Mechanicals Behavior of RC Columns Strengthened with GFRP and Subjected to Cyclic Temperatures

Ibrahim Abdel-Latif Yousef [1]

Abstract— Egypt is one of the countries with a hot climate and degree of temperature reaches to 45 °C in Summer and the solar radiation can increase the degree of temperature for out-door surface to 70 °C. During the two decades ago, the use the technique of strengthening and rehabilitation of RC structures by externally bonded Fiber reinforced plastics (FRP) became widespread all over the world. The main goal of this research is to investigate the mechanical behavior of RC column strengthened with GFRP and subjected to cyclic temperatures (similar to severe climate condition in Egypt). Six RC circular columns, nine concrete standard cubes and six concrete standard cylinders were used to investigate the mechanical properties before and after subjecting to thermal cycles. The six RC columns are two control columns (with no GFRP strengthening) and four columns strengthened with one and three GFRP layers. Three from the six columns were not subjected to thermal cycles and the other three were subjected to thirty thermal cycles. Results of the conducted experimental study have showed that: Concrete tensile strength was more sensitive to the effect of thermal cycles than the compressive strength - Failure modes of RC columns prior to and after being subjected to thermal cycles were obviously identical - The ultimate loads of all RC column were about 98 % from the control case - The thermal cycles increase the brittleness of the RC columns.

Index Terms— Retrofitting, RC Column, Glass Fiber reinforced Plastic (GFRP), Polymer Adhesive, Thermal Cycles, Confined Compressive Strength, Axial Strain.

◆

1 INTRODUCTION

In the recent 20 years, the externally bonded Fiber reinforced plastics (FRP) have been established as a new technique for the strengthening and rehabilitation of RC structures. The advantages of this technique are high strength to weight ratios, high stiffness, and durability. The success of this technique critically depends on the performance of the polymer adhesives that bonds concrete to FRP. Bond is the only mean to develop composite action by the stress transfer between concrete and FRP and between the multiple layers of FRP. Polymer adhesive materials differ from metals in several aspects that can affect their behavior in critical structural applications. The mechanical properties of composites depend strongly on ambient temperature and loading rate. Glass Transition Temperature (Tg) is one of important properties for polymer adhesive materials which subjected to thermal exposure. Above the “Tg” range, polymeric materials change from a hard, often brittle solid to a soft, tough solid. The tensile modulus of the matrix polymer can be reduced by as much as five orders of magnitude. Also, about 50% of Poisson’s ratio, elastic modulus and bond strength of the adhesive layers are lost at a temperature 15 °C higher than the “Tg” [1]. the behavior of FRP joints subjected to elevated temperature is usually governed by the behavior of adhesive [2].

E. Ferrier et.al (2107) [3] investigates the combined effect of the temperature and mechanical loads on FRP-concrete bonds. The standard double-lap shear test was in experimental study. The range of temperature was from 40 °C to 120 °C. The test results showed that, the failure loads were decrease for temperatures higher than the Tg (40 °C) of the adhesive matrix and it were increased lower than Tg. Also, the cyclic variations of stress due to the sun thermal effects highlight the need of using an adhesive matrix with a high fatigue limit for FRP reinforcement. Samir H. O et al (2107) [4] studied the effect of elevated temperature on bond strength using concrete-polymer adhesive-FRP specimens. Four different test methods were used namely; tensile bond, slant shear, shear bond and double-face shear bond test. The test results showed that, the residual bond strength was decreased. The mode of failure was depending on the high temperature, type of adhesive, prolonged exposure time, and the increase in the surface area of bond. K.H. Tan et al (2009) [5] studied the behavior of RC beams strengthened by GFRP were subjected to sustained loads under the tropical climate (outdoors, indoors). Beams subjected to outdoor weathering had up to 18% larger crack widths and 16% larger deflections compared to those kept indoors. Also, the failure mode of the beams changed from concrete crushing to FRP rupture, indicating a deterioration in the mechanical properties of the FRP laminates.

Also, many of researches carried out analytical models of behavior of fiber-reinforced polymer-to-substrate bonded joints subjected to thermal loading [3,6,7]. Clarisse et al (2015) [8] investigated the effects of high temperature (100 and 180 °C) on bond strength and failure modes. The test results showed that, the most detrimental to bond strength is a combination of high temperature and low humidity. Latif et al (2004) [9] studied the effect of thermal cycles on the mechanical properties of concrete and the behavior of RC beams retrofitted using externally

---

[1] *Assistant Professor, Structural Engineering Department, Ain Shams University, Egypt. E-mail: ibrahim.yousif@eng.asu.edu.eg*

bonded CFRP wraps. Six RC beams were divided into two groups (flexural and shear Group). Concrete specimens and two retrofitted RC beams were subjected to thirty thermal cycles. The test results showed that, thermal cycles had insignificant effect on the concrete compressive strength, modulus of rupture, and modulus of elasticity. But thermal cycles decreased the tensile splitting strength, and bond strength between concrete and steel rebars. RC beams the gain in strength due to retrofitting process was reduced. The ultimate load capacity recorded was less than the original RC beam depends on cycle range, time and number of cycles.

2 OBJECTIVE

The main objective of this research is to study the effect of thermal cycles (similar to severe climate condition) on the mechanical behavior of axially loaded R.C. circular columns wrapped externally with GFRP which adheres by the recommended types of the commercially available polymer adhesives.

3 EXPERIMENTAL PROGRAM

The experimental study consists of six RC circular columns divided into two group. The first group was labelled as (C) and consists of three RC columns. All columns in group (C) **were not subjected** to thermal cycles. The first RC column is the control RC Column with no strengthening and was labelled as (C/0). The second RC column is the strengthened RC column with one layer of GFRP wraps which was labelled as (C/1). The third RC column is the strengthened RC column with three layers of GFRP wraps which was labelled as (C/3). The second group was labelled as (T) and consists of three RC columns. All columns in group (T) **were subjected** to thermal cycles. The first RC column is the RC Column which was not strengthened and was labelled as (T/0). The second RC column is the strengthened RC column with one layer of GFRP wraps which was labelled as (T/1). The third RC column is the strengthened RC column with three layers of GFRP wraps which was labelled as (T/3).

All RC columns have the same dimensions and the same steel reinforcement. The degrees of temperature for the thermal cycles were chosen to simulate the sever climate in Egypt. The degree of temperature of out-door element is the sum of temperature of air and additional temperature due to the solar radiation. According to the data from Egyptian Meteorological Authority for 2019: the maximum temperature in Egypt was 45 °C and the corresponding solar radiation increased the temperature to 70 °C. So that, the thermal cycles consisted of alternatively rising the temperature of the specimens from room temperature 23 °C to 70 °C as shown in Fig. (1). Then the temperature is lowered from 70 °C to room temperature 23 °C. The oven was heated up from room temperature to 70°C over a 30-minutes period that was not accounted for in the exposure time. The temperature was kept constant at 70 °C continuously over an 8-hours period inside the closed oven. After that the RC column were allowed to cool by switch off the oven and opening the oven's door of the to decrease the temperature gradually to room temperature. After 16-hour, the door of the oven was closed. The oven was switched back on for the next cycles.

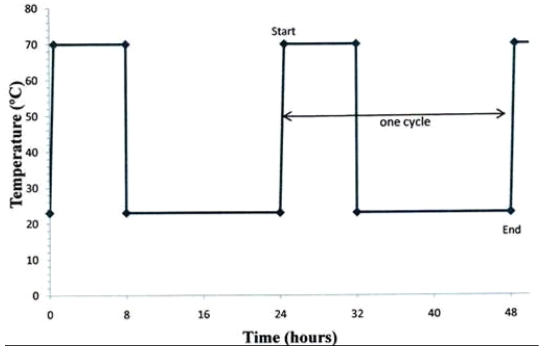

Fig. 1. Temperature-Time Relation During the Thermal Cycles

4 MATERIALS, TEST SPECIMENS AND STRENGTHENING PROCESS

4.1 Aggregate, cement and steel reinforcement

The cement used was ordinary Portland cement that complies with the requirement of the Egyptian standard specifications [10] of cement grade N42.5. The coarse aggregate was crushed stone. The used sand was natural sand with fineness modulus of 2.47. Table (1) gives the sieve analysis test results for the used sand and crushed stone. Table (2) gives physical properties of the used sand, crushed stone.

TABLE 1: SIEVE ANALYSIS TEST RESULTS FOR FINE AND COARSE AGGREGATES

Fine Aggregate	Sieve size (mm)	4.75	2.36	1.18	0.60	0.30	0.15
	% passing	98.0	95.6	88.8	55.7	27.2	3.0
Coarse Aggregate	Sieve size (mm)	37.5	31.5	28.0	20.0	10.0	5.0
	% passing	100	100	100	100	96.0	4.00

TABLE 2: PROPERTIES OF FINE AND COARSE AGGREGATES

Property	Fine Agg.	Coarse Agg.
Specific gravity	2.56	2.61
Unit weight (t/m3)	1.53	1.63
Crushing value (Los Anglos)	---	23.6%
% Fine materials (by volume)	2.00	---
% Absorption	---	1.8%

The used steel reinforcement was high tensile steel with oblique ribs of grade B500DWR and a nominal diameter was 10 mm. The used stirrups were mild steel with grade B300D-P and a nominal diameter was 8 mm.

4.2 Strengthening Materials

Locally available glass fiber reinforced plastic (GFRP) wraps were used in the strengthening of tested columns. The relevant mechanical properties for GFRP wraps, as stated in the manufacturer's product data sheet, are summarized in Table 3. Unsaturated polyester (UP) adhesive was used to bond the GFRP wraps.

TABLE 3: MECHANICAL PROPERTIES OF GFRP WRAPS

Property		GFRP
Fiber orientation		0 & 90° plane weave
Fiber weight	**(g/cm²)**	0.04
Equivalent thickness of the longitudinal fibers[1]	**(mm)**	0.08
Fabric width	**(mm)**	1000
Tensile strength of fibers	**(MPa)**	2500
Tensile E-modulus of fibers	**(GPa)**	70
Elongation at break	**(%)**	2.14

[1] Equivalent thickness of the longitudinal fibers was calculated according to Hamid [11]

4.3 Concrete Mix

The concrete mix was designed to achieve cube compressive strength after 28 days of 30 MPa as given in Table 3. The average measured 7 and 28 days cubes compressive strength were 29 and 37.5 MPa respectively.

TABLE 4: MIX PROPORTIONS (BY WEIGHT) OF ONE CUBIC METER OF CONCRETE

Cement (OPC) (Kg)	Sand (Kg)	Crushed Stone (Kg)	Water (Liter)
350	690	1092	200

4.4 R.C Column

Fig. (2) shows geometry, dimensions, and details of reinforcement of circular column. Six RC columns are circular cross section with 152.3 mm diameter and 1000 mm height. The columns were reinforced with 6Φ10 as main reinforcement. Closed stirrups 5Φ8 in the first and last 250 mm of column height were used as stirrups concentration at both ends of the column. Closed stirrups 5Φ8 were used middle 500 mm for column height.

Six plastic forms were assembled then the steel cages were placed inside them as shown in figure (3). Plastic spacers were used to adjust the concrete cover around the steel cages. Nine concrete cube specimens of size 150 mm were tested to determine the compressive strength as per BS 1881: Part 115. Six concrete cylinder specimens of size 150 mm diameter and 300 mm height were tested to determine the tensile splitting strength as per BS 1881: Part 117. Cubes and cylinders of concrete were cast to study the effect of thermal cycles on mechanical properties of concrete. The concrete was compacted using mechanical vibrators as shown in figure (4). Few hours after casting, the surface was finished and then covered with wet burlap and plastic sheets. Next day, the forms were demolded and RC column were covered with wet burlap for another15 day as shown in fig. (5) and the cubes and cylinders were submerged under water in a curing tank for 28 days. There was no evidence of segregation or honeycombing in all RC column.

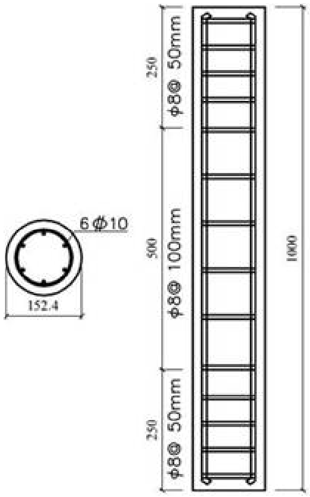

Fig. 2. Dimensions and Reinforcement of RC Columns

Fig. 3. Dimensions and Reinforcement of RC Columns

Fig. 4. Compaction of RC Columns

Fig. 5. Curing of RC Columns

4.5 Strengthening Process

The RC column were left to dry out in the open atmosphere for 7 days prior to strengthening process. The external layer of concrete was grinned and chipped away using an electrical brush. The surface was thoroughly cleaned using only compressed air to remove all loose particles and dust. The GFRP wrap were cut to size. One piece GFRP wrap of 630 mm wide X 1000 mm length was used to strengthen each column as a one layer. The polyester adhesive was used to bond the GFRP wrap to the RC columns, because it is the compatible polymer adhesive review by the technical data sheet of GFRP wrap. Additional GFRP wraps were cut to size 630 mm wide X 150 mm length which were applied as add stiffness at columns heads during the compression test. The polyester adhesive was applied to concrete surface of beams by a paint-brush in quantity of approximately 2.0 kg/m2 as shown in fig. (6). The concrete column was wrapped using the GFRP wraps while manually pressing against the concrete surface as shown in fig. (7). In all cases, the outside layer was extended by an overlap of 150 mm to ensure the development of full composite strength.

Strengthened RC column was left to cure for 7 days in the ambient temperature prior to subjecting to thermal cycles. Four RC columns and three concrete cubes were entranced in the electrical oven in order to be exposure the thermal cycles as shown in Figs. (8, 9).

Fig. 6. Painting the Polyester on RC Columns

Fig. 7. Retrofitting of RC Columns

Fig. 8. An Electrical Automatic Oven

Fig. 9. The Specimens in the Oven

5 TEST RESULTS

After thermal cycles finished, all columns were capped using the grout. All columns, cubes, and cylinders were subjected to axial compression load until failure. A hydraulic machine of 200-ton capacity and 0.5-ton sensitivity was used. Two steel cylinders made from 10 mm thickness steel cylinder of 100 mm height were confined the two ends of column to avoid ends failure. Two mechanical dial gauge of 0.01 mm sensitivity were used to measure the deformation during loading process as shown in Fig. (10). The First dial gauge was monitored on the movables head of the hydraulic machine to measure the vertical deformation of column (Δ1). The second dial gauge was monitored on the column to measure the vertical deformation at the mid-height of column (Δ2) at 180 mm from both ends of column. Table (5) presents the experimental results of the compressive strength of concrete before and after been subjected to thermal cycles.

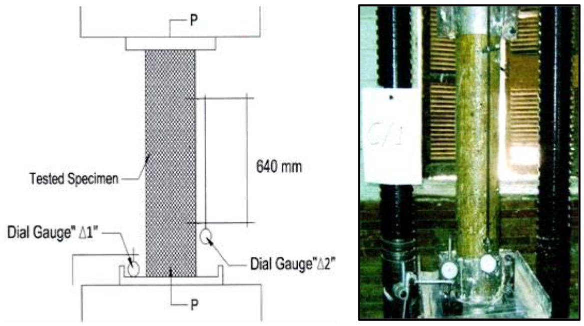

Fig. 10. Test Setup

TABLE 5: EFFECT OF THERMAL CYCLES ON COMPRESSIVE STRENGTH OF CONCRETE

Status		Prior to Thermal Cycles*	After been subjected to Thermal Cycles*
Compressive Strength	Kg/cm^2	375	371
	Percentage**	100	98.9
Tensile Splitting Strength	Kg/cm^2	35.5	26.8
	Percentage**	100	75.5

* Results was determined as the arithmetic mean of 3 specimens.
** Percentage is calculated with respect to specimens prior to thermal cycles.

Table (6) summarizes the ultimate load carrying capacities, the maximum deformations and the failure modes of RC columns prior to and after being subjected to thermal cycles respectively.

TABLE 6: SUMMARY OF EXPERIMENTAL RESULTS FOR RC COLUMNS

Column Group	No GFRP strengthening		GFRP strengthening			
Exposure Condition	Control	Heated	Control		Heated	
Column Label	C/0	T/0	C/1	C/3	T/1	T/3
Ult. Load (ton)	76	74	88	104	87	102
Max. Axial Deformation (mm)	2.10	0.53	4.22	3.34	2.82	1.56
Mode of Failure	Vertical cracks along column and crushing in concrete and buckling of longitudinal bars at the end of column		Splitting and debonding of GFRP and crushing in concrete and buckling of longitudinal bars at the end of column			

Modes of failure of RC columns are shown in Figs. (11, and 12).

Load-deformation curves of RC columns are shown in Figs. (13) to (18).

Fig. 11. Mode of Failure of Control RC column (C/0 and T/0)

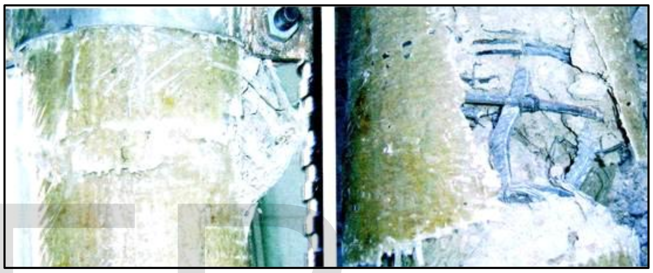

Fig. 12. Mode of Failure of Strengthened RC column

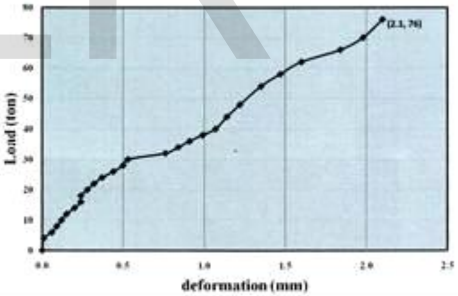

Fig. 13. The load-deformation of (C/0) Column

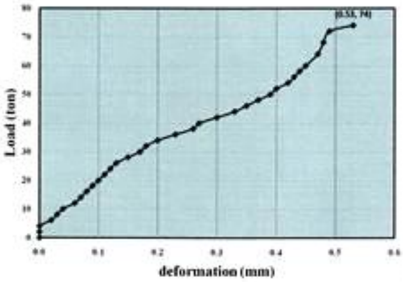

Fig. 14. The load-deformation of (T/0) Column

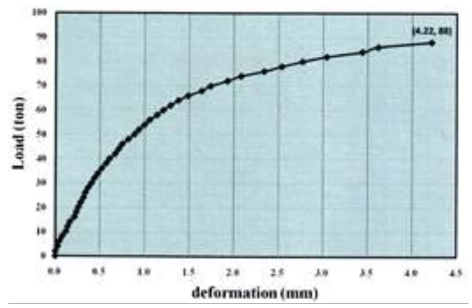

Fig. 15. The load-deformation of (C/1) Column

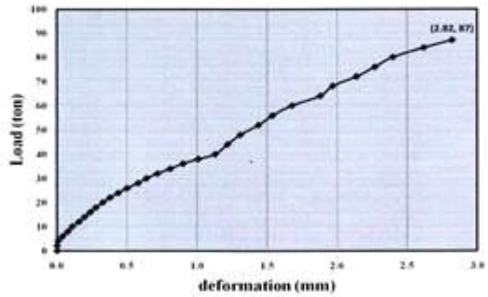

Fig. 16. The load-deformation of (T/1) Column

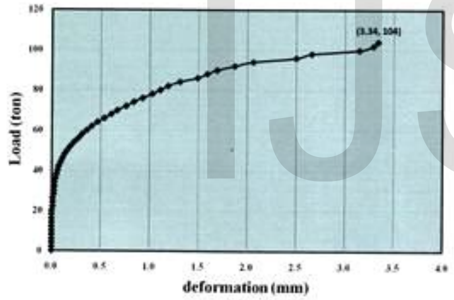

Fig. 17. The load-deformation of (C/3) Column

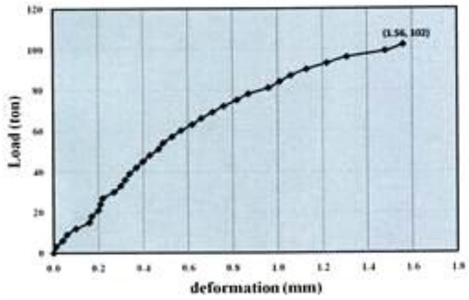

Fig. 18. The load-deformation of (T/3) Column

6 DISCUSSION OF TEST RESULTS

6.1 Behavior of RC columns strengthened with GFRP wraps

Figure (19) represents a comparison between the stress-axial strain relation of RC columns in the control group (C/0, C/1, and C/3) to illustrate the effect of strengthening on the structural behavior of RC columns.

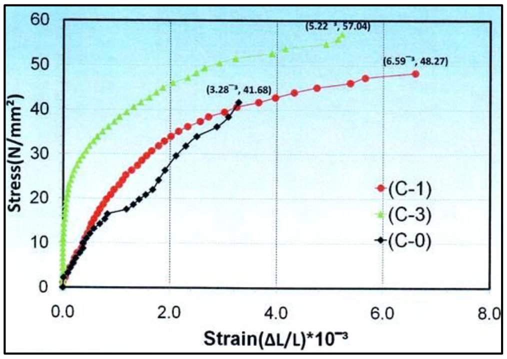

Fig. 19. Stress-axial strain relation of RC columns in the control group (C/0, C/1, and C/3)

As shown if Fig. (19) The stress - axial strain relation for RC columns confined with externally bonded GFRP wraps indicate significant increases in strength and improves the stiffness of RC when compared to the behavior of unconfined columns. The ultimate strength, maximum axial strain, and energy absorption capacity for tested RC columns, as measured experimentally, are given in Table (7).

TABLE 7: THE ULTIMATE STRENGTH, MAXIMUM AXIAL STRAIN, ENERGY ABSORPTION CAPACITY FOR RC COLUMNS.

Column Label		**C/0**	**C/1**	**C/3**
Ultimate Strengths	**(MPa)**	41.70	48.28	57.06
	Percentage*	100	115.8	136.8
Max. Axial Strain	**x10^3(mm/mm)**	3.28	6.59	5.22
	Percentage*	100	201	159
Approximate Energy Absorption Capacity**	**(KN.mm)**	798	2475	2315
	Percentage*	100	310	290

* Percentage is calculated with respect to RC column C/0.
** Approximate energy absorption capacity was calculated as the area under the load-deformation curve.

As can be seen from Table (7), the external confinement with GFRP wraps increased the ultimate strength were 15.8 and 36.8% for one layer and three layers higher than the control RC column respectively. Also, the maximum axial strains were 101 and 59 % for one layer and three layers higher than the control RC column respectively. So, the approximate energy absorption capacities were 210 and 190 % for one layer and three layers higher than the control RC column respectively.

6.2 Effect of thermal cycles on the compressive and tensile splitting strength of Concrete

As can be seen from Table (5), the thermal cycles have a slight effect on the compressive strength of concrete specimens. However, the indirect tensile strength of concrete specimens after been subjected to thermal cycles was reduced to 75.5% of the control specimens. This means that, the thermal cycles have a remarkable effect on splitting tensile strength. It may be due to the generation of micro cracks because of subjecting to thermal cycles [9].

6.3 Effect of thermal cycles on behavior of RC column strengthened using GFRP wraps

The ultimate strength, maximum axial strain, and energy absorption capacity for control RC columns, as measured experimentally, are given in Table (8).

TABLE 8: THE ULTIMATE STRENGTH, MAXIMUM AXIAL STRAIN, ENERGY ABSORPTION CAPACITY FOR CONTROL RC COLUMNS.

Column Label		C/0	T/0
Ultimate Strengths	**(MPa)**	41.70	40.60
	Percentage*	100	97.4
Max. Axial Strain	**x10^{-3}(mm/mm)**	3.28	0.88
	Percentage*	100	25.2
Approximate Energy Absorption Capacity**	**(KN.mm)**	798	196
	Percentage*	100	24.6

* Percentage is calculated with respect to RC column C/0.
** Approximate energy absorption capacity was calculated as the area under the load-deformation curve.

As can be seen from Table (8), due to subject to thermal cycles, the ultimate strength of RC column (T/0) was reduced to 97.4 % of the control unheated RC beam. Also, the maximum axial strain was reduced to 25.2 % of the control unheated RC column. So, the approximate energy absorption capacity was reduced to 24.6 % of the control unheated RC column. Mode of failure of RC columns prior to and after been subjected to thermal cycles did not changed. So, the major effect of the thermal cycles is increasing the brittleness of RC column.

Figure (19) represents a comparison between the stress-axial strain relation of RC column in the control group (C/0, C/1, and C/3) to illustrate the effect of strengthening on the structural behavior of RC columns.

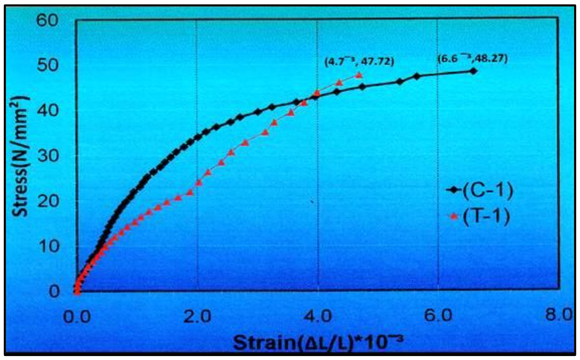

Fig. 20. stress-axial strain relation of strengthened RC column (C/1 and T/1)

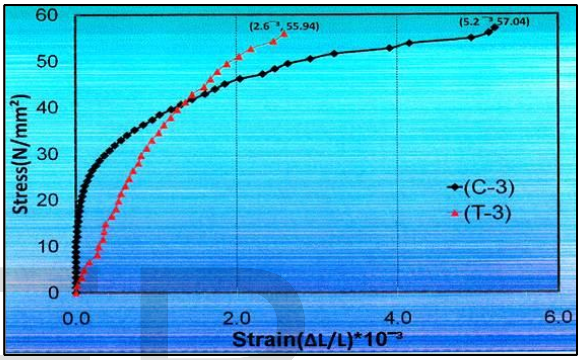

Fig. 21. stress-axial strain relation of strengthened RC column (C/3 and T/3)

The ultimate strength, maximum axial strain, and energy absorption capacity for strengthened RC columns, as measured experimentally, are given in Table (9).

TABLE 9: THE ULTIMATE STRENGTH, MAXIMUM AXIAL STRAIN, ENERGY ABSORPTION CAPACITY FOR STRENGTHENED RC COLUMNS.

Column Label		C/1	T/1	C/3	T/3
Ultimate Strengths	**(MPa)**	48.28	47.73	57.06	55.96
	Percentage	100	98.9*	100	98.1**
Max. Axial Strain	**x10^{-3}(mm/mm)**	6.59	4.68	5.22	2.59
	Percentage	100	66.8*	100	46.7**
Approximate Energy Absorption Capacity***	**(KN.mm)**	2475	1226.7	2315	1060.8
	Percentage	100	49.5*	100	45.8**

*Percentage is calculated with respect to RC column C/1.
**Percentage is calculated with respect to RC column C/3.
*** Approximate energy absorption capacity was calculated as the area under the load-deformation curve.

As can be seen from Table (9), due to subject to thermal cycles, the ultimate strengths of strengthened RC columns were reduced to 98.9 and 98.1% of the identical unheated RC column for one layer and three layers respectively. Also, the maximum axial strains of strengthened RC columns were reduced to 66.8 and 46.7 % of the identical unheated RC column for one layer and three layers respectively. So, the approximate energy absorption capacities of strengthened RC columns were reduced to 49.5 and 45.8 % of the identical unheated RC beam for one layer and three layers respectively. Mode of failure of strengthened RC columns prior to and after been subjected to thermal cycles did not changed.

It is concluded that thermal cycles have a slight effect on the ultimate strength of concrete. But, it has a harmful effect on the stiffness of RC columns and consequent major reduction in energy absorption capacity as shown in Fig. (20, 21). The thermal cycles increased the brittleness of concrete. However, present of GFRP wrap decreases the harmful effect thermal cycles on stiffness of RC column. This damage effect may be due to the difference in coefficient of thermal expansion (CTE) between concrete, polymer adhesive and GFRP wraps resulted in a reduction of bond property of the polymer adhesive. Bond plays an important role in the retrofitting of concrete elements using externally bonded GFRP wraps. Also, the thermal cycles had resulted in a generation of micro cracks. This may have reduced the ultimate capacities of RC columns [9].

6.4 Comparison between Experimental Test Results and Mathematical Model for Predicting confined compressive strength of RC columns

According to the equations given by the ECP (208-2005) [12], the confined compressive strength (f_{cc}) the maximum compressive strain ($e_{cuc}^{/}$) of RC columns strengthened with FRP wrap can be calculated as follows:

$$f_{cc} = f_{cu}\left[2.25\sqrt{1+9.875\left(\frac{f_l}{f_{cu}}\right)}-2.5\left(\frac{f_l}{f_{cu}}\right)-1.25\right] \qquad (1)$$

$$f_l = \frac{\mu_f E_f e_{fe}}{2\gamma_f} \qquad (2)$$

$$\mu_f = \frac{4nt_f}{D} \qquad (3)$$

$$e_{cuc}^{/} = \frac{1.37(f_{cuc}-4f_{cu})}{E_c} \qquad (4)$$

where:

f_{cu} is the characteristic compressive strength of concrete.

f_l is the confining pressure due to FRP jacket.

μ_f is the volumetric ratio of FRP reinforcement in case of full wrapping.

E_f is the tensile modulus of elasticity of the FRP.

e_{fe} is the effective strain if the FRP.

γ_f is the reduction factor of the FRP (take=1).

n is the number of layers of FRP.

t_f is the nominal thickness of one layer of FRP.

D the diameter of RC column.

E_c is the modulus of elasticity of concrete.

The confined compressive strength (f_{cc}) the maximum compressive strain ($e_{cuc}/$) for the tested columns, as measured experimentally, are given in Table (10) along with the predicted values.

TABLE 10: MATHEMATICAL AND EXPERIMENTAL VALUES OF CONFINED COMPRESSIVE STRENGTH AND MAXIMUM AXIAL STRAIN, FOR STRENGTHENED RC COLUMNS.

Column Label		**C/1**	**T/1**	**C/3**	**T/3**
No. of GFRP wrap layer		**One**		**Three**	
Confined Comp. Strength	**Exp. (MPa)**	48.28	47.73	57.06	55.96
	Math. Model (MPa)	48.0		64.3	
	Percentage*	100.6	99.4	88.7	87.0
Max. Axial Strain	**Exp. x10^{-3}(mm/mm)**	6.59	4.68	5.22	2.59
	Math. Model x 10^{-3}(mm/mm)	4.57		8.71	
	Percentage*	144.2	102.4	59.9	29.7

*Percentage is calculated with respect to corresponding mathematical value.

The analysis of the results shown in Table (10) indicates that good correlation between the measured and predicted confined compressive strength for tested columns prior to and after been subjected to thermal cycles. A better correlation is achieved for RC columns strengthened by one layer of GFRP wraps while, for RC columns strengthened by three layers of GFRP wraps the mathematical model was overestimate.

The ratios of the measured maximum axial strain at ultimate load to the predicted from 1.44 to 1.02 for RC columns strengthened by one layer of GFRP wraps while, for RC columns strengthened by three layers of GFRP wraps the mathematical model was overestimate.

7 CONCLUSION

Based on the results of the experimental work reported in this study, the following conclusions are drawn:

a. Strengthening of RC column by external confinement with bonded GFRP wraps proved to be an easy and reliable strengthening technique.

b. Strengthening of RC column by external confinement using bonded GFRP wraps can increase the ultimate capacity and improve the ductility, which leads to increase the energy absorption capacity.

c. Increasing in ultimate strength and ductility of confined concrete is proportional to the number of layers of GFRP wraps.

d. For the thermal cycles used, the compressive and tensile splitting strengths of concrete were reduced to 98 and 25 % of the control specimens respectively. Tensile strength was more sensitive to the effect of thermal cycles than the compressive strength of concrete.

e. The thermal cycle reduces the ultimate strength and the maximum axial strain to 97 and 25 % of identical unheated RC column respectively. The thermal cycles increase the brittleness of RC columns.

f. The thermal cycle reduces the ultimate strength to 99 and 98 % from those of similar unheated strengthened RC columns for one layer and three GFRP layers respectively

g. The thermal cycle reduces the maximum axial strain to 67 and 47 % from those of similar unheated strengthened RC columns for one layer and three GFRP layers respectively.

h. The failure modes of RC columns prior to and after subjected to thermal cycles were obviously identical.

i. The thermal cycles reduce the ductility of control and strengthened RC columns.

j. Good correlation was obtained between most obtained experimental test results and the predicted results based on the mathematical model given be the ECP (208-2005).

ACKNOWLEDGEMENT

The author would like to thank all the members of properties and testing of materials laboratory (Faculty of Engineering, Ain Shams University, Egypt) for their help in conducting the experimental work.

REFERENCES

[1] Ayesha Siddika, Md. Abdullah Al Mamun, Wahid Ferdousc,, Rayed Alyousef (2020), "Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs – A state-of-the-art review "", International Journal of Engineering Failure Analysis, V 111, 104480

[2] S. Cabral-Fonsecaa, J.R. Correia, J. Custódio, H.M. Silva, A.M. Machado, J. Sousa (2018), "Durability of FRP - concrete bonded joints in structural rehabilitation: A review"", International Journal of Adhesion and Adhesives, V.83, No. 156, pp.153-167.

[3] E. Ferrier, A. Agbossou (2017), "Temperature effects on the shear capacity of external bonded fiber reinforced polymer on concrete", Journal of Construction and Building Materials, V152, pp. 333–344

[4] Samir H. Okb, El-Sayed A. Nasr, Amr I.I. Helmy, Ibrahim Abdel-latif Yousef, (2017), "Effect of thermal exposure on the mechanical properties of polymer adhesives", Journal of Construction and Building Materials, V135, pp. 490–504

[5] K.H. Tan, M.K. Saha , Y.S. Liew, (2009) 'FRP-strengthened RC beams under sustained loads and weathering", Journal of Cement & Concrete Composites, V 31, pp. 290–300

[6] Wan-Yang Gao, Jian-Guo Dai, J.G. Teng, (2015), "Analysis of Mode II debonding behavior of fiber-reinforced polymer-to-substrate bonded joints subjected to combined thermal and mechanical loading", Journal of Engineering Fracture Mechanics, V 136, pp. 241–264.

[7] Hugo C. Biscaia, (2019), "The influence of temperature variations on adhesively bonded structures: A non-linear theoretical perspective", International Journal of Non-Linear Mechanics, V113, pp. 67–85.

[8] Clarisse Mikami, Hwai-Chung Wu, Abulgasem Elarbi, (2015), "Effect of hot temperature on pull-off strength of FRP bonded concrete Clarisse", Journal of Construction and Building Materials, V 91, pp. 180–186

[9] Latif, I.A (2004), "Effect of Temperature on The Behaviour of RC Beams Retrofitted Using Externally Bonded Fibre Reinforced Plastics", Master of Science, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

[10] ES (4756-1/2006), "Specification for Portland Cement CEMI", Egyptian Standardization Authority.

[11] Hamid, A. A., Elshafie, H., Nasr, E. A., and Fahmy, E. (2001), "Retrofitting of Reinforced Concrete Beams Using Advanced Composite Overlays," Proceedings of Ninth International Colloquium on Structural and Geotechnical Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

[12] Egyptian Code of Practice, (ECCS 208), (2005), "EGYPTIAN CODE OF PRACTICE FOR THE USE OF FIBER REINFORCED POLYMER (FRP) IN THE CONSTRUCTION FIELDS", 1st Edition, Ministry of Building Construction, Egypt.