EXPERIMENTAL INVESTIGATION OF CIRCULAR ALUMINUM COLUMNS ENHANCED BY FRP

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ABSTRACT

In structural engineering, introducing an efficient structural elements with high ratio of strength or ductility to weight is a challenge. This paper is presenting and developing aluminum columns having circular hollow section strengthened with CFRP possess the highest specific (divided - by weight) mechanical properties to be advantageous in lightweight and space limited structures. The structural performance of these columns was investigated experimentally by using different strengthening orient styles and CFRP piling layers. The column specimens were subjected to uniform axial compression. The strength, ductility, axial load- shortening displacement relationships, lateral strains, and failure modes of columns were presented. Designing guideline empirical equations were derived from experimental results, the predicted unfactored strengths are found to be in a good agreement with the experimental values.

Key words: Aluminum column, CFRP, Strengthening and fiber orient.

دراســـة عمليــة لأعمدة الالمنيــوم دائريــة المقطــع و المعــززة بأليــاف الكاربــون

الخـلاصـة

ان عملية تقديم عناصر انشائية بمقاومة او مطيلية عالية بالنسبة لوزنها تمثل تحدي. ان هدف البحث هو تطوير اعمدة من مقاطع الالمنيوم المقواة بألياف الكاربون ذات خواص ميكانيكية عالية بالنسبة لوزنها لتكون ذات اهمية في المنشآت خفيفة الوزن او ذات الفضاءات المحددة. ان الاداء الانشائي لهذه الاعمدة تم التحري عنه مختبريا باستخدام انماط مختلفة و بعدد طبقات مختلف من الياف الكاربون. تم تعريض النماذج الى احمال محورية و تم بيان ألمقاومة، المطيلية، علاقات الاحمال المحورية مع ازاحات التقاصر، الانفعالات الجانبية بالإضافة الى انماط الفشل. تمت الاستفادة من النتائج المختبرية في اشتقاق معادلات وضعية يمكن ان تكون مفيدة في تصميم الاعمدة المعدنية المجوفة و المعززة بألياف الكاربون، النتائج المستخلصة من هذه المعادلات كانت متوافقة مع النتائج المختبرية .

1. INTRODUCTION

Aluminum is easily the second most important structural metal. 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]. FRP is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass, carbon, basalt or aramid, although other fibres such as paper or wood or asbestos have been sometimes used. The proper properties of used materials in additional to composite action benefits have encouraged the author to propose, fabricate and study proposed composite columns. The target is utilizing the respective advantage of used materials to the fullest extent. The objective of this work is to generate data and provide information about the axial strength, stiffness, ductility and energy dissipation of aluminum columns enhanced by FRP. A substantial amount of research focusing on the effectiveness of FRP confinement in improving the structural behavior of concrete-filled steel tubular columns [3-7]. A few studies have concentrated on the behavior of hollow metal sections and was limited on steel sections. In 2006, J.G. Teng [8] presented study in which the benefit of FRP confinement of hollow steel tubes was explored. Axial compression tests on FRP-confined steel tubes are first described. Finite element modeling of these tests is next discussed. Both the test and the numerical results show that FRP jacketing is a very promising technique for the retrofit and strengthening of circular hollow steel tubes. In other hand, using the FRP and strengthening aluminum in various structural elements limited too. In 1991, Triantafillou [9] investigated the flexural behavior of hybrid aluminum/CFRP members, in which a principal aluminum structure is reinforced with unidirectional carbon fiber reinforced polymer CFRP composite laminates.

1.1 Preliminary Structural Benefits of Aluminum and FRP

To select a particular structural material for a given application, its properties are evaluated and compared with other competing materials. The following points are reflected powerful properties of aluminum and CFRP as they are utilizing together in composite unit.

1- The applicability and cost-efficiency of the FRP strengthening concept depends largely on the material behavior of the member to be strengthened. Aluminum is much more feasible (i.e. economical) to satisfy the following key requirement: the strengthening material must be stiffer than the base material of the strengthened member. Since aluminum members are considerably softer (less stiff) than the most commonly used FRP composites, so strengthening them much positive than bare steel member which is stiffer than more common FRP and so requires expensive high-strength fibres and, thus, this procedure has fibers stress transfer can only occur after steel has started to yield.

2- They possess the highest specific (divided - by weight) mechanical properties: modulus of elasticity and strength.

3- Avoiding the reduction of aluminum strength due to the effect of welding heat required to connect metals stiffeners .

4- As aluminum is more prone to fatigue problem than steel, so strengthening aluminum columns by FRP will develop high improvement for ductility and so energy dissipation which are enhancing fatigue strength.

2. EXPERIMENTAL INVESTIGATION

2.1 MATERIAL PROPERTIES

2.1.1 Aluminium Circular Hollow Section

Structural aluminum alloy sections has been used in this investigation. The geometrical details are shown in Table (1). 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, [10] 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.

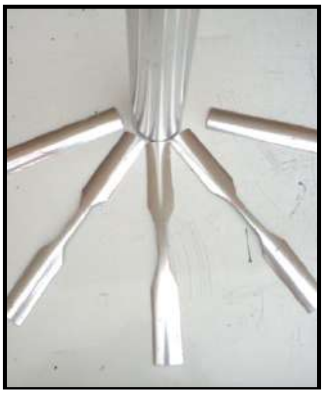

Plate (1) Aluminum tensile coupons

Plate (3) Test setup of aluminum coupons

Table (1) Details of aluminum section

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

Table (2) Aluminum tensile coupons results

No.	$f_{0.2}$ 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 (E), the static 0.2% tensile proof stress $f_{0.2}$, the static tensile strength f_u [10], 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].

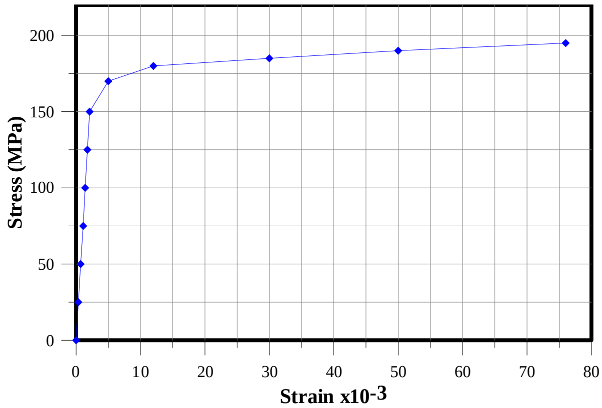

Figure (1) Stress –Strain relationship for aluminum alloy

2.1.2 Carbon Fiber Reinforced Polymer (CFRP) and Epoxy Resin

Sikawrap 300, unidirectional woven carbon fibers fabric equipped with weft fiber had a thickness of 1.7 mm is used to enhance aluminum columns, Plate (2).

Plate(2) Aluminum tube and CFRP before retrofitting

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. Mechanical properties of them are listed in Table (3).

Table (3) Material properties of CFRP and epoxy resin

CFRP sheet (sikawrap 300c)[11]	Fiber mass per unit area (g/m^2)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation (%)
	300	3900	230000	1.5
Epoxy resin (sikadur 330) [12]	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Elongation (%)
	81.3	33.8	60.6	1.2

2.2 TEST SPECIMENS

The tests were conducted on specimens retrofitted with CFRP, which are bonded to their fully outer surfaces in different layer numbers and fibres oriented either longitudinally ($\alpha = 0^o$) , transversally ($\alpha = 90^o$) or inclined ($\alpha = 45^o$). The bare aluminum column is also tested for reference purposes. The column length (L=300 mm) is chosen so that the length to diameter (D=80mm) ratio generally remained at a constant value of 4.25 to prevent overall buckling. The fibers orient of CFRP retrofitting layers are shown in Figure (2) while briefly details and configurations of column specimens are shown in Table (4).

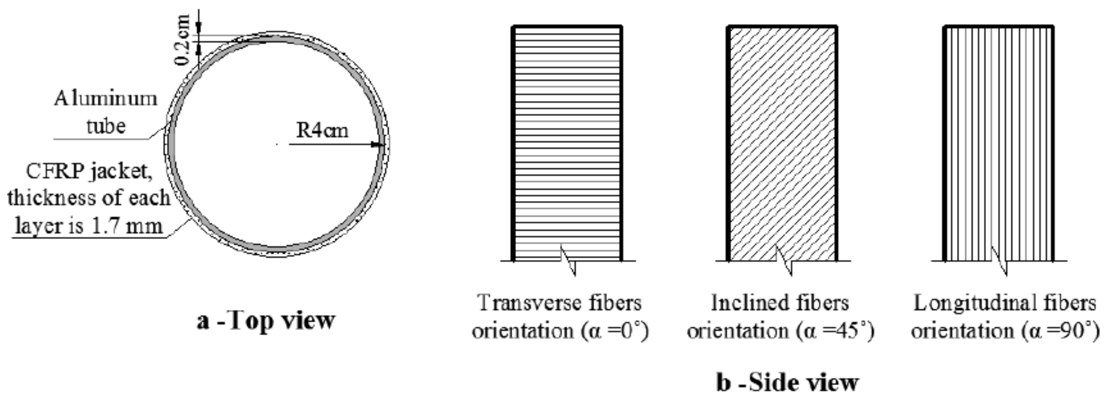

Figure (2) Fibers orient configuration

Table (4) Details of columns*

No.	Specimens Designation	Column Description	CFRP layers numbers	CFRP orient
1	A	Bare aluminum column	-	
2	A_{FT}	Aluminum columns jacketed by CFRP	1	Transverse
3	A_{FTT}		2	Transverse for both layers
4	A_{FL}		1	Longitudinal
5	A_{FLL}		2	Longitudinal for both layers
6	$A_{FTL\#}$		2	Longitudinal and transverse fibres orient, first layer perpendicular on second layer
7	A_{FI}		1	Inclined
8	A_{FII}		2	Inclined fibres orient, first layer parallel to second layer
9	$A_{FII\#}$		2	Inclined fibres orient, first layer perpendicular on second layer

***Designations;** A_{Fij} **#**

A: **A**luminium tube.

F: Jacketed by C**F**RP.

i and j: CFRP orientation of first and second layer (if available), respectively.

T **T**ransverse fibres orient, $\alpha = 0^o$.

L **L**ongitudinal fibres orient, $\alpha = 90^o$.

I **I**nclined fibres orient, $\alpha = 45^o$.

#: CFRP layered with opposite orients, the first orient 0^o and the second 90^o or the first 45^o and the second -45^o.

2.2.1 Fabrication of the specimens

The epoxy resin 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 fibre ply attached, the column specimens were completely cured for 7 days. Plate (3) clearly shows manufacture process.

3. TESTING PROCEDURE

A hydraulic compression testing machine (200 Ton) was used to apply compressive axial load to the column specimens, Plate (4). The load on columns was applied monotonically in increments. These increments were reduced in magnitude as the load reaches the ultimate load.

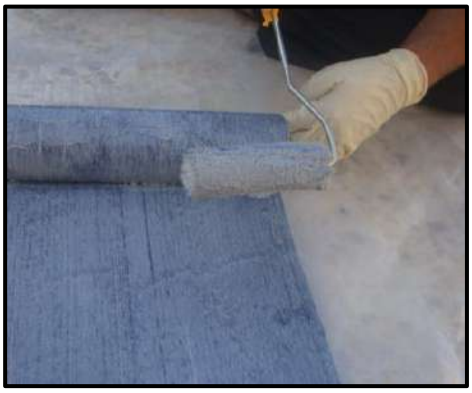

Plate (3) Specimens manufacture process

Plate (4) Testing arrangement

3.1 TEST RESULTS

The strength, load–axial shortening relationships, lateral strains and energy absorption were measured for each column specimens.

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) and Fig. (2), the ultimate load of the aluminum tube was enhanced by 17–34% when using CFRP jackets of different orients. For all specimens, the ratio P_{co}/P_a is always larger than one, ranging between 1.18 and 1.32. The increase ratios are high compare with steel hollow columns retrofitted with FPR which are enhanced by 5–10% by FRP jackets of different thicknesses [8], since aluminum members are considerably softer (less stiff) than the used CFRP composites, so strengthening them more positive than bare steel member which is stiffer than more common FRP.

Also from Table (5), it can be seen that the use of CFRP is extremely efficient in term of ductility. The ratio $\varepsilon_{co}/\varepsilon_{a}$ is always more than one, ranged between (1.5) and (2.98), except for specimens retrofitted with longitudinal fibres orient, the effect is so limited as the ratio vary between 1.1 and 1.15.

An efficiently concise comparison can be made in term of energy absorption. The energy absorbed by each of the columns was calculated as the area under the curve of the axial load versus the axial deformation curve. These energies are shown in Fig. (3). It is clear that the CFRP wrapped columns had more energy before collapse. Specimens which are transversely wrapped CFRP exhibited highly energy absorption compared with other warping styles.

Table (5) Specimens test results*

No.	Specimen designation	P_{al} (kN)	P_{co} (kN)	P_{co}/P_{al}	ε_{al}	ε_{co}	$\varepsilon_{co}/\varepsilon_{al}$	ε'
1	**A**	102.7			0.0085			0.011
2	**A_{FT}**		119.9	1.17		0.0254	2.98	0.003
3	**A_{FTT}**		132	1.29		0.0245	2.88	0.005
4	**A_{FL}**		118.1	1.15		0.0094	1.1	0.002
5	**A_{FLL}**		126.3	1.23		0.0098	1.15	0.0022
6	**$A_{FTL\#}$**		136	1.32		0.0127	1.5	0.0039
7	**A_{FI}**		117.7	1.15		0.0172	2.02	0.00213
8	**A_{FII}**		122.4	1.19		0.0136	1.6	0.006
9	**$A_{FII\#}$**		128.2	1.25		0.0188	2.22	0.0025

*P_{al} and P_{co} are aluminum tube and composite columns ultimate strengths, respectively.

ε_{al} and ε_{co} are aluminum tube and columns axial ultimate strains, respectively.

ε' lateral ultimate strain of different specimens

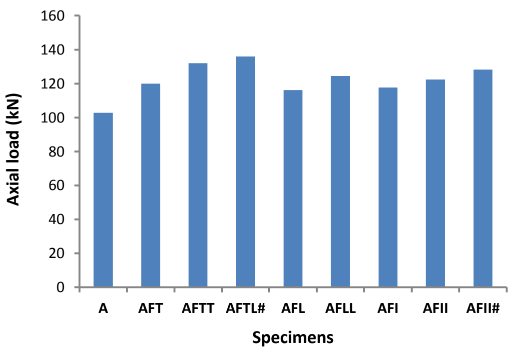

Figure (2) Axial loading capacity of tested column specimens

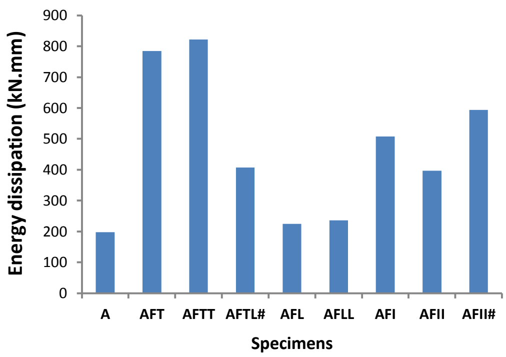

Figure (3) Columns absorbed energy before failure

Figur ... (P-δ ... column axial shortening with the applied load. The observation of the results presented in these figures and tables prompts clearly the effect of CFRP orient upon columns behavior. Specimens retrofitted with transvers mode exhibited relatively high loading capacity improvement and more plastic deformation resistance than other orient modes (longitudinal or inclined) and so it is seem more fit for enhancing such columns especially when ductility is the extremely dominated factor. Specimens retrofitted with longitudinal mode did not show acceptable plastic deformation before failure.

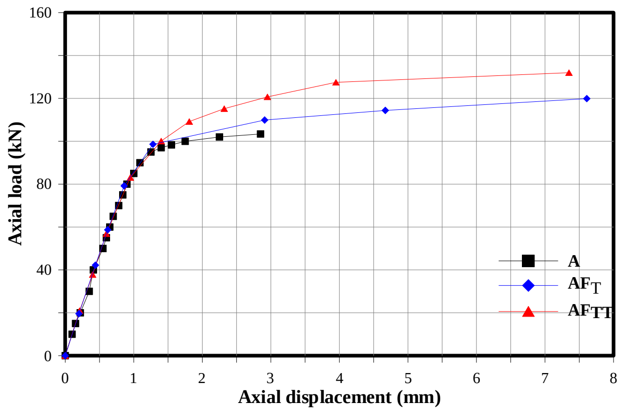

Figure (4) Variation of axial loading capacity verse axial deformation with different CFRP layer numbers (transvers fibre orient)

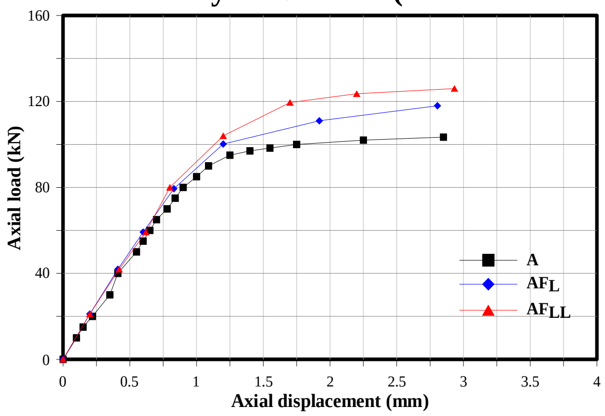

Figure (5) Variation of axial loading capacity verse axial deformation with different CFRP layer numbers (longitudinal fibre orient)

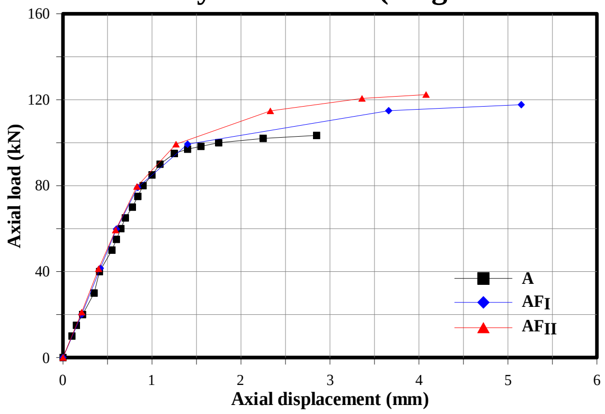

Figure (6) Variation of axial loading capacity verse axial deformation with different CFRP layer numbers (inclined fibre orient)

The comparison of Fig. (7) with Fig. (8) denoted that the CFRP piling numbers effect upon columns strength capacity and energy absorption for columns with inclined, transversely or longitudinal orient. Columns transversely retrofitted are relatively reflected high effect, the capacity increases ratio of column retrofitted with two layer in respect to that of one layer is (1.17) while the increase ratio of column retrofitted with one layer in respect to bare aluminium column is (1.1).

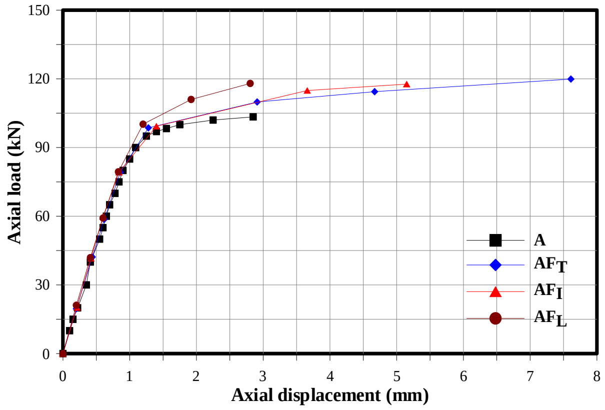

Figure (7) Variation of axial loading capacity verse axial deformation with different CFRP fibre orient (one CFRP layer)

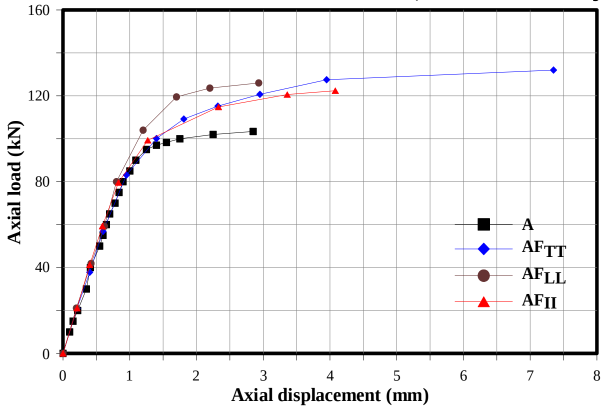

Figure (8) Variation of axial loading capacity verse axial deformation with different CFRP fibre orient (two CFRP layers)

Figure (9) illustrated the effect of using two layers with opposite fibre orients. The figure denoted that using inclined mode with anti-direction provide much ductility and so much energy absorption, the ratio ($\varepsilon_{co}/\varepsilon_{al}$) is 2.22 compares with 1.6 when two layers are parallel while column retrofitted with two layer, the first orient was longitudinal and the second was transvers, provide highest loading capacity increase ratio (P_{co}/P_a = 1.35).

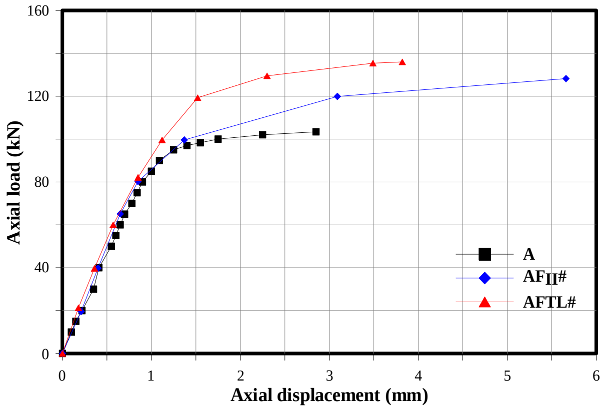

Figure (9) Effect of CFRP opposite fibre orients of retrofitted two layers upon columns axial loading capacity

3.2 FAILURE MODES

The failure of aluminum column enhanced by CFRP may stem from i- Outward local buckling (elephant food configuration) ii- Inward local buckling iii-Shear mode companies with inside crimpling. Thus, an efficient (safe and economical) design of such members must be based on an in-depth knowledge concerning all these potential failure modes. Plate (5) crudely shows a photograph of the tested column specimens while Plate (6) presents closely photographs of failure modes of tested specimens.

The hollow aluminum tube, Plate (6 a), fails prematurely by outward local buckling and so specimens with longitudinal wrapping, fail quietly by outward local buckling after CFRP layer debonding, Plate (6 b). For specimens transversely wrapped, the failure is signified by inward local buckling as shown in Plate (6 c), while specimens wrapped with inclined mode of fibers orient, the typical failure is shear failure with angle of approximately 45°, companies with inside crimpling, Plate (6 d). It seems that the confinement exerted by the CFRP could fully prevent the tube from local buckling in the case of inclined wrapping and in case of opposite fiber orient of retrofitting two layers. In all column specimens, the confinement supports the aluminum tube and prevents premature failure and restrains its excessive expansion. Failure usually occurred quietly.

Plate (5) Photograph of the tested columns

Outward local buckling, elephant foot

Outward local buckling after CFRP debonding.

Inward local buckling without CFRP debonding

Shear failure companies with inside crimpling.

Plate (6) Failure modes

4. DERIVED EMPERICAL EQUATIONS

An empirical equations had been derived depending on experimental results and could be useful as a guideline for designing and analysis of such columns. In this approach the CFRP is treated as an external reinforcement to the aluminum tube. The adopted approach was based on the experimental results presented in this study.

In aluminum columns enhanced by CFRP, the volume fraction (ρ) is the ratio of CFRP volume to aluminum tube volume, this ratio define as; ($\rho = A_{CFRP} / A_{al}$) , and can be reduced to ($\rho = n\ t_{CFRP} / t_{al}$), where n is layer numbers and 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:

$$\eta = \rho \left(\frac{f_{FRP}}{f_{0.2}} \right) \quad \text{-------------------------- (1)}$$

The ultimate strength (P_c) of aluminum- column enhanced by CFRP is normalized with respect to the strength of a corresponding aluminum tube column (P_{al}) in a dimensionless form at as follows:

$$\emptyset = \frac{P_c}{P_{al}} \quad \text{-------------------------- (2)}$$

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

$$\emptyset = f(\eta) \quad \text{-------------------------- (3)}$$

After investigating several possible forms of expressions for the reinforcement index η aluminum columns enhanced by CFRP, the following expression was obtained:

$$\emptyset = a + b\,\eta + c\,\eta^2 \quad \text{---------------------------- (4)}$$

where a, b, and c are constants to be determined empirically, Pc is the ultimate strength of composite column, and P_{al} is the strength of aluminum tube columns ($P_{al} = A_a f_{0.2}$). 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 Fig. (10) and empirical equations displayed as following:

For α=0°

$$\emptyset = (-0.0066\,\eta^2 + 0.0987\,\eta + 1) \quad \text{------------------------} \quad (5)$$

For α=π/4

$$\emptyset = (-0.01318\,\eta^2 + 0.1006\,\eta + 1) \quad \text{------------------------} \quad (6)$$

For α=π/2

$$\emptyset = (-0.009206\,\eta^2 + 0.0949\,\eta + 1) \quad \text{---------------------} \quad (7)$$

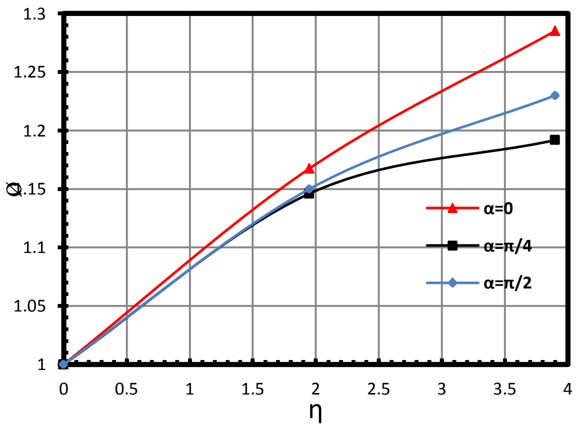

Figure (10) Variation of reinforcement (η) index with normalized axial strength (Ø)

The experimental results conducted by Teng[8], which are concerned with steel columns strengthen by GFRP, were used for verification of the derived empirical equations. The ultimate load of columns was calculated by using eq.(7) based on mechanical properties of steel tube and FRP, which are listed in Table (6). The comparison results in Table (6) show a good agreement between the experimental and predicated ultimate loads.

Table (6) Experimental and predicted ultimate load capacity using empirical equations*

No.	Steel tube				FRP				P_c (kN)	P_p (kN)	P_c/P_p	Ref.
	$f_{0.2}$ (MPa)	E_s (GPa)	D (mm)	t (mm)	f_{FRP} (MPa)	E_{FRP} (GPa)	t (mm)	Piling No.				
1	333.6	201	165	4.2	1825.5	80.1	1.7	0	717.5	717.5	1	[8]
2			165					1	740.4	743.33	0.9961	
3			165					2	771	765.57	1.0071	
4			165					3	782.2	786.38	0.9947	

*P_c Experimental ultimate load of strengthening columns (kN)

P_p Predicated ultimate load calculated by using empirical equations (kN)

5. CONCLUSTION

The proposed columns could be utilize in new construction or retrofit applications to increase the load carrying capacity, ductility and energy dissipation capacity of aluminum columns.

The strength capacity increase ratios are high compare with steel hollow columns retrofitted with FPR which are enhanced by 5–10% by FRP jackets of different thicknesses[8] while for aluminum hollow columns are enhanced by 17-34 %. The most effective CFRP-strengthening in term of axial loading capacity is associated with gluing layers of FRP with opposite fibers orient (transversely and longitudinally) with load direction.

The use of CFRP is extremely positive in term of ductility. The ratio $\varepsilon_{co} / \varepsilon_{\mathrm{a}}$ is always more than one, ranged between (1.5) and (2.98), except for specimens retrofitted with longitudinal fibres orient, the effect is so limited as the ratio vary between 1.1 and 1.15. Specimens which are transversely wrapped CFRP exhibited highly energy absorption compared with other warping styles.

Specimens retrofitted with transvers orient fibre exhibited relatively high loading capacity increase and more plastic deformation than other orient modes (longitudinal or inclined) before failure and so it is seem more fit for enhancing such columns especially when ductility is the extremely dominated factor.

The CFRP piling numbers are effected upon columns strength capacity and energy absorption Columns transversely retrofitted are relatively reflected high effect, the capacity increase ratios of column retrofitted with two layer in respect to that of one layer is 1.17 while the increase ratio of column retrofitted with one layer in respect to bare aluminium column is 1.1.

It seems that the confinement exerted by the CFRP could fully prevent local buckling in the case of inclined wrapping and in case of opposite fiber orient of retrofitting two layers. In all column specimens, the confinement supports the aluminum tube and prevents premature failure and restrains its excessive expansion. Failure usually occurred quietly.

Finally, one should point out that, the derived empirical equations, which are based on experimental results in this study, are efficient to determine loading capacity of metals hollow columns strengthening by FRP.

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I would like to show my greatest appreciation, gratitude and highly indebted to my lovely young brother, the murdered **Muamal Fahad Resan** who taught me how to give and informed me that the brotherhood is a life. He killed between flowers in initiation of Spring on 21-3-2014.

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