Retrofitting of Reinforced Concrete Damaged Short Column Exposed to High Temperature

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ABSTRACT

Experimental research was carried out to investigate the performance of CFRP wrapping jackets used for retrofitting twelve square reinforced concrete (CR) column specimens damaged by exposure to fire flame, at different temperatures of 300, 500 and 700ºC, except for two specimens that were not burned. The specimens were then loaded axially till failure after gradual or sudden cooling. The specimens were divided into two groups containing two main reinforcement ratios, $\rho= 0.0314$ and $\rho= 0.0542$. This was followed by the retrofitting procedure that included wrapping all the specimens with two layers of CFRP fabric sheets. The test results of the retrofitted specimens showed that the fire damaged RC column specimens can be retrofitted efficiently by using CFRP wrap jackets, as they provided good confinement of the damaged concrete core. Also, the ultimate load capacity of each retrofitted specimen was increased compared to that before retrofitting by about 16, 34 and 44% for the specimens burned at 300, 500 and 700ºC respectively, and cooled gradually, whereas this increase was 44% and 111% for the specimens subjected to burning temperatures of 500 and 700ºC, respectively, but cooled suddenly. This ability of each column specimen to absorb energy before and after retrofitting was also improved. The average improvement in modulus of toughness before and after retrofitting was 8% for the specimens not exposed to fire flame and 10, 100, 250% for the specimens exposed to 300, 500 and 700ºC respectively.

Key words: retrofitting, reinforced concrete column, CFRP, high temperature

اعادة تاهيل الاعمدة القصيرة الخرسانية المسلحة المتضررة المعرضة الى درجات حرارية عالية

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الخلاصة

بحث عملي اجري لغرض فحص قابلية استخدام لف سترة من CFRP لتطويق اعمدة استخدم لاعادة تاهيل اثنا عشر عمود خرساني مسلح مقطعه العرضي مربع،والتي تضررت نتيجة التعرض الى لهب بدرجات حرارة عالية مختلفة تصل الى 300, 500 و 700مº , عدا نموذجين لم يتم حرقهما. ثم تم تحميلها محوريا لحد الفشل بعد تبريدها بصورة سريعة او تدريجية. تم تقسيم النماذج الى مجموعتين حسب محتوى الحديد الطولي $\rho= 0.0314$ and $\rho= 0.0542$. بعده تم اجراء خطوات اعادة التاهيل, والتي تضمنت لف جميع النماذج بطبقتين من CFRP . اظهرت النتائج ان النماذج المحروقة يمكن بكفاءة عالية اعادة تاهيلها باستخدام CFRP لانها توفر تقييد جيد للخرسانة في وسط العمود. كذلك زيادة في تحمل الاعمدة بحوالي 16, 34 و 44% للنماذج المحروقة بدرجة 300, 500 و 700مº والمبردة تدريجا على التوالي بينما كانت 44و 111% للنماذج المحروقة

في 500و 700م ولكن المبردة فجائيا . قابلية امتصاص الطاقة لكل نموذج بعد و قبل اعادة التاهيل اظهرت ارتفاع بمقدار 8% للنماذج غير المحروقة بينما كانت 10, 100و 250% للنماذجد المحروقة في 300, 500 و 700مº .

الكلمات الرئيسية: اعادة التاهيل ، عمود خرساني مسلح، CFRP، الحرارة العالية

1. INTRODUCTION

Columns are among the most important structural elements, as their collapse or damage affects the safety of the structure they support. Exposure of reinforced concrete buildings to an accidental fire may result in cracking and loss in the bearing capacity of their major components, i.e. slabs, beams, and columns. Structural engineers are faced with the challenge of developing efficient retrofitting techniques that enable restoring the structural integrity of RC columns exposed to intense fires for long periods of time. Increasing the confinement of the column is the most effective approach to retrofitting reinforced concrete columns.

The use of fiber reinforced polymer (FRP) composites for external reinforcement has proved to be a very effective means of strengthening and retrofitting reinforced concrete (RC) structures over the last two decades , **Jian-Guo D. et al., 2011.**

Many researchers have focused on circular shaped columns. As rectangular sections are not uniformly confined, they have recommended that the high stresses should be concentrated at the corners. Also, they have preferred to develop plastic hinges at the ends of the column, with FRP wraps being used over most of middle length of the column ,**Benzaid et al.,2008. Wang and Wu, 2008,** investigated the effect of corner radius on the performance of CFRP confined square columns. They concluded that the corner radius directly influences the efficiency of confinement of square columns. Their results showed that confinement provided by a jacket with sharp corners is insignificant in increasing column strength. Furthermore, most research has dealt with reinforced columns strengthened by FRP jackets against lateral seismic motion to find out how to improve their shear capacity ,**Yoshimura, et al.,2000.**

Yoshimura, et al.,2000, conducted an experimental study on the behavior of short RC columns strengthened externally by (CFRP). Eight different specimens measuring 150x150x300mm with no transverse ties were tested under constant gravity load and repeated lateral forces. It was concluded that brittle shear failure was prevented by using CFRP jackets.

Ye et al.,2002 , tested short square RC columns strengthened with CFRP under lateral cyclic loading. Two of the specimens were fully wrapped with continuous CFRP sheets along the column height, while four were wrapped with discontinuous CFRP wraps with different widths and spacings. The results showed that the ductile behavior of the strengthened specimens was better in comparison to that of those not treated.

The retrofitting of short square columns exposed to fire flame using fiber-reinforced polymer (FRP) materials has not been studied extensively. Therefore the objective of this study was to evaluate the performance of retrofitting short reinforced concrete columns exposed to fire flame. Twelve reinforced concrete column specimens were cast and exposed to fire flame at different temperatures. All the characteristics of the specimens are given in **Table 1** and **Fig.1.** In this study, these columns were retrofitted and strengthened by CFRP laminate then tested up to failure.

2. EXPERIMENTAL PROGRAM

2.1 Material Properties

- The coarse aggregate used was natural aggregate with a maximum grain size of 10mm.

- Glenium51: (modified polycarboxylic ether) was used as a water reducing and stabilizing agent with a specific gravity of 1.1, at 20^{o}C, pH = 6.5 as announced by the producer.

- Silica fume mineral admixture or micro silica composed of ultrafine, amorphous glassy spheres of silicon dioxide (SiO_2), produced by Crosfield Chemicals, Warrington, England. Properties are shown in **Table 2**.

- Deformed steel bars with diameters of 10mm and 12mm were used for longitudinal reinforcement. To reduce the effect of rebar tie confinement, tie reinforcement was provided by smooth 3 mm diameter bars spaced at 100mm. The mechanical properties are shown in **Table 3**.

- Unidirectional SikaWrap Hex-230C is an externally applied retrofitting system for RC columns. The properties of carbon fiber fabric SikaWrap Hex- 230C and epoxy based impregnating resin Sikadur-330 are shown in **Tables 4.** and **5.** as announced by the manufacturer**.**

2.2 Concrete Mix Proportions

The mix proportions used were 1:1.5:1.6 with a water cement ratio of 0.5 in addition to 3 liters of glenium-51 admixture for each 100kg of cement. The mixture proportions are summarized in **Table 6**.

The slump flow for the self-compacting concrete was 685mm (using cone test ASTM C1611-05) and the slump test for the normal concrete was 100mm (ASTM C143-00).

2.3 Setting up the Column Specimens

Twelve approximately 1/4 scale models of reinforced concrete columns were cast. The overall length was 700 mm and the cross-sectional area was 100 x 100 mm, as shown in **Fig. 1-A**, and reinforced with four longitudinal steel bars, see details in **Table 1**. The ties consisted of 3mm diameter smooth bars spaced at 100mm in all specimens with a clear cover of 6mm. All column specimens were fitted with a top and bottom bearing hat with a square tie ring made of 2mm thick steel plate to prevent end bearing failure and ensure that the loads were distributed uniformly over the column ends. To prevent differences in concrete strength between the specimens, the latter were all cast at the same time.

Two column specimens were left unburned as control specimens C_1 and C_7. The other specimens were burned in a furnace constructed of 3mm thick steel plate, as shown in **Fig. 2**. One column was burned at a time with three control cube specimens (100mm x 100mm x 100mm). Also three cubes were used to determine the strength of the concrete before burning. Furnace dimensions were: height: 800mm; width: 500mm; length: 400mm. These dimensions were appropriate for the dimensions of the specimens, to maintain enough space to allow the flames to reach them from the fire sources (nozzles). The nozzles were positioned eccentrically, four on each side of the furnace, as shown in **Fig. 2-A**, to distribute the fire flame over the entire height of the specimen. The specimen was rotated and positioned in the furnace, as shown in

Fig. 2-B to direct the flames from a series of methane burners positioned on two sides of the furnace onto the four faces of the specimen.

The specimens were cast, then moist cured for seven days after which they were air dried in the laboratory. Ten specimens were subjected to burning by fire flame at age 45 days at three temperature levels, 300, 500 and 700 $^{\circ}C$, as described in **Table 1.** for similar exposure periods of 1 hour after reaching the target temperature. After this period, the fire flame was turned off, the steel case of the furnace removed and the specimen was cooled gradually by leaving it in the air or suddenly by splashing it with water till reaching normal temperature. The temperature was monitored using digital thermometers inside the furnace and a Nickel-Chromium thermocouple wire (Type K) covered with cement to resist the temperature, with a digital temperature reader. Afterwards, the specimens were loaded till failure in the structural lab of Al-Mustanseria University. The results are shown in **Table 7**.

2.4 Retrofitting Procedure

Column specimens damaged by exposure to the fire flame were loaded till failure after cooling. Cracks had formed throughout the burning and cooling processes, and spalling of the concrete covers had occurred, especially at corners. This phenomenon was observed at high temperature exposure of 700 $^{\circ}C$,**Khoury , 2000**. Also some specimens spalled during the loading stages. Furthermore, the color of the concrete had changed to pink, perhaps due to the hydration of iron oxide and other minerals in the cement and the aggregate ,**Nevile,1995**, as shown in **Fig 3**. Failure of the burned concrete specimens occurred in all cases due to crushing under different axial loads, as shown in **Table 7.** and **Fig. 4**.

As shown in **Fig.5** the retrofitting procedure was as follows:

The unsound concrete was removed by using a steel brusher and the surface of the concrete was cleaned of all pink and sooty damaged concrete and any dust. Then the reinforcement was repositioned in its original place and ties were fixed. The damaged concrete that had been removed was replaced with concrete having the same mix properties. After 28 days, the corners of the column specimens were chamfered (rounded) at a width of 15 mm by grinding.

Two-component epoxy impregnation resin was mixed by hand according to the manufacturer’s instructions and applied to the prepared concrete surfaces by brush. The fabric carbon fibers were cut out and wrapped around the specimen. A roller was used parallel to the direction of the fabric until the resin was squeezed between and through the carbon fibers. Two layers of CFRP were wrapped around the entire length of the column. According to the manufacturer’s instructions, the CFRP fabric sheet must be covered by a second layer of epoxy.

The retrofitted column specimens were left for about ten days at lab temperature before loads were applied.

The column specimens were tested in the rig shown in **Fig.6** using a testing machine with a 100 ton hydraulic jack capacity.

3. RESULTS AND DISCUSSION

3.1 Maximum Load Bearing Capacity

The results showed that concrete compressive strength decreased as exposure to temperature increased. The average percentage of residual compressive strength after exposure to 300, 500 and 700 °C was 82%, 65% and 43%, respectively, for the specimens cooled gradually. The results agreed with those obtained by other researchers for normal concrete,**Nevile and Brooks,1987** . The decrease in the compressive strength of concrete was due to the breakdown of interfacial bonds caused by the change in volume between the concrete components during heating and cooling, ,**Venecanin,1977**. However, for the specimens cooled suddenly (high cooling rate), the residual compressive strength was slightly lower, with 61% 39% for exposure to temperatures of 500 and 700 C^{o}, respectively. The results are shown in **Table 8**.

Column number **2** in **Table 7.** shows that the ultimate axial load capacity before retrofitting decreased with increasing fire flame temperature. At burning temperature levels of 300, 500 and 700 ºC, the average residual ultimate load capacities for gradually cooled specimens were 95%, 81% and 74%, respectively. As the temperature increased, the number of cracks and crack growth also increased. This led to lower bond strength between the concrete components as well as between the concrete and the reinforcing bars due to the difference in the thermal expansion coefficients of these different materials. The steel expanded while the concrete was subject to shrinkage. At 500 ^{o}C and for the same longitudinal reinforcement ratio, the ultimate load capacities of the specimens cooled rapidly were lower than those of the specimens cooled gradually, by about 5% for C_4 in comparison to to C_3 and 10% for C_{10} in comparison to C_9. At 700$^{\circ}C$ the two longitudinal reinforcement ratios of the specimens cooled suddenly were about 32% lower than those of the specimens cooled gradually.

After retrofitting, **Table 7.** (column number **3**) shows the ultimate load capacity. By comparing each column specimen with its non burned control specimen as shown in (column number **4**), the ratio was higher than that before retrofitting (column number **2**). The values for the specimens burned at temperatures of 300, 500 and 700 ^{o}C, and for gradually cooled specimens were 95%, 93% and 87% respectively. However for the retrofitted specimens cooled suddenly, it was slightly lower than that for the gradually cooled ones, by about 2% for specimens C_6 and C_9 in comparison to C_5 and C_{10}, respectively. This means the confinement of the two wrapped CFRP sheet layers improved the ultimate load capacity of the columns.

The comparison (column number **5**) for each specimen with the control specimen before burning shows an increase in ultimate load capacity. Except for column specimens C_{11} and C_{12}, there was a slight decrease of about 3%. Whatever the case, this was higher than that before retrofitting, as shown in (column **2**). This was due to the greater damage caused by the destruction of bonds between the inner composition of the concrete in the first period of burning and cooling. However, the ratios of ultimate load capacity were 97% and 96% for C_{11} and C_{12}, respectively, which can be considered to be higher than that of 74% and 48%, respectively, before the retrofitting of the same specimens. This finding means that a retrofitting system using CFRP fabric sheets enhances the ultimate load capacity of the columns.

The last column in **Table 7.** shows the improvement in the ratio of each specimen before and after retrofitting (confinement efficiency). In specimens C_2 and C_8 the ratios were 17% and 14% respectively, which are the lowest because these two specimens had been subject to the least damage due to burning effects. This average ratio increased as the burning temperature increased: it was 34% and 44% for the specimens burned at 500 and 700 C^{o}, respectively, and gradually cooled. Also, it was 44% and 111% for the specimens subjected to the same burning temperature cooled but suddenly. Therefore, confinement by CFRP results in improved compressive strength of the burned and damaged concrete.

3.2 Column Specimen Failure Mode (Failure Mechanism)

Cracks could not be monitored due to the CFRP sheets wrapping the entire height of the specimens. Failure was sudden in all the specimens, with the explosion of the CFRP sheet and the destruction of the concrete core, as reported by ,**Ogata and Osada, 2000 and ,Massone, and Wallace, 2004** . However, this happened after recording a large scale of axial deformation compared to that recorded after burning and before using the CFRP sheets for retrofitting the specimens.

Failure occurred suddenly in a rapid progressive process. It was not possible to determine which event occurred before the other, namely the explosion of the CFRP wrapping, the crushing of the concrete core or the rapid buckling of the longitudinal steel reinforcement. **Fig. 7** shows the failure of retrofitted specimens with the same longitudinal reinforcement: C_1, C_2, C_5 and C_7. The control column specimens not exposed to fire flame are compared to the specimens exposed to different temperature levels, 300, 500 and 700 respectively. Specimens that exploded laterally after smashing the CFRP sheets of all the column specimens were recorded. Failure was more explosive and sudden in specimens C_5 and C_7 than that in specimen C_1. This means that the damage to concrete increases when increasing the exposure temperature, causing a greater burden on the CFRP sheet confining the column. Also, in most of the specimens, failure was observed at the outer, upper or lower third of the column, due to the flow of the axial stresses transmitted from the end bearing toward the middle of the column.

Axial deformation caused the specimens to expand laterally. After the first earlier loading period, this deformation occurred along with the destruction of the CFRP sheets as the load applied was increased. The epoxy-CFRP-epoxy sandwich behaved like a stiff, brittle composite layer. The load was shared by the rehabilitated concrete and the CFRP layers wrapped around it. The axial load was transmitted by the shear stress from the reinforced concrete core to the CFRP jacket. As load was increased and the specimen shortened (axial deformation), lateral deformation increased, acting on the CFRP which reacted by confining the concrete. On the other hand, the applied axial load was shared between the reinforced concrete column and the composite CFRP fabric sheet. Obviously, the composite CFRP fabric sheets had very little axial compressive stiffness, because of their small thickness in comparison to the concrete column. This caused the epoxy layer to break. Thus the main component of the composite sheet was the uniaxial fibers of the CFRP, which could not bear any axial compression load. Therefore the contribution of the axial load applied on the CFRP composite sheet was borne by the epoxy alone; however this value is so small it can be ignored. Thus, when a CFRP confined concrete column is subjected to axial load, the CFRP wrapping jacket is loaded by hoop tension while the concrete is subjected to triaxial compression ,**Nicolae, and Gabriel,2008.**

3.3 Load-axial Deformation Curves:

Figs. 8 and 9 show the axial load deformation curves for the retrofitted column specimens versus the specimens reinforced with 8 longitudinal bars (4xØ10mm and 4xØ12mm).. The curves show an almost linear relationship, as recorded by **Triantafillou, 2003**, but the slope of the curves near the ultimate load fell little. Also, the figures show that the stiffness of the specimens decreases with increased exposure to fire flame temperature. As shown in **Fig. 8**, the stiffness of column specimen C_2 burned at 300ºC, is slightly lower than that of unburned specimen C_1. While in **Fig .9**, for the same compression between specimens C_8 and C_7, stiffness was approximately the same with a slight difference near ultimate load capacity. In both **Figs. 8 and 9**, the stiffness of the retrofitted column specimens decreased with increasing exposure temperature. **Fig. 8** shows that the percentage decreases in stiffness in comparison to the retrofitted unburned specimen C_1, were 5, 17, 24, 24 and 28% for specimens C_2, C_3, C_4, C_5 and C_6, respectively. While with the same comparison in **Fig. 9**, the percentage decreases were lower, with 2, 15, 21, 19 and 23% for specimens C_8, C_9, C_{10}, C_{11} and C_{12}, respectively, with respect to C_7. This means that the confinement by the CFRP jacket becomes the main reinforcement and delays buckling.

The stiffness of the retrofitted specimens increased in comparison to the same specimens before retrofitting. **Figs. 10 to 15** show the difference in stiffness before and after retrofitting the column specimens exposed to the same burning conditions. The average difference was 10% for the specimens not exposed to fire flame and 14, 12, 10% for specimens exposed to 300, 500 and 700 ºC, respectively**. Sandeep et al., 2007,** concluded that CFRP helps to increase strength without excessive increase in stiffness.

Comparing the modulus of toughness of each column specimen (defined as the area under the curve) before and after retrofitting permits determining the material's capacity to absorb energy. As shown in **Figs.10 to 15,** the average improvement in modulus of toughness before and after retrofitting was 8% for specimens not exposed to fire flame and 10, 100, 250% for specimens exposed to 300, 500 and 700ºC respectively.

4. CONCLUSIONS

The test results showed that burned- damaged RC column specimens can be retrofitted efficiently by using CFRP wrap jackets, as they provide good confinement of the damaged concrete core.

- Comparing the ultimate load capacity of each specimen before and after retrofitting shows high confinement efficiency. In specimens C2 and C8, the ratio was 17% and 14%, respectively. This average ratio increased as burning temperature increased, it was 34% and 44% for the specimens burned at 500 and 700 Cº, respectively, and cooled gradually. Moreover, it was 44% and 111% for the same burning temperature but with sudden cooling Therefore CFRP confinement improved the compressive strength of the burned-damaged concrete core.
- The stiffness of the retrofitted specimens increased in comparison to the same specimens before retrofitting.
- Regarding the difference in stiffness before and after retrofitting the column specimens exposed to the same burning conditions, the average difference was 10% for the specimens not exposed to fire flame and 14, 12, 10% for specimens exposed to 300, 500 and 700ºC, respectively.
- Furthermore, the stiffness of the retrofitted specimens decreased with increasing exposure to fire flame temperature. The percentage decreases in stiffness in comparison to the retrofitted unburned specimen C_1, were 5, 17, 24, 24 and 28% for specimens C_2, C_3, C_4, C_5 and C_6, respectively, for specimens with $\rho = 0.0314$ bars (main longitudinal reinforcement ratio). Regarding the same comparison for specimens with $\rho = 0.0542$ bars, the percentage decrease was lower, with 2, 15, 21, 19 and 23% for specimens C_8, C_9, C_{10}, C_{11} and C_{12}, respectively, in comparison to C_7. This means that the confinement by a CFRP jacket strengthens the main reinforcement and delays its buckling.

- Comparing the modulus of toughness (ability of to absorb energy) of each column specimen before and after retrofitting showed an improvement. The average improvement in modulus of toughness before and after retrofitting was 8% for specimens not exposed to fire flame and 10, 100, 250% for specimens exposed to 300, 500 and 700ºC, respectively.

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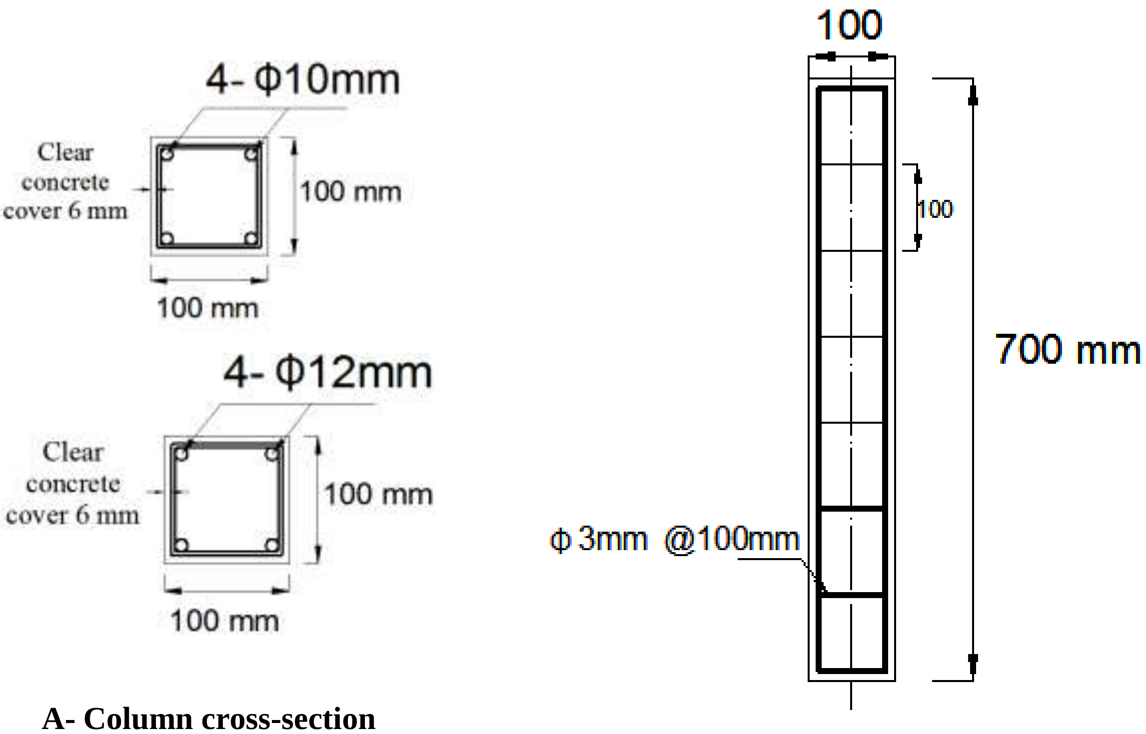
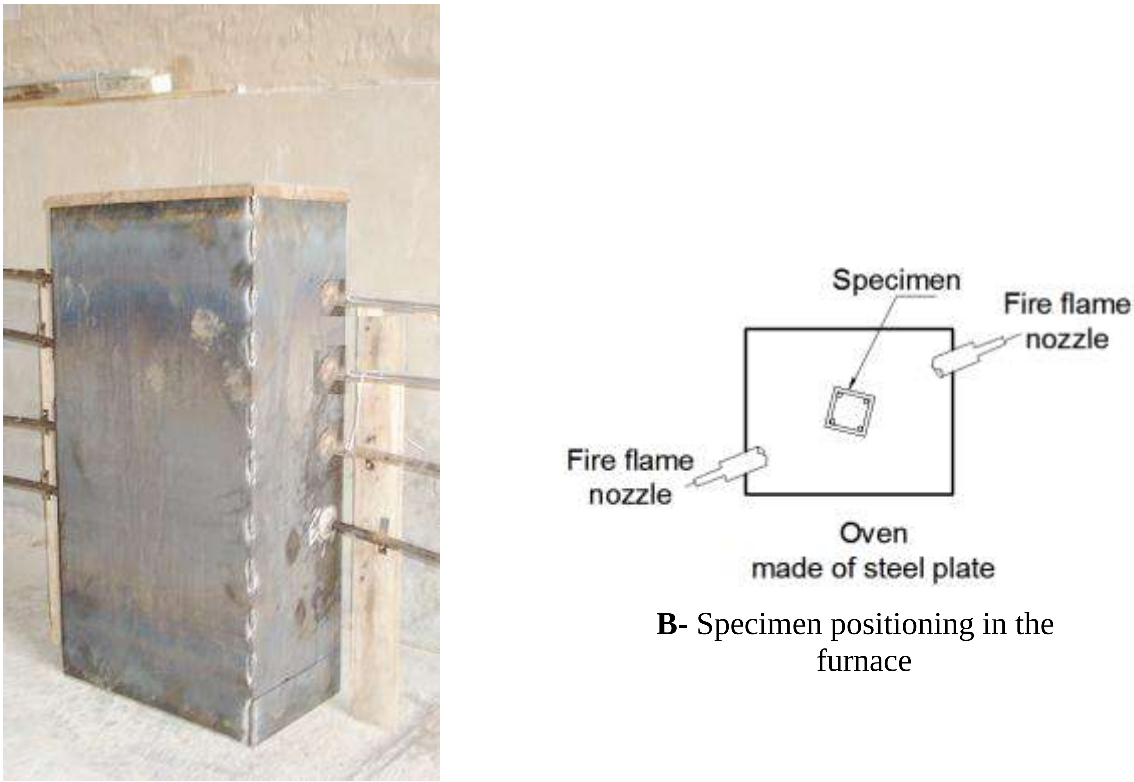


A- Column cross-section

B-Column dimensions

Figure 1. Details of dimensions and reinforcement of concrete column specimens.



B- Specimen positioning in the furnace

A- furnace with nozzles

Figure 2. Details of furnace, distribution of the nozzles and specimen position in the furnace during burning

A- Column specimen C_4 after exposure to 500 $^{\circ}C$ and cooled suddenly

B- specimen C_6 after exposure to 700 $^{\circ}C$ and cooled suddenly

C- specimen C_5 after exposed to 700 $^{\circ}C$ and cooled gradually

Figure 3 . Crack formation at different conditions of cooling and exposure temperature before the loading test.

A- Column specimen C_5 **B-** Column specimen C_6

A- Column specimen C_{11} **B-** Column specimen C_{12}

Figure 4. Failure mode of several column specimens after burning and loading till failure

A-Brushing the concrete to remove unsound materials and dust.

B-Repositioning the main reinforcement **C-** Rounding of columns corners
rounding

D-Replacement of **E-** Wrapping the CFRP fabric sheet using a roller
damaged concrete to coat the CFRP Sheet with additional epoxy layer

Figure 5. Column specimen retrofitting procedure.

Figure 6. Test set-up ,Structural Lab - University of Al-Mustanseria.

A-Column specimen C_1 **B-** Column specimen C_2

C- Column specimen C_5 **D-** Column specimen C_7

Figure 7. Failure of column specimens by rupturing of the two layers of CFRP.

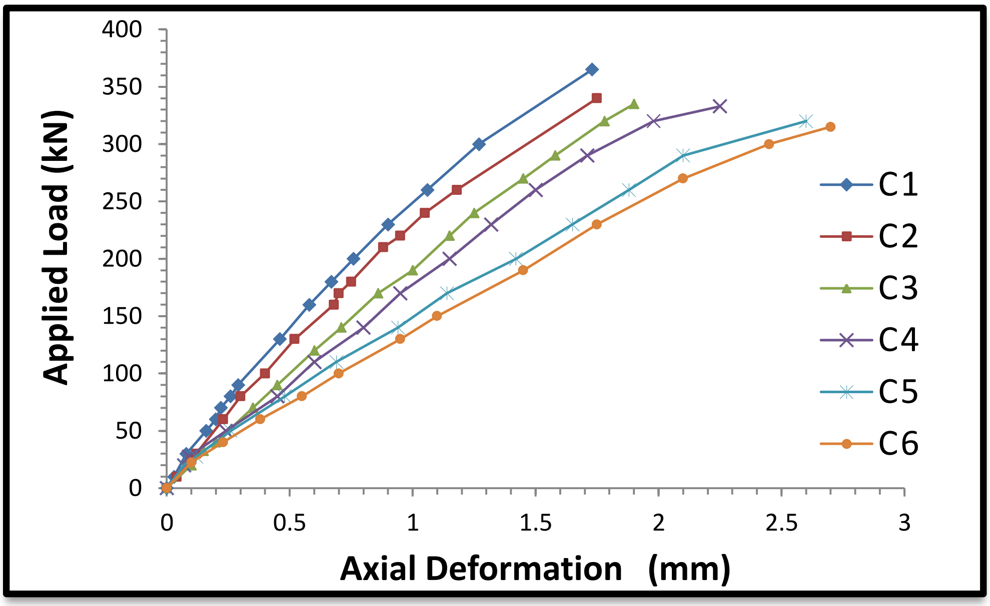


Figure 8. Load-Axial deformation curves for specimens with (4-*Ø10mm*) longitudinal bars . After retrofitting with CFRP fabric sheet.

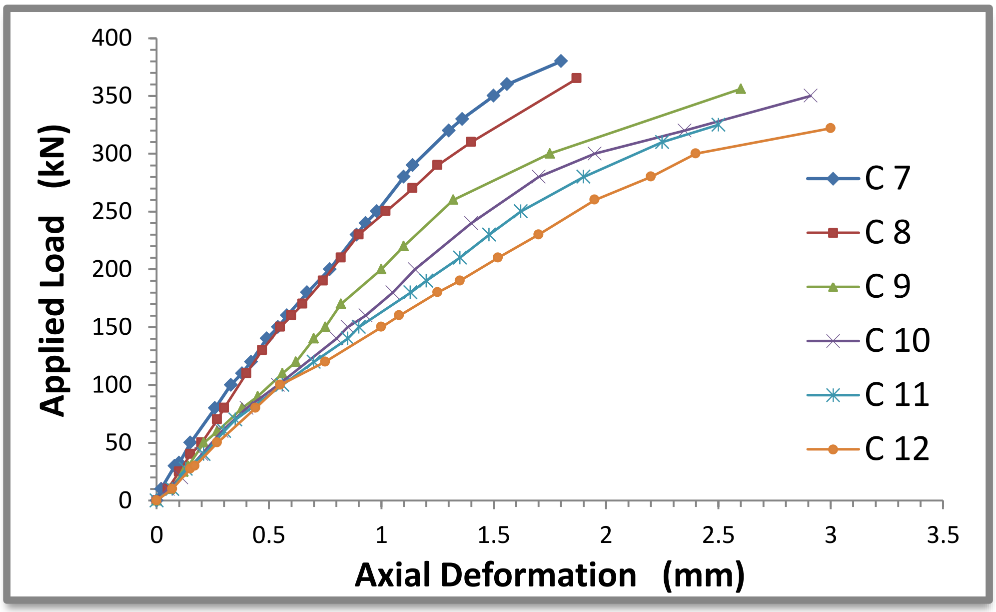


Figure 9. Load-Axial deformation curves for specimens with (4-*Ø12mm*) longitudinal bars
After retrofitting with CFRP fabric sheet.

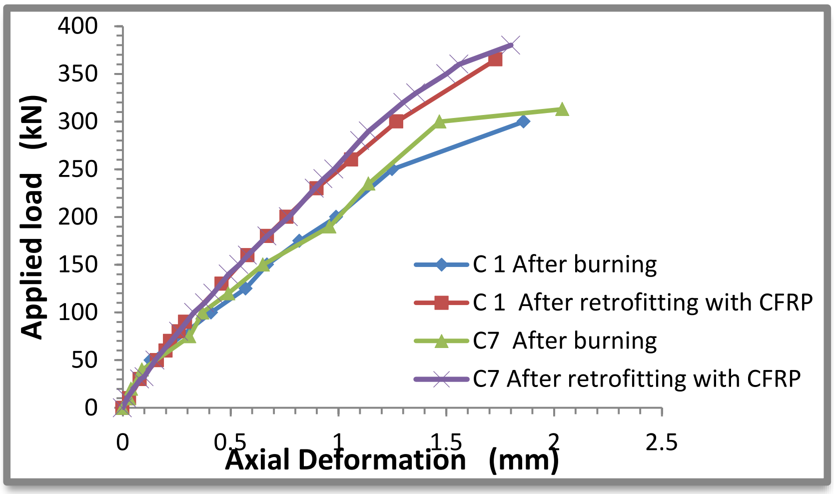


Figure 10. Load-Axial deformation curves for unburned column specimens After retrofitting with CFRP fabric sheet.

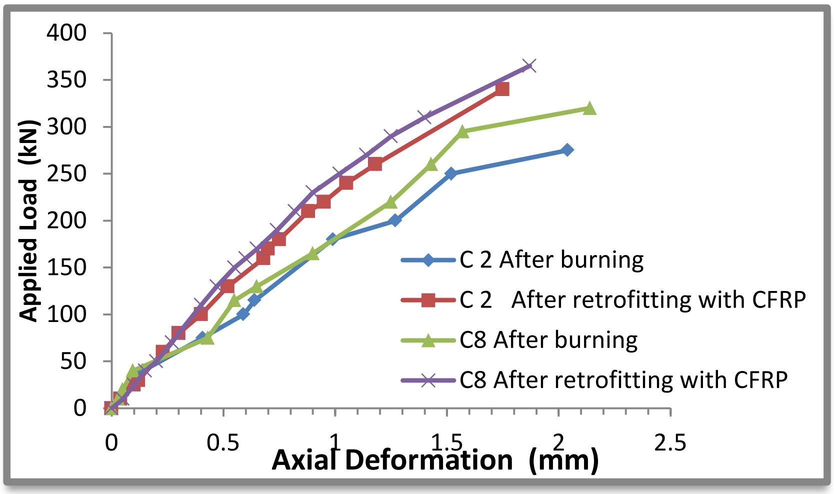


Figure 11. Load-Axial deformation curves for column specimens exposed to 300ºC After retrofitting with CFRP fabric sheet.

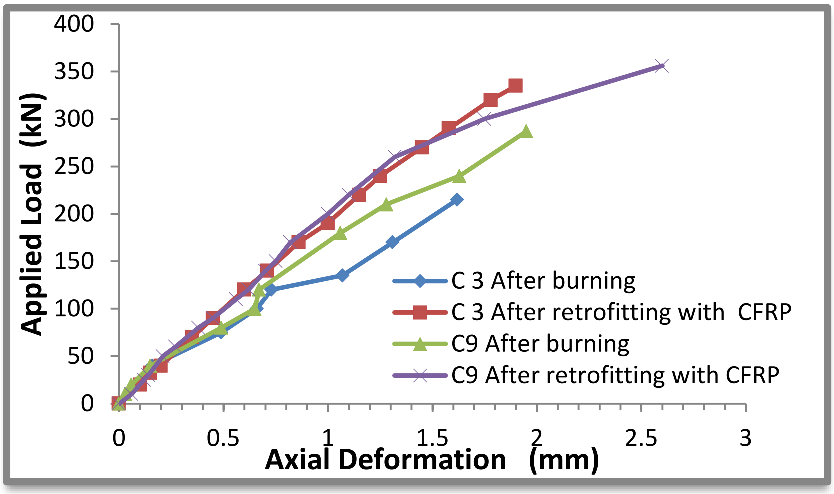


Figure 12. Load-Axial deformation curves for column specimens exposed to 500ºC and cooled gradually
After retrofitting with CFRP fabric sheet.

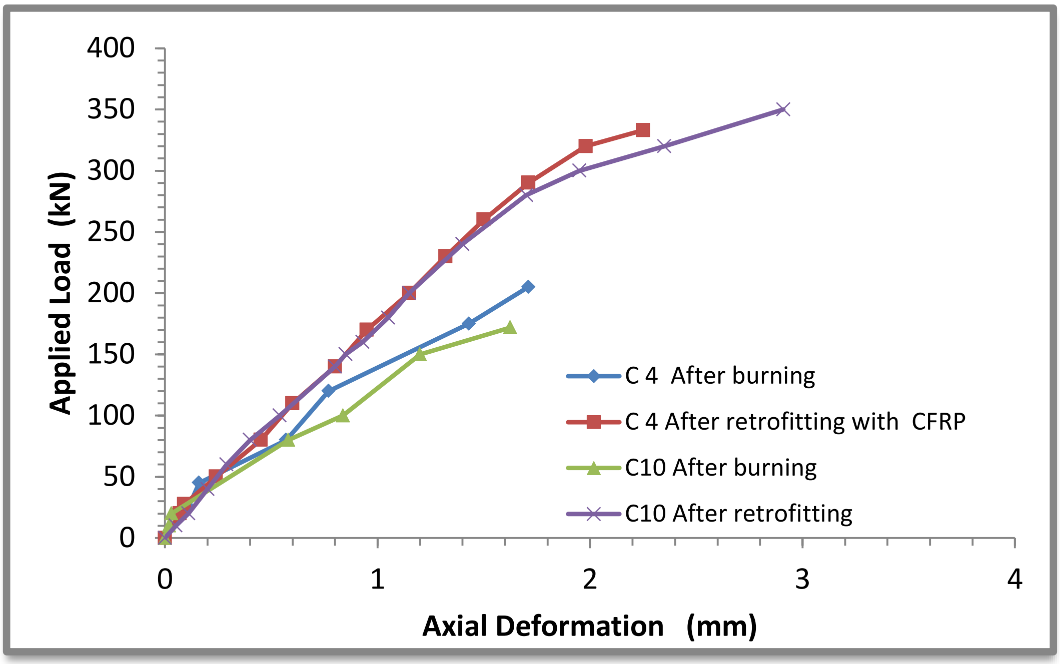


Figure 13. Load-Axial deformation curves for column specimens exposed to 500ºC and cooled suddenly
After retrofitting with CFRP fabric sheet.

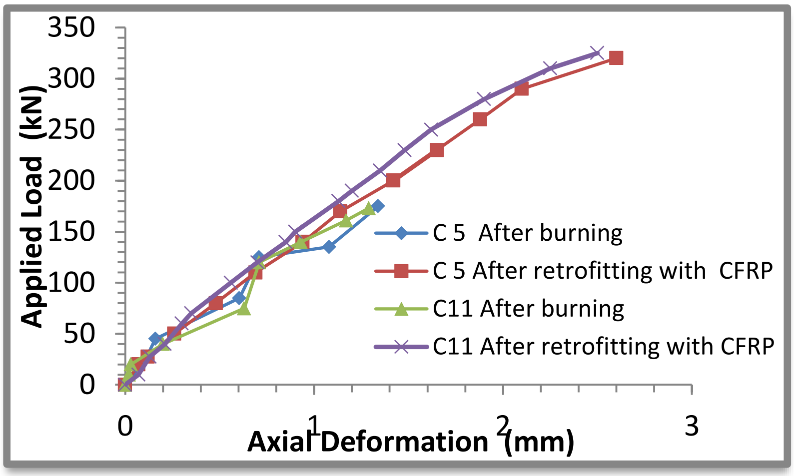


Figure 14. Load-Axial deformation curves for column specimens exposed to 700ºC and cooled gradually
After retrofitting with CFRP fabric sheet.

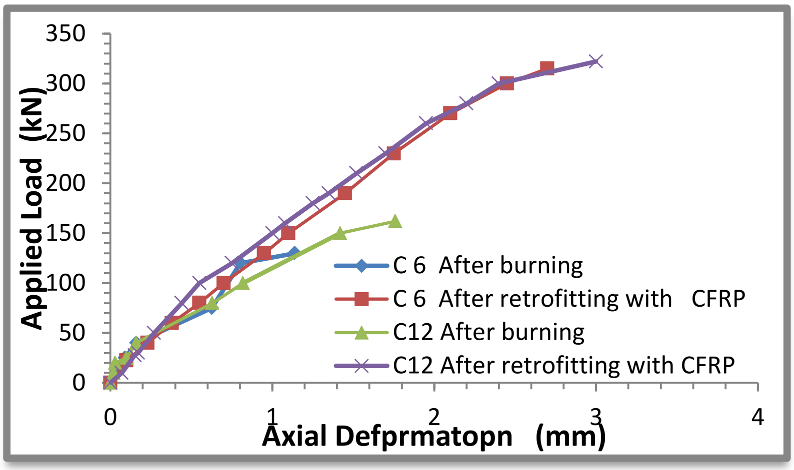


Figure 15. Load-Axial deformation curves for column specimens exposed to 700ºC and cooled suddenly
After retrofitting with CFRP fabric sheet.

Table 1. Details of the column specimens.

Column designation	Longitudinal reinforcement	Longitudinal bar diameter (mm)	Tie reinforcement	Burning temperature C	Type of cooling
C1	4 –Ø10mm.	10	Ø3mm / 100mm	-	-
C2	4 –Ø10mm.	10	Ø3mm / 100mm	300	gradual
C3	4 –Ø10mm.	10	Ø3mm / 100mm	500	gradual
C4	4 –Ø10mm.	10	Ø3mm / 100mm	500	sudden
C5	4 –Ø10mm.	10	Ø3mm / 100mm	700	gradual
C6	4 –Ø10mm.	10	Ø3mm / 100mm	700	sudden
C7	4 –Ø12mm.	12	Ø3mm / 100mm	-	-
C8	4 –Ø12mm.	12	Ø3mm / 100mm	300	gradual
C9	4 –Ø12mm.	12	Ø3mm / 100mm	500	gradual
C10	4 –Ø12mm.	12	Ø3mm / 100mm	500	sudden
C11	4 –Ø12mm.	12	Ø3mm / 100mm	700	gradual
C12	4 –Ø12mm.	12	Ø3mm / 100mm	700	sudden

- All specimens were made of SCC: self-compacting concrete.
- Average concrete strength before burning was 49MPa for the cubes 100 x 100 x 100mm.
- Steel reinforcement ratio $\rho = 0.0314$ for specimens with 4-Ø10mm longitudinal bars.
- Steel reinforcement ratio $\rho = 0.0452$ for specimens with 4-Ø12 longitudinal bars.
- The period of exposure temperature was one hour after reaching the target temperature.
- Sudden cooling was done by splashing with water till reaching normal temperature.

Table 2. Chemical and physical properties of Silica fume.

Properties	SikaWarp$^{®}$ Hex-230C
SiO_2	90 %
SO_3	0.15 %
Cao	0.8 %
Surface area	25000-28000
Grading below 1µm	90%

Table 3. Mechanical properties of steel bars.

Bar diameter (mm)	Yield stress (MPa)	Strain at yield stress (microstrain)	Ultimate stress (MPa)
3	542	2710	632
10	512	2497	622
12	504	2571	618

Table 4. Technical properties of CFRP sheets [manufacturer's data].

Properties	SikaWarp$^{®}$ Hex-230C
Tensile strength (MPa)	4100
E-modulus (GPa)	230
Elongation at break (%)	1.7
Width (mm)	300/600
Thickness (mm)	0.12

Table 5. Technical properties of impregnation resin [manufacturer's data].

Properties	Sikadur$^{®}$-330
Tensile strength , MPa	30
Density	1.30kg/l$_{\pm.1}$ kg/l
E-modulus , GPa	4.5
Open time , min.	30 (at +35^{o}C)
Full cure , days	7(at +35^{o}C)
Mixing ratio	1:4
Elongation at break	0.9%

Table 6. Concrete mix proportions.

Contents of Materials	
Water kg/m^3	200
Superplasticizer lit./100kg (powder)	3
Cement kg/m^3	392
Silica fume kg/m^3	8
Total powder kg/m3	400
Gravel kg/m3	640
Sand kg/m3	600

Table 7. Columns test results.

Column designation	After Burning		After Retrofitting			Load capacity after Retrofitting / load capacity after burning before retrofitting
	1	2	3	4	5	
	Ultimate load capacity kN	Load capacity /reference column %	Ultimate load capacity kN	Load capacity /reference column %	Load capacity /reference column £ %	
C1	305 £	100	365	100	120	1.20
C2	290	95	340	93	111	1.17
C3	232	76	335	92	110	1.44
C4	220	72	333	92	109	1.51
C5	207	68	320	88	105	1.55
C6	142	46	315	86	103	2.22
C7	335 £	100	380	100	113	1.13
C8	320	96	365	96	109	1.14
C9	287	86	356	94	106	1.24
C10	258	77	350	92	104	1.36
C11	247	74	325	86	97	1.32
C12	162	48	322	85	96	1.99

£ Reference Column not exposed to fire flame

Table 8. Cube compressive strength before and after exposure to high temperature.

Burning temperature C°	Type of cooling	Compressive strength MPa	Residual compressive strength %
-	-	49	100
300	gradual	40	82
500	gradual	32	65
700	gradual	21	43
500	sudden	30	61
700	sudden	19	39

- The results are average of three cubes