (CFRP) laminates for structural strengthening of concrete structures. Corp., Lyndhurst NJ (1997).
6. P. L. Kelley, M. L. Brainerd and M. Vatovec, Design philosophy for structural strengthening with FRP, *ACI Concrete International* (February), 77–82 (2000).