Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

STRAIN EFFICIENCY OF CARBON FIBRE REINFORCED POLYMER-CONFINED RC COLUMNS

YAMAN S. S. AL-KAMAKI[*], RIADH AL-MAHAIDI[**] and IAN BENNETTS[***]
[*]University of Duhok (UoD), Duhok, Kurdistan Region, Iraq & Faculty of Science, Engineering and Technology, Swinburne University of Technology-Australia.
[**]Faculty of Science, Engineering and Technology, Swinburne University of Technology-Australia.
[***]Faculty of Science, Engineering and Technology, Swinburne University of Technology-Australia.

ABSTRACT

Fibre reinforced polymer (FRP) composite materials in the form of FRP wraps provide one of the most effective means of confining existing reinforced concrete columns where the strength of these columns must be enhanced. Such wraps are often formed in a wet layup process with the fibres being mainly in the hoop (lateral) direction. Numerous studies have found that the nominal properties published by the manufacturer are different from the properties of materials obtained from testing the combination of CFRP and epoxy (i.e. CFRP coupons) as tensile coupons. Research studies have also shown that the CFRP wraps when applied to reinforced concrete columns have a lower ultimate hoop strain (and therefore a lower ultimate hoop stress) compared to the failure strain measured from direct tensile tests of the CFRP coupons. This is the result of differences in the fabrication processes and the in-situ forms. It was also noted that it is possible to repair or even restore the lost strength of columns damaged by elevated temperature, depending on the performance of the CFRP material. This paper presents also the results of a study that reports and compares the ultimate tensile strains of CFRP obtained from flat coupon tensile tests and CFRP-confined concrete columns tests using an innovative digital image correlation (DIC) technique. It was found that the CFRP lateral rupture strains in CFRP-confined RC columns are reduced below the ultimate tensile strains from flat coupon tests. Based on comparisons of these test results, for all columns wrapped with 1 or 2 CFRP layers, the strain efficiency was found to be in the range of 0.54 to 0.9 or 0.54 to 0.94 respectively.

KEYWORDS: Carbon fibre reinforced polymer, Confined RC columns, Heating, Strain efficiency, Structural testing.

1. INTRODUCTION

The increase in strength and ductility of carbon fibre-reinforced concrete members is highly dependent on the performance of fibre reinforced polymer (FRP) composite material (Micelli & Modarelli, 2013). Several studies have indicated that the nominal properties provided by the manufacturer for the fibre are different from those gained from the testing of FRP coupons (Fawzia, 2007; Harries & Kharel, 2002; Matthys, Taerwe, & Audenaert, 1999; Schnerch, 2005; Shahawy, Mirmiran, & Beitelman, 2000); Watanabe et al. (1997). This is due to the difference in testing a single fibre (manufacturer's data) and a practical tensile coupon (Al-Kamaki, Al-Mahaidi, & Bennetts, 2016).

Also, research on the use of FRP composites has shown that FRP material breaks earlier when it is used to wrap columns/cylinders than when undertaking flat coupon tests (Al-Kamaki et al., 2016; Benzaid, Mesbah, & Chikh, 2010; Berthet, Ferrier, & Hamelin, 2005; L. A. Bisby & Take, 2009; Bullo, 2003; Ciupala, Pilakoutas, & Mortazavi, 2007; De Lorenzis, Micelli, & La Tegola, 2002; Harries & Carey, 2003; Jiang & Teng, 2006, 2007; L Lam, Teng, Cheung, & Xiao, 2006; L. Lam & Teng, 2004; Pessiki, Harries, Kestner, Sause, & Ricles, 2001; Rousakis & Tepfers, 2004; Smith, Kim, & Zhang, 2010; Wang & Wu, 2008); Xiao and Wu (2000). In other words, FRP column jacketing leads to a substantial reduction in FRP's effective strain capacity. To allow for this reduction, an efficiency factor has been proposed for FRP wraps (Pessiki et al., 2001). This is defined as the strain efficiency factor: the ratio of hoop (lateral) strain in the FRP wrap at failure of the compression member to the failure strain measured from direct tensile tests of the flat FRP coupons (Abdelrahman & El-Hacha, 2012; Luke A Bisby & Stratford, 2011). A survey by Wu and Jiang (Wu & Jiang, 2013) reported that the strain reduction factors recommended in the literature

eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

vary substantially from 0.274 to 1.133 for FRP confined columns, indicating that extra targeted studies are required for more accurate evaluation of hoop rupture strain efficiency of FRP wraps. In all these studies, the test samples were unheated and wrapped at ambient temperature and conventional discrete foil strain gauges were used for measuring FRP axial and hoop strains at failure.

For a compression member (column), the use of FRP wrapping can result in an increase in the strength and ductility of the column. Very limited research has been reported in the literature in relation to assessing the residual strength (i.e. strength after a fire) of circular specimens that have been repaired using FRP following the fire event. However, in these studies, the test columns were unstressed during heating and cooling, despite the fact that columns are expected to be stressed during any fire incident.

This paper presents experimental results for RC specimens that were heated and subsequently cooled under load to ambient conditions prior to wrapping with FRP. The composite specimens were then tested under ambient conditions. The paper is aimed at more closely evaluating the influence of the elevated temperature history and FRP layers on the hoop strain efficiency of FRP wraps. Furthermore, the strain distributions over the surface of FRP wraps may be variable along the height of the compression member and may not be able to be reliably determined using single point gauges. Strains were measured using an innovative digital image correlation technique (DICT), based on the principles of photogrammetry. This paper (i) provides experimental data on the residual compressive strength of loaded RC circular columns (during heating and cooling) exposed to temperatures up to 1000 °C following the ISO 834 (ISO 834, 2012) fire curve; (ii) presents information on the hoop (lateral) strain variations over the surfaces of unwrapped and CFRP-wrapped RC columns as found using the digital image correlation (DIC) technique; (iii) provides data on the strain efficiency factor for unheated and heat-damaged RC columns wrapped with CFRP fabrics.

2. EXPERIMENTAL PROGRAM

3.1 Materials

The specimens were constructed using ready-mix normal strength concrete (NSC). Target concrete strengths of 32 MPa was designed for the specimens. The slump was 80 mm and maximum aggregate size was 14 mm. Two types of deformed bar reinforcement were used as longitudinal and transverse (circular ties) reinforcement of Ø 10 mm and Ø 6.0 mm @ 130 mm c/c respectively. A longitudinal steel reinforcement ratio of approximately 1.44 % was used. The columns had a concrete cover of 20 mm to the circular ties. The MBrace Saturant resin system was used as the epoxy which consists of a main resin component (Part A) and a hardener (Part B) which are mixed together at a specific volume ratio (3A:1B) for about 5 minutes. High-tensile unidirectional CFRP sheet (CF 230/4900 400/30) was used for jacketing. The nominal thickness of the CFRP fabric was 0.227mm/ply. The CFRP fabric was continuously wrapped around the 204mm dia. concrete columns, ending with an overlap of 150 mm length in the hoop direction. The mechanical properties of CFRP were obtained through tensile testing of four (50 mm × 250 mm) flat coupons with a clear distance between the two grips equal to 150 mm including 2 configurations (i.e. single layer and double layers) following the (ASTM D 3039/D 3039M (ASTM D 3039/D 3039M, 2008), BS EN ISO 527-5 (BS EN ISO 527-5, 2009) recommendations using a 250 kN MTS machine (see Table 1). For testing, the coupons were clamped in the jaws of the testing machine and statically loaded under displacement control at a rate of 1 mm/min. The coupons had a speckle pattern to enable the use of the DICT system. The pattern was prepared by first applying a coat of white paint on the face of the coupon and then applying a detailed pattern of black speckles. This pattern enables the measurement of axial strains using a Vic-3-D digital image correlation system camera. Tensile flat CFRP-coupon preparation and testing are shown in Figure 1.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

Table (1): Material characteristics of CFRP sheet

Coupon		One CFRP layer (0.227 mm/ply)			
		Avg. thick. (mm) [a]	Max. load (kN)	Max. tensile stress (MPa)	Max. tensile strain
1	1 layer	1.30	46.01	3974.3	0.013
2	1 layer	1.42	50.05	4409.7	0.012
Average		1.36	48.25	4192.4	0.0125
Coupon		Two CFRP layers (0.227 mm/ply)			
1	2 layers	1.80	80.1	3542.8	0.016
2	2 layers	1.73	86.3	3727.2	0.014
Average		1.78	82.4	3586.9	0.015
Manufacturer's data		-	-	4900	0.021

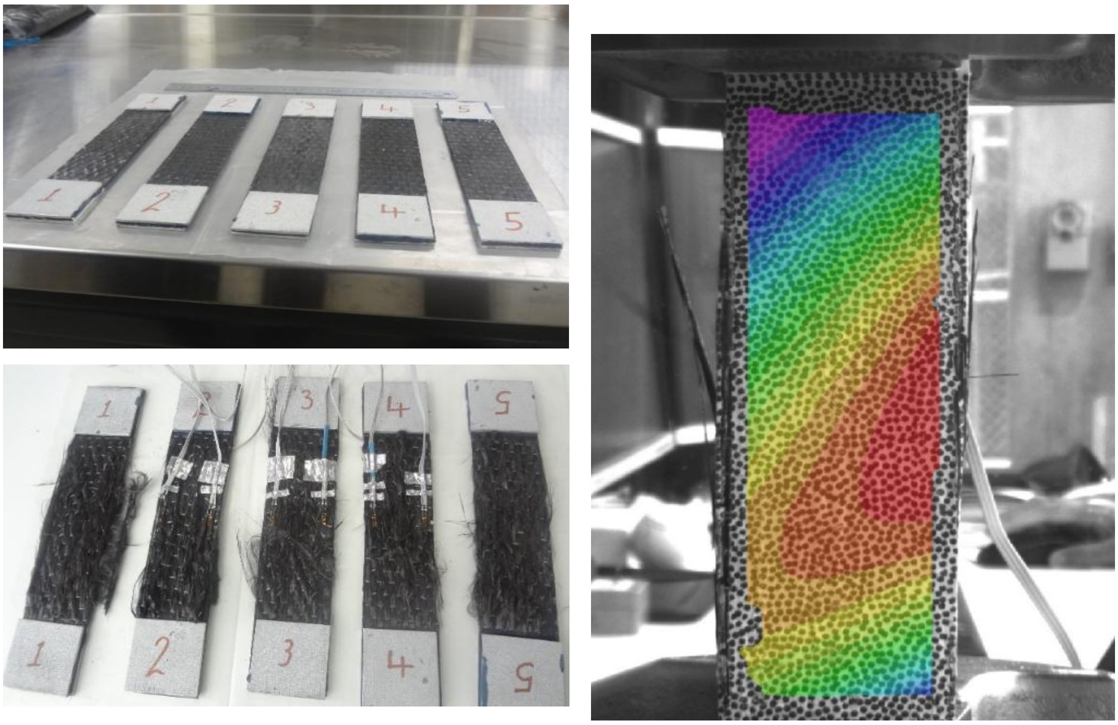

Fig. (1): CFRP coupons and test set-up

3.2 Details and preparation of columns

The circular columns were cast in the Smart Structures Testing Laboratory at Swinburne University of Technology. The experiment involved the preparation and testing of eighteen Ø 204 mm × 750 mm RC columns which were divided into three groups. Figure 2 shows the dimensions and reinforcement details of the columns. The test variables included, number of CFRP layers, elevated temperatures and heated and unheated columns, see Table 2. Of the total columns, six were left as reference columns and 12 were heated under sustained axial compressive load of 0.3 f'_{co}. This load was applied prior to heating and maintained during heating and cooling. Of the heated columns, only six were instrumented with type-K thermocouples (see Table 2) to measure the temperature at different locations. Each of the six columns was instrumented with four thermocouples at mid-height as follows: thermocouples 1 to 3 were located at the centre of the cross-section, 25 mm from the centre and 50 mm from the centre, respectively. Thermocouple no. 4 was attached to one of the vertical reinforcing bars using an electrical spot welder. A fifth thermocouple was attached to the surface of each of the instrumented columns just prior to the commencement of heating.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

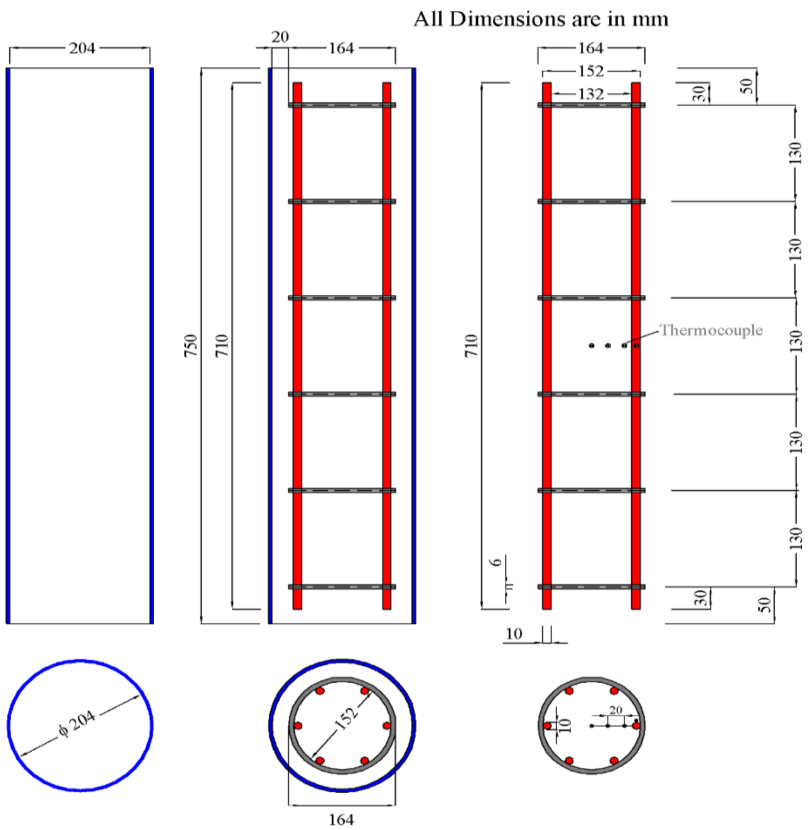

Fig. (2): Dimensions and reinforcement details of test columns

Table (2): Details of circular RC columns

No.	Group	Column Symbol	Heating Condition	CFRP Layers	Description
1	1	C-UH-0	Ambient	0	Unheated unwrapped (control column)
2		C-UH-0		0	
3		C-UH-1		1	Unheated wrapped column with 1 CFRP layer
4		C-UH-1		1	
5		C-UH-2		2	Unheated wrapped column with 2 CFRP layers
6		C-UH-2		2	
7	2	[1]HC-L-800°C-0	800°C for 2 hours	0	Exposed to 800°C under load, unwrapped
8		HC-L-800°C-0		0	
9		[1]HC-L-800°C-1		1	Exposed to 800°C under load, wrapped with 1 CFRP layer
10		HC-L-800°C-1		1	
11		[1]HC-L-800°C-2		2	Exposed to 800°C under load, wrapped with 2 CFRP layers
12		HC-L-800°C-2		2	
13	3	[1]HC-L-1000°C-0	1000°C for 2 hours	0	Exposed to 1000°C under load, unwrapped
14		HC-L-1000°C-0		0	
15		[1]HC-L-1000°C-1		1	Exposed to 1000°C under load, wrapped with 1 CFRP layer
16		HC-L-1000°C-1		1	
17		[1]HC-L-1000°C-2		2	Exposed to 1000°C under load, wrapped with 2 CFRP layers
18		HC-L-1000°C-2		2	

C = column, UH = unheated, L = loaded, H = heated, 0, 1, 2 = number of CFRP layers.
[1] Column instrumented with 4 type-K thermocouples when exposed to heating and subsequent cooling.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

For the purpose of determining the benchmark strength of the concrete, nine Ø 100 mm × 200 mm standard cylinders were cast (three cylinders per each group). The stress was applied at 0.3 MPa / second later for test purposes. After casting process (see Figure 3 (a)), the columns and cylinders were left inside the mould for 24 hours to harden. After 24 hours, the formwork was removed and the outside of the specimens was coated with a wax emulsion curing compound (Masterkure 100WB). The samples were then cured in the laboratory in a humidified enclosure at 24 °C and 90 % relative humidity for 28 days. At the end of the curing time, the specimens were removed from the humidity chamber and placed in the laboratory at ambient temperature until they were ready for heating, wrapping or testing. Before heating, the top surfaces of columns were capped using self-leveling grout (Ardex LQ 92) with a thickness of about 10 mm to provide a smooth horizontal loading surface. The capped columns were air-cured until the day of heating.

3.3 Column heating and cooling cycle

The columns were placed individually in an electric furnace and the applied load was gradually increased up to the full-service load (360 kN ≈ 0.3 f'_{co}). Figure 3 (b) show the general view of the column test furnace. During this phase, no heat was applied to the columns, and once the target load was reached, it was maintained during the heating and cooling phases. Load and temperature were monitored during the preload phase, which began approximately one hour before the heating phase. The load was applied to the columns using a hydraulic jacking system designed for this study. As explained earlier, only 12 columns were subjected to a stress of 30% of maximum load at ambient temperature while they were exposed to 800 °C or 1000 °C following the ISO 834 (ISO 834, 2012) curve, as shown in Figure 4. The temperature was kept constant at the target temperature for two hours and then cooled to room temperature. These temperatures should not be confused with the temperatures measured by the thermocouples within the specimens.

Fig. (3): (a) Formwork before and after concrete casting (b) General view of the column test furnace.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

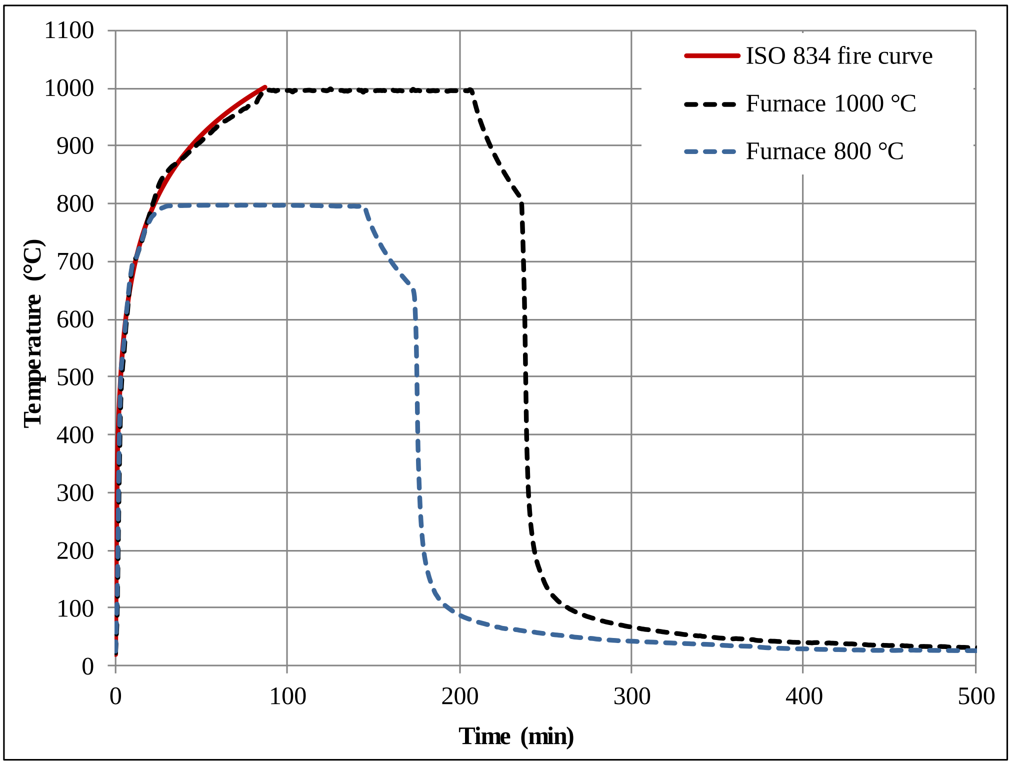

Fig. (4): ISO 834 and heating-cooling cycles for RC columns

3.4 Method of CFRP wrapping

The wet lay-up method was used for CFRP columns wrapping. Since the CFRP supplied by the manufacturer was supplied in 300 mm lengths, two 300 mm sheets were first applied and additional 75 mm strips were cut to complete the wrapping to the top and bottom of the column. Attachment of the fabric was undertaken as follows:

• A thin layer of a priming coat (MBrace Primer) was applied to the clean column surface and permitted to cure for a minimum of one hour.

• The epoxy (MBrace Saturant) was then applied on top of the primer layer and on the CFRP sheets.

• The CFRP sheet was pressed on to the concrete surface using a hand roller.

• If more than one layer of fabric was required, another coat of epoxy was applied to the top of the first CFRP sheet.

• Another two 75 mm strips were applied to the top and bottom part of the column to ensure full wrapping.

• Each layer of CFRP wrapping was extended in the circumferential direction (i.e. in the fibre direction) past its starting point to give an overlap of 150 mm.

3.5 Digital image correlation technique (DICT) system

The digital image correlation technique (photogrammetry) uses optical measurements taken with linked digital cameras (with appropriate lenses and resolution) to determine 2-D and 3-D surface strains. This system captures successive digital images during a loading event in which deformations occur. A view of the Vic-3D measurement system (Vic-3D, 2010) is shown in Figure 5. The area on a column for which strains are required needs to incorporate a random dot pattern (speckle pattern) for strain calculating purposes. A layer of white paint (i.e. brush paint or spray paint) is first applied to the column surface, followed by the application of black speckles. Figure 5 shows the progression from surface preparation to a speckled pattern. The conversion of optical images to strains is achieved as follows. Two high-resolution cameras take a picture of the pattern before loading (i.e. during image calibration stage) using the Vic-Snap software and then new images are taken at prescribed times or load steps when the column is under test and subjected to external loads. Using the Vic-3D software, the images are analyzed considering the difference between pixels of the different images and correlated to create a contour

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

map of surface strains. The strain components can be presented and stored as sectional strain plots and contour lines for any point on the surface. This technology was used to capture detailed strain histories of both the unwrapped RC circular columns (heated and unheated) and the CFRP-wrapped concrete circular columns (heated and unheated).

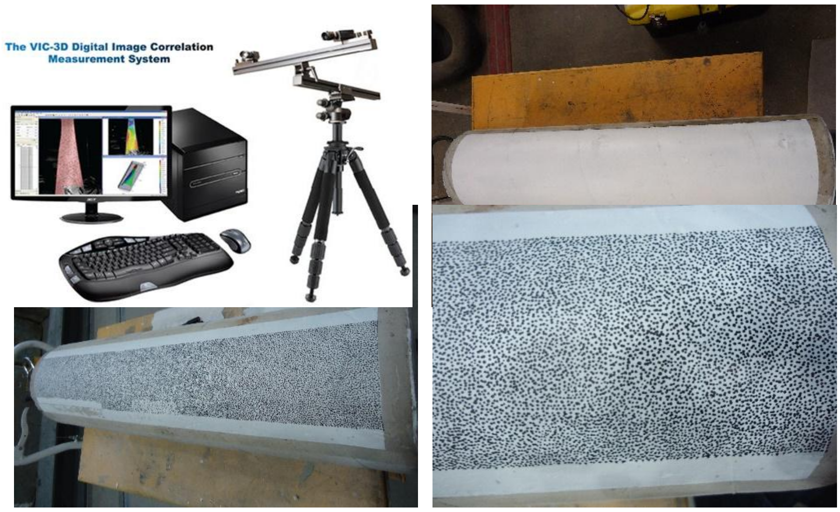

Fig. (5): Vic-3D measurement system and Surface preparation with a random dot pattern

3.6 Testing Technique

All columns were loaded using an Instron testing machine with a capacity of 5 MN at a displacement rate of 0.5 mm / min. A view of the machine during the testing of a circular column is shown in Figure 6. Information was recorded by two different systems. Load and displacement data were recorded by the 5 MN Instron testing machine and Vic-3D was used to determine the strains on the column surface. All data were recorded every second throughout each of the tests.

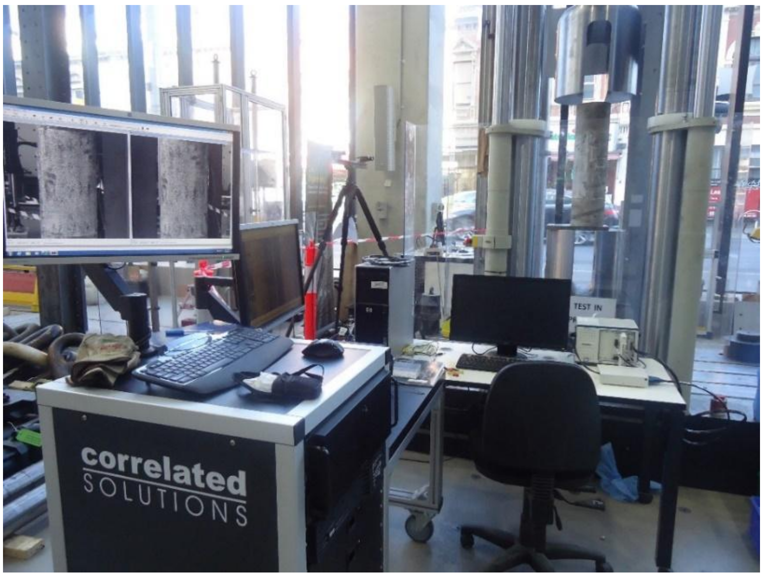

Fig. (6): A view of the testing machine.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

4.RESULTS AND DISCUSSION

4.1 Temperature distributions in furnace, concrete and reinforcement

In real fires, columns may be exposed to significant heating over a period. Such fire exposure is often expressed in terms of a Standard Fire duration, which in turn, is defined by reference to ISO 834 (ISO 834, 2012) Standard Time Temperature Curve (STTC). The testing described in this paper involved heating columns up to a target level that is like that which would be experienced by members subjected to an STTC of at least 120 minutes prior to air cooling.

For the column exposed to 800 °C (i.e. furnace temperature) the temperature of the thermocouple at the centre reached 464 °C after 145 min (i.e. time after the furnace was turned off), but later reached 544 °C after 175 min (i.e. the time when the furnace doors were opened), finally reaching a maximum temperature of 583 °C. This was due to heat continuing to be transferred to the interior from the hotter exterior parts of the column. On the other hand, for the RC columns exposed to 1000 °C (i.e. furnace temperature), the core thermocouple temperature reached 790 °C after 207 min (i.e. time when the furnace was turned off), 839 °C after 237 min (i.e. time when the furnace doors were opened), finally reaching a maximum of 845 °C. In addition, the time required to reach the maximum temperatures also increases with depth. The measured maximum temperatures of the longitudinal steel bar were about 643 °C and 910 °C after exposure to 800 °C and 1000 °C heating regimes, respectively.

4.2 Effect of heating and CFRP wrapping

The residual compressive strength of RC columns was found to have been reduced after being exposed to 800 °C and 1000 °C for two hours prior to cooling, respectively. The average strengths (of two columns at each temperature) were reduced by 43 % and 72 % respectively, as shown in Figure 7. The Figure shows also the enhancement in the ultimate RC columns residual compressive strength relative to that of the unwrapped columns because of full CFRP wrapping system. Overall, the post-heated columns wrapped with one or two layers of CFRP fabric regained more strength than the control columns (i.e. unheated unwrapped columns). This indicates that it is possible to repair RC circular columns damaged by elevated temperature using CFRP sheets. The strength of heat damaged columns was reduced to 23.2 MPa and 11.5 MPa after exposure to 800 °C and 1000 °C respectively. When repaired with 1 or 2 layers of CFRP sheets, it increased by 63 %, 126 % and by 14 %, 75 % more than the original strength of control RC columns. Table 3 compares the stresses of 1 and 2 CFRP layers after exposure to 800 °C and 1000 °C with the corresponding columns at the same temperature level. It is clear that the CFRP layers are more effective at higher temperature and 2 layers are more effective than 1 layer.

Table (3): Details of circular RC columns

Temp.	No. of layers			% of Increase with respect to the same temp.		
	0	1	2	0	1	2
Room	40.6	85.2	104.9	---	110	158
800 °C	23.2	66.1	91.9	---	185	296
1000 °C	11.5	46.3	71.1	---	303	523

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

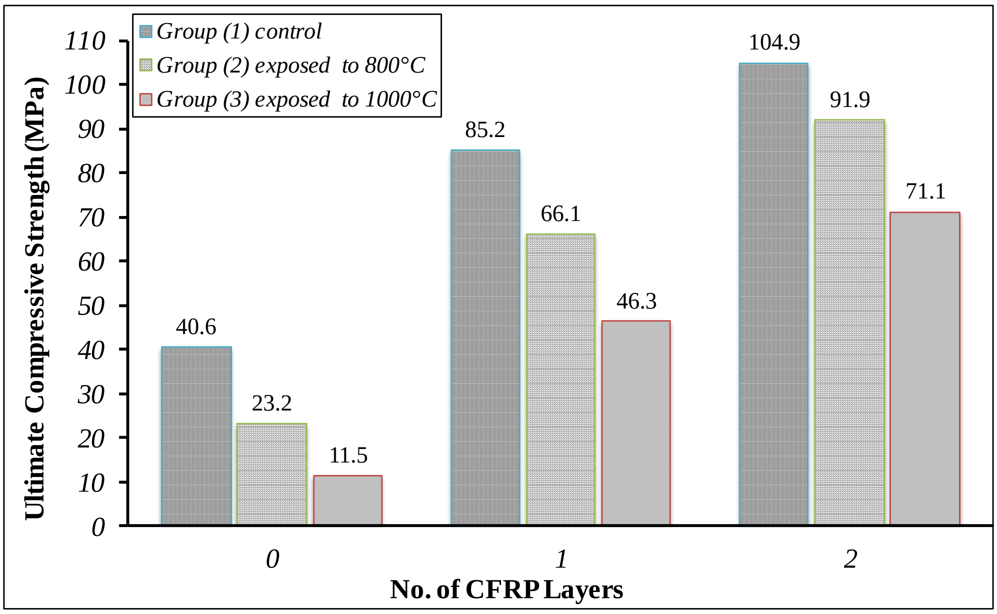

Fig. (7): General view of the column test furnace.

4.3 Factors affecting confinement efficiency

Method of measurement is the first factor. Almost all the tests reported in the literature used foil strain gauges for strain measurements. The tests used 2 or 4 strain gauges axisymmetrically mounted at the mid-height of a sample without distinguishing the overlapping and non-overlapping zones. Obviously, variation in the FRP ply thickness and the heterogeneity of concrete material would produce nonuniformity of strain distribution. When number of strain gauges increases such variation decreases. Secondly, workmanship is another factor due to the difference in the fabrication way of the FRP wrap and the flat FRP-coupons (L. Lam & Teng, 2004). Also, it is generally believed that the strain capacity can significantly reduce due to the curvature difference of the FRP jacket fibres compared to the straight fiber in flat coupons. Furthermore, Carey and Harries (Carey & Harries, 2005) stated that different products could produce various efficiency factors.

4.4 Strain efficiency

The ratio of hoop strain in the CFRP wraps at failure to the failure strain measured from direct tensile tests of the flat CFRP coupons is referred to the strain efficiency (η). As noted by others, the hoop strain at failure is typically less than the ultimate strain obtained from direct tension coupon tests. In other words, the failure of concrete wrapped by FRP or CFRP does not happen at the ultimate tensile strains determined from flat coupons. The variation in the data could also be due to the fact that the strain data were obtained using only conventional strain gauges.

In the present study, the strain efficiency was determined from the ratio of hoop strain measurements using the Vic-3D camera within the middle 400 mm (at 20 mm intervals) of each column (i.e. the column height = 750 mm) to the average of the ultimate strains measured from the tensile coupon tests described in Section 3.1. The strain efficiency was determined for all CFRP-wrapped columns. This required the calculation of the strain efficiency at 252 locations (13 locations for each column × 12 columns). For all columns wrapped with 1 or 2 CFRP layers, the strain efficiency was found to be in the range of 0.54 to 0.9 or 0.54 to 0.94 respectively, see Figures 8 and 9 respectively.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

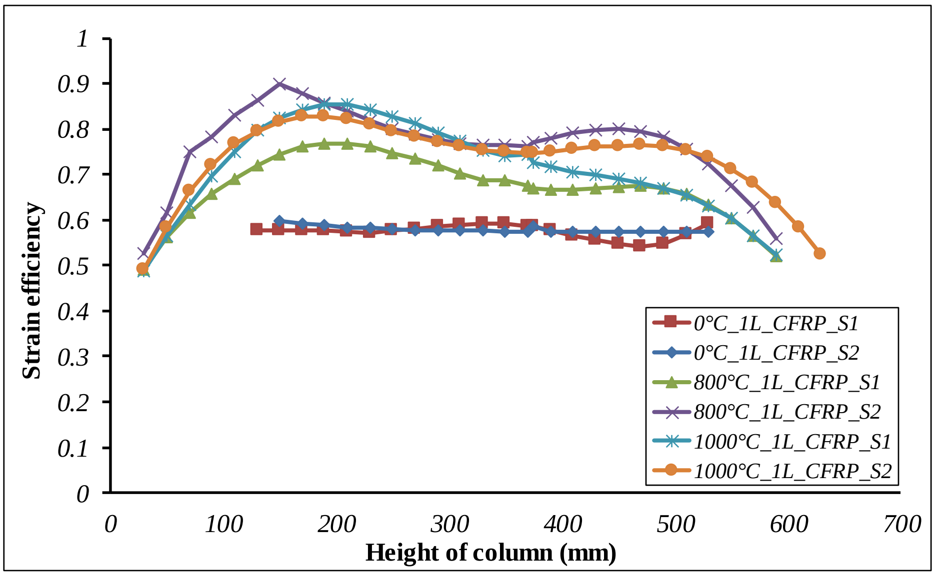

Fig. (8): Strain efficiency of column wrapped with 1 layer of CFRP.

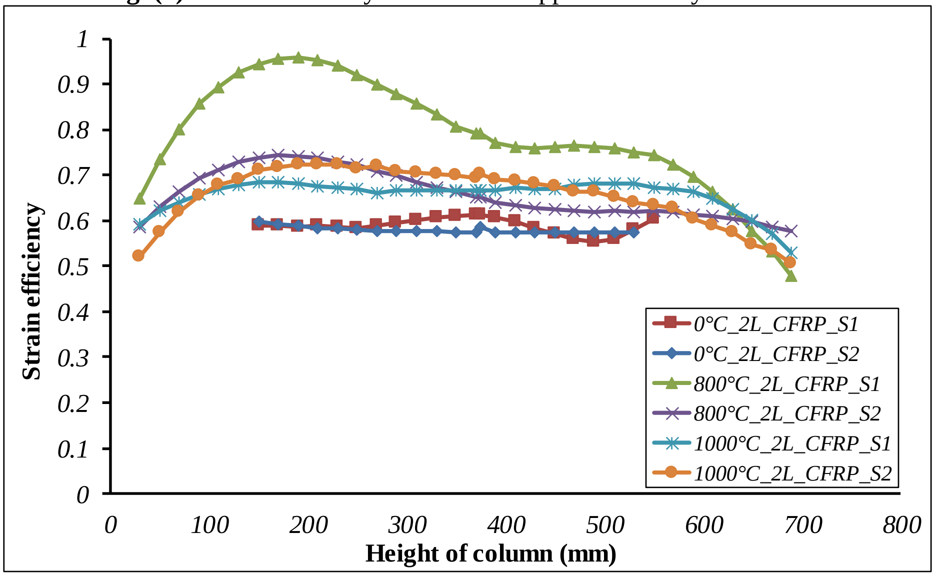

Fig. (9): Strain efficiency of column wrapped with 2 layers of CFRP.

4.5 Failure modes

Figure 10 shows typical failure modes of the control and CFRP-wrapped columns tested until failure. The failure mode for unconfined columns exhibited, prior to failure, vertical cracking starting from the top of the columns and propagating downward along the length in the direction of loading. These columns failed by splitting as the result of shear stresses. The maximum compressive load of these columns was achieved shortly after cracks developed and propagated with a corresponding rapid reduction in load resistance. The wrapped columns failed by tensile rupture of the CFRP wrap in a sudden explosive manner with loud sound as the CFRP wrapping experienced excessive tension in the lateral direction. None of the confined RC columns failed at the lap location of the CFRP wrapping, demonstrating adequate load transfer at the lapped joint. The failed CFRP wrapping had concrete bonded to it after failure, indicating adequate adhesion and load transfer between the CFRP and concrete substrate.

Journal of University of Duhok, Vol. 20,No.1(Pure and Eng. Sciences), Pp 484-495, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.43

Fig. (10): Typical failure modes.

5.CONCLUSIONS

The following conclusions can be drawn based on the results of the present research:

1. At least 1 layer of CFRP wrapping elevated the ultimate load of heat-damaged columns to the level of undamaged unwrapped RC columns (control columns). The strength of post-heated columns was reduced to 11.5 MPa after exposure to 1000 °C. When repaired with 1 layer and 2 layers of CFRP sheets, the corresponding strength increase was 14 % and 75 % above the strength of the control columns, respectively.
2. It was noted from the Vic-3D camera system that the strains varied considerably along the height of the specimens, especially for columns that had been heated and wrapped.
3. The ultimate lateral strains measured on the surface of CFRP-confined columns are less that those obtained from CFRP tensile coupon tests.
4. All wrapped columns failed by tensile rupture of the CFRP fabric. The failure was close to the mid-height region.

REFERENCES

– Abdelrahman, K., & El-Hacha, R. (2012). Behavior of large-scale concrete columns wrapped with CFRP and SFRP sheets. *Journal of Composites for Construction, 16*(4), 430-439.
– Al-Kamaki, Y. S. S., Al-Mahaidi, R., & Bennetts, I. (2016). An experimental investigation of the behaviour of heat-damaged RC columns confined with CFRP fabrics using photogrammetry. Materials and Structures, (1), 43. doi:10.1617/s11527-016-0873-x
– ASTM D 3039/D 3039M. (2008). *Standard test method for tensile properties of polymer matrix composites materials* (Vol. Vol. 14.02). West Conshohocken, PA, USA: Annual Book of ASTM Standards.
– Benzaid, R., Mesbah, H., & Chikh, N. E. (2010). FRP-confined concrete cylinders: axial compression experiments *and* strength model. *Journal of Reinforced Plastics and Composites, 29*(16), 2469-2488.
– Berthet, J. F., Ferrier, E., & Hamelin, P. (2005). Compressive behavior of concrete externally confined by composite jackets. Part A: Experimental study. *Construction and Building Materials, 19*(3), 223-232.
– Bisby, L. A., & Stratford, T. J. (2011). The ultimate condition of FRP confined concrete columns: New experimental observations and insights Advances in FRP Composites in Civil Engineering (pp. 599-602): Tsinghua University Press, Beijing and Springer-Verlag Berlin Heidelberg
– Bisby, L. A., & Take, W. A. (2009). Strain localisations in FRP-confined concrete: New insights. *Proceedings of the Institution of Civil Engineers: Structures and Buildings, 162*(5), 301-309. doi:10.1680/stbu.2009.162.5.301
– BS EN ISO 527-5. (2009). Plastics-Determination of tensile properties Part 5: Test conditions for unidirectional *fibre*-reinforced plastic composites. West Conshohocken, PA, USA: ISO international standards.
– Bullo, S. (2003). *Experimental study of the effects of the ultimate strain of fiber reinforced plastic jackets on the behavior of confined concrete.* Paper presented at the Proceedings of the

international conference composites in construction, Cosenza, Italy.

– Carey, S. A., & Harries, K. A. (2005). Axial behavior and modeling of confined small-, medium-, and large-scale circular sections with carbon fiber-reinforced polymer jackets. *ACI Structural Journal*, *102*(4), 596-604.

– Ciupala, M., Pilakoutas, K., & Mortazavi, A. (2007). *Effectiveness of FRP composites in confined concrete.* Paper presented at the Proceedings of the 8th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-8, Patras, Greece, July.

– De Lorenzis, L., Micelli, F., & La Tegola, A. (2002). *4.1 Influence of specimen size and resin type on the behaviour of FRP-confined concrete cylinders.* Paper presented at the Advanced Polymer Composites for Structural Applications in Construction: Proceedings of the First International Conference, Held at Southampton University, UK, on 15-17 April 2002.

– Fawzia, S. (2007). *Bond characteristics between steel and carbon fibre reinforced polymer (CFRP) composites.* (Ph.D.), Ph.D thesis, Monash University, Melbourne, Australia.

– Harries, K. A., & Carey, S. A. (2003). Shape and "gap" effects on the behavior of variably confined concrete. *Cement and Concrete Research*, *33*(6), 881-890. doi:10.1016/S0008-8846(02)01085-2

– Harries, K. A., & Kharel, G. (2002). Behavior and modeling of concrete subject to variable confining pressure. *ACI Materials Journal*, *99*(2), 180-189.

– ISO 834. (2012). *Fire resistance tests-Elements of building construction*: International Organization for Standardization, Geneva, Switzerland.

– Jiang, T., & Teng, J. (2006). Strengthening of short circular RC columns with FRP jackets: a design proposal.

– Jiang, T., & Teng, J. (2007). Analysis-oriented stress–strain models for FRP–confined concrete. *Engineering Structures*, *29*(11), 2968-2986.

– Lam, L., Teng, J., Cheung, C., & Xiao, Y. (2006). FRP-confined concrete under axial cyclic compression. *Cement and Concrete Composites*, *28*(10), 949-958.

– Lam, L., & Teng, J. G. (2004). Ultimate condition of fiber reinforced polymer-confined concrete. *Journal of Composites for Construction*, *8*(6), 539-548.

– Matthys, S., Taerwe, L., & Audenaert, K. (1999). Tests on axially loaded concrete columns confined by fiber reinforced polymer sheet wrapping. *ACI Special Publication*, *188*.

– Micelli, F., & Modarelli, R. (2013). Experimental and analytical study on properties affecting the behaviour of FRP-confined concrete. *Composites Part B: Engineering*, *45*(1), 1420-1431.

– Pessiki, S., Harries, K. A., Kestner, J. T., Sause, R., & Ricles, J. M. (2001). Axial behavior of reinforced concrete columns confined with FRP jackets. *Journal of Composites for Construction*, *5*(4), 237-245.

– Rousakis, T., & Tepfers, R. (2004). Behavior of concrete confined by high E-modulus carbon FRP sheets, subjected to monotonic and cyclic axial compressive load. *NORDIC CONCRETE RESEARCH-PUBLICATIONS-*, *31*, 73.

– Schnerch, D. (2005). *Strengthening of steel structures with high modulus carbon fiber reinforced polymer (CFRP) materials.* (Ph.D. thesis), Ph.D. thesis, North Carolina State University, Raleigh, United States.

– Shahawy, M., Mirmiran, A., & Beitelman, T. (2000). Tests and modeling of carbon-wrapped concrete columns. *Composites Part B: Engineering*, *31*(6-7), 471-480.

– Smith, S. T., Kim, S. J., & Zhang, H. (2010). Behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders. *Journal of Composites for Construction*, *14*(5), 573-582. doi:10.1061/(ASCE)CC.1943-5614.0000119

– Vic-3D. (2010). *The Vic-3D™ measurement system*. Dutchman Blvd, Irmo, SC 29063, USA: Correlated Solutions.

– Wang, L.-M., & Wu, Y.-F. (2008). Effect of corner radius on the performance of CFRP-confined square concrete columns: Test. *Engineering Structures*, *30*(2), 493-505.

– Watanabe, K., Nakamura, H., Honda, Y., Toyoshima, M., Iso, M., Fujimaki, T., . . . Shirai, N. (1997). Confinement effect of FRP sheet on strength and ductility of concrete cylinders under uniaxial compression. *Non-metallic (FRP) Reinforcement for Concrete Structures*, *1*, 233-240.

– Wu, Y.-F., & Jiang, J.-F. (2013). Effective strain of FRP for confined circular concrete columns. *Composite Structures*, *95*, 479-491. doi:http://dx.doi.org/10.1016/j.compstruct.2012.08.021

– Xiao, Y., & Wu, H. (2000). Compressive behavior of concrete confined by carbon fiber composite jackets. *Journal of Materials in Civil Engineering*, *12*(2), 139-146.