Effect of Carbon Fiber Reinforced Polymer Confinement on the Fire Damaged and Un-heated Reinforced Concrete Square Columns

M. Faizan Tahir[1], M. Yaqub[2], Imran Bukhari[3], R. Faisal Tufail[4], Arslan Tahir[5]

[1.] Postgraduate Student, Department of Civil and Environmental Engineering, University of Engineering and Technology, Taxila, Rawalpindi 46000, Pakistan
[2.] Assistant Professor, Department of Civil and Environmental Engineering, University of Engineering and Technology, Taxila, Rawalpindi 46000, Pakistan
[3.] Director Research & Development Organization, Government of Pakistan, Islamabad 44000, Pakistan
[4.] Research Associate, Department of Civil and Environmental Engineering, University of Engineering and Technology, Taxila, Rawalpindi 46000, Pakistan
[5.] Undergraduate Student, Department of Engineering, Federal Urdu University of Arts, Science and Technology, Islamabad 44000, Pakistan
m_faizan_tahir@yahoo.com

Abstract: This paper presents the results of the experimental study for the un-heated and fire damaged reinforced concrete square columns confined with a single layer of Carbon Fiber Reinforced Polymer (CFRP) jacket. A total of four un-heated reinforced concrete square columns, two unconfined control specimens and two CFRP confined square columns were tested under axial compression. The experimental data of the four fire damaged reinforced concrete square columns, two unconfined fire damaged control specimens and two CFRP confined fire damaged square columns tested under axial compression were selected from the already published research study. The results of the experimental tested data of un-heated reinforced concrete square columns were compared with the published data of the fire damaged reinforced concrete square columns in terms of confined compressive strength and the gain in axial load bearing capacity. The results showed that a single layer of CFRP jacket is more effective for enhancing the confined compressive strength and the axial load bearing capacity of the fire damaged square reinforced concrete columns compared to un-heated reinforced concrete square columns.
[Muhammad Faizan Tahir, Muhammad Yaqub, Imran Bukhari, Rana Faisal Tufail, Arslan Tahir. **Effect of Carbon Fiber Reinforced Polymer Confinement on the Fire damaged and Un-heated Reinforced Concrete Square Columns.** *Life Sci J* 2013;10(12s):791-799]. (ISSN:1097-8135). http://www.lifesciencesite.com. 125

Keywords: CFRP; confinement; reinforced concrete; fire damaged concrete; un-heated concrete; square columns

1. Introduction

The extreme loading (earthquakes or hurricanes, fire or explosion) showed that the strengthening and repairing of existing reinforced concrete structures has become more communal issues in the field of civil engineering during the last two decades. For the repairing, retrofitting and rehabilitation of concrete structures many conventional strengthening procedures has been used in the past. For instance, section enlargement, steel plate bonding, and external post-tensioning are the most common strengthening techniques. However, due to many drawbacks of such conventional strengthening techniques, the fiber reinforced polymer (FRP) composite materials have gained the good reputation in the field strengthening and repairing of concrete structures. Repairing of concrete structures with externally bonded FRP wraps is beneficial due to its many advantages. There are many types of fiber reinforced polymer. However, the most commonly used FRP are made of carbon, glass and aramid.

Concrete has a history to performance better against fire events for being a non-combustible and having low thermal conductivity. The mechanical properties of concrete such as its tensile strength, modulus of elasticity & Poisson's ratio will be affected when exposed to high temperature. It has been found that the exposure to high temperature adversely affects the residual strength of concrete [1 to 5]. Compressive strength of concrete decreases with increasing temperature and there is further decrease on cooling probably because of additional micro cracking [2]. When concrete cools down, the quicklime (calcium oxide) absorbs moisture and converts to slaked lime (calcium hydroxide). When this happens, disintegration of the affected concrete will occur. Generally, the residual strength of concrete remains approximately in the range of 75% to 25% of the original strength when heated in the range of 300°C to 600°C respectively in most concrete structures [1]. The studies [6 to 10] have clearly showed that the confinement with a carbon fiber reinforced polymer (CFRP) jackets leads to a considerable enhancement in the ductility and strength of concrete when wrapped around circular or square concrete sections. In the literature, analytical models [11 to 13] exist to support the applications of CFRP wrapping around the concrete columns.

It has been found that the fiber reinforced polymer perform better in fire when wrapped around columns with the application of proper insulation [14 to 18]. While the efficiency of CFRP confinement for the fire damaged reinforced concrete square columns was investigated in the previous studies [19, 20] However, to the knowledge of the authors, no research has been carried out to evaluate the effectiveness of the CFRP confinement for the un-heated and fire damaged reinforced concrete columns. It is well known that the stress-strain behaviour of un-heated and fire damaged concrete is different under axial compressive loading.

This paper provides the comparison of the CFRP confined fire damaged and un-heated reinforced concrete square columns. The main objective of the current study is to evaluate the effectiveness of CFRP confinement both for the un-heated and fire damaged reinforced concrete square columns in terms of confined compressive strength and the gain in axial load bearing capacity.

2. Material Properties

The following material properties were used in the current experimental study:

2.1 Concrete

The concrete mix, comprising Ordinary Portland Cement (OPC), sand and aggregate was used for the construction of all concrete test specimens in this experimental research work. The mix ratio, water cement ratio and 28 days compressive strength of the control specimens are shown in Table 1. The specifications of all the concrete constituents used in this experimental work are described in the following sections:

Table 1. Concrete Properties

Avg. Compressive Strength (fc')	24.51 MPa
Slump	75mm
Concrete Mix Ratio Water to Cement Ratio Lab Temperature	1:3:6 0.6 27^{O} C

2.1.1 Cement

The Ordinary Portland cement (OPC) provided by "Bestway Cement" industry was used in this experimental programme (ASTM C-150 Type 1).

2.1.2 Water

Laboratory tap water was used for mixing of concrete. The tap water has pH value between 6.5-7.5. The Chemical analysis was carried in order to confirm that the water is drinkable.

2.1.3 Coarse Aggregates

Margalla crush is used as a coarse aggregate in the concrete mix. ASTM C136-06 was followed for gradation of coarse aggregates. The minimum and maximum size of aggregate used in this experimental programme was ranged between 2 mm to 20 mm respectively.

2.1.4 Reinforcing steel

Deformed reinforcing steel bars with diameter 12.5 mm and 10 mm was selected for the main longitudinal and for the lateral link bars, for the construction of all test specimens. Tension test was performed in the laboratory for each bar size. Average yield strength of all steel bars was found 414 MPa.

2.2 Composite Materials

The commercially available unidirectional carbon fiber reinforced polymer (CFRP) sheet was used for jacketing around the square columns. The properties of Sika Wrap Hex 230C, Sikadur 330 epoxy resin and their laminate properties provided by the supplier [21, 22, and 23] are shown in Tables 2 and 3.

Table-2 Properties of Sika Wrap Hex 230C

Tensile Strength	3,450 MPa
Tensile Modulus	230,000 MPa
Tensile Elongation Density	1.5% 1.8 g/cc

Table-3 Properties of Sikadur 330 Epoxy Resin (7 days at+23°C)

Tensile Strength	30 N/mm^2
Tensile Modulus	4,500 N/mm^2
Tensile Elongation Density	0.9% 1.3 Kg/Ltr

Cured Laminate Properties of Sika Wrap Hex 230C with Sikadur 330 Epoxy after standard cure of 5 days are described in Table-4.

Table-4 Cured Laminate Properties (5 days)

Tensile Strength	894 MPa
Tensile Modulus	65,402 MPa
Tensile Elongation	1.33 %
Ply Thickness Splice Length	0.381mm 200 mm

Table-5 Compressive Strength Summary of Un-heated reinforced concrete columns

Type of Columns	No. of Tests	Un-Confined Compressive Strength (MPa) f'_{co}	CFRP Confined Compressive Strength(kN) f'_{cc}	$\frac{f'_{cc}-f'_{co}}{f'_{co}}$ (%)
Un-heated Reinforced Concrete Columns	T1	21.859	-	-
	T2	22.266	-	-
	T3	-	26.7	22%
	T4	-	26.93	21%

Table-6 Compressive Strength Summary of Fire damaged reinforced concrete columns

Type of Columns	No. of Tests	Un-Confined Compressive Strength (MPa) f'_{co}	CFRP Confined Compressive Strength(kN) f'_{cc}	$\frac{f'_{cc}-f'_{co}}{f'_{co}}$ (%)
Fire damaged Reinforced Concrete Columns	T5	20.708	-	-
	T6	20.149	-	-
	T7	-	27.805	34%
	T8	-	30.215	50%

Table-7 Axial Compressive Strength Summary of Un-heated reinforced concrete column

Type of Columns	No. of Tests	Un-Confined Axial Compressive Strength (kN) P_{uo}	CFRP Confined Axial Compressive Strength (kN) P_{ucc}	$\frac{P_{ucc}-P_{uo}}{P_{uo}}$ (%)
Un-heated Reinforced Concrete Columns	T1	1132	-	-
	T2	1148	-	-
	T3	-	1296	14%
	T4	-	1305	14%

Table-8 Axial Compressive Strength Summary of Fire damaged reinforced concrete column

Type of Columns	No. of Tests	Un-Confined Axial Compressive Strength (kN) P_{uo}	CFRP Confined Axial Compressive Strength (kN) P_{ucc}	$\frac{P_{ucc}-P_{uo}}{P_{uo}}$ (%)
Fire damaged Reinforced Concrete Columns	T5	1121	-	-
	T6	1099	-	-
	T7	-	1496	33%
	T8	-	1401	27%

3. Experimental Program

In order to investigate the effect of carbon fiber reinforced polymer (CFRP) on the un-heated and fire damaged reinforced concrete square columns, four un-heated reinforced concrete square columns were cast within the reinforced concrete laboratory at the University of Engineering and Technology, Taxila. Four fire damaged reinforced concrete square columns were selected from the previous published research work [19] for the comparison purpose. The summary of total eight reinforced concrete square columns (four un-heated and four fire damaged) is shown in the Tables 5 to 8.

The columns were divided into two series. The first series contained four un-heated reinforced concrete square columns. However, the second series contained four fire damaged reinforced concrete square columns [19].The columns of each series were further divided into the following two groups:

1) Un-heated reinforced concrete square columns: In this group of columns, two un-heated reinforced concrete square columns (Tests 1&2) were tested

without carbon fiber reinforced polymer (CFRP) wrapping while the other remaining two un-heated columns were tested after wrapping with a single layer of carbon Fiber reinforced polymer (Tests 3&4).

2) Fire damaged reinforced concrete square columns: In this group of columns, two fire damaged reinforced concrete square columns were selected from the previous published research work [19] without carbon Fiber reinforced polymer wrapping. However, the other two fire damaged reinforced concrete square columns were selected from the previous published research work [19] which was confined with a single layer of carbon Fiber reinforced polymer wrap.

All the columns have the same cross-sectional size 200 mm x 200 mm and the length 1000 mm in height. All the specimens were reinforced with longitudinal reinforcement ratio of 1.6%. All the link steel bars were equally spaced throughout the length of columns at 150 mm centre to centre. The same concrete cover of 25 mm to the main reinforcement (Fig. 1) was provided in the square columns. The link steel bars were anchored with a 135^{o} hook at each end, which extended nearly 60 mm into the concrete cores, as shown in Fig. 1.

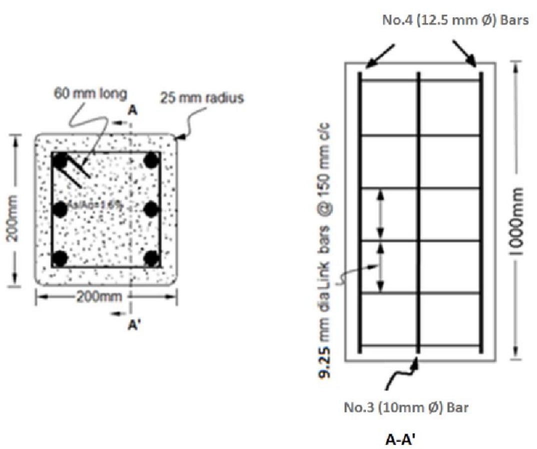

Fig. 1. Geometry and steel reinforcement detail of specimen

3.1 Casting of specimens

In order to evaluate the effect of CFRP wrap on the un-heated reinforced concrete square columns, four reinforced concrete square columns were cast within the Reinforced Concrete laboratory at the university of Engineering and Technology Taxila, Pakistan. The casting procedure, compaction, properties and dimensions of all the un-heated test specimens were kept similar to the previous published research work [19] in order to make the reasonable comparison (Figs.2 and 3). Only one column was cast at a time from one consignment of concrete along with three cylinders having 300mm in height and 150mm in diameter, in order to monitor the normal strength of concrete at the time of testing.

Fig.2 Steel plates formwork for casting concrete columns

Fig.3 Casting of RC concrete columns

To prevent stress concentration in the fiber reinforced polymer wrap during testing, all the corners of each square column were rounded up to 25mm radius (similar to previous published work) using PVC pipe pieces which were placed inside the formwork at the time of casting. All the concrete test specimens were cured using moist gunny bags. The specimens were cured for at least 14 days. The strength controlling specimens were also kept with the columns for curing until they were tested. All the specimens after curing were left in the laboratory environment up to the day of testing.

3.2 Carbon fiber reinforced polymer jacketing

The rounded corners and the faces of the square columns to be wrapped with carbon Fiber reinforced polymer (CFRP) were further grounded using the electric grinder (Fig.4). The surface of all square concrete columns was cleaned with a steel wire brush to remove dust, curing compounds, impregnations, waxes, laitance, grease, foreign particles and other bond inhibiting materials before the application of CFRP jackets.

The primer coat of Sikadur 330 epoxy (resin and hardener with a standard mix ratio 4:1 by weight according to the supplier instructions) was applied to the substrate of the square concrete columns to fill all voids and cavities (Fig.5). Commercially available unidirectional Sika Wrap Hex-230C fabric sheets were then wrapped around the square columns with the main fibers oriented in the transverse direction, using a wet layup procedure (Fig.6). The fabric sheets overlap in the longitudinal and in the transverse direction was kept similar to the previous published research work [19].

Fig.4 Preparation of concrete columns for CFRP confinement

The similar wrapping procedure of carbon fiber reinforced polymer (CFRP) was used as described in the previous research work [19] in order to study the effect of fiber reinforced polymer on the performance of un-heated reinforced concrete columns. A minor gap of 25 mm was left between the CFRP jacket and the top and bottom ends of each column in order to prevent the fiber sheet from direct axial loading during testing. The confined test specimens were then cured in the laboratory environment at room temperature, for approximately two months until the testing was carried out.

Fig.5 Application of epoxy resin on concrete column for CFRP confinement

Fig.6 CFRP wrapping on concrete columns

3.3 Instrumentation and testing procedure

All the square concrete columns were tested under axial compression in the similar manner as described in the previous published research work [19]. Before testing, the top & bottom faces of all columns were capped using sulphur in order to ensure the smooth & parallel surfaces for the application of load during load testing. A 3,000 kN capacity hydraulic jack was used for the application of axial loading at a rate 5kN/minute and all data was monitored and recorded throughout the test. The testing arrangement is shown in Figs.7 to 9.

Fig.7 Placement of specimen for axial load testing

Fig.8 Arrangement of specimens for axial load testing

Fig.9 Axially loaded test specimen

5. Results and Discussions

In this section, the results of the un-heated un-confined, un-heated CFRP confined were compared with the results of the previous published work of the fire damaged un-confined and fire damaged CFRP confined square columns in terms of confined compressive strength and the gain in axial load bearing capacity. The effect of carbon fiber reinforced polymer (CFRP) on the confined compressive strength and the axial load bearing capacity for fire damaged and un-heated square columns was investigated and described in detail in the following sections:

5.1 Effect of carbon fiber reinforced polymer on the confined compressive strength of fire damaged and un-heated reinforced concrete square columns

The test results in terms of un-confined and CFRP confined compressive strength of un-heated and fire damaged columns are shown in Fig.10 and Tables 5-6. The numbers T1, T2 on the x-axis in Fig.10 and Table.5 indicate the un-heated and un-confined compressive strength of reinforced concrete square columns. However, the numbers T3, T4 show the un-heated and CFRP confined compressive strength of reinforced concrete square columns. It can be seen from Table.5 that carbon fiber reinforced polymer jacketing increases the confined compressive strength of un-heated reinforced concrete square columns significantly. However, it is interesting to note that the effect of carbon Fiber reinforced polymer on the confined compressive strength of fire damaged reinforced concrete square columns (Tests 5,6,7,8 carried out in the previous study [19]) was more pronounced compared to the un-heated reinforced concrete square columns (Tests 1,2,3 and 4).

Fig.11 shows the percentage increase in the confined compressive strength of un-heated and fire damaged reinforced concrete square columns. It was found that a single layer of carbon fiber jacketing increased the confined compressive strength from 21% to 22% in case of un-heated reinforced concrete square columns and 34% to 50% in case of fire damaged reinforced concrete square columns.

This indicates that the carbon fiber reinforced polymer is more effective for improving the confined compressive of fire damaged concrete structures compared to the non-fire damaged concrete structural members. This is ascribed to the fact that under axial compressive loading the fire damaged concrete displayed more lateral expansion than the un-heated concrete. Due to the more lateral expansion, the tensile strength of carbon fiber reinforced polymer was more utilized in enhancing the confined compressive strength of fire damaged concrete compared to the un-heated concrete before going to the failure.

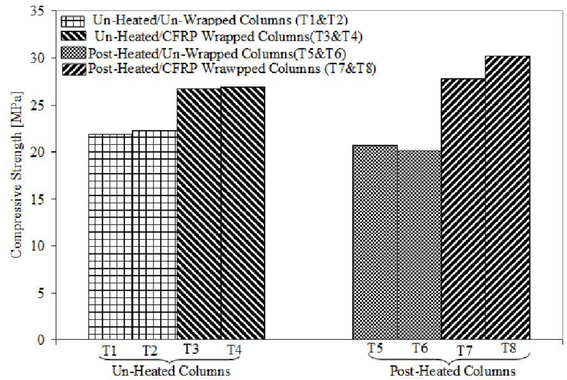

Fig.10: Effect of CFRP Confinement on Un-Heated and Fire damaged T5, T6, T7 and T8 tests were carried out by M.Yaqub and C.G.Bailey [19]

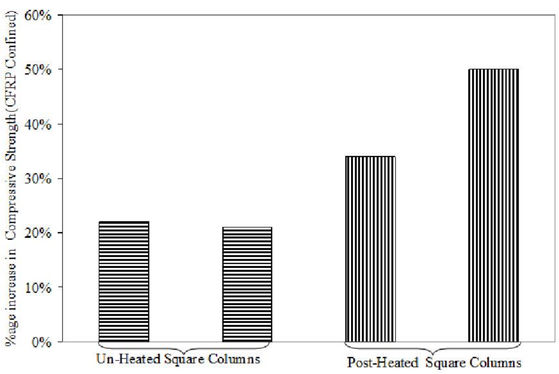

Fig.11: Comparison of %age increase in confined compressive strength for un-heated and fire damaged columns wrapped with CFRP

5.2 Effect of carbon fiber reinforced polymer jacketing on the axial load bearing capacity of un-heated and fire damaged reinforced concrete square columns

Fig.12 shows the effect of unidirectional carbon fiber reinforced polymer jacketing on the axial capacity of un-heated and fire damaged reinforced concrete square columns. The numbers on x-axis in Fig.12 point towards:

1) Un-heated reinforced concrete square column without CFRP jacketing Test-1 (T1)
2) Un-heated reinforced concrete square column wrapped with CFRP jacketing Test-2 (T2)
3) Un-heated reinforced concrete square column wrapped with CFRP jacketing Test-3 (T3)
4) Un-heated reinforced concrete square column wrapped with CFRP jacketing Test-4 (T4)
5) *Fire damaged reinforced concrete square column without CFRP jacketing Test-5 (T5)
6) *Fire damaged reinforced concrete square column without CFRP jacketing Test-6 (T6)
7) *Fire damaged reinforced concrete square column wrapped with CFRP jacketing Test-7 (T7)
8) *Fire damaged reinforced concrete square column wrapped with CFRP jacketing Test-8 (T8)

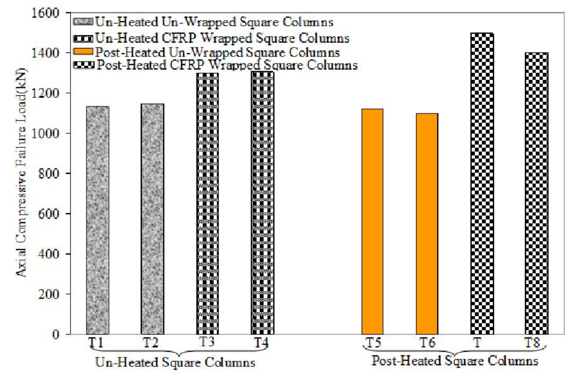

Fig.12: Effect of CFRP confinement on axial compressive strength of un-heated and fire damaged reinforced concrete square columns

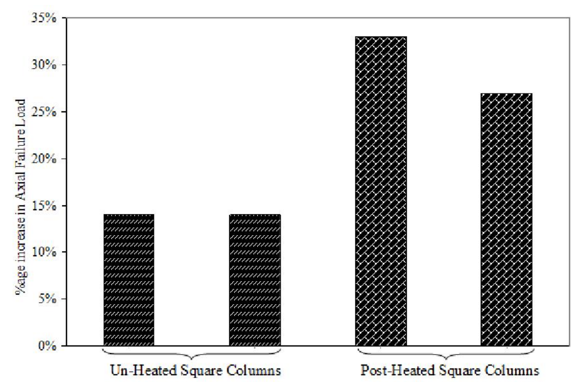

Fig.13: Comparison of %age increase in axial compressive strength for un-heated and fire damaged square columns wrapped with CFRP

The results of the above mentioned tests T1, T2, T3, and T4 (carried out in the current research work) were compared with the test results T5, T6, T7 and T8 (*carried out in the previous study [19]) in terms of gain in axial load bearing capacity. It can be seen from Fig.12 that the carbon fiber reinforced polymer jacketing increased the axial load bearing capacity significantly both for the un-heated and fire damaged reinforced concrete square columns. However; the carbon fiber reinforced polymer was more effective in enhancing the load bearing capacity of the fire damaged reinforced concrete square columns compared to the un-heated reinforced concrete square columns.

Fig.13 shows the percentage increase in the axial load bearing capacity of un-heated and fire damaged reinforced concrete square columns. It is worth mentioning here that the percentage increase in the axial load bearing capacity was more for the fire damaged reinforced concrete square columns compared to the un-heated reinforced concrete square columns when confined with the single layer of CFRP jacket.

Fig.13 and Tables (7 and 8) clearly highlight that the single layer of CFRP jacketing could enhance the axial load bearing capacity by 14 % in case of un-heated columns and by 27% to 33% for the fire damaged reinforced concrete square columns. This could be due to the fact that the fire damaged concrete square columns displayed more lateral enlargement under axial compression compared to the unheated reinforced concrete square columns [20].

The more lateral expansion of the fire damaged concrete generates more lateral pressure on the CFRP jacketing compared to the un-heated concrete square columns. The CFRP jacket in response to the more lateral pressure (created in the fire damaged concrete square columns) utilizes more tensile stresses compared to the un-heated square columns. Consequently, the gain in axial load bearing capacity was more in the fire damaged square columns compared to the un-heated square columns.

7. Conclusions:

The main objective of the current research study is to evaluate the effect of carbon fiber reinforced polymer jacketing on the un-heated and fire damaged reinforced concrete square columns. The results of CFRP confined un-heated reinforced concrete square columns were compared with the previous published research work [19] of CFRP confined fire damaged square columns. The results were investigated in terms of confined compressive strength and the gain in axial load bearing capacity. The following conclusions were drawn from this investigation:

1. The CFRP jacketing is effective both for un-heated and fire damaged reinforced concrete square columns in terms of enhancing the confined compressive strength. However, the CFRP jacketing is more effective for the fire damaged concrete square columns compared to the un-heated reinforced concrete square columns in terms of enhancing the confined compressive strength.
2. The CFRP jacketing increased the confined compressive strength by 21% to 22% in case of un-heated reinforced concrete square columns when compared to the reference control specimens. However, the CFRP jacketing could increase the confined compressive strength by 34% to 50% for the fire damaged reinforced concrete square columns when compared to the un-confined fire damaged reinforced concrete square columns (control specimens).
3. The CFRP jacketing could increase the axial load bearing capacity both for the un-heated and fire damaged reinforced concrete square columns significantly. However, the CFRP jacketing is more effective for enhancing the load bearing capacity of the fire damaged reinforced concrete square columns when tested under axial compression.
4. The single layer of CFRP confinement could increase the axial load bearing capacity by 14% in case of un-heated reinforced concrete square columns. However, the axial load bearing capacity of the fire damaged reinforced concrete square columns was increased by 27% to 33% when confined with the single layer of CFRP jacketing.

8. Acknowledgements:

Authors are grateful to the Department of Civil Engineering, University of Engineering and Technology, Taxila for providing technical facilities to carry out this work.

9. Corresponding Author:

Engr. Muhammad Faizan Tahir
Postgraduate Student, Department of Civil and Environmental Engineering,
University of Engineering and Technology, Taxila, Rawalpindi 46000, Pakistan.
E-mail: m_faizan_tahir@yahoo.com

References:

1. Concrete Society, Assessment, Design and Repair of Fire-Damaged Concrete Structures, TR 68, The Concrete Society, UK (2008).
2. Perkins.P.H, Repair protection and waterproofing of concrete structures. Elsevier applied science publishers Ltd.
3. Lee.J,Xi.Y and William.K, Properties of concrete after high-temperature heating and cooling. ACI, Materials Journal. 105(4): p. 334-341.

4. Chang.Y.F, ChinY.H, Sheu.M.S and Yao.G.C, Residual stress-strain relationship for concrete after exposure to high temperatures. Cement and Concrete Research 2006; 36(10): p. 1999-2005.
5. Xiao.J,Konig.G, Study on concrete at high temperature in China-an overview. Fire safety Journal 2004; 39(1): p. 89-103.
6. Miyauchi, K, Nishibayashi, S., and Inoue, S., 1997, "Estimation of Strengthening Effects with Carbon Fiber Sheet for Concrete Column," Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the 3nd International RILEM Symposium, Vol. 1, pp. 217-224.
7. Picher, F., Rochette, P., and Labossiere, P., 1996, "Confinement of Concrete Cylinders with CFRP," Fiber Composites in Infrastructure, Proceedings, 1st International Conf. on Composites in Infrastructure, pp. 829-841.
8. Rizkalla S.H., Fam A.Z. Confinement model for axially loaded concrete confined by circular fiber reinforced polymer tubes. ACI Structural Journal, Vol. 98, No. 4, July-August 2001, pp: 451-461.
9. Chaallal, O, Shahawy, M., and Hassan, M., 2003., "Performance of Axially Loaded Short Rectangular Columns Strengthened with Carbon Fiber-Reinforced Polymer Wrapping," J. Comp. for Costr., ASCE, 7(3), pp. 200-208.
10. Ramakrishnan S., Harmon T.G., Wang E.H. Confined Concrete Subjected to Uniaxial Monotonic Loading. ASCE Journal of Engineering Mechanics, Vol. 124, No. 12, 1998. pp. 1303-1309.
11. Dent, A., Bisby, L., Green, M. Comparison of confinement models for fiber reinforced-polymer-wrapped concrete. ACI Struct J, 102(1), 62-72 (2005).
12. Tepfers, R., DeLorenzis, L. Comparative Study of Models on Confinement of Concrete Cylinders with Fiber-Reinforced Polymer Composites. ASCE J of Comps for Constr, 7(3), 219-237 (2003).
13. Lam.L and Teng.J.G. Design-oriented stress-strain model for FRP-confined concrete in rectangular columns. Journal of Reinforced plastics and composites 2003; 22(13):1149-1186.
14. Bisby, L., Green, M., Kodur, V. Fire endurance of fiber-reinforced polymer confined concrete columns. ACI Struct J, 102(6), 883-891 (2005).
15. Green, M., Chowdhury, E., Bisby, L., Kodur, V. Investigation of insulated FRP wrapped reinforced concrete columns in fire. Fire Safety J, 42(6), 452-460 (2007).
16. Freskakis, G., Burrow, R., Debbas, E., Strength Properties of Concrete at Elevated Temperature. Presented at Civil Engineering Nuclear Power, ASCE National Convention, Boston, USA, 1979.
17. Chowdhury.E.U, Bisby.L.A, Green.M.F, Kodur V.K.R, Residual behaviour of fire exposed reinforced concrete beams pre-strengthened in flexure with Fiber reinforced polymer sheets. Journal of Composites for Construction 2008; 12(1): 44-52.
18. Kodur.V.K.R,Bisby.L.A and Green.M.F, Fire endurance of FRP strengthened reinforced concrete columns. Proceedings of the fourth international conference on concrete under severe conditions, Seoul, Korea, June 27-30, 2004, pp. 872-881
19. M. Yaqub, C.G. Bailey , P. Nedwell, Axial capacity of fire damaged square columns wrapped with FRP composites. Cement & Concrete Composites 33 (2011) 694–701
20. M. Yaqub, C.G. Bailey, P. Nedwell, Q.U.Z. Khan a, I. Javed, Strength and stiffness of fire damaged columns repaired with ferrocement and Fiber reinforced polymer jackets. Composites: Part B 44 (2013) 200–211
21. www.sika.com, Sika Services AG, Tuffenwies 16, CH-8048, Zurich, Switzerland.
22. www.pak.sika.com, Sika Pakistan Pvt. Ltd, City Plaza, DHA Phase 2, Islamabad, Pakistan.
23. www.sikausa.com, Edition no. 7.2003, Identification no. H33230.

.

12/16/2013