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Experimental Investigation of Plain Concrete-Filled Plastic Tubular Columns

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ABSTRACT: The main objective of the present study is to investigate experimentally the structural behavior of PVC-concrete composite columns consisting of a PVC tube filled with plain concrete. A series of thirty columns under axial compressive load were tested. The parameters considered were the concrete compressive strength, PVC tube thickness, and column slenderness ratio. It was found that the plastic pipe (PVC tube) provided sufficient lateral support of the concrete core and increased the ultimate strength of the column. The ratio of strength of PVC-concrete composite column to strength of plain concrete column ranged between 1.419 and 1.896 for columns with 30 MPa concrete compressive strength, whereas it was between 1.118 and 1.405 for columns made with 50 MPa.

KEY WORDS: Composite columns, PVC tubes, Confinement, Concrete-filled, Tubular columns.

I. INTRODUCTION

The term 'composite column' implies 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. Strictly speaking, ordinary reinforced concrete columns fall within the scope of this definition. However, the term is normally used to indicate applications like either concrete-encased sections or concrete-filled tubes of rectangular or circular cross-section (Fig. 1).

Concrete filled tubes offer a number of advantages in both design and construction:
1. The tube confines the concrete. This results in an increased strength and ductility of the concrete.
2. The concrete prevents the tube from local buckling.
3. The tube provides well-distributed reinforcement.
4. The tube protects the surface of the concrete from physical damage and deterioration by environmental effects such as carbonation and chloride penetration.
5. The tube provides a formwork for the casting of the concrete, which stays in place and does not need to be removed. This results in time and cost savings on site.

Rapid deterioration of infrastructures enhances the demand for rehabilitating and retrofitting of 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.

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

Fig. 1: Different types of composite columns

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Polyvinyl Chloride (PVC) is a thermoplastic material. Thermoplastic materials are those that can be melted again and again and after being heated up to a certain temperature they will harden again as they cool. They are 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. It is lightweight, which permits easy handling, impermeable to gases and fluids, and durable.

II. RELATED WORK

Composite columns, made of structural steel tubing filled with concrete, have been used in building construction with great efficiency for many years. Theoretical and experimental investigations were conducted on the behavior of concrete-filled steel columns [1–4]. Advances in the field of advanced composite materials have resulted in development of fiber reinforced polymers (FRP) to confine existing concrete columns. This leads to enhancing the compressive strength and ductility and improving the durability over conventional methods [5-8]. The use of commercially available PVC pipes in composite columns was investigated [9,10] to calculate the ultimate strength of plastic columns with concrete core. However, a comprehensive experimental study is required to provide database for the PVC-concrete composite columns. This database must reveal the effect of tube size, slenderness ratio of column, and concrete properties.

The main objective of the present study is to investigate the structural behavior of PVC-concrete composite columns consisting of a PVC tube filled with plain concrete. Different PVC tube thicknesses, column slenderness ratios and concrete compressive strengths are used in order to assess the effect of these variables on the strength of columns.

III. EXPERIMENTAL WORK

A. Materials

Ordinary Portland cement was used throughout the investigation. Natural silica sand and crushed natural gravel obtained from Zubair area were used. Ordinary potable water was used in making and curing concrete. The PVC tubes used were commercially available PVC tubes with an ultimate tensile stress (f_t) of 51.7 MPa as given by the manufacturer. The tubes were of circular cross section with 110 mm external diameter and wall thicknesses of 3.2 mm and 5.3 mm. Two concrete mixes were used. The mix proportions of the ingredients of the first mix, Mix 1, by dry weights were [1 cement : 2 sand : 3.2 gravel], and the water cement ratio (w/c) was 58% (which gave a cube compressive strength (f'_c) of about 30 MPa at age of 28 days). For the second mix, Mix 2, the mix proportions of the ingredients by dry weights were [1 cement : 1.12 sand : 2.3 gravel], and the water cement ratio (w/c) was 40% (which gave a cube compressive strength of about 50 MPa at age of 28 days).

B. Test Specimens

A total of thirty columns were tested under axial compression. The columns were divided into six groups (G1 to G6). For each group, five specimens were prepared with heights of 220, 400, 600, 800, and 1000 mm. All groups were casted without steel reinforcement and groups G1 and G4 were non-composite without PVC tubes. Two concrete mixes were used, Mix 1 was used for groups (G1 to G3) and Mix 2 was used for groups (G4 to G6). The variables in this stage were the column height (220 to 1000 mm), tube thickness (3.2 and 5.3 mm), and concrete cube compressive strength (30 and 50 N/mm2). Specimen diameter was constant. All specimens were tested under compressive axial force upto failure. Table 1 gives the details of the columns including their designation. In the specimen designation, as shown in the second column of Table 1, the first number indicates the length of the column in mm. The letters A, B, and P relate to the PVC tube, 'A' refers to 3.2 mm thick tube, 'B' refers to 5.3 mm thick tube, and 'P' refers to a non-composite column (without PVC tube). The numbers 1 and 2 in the designation refer to the concrete mix used (Mix 1 or Mix 2 as previously explained).

C. Fabrication of Specimens

The PVC tubes were cut to the desired length of the columns and cleaned. Tubes were positioned vertically, fixed on the laboratory floor, and filled with concrete. For casting the specimens, tubes were positioned vertically and fixed on the laboratory floor. Tubes were filled with concrete in approximately 10 cm layers, and each layer was compacted by a steel rod. To prevent the leakage of cement paste from the bottom of the PVC tube, it was closed with nylon. After the tube was filled, the top surface was flattened carefully. The composite columns were left in the laboratory till the time of testing. The specimens were moistened with water every day after twenty four hours after casting.

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D. Instrumentation and Test Setup

All specimens were tested under axial compression using a Torsee's universal testing machine with a capacity of 1000 kN at the laboratory of construction materials – University of Basrah. The column specimen was centered in the testing machine to ensure that the compressive axial load was applied without any eccentricity. The top and bottom faces of specimen were grinded and made smooth and levelled to remove surface imperfections and maintain uniformity of loading on the surface. The vertical displacement of the lower movable head of the testing machine was measured in relation to the upper head of the testing machine by a dial gauge with magnetic base. This measured displacement was assumed to be equal to the vertical shortening of the test specimen. The accuracy of the dial gauge was 0.01 mm. Readings of applied load and displacement were recorded at regular intervals during the tests. Figure 2 depicts the test setup. The application of the load was continued until the failure of columns.

Table 1: Details of columns

Group No.	Column Designation	Concrete Mix	External Diameter (D) (mm)	Tube Thickness (t) (mm)	Length (L) (mm)	Slenderness Ratio (L/r)
G1	220P1	1	103.6	–	220	8.5
	400P1	1	103.6	–	400	15.4
	600P1	1	103.6	–	600	23.2
	800P1	1	103.6	–	800	30.9
	1000P1	1	103.6	–	1000	38.6
G2	220A1	1	110.0	3.2	220	8.0
	400A1	1	110.0	3.2	400	14.5
	600A1	1	110.0	3.2	600	21.8
	800A1	1	110.0	3.2	800	29.1
	1000A1	1	110.0	3.2	1000	36.4
G3	220B1	1	110.0	5.3	220	8.0
	400B1	1	110.0	5.3	400	14.5
	600B1	1	110.0	5.3	600	21.8
	800B1	1	110.0	5.3	800	29.1
	1000B1	1	110.0	5.3	1000	36.4
G4	220P2	2	103.6	–	220	8.5
	400P2	2	103.6	–	400	15.4
	600P2	2	103.6	–	600	23.2
	800P2	2	103.6	–	800	30.9
	1000P2	2	103.6	–	1000	38.6
G5	220A2	2	110.0	3.2	220	8.0
	400A2	2	110.0	3.2	400	14.5
	600A2	2	110.0	3.2	600	21.8
	800A2	2	110.0	3.2	800	29.1
	1000A2	2	110.0	3.2	1000	36.4
G6	220B2	2	110.0	5.3	220	8.0
	400B2	2	110.0	5.3	400	14.5
	600B2	2	110.0	5.3	600	21.8
	800B2	2	110.0	5.3	800	29.1
	1000B2	2	110.0	5.3	1000	36.4

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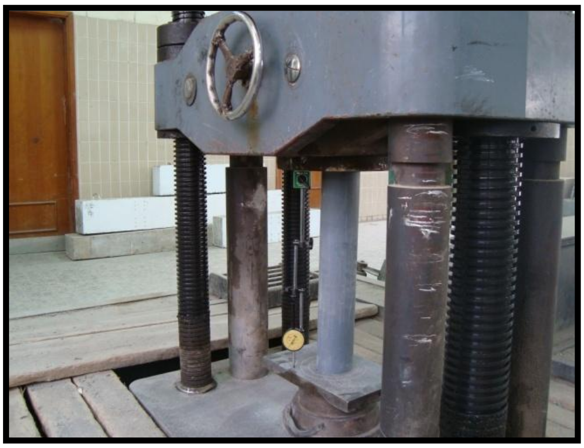

Fig. 2: Test setup

IV. RESULTS AND DISCUSSION

A. Strength and Strain of PVC-Concrete Composite Columns

The ultimate load and the corresponding strain for all specimens are summarized in Table 2. From this table, it can be seen that the use of PVC tubes increases the load carrying capacity of concrete columns. For all the specimens, the ratio P_{cc}/P_{co} is always larger than one, ranging between 1.419 and 1.896 for columns with 30 MPa concrete compressive strength, whereas it is between 1.118 and 1.405 for columns made with 50 MPa. The average increase in strength is of the order of 42.9%. Explanation to this behavior of PVC-concrete composite columns under compression loads can be given as follows. In composite columns with concrete filled hollow sections the load bearing capacity is significantly affected by the difference between the Poisson's ratios of the PVC tube and the concrete core. The Poisson's ratio of PVC tube is approximately 0.41 in the elastic range as given by the manufacturer. In contrast to PVC tube the Poisson's ratio of concrete is approximately 0.1 in the elastic range and can reach values up to 0.75 in case of large strains [11]. Thus in case of loading on the entire section in the initial stage of loading the PVC tube and the concrete act separately due to the faster expansion of the PVC tube in radial direction. This behavior changes abruptly when concrete starts to expand excessively at a stress level of about 87 percent of the concrete strength [12]. The lateral strain of the concrete increases rapidly and further loading leads to lateral expansion greater than that of the PVC tube. From that stage the concrete is under triaxial compression due to restraint by the PVC tube, which is under vertical compression and transverse tension. Due to the confinement of the concrete the triaxial stress state causes a reduction of the axial compressive strength of the PVC tube while there is an increase in the longitudinal compressive strength of the concrete. The interaction between the hollow section and the concrete core works beneficially and leads to an ultimate load exceeding the sum of the uniaxial compression loads of PVC tube and concrete.
Also from Table 2, it can be seen that the use of PVC tubes enhances the approximate axial strain at ultimate load of concrete columns (as obtained by extrapolation). For all the specimens, the ratio $\varepsilon cc/\varepsilon co$ is always larger than one, ranging between 1.687 and 2.473 for columns with f'_c=30 MPa, whereas it is between 1.367 and 2.145 for columns with f'_c=50 MPa. The average increase in axial strain at ultimate load is of the order of 82.4%. This increase in strain could be attributed to the containment of concrete inside the PVC tube and the restrained lateral expansion of concrete during loading, and because of that the plastic (PVC) can withstand large strains without rupture of the tube material.

B. Load–Axial Displacement Relationship

In PVC-concrete composite columns, the PVC tube causes the development of a triaxial stress field within the confined concrete, constraining it during dilation and thereby increasing the load carrying capacity. Figures 3 and 4 show the axial load plotted as a function of axial displacement for the shortest and longest PVC-concrete composite columns and plain concrete columns, respectively. The figures clearly show that the PVC tubes can improve the performance of concrete, both its strength and ductility, under axial load. The load-displacement relationships of PVC-concrete composite columns are generally bilinear in nature with a small transition zone. Therefore, the behavior of composite columns under axial loading can be divided into three regions. In the first region, the behavior of composite column is

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Table 2: Test Results*

Group No.	Column designation	P_{co} (kN)	ε_{co}	P_{cc} (kN)	ε_{cc}	P_{cc}/P_{co}	$\varepsilon_{cc}/\varepsilon_{co}$
G1	220P1	196.4	0.00364	–	–	–	–
	400P1	191.4	0.00350	–	–	–	–
	600P1	185.7	0.00317	–	–	–	–
	800P1	174.8	0.00301	–	–	–	–
	1000P1	158.6	0.00281	–	–	–	–
G2	220A1	–	–	278.7	0.00764	1.419	2.099
	400A1	–	–	272.3	0.00693	1.423	1.980
	600A1	–	–	265.6	0.00580	1.430	1.830
	800A1	–	–	254.3	0.00513	1.455	1.704
	1000A1	–	–	240.1	0.00474	1.514	1.687
G3	220B1	–	–	331.6	0.00900	1.688	2.473
	400B1	–	–	327.0	0.00828	1.708	2.366
	600B1	–	–	322.3	0.00677	1.736	2.136
	800B1	–	–	316.3	0.00595	1.809	1.976
	1000B1	–	–	300.7	0.00499	1.896	1.776
G4	220P2	330.2	0.00318	–	–	–	–
	400P2	322.2	0.00298	–	–	–	–
	600P2	311.3	0.00277	–	–	–	–
	800P2	294.4	0.00256	–	–	–	–
	1000P2	278.5	0.00246	–	–	–	–
G5	220A2	–	–	369.2	0.00536	1.118	1.686
	400A2	–	–	360.8	0.00430	1.120	1.443
	600A2	–	–	350.3	0.00408	1.125	1.473
	800A2	–	–	338.6	0.00350	1.150	1.367
	1000A2	–	–	328.9	0.00345	1.181	1.402
G6	220B2	–	–	438.0	0.00682	1.326	2.145
	400B2	–	–	428.6	0.00570	1.330	1.913
	600B2	–	–	420.7	0.00507	1.351	1.830
	800B2	–	–	408.1	0.00423	1.386	1.652
	1000B2	–	–	391.2	0.00381	1.405	1.549

* P_{cc} *and* ε_{cc} *are the ultimate load and the corresponding strain of PVC-concrete composite columns, respectively.*
P_{co} *and* ε_{co} *are the ultimate load and the corresponding strain of corresponding concrete columns, respectively.*

Similar to that of plain concrete column: this is due to the fact that the confining effect of PVC tube is still not activated by the lateral expansion of the concrete core. In the vicinity of the peak load of 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. This region of response is characterized by a transition curve at approximately the ultimate load of the plain concrete column. Finally, a third region is recognized in which the PVC tube is fully activated and the load-displacement relationship continued as a straight line with a second slope up to the failure at ultimate load. The figures show that the slope of third part of relationship is less than the slope of the first part, and proportional to the stiffness of the PVC tube used, that is, the slope of relationships of columns with 5.3 mm thickness PVC tube is larger than those for columns with 3.2 mm thickness PVC tube.

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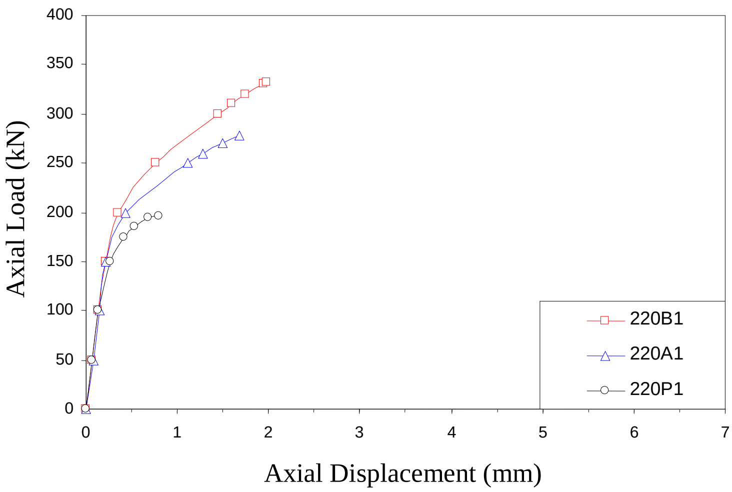

Fig. 3: Load-displacement relationship of specimens with L = 200 mm and f'_c = 30 MPa

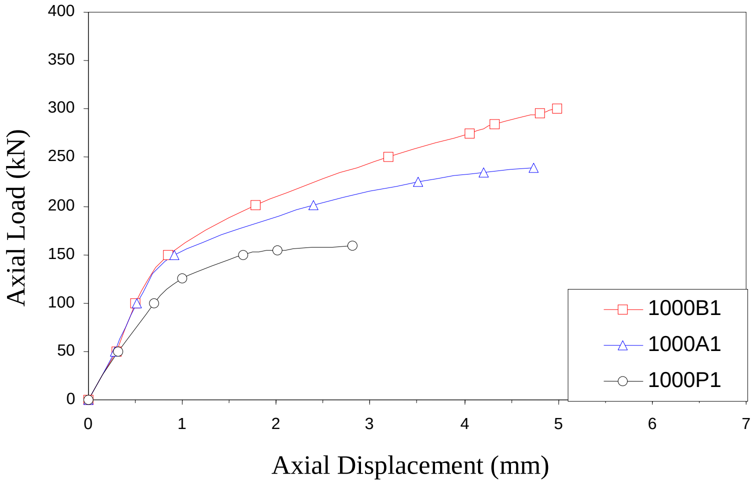

Fig. 4: Load-displacement relationship of specimens with L = 1000 mm and f'_c = 30 MPa

C. Effect of Tube Thickness

It can be seen from Table 2 that, when all other parameters are the same, the increase of thickness of PVC tube leads to greater increase in ultimate strength and the corresponding strain of the composite columns. This could be attributed to the different ratios of the PVC reinforcement. The PVC reinforcement ratio ρ_t in this study is defined by 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:

$$\rho_t = 4t/D, \quad (1)$$

where t and D are the wall thickness and the external diameter of the PVC tube, respectively. The reinforcement ratios for columns with 3.2 and 5.3 mm PVC tube were 11.6 and 19.3 percent, respectively. Figure 5 shows the ultimate load versus reinforcement ratio ρ_t of PVC tube. From this figure, it can be seen that the ultimate load increases as the reinforcement ratio is increased.

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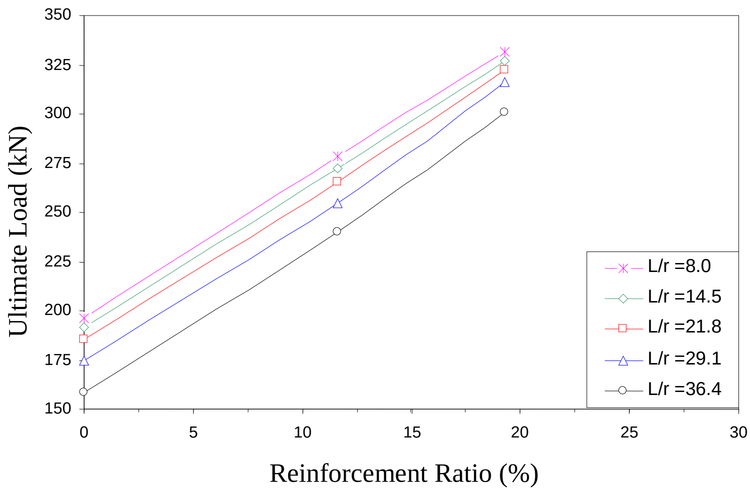

Fig. 5: Ultimate load versus reinforcement ratio of specimens with f'c = 30 MPa

D. Effect of Concrete Strength

From Table 2, it can be seen that the strength of the composite columns increases as the concrete strength increases. However the rate of increase in load carrying capacity of the composite columns decreases as the concrete strength increases. The ratio P_{cc}/P_{co} for columns with 30 MPa concrete compressive strength is between 1.419 and 1.896, whereas it is between 1.118 and 1.405 for columns made with 50 MPa. This behavior could be attributed to that a given PVC tube could increase the ultimate strength of a column to a specific ratio P_{cc}/P_{co} according to the confinement ratio f_r/f'_c, where f_r is the confining stress of the tube and f'_c is the concrete compressive strength of the column. Thus, if f'_c increases this would decrease the confinement ratio and consequently would decrease the increase in ultimate strength of the column.

E. Effect of Slenderness Ratio

Figure 6 shows the effect of the column slenderness ratio on the strength of PVC-concrete composite columns. For each tested specimen, the ratio of the column ultimate load to the ultimate load of the shortest column (220 mm height) was calculated. As shown in this figure, the increase of slenderness ratio causes a reduction in the ultimate compression load of the column. This reduction in ultimate strength is not significant and could be attributed to that with an increase in the column height, the effect of the friction between the machine loading plates and the ends of the column decreases providing a region at the midheight of the column far from the ends which are subjected to combined stresses. The region at the midheight of column will be free to expand laterally and this will cause excessive cracking of concrete which leads to failure of columns. Also this reduction could be attributed to that with an increase in the slenderness ratio, lateral buckling may occur which causes some bending to develop causing failure at loads less than the failure loads of short columns.

F. Failure Modes

The failure modes of some test specimens are shown in Fig. 7. The non-composite (plain concrete) columns suffers from excessive lateral expansion due to unstable propagation of the internal micro-cracks, which causes the strain softening behavior and eventually the concrete mass loses its integrity and fails in splitting manner. The complete collapse of the column usually occurred suddenly at strains between 0.0025 and 0.0036. For the PVC-concrete composite columns, the typical failure mode for short and intermediate length columns (L/r = 8 – 29.1) is a classical shear mode failure. The concrete core typically failed in a classical shear mode failure with angle of failure of approximately 45°. It was observed, when the PVC tube is cut, that a smooth interface between the PVC tube and concrete exists. This led to the conclusion that no bond is developed between concrete and PVC tube. It seems that the confinement exerted by the PVC tube could not fully prevent the concrete core from shear failure, although the PVC tube did provide good confinement on the concrete core. This indicates that the composite system fully utilizes the two

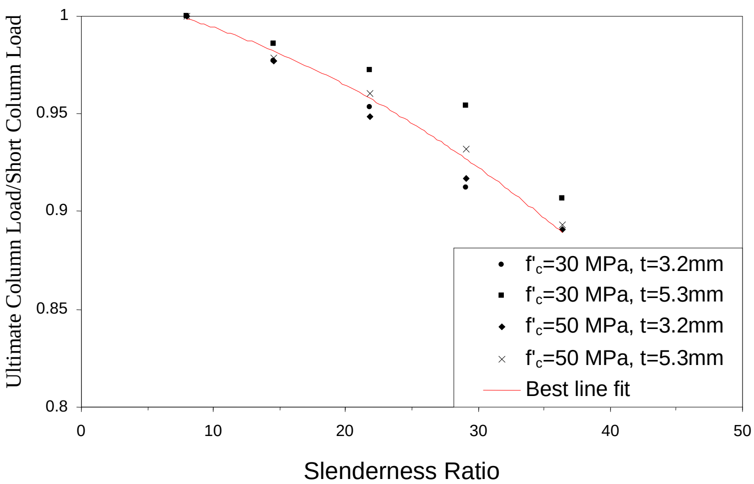

Fig. 6: Effect of slenderness ratio on columns strength

materials. The concrete supports the PVC tube and prevents premature failure while the tube confines the concrete and restrains its excessive expansion. Failure usually occurred quietly, but for some specimens, a soft cracking noise was heard when the ultimate load was attained revealing the fracture of the PVC tube. It was noticed that for most of specimens, the failure occurred within the upper or lower quarter or one third of the specimen height. For the most slender composite columns (L/r = 36.4), the failure mode of specimens with concrete strength of 50 MPa (specimens 1000A2 and 1000B2) is also a classical shear mode failure as the shorter specimens. Specimens with concrete strength of 30 MPa (specimens 1000A1 and 1000B1) fail by a long column buckling mode failure. In specimen 1000B1, with f'_c=30 MPa, lateral buckling occurs during loading, but the column finally fails in a shear mode as shown in Fig 7.

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Fig. 7: Failure modes of specimens

V. CONCLUSIONS

1- The plastic pipe (PVC tube) provided sufficient lateral support to the concrete core and increased the ultimate strength of the column.
2- The ratio of strength of PVC-concrete composite column to strength of plain concrete column ranged between 1.419 and 1.896 for columns with 30 MPa concrete compressive strength, whereas it was between 1.118 and 1.405 for columns made with 50 MPa.
3- The increase of the ratio ρt of PVC tube (in the range used) leads to greater increase in ultimate strength and the corresponding strain of the composite columns.
4- The failure mode for short and intermediate length composite columns (L/r = 8 – 29.1) is a classical shear mode failure. For the most slender composite columns (L/r = 36.4), the failure mode of specimens with high concrete strength (50 MPa) is also a shear mode failure, while specimens with relatively low concrete strength (30 MPa) fail by a long column buckling mode failure.
5- The failure of most of the tested composite columns occurred near the top or bottom of the columns (within the upper or lower quarter or one third of the column height).

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