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Empirical Design Equations For PVC-Concrete Composite Columns

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Abstract: *In this research, an attempt is made to propose empirical design equations to predict the ultimate strength of PVC-concrete composite columns (a new type of composite columns consisting of a PVC tube filled with concrete). The empirical equations proposed in the present study are capable of predicting the values of ultimate loads of PVC-concrete composite columns in a good agreement with the experimental values. The average values of ratios of experimental to predicted values of ultimate loads are 0.990 and 0.991 for the first and second proposed empirical equations, respectively.*

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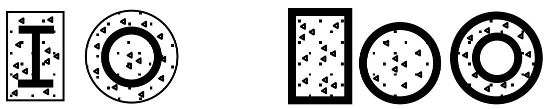
I. Introduction

A composite column is a column constructed from two or more different materials in such a way that they work together in resisting stresses and strains induced by forces or conditions external to the column. However, the term 'composite column' is normally used to indicate applications like either concrete-encased sections or concrete-filled tubes of rectangular or circular cross-section (Fig. 1). Rapid deterioration of infrastructures enhances the demand on rehabilitating and retrofitting existing concrete columns and piles in building and bridge substructures. Recently, attempts are made toward alternative columns (or piles) which make use of FRPs, recycled plastics, and other materials to replace and/or protect steel or concrete, with the intent to produce columns (or piles) that have lower maintenance costs and longer service lives than conventional columns (or piles), especially when used in marine applications and other corrosive environments.

Another alternative to the advanced composite materials tubing is the commercially available Polyvinyl Chloride (PVC) pipes. The use of PVC tubes in composite columns and piles in light construction will eliminate the reinforcing steel and the formwork. PVC is a thermoplastic material used to make long-lasting products, often with a life expectancy exceeding 60 years. This provides some main attributes that make it useful in the construction of certain structures exposed to corrosive environments. PVC pipe is a combination of plastic and vinyl materials; as such a pipe made from PVC is durable to the extreme. Fundamentally, PVC pipe is hard to damage and lasts for long periods of time without the need for replacement and having lightweight, which permits easy handling, and impermeable to gases and fluids and durable. Hence these pipes are used extensively in the construction industry.



(a) concrete-encased **(b) concrete-filled**

Figure (1) Different types of composite columns

Very few authors have studied the structural behavior of PVC-concrete composite columns (columns consisting of a PVC tube filled with concrete) [1-3]. However, no work is found related to the prediction of the ultimate strength of these composite columns. The main objective of the present study is to predict the ultimate strength of PVC-concrete composite columns by proposing a design method for predicting the strength of these columns.

II. Proposed Design Equations

In this study, two design approaches are proposed. In the first approach, Approach I, the PVC tube is treated as an external reinforcement to the concrete core in the PVC-concrete composite column, while in the second approach, Approach II, the PVC tube is treated as an individual component of the composite column. Both approaches were based on the experimental results of twenty PVC-concrete composite columns obtained by Saadoon [3]. While the experimental results of Kurt [1] and Marzouck and Sennah [2] were used for verification of the proposed design equations. All these experimental results are given in Table (1).

Table (1) Actual (experimental) data for PVC-concrete composite columns

Column No.	Cylinder compressive strength (f'_c) (MPa)	Tube diameter (D) (mm)	Tube thickness (t) (mm)	Length (L) (mm)	Slenderness ratio (L/D)	Ultimate compressive load (P) (kN)	Reference
1	20.6	114.3	6.35	203.2	1.8	315.1	Kurt [1]
2	20.6	114.3	6.35	457.2	4.0	309.3	
3	36	106	3	270	2.5	318.0	Marzouck and Sennah [2]
4	36	106	3	416	3.9	311.0	
5	36	106	3	562	5.3	291.0	
6	36	106	3	758	7.2	287.0	
7	24	110	3.2	220	2.0	278.7	Saadoon [3]
8	24	110	3.2	400	3.6	272.3	
9	24	110	3.2	600	5.5	265.6	
10	24	110	3.2	800	7.3	254.3	
11	24	110	3.2	1000	9.1	240.1	
12	24	110	5.3	220	2.0	331.6	
13	24	110	5.3	400	3.6	327.0	
14	24	110	5.3	600	5.5	322.3	
15	24	110	5.3	800	7.3	316.3	
16	24	110	5.3	1000	9.1	300.7	
17	40	110	3.2	220	2.0	369.2	
18	40	110	3.2	400	3.6	360.8	
19	40	110	3.2	600	5.5	350.3	
20	40	110	3.2	800	7.3	338.6	
21	40	110	3.2	1000	9.1	328.9	
22	40	110	5.3	220	2.0	438.0	
23	40	110	5.3	400	3.6	428.6	
24	40	110	5.3	600	5.5	420.7	
25	40	110	5.3	800	7.3	408.1	
26	40	110	5.3	1000	9.1	391.2	

2.1. Approach I

In PVC-concrete composite columns, the reinforcement ratio ρ_t is proposed in this work to be taken as the ratio of the cross-sectional area of PVC tube to the area of the concrete core. For large diameter-to-thickness ratios of PVC tube, this ratio can be reduced to:

$$\rho_t = \frac{4t}{D}, \tag{1}$$

where t and D are the wall thickness and the external diameter of the PVC tube, respectively. However, PVC tubes are available with different tensile strengths (according to the manufacturers specifications) and also concrete of different strengths may be used to fill these tubes, Therefore a parameter, called reinforcement index ω, is introduced instead of ρ_t to allow for comparing composite columns of different PVC tubes and concrete strengths. The reinforcement index is defined as the reinforcement ratio ρ_t multiplied by the ratio of the axial tensile strength of the PVC tube f_t to the concrete cylinder compressive strength f'_c as follows:

$$\omega = \rho_t \frac{f_t}{f'_c}. \tag{2}$$

By substituting Eq. (1) into (2), the reinforcement index ω can be calculated by:

$$\omega = \left(\frac{4t}{D}\right)\frac{f_t}{f'_c}. \tag{3}$$

The ultimate strength (P_{cc}) of a PVC-concrete composite column is normalized with respect to the maximum strength of a corresponding concrete column ($P_\circ$) in a dimensionless format as follows:

$$\overline{P} = \frac{P_{cc}}{P_o}. \tag{4}$$

The relationship between the reinforcement index ω and the normalized strength $\overline{P}$ may be assumed of the form:

$$\omega = f\left(\overline{P}\right). \tag{5}$$

After investigating several possible forms of expressions for the reinforcement index ω (Eq. (5)) of PVC-concrete composite columns, the following expression was obtained based on the experimental results:

$$\omega = a_1 + a_2\left(\frac{P_{cc}}{P_o}\right)^{a_3}, \tag{6}$$

where a_1, a_2, and a_3 are constants to be determined empirically, P_{cc} is the ultimate strength of composite column, and $P_\circ$ is the maximum strength of concrete columns ($P_\circ = A_c f'_c$). Using the results of compact specimens ($L/D \leq 3$), a regression analysis was performed to find constants a_1 and a_2 for selected values of a_3 between 1 and 3.

The expression for reinforcement index ω, evaluated by the best-fit curve from the regression analysis shown in Fig. (2), is

$$\omega = -0.017 + 0.134\left(\frac{P_{cc}}{P_o}\right)^2. \tag{7}$$

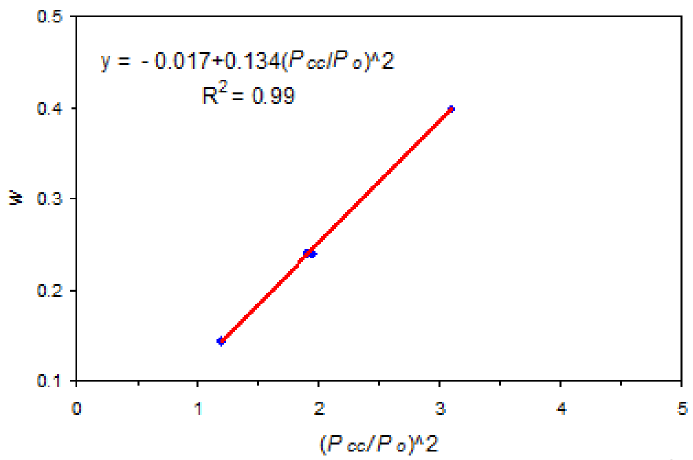


Figure (2) Variation of reinforcement index with ($P_{cc}/P_\circ$)^2

Thus, from Eq. (2), the reinforcement ratio ρ_t in PVC-concrete composite columns may be calculated using the following equation:

$$\rho_t = \frac{f'_c}{f_t}\left\{0.134\left(\frac{P_{cc}}{A_c f'_c}\right)^2 - 0.017\right\}, \tag{8}$$

where A_c is the area of the concrete core. Once the required percentage of PVC reinforcement is determined, the PVC tube thickness may be selected using the following expression:

$$t = \frac{D\rho_t}{4}, \tag{9}$$

Then one can assume a diameter for the PVC tube and solve for the thickness required.
From Eq. (8), the ultimate nominal load of PVC-concrete composite columns can be estimated by:

$$P_{cc} = \left[\frac{7.463\rho_t f_t}{f'_c} + 0.127\right]^{1/2} A_c f'_c. \tag{10}$$

Equation (10), which is proposed for the ultimate strength of compact columns, can be used for slender columns, where *L/D* > 3, by introducing a modification factor that takes into account the effect of column slenderness ratio. Such modification must be based on experimental results. It was found that a modified expression for the ultimate strength may be assumed in the form of:

$$P_{slender} = P_{compact}\, f(L/r), \tag{11}$$

where $P_{slender}$ is the ultimate strength of the slender column, and $P_{compact}$ is the ultimate strength of the corresponding short column, and (*L/r*) is the column slenderness ratio of the slender specimen.
Figure (3) shows the normalized ultimate strength (P_{cc}/P) versus the slenderness ratio (*L/r*) for the experimental results of the present study, where P_{cc} is the ultimate strength of the slender specimen and *P* is the ultimate strength of the corresponding short specimen. Based on the figure, the linear Eq. (12) is proposed for the relation between the normalized strength and the slenderness ratio by regression analysis. A good correlation is noted with R^2 = 91%:

$$\frac{P_{cc}}{P} = \left[1.036 - 0.004\left(\frac{L}{r}\right)\right]. \tag{12}$$

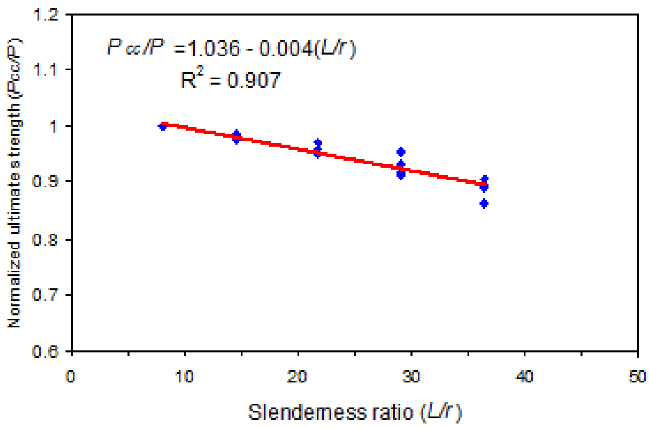


Figure (3) Normalized ultimate strength versus slenderness ratio

Thus, From Eq. (10) and replacing the slenderness ratio by its value for circular columns, the ultimate strength of slender PVC-concrete composite columns can be estimated by:

$$P_{cc} = \left[\frac{7.463\rho_t f_t}{f'_c} - 0.127\right]^{1/2}\left[1.036 - 0.004\left(\frac{4L}{D}\right)\right]A_c f'_c \cdot \tag{13}$$

2.2. Approach II

When full interaction between the concrete core and the PVC tube in PVC-concrete composite columns is assumed, the theoretical ultimate load resistance (N) for the compact columns, where $L/D \leq 3$, can be determined as:

$$N = P_o + P_t, \tag{14}$$

where P_o and P_t are the maximum resistance of the concrete core and the PVC tube, respectively, and are calculated as:

$$P_o = A_c f'_c, \tag{15}$$

$$P_t = A_t f_t, \tag{16}$$

where A_c and A_t are the cross-sectional area of the concrete core and the PVC tube, respectively, f'_c is the concrete cylinder compressive strength, and f_t is the ultimate strength of the PVC tube (it is assumed that the behavior of the tube material is same in tension and compression).

A formula relating the experimental ultimate strength of composite columns (P_{cc}) to the theoretical ultimate strength (N) may be defined in the form:

$$P_{cc} = f(p)N, \tag{17}$$

where $f(p)$ is an empirical function includes the main parameters which affect the strength of PVC-concrete composite columns. The main parameters that are likely to influence the ultimate strength of compact columns are the following; (i) wall thickness to diameter ratio of the PVC tube, t/D; (ii) ultimate tensile strength of the PVC tube, f_t; (iii) compressive strength of concrete, f'_c; (vi) cross-sectional area of the concrete core.

Thus, a formula relating P_{cc} to N may be defined in the form:

$$P_{cc} = k\left(\frac{tf_t}{Df'_c}\right)^n N, \tag{18}$$

where k and n are coefficients to be determined from regression analysis.

Regression analysis is performed for the purpose of this study between (P_{cc}/N) and (tf_t/Df'_c). Figure (4) shows the results for such regression analysis. As shown in this figure, the correlation coefficient is 98%, k = 2.1, and n = 0.24. Thus, the ultimate strength of compact PVC-concrete composite columns can be calculated by:

$$P_{cc} = 2.1\left(\frac{tf_t}{Df'_c}\right)^{0.24}\left[A_c f'_c + A_t f_t\right]. \tag{19}$$

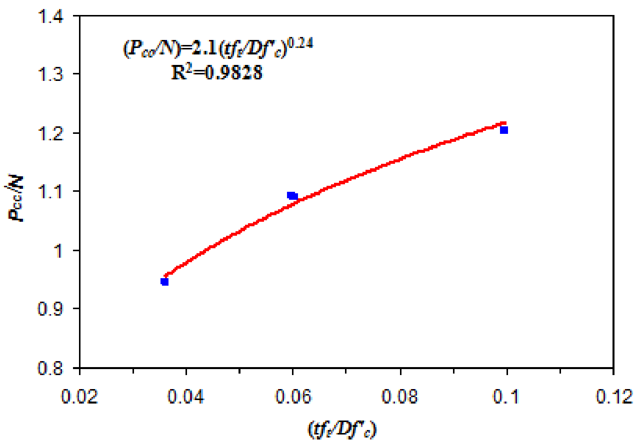


Figure (4) Variation of (P_{cc}/N) with (tf_t/Df'_c)

As in Approach I, the empirical equation Eq. (14), which proposed for the ultimate strength of compact columns, can be used for slender columns, where L/D > 3, by introducing a modification factor that takes into account the effect of column slenderness ratio. Consequently, the same formula of Approach I (Eq. (12)), which is based on experimental results and relates the ultimate strength of slender specimens to the ultimate strength of compact specimens, can be used here in Approach II. Thus, the ultimate strength of slender PVC-concrete composite columns can be calculated by:

$$P_{cc} = 2.1\left(\frac{tf_t}{Df'_c}\right)^{0.24}\left[1.036 - 0.004(\frac{4L}{D})\right]\left[A_c f'_c + A_t f_t\right]. \tag{20}$$

2.3. Verification of the proposed design equations

The proposed design equations were used to estimate the ultimate compressive load of PVC-concrete composite columns. The experimental results conducted by Kurt [1] and Marzouck and Sennah [2], which are listed in Table (1), were used for verification of the proposed design equations. The ultimate load of the columns was calculated, by using Eqs. (10) and (13) for Approach I and Eqs. (19) and (20) for Approach II, based on the mechanical properties of the PVC tube and the concrete core. Table (2) shows a comparison between the experimental and predicted ultimate loads. As can be seen from this table, good agreement with the test data is obtained. The average values of ratios of experimental to predicted ultimate loads are 0.990 and 0.991 for Approach I and Approach II, respectively.

Figures (5) and (6) show the regression analysis of the results of the proposed empirical equations of Approach I and Approach II, respectively. The total available 26 specimens of Table (1) are considers. As shown in these figures, R^2 = 0.9882 and 0.9893 for Approach I and II, respectively. These values indicate a good agreement between the predicted and the actual values.

Table (2) Actual and predicted ultimate load capacity using empirical equations

Column No.	Length to diameter ratio (L/D)	Actual ultimate compressive load (P_a) (kN)	Predicted ultimate compressive load (P_p) (kN)			
			Approach I		Approach II	
			P_p	P_a / P_p	P_p	P_a / P_p
1	1.78	315.1	308.8	1.020	315.6	0.998
2	1.78	309.3	300.2	1.030	304.9	1.014
3	2.55	318.0	322.4	0.986	320.0	0.994
4	3.92	311.0	313.8	0.991	309.7	1.004
5	5.3	291.0	306.7	0.949	303.3	0.959
6	7.15	287.0	297.2	0.966	293.1	0.979

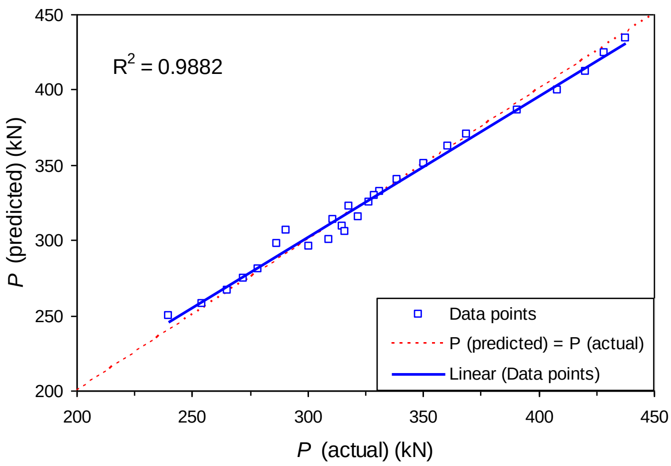


Figure (5) Regression analysis between predicted and actual values (empirical equations-Approach I)

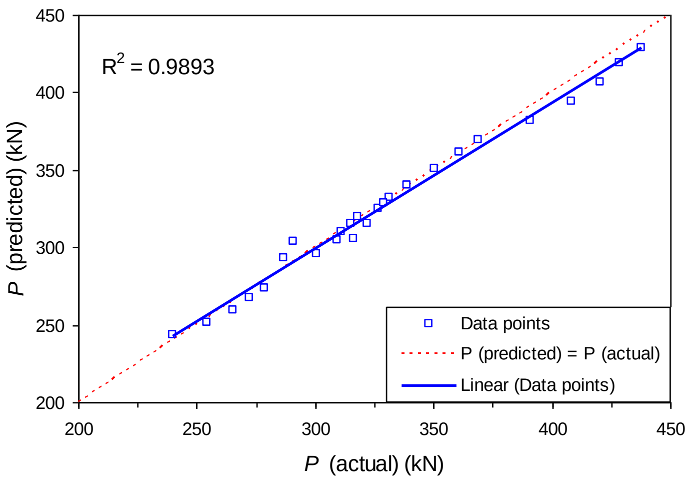


Figure (6) Regression analysis between predicted and actual values (empirical equations-Approach II)

III. Design examples

3.1 Example 1

Design a circular PVC-concrete composite column subjected to concentric axial load.

Given: Axial load P=450 kN, concrete cylinder compressive strength f'c=35 MPa, ultimate tensile strength of PVC tube ft=40 MPa.

Required: Diameter of column and thickness of PVC tube.

Solution:

Assume concrete core diameter =100 mm

Using Eq. (8)

$$\rho_t = \frac{f'_c}{f_t}\left\{0.134\left(\frac{P_{cc}}{A_c f'_c}\right)^2 - 0.017\right\} = \frac{35}{40}\left\{0.134\left(\frac{450\times10^3}{\frac{\pi}{4}(100)^2\times35}\right)^2 - 0.017\right\} = 0.299,$$

but $\rho_t = \dfrac{4t}{D} = \dfrac{4t}{(100+2t)}$ from which $t = 8.79mm$.

Thus, use t=8.8 mm and circular column of outside diameter=117.6 mm.

3.2 Example 2

Verify the answer of example 1 using the procedure in Approach II.

Given: Column outside diameter =117.6 mm, thickness of PVC tube t=8.8 mm, concrete cylinder compressive strength f'c=35 MPa, ultimate tensile strength of PVC tube ft=40 MPa.

Required: Check adequacy of the section for the given loading using the procedure in

Approach II.

Solution:

Using Eq. (19)

$$P_{cc} = 2.1\left(\frac{tf_t}{Df'_c}\right)^{0.24}\left[A_c f'_c + A_t f_t\right],$$

$$= 2.1\left(\frac{8.8\times40}{117.6\times35}\right)^{0.24}\left[\frac{\pi}{4}\{(117.6-2\times8.8)^2\times35 + ((117.6)^2-(117.6-2\times8.8)^2)\times40\}\right]$$

$$= 460kN > 450kN.$$

Thus, the section is adequate for the given loading.

3.3 Example 3

Check for the adequacy of load capacity of a circular PVC-concrete composite column against given loading.

Given: Column outside diameter =200 mm, thickness of PVC tube t=14.9 mm, column length L=2500 mm, axial load P=1500 kN, concrete cylinder compressive strength f'c=35 MPa, ultimate tensile strength of PVC tube ft=50 MPa.

Required: Check whether the section is sufficient or not.

Solution:

$L/D = 12.5 > 3,$ the given column is a slender column.

Approach I,

From Eq. (1)

$$\rho_t = \frac{4t}{D} = \frac{4 \times 14.9}{200} = 0.298 \,,$$

From Eq. (13)

$$P_{cc} = \left[\frac{7.463 \rho_t f_t}{f_c'} - 0.127 \right]^{1/2} \left[1.036 - 0.004 \left(\frac{4L}{D} \right) \right] A_c f_c' \,,$$

$$= \left[\frac{7.463 \times 0.298 \times 50}{35} - 0.127 \right]^{1/2} \left[1.036 - 0.004 \left(\frac{4 \times 2500}{200} \right) \right] \left[\frac{\pi}{4} (200 - 2 \times 14.9)^2 \times 35 \right]$$

$$= 1162.6 kN < 1500 kN \,.$$

Thus, the section is insufficient for the given loading.

Approach II,

From Eq. (20)

$$P_{cc} = 2.1 \left(\frac{t f_t}{D f_c'} \right)^{0.24} \left[1.036 - 0.004 \left(\frac{4L}{D} \right) \right] \left[A_c f_c' + A_t f_t \right],$$

$$= 2.1 \left(\frac{14.9 \times 50}{200 \times 35} \right)^{0.24} \left[1.036 - 0.004 \left(\frac{4 \times 2500}{200} \right) \right] [\frac{\pi}{4} \{ (200 - 2 \times 14.9)^2 \times 35 + ((200)^2 - (200 - 2 \times 14.9)^2) \times 50 \}]$$

$$= 1260.8 kN < 1500 kN \,.$$

Thus, the section is insufficient for the given loading.

IV. Conclusions

The empirical equations proposed in the present study were used to estimate the ultimate compressive load of PVC-concrete composite columns. The average values of ratios of experimental to predicted ultimate loads are 0.990 and 0.991 for Approach I and Approach II, respectively. These values indicate a good agreement between the predicted and the actual values. Therefore, the proposed empirical equations are capable of predicting the values of ultimate loads of PVC-concrete composite columns.

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