Structural Behavior of Concrete Filled Aluminum Tubular Columns

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ABSTRACT

The paper presents an experimental and theoretical study on the behavior of circular concrete filled aluminum tubular columns. The main purpose of the experimental program was to investigate the structural behavior of aluminum-concrete composite columns under axial compression loading conditions. Twenty four specimens were tested to investigate the effect of diameter, D/t ratio and slenderness ratio of a aluminum tube on the load carrying capacity of the concrete filled tubular columns. Diameter to wall thickness ratio ranged between $11.9 \leq D/t \leq 22.8$, and the length to tube diameter ratios of $3 \leq L/D \leq 10$ were investigated. The main purpose of the theoretical investigation was to predict the strength of aluminum -concrete composite columns subjected to axial compression loading conditions. The empirical equations proposed in the present study are capable of predicting the values of ultimate loads of aluminum -concrete composite columns and were in good agreement with the experimental values. The average values of ratios of experimental to predicted values of ultimate loads are 1.0104 for the proposed empirical equations. The circular hollow section tubes were fabricated by extrusion using 6061-T6 heat-treated aluminum alloy. The column strengths, load-axial shortening relationship and failure modes of columns were presented.

السلوك الإنشائي للأعمدة المركبة من أنابيب الألمنيوم المملوء بالخرسانة

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الخلاصة

يتضمن البحث الحالي دراسة عملية ونظرية لخواص الأعمدة الدائرية المكونة من أنابيب الألمنيوم والمملوء بالخرسانة. الهدف الأساسي من الدراسة العملية معرفة التصرف الإنشائي للأعمدة المركبة من الألمنيوم والمملوه بالخرسانة تحت تأثير أحمال الانضغاط المحورية. أربعة وعشرون نموذج تم فحصها لدراسة تأثير القطر، نسبة القطر \ السمك ونسبة النحافة لأنابيب الألمنيوم وتأثيرها على تحمل الأعمدة الأنبوبية المملوء بالخرسانة. تم تحقيق نسبة القطر \ السمك ما بين (11.9 - 22.8)ونسبة الطول \ القطر ما بين (3 – 10). إما الهدف الأساسي من الدراسة النظرية فهو تقدير مقاومة الأعمدة المركبة من الألمنيوم والخرسانة والمعرضة لأحمال ضغط محورية. المعادلات الوضعية المقترحة في هذه الدراسة كانت قادرة على تقدير قيم مقاومة الأعمدة وباتفاق جيد مع القيم المختبرية حيث كانت القيم المتوسطة لنسب المقاومة المختبرية إلى المقاومة المقدرة هي 1.0104 باستخدام المعادلات الوضعية المقترحة في هذه الدراسة. الأنابيب الدائرية المجوفة صنعت باستخدام سبيكة الألمنيوم نوع 6061 – T6 والمعامل حراريا. مقاومة الأعمدة، العلاقة بين الحمل والقصر المحوري ونوع الفشل للأعمدة تم تعينها.

1. INTRODUCTION

Composite columns have been widely used in the construction industry for a number of decades. The increase in the use of the concrete filled steel columns throughout the world in recent years is mainly due to the significant advantages that this type of columns which could offer in comparison to more traditional construction methods. Composite columns consist of a combination of concrete and steel, and make use of the best properties of these constituent materials. The use of composite columns can result in significant savings in column size, which ultimately can lead to significant economic savings. The reduction in column size can provide substantial benefits where floor space is at a premium such as in car parks and office blocks.

It is well known that concrete-filled steel composite columns have the advantages of high-bearing capacity and ductility, easy construction and cost saving [1–11]. Similarly, aluminum tube columns filled with concrete can effectively take advantages of these two materials to provide both high strength and high stiffness. There are many advantages in using aluminum alloy as a structural material, such as appearance, lightness, corrosion resistance and ease of production. Furthermore, the aluminum tubes surrounding the concrete eliminate permanent formwork, and as such, construction time can be reduced.

However, little research has been carried out on concrete-filled aluminum tube composite columns. Hence, there is a need to investigate the structural performance of concrete-filled aluminum tube columns [12 – 13].

Composite columns are a very important application of composite construction. The principle of a column is to deliver vertical forces to the base of a structure, with the term 'composite column'[14-17] referring to a compression member in which a steel element acts compositely with the concrete element. The role of the concrete core in a composite column is not only to resist compressive forces but also to reduce the potential for buckling of the steel member. The steel tube reinforces the concrete to resist any tensile forces, bending moments and shear forces.

2. Experimental investigation

2.1. Concrete Properties

Concrete of design strength of 24.1 MPa was produced using commercially available materials with normal mixing and curing techniques. Mix design was carried out in accordance to the American Specification [18]. The concrete used in the test program had a water/cement ratio of 0.6, made with ordinary Portland cement. e

Mix proportions were as follows: cement: 342 kg/m3; water: 205 kg/m3; sand: 720 kg/m3; and coarse aggregate: 1173 kg/m3. The coarse aggregate was well graded with a maximum size of 10 mm.

Standard cylinder tests were used to determine the compressive strength of concrete. A total of nine concrete cylinder tests were conducted. The mean value of the measured compressive concrete cylinders strength is 24.1 MPa

Concrete cylinders tests were conducted at the time of the concrete-filled aluminum tubular column tests.

2.2 Aluminum tubes properties

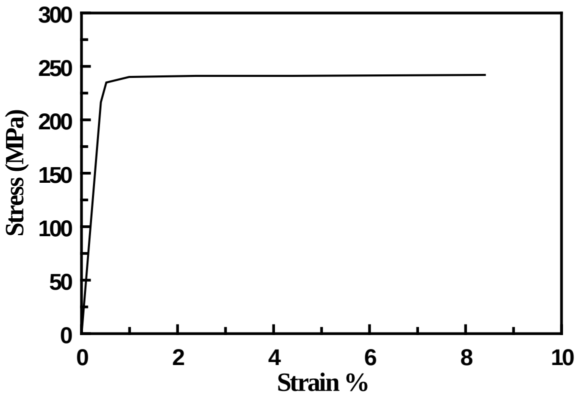
Standard tensile coupon tests were conducted to measure materials properties of aluminum tubes. The coupon specimens of 6 mm wide with a gauge length of 25mm were extracted from the hollow section of tubes. Material properties obtained from the tensile coupon tests are summarized in Table(1), which includes the static 0.2% tensile proof stress($\sigma_{0.2}$), static tensile strength(σ_u) and initial Young's modulus (E_o). The typical stress–strain curves obtained from the tensile coupon tests for group 1 and group 2 are shown in Figs 1(a) and (b), respectively.

2.3. Test specimens

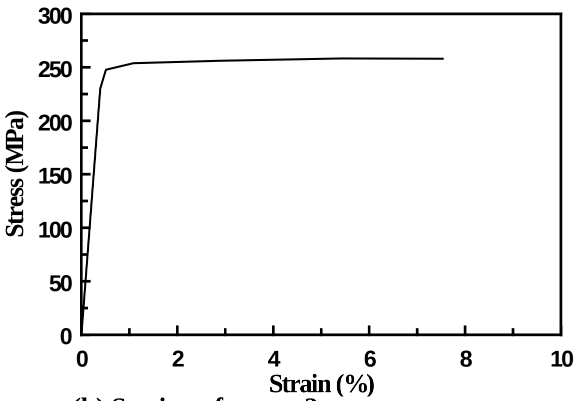
A total of twenty four columns were tested under axial compression The aluminum tubes were fabricated by extrusion using 6061-T6 heat-treated aluminum alloy the nominal dimension of each tube is given outside diameter and wall thickness are measured at several location, these measurement values have been used to determine the properties of tubes.

Table (1) Measured material properties obtained from tensile coupon tests.

Test Group	Section D*t (mm)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	E_o (GPa)
G1	38*3.2	241.4	261.4	66.7
G2	50*3.0	253.6	269.2	71.4
G3	60*4.2	254.8	267.3	70.7
G4	100.1*4.4	242.1	272.1	69.4



(a) Section of group 1



(b) Section of group 2

Fig. (1)Typical stress–strain curves of coupon test

The diameter to thickness ratio (*D/t*) of the CFTa ranges from 11.9 to 22.8. The column length to diameter (*L/D*) ratio for the CFTa ranges from 3 to 10 (3 ≤ *L/D* ≤ 10). The measurement dimension and details of the CFTa columns tested specimen are shown in Table (2). The program consists of four groups (G1 – G4). For each group, six specimens were prepared, the first specimen of each group without concrete infill and with constant (*L/D)* ratio equal to 3. The other five specimens from each group fill with concrete with (*L/D*) ratio ranges from 3 to 10.

The column specimens were tested using nominal concrete cylinder strength of 24.1 MPa. The aluminum hollow section stub column without concrete infill were also tested for reference purpose. All specimen were tested up to failure.

Table (2) gives details of the columns including their designation. In the specimen designation as shown in the second column of Table (2) as follows:

- The first two letters indicated the diameter (*D*) of specimens.
- The second two letters indicated the slender ratio (*L/D*) of specimens.
- The designation of the specimen without concrete infill followed by letter (*E*).

Table (2) Measured test specimen dimensions of circular hollow sections.

Group No.	Column designation	External Diameter, *D* (mm)	Tube Thickness, *t* (mm)	Length, *L* (mm)	*L/D*	*D/t*
G1	D1S3E	38.0	3.2	114.0	3	11.9
	D1S3	38.0	3.2	114.0	3	11.9
	D1S4	38.0	3.2	152.0	4	11.9
	D1S6	38.0	3.2	228.0	6	11.9
	D1S8	38.0	3.2	304.0	8	11.9
	D1S10	38.0	3.2	380.0	10	11.9
G2	D2S3E	50.0	3.0	150.0	3	16.7
	D2S3	50.0	3.0	150.0	3	16.7
	D2S4	50.0	3.0	200.0	4	16.7
	D2S6	50.0	3.0	300.0	6	16.7
	D2S8	50.0	3.0	400.0	8	16.7
	D2S10	50.0	3.0	500.0	10	16.7
G3	D3S3E	60.0	4.2	180.0	3	14.3
	D3S3	60.0	4.2	180.0	3	14.3
	D3S4	60.0	4.2	240.0	4	14.3
	D3S6	60.0	4.2	360.0	6	14.3
	D3S8	60.0	4.2	480.0	8	14.3
	D3S10	60.0	4.2	600.0	10	14.3
G4	D4S3E	100.1	4.4	300.3	3	22.8
	D4S3	100.1	4.4	300.3	3	22.8
	D4S4	100.1	4.4	400.4	4	22.8
	D4S6	100.1	4.4	600.6	6	22.8
	D4S8	100.1	4.4	800.6	8	22.8
	D4S10	100.1	4.4	1001.0	10	22.8

2.4 Testing of CFTa

The total twenty four tubes including four hollow tubes (as shown in Table 1) were tasted after 28 days 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 inside the testing machine to ensure that the compressive axial load was applied without any eccentricity. The top and bottom faces of the specimen were grinded and made smooth and leveled to remove surface imperfections and to 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 takes place.

2.5 Test result

2.5.1 Strength of Aluminum-concrete composite columns

The test strengths and load–axial shortening relationship were measured for each column specimen. The test strengths

Figure (2) Test setup

(P_{co}) of the concrete-filled aluminum tube columns are shown in Table (3). From this table, it can be seen that the use of aluminum tubes increases the load carrying capacity of concrete columns. For all the specimens, the ratio P_{co}/P_{al} is always larger than one, ranging between 1.405 and 1.751.The average increase in strength is of the order of 50.45 %.

As explained above, this increase in strength is due to the confinement of the concrete by the aluminum tube.

Also from Table (3), it can be seen that the use of aluminum tubes increases the approximate axial strain at ultimate load of concrete columns. For all the specimens, the ratio $\varepsilon_{co}/\varepsilon_{al}$ is always larger than one, ranging between 1.814 and 1.997.The average increase in axial strain at ultimate load is of the order of 90.7%.

Table (3)Test Results of Composite Columns *

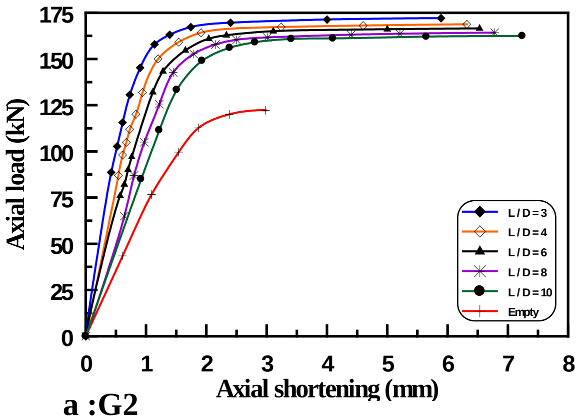
Group No.	Column designation	P_{al} (kN)	ε_{al}	P_{co} (kN)	ε_{co}	P_{co}/P_{al}	$\varepsilon_{co}/\varepsilon_{al}$
G1	D1T1S3E	104.5	0.02816				
	D1T1S3			148.5	0.05623	1.421	1.997
	D1T1S4			145.8	0.04355		
	D1T1S6			143.7	0.03079		
	D1T1S8			141.9	0.02434		
	D1T1S10			138.9	0.02079		
G2	D2T1S3E	121.3	0.01987				
	D2T1S3			170.4	0.03927	1.405	1.976
	D2T1S4			168.6	0.0316		
	D2T1S6			165.1	0.02177		
	D2T1S8			162.8	0.01695		
	D2T1S10			161.8	0.01448		
G3	D3T1S3E	210.1	0.01917				
	D3T1S3			302.7	0.03478	1.441	1.814
	D3T1S4			298.5	0.02833		
	D3T1S6			289.6	0.01972		
	D3T1S8			278.5	0.01583		
	D3T1S10			275.4	0.01317		
G4	D4T1S3E	326.4	0.01229				
	D4T1S3			571.4	0.02264	1.751	1.842
	D4T1S4			566.7	0.01736		
	D4T1S6			562.7	0.01232		
	D4T1S8			551.5	0.01011		
	D4T1S10			545.8	0.00874		

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

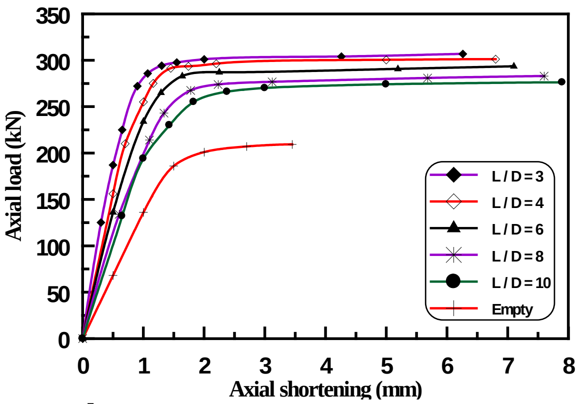
These increase in strain could be attributed to the containment of concrete inside the aluminum tube and the restrained lateral expansion of concrete during loading, and because of the aluminum tube can withstand large strains without rupture of the tube material, the axial strain at ultimate load of the composite columns at failure was relatively large.

The load-axial shortening relationship of the concrete-filled aluminum columns for groups G2 and G3 obtained from the displacement readings are shown in Fig 3.

The initial parts of the load-axial shortening curves of the concrete-filled aluminum tube columns have larger slopes compared to the aluminum tube columns without concrete infill. It is shown that the stiffness of the composite columns improves. It is also shown that the ductility of concrete- filled aluminum tube columns increases with using aluminum tube shell. as shown in Fig.(3).



a :G2



b :G3

Figure(3) Load-displacement relationship of specimens: (a) G2 and (b) G3

2.5.2 Effect of slenderness ratio

Tables (3) demonstrates the effect of the column slenderness ratio on the ultimate strength of aluminum-concrete composite columns. As it is evident from this table, the increase of the slenderness ratio led to decreased ultimate strengths.

As shown in Fig. 4, slenderness effect reduces the ultimate compressive load capacity of the column. For each specimen tested, a ratio of the ultimate column capacity to the load shortest column for each column diameter was calculated. 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 is decreased 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.

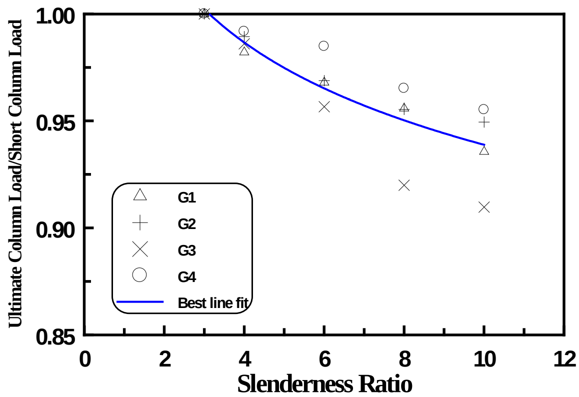


Figure (4) Effect of slenderness ratio on columns strength

2.5.3 Failure modes

Failure modes for the aluminum–concrete composite column are shown in Fig.(5), the typical failure mode for short and intermediate length columns (*L/D* = 3 – 4) is a classical shear mode failure. The concrete core typically failed in a classical shear mode failure with angle of failure of approximately 45°.

For the most slender composite columns (*L/D* = 6-10), the failure mode of specimens fail by a long column buckling mode failure as shown in Fig. (5a,d).

3. Proposed Empirical Equations

In this study, a design approach was proposed. In this approach the aluminum tube is treated as an external reinforcement to the concrete core in the aluminum-concrete composite column. The adopted approach was based on the experimental results presented in this study for twenty aluminum-concrete composite columns. While the experimental results conducted by Beng Young [13] were used for verification of the proposed design equations. All these experimental results are given in Table (4).

3.1. Design Approach

In aluminum-concrete composite columns, the reinforcement ratio ρ_t is proposed in this work to be taken as the ratio of the

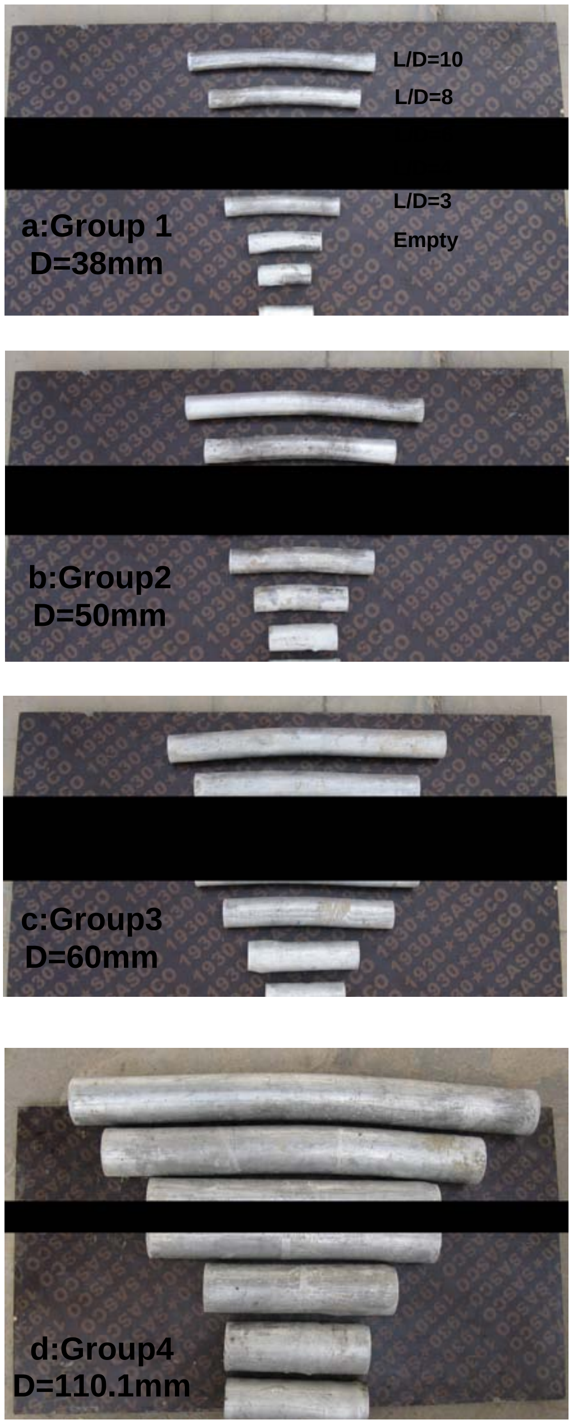


Figure (5) Failure modes of specimens

cross – sectional area of the aluminum tube to diameter-to-thickness ratios of aluminum tube, this ratio can be reduced to [19]:

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

where t and D are the wall thickness and the external diameter of the aluminum tube, respectively. However, aluminum 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 $\Re$, is introduced instead of ρ_t to allow for comparing composite columns of different aluminum 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 aluminum tube $\sigma_{0.2}$ to the concrete cylinder compressive strength f'_c as follows:

$$\Re = \rho_t \frac{\sigma_{0.2}}{f'_c}, \qquad (2)$$

by substituting Eq. (1) into Eq. (2), the reinforcement index $\Re$ can be calculated by:

$$\Re = \left(\frac{4t}{D}\right)\frac{\sigma_{0.2}}{f'_c}, \qquad (3)$$

The ultimate strength (P_{cc}) of a aluminum-concrete composite column is normalized with respect to the strength of a corresponding aluminum tube column (P_a) in a dimensionless format as follows:

$$\overline{P} = \frac{P_{cc}}{P_{al}}, \qquad (4)$$

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

$$\overline{P} = f(\Re). \qquad (5)$$

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

$$\overline{p} = a_1 + a_2(\Re)^{a_3}, \qquad (6)$$

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_{al} is the strength of aluminum tube columns ($P_{al}=A_a\sigma_{0.2}$). Using the results of compact specimen ($L/D \leq 3$), a regression analysis was performed to obtain the constants a_1 and a_2 for selected values of a_3 between 1 and 3. The expression for reinforcement index $\Re$, evaluated by the best-fit curve from the regression analysis shown in Fig. (6), is

$$P_{cc} = \left(0.369\Re^2 - 1.907\Re + 3.997\right) P_{al} \qquad (7)$$

Equation (7), 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

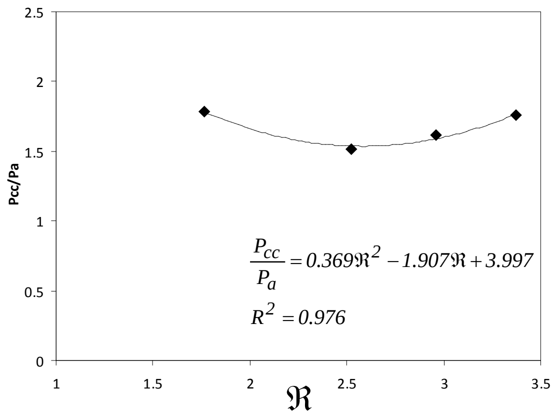


Figure (6) Variation of reinforcement index($\Re$) with (P_{cc}/P_a)

found that a modified expression for the ultimate strength may be assumed in the form of:

$$P_{slender} = P_{compact}\, f\,(L/D)\,, \qquad (8)$$

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/D) is the column slenderness ratio of the slender specimen.

Figure (7) shows the normalized ultimate strength (P_{cc}/P) versus the slenderness ratio (L/D) 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 exponential Eq. (9) is proposed for the relation between the normalized strength and the slenderness ratio by regression analysis. Good correlation is noted with R^2 = 87.19%:

$$\frac{P_{cc}}{P} = \left[1.0637(\frac{L}{D})^{-0.0542}\right] \qquad (9)$$

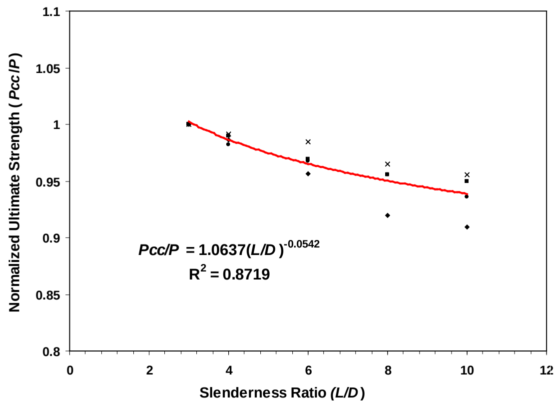


Figure (7) Normalized ultimate strength versus slenderness ratio

Thus, From Eq. (7) and replacing the slenderness ratio by its value for circular columns, the ultimate strength of slender aluminum-concrete composite columns can be estimated by:

$$P_{cc} = \left(0.369\Re^2 - 1.907\Re + 3.997\right)* \left[1.0637(\frac{L}{D})^{-0.0542}\right] P_{al} \qquad (10)$$

3.2. Verification of the proposed design equations

The proposed design equations were used to estimate the ultimate compressive load of aluminum-concrete composite columns. The experimental results conducted by Beng Young [13], which are listed in Table (4), were used for verification of the proposed design equations. The ultimate load of the columns was calculated, by using Eqs. (7) for design based on the mechanical properties of the aluminum tube and the concrete core strength. Table (4) shows a comparison between the experimental and predicted ultimate loads. As can be seen from this table, good agreement with the test data was obtained. The average values of ratios of experimental to predicted ultimate loads are 1.0104 for the adopted design approach.

Figure (8) shows the regression analysis of the results of the proposed empirical equations of the adopted design approach. As shown in these figures, R^2 = 0.995, These values indicate a good agreement between the predicted and the actual values.

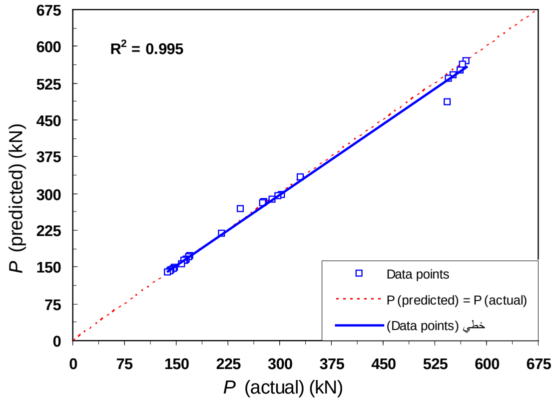


Figure (8) Regression analysis between predicted and actual values for empirical equations

Table (4) Actual and predicted ultimate load capacity using empirical equations

Cylinder compressive strength (f'_c) (MPa)	Slenderness ratio (L/D)	tube thickness (t) (mm)	diameter (D) (mm)	$\sigma_{0.2}$ (MPa)	A_a (mm^2)	Actual ultimate compressive load (P_{ac}) (kN)	Predicted ultimate compressive load (P_p) (kN)		Reference
							P_p	P_{ac}/P_p	
40	3	3.91	38	242.4	418.54	158.9	155.8	1.020	Beng Young [13]
40	3	3.13	50	238.4	460.65	217	216.7	1.001	
40	3	2.55	60	237.8	460.00	244.1	267.6	0.912	
40	3	2.06	76.1	237.0	478.92	329.9	332.0	0.994	
40	3	2.06	99.8	244.3	632.22	543.6	483.4	1.125	

4. Conclusions

This paper presents an experimental and theoretical study on concrete-filled aluminum circular hollow section columns. A series of tests was performed subjected to uniform axial compression to investigate the structural performance of the concrete-filled aluminum. The diameter-to-thickness ratio of the aluminum tubes ranged from 11.9 to 22.8. Various slenderness ratio were investigated. A total of 24 column specimens were tested. The column strengths, load- axial shortening relationship and failure modes of the columns have been presented. Based on the results of this study, the following conculutions can be drawn within the scope these test:

1. The aluminum pipe tube provided sufficient lateral support to the concrete core and increased the ultimate strength of the column.
2. The ratio of strength of aluminum-concrete composite column to strength of aluminum tube column ranged between 1.405 and 1.751 for columns with slenderness ratio = 3.
3. the ductility of concrete- filled aluminum tube columns increases with using aluminum tube columns.
4. Slenderness effect reduces the ultimate compression load capacity of the column.
5. The failure mode for short and intermediate length composite columns (L/D = 3 – 4) is a classical shear mode failure. For most slender composite columns with (L/D = 6 - 10), the failure mode of specimens fail by a long column buckling mode failure.
6. The empirical equations proposed in the present study are capable of predicting the values of ultimate loads of aluminum-concrete composite columns and the result are in good agreement with the experimental values. The average values of ratios of experimental to predicted values of ultimate loads are 1.0104 for the proposed empirical equations.

General Symbol

The following symbols are used in this paper:

A_a area of aluminum tube, mm

D outer diameter of aluminum circular hollow section tube, mm

E_0 initial Young's modulus, GPa

f_c measured concrete cylinder strength, MPa

L length of column specimen, mm

P_{ac} Actual load, kN

P_{al} Ultimate strength of aluminum tube column, kN

P_{co} Ultimate strength of aluminum-concrete composite columns, kN

P_p Predicted load, kN

$P_{compact}$ Ultimate strength of compact column, kN

$P_{slender}$ Ultimate strength of slender column, kN

R^2 Correlation coefficient

t thickness of aluminum circular hollow section tube, mm

$\sigma_{0.2}$ static 0.2%proof stress, MPa

σ_u static ultimate stress, MPa

ε_{al} Corresponding strain of aluminum tube

ε_{co} corresponding strain of aluminum-concrete composite columns

ρ_t Reinforcement ratio of aluminum tube

$\Re$ Reinforcement index

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