Structural Behaviour of Slender PVC Composite Columns Filled with Concrete

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Abstract. In this study, the performance of slender PVC-concrete columns was investigated using variables including concrete filling compressive strength, column slenderness ratio, and PVC section compactness ratio. The specimens were subjected to uniaxial compression in two loading modes; in the first mode, a PVC tube was utilised to enhance the concrete core as a composite element, and in the second mode, a PVC tube was utilised to confine the concrete core only. Nine PVC-concrete sections with different polyvinyl chloride tube characteristics and different filled concrete compressive strengths were considered in several fabricated slender PVC-concrete columns. The column lengths were varied so that overall column buckling could be investigated. The results showed that the composite mode columns exhibited more strength improvement than those in confined mode. Experimentally predicted effective flexural stiffness was thus normalised in terms of filling concrete stiffness and PVC tube stiffness, and the normalised results indicated that effective flexural stiffness depends on the mode (confining or composite), PVC and filling concrete strength, and column slenderness ratio.

Keywords: slender column, composite mode, confining mode, PVC tube, effective flexural stiffness, column slenderness, section compactness.

1. Introduction
Optimisation among various materials and applicable construction techniques with the objective of implementing structures at minimum cost that satisfy requirements is extremely desirable. This often necessitates utilising two or more materials together to combine their desirable properties to produce a specific structural element known as a composite element. The performance of such elements is thus of major interest for researchers. Developing slender columns that utilise composite materials offers economic cost benefits in terms of meeting architectural design demands, and size reduction in conjunction with challenges related to geometric nonlinearity and material nonlinearity should be taken into account in designing such items. The efficiency of construction using PVC tubes with concrete is related to the availability of plastic pipe as a convenient slender segment offering an alternative to reinforcement with steel; plastic is characterised by high ductility, and thus using PVC as a casing tube or confining mechanism for a concrete core improves system ductility. In addition, PVC is highly resistant to environmental deterioration and so protects the concrete. Fundamentally, PVC pipe is hard to damage, durable, and lightweight, as well as permitting easy handling and installation. However, although such pipes are utilised widely in the construction industry, studies on the use of PVC in composite columns are few, though some researchers [1-6] have worked to develop composite columns using non-metallic tubes using commercially available plastic pipes filled with concrete, and the aim of these studies has generally been to evaluate the upgrading of strength capacity in short composite columns and the effect of the slenderness ratio on ultimate strength.
The most efficient structural sections used in composite columns are steel hollow sections filled with plain concrete, which upgrades the overall section capacity and offers a number of advantages such as developing greater strength and stiffness due to combining the tensile properties of steel with the compression properties of concrete, generating ductility enhancement in addition to size reduction [7-12]. Many studies have thus been concerned with confinement concepts including retrofitting shell-like FRP casings to concrete with or without steel reinforcement, mainly intended to improve the failure strength of concrete by increasing ductility and energy absorption by selecting appropriate casing materials. Several researchers have also tested FRP-confined RC columns to examine the effects of height-to-diameter ratios [13-18]. From previous studies, it is obvious there is a difference in effect between composite concepts and confining concepts. Thus, a comparison of these was considered in the current study. The major purpose of this experimental program, however, was to assess the effect of column slenderness ratio on strength capacity and ductility ability in both composite and confining columns. The parameters of interest were thus effective slenderness, applied loading style, PVC casing geometrical properties, and the compressive strength of concrete filling. The flexural effective stiffness of the composite specimens was also investigated.

**Notation**

Codes used throughout this research:

- PVC Polyvinyl chloride.
- $f_{yp}$ PVC yield tensile stress, MPa.
- $f_c$ Concrete compressive strength, MPa.
- $f_r$ Radial stress, MPa.
- $L$ Specimens length, mm.
- $t_p$ PVC tube thickness, mm.
- $D$ Outer section diameter, mm.
- $A_c$ Concrete core cross section area, mm$^2$.
- $A_p$ PVC tube section area, mm$^2$.
- $\lambda$ Slenderness ratio, $L/r$.
- $\lambda'$ Section element compactness ratio, $D/tp$.
- $P_p$ Ultimate strength of PVC-concrete columns, kN.
- $P_e$ Euler buckling strength, kN.
- $P_c$ Ultimate strength of concrete columns, kN.
- $P_{cm}$ Experimental plastic capacity of composite mode columns, kN.
- $P_{cn}$ Experimental plastic capacity of confining mode columns, kN.
- $E_I$ Effective stiffness.
- $E_c$ Concrete modulus of elasticity, MPa.
- $E_p$ PVC modulus of elasticity, MPa.
- $I_c$ Concrete core second moment inertia, mm$^4$.
- $I_p$ PVC tube second moment inertia, mm$^4$.
- $\gamma_2, \gamma_1$ Coefficient depending on loading mode, material strength and slenderness ratio.
- $G$ Modulus of rigidity.

**2. Experimental Methodology**

**2.1 Materials**

All columns were vertically cast using normal weight ready-mixed concrete. The compressive strength of concrete was based on the average values of 150x300mm cylinders [19], and a splitting test was carried out to predict concrete rupture [20]. Concrete compressive strength for three different batches was used. The reference batch was batch II, which was used when considering other variables. Table 1 depicts the mixing proportions of the adopted batches of filling concrete, while Table 2 lists their mechanical characteristics. PVC pipes were used in both composite and confining modes and their mechanical properties are taken to be as listed manufacturer’s data sheet. Table 3 shows the mechanical properties of the PVC tubes used.
Table 1. Mixing Proportions of Filling concrete

| No. | Batch code | Max agg. size mm | Cement kg/m³ | Silica Fume % | Binder kg/m³ | Sand kg/m³ | Gravel kg/m³ | Superplasticizer kg/m³ | Water/Binder % |
|-----|------------|------------------|--------------|---------------|--------------|------------|-------------|------------------------|---------------|
| 1   | I          | 9.6              | 501.6        | 5             | 26.5         | 527.5      | 982.5       | 1274.5                 | 0.2           |
| 2   | II         | 9.6              | 501.6        | 10            | 53           | 527.5      | 982.5       | 1274.5                 | 0.2           |
| 3   | III        | 9.6              | 557.8        | 5             | 22.6         | 450        | 591.3       | 1087                   | 0.2           |

Table 2. Concrete properties

| Batch | Compressive strength, $f'_c$ | Unit weight $\gamma$, kN/m³ | Rupture modulus $f_t$, MPa |
|-------|-----------------------------|-----------------------------|-----------------------------|
| I     | 42.25                       | 23                          | 2.3                         |
| II    | 34.8                        | 23                          | 4.1                         |
| III   | 58.7                        | 23                          | 3.1                         |

Table 3. PVC properties

| Properties          | Units   | Value  |
|---------------------|---------|--------|
| Tensile strength at break | MPa     | 47.07  |
| Specific gravity    | g/cm³   | 1.43   |
| Elongation          | %       | 80%    |
| Modulus of elasticity | MN/m³  | 2000   |

2.2 Specimen Description

Nine PVC-concrete sections with different polyvinyl chloride tube characteristics and different concrete compressive strength were considered based on the fabrication of 11 slender PVC-concrete composite columns, 11 slender plain concrete columns confined by PVC tubes, 4 slender PVC tubes without concrete filling and 5 long plain concrete cores without PVC casing. Specimens of the combined sections were tested under compressive uniaxial loading in two different modes as determined by PVC tube use (composite or confining). In the Composite mode, PVC was utilized as a full external enhancing material associated with concrete resisting applied loads directly, while in the Confining mode, PVC was utilized for confinement only. The major purpose of the experimental studies was to assess the effect of column slenderness ratios on strength capacity and ductility ability in composite and confining columns. The column lengths were varied so that overall column buckling could be investigated. Sectional definitions of the considered specimens are depicted in Figure 1, and typical configurations of the columns under different loading conditions are shown in Figure 2. The overall set of testing specimens is shown in photo 1, and column descriptions are listed in Table 4, where the specimen matrix is classified into four groups according to PVC utilisation within the tested specimens (composite and confining modes), for full specimens and columnar constituents (PVC, concrete core) of corresponding lengths.
| No | Groups | Specimen | Section | $E_c$, MPa | $L_c$, mm | $D_{op}$, mm | $D_{io}$, mm | $A_g$, mm$^2$ | $I_c$, mm$^4$ | $r_c$, mm | $L/r$ | $L/D$ | $D/h$ | Description |
|----|--------|----------|---------|-----------|----------|-------------|-------------|-------------|-----------|---------|-------|-------|-------|----------------|
| 1  | G2     | SA2      |         | 3.6       | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 34.09 |       |        | Long PVC tube, without filling concrete |
| 2  |        | SB2      |         | 5.6       | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 3  |        | SC2      |         | 3.6       | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 13.39 |       |        |                       |
| 4  |        | SD2      |         | 5.6       | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 13.39 |       |        |                       |
| 5  | G4     | SA4      |         | 2.2       | 70.6     | 3913        | 19502418    | 70.6        | 15.58     | 15.58   |       |       |        | Long concrete columns, without plastic casing |
| 6  |        | SB4      |         | 3.6       | 67.8     | 3609        | 16587786    | 67.8        | 16.22     | 16.22   |       |       |        |                       |
| 7  |        | SC4      |         | 5.6       | 63.8     | 3195        | 13006258    | 63.8        | 17.24     | 17.24   |       |       |        |                       |
| 8  |        | SD4      |         | 3        | 57       | 2550        | 8286460.8   | 57          | 19.3      | 19.30   |       |       |        |                       |
| 9  |        | SE4      |         | 4.7      | 53.6     | 2255        | 6479310.8   | 53.6        | 20.52     | 20.52   |       |       |        |                       |
| 10 | G7     | SA7      | Section1 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 34.09 |       |        | Composite Slender PVC-Concrete Column |
| 11 |        | SB7      | Section2 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 12 |        | SC7      | Section3 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 13.39 |       |        |                       |
| 13 |        | SD7      | Section4 | 5.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 14 |        | SE7      | Section5 | 5.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 15 |        | SF7      | Section6 | 3        | 63       | 3116        | 12366074    | 63          | 17.46     | 17.46   | 21.00 |       |        |                       |
| 16 |        | SG7      | Section7 | 4.7      | 63       | 3116        | 12366074    | 63          | 17.46     | 17.46   | 21.00 |       |        |                       |
| 17 |        | SJ7      | Section8 | 3.6      | 63       | 3116        | 12366074    | 63          | 17.46     | 17.46   | 21.00 |       |        |                       |
| 18 |        | SK7      | Section9 | 3.6      | 63       | 3116        | 12366074    | 63          | 17.46     | 17.46   | 21.00 |       |        |                       |
| 19 |        | SA8      | Section1 | 2.2      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 34.09 |       |        | Confined slender PVC-Concrete Column |
| 20 |        | SB8      | Section2 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 21 |        | SC8      | Section3 | 5.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 13.39 |       |        |                       |
| 22 |        | SD8      | Section4 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 23 |        | SE8      | Section5 | 5.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 24 |        | SF8      | Section6 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 25 |        | SG8      | Section7 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 26 |        | SH8      | Section8 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 27 |        | SI8      | Section9 | 3.6      | 75       | 4416        | 24837891    | 75          | 14.67     | 14.67   | 20.83 |       |        |                       |
| 28 |        | SK8      | Section10| 3.6     | 63       | 3116        | 12366074    | 63          | 17.46     | 17.46   | 21.00 |       |        |                       |

Table 4. Specimen Matrix
**Figure 1.** Sectional definitions of considered specimens

| Section | 
|---------|
| 1       |
| $f_c = 42.25$ MPa |
| D = 75 mm |
| $t = 2.2$ mm |
| Related specimens: SA5, SA6, SA7 and SA8 |

| Section | 
|---------|
| 2       |
| $f_c = 42.25$ MPa |
| D = 75 mm |
| $t = 3.6$ mm |
| Related specimens: SB5, SB6, SB7, SF7, SG7, SB8, SF8, and SG8 |

| Section | 
|---------|
| 3       |
| $f_c = 39$ MPa |
| D = 75 mm |
| $t = 5.6$ mm |
| Related specimens: SC5, SC6, SC7 and SC8 |

| Section | 
|---------|
| 4       |
| $f_c = 34.7$ MPa |
| D = 75 mm |
| $t = 3.6$ mm |
| Related specimens: SD7, and SD8 |

| Section | 
|---------|
| 5       |
| $f_c = 58.8$ MPa |
| D = 72 mm |
| $t = 3.6$ mm |
| Related specimens: SE7, and SE8 |

| Section | 
|---------|
| 6       |
| $f_c = 42.25$ MPa |
| D = 63 mm |
| $t = 3$ mm |
| Related specimens: SD5, SD6, SH7 and SH8 |

| Section | 
|---------|
| 7       |
| $f_c = 42.25$ MPa |
| D = 63 mm |
| $t = 4.7$ mm |
| Related specimens: SE5, SE6, SE7 and SE8 |

| Section | 
|---------|
| 8       |
| $f_c = 58.7$ MPa |
| D = 63 mm |
| $t = 3$ mm |
| Related specimens: SJ7and SJ8 |

| Section | 
|---------|
| 9       |
| $f_c = 58.8$ MPa |
| D = 63 mm |
| $t = 3$ mm |
| Related specimens: SK7 and SK8 |

**Figure 2.** Loading modes

a. Composite loading mode    b. Confining loading mode
2.3 Test Setup
The specimens were tested under uniaxial compressive loading using a 600 KN test machine up to failure. The tested specimens were set within a testing frame to allow both binned ends to be set. The test was performed in force control conditions. During the test, axial force and displacement were measured using dial gauges, and the lateral displacements at the middle height were measured by three surrounding gauges. In addition, the hoop strain at the middle height of the specimen was digitally recorded using an electrical strain gauge and recorded within a digital data collecting system. Both ends were strengthened with tightening steel rings to prevent failure at specimen ends [21,22]. Photo 2 shows the testing setup.

3. Results and Discussion

3.1 Comparative analysis
Table 5 briefly depicts the slender specimens’ comparative results. The sustained loading resistance of PVC composite concrete specimens exhibited more strength improvement (with respect to their constituent parts) than those of PVC confined concrete, with upgrading rates varying from 2.42 to 1.645 for composite modes versus 2.047 to 1.345 for confining modes. A similar comparison was observed in terms of ductility where specimens of PVC composite concrete exhibited more axial and
lateral deformations than the corresponding samples in confined mode. The assigned strength upgrades for composite modes related to the PVC acting as reinforcement while the enhancement in confined mode related to confining efficiency upgrading the filling concrete strength; the difference of the Poisson's ratios between PVC tubes and concrete clearly affects column resistance. The Poisson's ratio of PVC is about 0.41 in the elastic range and about 0.1 for concrete in the elastic range, though the latter can reach values of up to 0.75 in case of large strains [2]. Thus, in case of loading onto the entire section in the initial stage, the PVC tube and the concrete act separately due to the fast expansion of the PVC tube in the radial direction. Rapid further loading thus leads to lateral expansion greater than that of the PVC tube.

Figures 3 and 4 illustrate the ultimate strength variation of slender specimens of PVC in composite and confining modes compared with their constituents. The obtained test results for columns capacity are greater than the summation of strengths relating to the corresponding PVC and concrete cores. Although the slender PVC samples exhibited small resistance due to assigned elastic local buckling, the slender composite samples showed greater improvement.

3.2 Slenderness ratio effect ($L/r$)

Figures 5 depicts the influence of slenderness on the ultimate strength of slender composite and confined columns compared with their constituents. The figure reveals a trend of strength reduction due to the slenderness increasing for columns in both composite and confining modes. The column strength of composite mode samples is greater than for corresponding columns in the confining mode; however, in both cases, the strength of the columns is greater than the summation of their constituent parts’ strength.
| No | Groups | Specimens | Sections | Description | $L/r$ | $f_c'$ | $t_p$ | $D_{hp}$ | $f_e/f_{y}$ | $P_p$  | $P_c$  | $P_{cm}$ | $P_{cn}$ | $P_{cm}/P_{cn}$ | $P_{en}/P_c$ | $P_{cm}/P_{en}$ | $P_{cm}/P_{cn}$ |
|----|--------|-----------|----------|-------------|------|-------|------|--------|----------|-------|-------|--------|--------|-----------------|-------------|-----------------|----------------|
| 1  | 1       | SA2       | Sction#1 | Slender PVC tube, without filling concrete | 14.67 | 2.2   | 34.09 | 3.46   | 20.00    | ---   | 26.00 | 39.00  | 23.00  | 3.46            | 3.46        | 2.00            | 1.20            |
| 2  | G1      | SB2       | Sction#2 | Slender concrete columns | 14.67 | 3.6   | 20.83 | 6.73   | 20.00    | ---   | 26.00 | 39.00  | 23.00  | 3.46            | 3.46        | 2.00            | 1.20            |
| 3  | SC2     | SC3       | Sction#3 | Slender concrete columns | 14.67 | 5.6   | 13.39 | 11.98  | 39.00    | ---   | 20.00 | 15.01  | 23.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 4  | SD2     | SE4       | Sction#4 | Slender concrete columns | 17.46 | 3     | 13.40 | 5.91   | 23.00    | ---   | 15.01 | 26.08  | 18.99  | 3.46            | 3.46        | 3.46            | 3.46            |
| 5  | G2      | SA4       | Sction#1 | Slender PVC-Concrete Column- Composite mode | 29.34 | 42.25 | 56.70 | 5.00   | 88.50    | ---   | 50.07 | 70.80  | 54.80  | 20.00          | 20.00       | 20.00          | 20.00          |
| 6  | SB4     | SC4       | Sction#2 | Slender concrete columns | 29.34 | 42.25 | 53.13 | 5.54   | 5.54     | ---   | 5.54  | 5.54   | 5.54   | 3.46            | 3.46        | 3.46            | 3.46            |
| 7  | SC4     | SC5       | Sction#3 | Slender concrete columns | 29.34 | 42.25 | 49.58 | 2.10   | 2.10     | ---   | 2.10  | 2.10   | 2.10   | 3.46            | 3.46        | 3.46            | 3.46            |
| 8  | SC4     | SC6       | Sction#4 | Slender concrete columns | 29.34 | 42.25 | 34.50 | 0.43   | 0.43     | ---   | 0.43  | 0.43   | 0.43   | 3.46            | 3.46        | 3.46            | 3.46            |
| 9  | SC4     | SC7       | Sction#5 | Slender concrete columns | 29.34 | 42.25 | 13.39 | 11.00  | 11.00    | ---   | 11.00 | 11.00  | 11.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 10 | G3      | SA7       | Sction#1 | Slender PVC-Concrete Column- Composite mode | 14.67 | 42.25 | 22.00 | 34.09  | 22.00    | ---   | 22.00 | 22.00  | 22.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 11 | SB7     | SB8       | Sction#2 | Slender concrete columns | 14.67 | 42.25 | 36.20 | 20.83  | 12.00    | ---   | 12.00 | 12.00  | 12.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 12 | SC7     | SC8       | Sction#3 | Slender concrete columns | 14.67 | 42.25 | 56.13 | 14.00  | 14.00    | ---   | 14.00 | 14.00  | 14.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 13 | SD7     | SE7       | Sction#4 | Slender concrete columns | 14.67 | 42.25 | 26.80 | 20.83  | 26.80    | ---   | 26.80 | 26.80  | 26.80  | 3.46            | 3.46        | 3.46            | 3.46            |
| 14 | G4      | SE7       | Sction#1 | Slender PVC-Concrete Column- Composite mode | 14.67 | 42.25 | 22.00 | 34.09  | 22.00    | ---   | 22.00 | 22.00  | 22.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 15 | SF7     | SF8       | Sction#2 | Slender concrete columns | 14.67 | 42.25 | 36.20 | 20.83  | 12.00    | ---   | 12.00 | 12.00  | 12.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 16 | SG7     | SC9       | Sction#3 | Slender concrete columns | 14.67 | 42.25 | 56.13 | 14.00  | 14.00    | ---   | 14.00 | 14.00  | 14.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 17 | SB9     | SB10      | Sction#4 | Slender concrete columns | 14.67 | 42.25 | 26.80 | 20.83  | 26.80    | ---   | 26.80 | 26.80  | 26.80  | 3.46            | 3.46        | 3.46            | 3.46            |
| 18 | SC9     | SC10      | Sction#5 | Slender concrete columns | 14.67 | 42.25 | 22.00 | 34.09  | 22.00    | ---   | 22.00 | 22.00  | 22.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 19 | SC10    | SC11      | Sction#6 | Slender concrete columns | 14.67 | 42.25 | 36.20 | 20.83  | 12.00    | ---   | 12.00 | 12.00  | 12.00  | 3.46            | 3.46        | 3.46            | 3.46            |
| 20 | SK7     | SK8       | Sction#7 | Slender concrete columns | 14.67 | 42.25 | 22.00 | 34.09  | 22.00    | ---   | 22.00 | 22.00  | 22.00  | 3.46            | 3.46        | 3.46            | 3.46            |

Table 5. Slender Specimens' Comparative results
3.3 PVC section compactness effect ($D/t_p$)

PVC tube thickness, or tube compactness, leads to great increases in the ultimate strength and to reasonable increases in the corresponding strain of composite columns. This could be attributed to the effects of the confining PVC tubes, as a major effect of PVC is reinforcement with respect to overall section area. Figure 6 depicts the effects of PVC section compactness on the ultimate strength of slender specimens; the trend of PVC-concrete specimens is exhibited as decreasing as the slenderness of the section increase, which could be related to the failure mode of slender columns, itself extremely affected by local buckling.

![Figure 6. Effect of PVC section compactness on ultimate strength of slender specimens in confined columns as compared with their constituents](image)

3.4 Composite verse confining mode analysis

Figure 7 clearly depicts variation of strength upgrading ratios in composite and confining modes with respect to concrete strength. The improved strengths of slender composite specimens with respect to the confined specimens’ ratio ($P_{cm}/P_{cn}$) is greater than one; the same finding occurs in terms of improvements in the strength ratio with respect to concrete core, which could be related to the contribution of PVC casings as reinforcement in the composite mode.

![Figure 7. Variation of upgrading ratios of composite and confining modes in respect to slender concrete core specimens](image)

3.5 Load – Axial Deformation Response

Figure 8 illustrates the effect of section compactness ($D/t_p$) on load–axial deformation responses for different modes. Compacted PVC sections provide more strength enhancement in four different modes. The variation of loading mode’s effect on load-deformation response is significant, and strength upgrading for composite modes relate to PVC reinforcement in the confining mode is related to confining efficiency upgrading the filling concrete’s strength.
Figure 8. Load-axial deformation of specimens of $L/r = 14.67, f'_c = 42.25$, various $D/tp$.

Figure 9 depicts the effect of column slenderness ($L/r$) on load-axial deformation responses for different modes. As slenderness increases, loading capacity decreases, and the confining mode is more sensitive to slenderness than the composite mode; the composite mode is thus the more efficient mode for slender PVC-concrete columns, and comparisons in scope of load-deformation responses confirm that the stiffness, strength capacity, and ductility of columns of composite mode are more acceptable than those of corresponding columns in confining mode.

**Figure 9.** Load-axial deformation of composite specimens of various slenderness ratios

3.6 Lateral deformation

In terms of lateral deformation, the initial behaviour of the PVC-concrete column is similar to that of the plain concrete column, due to the fact that the confining effect of the PVC tube is not yet activated by the
lateral expansion of the concrete core. In the vicinity of the peak load for plain concrete columns, the confined concrete reaches a state of unstable volumetric growth caused by excessive cracking. At this point, the PVC tube is activated and starts to gradually restrain the rapid growth of the lateral strains. Generally, the same effectiveness of slenderness, section compactness, which is assigned in axial deformation is observed in lateral expansion. The effect of PVC section compactness on load-lateral deformation response is illustrated in Figure 10 for composite and confining modes, while Figure 11 shows column slenderness effect on load-lateral deformation for composite and confining modes.

![Figure 10](image1.png)  
**Figure 10.** Load-lateral deformation of composite specimens of various D/tp (L/r=14.67, f'_c=42.25)

![Figure 11](image2.png)  
**Figure 11.** Load-lateral deformation of specimens of various L/r, (f'_c=42.25, D/tp=20.83)

### 3.7 Stress-strain response

Strain was determined by using electrical strain gauges distributed at the specimens’ mid spans, placed equally around the tube circumference. Figure 12.a shows the longitudinal stress-strain responses of composite columns, while Figure 12.b shows the transverse stress-strain responses of confining columns. The strain distribution is distinguished by a slightly inelastic response. The same observations are noted in confining columns, where slight transverse plastic strains develop prior to sudden lateral buckling.
3.8 Failure modes

The non-composite slender specimens suffer from slight lateral expansion and exhibit sudden explosive failure without any visible cracks, while slender PVC tubes suffer from global elastic buckling followed by significant local buckling deformation, leading to a sudden loading capacity reduction.

For slender PVC concrete columns, stability failure dominates in all tested specimens, which suffer from global elastic buckling complicated by significant concrete failure and local buckling deformation, which leads to sudden loading capacity reduction with assigned sustainable lateral deformation. Photo 3 depicts the assigned typical failure modes of various specimens.

**Figure 12.** Stress-strain behaviour of PVC-concrete columns of various PVC compactness

**Photo 3.** Failure Modes
4. Effective Flexural Stiffness $EI_e$

Inelastic flexural buckling is the significant failure mode, as confirmed by indicated strains, as shown in Figures 12 and 13, which show that determined strains are within the elastic range. The Euler buckling mode occurs in the tested slender columns, distinguished by a sudden lateral deflection followed by deformation of the cross-section where the filling concrete undergoes shear failure. The Euler buckling equation is

$$P_e = \frac{n^2 EI_e}{(\frac{L}{r})^2}$$  \hspace{1cm} (1)

which accurately predicts critical elastic buckling load for columns of slender section in terms of slenderness ratio and flexural stiffness ($EI$). The effective stiffness ($EI_e$) of PVC-concrete composite slender columns of different modes was assigned according to ACI 318-14 [23] using the Euler formula, and elastic buckling was attained for all tested slender specimens. No interface bonding developed between the concrete cores and PVC tubes and the confinement exerted by the PVC tubes did not fully prevent customary shear failure; the reduction of buckling load due to shear deformation must thus be considered during the design phase.

Table 6. Experimental predictions for columns’ effective stiffness

| Groups | Specimens | Sections | Description | $kl$ | $L/r$ | $f_c$ | $f_p/f_c$ | $f_y$ | $D$ | $A_p$ | $A_{c}$ | $A_p/A_{c}$ | $Pcm$, kN | $Pcn$, kN | $EI_e \times 10^9$, N.mm$^2$ |
|--------|-----------|----------|-------------|------|------|-------|------------|------|-----|-------|-------|------------|----------|----------|----------------|
| SA7    | Section1  | 1100     | 14.67      | 42.3 | 1.006| 2.2   | 75         | 503  | 3913| 0.12853| 93.27 | 11.45       |
| SB7    | Section2  | 1100     | 14.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 108.30| 13.29       |
| SC7    | Section3  | 1100     | 14.67      | 42.3 | 1.006| 5.6   | 75         | 1220 | 3195| 0.381914| 120.00| 14.73       |
| SD7    | Section4  | 1100     | 14.67      | 34.7 | 0.826| 3.6   | 75         | 807  | 3609| 0.223667| 65.01 | 7.98        |
| SE7    | Section5  | 1100     | 14.67      | 58.8 | 1.4  | 3.6   | 75         | 807  | 3609| 0.223667| 114.00| 13.99       |
| G3     | Section2  | 950      | 12.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 121.00| 11.08       |
| SG7    | Section2  | 1250     | 16.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 108.30| 17.16       |
| SH7    | Section6  | 1100     | 17.46      | 42.3 | 1.006| 3    | 63         | 565  | 2550| 0.221607| 58.10 | 7.13        |
| SJ7    | Section7  | 1100     | 17.46      | 42.3 | 1.006| 4.7   | 63         | 860  | 2255| 0.381502| 62.00 | 7.61        |
| SJ7    | Section8  | 1100     | 17.46      | 34.7 | 0.826| 3    | 63         | 565  | 2550| 0.221607| 33.64 | 4.13        |
| SK7    | Section9  | 1100     | 17.46      | 58.8 | 1.4  | 3    | 63         | 565  | 2250| 0.221607| 72.00 | 8.84        |
| SA8    | Section1  | 1100     | 14.67      | 42.3 | 1.006| 2.2   | 75         | 503  | 3913| 0.12853| 76.80 | 9.43        |
| SB8    | Section2  | 1100     | 14.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 88.50 | 10.86       |
| SC8    | Section3  | 1100     | 14.67      | 42.3 | 1.006| 5.6   | 75         | 1220 | 3195| 0.381914| 101.50| 12.46       |
| SD8    | Section4  | 1100     | 14.67      | 34.7 | 0.826| 3.6   | 75         | 807  | 3609| 0.223667| 53.13 | 6.52        |
| SE8    | Section5  | 1100     | 14.67      | 58.8 | 1.4  | 3.6   | 75         | 807  | 3609| 0.223667| 92.98 | 11.41       |
| G4     | Section2  | 950      | 12.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 103.61| 9.48        |
| SG8    | Section2  | 1250     | 16.67      | 42.3 | 1.006| 3.6   | 75         | 807  | 3609| 0.223667| 70.80 | 11.22       |
| SH8    | Section6  | 1100     | 17.46      | 42.3 | 1.006| 3    | 63         | 565  | 2550| 0.221607| 50.07 | 6.14        |
| SB8    | Section7  | 1100     | 17.46      | 42.3 | 1.006| 4.7   | 63         | 860  | 2255| 0.381502| 53.20 | 6.53        |
| SJ8    | Section8  | 1100     | 17.46      | 34.7 | 0.826| 3    | 63         | 565  | 2550| 0.221607| 33.79 | 4.15        |
| SK8    | Section9  | 1100     | 17.46      | 58.8 | 1.4  | 3    | 63         | 565  | 2550| 0.221607| 60.05 | 7.37        |

Using the experimental results, the determined effective stiffness was normalised in term of filling concrete stiffness and PVC tube stiffness, as indicated in Eq. (2).

$$EL_e = (\gamma_1 E_I c + \gamma_2 E_p I_p)$$  \hspace{1cm} (2)

where $\gamma_1$ and $\gamma_2$ are constant depending on the considered mode (confining or composite), and PVC and
filling concrete strength as well as column slenderness ratio as shown in Figure 13 are considered.

![Figure 13. Effective stiffness normalisation](image)

**Conclusion**

1. The sustained loading resistance of PVC composites with concrete exhibited more strength improvement compared to their constituent parts than that of PVC confined concrete; upgrading rates varied from 2.42 to 1.645 for composite mode and from 2.047 to 1.345 for confining mode. Similar effects were observed in the scope of ductility, where specimens of PVC composite concrete exhibited more axial and lateral deformation than corresponding samples in confined mode.
2. The variation of loading effect on load-deformation response was significantly indicated as having an effect on strength upgrading for composite mode samples due to PVC acting as reinforcement, while samples assigned to the confining mode showed improvements relating to confining efficiency upgrading filling concrete strength.
3. Strength, stiffness, and ductility of PVC-concrete columns of various loadings were significantly affected by the column slenderness ratio ($l/r$) and PVC section compactness, as well as filling concrete strength.
4. Stability failure dominated in all tested slender PVC concrete columns, with all samples suffering from global elastic buckling accompanied by significant concrete failure and local buckling deformation, leading to sudden loading capacity reduction with matching lateral deformation.
5. Interface bonding did not develop between concrete cores and PVC tubes, and the confinement exerted by the PVC tubes did not fully prevent customary shear failure; a reduction of buckling load due to shear deformation must be considered in the design phase.
6. Effective flexural stiffness ($E_{Ie}$) of PVC-concrete slender columns of different modes can be assigned according to ACI 318-14, using the Euler formula, as elastic buckling was attained for all tested slender specimens.
7. Determined effective flexural stiffness can be normalised in term of filling concrete stiffness and PVC tube stiffness, and the normalised results indicate that effective flexural stiffness depends on the considered mode (confining or composite), PVC and filling concrete strength, and column slenderness ratio.

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