Journal of Al-Azhar University Engineering Sector

Vol.17, No. 65, October 2022, 1200-1220

STRUCTURAL DESIGN MODEL AND ECONOMIC FEASIBILITY OF USING CONCRETE FILLED GLASS FIBER REINFORCED EPOXY TUBE COLUMNS

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Received: 30 May 2022 **Accepted: 28 August 2022**

ABSTRACT

Structural design of Concrete Filled Tube CFT columns requires defining an appropriate thickness and material of confining tube. The Glass Fiber Reinforced Epoxy GFRE is a sustain material that provides resistance against salt and sulphates.

Experimental program of circular CFT columns was carried out to verify the applicability of the ACI provisions using available local materials, which consists of six specimens divided into two groups: reinforced and un-reinforced CFT columns, studied parameters were: compressive strength of CFT columns, axial strain, hoop strain, load – strain behavior, and failure behavior.

It was found that satisfying the ACI requirements achieves a conservative evaluation of CFT ultimate compressive strength and axial strain of concrete with average factor of safety of 2.15 in predicting compressive strength.

An applicable design model proposed depending on ACI 318 [3] and ACI 440.02 [4] specification, providing reasonable prediction of confined concrete strength f'_{cc} and the size effect of CFT columns.

Also, an economic study of using CFT columns based on volume of its peer reinforced concrete was made to assure its economic feasibility comparing to the traditional reinforced concrete columns.

Keywords: Design of CFT columns, GFRE tubes, Confined concrete, Economic feasibility of CFT columns.

نموذج التصميم الإنشائي والجدوى الاقتصادية لاستخدام أعمدة أنابيب الإيبوكسي المقواة بالألياف الزجاجية والمملوءة بالخرسانة

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الملخص
يتطلب التصميم الإنشائي للأعمدة المكونة من أنابيب الإيبوكسي المقواة بالألياف الزجاجية والمملؤة بالخرسانة CFT تحديد السمك والمادة المناسبة لأنبوب الحصر. ويعد الإيبوكسي المقوى بالألياف الزجاجية GFRE مادة مستدامة توفر مقاومة ضد الملح والكبريتات.
تم تصميم وتنفيذ برنامج تجريبي لأعمدة CFT الدائرية للتحقق من سهولة تطبيق مواصفات الكود الأمريكي علي الخامات المحلية المتوافرة ، والذي يتكون من ست عينات مقسمة الي مجموعتين: أعمدة CFT مسلحة وأخري غير مسلحة، وكانت العوامل المدروسة هي: مقاومة الضغط لأعمدة CFT ، الانفعال المحوري ، الانفعال الدائري ، ومنحنيات الحمل - الإجهاد ، وسلوك انهيار العينات.
لقد وجد أن تلبية متطلبات الكود الأمريكي ACI يحقق تنبؤا متحفظًا لمقاومة الضغط القصوى لـ CFT وكذلك الانفعال المحوري للعينات بمتوسط عامل أمان يبلغ ٢,١٥ في التنبؤ بمقاومة الانضغاط.
تم اقتراح نموذج تصميمي قابل للتطبيق بناءا علي مواصفات الكود الأمريكي [3] ACI 318 و [4] ACI 440.02 ، موفرا تنبأ مسئول لمقاومة الانضغاط الخاصة بالخرسانة المحصورة وأخذا في الاعتبار تأثير حجم (قطر) أعمدة الـ CFT
أيضًا ، تم إجراء دراسة اقتصادية لاستخدام أعمدة CFT بناءً على حجم الخرسانة المسلحة المماثلة لها لضمان جدواها الاقتصادية مقارنة بالأعمدة الخرسانية المسلحة التقليدية.

1. INTRODUCTION

World watch Institute report 2006 [1] stated that the construction industry consumes about 16% of the global fresh water. According to cement sustainable initiative CSI 2009 [2] which issued from world business council for sustainable development, the Portland cement concrete consumes 1.85 billion m3 of water which represents about 30% of the annual demand for all population in the entire world.

By 2050, 75% of the fresh water needed to produce concrete will be in cities which suffer from water shortage. Also, recent using of carbon steel represent serious challenges to sustainable development. This result in utilizing all available sources of water such as seawater or well water to produce concrete, in addition to using new reinforcing material instead of carbon steel because of corrosion in the new construction environment as coastal and new generation cities.

For the record, in Egypt major of the new generation cities are far away from the Nile Valley and fresh water sources such as new administration capital and El Alamin City.
The international construction codes dealt with the Concrete reinforced with new material as Glass and Carbon Fibers such as both of American Institute of Concrete editions ACI 318 -14 [3] and ACI 440.02R-17 [4].
In this paper, the focus will be on using concrete filled (CF) in Glass Fiber Reinforced Polymer (GFRP) tubes as columns, which is necessary in severe environment such as coastal cities.
This type of columns is easy to apply especially in severe environment such as marine ports, coastal structures. Also, it more economic and ecologic wise than traditional reinforced concrete columns.
Concrete filled Glass Fiber Reinforced Polymer Tubes were used instead of ordinary reinforced concrete columns many times before, but in traditional way and without studying the ecological and economic reasons, the GFRE tube will do two functions:
1. Casing the concrete core and protecting it from the chemical attacks due to sulphates and chloride in the seawater or coastal environment.

2. Reinforcing and confining the concrete core of column, in case of satisfying the thickness requirement of the ACI code.
Both of ACI 318-14 [3] and ACI 440.02R-17 [4] present equations for design of composite columns confined with GFRP tubes or laminates.
First, The ACI 318-14 in article 10.3.1.6 states that: in case of using tubes as reinforcement of the composite columns, the minimum thickness of this encasing tubes shall be at least $t_{min.} = h\sqrt{\frac{f_y}{8\,E_s}}$, with no definition of the encasement tube material.
Where:
h is the diameter of concrete core
f_y is the yield strength of tube material.
E_s is young's modulus of confining material.
This mean that the minimum thickness of the encasing tube shall be at least the square root of the 0.125 εy (strain at yield)
Then, ACI 440.02R-17 [4] Chapter 12, defines the ultimate compressive strength of composite columns as follow:

$$P_u = 0.85 f'_{cc}\left(A_g - A_{st}\right) + f_y\, A_{st} \quad (1)$$

Where:
f'_{cc} is the peak strength of confined concrete, which will be defined later.
A_g is the gross area of concrete core.
A_{st} is the area of steel reinforcement.
f_y is the yield strength of ordinary reinforcement.

$$f'_{cc} = f'_c + \Psi_f 3.3 K_a f_l \quad (2)$$

$$f_l = \frac{2E_f\, n\, t_f\, \varepsilon_{fe}}{D} \quad (3)$$

Where:
E_f is the longitudinal modulus of elasticity of the tube material
n is number of confining tube layers
t_f is the thickness of the encasement tube
$\varepsilon_{fe} = K_\varepsilon \varepsilon_{fu}$, where $\varepsilon_{fu} = \frac{f_u}{E_{fu}}$, $K_\varepsilon = 0.5$ is strain efficiency factor, which equal to 0.55 in case of GFRP
Ψ_f is reduction factor = 0.95
K_a is factor depends on the shape of the section equal to 1 in case of circular sections.
f_l is the maximum confinement pressure due to tubes.
D is the diameter of the confined section.
According to the ACI 440.02 [4], any contribution of the confining tubes to the axial compressive strength of the concrete member shall be neglected.
Figure 1 presents The schematic stress-strain behavior of unconfined and confined concrete of the ACI 440.02R-17 which proposed by Concrete society 2012 [5]

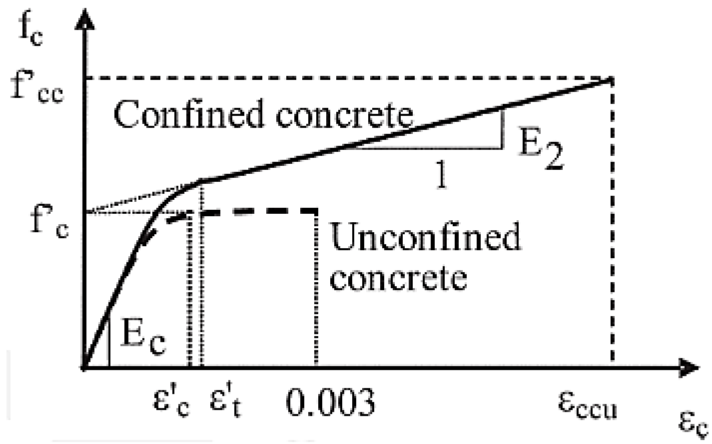


Figure 1: Stress – strain behavior for both of confined and un-confined concrete ACI 440.02R-17 [4]

Depending on this model the ultimate confined concrete strain can be predicted as follow:

$$\varepsilon_{ccu} = \varepsilon_c' \left(1.50 + 12K_b \frac{f_l}{f_c'}\left(\frac{\varepsilon_{fe}}{\varepsilon_c'}\right)^{0.45}\right) \quad (4)$$

The concrete society proposed an ultimate limit of axial strain in case of confined concrete of 0.01.
Asmaa A. H. et al. [6] investigate the behavior of concrete-filled fiber-reinforced-polymer tubes long columns reinforced with longitudinal steel or carbon and glass FRP bars under axial compression loading. They found that increasing GFRP encasing tube thickness resulted in an increase in the strength and strain. Their study showed the success of reinforcing the CFFT columns with FRP bars and subjected to axial compression load.
Wang, Xuxu et al. [7] tested and studied the behavior of columns consisted of different GFRP confined concrete cores with and without outside concrete and stirrups. They found that the strength and ductility of the tested confined columns were enhanced by 20% and 500% respectively, then they developed a FEM to predict the axial compression behavior of tested columns
Li, Ying Lei and Zhao, Xiao Ling [8] studied the seawater concrete filled GFRP tubes and double skin tubes and they proposed a theoretical model to predict the load – axial strain curves for the concrete filled double skin tubes.
A. Raza, et al. [9] have developed FEA model to predicting the behavior of concrete filled FRP tube from previous literature, then they used 12 specimens from literature to verify the FEA model by comparing its output with the experimental data. They found that the average discrepancies were 3.03% and 10.75% for ultimate load and axial deflection respectively.
They proposed analytical model in order to predict the axial load capacity for concrete filled GFRP tubes, based on statistical analysis of previous experimental results, and the proposed equation was:

$$P_n = A_{cc}\left[f_{co}' + 2.8 f_{co}'^{0.256} f_l^{0.744}\right] + A_{FRP\ tube}\sigma_{LB} \quad (5)$$

Where:

$$\sigma_{LB} = E\ \varepsilon_{LB}\ , \frac{\varepsilon_{LB}}{\varepsilon_{0.2}} < 1$$

$$\sigma_{LB} = E_{sh}\ \varepsilon_{0.2}\ \left(\frac{\varepsilon_{LB}}{\varepsilon_{0.2}} - 1\right), \frac{\varepsilon_{LB}}{\varepsilon_{0.2}} \geq 1$$

Checking the applicability of ACI requirement in design and proportion of the thickness of encasing tube and size effect of the CFT columns didn't attract enough attention of scientific society.

This paper presents an applicable method for selecting the confining material of CFT columns and its thickness according to the ACI requirements, also it measures the conservativity of ACI code, in addition to proposed modification factor on the ACI equation which reflects the size effect. Finally economic feasibility of using this type of columns was approved.

2. EXPERIMENTAL PROGRAM

Experimental program was designed to investigate the application of The ACI requirement in proportioning between confining material and concrete core of a CFT columns using the previous sequence in the introduction.

Experimental study consists of 6 short columns of concrete filled GFRP tubes, three of them were reinforced with traditional steel while the other were un-reinforced, to observe the effect of the outer encasement as main longitudinal reinforcement.

The tested Concrete Filled GFRP tube specimens were designed according to ACI 318-14 [3] and was verified with ACI 440.02R-17 [4] as follow:

The Size of tubes was 125, 150, and 200 mm diameter as shown in figure 2, and they were divided into two groups: ordinary reinforced and un-reinforced specimens.

The details and properties of the tested short columns of CFGRP Tubes were illustrated in table 1, and main reinforcement of columns were illustrated in the figure 3

Ordinary reinforced specimens have reinforcement details as shown in figure 2, and the details of stirrups as illustrated in table 1

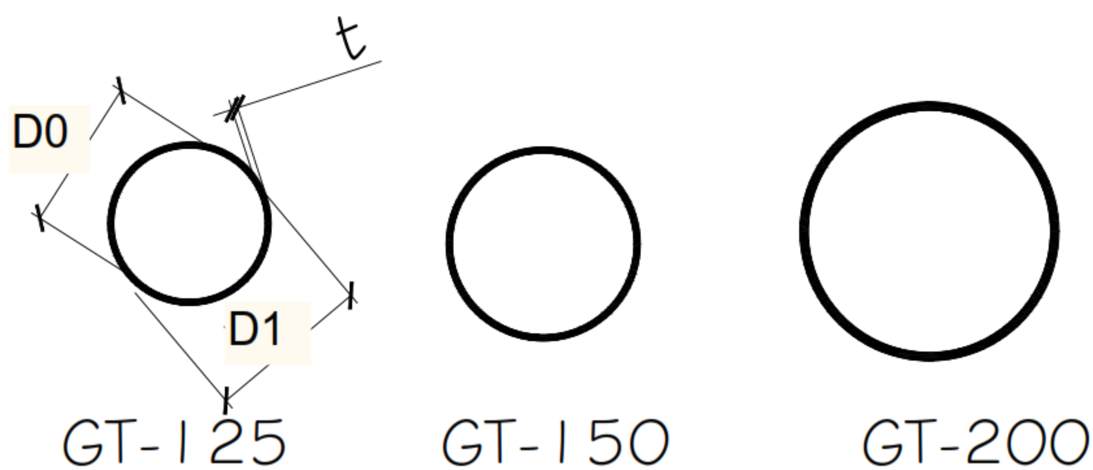


Figure 2: Description, dimensions, and details of Concrete Filled Glass Fiber Reinforced Polymer tube columns (Un- reinforced)

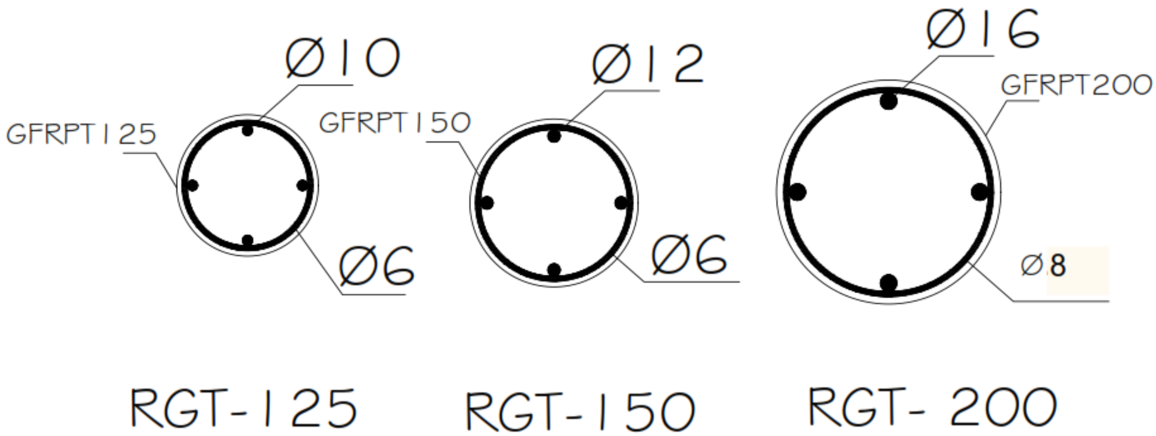


Figure 3: Description, dimensions, and details of Concrete Filled Glass Fiber Reinforced Polymer tube columns (Reinforced)

All used GFRP tubes have axial and hoop modulus of elasticity E of 10500 and 20500 MPa and tensile strength in the axial and hoop directions of 65 and 210 MPa, according to the supplier datasheet.

Table 1: Dimensions and properties of CFGFRPT columns and its reinforcement details

Specimen name	D0 (mm)	D1 (mm)	Length, h (mm)	Thickness of tube (mm)	t/h ratio	Hoop fy (N/mm2)	Main rft As	Ties	S (mm)
RGT-125	125	133	400	4	0.032	210	4Φ10	Φ6	125
RGT-150	150	160	500	5	0.033	210	4Φ12	Φ6	150
RGT-200	200	212	600	6	0.03	210	4Φ16	Φ8	200
GT-125	125	133	400	4	0.032	210	--	--	--
GT-150	150	160	500	5	0.033	210	--	--	--
GT-200	200	212	600	6	0.03	210	--	--	--

2.1. Material properties

2.1.1. Concrete

Filling concrete has f_c' of 40 MPa and modulus of elasticity E = 18574 MPa as illustrated in table 2. Concrete compressive strength was measured from casted cylinders which tested in the same day of experiment.

Figure 4 illustrate the testing of casted concrete cylinders in order to calculate the compressive strength f_c' and modulus of elasticity E_c

Figure 4: Testing of concrete compressive strength of filling in CFT columns in order to calculate modulus of elasticity E_c

2.1.2. Reinforcing steel

Main and transverse reinforcement used in Reinforced CFT columns were described in table 2 and figure 5, and it were in accordance with ACI 318-14 requirements.

Figure 5: Reinforcement details of CFT column specimens in experimental program

2.1.3. GFRP tubes

Encasement tubes were GFRP with three sizes of 125, 150, and 200 mm diameter and 4, 5, 6 mm thickness as mentioned previously all tubes have material properties in axial direction of 65 MPa, 10500 MPa, 0.0062 for axial strength, axial modulus of elasticity, and ultimate axial strain respectively.

Table 2: Material properties of filling concrete and reinforcing steel

Material	f'_c MPa	E MPa
Concrete	40	175000
	f_y MPa	E MPa
Main Steel	500	210000
Ties	400	210000

2.2. Test setup

All specimens were tested in the Egyptian Housing and Building Research Center HBRC material laboratory using Universal Testing Machine AMSELLER with maximum load capacity of 500 ton.

All specimens were tested under axial compression till failure as shown in figure 6. One strain gauge was installed horizontally at the mid-height of specimen to obtain the hoop (lateral) strain, while the axial strain was obtained using vertical strain gauge or the applied LVDT as shown in figure 6.

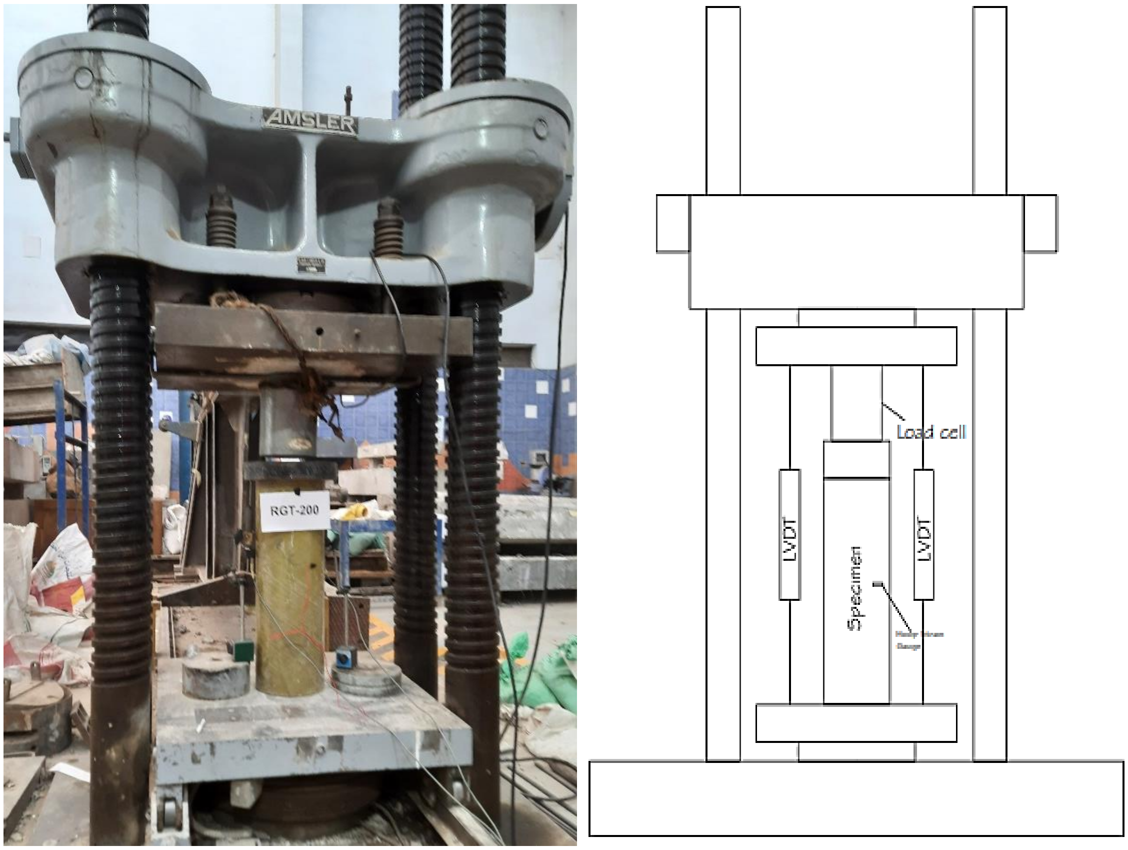


Figure 6: Test setup and instruments configuration of specimens

3. TEST RESULTS

3.1. Compressive strength of columns

Calculating the compressive strength of CFT columns according to ACI code was done using excel spread sheet which contains application of the ACI equations according to the previous sequence.
The resulted compressive strength of tested columns is illustrated in table 3, which indicate that experimental compressive strength of tested columns equal 2.15 times the expected ones. Also hoop / transverse strain of columns equal 10 times the average strain of unconfined concrete, while axial compressive strain at failure equal 14 times strain of concrete due to GFRP confinement.
It was observed that the hoop strain of concrete was lower than the longitudinal one.

Table 3: List of experimental and calculated compressive strength of tested CFT columns

Specimen	P_{exp}.(kN)	P_{ACI} (kN)	$P_{exp.}/P_{ACI}$	Hoop stain at failure	Axial strain at failure
RGT-200	3560	2008.22	1.77272	0.036	0.07
RGT-150	2200	1164.95	1.88849	0.033	0.04
RGT-125	2100	799.18	2.62769	0.03	0.04
GT-200	3238	1648.29	1.96446	0.03	0.016
GT-150	2166	963.42	2.24823	0.0328	0.066
GT-125	1610	658.97	2.44320	0.024	0.027
Average			2.15	0.031	0.043

3.2. Load- hoop strain of tested columns

All obtained figures agree with the ideal stress – strain of confined concrete, as shown in figures 7 to 18 each curve consists of two parts: first one is steeper ascending till yielding of specimen and the second one is ascending with lesser grading unlike un-confined concrete.

This led to more ductile behavior than unconfined concrete with ductility index ($\frac{\varepsilon_u}{\varepsilon_y}$) of 33 in case of reinforced specimens and 43 in case of un-reinforced specimens, it can be explained as follow: when using longitudinal reinforcement, the ability of side displacement of concrete core will be limited with lateral buckling of longitudinal bars unlike the un-reinforced CFT columns.

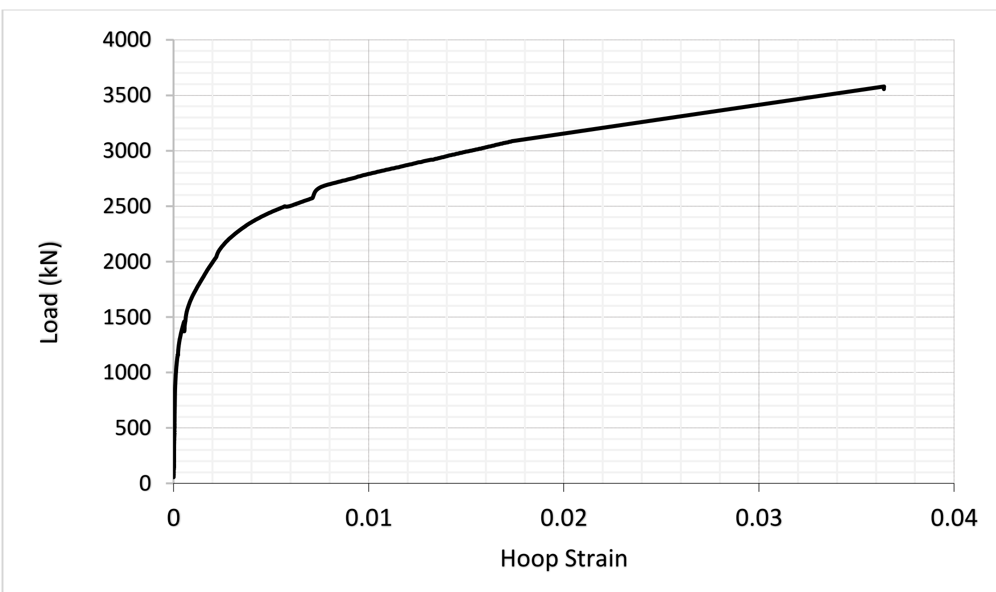


Figure 7: Load - hoop strain relation of RGT-200

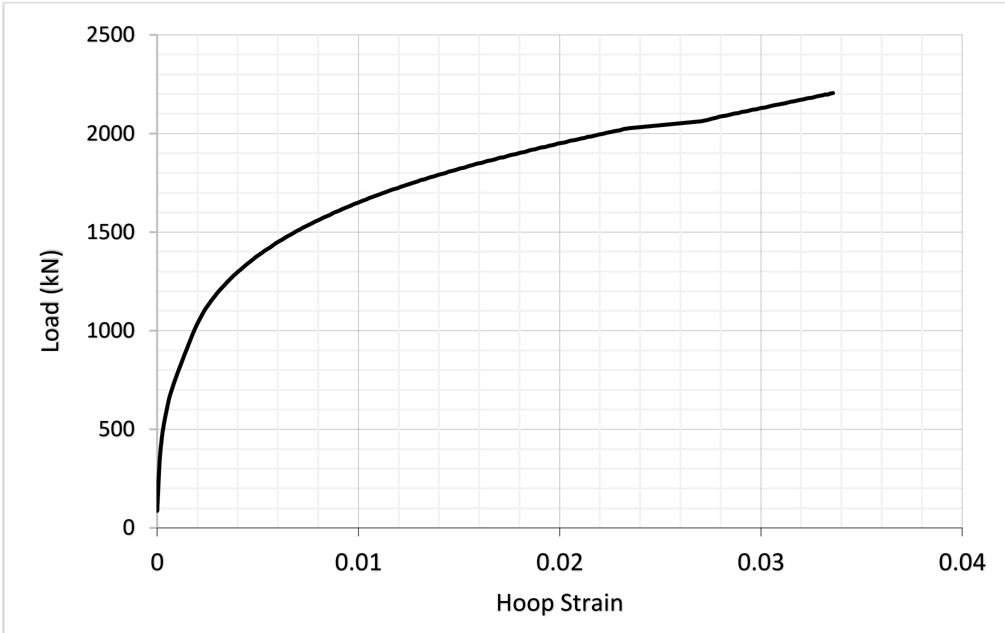


Figure 8: Load - hoop strain relation of RGT-150

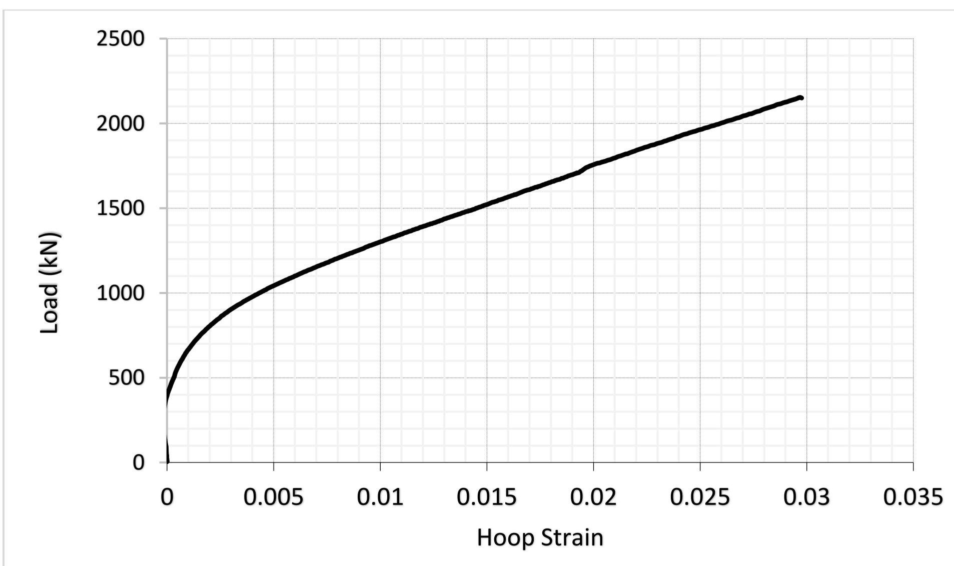


Figure 9: Load - hoop strain relation of RGT-125

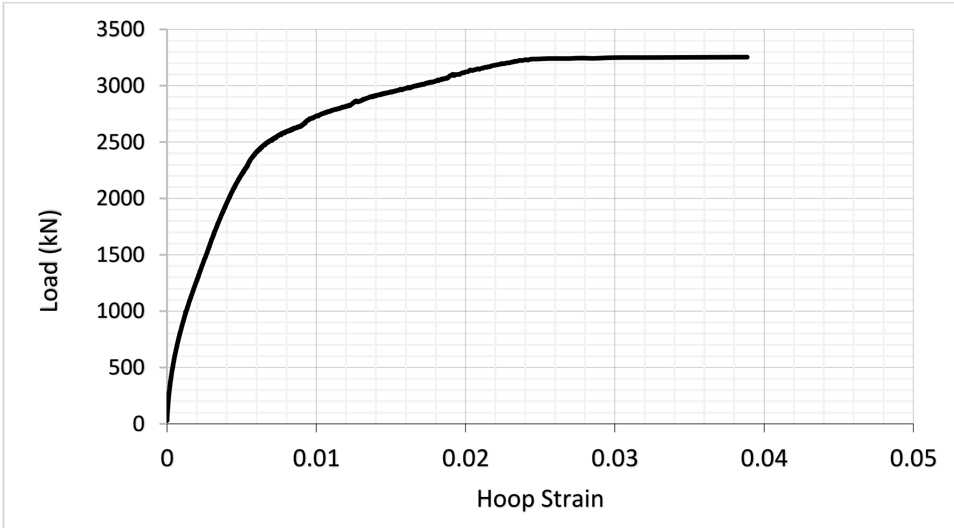


Figure 10: Load - hoop strain relation of GT-200

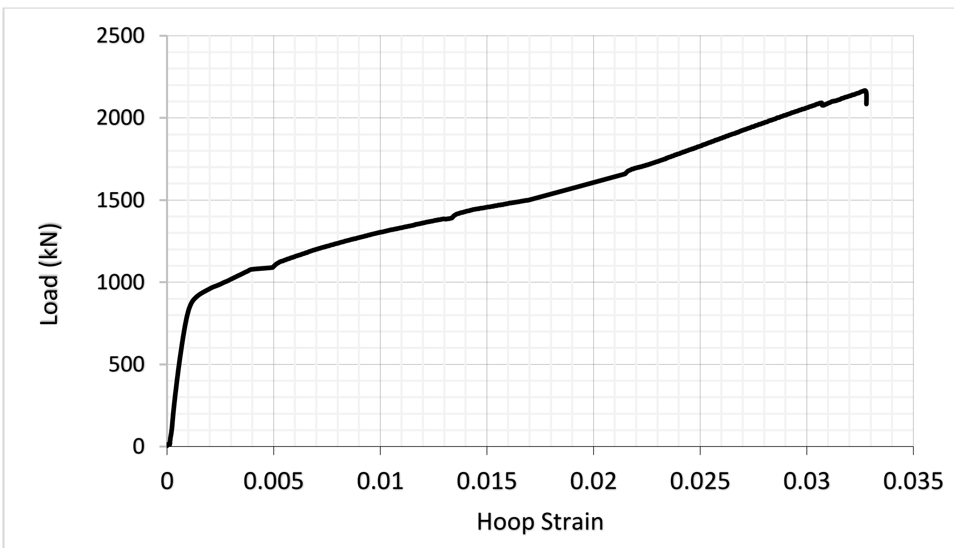


Figure 11: Load - hoop strain relation of GT-150

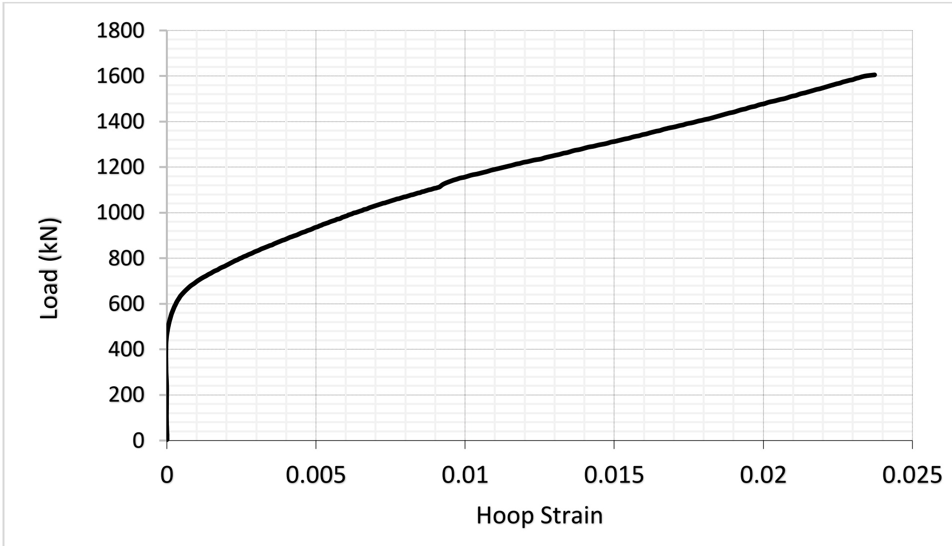


Figure 12: Load - hoop strain relation of GT-125

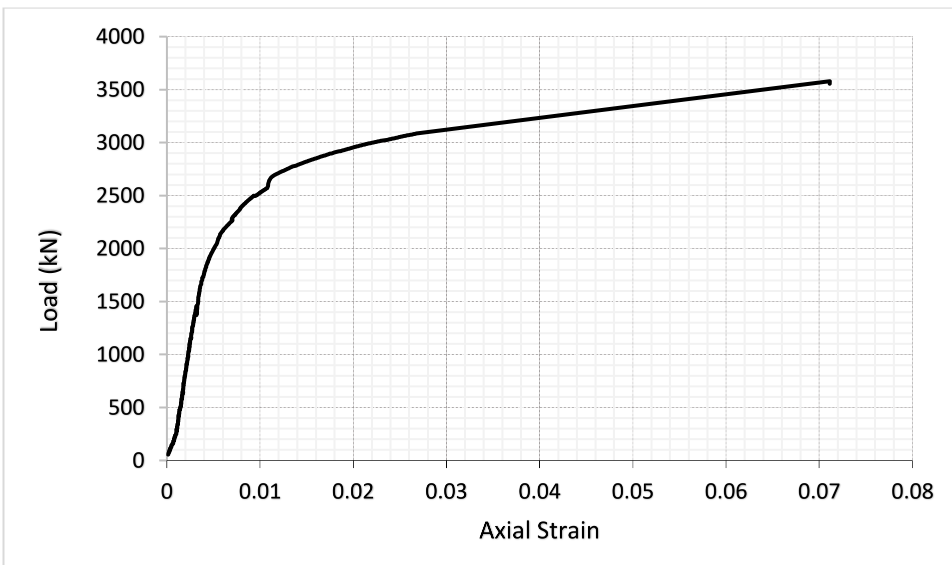


Figure 13: Load - Axial strain relation of RGT-200

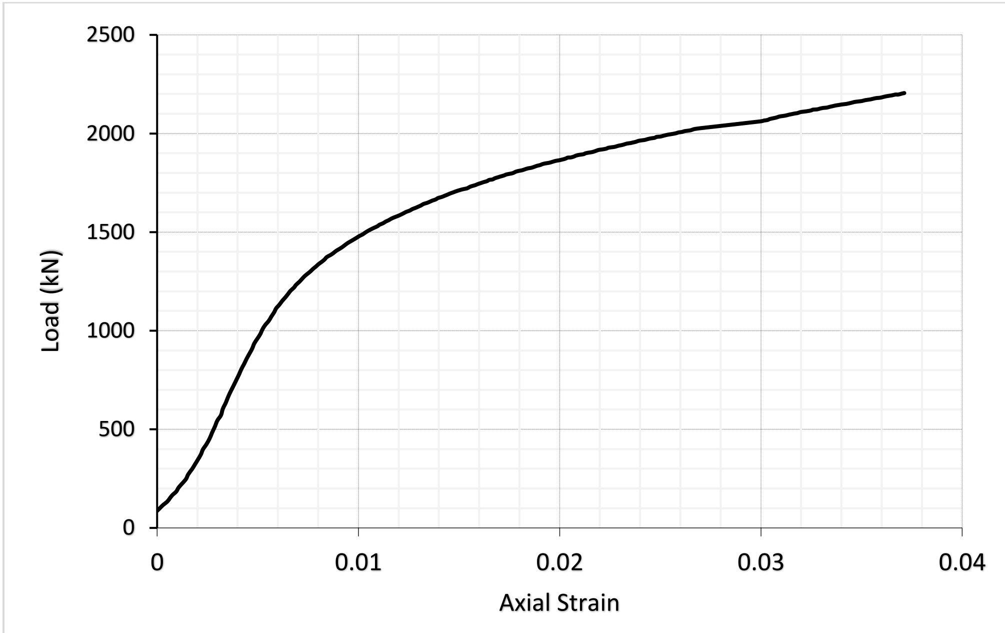


Figure 14: Load - Axial strain relation of RGT-150

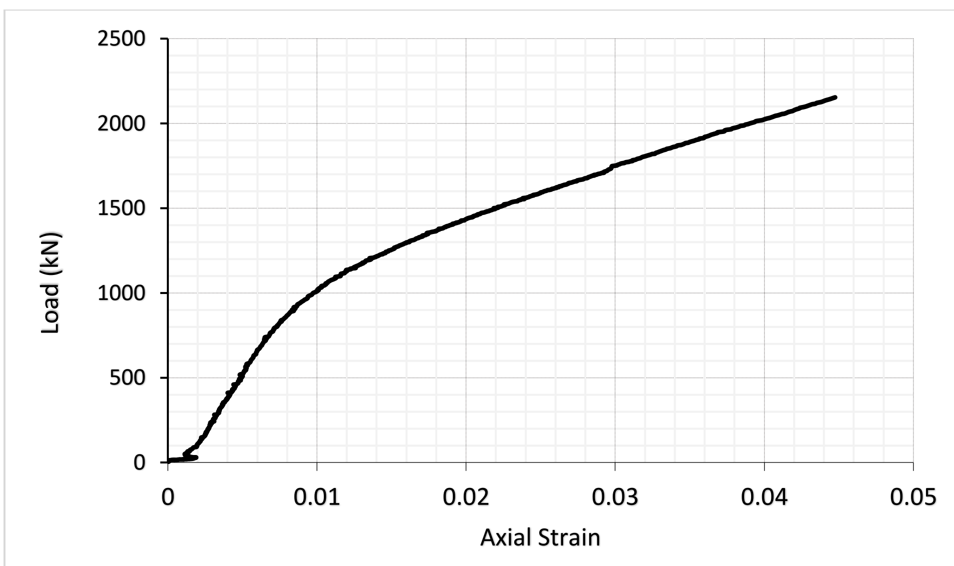


Figure 15: Load - Axial strain relation of RGT-125

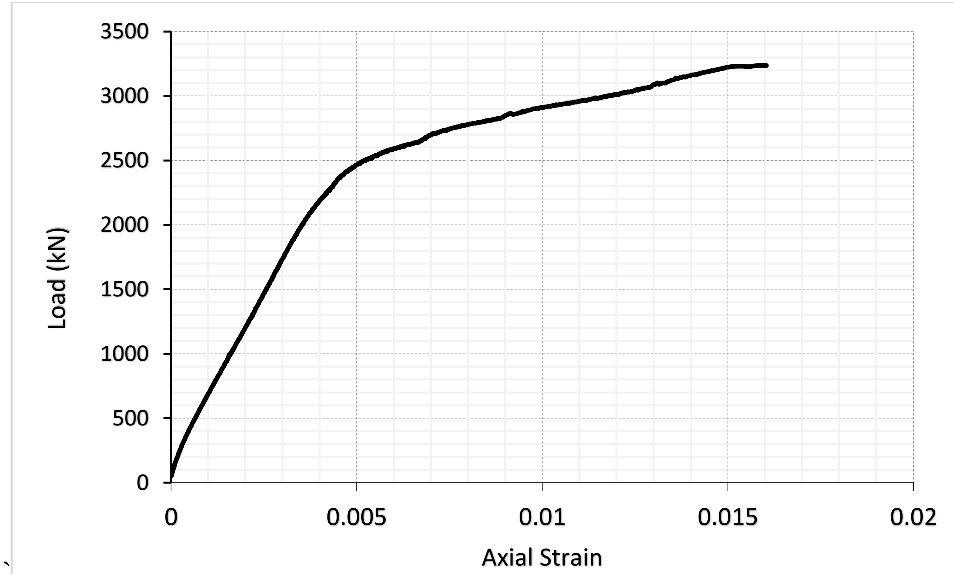


Figure 16: Load - Axial strain relation of GT-200

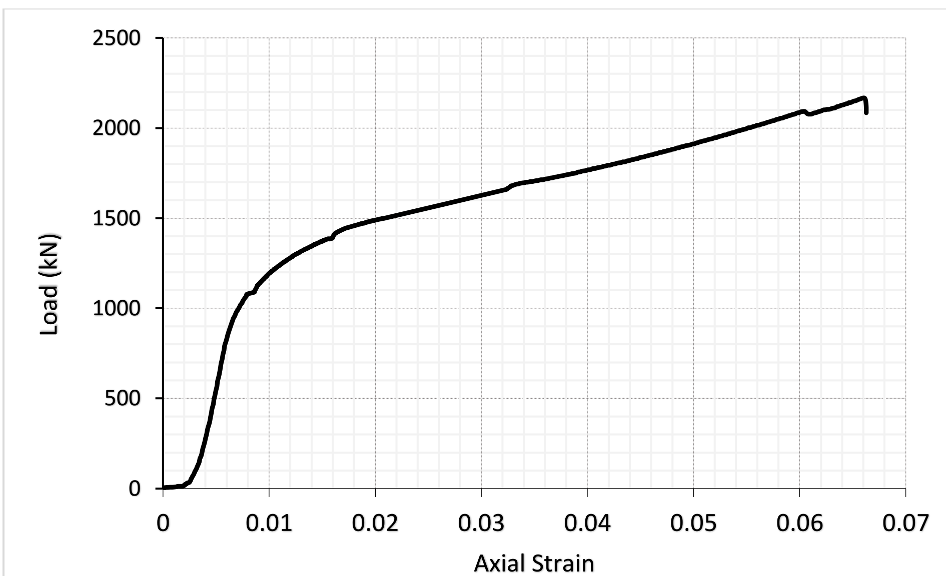


Figure 17: Load - Axial strain relation of GT-150

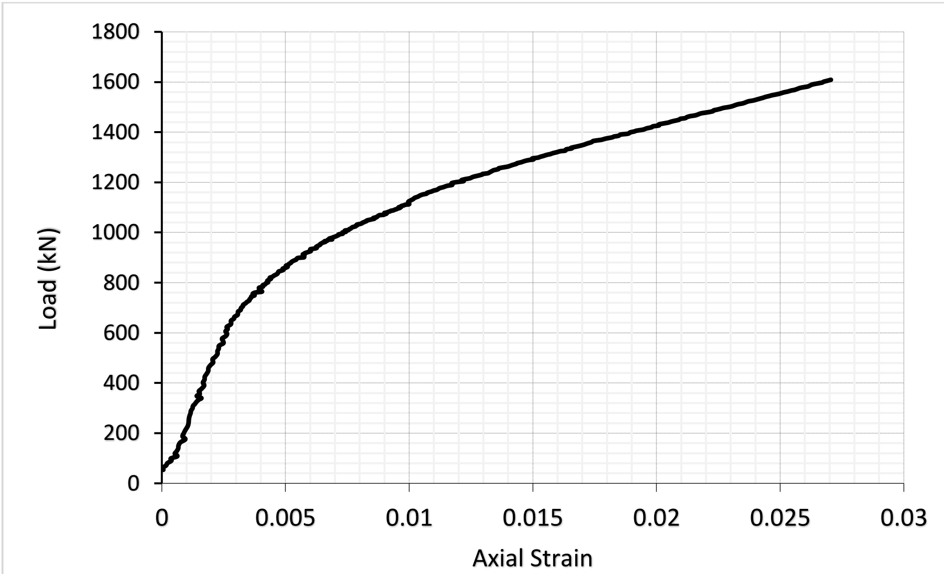


Figure 18: Load - Axial strain relation of GT-125

4. ANALYSIS OF TEST RESULTS AND FAILURE MECHANISM

Figures 19 to 21 show the failure of all tested columns. Failure of column strength was initiated with failure of GRE fibers, as shown in figures 19-21.

Failure in all CFT columns was sudden after excessive strain in case of un-reinforced CFT columns causing longitudinal rapture of the fiber of the GRE tubes as shown in the figures 19 and 20. Also, the concrete core was cohesive in all un-reinforced CFT columns except in case of GT-125 which has lowest stiffness with catastrophic total loss of load and concrete core.

While the failure of reinforced CFT columns was smooth and preceded by alarms.

All tested CFT columns achieved higher compressive strength of an average 2.15 times the calculated ones as previously mentioned in table 3

Although using reinforcement in the first three specimens of experimental program, the increase in compressive strength is limited with average of 13.5% relative to un-reinforced columns because of smaller effect of longitudinal bars in confining the concrete core of CFT columns.

For more illustration, see the term of $P_{exp.}/P_{ACI}$ in table 3 for both of reinforced and un-reinforced CFT columns which have average values of 2.21 and 2.1 respectively.

As size of CFT column increase the safety factor of the ACI specification decrease.

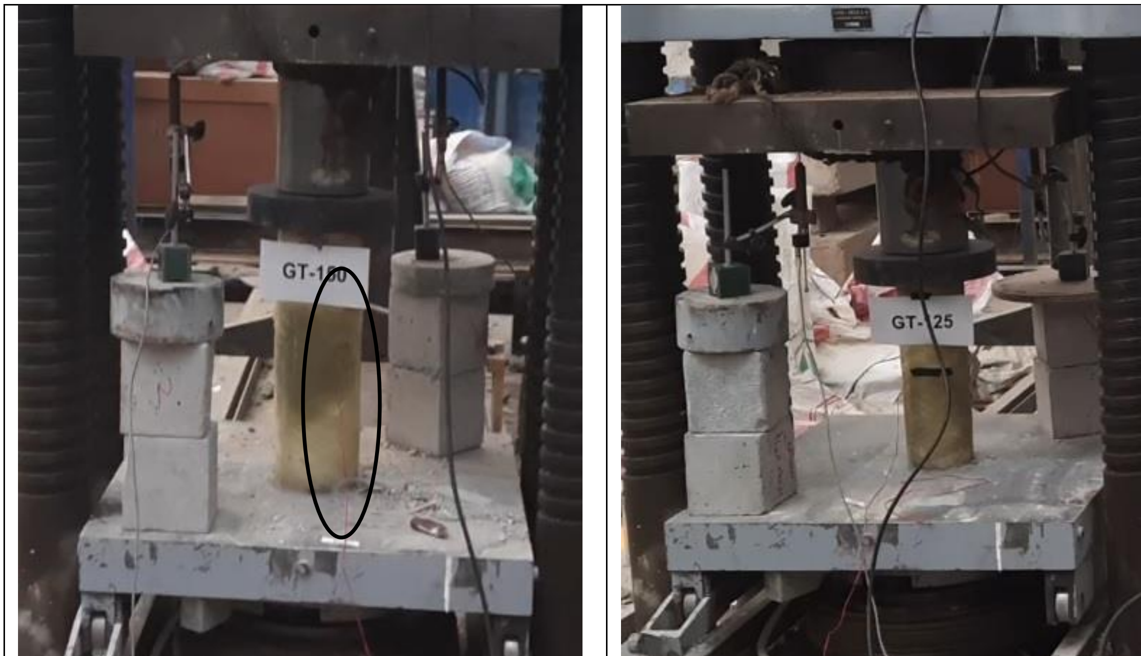
Providing GFRP tubes to confine columns led to increase of hoop and axial strains of the concrete with almost 10 and 14 times the strain of un-confined concrete (0.003) respectively as shown in table 3.

RGT-200	RGT-150

Figure 19: Failure mode of RGT-200 and RGT-150

RGT-125	GT-200

Figure 20: Failure mode of RGT-125 and GT-200



GT-150	GT-125 (just before explosive failure)

Figure 21: Failure mode of GT-150 and GT-125

5. PROPOSED MODIFICATION FACTOR ON THE CONFINED CONCRETE STRENGTH IN THE ACI CODE

In case of practical design of CFT, there is need for simplifying the relation between confined concrete and size (diameter) of CFT columns.

Therefore, an analysis of the relation between experimental compressive strength of un-reinforced CFT columns and the confined concrete f'_{cc}, which sequentially led to both of compressive strength of concrete f'_c and the confining pressure of tube f_l as follow:

$$P_{exp.} = 0.85\, f'_{cc}\left(A_g - A_{st}\right) + f_y A_{st} \quad (6)$$

In case of un-reinforced CFT columns the previous equation will be zero resulting in the equation 7:

$$P_{exp.} = 0.85\, f'_{cc}\left(A_g\right) \quad (7)$$

Then, we can obtain the actual confined concrete strength $f'_{cc\,actual.}$ as flow:

$$f'_{cc\,actual.} = \frac{P_{exp.}}{(0.85 \times A_g)} \quad (8)$$

Which related to both of f'_c and f_l as previously stated in equation 2:

$$f'_{cc} = f'_c + \Psi_f 3.3 K_a f_l$$

by substituting the obtained value of $f'_{cc\,actual.}$ in the previous equation, equation will be:

$$f'_{cc} - f'_c = \Psi_f 3.3 K_a f_l$$

as the parameters $\Psi_f, 3.3,\ and\ K_a$ are constant in this case with value of 3.135, we can get the proposed modification factor which cause the balancing of the previous equation, as follow:

$$m.f. = \frac{f'_{cc} - f'_c}{\Psi_f 3.3 K_a f_l} \quad (9)$$

By plotting this modification factor for all tested diameters as shown in table 4 and figure 22

Table 4: value of proposed modification factor depending on different diameter of CFT columns

Specimen	Dia. (mm)	Pexp.(kN)	$\mathbf{0.85 \times A_g}$	$\boldsymbol{f'_{cc}}$ (MPa)	$\boldsymbol{f'_{cc} - f'_c}$	$\boldsymbol{m.f. = \frac{f'_{cc} - f'_c}{\Psi_f 3.3 K_a f_l}}$
GT-200	200	3238	26703.54	121.26	81.26	3.74
GT-150	150	2166	15020.74	144.20	104.20	4.32
GT-125	125	1610	10431.07	154.35	114.35	4.93

This factor, which causes the balancing of the equation of confined concrete strength f'_{cc}, has relationship with the dimeter of the CFT columns, as shown in figure 22.

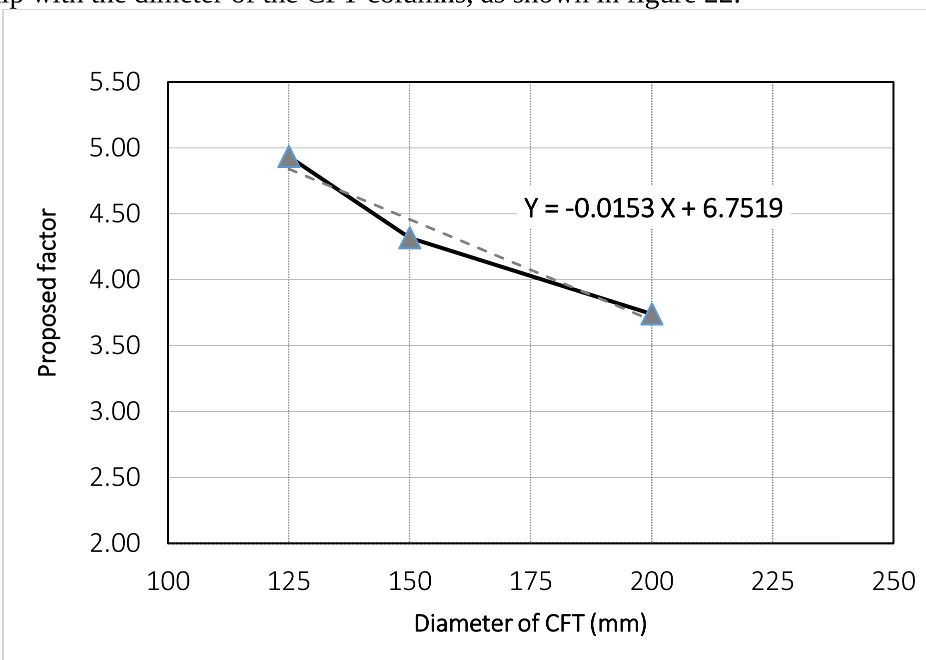


Figure 22: linear relation between the size of CFT columns and proposed modification factor

To simplify this relation, linear option was utilized to represent the effect of size of CFT columns on the proposed modification factor as follow:

$$m.f. = -0.0153 \times D + 6.752 \qquad (10)$$

Where: D is diameter of CFT columns.

Using linear relationship between the size effect and proposed modification factor *m.f.* will extend the influence of this *m.f.* beyond the boundary of this experimental study, especially when you know that the agreement between reinforced and un-reinforced CFT columns compressive strength in comparison to the ACI code equation.

The same harmony was observed in proportion to the size of CFT columns based on $P_{exp.}/P_{ACI}$, but it was necessary to use only the un-reinforced CFT columns to neglect the effect of reinforcement.

6. ECONOMICAL STUDY OF USING GFRP TUBES AS REINFORCEMENT OF COLUMNS

In case of using traditional reinforced concrete columns, the calculated compressive strength equal to 0.73, 0.58 of its peer CFT un-reinforced and reinforced columns respectively according to the ACI 318-14 equation, which economize the cost and raw material.

$$P_u = 0.85 f_c' \left(A_g - A_{st}\right) + f_y A_{st}$$

Considering that compressive strength of concrete equal to 40 MPa, steel yield strength equal to 500 MPa, and the chosen reinforcement ratio of 0.01 for all studied columns.

This comparison was made depend on comparison between volume of concrete column sections regardless of the ratio between experimental and calculated strength of studied columns, which is relatively high.

Table 5 shows the comparison between the CFT and Traditional Reinforced Concrete column area sections and the saved area due to using GFRE confining tube.

If both of GFRE and reinforcing steel were neglected, minimum of 27% of the total cost of the Traditional column can be saved. This reduction of total cost will be enormous, if its merit of protecting the concrete core from any hard / severe environment was taken in consideration.

Table 5: Comparison between section dimensions of CFT and traditional reinforced concrete columns

Calculated Load	RGT-200	RGT-150	RGT-125	GT-200	GT-150	GT-125
CFT PACI	2008	1165	799	1648	963	659
ACFT (mm2)	30611.7	17219	11957	31416	17671	12272
ATRC (mm2)	51492	29870.6	20492	42264	24703	16897
Ratio ATRC / ACFT	0.594	0.576	0.58	0.743	0.715	0.726

7. CONCLUSIONS

- Using outer tube of GFRP in CFT columns provide protection from salt and sulphates in columns located in severe environment such as marine construction, which facilities dealing with shortage in water supply.
- Using Concrete filled tubes CFT columns enhance ductility and yielding behavior of concrete core of columns leading to increasing of ultimate load of it.
- Despite of visibility and applicability of The ACI specifications [3,4] in designing of CFT columns, it is very conservative with average safety factor of 2.15, which need consideration. So, within experimental domain, modification factor of the concrete confined strength $f_{cc}'$was proposed as follow:

$$f_{cc}' = f_c' + m.f. \times \Psi_f 3.3 K_a f_l$$
$$m.f. = -0.0153 \times D + 6.752$$

- Using Concrete filled tubes CFT columns save 27% and 42% of the total cost based on volume of concrete for un-reinforced and reinforced section, respectively.
- GFRP Confined concrete can reach more than 14 times the maximum of un-confined concrete axial strain which exceed the limit of the ACI-440.02 [4] recommended value of ultimate axial strain of confined concrete of (0.01) depending on The Concrete Society [5], which need consideration.
- More economic feasibility and safety factor in case of un-reinforced CFT than reinforced CFT columns.
- Despite of satisfying the requirement of the ACI 318-14 [3] requirement in the stiffness of CFT column tube, it was found that failure of small sections was aggressive without decreasing in compressive strength capacity.

DECLARATION OF INTERESTS

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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