Behavior of Aluminum Columns Enhanced with CFRP and Filled by Lightweight Concrete

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ABSTRAT

An experimental study of composite columns of hollow circular aluminum tubes enhanced with a fibers reinforced polymer (FRP) sheet and filled by lightweight concrete are presented in this paper. The study's scope is introducing and developing lightweight columns to be advantageous in lightweight and size limited structures. The test results discussed the influence of internal and external confinement effectiveness introduced by lightweight concrete and carbon fiber reinforced polymer (CFRP) retrofitting sheet, respectively. The column specimens were subjected to uniform axial compression load. Structural aluminum alloy circular hollow section has been used in this investigation. Carbon fiber reinforced polymer (CFRP) is used to piling aluminum tubes. Light weight expansion clay aggregate (LECA) is used to fabricate light weight concrete filling aluminum tubes. The strengths, shortening displacement, axial strains, lateral strains, and failure modes of columns were presented. The test results indicated that confinement and composite action between the constituent materials resulted in enhanced compressive strength, ductility and energy dissipation capacity of the proposed composite column. Finally, a simplified design equation is proposed to predict the compressive load capacity of this type of composite column.

Keyword: Fiber reinforced polymer, Light weight concrete, Axial load, Hollow aluminum tube, Ductility.

تصرف اعمدة الالمنيوم المعززة بألياف الكاربون و المملوءة بالخرسانة خفيفة الوزن

الخلاصة

تم اجراء دراسة عملية لبيان تصرف اعمدة دائرية الشكل مكونة من انابيب الالمنيوم المملوءة بالخرسانة خفيفة الوزن والمعززة بألياف الكاربون. ان هدف الدراسة هو تقديم وتطوير اعمدة خفيفة الوزن تكون مفيدة في المنشآت خفيفة الوزن و ذات الفضاءات المحددة. ان النتائج المختبرية ناقشت تأثير التقييد الداخلي بواسطة الخرسانة خفيفة الوزن والتقييد الخارجي بواسطة الياف الكاربون على الاداء الانشائي لهذه الاعمدة. واختبرت جميع النماذج تحت تأثير حمل الانضغاط المحوري. وتم استخدام مقاطع المنيوم انشائية دائرية الشكل بينما الركام المستخدم في صناعة الخرسانة الخفيفة المالئة لأنابيب الالمنيوم هو الركام الخفيف المصنوع من الطين المحروق المنتفخ و المعروف باسم ليكا. وتم تعيين مقاومة الاعمدة للانضغاط, العلاقة بين الحمل والنقص في الطول المحوري, الانفعالات

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المحورية و الجانبية, و نمط الفشل للأعمدة. ان تأثير التقييد الجانبي و تراكب المواد المختلفة نتج عن زيادة في مقاومة الانضغاط و مقاومة التشوهات اللدنة. كما تم اقتراح معادلة مشتقة من النتائج المختبرية لتحديد تحمل هذا النوع من الاعمدة المركبة.

INTRODUCTION

Aluminum, lightweight concrete and fiber reinforced polymer (FRP) materials are favorably being utilized in the construction of structural members due to their high strength to weight ratio. Composite structures combine two or more materials in a unit structure to provide tangible benefits and a versatile solution to suite different applications. A composite system reduces the unnecessary and unwanted material properties, such as weight and cost, without sacrificing required capacity. In conventional composite columns, concrete core filled steel tubes, though steel and concrete are the most commonly used materials for composite columns, other material can be used. Aluminum is easily the second most important structural metal, yet few designers seem to know much about it. Since the 1940s, as aluminum rapidly became more important, engineers have been slow to investigate what it has to offer and how to design with it [1]. Aluminum alloys are used in a variety of structural engineering applications due to their high strength-to-weight ratio and durability [2].

Light weight concrete is a type of concrete commonly constructed of light weight coarse aggregate, normal or light weight fine aggregate, hydraulic cement and water [3]. It is used as filling material to provide sufficient lateral support of aluminum tube to prevent inward metal local buckling. FRP is a composite material made of a polymer matrix reinforced with fibers. The fibers are usually glass, carbon, basalt or aramid, although other fibers such as paper or wood or asbestos have been sometimes used. FRPs are commonly used in repairing and strengthening structures. The proper properties of light weight concrete, aluminum and FRP in additional to composite action and confinement action benefits have encouraged the author to propose, fabricate and study composite columns consists of light weight concrete and aluminum components enhanced by CFRP. The main purpose of the study is to generate data and provide information about the axial strength of aluminum lightweight concrete composite columns enhanced by FRP. In 1996, Mirmiran [4] proposed a novel composite column which is similar to the classic concrete-filled steel tubes, except that steel has been replaced with a hollow FRP shell. The FRP shell, while an integral part of the structure, is also the pour form for concrete. The proposed column offers high strength and ductility in addition to excellent durability. Behavior of the proposed column is studied by developing two analytical tools; a new passive confinement model for externally reinforced concrete columns, and a composite action model that evaluates the lateral stiffening effect of the jacket.

Experimental Investigation

Material Properties

The material properties of the different materials used in this study have been listed below;

Aluminum Circular Hollow Section

The geometrical details of the structural aluminum alloy section produced by Turkish aluminum industry used in this investigation are given in Table (1).

Aluminum material standards quote two levels of stress, both of which must be attained for a batch of material to be accepted:

f0.2 minimum value of the 0.2% proof stress (or '0.2% offset') and;

*f*u minimum tensile strength (or 'ultimate stress').

So the mechanical properties of the aluminum test specimens were determined by tensile coupon tests. The tensile coupons were taken from shell plate in the longitudinal direction of the untested specimens. The tensile coupons were prepared and tested according to the American Society for Testing and Materials standard (B557M -ASTM 2003) for the tensile testing of metals using 12.5 mm wide coupons of 50 mm gauge length [5], as shown in Plate (1). The material properties obtained from the tensile coupon tests are summarized in Table (2). The reported results are the average.

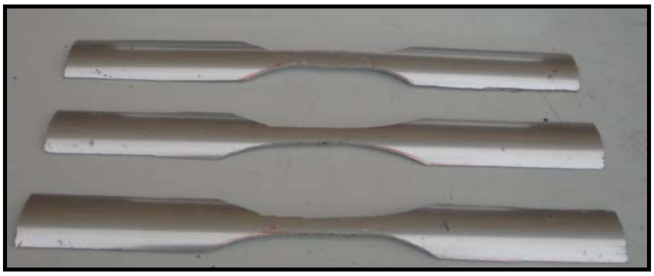


Plate (1) Aluminum tensile coupons

Table (1) Details of aluminum tube

Configra-tion	Height H, (mm)	Full diameter D, (mm)	Wall thickness t, (mm)	L/D	Mass (kg/m.l)
Circular hollow section	300	80	2	3.75	1.5

Table (2) Aluminum tensile coupons results

No.	*f0.2* yield stress (MPa)	Ultimate stress (MPa)	E (GPa)	Fracture elongation (%)
1	162.9	194.5	70.4	7
2	161.2	193.42	69.6	6.8
3	165.3	189.58	70.5	7.3

The Table includes the measured initial Young's modulus ($E0$), the static 0.2% tensile proof stress $f\,0.2$, the static tensile strength $f\,u$ [5] and the elongation after fracture which is typically measured on a gauge-length of 50 mm and gives a crude indication of ductility. Figure (1) shows the stress-strain curve for one of tested specimens. The compressive proof stress is assumed to be the same as in tension [1].

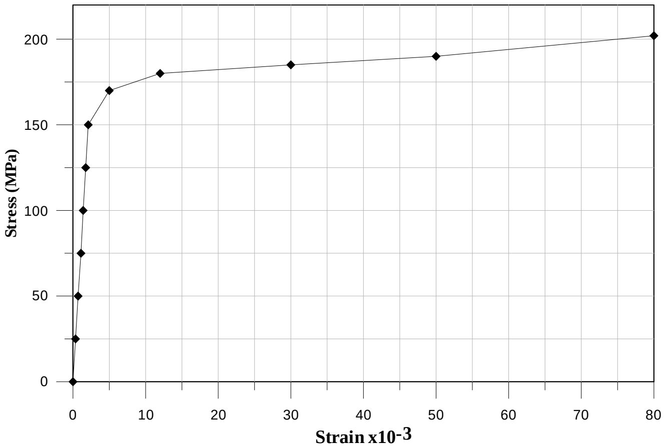


Figure (1) Stress –Strain relationship for used aluminum alloy

Carbon Fiber Reinforced Polymer (CFRP)

Sikawrap 300, unidirectional woven carbon fibers fabric equipped with weft fiber had a thickness of 0.17 mm is used to enhance aluminum columns. Sikadur 330 structural impregnating resin epoxy adhesive is used in this study which is a solvent-free, two component adhesive non sag paste. Mechanical properties of both materials (CFRP and adhesive resin) were obtained from manufacturer and listed in Table (3).

Table (3) Material properties of CFRP and epoxy resin

CFRP sheet (Sikawrap 300c)	Fiber mass per unit area (g/m2)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation (%)
	300	3900	230000	1.5
Epoxy resin (Sikadur 330)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Elongation (%)
	81.3	33.8	60.6	1.2

Lightweight Concrete

The crushed lightweight aggregate (LECA) was used to product light weight concrete. The volumetric method which is recommended by ACI adopted to specify mix proportions of light weight concrete [3].

The concrete mixture was intended to provide 21 MPa a concrete compressive strength. Concrete mix Proportions (cement: fine: coarse aggregate - w/c) are (1: 1.5: 0.8 - 0.41), the average compressive strength at 28 days was found to be 20 MPa. The density of used lightweight concrete found to be 17.1 kN/m3. It is compatible with the study's scope to develop lightweight units.

Light Expanded Clay Aggregate (LECA)

Light Expanded Clay Aggregate (LECA) is consist of small, lightweight, bloated particles of burnt clay. The thousands of small, air-filled cavities give LECA its strength, lightness and thermal insulation properties. The base material is plastic clay which is extensively retreated and then heated and expanded in a rotary kiln. Finally, the product is burned at 1100 °C to form the finished LECA product. The sieve analysis and water absorption of the aggregate with different fashions are given in Table (3).

The results show that the grading was within specification limits determined by ASTM [6]. The size of LECA aggregates were between (4.75 to 19.5) mm. The water absorption of the LECA aggregate was 17.02%. The grading and physical properties of LECA coarse aggregate and normal fine aggregate are summarized in Table (3).

Table (3) Grading and physical properties of LECA aggregate and normal aggregate

Sieve size (mm)	Normal weight aggregate (% passing mass)	Light weight aggregate, LECA (% passing mass)
	Fine	Coarse
25	_	100
19	_	91
12.5	_	
9.5	_	14
4.75	100	0
2.36	93	_
1.18	67	_
300Mm	48	_
150 Mm	22	_
75 Mm	3	
Water absorption (%)	1.08	17
Bulk density (kg/m3)	1720	790

TEST SPECIMENS

The tests were conducted on specimens with and without lightweight concrete filling which retrofitted with CFRP bonded to their fully outer surfaces in different fibers orientation; either transversally (α = 0o) or inclined (α = 45o) as shown in Fig.(2). The bare aluminum column is also tested for reference purposes. The column length (L=300 mm) is chosen so that the length to outer diameter (D=80mm) ratio generally remained at a constant value of 3.75n to prevent overall buckling. The details and configurations of column specimens are shown in Table (4).

Table (4) Column specimens *

No.	Specimens Designation	Specimens Description	CFRP orient
1	A	Bare aluminum column	-
2	C	Lightweight concrete core	-
3	AC	Aluminum columns filled by light weight concrete	-
4	AFT1	Aluminum columns jacketed by CFRP	Transverse fibers orientation
5	AFI1		Inclined fibers orientation
6	ACFT1	Aluminum columns filled with light weight concrete and jacketed by CFRP	Transverse fibers orientation
7	ACFI1		Inclined fibers orientation
8	ACFT2	Aluminum columns filled with light weight concrete and jacketed by two layer of CFRP	Transverse fibers orientation
9	ACFI2		Inclined fibers orientation

* Designations; ACFij
A: Aluminium tube.
C: Light weight Concrete core.
F: CFRP Jacket.
i : CFRP orientation.
T Transverse fibers orientation, α = 0o.
I Inclined fibers orientation, α = 45o.
j : CFRP layers number.

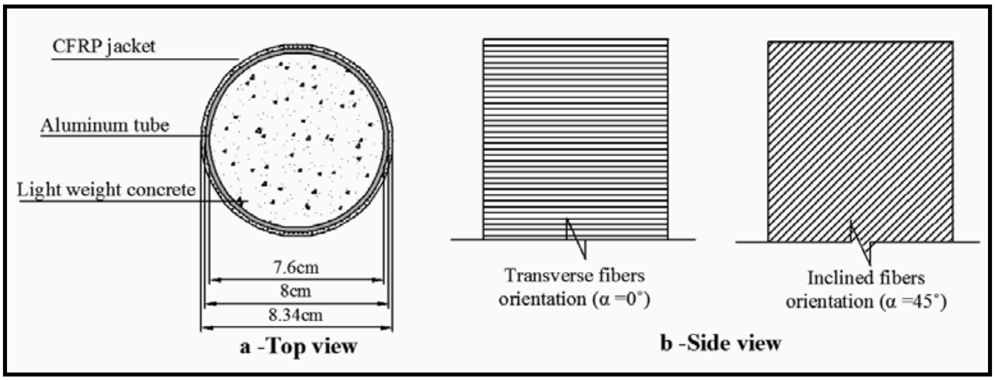


Figure (2) Column specimens details and fibers orientation configuration

Fabrication of the specimens

The concrete filled into aluminum tube gradually with carefully compaction. All specimens were cured in same conditions by immersing the specimens in water basin for seven days. Epoxy resin is used to glue the CFRP onto the aluminum column outer surfaces. The CFRP sheets impregnating with epoxy resin which is prepared by mixing its components (A+B) together for at least 5 minutes with a mixing paddle attached to a slow speed electric drill (max. 600 R.P.M.) until the material became smooth in consistency and even light grey colored of the mixture was obtained. After having the carbon fiber ply attached, the column specimens were completely cured for 7 days. Plate (2) clearly shows retrofitting process.

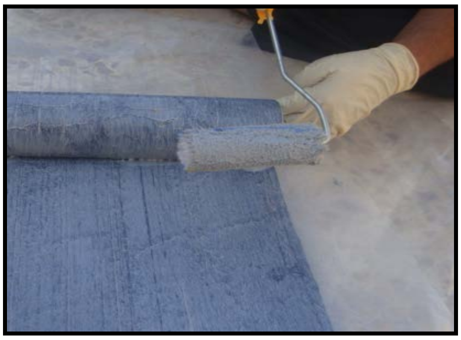


Plate (2) Specimens retrofitting process

TESTING PROCEDURE

A hydraulic compression testing machine (200 Ton) was used to apply compressive axial load to the column specimens, Plate (3). The load on columns was applied monotonically in increments. These increments were reduced in magnitude as the load reaches the ultimate load.

Plate (3) Testing arrangement

TEST RESULTS

The specimens' strength, load–axial displacement relationships, lateral strains and were measured for each column specimens.

Figure (3) denoted the measured load-axial displacement behavior of hollow aluminum tube filled by light weight concrete. On the same figure, the behavior is also compared with the response of the column excluding the infill concrete (hollow aluminum tube, A). The figure and listed results in Table (5) clearly indicate that the load capacity of the composite column significantly were more than concrete core or aluminum tube, where Pco/Pc and Pco/Pal ratios are (2.54) and (1.83).

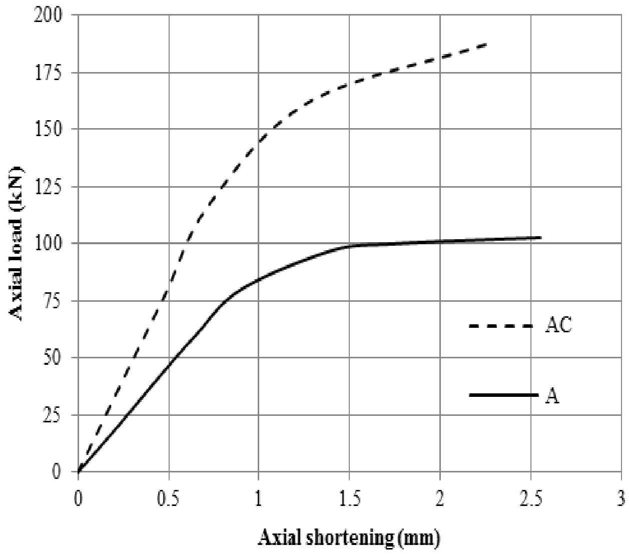


Figure (3) Variation of axial shortening with applied axial load for aluminum columns with and without light weight concrete

Figure (4) displayed equilibrium path (load-displacement curve) that provides the variation of the axial shortening with the applied load for hollow aluminum columns without and with different CFRP orientation. The observation of the results presented in the figure and Table (5) prompts clearly the effect of CFRP orientation upon hollow columns behavior. Specimens retrofitted with transvers mode exhibited higher loading capacity increment and more plastic deformation resistance than another orientation mode before failure. For all specimens, the ratio *P/Pa*l is larger than (1), the average is (1.16). In term of ductility, the ratio ε/εal varies between (2.09 and 2.99) as the fibers orientation change from inclined to transvers mode.

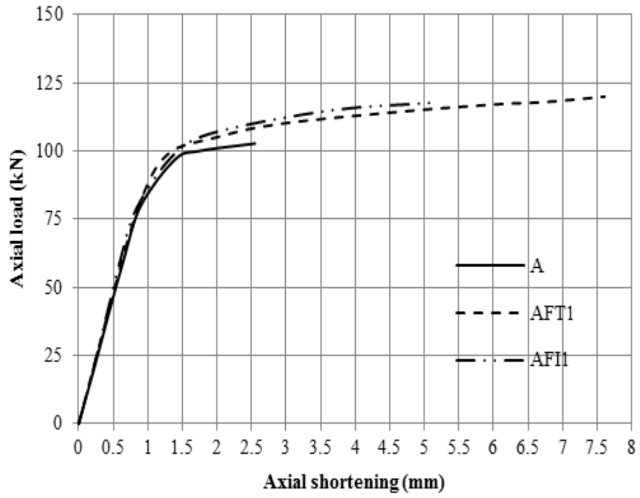


Figure (4) Variation of axial shortening with applied axial load for hollow aluminum columns with CFRP enhancing

The confinement effectiveness of the CFRP jacket can be gauged by examining the degrees of enhancement in the ultimate load and the axial shortening at peak load. As seen in Table (5), the strength ratios *(P/PAc*) of external confined aluminum filled by lightweight concrete columns (ACFT1 and ACFI1) to control column (AC) are 1.32 and 1.21. To study the effect of thickness of confined layer of CFRP, the layers doubles in specimens (ACFT2 and ACFI2), these ratios change to 1.43 and 1.31. Also a significant improvement in the ductility (axial deformation at the ultimate load) was observed for the same columns. The axial displacement data were plotted against the axial load for specimens and control column as shown in Figures (5) and (6). It is clear that the ductility of the columns increased significantly due to the confinement action, the ductility ratios ($\varepsilon/\varepsilon AC$) vary between (1.67 and 2.12) as the fibers orientation change from inclined to transvers mode. Although the strength increases with CFRP layers numbers, the ductility ratios dropped as CFRP jacket layers double in specimens, the same ratios became (1.54 and 2.02).

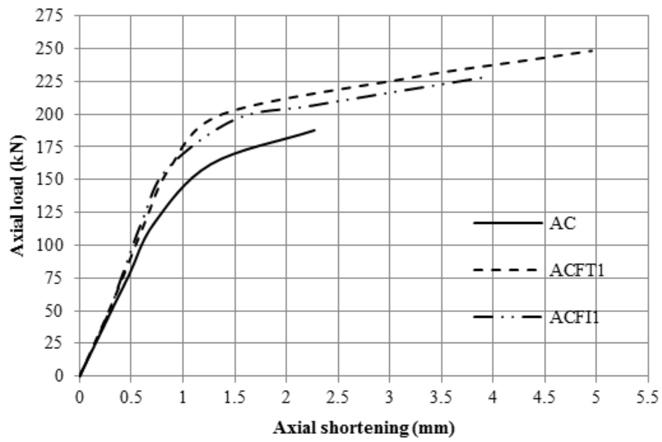


Figure (5) Variation of axial shortening with applied axial load for aluminum columns filled with light weight concrete and enhanced by one layer of CFRP sheet

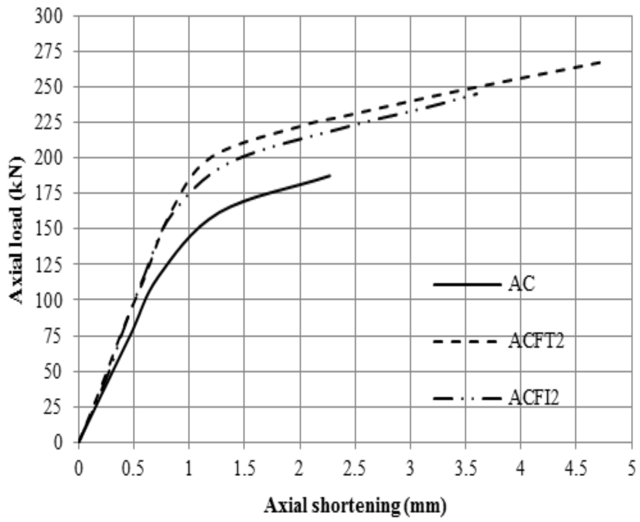


Figure (6) Variation of axial shortening with applied axial load for aluminum columns filled with light weight concrete and enhanced by two layers of CFRP sheet

The load–displacement curves shown in Figures (7) and (8) and results given in Table (5) illustrate the effect of inside confinement of lightweight concrete with remarkable difference in the external confinement effectiveness by CFRP, it can be seen that the use of light weight concrete filling is extremely positive for specimens with external confinement, filling prevent inward local buckling as outward local buckling prevented by external confinement. The strength ratios of external confined aluminum - lightweight concrete column (ACFT1, ACFT2) to control column (AFT1) are 2.07 and 2.24, when the external fibers orient of retrofitting sheet change from transversely (0̊) to inclined mode (45̊) in specimens (ACFI1, ACFI2) the previous ratios change to 1.94 and 2.09. It is clear that as for externally confined hollow columns, the specimens retrofitted with transvers mode exhibited higher loading capacity increase and more plastic deformation than another orientation mode before failure and so it is seem fit for enhancing such columns especially when ductility is the extremely dominated factor. The significantly higher confinement effectiveness was almost twice the strength of those without filling.

It is evident from results that, while the CFRP jacketing hollow aluminum tubes increases the strength, it does not have much effect on stiffness as shown in Figure(4). The same system with filling lightweight concrete is efficient in increase strength as well as stiffness, Figures (7) and (8).

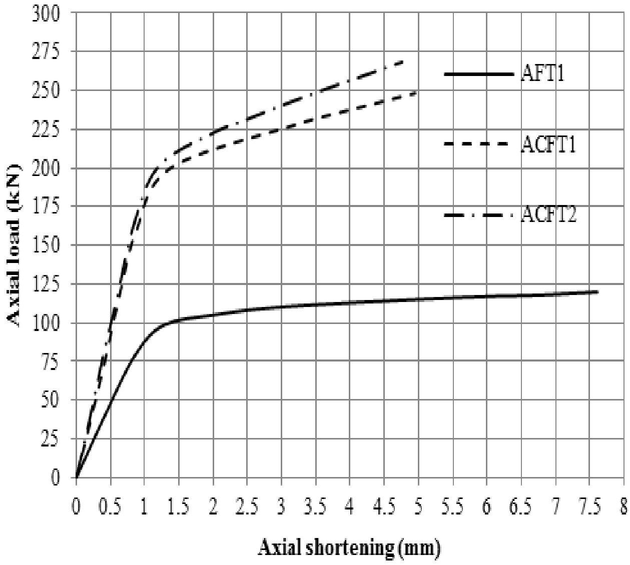


Figure (7) Variation of axial shortening with applied axial load for aluminum-lightweight concrete columns retrofitted transversely (α = 0o) by different numbers of CFRP sheet

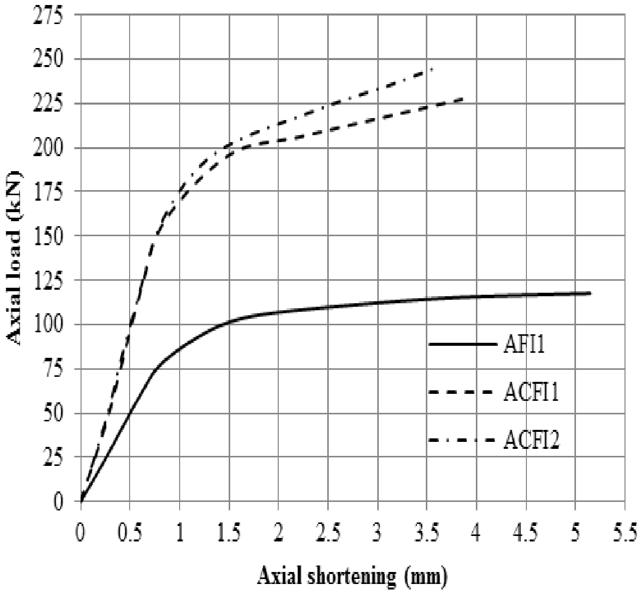


Figure (8) Variation of axial shortening with applied axial load for aluminum-lightweight concrete columns retrofitted inclinedly (α = 45o) by different numbers of CFRP sheet

Table (5) Test results

No.	Specimen designation	P* (kN)	P/Pal	P/Pc	P/PAC	P/PAF	Ultimate axial strain, ε	ε/εal	ε/εAC	Lateral strain, ε'
1	A	102.7	1				0.0085	1		0.011
2	C	74	0.72	1			0.0038			0.002
3	AC	187.72	1.83	2.54	1		0.0078	0.92	1	0.012
4	AFT1	119.9	1.17			1	0.0254	2.99		0.003
6	AFI1	117.7	1.15			1	0.0172	2.02		0.00213
7	ACFT1	248.35	2.42	3.36	1.32	2.07	0.0165	1.94	2.12	0.0057
8	ACFI1	228	2.22	3.08	1.21	1.94	0.013	1.53	1.67	0.0041
9	ACFT2	268.31	2.61	3.63	1.43	2.24	0.0158	1.86	2.03	0.0052
10	ACFI2	245.5	2.39	3.32	1.31	2.09	0.012	1.41	1.54	0.0038

*P is ultimate strength.
The subscript denotation (al), (c), (AC) and (AF) refer to bare hollow aluminum tube, concrete core, aluminum-lightweight concrete column and hollow aluminum tube enhanced by CFRP, respectively.

FAILURE MODES

The light weight concrete core suffers from 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 usually occurred suddenly at strain 0.0039. For hollow aluminum tubes, bare aluminum fails prematurely by outward local buckling (elephant foot mode), for specimen with transversely fibers orientation of CFRP sheet, the failure is signified by inward local buckling while specimen wrapped with inclined mode of fibers orientation, the typical failure is shear failure with angle of approximately 45°, companies with inside crimpling.

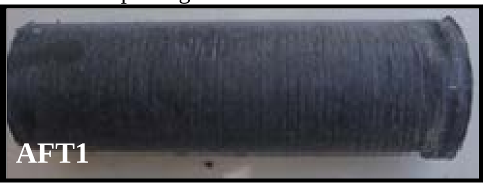
The failure mode of aluminum column filled by lightweight concrete without retrofitting is a classical shear mode failure.

For all specimens of aluminum tubes which are filled by lightweight concrete and retrofitted by CFRP layer, the signification failure mode is rupturing of the CFRP jacket then debonding of it after slightly lateral expansion, it seems that the confinement exerted by the CFRP and light weight filling concrete could fully supports the aluminum tube and prevents premature failure and restrains its excessive expansion. The failure modes of tested specimens are shown in Plate (4).

Outward local buckling, elephant foot

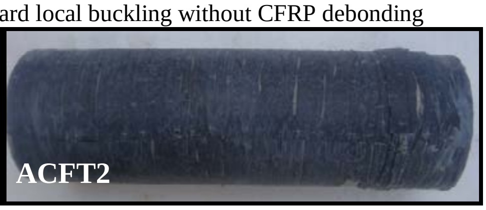
Splitting

Classic shear failure



Inward local buckling without CFRP debonding

Rupturing then debonding of the CFRP



Rupturing then debonding of the CFRP

Shear failure companies with inside crimpling

Rupturing then debonding of the CFRP

Rupturing then debonding of the CFRP

Plate (4) Failure modes of tested specimens

EMPERICAL ANALYSIS EQUATIONS

The confinement and composite action between the constituent materials result in enhanced compressive strength, ductility and energy dissipation capacity of the proposed composite column. For composite action, the axial strengths Pco were obtained by determining the strength of the aluminum tube (Aa *fa*) using the specifications for aluminum structures as well as the strength of concrete infill (0.85 *fcu* Ac) [7], as shown in Eq. (1).

$$Pco = Aa\, fa + 0.85 Ac\, fcu \qquad \ldots(1)$$

where:

Aa is the net cross-section area of aluminum tube, mm.

fa is the limit state stress of aluminum calculated using the Eurocode specification, MPa [8].

Ac is the area of concrete mm.

fcu is the concrete strength, MPa.

Materials properties obtained from the tensile coupon tests for aluminum tubes in the calculation of the first term Aa *f*a in Eq. (1). The measured material properties obtained from the tensile coupon tests are shown in Table 2. The calculation of the strength of the concrete infill for the term 0.85Ac *fc'* in Eq. (1) is carried out using the measured concrete cylinder strengths.

For confinement action (CFRP sheet confined aluminum tubes filled by lightweight concrete (composite columns), the experimental results had been translated to an empirical equations could be present a guideline for design of such columns. In this approach the CFRP is treated as an external reinforcement to the aluminum-lightweight composite column. The adopted approach was based on the experimental results presented in this study. In aluminum – lightweight columns enhanced by CFRP, the volume fraction (ρ) is the ratio of CFRP volume to aluminum tube volume, this ratio defines as:

$$\rho = vCFRP / val ,$$

and can be reduced to:

$$\rho = tCFRP / tal$$

where *t* is CFRP and aluminum wall thickness, respectively. However, aluminum tubes are available with different tensile strengths (according to the manufacturers specifications) and also CFRP of different strengths may be used to retrofitting these tubes, Therefore a parameter, called reinforcement index η , is introduced to allow for comparing composite columns of different material. The reinforcement index is defined as the ρ multiplied by the ratio of the axial tensile strength of CFRP to aluminum tube *f*0.2 as follows:

$$\eta = \rho\ (f\,FRP / f\,0.2) \qquad \dots (2)$$

The ultimate strength (*P*cc) of aluminum-lightweight columns enhanced by CFRP is normalized with respect to the strength of a corresponding aluminum – lightweight composite column (*Pco*) in a dimensionless form at as follows:

$$Ø = Pcc / Pco \qquad \dots(3)$$

The relationship between the reinforcement index η and the normalized strength Ø may be assumed of the form:

$$Ø = f\,(\eta) \qquad \dots(4)$$

After investigating several possible forms of expressions for the reinforcement index η , the following expression was obtained:

$$Ø = a + b\ (\eta\ c) \qquad \dots (5)$$

where a, b, and c are constants to be determined empirically, *P*cc is the ultimate strength of confined aluminum – lightweight concrete columns which are enhanced by CFRP, and *P*co is the strength of aluminum - lightweight columns (*Pco* = Aa *fa* + 0.85Ac *fcu*). Using the experimental results, a regression analysis was performed to obtain the constants. The expression for reinforcement index η , evaluated by the best-fit curve from the regression analysis are shown in Figure (9) and empirical equations displayed as following:

For α=0°

$$Ø = (-0.0285\ \eta 2 + 0.2213\ \eta + 1) \qquad \dots(6)$$

For α=π/4

$$Ø = (-0.0145\ \eta 2 + 0.1359\ \eta + 1) \qquad \dots (7)$$

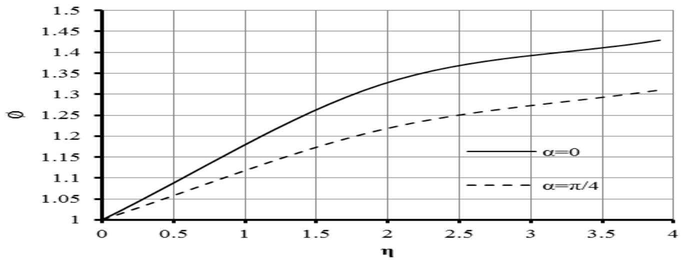


Figure (9) Variation of reinforcement (η) index with normalized axial strength(Ø)

CONCLUSIONS

A present type of column consisting of aluminum filled by lightweight concrete then enhanced by CFRP was introduced and tested under axial compressive loading. The proposed systems could be utilize in new structures or strengthening applications to increase the load carrying capacity, ductility and energy dissipation capacity of aluminum columns. It is advantageous in lightweight and size limited structures.

Specimens retrofitted with transvers mode exhibited higher loading capacity increase and more plastic deformation resistance than another orientation mode before failure and so it is seem more fit for enhancing such columns especially when ductility is the extremely dominated design factor. The ductility of the columns increased significantly due to the confinement action, the ductility ratios (ε/εAC) vary between (1.67 and 2.12) as the fibers orientation change from inclined to transverse mode. Although the strength increases with CFRP layers numbers, the ductility ratios dropped as CFRP jacket layers double in specimens, the same ratios became (1.54 and 2.02).

The confinement and composite action between the constituent materials result in enhanced compressive strength, ductility and energy dissipation capacity of the proposed composite column. The significantly higher confinement effectiveness was almost twice the strength of those without filling.

It is evident from test results that, as the CFRP jacketing of hollow aluminum tubes increases the strength, it does not have much effect on stiffness. The same system with lightweight concrete found to be efficient to increase strength as well as stiffness.

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