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Repair of Fire-Damaged Circular and Square Columns Using CFRP Composites: A Comprehensive Review

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Abstract

In the field of structural engineering, the repair and rehabilitation of fire-damaged circular and square columns pose significant challenges. Carbon Fiber Reinforced Polymer (CFRP) composites have gained popularity as a potentially effective method for restoring the structural integrity of damaged structural members. The purpose of this investigation is to provide a state-of-the-art review of existing experimental and numerical studies in the literature on repairing fire-damaged square/circular columns using CFRP composites. The effectiveness of CFRP as a repairing technique in restoring the axial load-carrying capacity and stiffness of fire-damaged circular, square, and rectangular columns is evaluated. Based on past investigations, it has been concluded that CFRP composites can restore 70-169.2% of the axial capacity and 0-29.2% of the lost resistance. Moreover, the review offers a critical assessment of previous experimental and numerical investigations, highlighting their significant contributions to the advancement of knowledge regarding CFRP-based column repair. A comparative analysis of the experimental results from available studies is carried out, accompanied by a concise examination of the gaps, and a pathway for future researchers is also suggested. In addition to this, probable challenges and limitations, such as stiffness loss after repairing fire-damaged columns with CFRP composites, and ways to counter them, are also summarized in this study. The article provides engineers, researchers, and practitioners involved in the restoration and repair of fire-damaged circular and square columns using CFRP composites with insightful recommendations derived from an exhaustive synthesis of prior literature and case studies.

Keywords: *Carbon Fiber Reinforced Polymer Confinement (CFRP), Heat Damaged Square Columns, Heat Damaged Rectangular Concrete, Heat Damaged Circular Columns*

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I. INTRODUCTION

The structural integrity of buildings is of paramount importance in ensuring the safety of occupants and preserving the functionality of infrastructure. Nevertheless, unexpected occurrences, such as fire breakouts, have the potential to undermine the structural integrity of columns, thereby presenting substantial obstacles for professionals in the field of structural repair and rehabilitation. Instances of fire pose significant risks to the structural integrity of buildings, resulting in property damage, loss of lives, and economic repercussions [1-3]. When subjected to fire, columns undergo increased temperatures, resulting in a reduction in their load-bearing capacity, and various other forms of damage are also induced, like loss of strength, spalling of concrete cover, and deterioration of reinforcement [4-7]. The extent of damage caused by fire is contingent upon several elements, including the duration of the fire, the temperature distribution, and the geometry of the column [8-9]. Buildings often use circular and square columns, which are more vulnerable to fire damage due to their exposed surfaces and limited thermal mass.[10-11].

Given the constraints above, the utilization of advanced materials and techniques for repair and reinforcement has emerged as a potentially fruitful approach to reinstate the damaged columns to their initial condition or even enhance their performance beyond pre-fire conditions. Carbon fiber-reinforced polymer (CFRP) composites have gained significant recognition in the realm of structural engineering due to their remarkable mechanical properties and adaptability. CFRP composites, which consist of carbon fibers with high strength contained inside a polymer matrix, provide enhanced tensile strength and stiffness in comparison to conventional building

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materials. Furthermore, CFRP materials may also be tailored to meet the specific needs of various structural applications by adjusting fiber orientation, thickness, and design [1,12]. Regarding the field of column repair, CFRP composites offer a viable solution for enhancing the structural performance of damaged structural elements, while minimizing the increased weight and spatial demands associated with traditional restoration techniques [13-14].

Fires in concrete buildings rarely cause significant damage to the whole structure, and most of the fire-damaged concrete buildings are effectively repairable. Because of this, fixing fire-damaged concrete buildings is seen as a more cost-effective choice than tearing them down and starting over [15]. Although CFRP composites have several benefits but repairing fire-damaged columns still presents a few obstacles [16-17]. One of the primary concerns is the degradation of CFRP material at elevated temperatures, which can compromise its mechanical properties and structural integrity [18-19]. The development of fire-resistant CFRP systems and the incorporation of additional protective measures to mitigate thermal degradation have been the focus of research [20-21] However, FRP can function well in a fire if it gets coated with extra fire protection after its application [22-30].

To gain a comprehensive understanding of the importance of fire-damaged column rehabilitation, it is essential to understand the historical precedents and consequences of structural failures. Throughout history, various calamities, including fires, earthquakes, and other catastrophic events, have highlighted the vulnerability of structures to external dangers [20,31]. The collapse of buildings due to compromised structural elements, such as columns, has not only resulted in human casualties but also inflicted substantial economic losses [32]. Consequently, the development of efficient restoration methodologies for columns damaged by fires is of critical importance in preventing structural collapses and ensuring the durability of constructed surroundings [33].

Several stages are typically involved in the rehabilitation process using CFRP composites [34-35]. These steps include surface preparation, the bonding of CFRP sheets or covers to the column surface, and post-installation curing. To ensure that the CFRP material adheres properly to the substrate column, surface preparation is crucial. This entails cleansing, roughening, and applying bonding agents to increase bond strength [36-37]. Subsequently, an epoxy adhesive or resin is used to adhere the CFRP sheets or covers to the column surface. Consolidation is performed to eliminate air pockets and guarantee proximity between the CFRP and the concrete. Ultimately, the repaired column is allowed to cure, resulting in a strengthened and protected structural element [38-39].

II. Fire damaged columns repair techniques.

There are typically three techniques used to repair fire-damaged columns, as suggested by Jun Zhou [40]. Each method has its own advantages and disadvantages, which are explained in the following sections.

2.1 Section enlargement using concrete jacketing.

The section enlargement technique involves expanding the cross-sectional area of the damaged columns with the goal of enhancing their ultimate axial load-bearing capacity, stiffness, and stability. Due to the ease of constructing section enlargement reinforcement, it has become one of the most prevalent methods of restoration for modern applications. However, its application is primarily limited to bridge reinforcement in the aftermath of fires, as the restricted space area of RC frame structures discourages its use [40]. Extensive research has been conducted in the literature regarding the behavior of section enlargement-repaired fire-damaged RC columns. The repaired specimens by the under-discussion method exhibited an increase in ultimate strength [41- 44].

2.2 Steel Wrapping/Jacketing

The steel wrapping procedure involved the use of a cement-based mortar or epoxy resin to adhere steel components, including steel plates, channels, and conduit, to the surfaces and corners of columns. Some examples are shown in figures 1, 2a, and 2 b. It is suggested that columns damaged moderately, with concrete temperatures varying from 400 to 500 °C, can be repaired using Steel Wrapping [40].

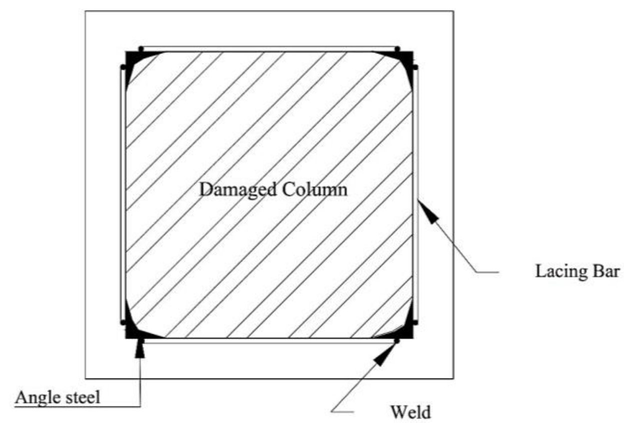

Fig. 1. Steel strengthening with angle steel and lacing bars.

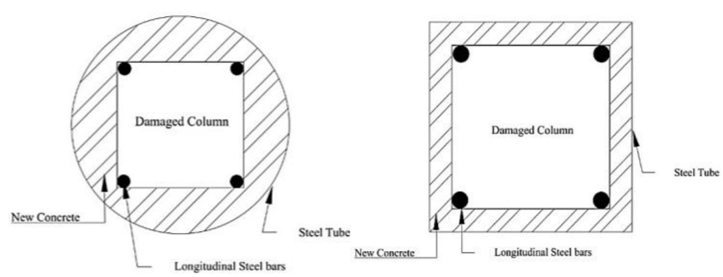

Fig. 2. Steel tube wrapping (a) Circular columns (b) Square columns.

The approach of repairing fire-damaged columns using post-compressed steel plates was devised by Wang and Su [45-51]. Seven RC columns were exposed to flames for a period of four hours. Two plates with a minor precamber were attached to an RC column for each column. The plates are designed to be longer than the column's clear height. As the anchor fasteners were progressively tightened, the end supports experienced thrust generation due to arching actions. This led to the development of a post-compressive force in the steel plates and an equivalent magnitude decompressive force in the RC column. The RC column and steel plates were therefore capable of resisting the existing applied pressures. As demonstrated by the test results, fire-damaged columns repaired with post-compressed plates can regain up to 72% of their initial strength.

2.3 Fiber-reinforced polymer (FRP)

The utilization of FRP in civil engineering applications has witnessed a notable surge, owing to its exceptional strength-to-weight ratio and resistance to corrosion [52-60]. By adhering FRP sheets to the surface of RC columns, the ultimate load capacity can be restored owing to the confinement effect. Therefore, extensive research has been conducted in the literature on FRP as a repair technique for columns with various types of damage [52-78]. Whether it's GFRP or CFRP, both resulted in enhanced ultimate axial capacity of the fire-damaged columns. Regarding the stiffness of repaired columns, Alone CFRP can't restore a significant amount, but hybrid techniques, explained later in the article, can help counter this problem.

III. Experimental studies on circular columns:

To study the effect of CFRP confinement as a repair technique for rehabilitating fire-damaged columns, five experimental investigations have been conducted by Yaqub M. [79], Yaman S.S. Al-Kamaki [80], Iqrar Hussain [81], Jia Xu. [82], and Hanan Al-Nimry [83]. In the current study, experiments with only complete wrapping of CFRP are considered. More details of the experimental programs and the results obtained are discussed in the following sections.

3.1 Experimental programs:

Yaqub M. [79] conducted a study on fourteen RC columns, each with a diameter of 200mm and a height of 1000mm, out of which two were tested unheated as control samples, and the remaining were heated at 500 °C for 210 minutes. The damaged columns were repaired using GFRP and CFRP confinement. Four columns were repaired using two types of CFRP jackets with varying thickness. The effect of Unidirectional CFRP layers is studied in this investigation. Yaman S.S. [80] tested twenty columns, each with a diameter of 204mm and a height of 720mm. Fourteen of the total 20 columns were damaged, and 8 of them were repaired with CFRP jackets. CFRP sheets with a thickness of 0.227mm are used in single and double layers to study the confinement effect. The initial compressive strength of the concrete before damage was 32 MPa, and the columns were damaged at 800 °C and 1000 °C for 120 minutes.

Iqrar [81] tested twenty-one column specimens, each with a diameter of 200mm and a height of 1200mm. In this study, the damage was done at three peak temperatures (at 300 °C, 500 °C, and 900 °C). The fire duration was kept at 3 hours in each case. Three of the total columns were tested unheated, and the remaining columns were heated at different temperatures. Six of them were repaired with one layer of Unidirectional CFRP, having a thickness of 0.131 mm. Numerical modeling was also conducted during the investigation. Jia Xu [82] conducted experimentation on RCC Columns to test the effectiveness of Steel jacketing and CFRP composite. The focus was given to high-strength concrete, so the Compressive strength of concrete was one of the considered variables. In total, three types of concrete were considered, having compressive strengths of 50 MPa, 65 MPa, and 90 MPa, respectively. Moreover, another critical variable studied in this investigation was the time of fire exposure. The columns were exposed to fire durations of 60, 90, and 120 minutes. The highest temperature of the fire in each duration was around 900 °C. All the columns were originally 300 mm in cross-section and 1000 mm in height. However, after retrofitting with CFRP and applying a thick 35 mm layer of high-strength mortar, the diameter of the columns increased to 370 mm. Hanan Al-Nimry [83] tested fifteen circular columns, exposing twelve columns to heat at a temperature of 500 °C for durations of 120 minutes and 180 minutes. All columns were 192 mm in diameter and 900 mm in height. The heat-damaged columns were repaired with 1 or 2 layers of Unidirectional CFRP, having a thickness of 0.131 mm. The effect of GFRP was also investigated. Parameters used by Yaqub M. [79], Yaman S.S. [80], Iqrar [81], Jia Xu. [82], and Hanan Al-Nimry [83] in their experimental programs are summarized in Table 1.

TABLE I. Parameters considered in existing experimental studies for fire damaged circular columns.

Parameters	Units	Yaqub M. [79]	Yaman S.S. [80]	Iqrar [81]	Jia Xu [82]	Hanan Al-Nimry [83]
Column Dia	mm	200	204	200	300	192
Specimen Height	mm	1000	750	1200	1000	900
Concrete's initial compressive strength	MPa	53	32	35	50, 65, 90	38
Fire Temperature	°C	500	800, 1000	300, 600, 900	300	500
Fire Exposed Time	Min	210	120	180	60, 90, 120	120, 180
CFRP Layers	Count	1	1, 2	1, 2	1, 2	1, 2
Thickness of CFRP	mm	0.117, 0.370	0.227	0.131	0.167	0.131
Tensile E-modulus of CFRP	GPa	240, 230	230	238	240	238

3.2 Results and findings:

In the experiments conducted by Yaqub M. [79], the specimens were heated at 500 °C for 210 minutes; after heating, the axial strength of the column was reduced by 37.5%. When the specimens were repaired with Webertec Force C-240 CFRP, having a thickness of 0.117 mm, an increment of 33.1% was noted. On the other hand, when the damaged specimens were repaired with Tyfo SCH-41 CFRP, having a thickness of 0.37 mm, an increment of 57.5% was observed in the residual strength, and the resulting repaired axial capacity of the column is almost 19% more than that of the undamaged original specimen. Yaman S.S. [80] found that after the columns were exposed to a fire of 800 °C for 120 minutes, the axial capacity was reduced by almost 42%. However, when the same columns were exposed to a fire of 1000 °C for 120 minutes, the axial capacity was reduced by 71%. According to the author's results, the CFRP repair had a significant impact on the axial strength of the damaged columns. The 800 °C damaged columns, when repaired with one layer of CFRP, regained almost 105% of their undamaged strength, and when repaired with two layers of CFRP, a regain of 169.2% was observed. The repaired strengths of damaged columns were 62.8% and 126% greater than their original strength. Meanwhile, when 1000 °C-damaged columns were repaired with one layer of CFRP, axial strength was regained by almost 85% of the original strength, and when repaired with two layers of CFRP, it was recovered by 146%. Once again, the total repaired strength was 14.1% and 75% greater than the original strength of the columns. The results obtained by this study were incredibly optimistic.

Iqrar [81] concluded that when the peak temperature was increased from 300 °C to 900 °C, columns lost their strength significantly. At the peak temperature of 300 °C, only 11.5% of the total axial capacity was lost. However, when the temperature increased to 500 °C, the strength dropped by 28%, and when the peak temperature increased to 900 °C, approximately 50% of the total axial strength was lost. But when the columns damaged at 300 °C were repaired with one layer of CFRP, 91.4% of the original strength was regained. Similarly, when columns damaged at 500 °C and 900 °C were repaired with one layer of CFRP, 87% and 77% of their total axial capacity was regained, respectively. In conclusion, the repaired strength exceeded the original undamaged strength. Jia Xu [82] concluded that columns with an initial compressive strength of 50 MPa, when exposed to fire for 60 minutes, had an axial capacity reduced by 12.4% from 3957 kN to 3465 kN. Moreover, axial capacity was reduced by 18% and 24% when exposed to fire durations of 90 minutes and 120 minutes, respectively.

When 60-minute damaged columns were retrofitted with one layer of CFRP jackets, the strength was regained to 40.7% of the original strength. However, when specimens were repaired with two layers of CFRP, a regain of 74.1% was observed. Moreover, when 90-minute and 120-minute damaged columns were repaired with two layers of CFRP jackets, a regain of 64% and 66%, respectively, was observed. When columns with an initial compressive strength of 65 MPa were exposed to fire for 60 minutes, the axial capacity was reduced by 21.2% from 4438 kN to 3498 kN. Moreover, axial capacity decreased by 31.3% and 31.7% when exposed to 90-minute and 120-minute fire duration, respectively. On the other hand, when 60-minute-damaged columns were retrofitted with two layers of CFRP jackets, the strength was regained to 84.8% of the original strength. When 90-minute- and 120-minute-damaged columns were repaired with two layers of CFRP jackets, a regain of 94.8% and 78.5%, respectively, was observed. When Jia Xu [82] exposed columns with an initial compressive strength of 90 MPa to fire for 60 minutes, the axial capacity was reduced by 22.7% from 6,213 kN to 4,802 kN. On the other hand, the axial capacity decreased by 24.0% and 23.8% when exposed to 90 and 120-minute fire duration, respectively. When 60-minute damaged columns were retrofitted with one layer of CFRP jackets, the strength was regained by 10.8% of the original axial strength, and when repaired with two layers of CFRP, a regain of 55.2% was observed. Moreover, when 90-minute and 120-minute damaged columns were repaired with two layers of CFRP jackets, a regain of 67.6% and 59.0% was observed, respectively. Conclusively, CFRP is highly effective in restoring the axial strength of fire damaged columns.

Hanan Al-Nimry [83] concludes that after exposing columns to a 500 °C fire for 120 minutes, the columns lost 45% of their axial strength, decreasing from 989 kN to 535 kN. When specimens were exposed to fire for 180 minutes, the columns lost 53.7% of their strength. And when 120-minute-exposed columns were repaired with one layer of CFRP wrap, 56.7% of the original axial strength was restored; hence, the repaired column was more substantial than the original strength of the control sample. Moreover, when 120-minute-exposed columns were retrofitted with two layers of CFRP wraps, 83.8% of the original axial capacity was restored. Meanwhile, when 180-minute-exposed columns were repaired using a single layer of CFRP wrap, 52.3% of the original axial strength was restored, and when repaired with two layers of CFRP wraps, 88.4% of the original axial capacity was restored. Table 2 summarizes the results of residual and repaired axial strength of circular columns after their exposure to fire from all the existing experimental studies available in literature.

TABLE II. COMPARISON OF REPAIRED AXIAL STRENGTH OF FIRE DAMAGED CIRCULAR COLUMNS IN EXISTING EXPERIMENTAL INVESTIGATIONS

	Initial Compressive Strength of Concrete (MPa)	**Temperature (°C)**	**Fire Exposure Time (Min)**	**Control specimen Strength (kN)**	**Residual strength (kN)**	**Decrement (%)**	**CFRP layers (Count)**	**Repaired strength (kN)**	**Increment (%)**
Yaqub M. [79]	53	500	210	1418 (CFRP thickness = 0.37mm)	886	-37.5	1	1356	33.1
						1701	57.5		
Yaman S.S. [80]	32	800	120	1326	758	-42.9	1	2159.4	105.7
							2	3002.2	169.2
		1000			376	-71.7	1	1514.2	85.8
							2	2322.7	146.8
Iqrar [81]	35	300	180	1353	1197	-11.5	1	2433.5	91.4
		600			974.5	-28.0	1	2161.5	87.7
		900			711	-47.5	1	1763	77.8
Jia Xu [82]	50	300	60	3957	3465	-12.4	1	5074	40.7
						-12.4	2	6397	74.1
			90		3222	-18.6	2	5782	64.7
			120		3004	-24.1	2	5642	66.7
	65		60	4438	3498	-21.2	2	7262	84.8
			90		3051	-31.3	2	7257	94.8
			120		3031	-31.7	2	6515	78.5
	90		60	6213	4802	-22.7	1	5471	10.8
						-22.7	2	8234	55.2
			90		4723	-24.0	2	8923	67.6
			120		4735	-23.8	2	8403	59.0
	38	500	120	989	535	-45.9	1	1096	56.7

Hanan Al-Nimry [83]	120			2	1364	83.8
	180	458	-53.7	1	975	52.3
	180			2	1332	88.4

Fig. 3 provides a general trend of how fire temperature affects the regain of axial strength of fire-damaged columns after repairing with CFRP composites. The increment in the axial capacity is higher when the damaged columns are repaired with two layers of CFRP composites as compared to when repaired with one layer of CFRP. Moreover, the regained axial capacity increases with temperature, but the value drops after 800 °C. One of the possible explanations of this behavior is that at higher temperatures, the damaged column loses more strength; therefore, the comparative restored strength is also high, but when the fire temperature is greater than 800 °C, the properties of concrete are lost to an extent that the regain in axial capacity of repaired fire-damaged columns declines.

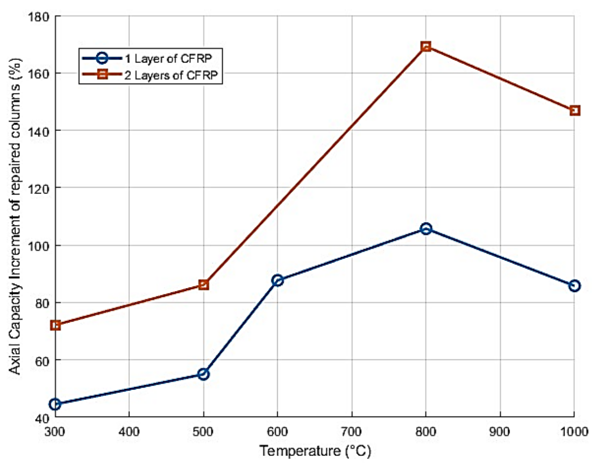

Fig. 3. Variation of axial capacity of CFRP repaired circular columns against fire temperature (°C)

Regarding the stiffness of the damaged columns Yaqub M. [79] concluded observed that after exposure to 500 °C for 210 minutes, the stiffness of the column was reduced by more than the axial capacity, by almost 72%. After repairing with both types of CFRP, there was no significant regain. In addition, Jia Xu [82] examined how different columns damaged by varying fire durations experienced a decrement in stiffness. However, no investigation was conducted to determine the effect of CFRP confinement on stiffness after retrofitting. As the fire duration increased from 60 to 120 minutes, stiffness loss also increased; meanwhile, an opposite trend was observed when the initial compressive strength of the concrete columns increased. On the other hand, Al-Nimry [83] concluded that 68% of stiffness was lost when the columns were exposed for 120 minutes, and 74% of stiffness was lost when exposed for 180 minutes. When the columns were retrofitted, no significant rise in stiffness was observed. CFRP wraps failed to restore the Stiffness of fire-damaged columns. Results from the experiments conducted by Yaqub M. [79], Jia Xu [82] and Al-Nimry [83] for circular are summarized in Table 3.

TABLE III. COMPARISON OF REPAIRED STIFFNESS OF FIRE-DAMAGED CIRCULAR COLUMNS IN EXISTING EXPERIMENTAL INVESTIGATIONS

Study Name	**Initial Compressive Strength of Concrete (MPa)**	**Temperature (°C)**	**Fire Exposure Time (Min)**	**Control specimen Stiffness(kN/mm)**	**Residual stiffness (kN/mm)**	**Decrement (%)**	**CFRP layers (Count)**	**Repaired strength (kN/mm)**	**Increment (%)**
Yaqub M. [79]	53	500	210	2715 (CFRP thickness = 0.37mm)	758	-72.1	1	522	-8.7
								842	11.1
Jia Xu [82]	50	300	60	1720	900	-47.7	N/A	N/A	N/A
			90		750	-56.4			
			120		470	-72.7			
	65		60	1730	950	-45.1			
			90		650	-62.4			
			120		550	-68.2			
	90		60	2150	1450	-32.6			
			90		1150	-46.5			
			120		850	-60.5			
Al-Nimry [83]	38	500	120	2764.9	870	-69	1	588	-10.2
			120				2	638	-8.4
			180		719	-74	1	549	-6.2
			180				2	570	-5.4

3.3 Numerical and analytical Modeling:

Yaman [80] conducted a finite element analysis and prepared a finite element model using ATENA-GiD software. ATENA (Advanced Tool for Engineering Nonlinear Analysis) is the FEM analysis program that interfaces with GiD. This pre- and post-processor program generates relevant input, and FE meshes and is capable of undertaking transport (thermal) analysis. Loading and boundary conditions used by Yaman [80] are shown in Fig. 4. Transpose analysis method was used for both heat-damaged and heat-damaged CFRP repaired columns. Meanwhile, the static analysis method was used for unheated and heated CFRP-wrapped columns. The resultant model accurately predicted the behavior of columns heated to 800 °C and 1000 °C. Moreover, the prepared model was also used to study different parameters that affect the confined strength of columns, which were not otherwise considered in the experimental investigation.

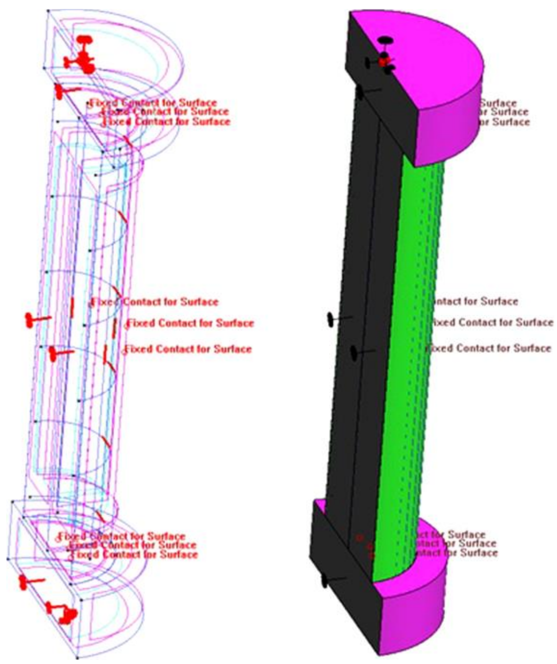

Fig. 4. Loading and boundary conditions by Yaman [80]

In addition to the experimental work, finite element modelling and regression analysis were also performed by Iqrar [81]. To predict the axial load–deformation performance of undamaged, fire-damaged, and fire-damaged circular RC columns that had undergone various composite retrofitting techniques, nonlinear finite element modeling was performed employing Abaqus Standard 6.12. The concrete damage plasticity (CDP) model in Abaqus Standard was used to simulate the performance of the concrete used for the circular columns. An eight-node brick block reduced by the hourglass element solid compound control C3D8R was used to model the concrete. The bar reinforcement properties used in the model are based on BS EN 1992-1-1:2004. The longitudinal and transverse reinforcements were modelled using the two-node linear three-dimensional truss element T3D2 in the Abaqus level library. A mesh size of 60 mm was adopted for the truss elements in this study. The same mesh size was adopted for meshing the solid brick elements (C3D8R) and the truss elements (T3D2). The full-size column was modelled with 8235 elements of type C3D8R. For the primary reinforcement, 348 linear line elements (T3D2) were used; 198 linear line elements (T3D2) were used for the transverse reinforcement. To simulate the experimental load-displacement behavior, two steel loading plates of very high stiffness were modeled, one at the top and the other at the bottom surface of the column, to apply boundary conditions and uniform eccentric compression loading. The boundary condition used in the full model of the axially loaded column was simulated as a simple pin support. With this boundary condition, displacement in the X, Y, and Z directions was prevented. The bottom of the column was fixed in all directions using the boundary condition. However, the top of the column was kept free in the direction of the axial applied loading. In addition to using CFRP alone for repairing the fire-damaged columns, a composite technique combining steel wire mesh (SWM) and CFRP jackets was also modeled. The predictions from the obtained model were quite accurate and closely matched the experimental work.

In addition to FEM, Iqrar [81] prepared three regression models and provided the equations to predict the residual strength of heat-damaged circular columns, the repaired strength of heat-damaged circular columns confined with CFRP, and the repaired strength of heat-damaged circular columns confined with CFRP and SWM. Equations 1, 2 and 3 present the regression models suggested by Iqrar [81]. Eq. 1 calculates the residual axial capacity of RC circular columns exposed to fire, Eq. 2 calculates the axial load capacity of fire-damaged columns confined with CFRP composites, and Eq. 3 calculates the axial load capacity of fire-damaged columns retrofitted with SWM and CFRP composites together.

$$P_{n\theta} = -0.6793\theta + 1.042\,[0.85\,f'_c\,(A_g - A_{st}) + F_y\,A_{st}] \quad \ldots 1$$

$$P_{ntf\theta} = 147.69t_f - 0.77\theta + 1.426\,[0.85\,f'_c\,(A_g - A_{st}) + F_y\,A_{st}] \quad \ldots 2$$

$$P_{nec\theta} = 47.69t_f - 0.89\theta + 1.426\,[0.85\,f'_c\,(A_g - A_{st}) + F_y\,A_{st}] \quad \ldots 3$$

$$100℃ \leq \theta \leq 900℃$$

Whereas:

$P_{n\theta}$ = Residual axial load capacity of fire damaged unconfined circular columns (kN)

$P_{ntf\theta}$ = Axial load capacity of fire damaged CFRP-confined circular columns (kN)

$P_{nec\theta}$ = Axial load capacity of the fire damaged columns repaired with epoxy injected SWM and CFRP (kN)

t_f = Thickness of the repair layer (i.e. CFRP or CFRP+SWM) (mm).

θ = Temperature (°C).

Jia Xu [82] utilized the commercial software ABAQUS to construct two three-dimensional finite element (FE) models for heat transfer analysis and the estimation of the ultimate axial strength of fire-damaged and CFRP-repaired columns. The experimental data were utilized to validate the FE models.

The model for thermal analysis was developed to simulate the temperature distribution inside the columns when exposed to the ISO 834 standard fire. The geometry of the columns was the same as that of the test columns, with a diameter of 300 mm and a length of 1000 mm. The temperature was assumed to be uniform in the longitudinal direction, and spalling was not taken into account. The thermal properties of the concrete and reinforcing steel were included in the proposed FE model for thermal analysis to simulate the history of the temperature distribution inside the columns through heating and cooling cycles. The thermal properties (Thermal conductivity and latent heat) of concrete were defined according to Eurocode 2-1-2 (2004) and fib 46 (2008). The thermal properties (thermal conductivity and specific heat) of reinforcing steel at elevated temperatures are adapted from Eurocode 3 (2005). The element type chosen for the concrete and reinforcing steel was the 3D eight-node linear element (DC3D8) for the heat transfer simulation. The finite element method (FEM) could generate the temperature field inside the columns fairly well for both the heating and cooling stages.

The geometry of the second model for predicting post-fire strength was the same as that of the first model; meanwhile, the diameter of the CFRP retrofitted columns increased to 370 mm. Two rigid plates with diameters of 300 mm were placed at both ends of the columns for load transfer. The concrete damage plasticity (CDP) model was adopted for concrete modelling. A compressive strength reduction factor of concrete was used to estimate the residual compressive strength of fire-damaged concrete. The 3-D stress solid element with eight nodes with hourglass control (C3D8R) was selected to simulate the axial capacity of RC columns. Steel reinforcements were assumed to have an elastic-perfect plastic stress-strain relationship. The residual yield strength ratio and the residual elastic modulus ratio were implemented in this model for steel reinforcements to account for the strength degradation caused by fire exposure. The linear 3D truss element with two nodes (T3D2) was used to model steel reinforcements. CFRP composites were modeled using a 2D shell element (S4R) with four nodes, and the material properties were adapted from data provided by the manufacturer. The finite element models with three mesh sizes – 20 mm, 25 mm, and 30 mm were developed to investigate the effect of element sizes.

Subsequently, a parametric investigation was conducted using the tested models to examine the additional impacts of fire duration up to 240 minutes and the number of CFRP layers up to three. The proposed FE model accurately predicted the axial capacity of fire-damaged columns repaired with CFRP. Utilizing the validated finite element models for structural behavior analysis, the efficacy of various CFRP layers was gauged.

3.3 Mode of Failures for square/rectangular columns:

All authors [79-83] observed the typical failure modes for unheated, heated, and CFRP-repaired circular columns. Unheated columns exhibited brittle failure, characterized by concrete crushing at the top of the column due to stress concentration, which then propagated downwards. Meanwhile, heated columns showed a more ductile behavior comparatively. On the other hand, CFRP-repaired columns failed due to the tensile rupture of the CFRP, typically resulting in a rupture noise.

IV. EXPERIMENTAL STUDIES ON SQUARE AND RECTANGULAR COLUMNS:

There are three studies in the literature conducted by Yaqub M. [84], Nima M. [85], and Hanan Al-Nimry [86] to investigate the effects of CFRP repair on fire-damaged rectangular and square concrete columns. All these studies considered unidirectional wrapping of CFRP sheets. From existing literature studies, it can be deduced that available experimentation is mainly conducted in a temperature range of 500-600 °C, and the duration of the fire is also between 180 and 240 minutes. Other than that, regarding the height of the column, only specimens with heights of 450 mm, 1000 mm, and 1500 mm are tested. The gaps are presented in detail in the later sections of the study. Details about the experimental programs and the corresponding results are summarized in Section 4.1.

4.1 Experimental programs:

Different parameters of the studies conducted to investigate the effect of CFRP composites as a repair technique for square/rectangular columns are presented in Table 4. Yaqub M, [84] tested nine columns, with three of them repaired with CFRP confinement, after undergoing heat damage. All the tested columns had a cross-sectional area of 200 x 200 mm, and a height of 1000 mm. Columns had an initial compressive strength of 53 MPa. Seven specimens were heated at 500 °C for 210 minutes. Two of the heat-damaged columns were repaired using the Webertec system, which had a CFRP thickness of 0.117 mm and a tensile E modulus of 240 GPa. One column was repaired with the Fyfe system, which had a CFRP thickness of 0.37 mm and an E modulus of 230 GPa. Moreover, the effect of GFRP confinement was also studied during the investigation.

Nima M. [85] investigated the behavior of CFRP-repaired short rectangular reinforced concrete columns damaged due to elevated temperatures. Thirty-three columns having a section of 150 mm × 200 mm and a height of 450 mm were constructed and studied in this investigation. Out of these 33 columns, six were heated at 500 °C for 240 minutes, and 4 of them were repaired with one layer of unidirectional CFRP sheets, while the other three were repaired with two layers of CFRP sheets. Similarly, six columns were heated at 600 °C for 240 minutes, and three of them were repaired again with one layer of CFRP, while the other three were repaired with two layers of CFRP. The effect of both fire temperature and the number of CFRP layers was studied in this way. Moreover, the impact of GFRP confinement was also examined during the investigation. The impact of CFRP confinement is also investigated by Hanan Al-Nimry [86].

During the investigation, 13 specimens were prepared, and 9 of them were damaged with fire and repaired with one or two layers of CFRP wraps. All columns were 170 x 100 mm, with a height of 1500 mm. Eleven columns out of thirteen were exposed to 500 °C for 180 minutes, out of which two were taken as control samples for comparative analysis, and the rest were repaired with CFRP to study its effects. The effect of partial wraps was also investigated. Moreover, externally bonded CFRP was used to retrofit two specimens at a 1.4% and 2.1% ratio.

TABLE IV. PARAMETERS CONSIDERED IN EXISTING EXPERIMENTAL STUDIES ON FIRE-DAMAGED SQUARE AND RECTANGULAR COLUMNS.

Parameters	Units	Yaqub M. [84]	Nima M. [85]	Al-Nimry [86]
Length of Columns	mm	200	200	100
Width of Columns	mm	200	150	170
Corner Radius	mm	25	20	10
Specimen Height	mm	1000	450	1500
Concrete's initial compressive strength	MPa	53	27	25
Fire Temperature	°C	500	500 & 600	500

Fire Exposure Time	Min	210	240	180
CFRP Layers	Count	1	1, 2	1, 2
Thickness of CFRP	mm	0.117, 0.37	0.117	0.131
Tensile E-modulus of CFRP	GPa	240, 230	230	238

4.2 Results and findings:

As per the investigation Conducted by Yaqub M. [84,84], after heating the column with 500 °C for 210 minutes the axial load capacity of the column was dropped by 43.5% and when the columns were repaired with Webertec system of CFRP, an increment of 17.2 % in the damaged strength of column was observed. Meanwhile, when the damaged column was repaired using the Fyfe system of CFRP, the axial strength increased by 29% of the total undamaged strength. If the stiffness of the fire-damaged and CFRP-repaired columns is concerned, there was no remarkable improvement after repairing the fire-damaged columns with CFRP.

Nima M. [85] performed the study at two temperatures, 500 and 600 °C. When the columns were exposed to 500 °C for 240 minutes, the axial capacity of the columns dropped by almost 57%. When they were exposed to 500 °C for 240 minutes, a loss of around 66% was observed in the axial load capacity of short columns. According to the author's observation, an increase of 14% and 29% in total axial strength was observed in the axial capacity of 500 °C heated columns when they were repaired with 1 and 2 layers of unidirectional CFRP, respectively. When the columns heated to 600 °C were repaired with 1 and 2 layers of unidirectional CFRP, increments of 12% and 19% of the total strength were noted, respectively. At 500°C, the regain was marginal, especially with two layers of CFRP, and the resultant total repaired strength reached 87% of the undamaged strength. Hanan Al-Nimry [86] exposed the columns to 500 °C for 180 minutes, after which the axial capacity of the columns was reduced by 54.8%. The damaged columns were then repaired with full wrapping of CFRP, Partial wrapping of CFRP, and full and partial wrapping with external FRP reinforcement of 1.4% and 2.1%, respectively. Partial wrapping of CFRP failed to restore the axial strength, while complete CFRP wrapping with two layers of CFRP restored 22.7% of the total strength. Moreover, full wrapping of CFRP with 1.4% external CFRP plate reinforcement was the most significant, restoring 37.4% of the original axial strength. The results of residual and regained axial strength of fire-damaged and CFRP-repaired square/rectangular columns are summarized in Table 5.

TABLE V. COMPARISON OF REPAIRED AXIAL STRENGTH OF FIRE-DAMAGED SQUARE/RECTANGULAR COLUMNS FROM THE LITERATURE

Study Name	Temperature (°C)	Control specimen Strength (kN)	Residual strength (kN)	Decrement (%)	CFRP layers (Count)	Repaired strength (kN)	Increment (%)
Yaqub M. [84]	500	1965 (with CFRP thickness = 0.37mm)	1110	-43.5	1	1448	17.2
						1680	29.0
Nima M. [85]	500	720	300	-58.3	1	400	13.9
					2	510	29.2
	600		240	-66.7	1	325	11.8
					2	370	18.1
Hanan Al-Nimry [86]	500	465.3	210.5	-54.8	1	250.4	8.6
					2	316.1	22.7
					1P	223	2.7
					2P	175.7	-7.5
					1F+1.4 % R	384.7	37.4
					1P+1.4 % R	333.4	26.4
					1P+2.1 % R	364.9	33.2

Fig. 5 presents the regained capacity of fire-damaged square/rectangular columns when repaired with CFRP columns. The temperature of the fire was 500 °C for all the observed values. Yaqub M. [84] reported the highest restored axial capacity, as the initial compressive strength of the concrete was 53 MPa. Meanwhile, Nimaa M. [85] and Hanan [86] used 27 and 25 MPa concrete, respectively, and reported a lower restored axial capacity.

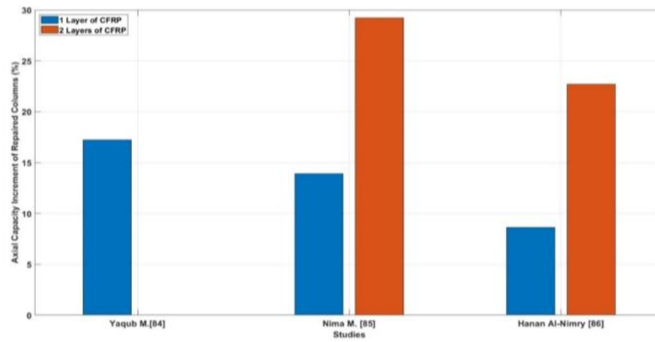

Fig. 5. Regained axial capacity of CFRP repaired square columns among different experimental programs

Meanwhile, about the stiffness of fire damaged square/rectangular columns, Yaqub M. [84] noted that after exposure to a 500 °C fire for 210 minutes, the stiffness was reduced by 83.1%, which represents a significant loss. Even after repairing the columns with the Webertec system of CFRP, the stiffness increased by only 7%. And while repairing with the Fyfe system of CFRP, the stiffness was even 2.3% less than the damaged columns. Hence as concluded by Yaqub M. [84], using one layer of CFRP confinement as a repair to the fire damaged columns has significant impact in regaining the lost axial strength of column but unfortunately complete strength of columns couldn’t be regained.

Moreover, there’s no noticeable impact of CFRP on the lost stiffness of the fire damaged columns. On the other hand, Nima M. [85] also concluded that after exposing the specimens to 500 °C for 240 minutes, overall stiffness of the columns was reduced by almost 70% of its original capacity and when the columns were exposed to 600 °C for 240 minutes 78% of its original capacity of the stiffness was reduced. Even after repairing the 500 °C-damaged columns with two layers of CFRP sheets, only 5% stiffness was regained, and no effect of CFRP was observed on the stiffness of the columns damaged at 600 °C. Hence, as concluded by the author, confinement restored the axial strength up to some extent when the columns were exposed to 500 °C.

Still, no significant improvement was observed while repairing the column damaged at 600 °C. Moreover, Yaqub M. [84] observed no noticeable difference in the stiffness of the damaged column after the confinement. As in other studies on rectangular columns, regaining stiffness was the problem; however, Hanan Al-Nimry [86], addressed this problem by applying external CFRP plates.

After exposing the columns to heat, the stiffness of the columns was lost by 63.4%. All techniques like applying wrapping of CFRP with 1 and 2 number of layers, Partial wrapping of CFRP with 1 and 2 number of layers and full and partial wrapping 1 CFRP layer with external FRP reinforcement of 1.4% failed to restore the lost stiffness by a significant margin but when partial wraps of 1 layer of CFRP were applied with externally bonded CFRP plates with increased reinforcement ration of 2.1%, a significant increment of 40.8% of the original stiffness was observed.

TABLE VI. COMPARISON OF REPAIRED STIFFNESS OF FIRE DAMAGED SQUARE/RECTANGULAR COLUMNS FROM LITERATURE

Study Name	Temperature (°C)	Control specimen Stiffness(kN/mm)	Residual stiffness (kN/mm)	Decrement (%)	CFRP layers (Count)	Repaired strength (kN/mm)	Increment (%)
Yaqub M. [84]	500	3854	653	-83.1	1	921	7.0
		(with CFRP thickness = 0.37mm)				564	-2.3
Nima M. [85]	500	2650	799	-69.8	1	753	-1.7
					2	931	5.0
	600		589	-77.8	1	492	-3.7
					2	497	-3.5
Hanan Al-Nimry [86]	500	299.6	109.6	-63.4	1	121.3	3.9
					2	117.9	2.8
					1P	150	13.5
					2P	124.3	4.9
					1F+1.4 % R	182.5	24.3
					1P+1.4 % R	184.1	24.9
					1P+2.1 % R	231.9	40.8

The results summary of the experimental investigation conducted in the literature about residual and regained stiffness is presented in Table 6.

4.3 Numerical and analytical Modeling:

Only Nima M. [85] prepared the FEM analytical model using ABAQUS general-purpose finite element software for fire-damaged and CFRP repaired square/rectangular columns. The concrete material was modelled using the 8-noded C3D8 elements. After a mesh sensitivity analysis, the size of concrete cubic elements was taken as 25mm. The T3D2 truss element was used for steel reinforcement and the S4 element was used to model the FRP sheets. The model performed well, with a prediction average error of approximately 20% in the case of CFRP confinement. However, the prepared model was unable to predict the initial nonlinearity in the response curve.

4.4 Mode of Failures for square/rectangular columns:

All researchers [84-86] observed the same mode of failure for unheated, heated, and repaired columns. Unheated columns exhibited brittle failure due to the crushing of concrete, whereas heated columns showed ductile failure. On the other hand, CFRP-repaired columns failed due to rupture of CFRP ropes or jackets at the corners due to the knife action of square columns.

V. PROBLEM ASSOCIATED WITH CFRP REPAIRS AND THEIR CORRESPONDING SOLUTION:

As most of the authors concluded that CFRP can fully restore the axial capacity of damaged circular columns and even mostly the repaired strength is more than the original strength and in rectangular columns too CFRP as a repairing technique restores a significant amount of axial load carrying capacity of the columns but almost all the authors concluded that stiffness of the columns is not improved while repairing the fire damaged columns alone with CFRP. Hence, to counter this problem, several researchers have suggested many hybrid or composite repairing techniques, as explained below.

By affixing externally bonded CFRP plates (measuring 50 mm in width and 1.2 mm in thickness) to the four sides of the column specimens in a direction parallel to the longitudinal column axis, Hanan Al-Nimry [85] successfully restored heat-damaged square columns. Subsequently, a single layer of CFRP sheet was utilized to cover the completed columns. The ratio between the total cross-sectional area of CFRP plates and the gross cross-sectional area of the column was 1.4% and 2.1%, respectively. The overall cross-section of the repaired column is presented in Fig. 6. Moreover, in addition to the plates, the specimens were fully and partially wrapped with CFRP to study the combination. From the results, it was found that using CFRP plates with a reinforcement ratio of 2.1% and partial wrapping of CFRP sheets significantly increased the stiffness regain by up to 40.8%.

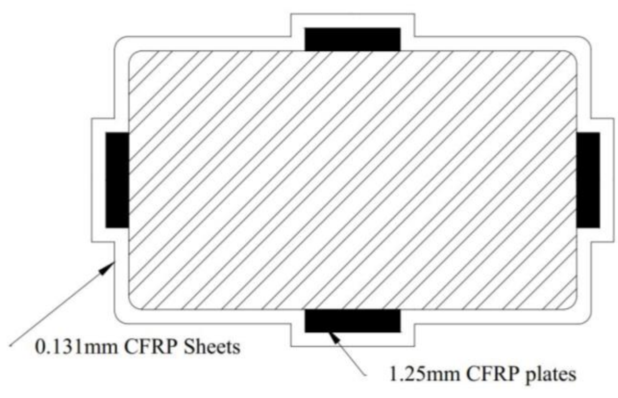

Fig. 6. Cross-section of repaired rectangular column by Hanan Al-Nimry [85]

Iqrar [81], after repairing the fire-damaged columns with CFRP, found that CFRP alone can restore the axial capacity of the columns; however, the lost stiffness was not restored, which is highly undesirable. To increase both the axial load capacity and stiffness, the author employed steel wire mesh (SWM) filled with cement-sand mortar and enveloped in CFRP sheets. The implementation of this repair technique yielded a significant enhancement in axial load capacity (100%) and controlled deformation, thereby ensuring the member has adequate stiffness for safely transferring load [81].

To sort out the stiffness issue, Aref A. [87] performed an experimental study to determine the efficacy of near-surface mounted (NSM) steel bars and CFRP sheets in repairing circular and square RC columns that had been weakened by exposure to extremely high temperatures, the repaired cross sections of columns are presented in Fig. 7a and Fig. 7b.Columns were exposed to 600 °C for three hours and then repaired with CFRP and NSM. Exposure to elevated temperatures decreased the load-bearing capacity of circular columns by 38% and square columns by 29%, as reported in the test results. Both restoration strategies successfully restored and exceeded the initial load-bearing capacity of heat-damaged RC columns by around 16%. In comparison to the use of CFRP strips alone, the combination of CFRP sheets and NSM steel rods restored the initial stiffness of the post-heated columns more effectively. Concurrently, the vertical and horizontal strains in the concrete and the axial and lateral deformations of the columns decreased substantially.

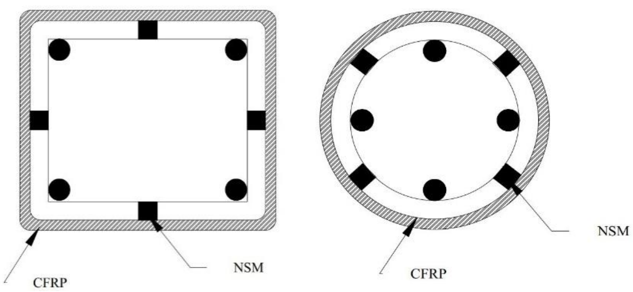

Fig. 7. Cross-sections of repaired columns by Aref A. [87] (a). Circular cross-section (b). Square Cross-section

VI. Research Gaps and Recommendations for Future Researchers/Practitioners

6.1 Research gap for fire-damaged circular columns:

The literature contains very detailed investigations of fire-damaged circular columns repaired with CFRP. As presented in Fig. 8, the researchers have covered a wide range of fire temperatures varying from 300 to 1000 °C.

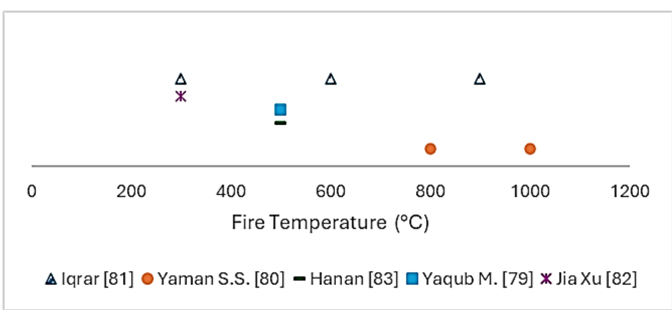

Fig. 8. Fire temperature range in existing experimental investigations for circular columns.

Hence, several studies are available to examine how different fire temperatures affect the strength regaining process after repair with CFRP sheets. As the CFRP repair technique is sufficient to recover a significant amount of axial strength even at fire temperatures of around 600 °C, there is no need to investigate the behavior at temperatures lower than 300 °C. Still, future investigations are needed to determine how lower temperatures, such as those below 300 °C, can affect the stiffness of the repaired columns.

In addition to temperature, there is significant research available in the literature concerning the initial compressive strength of concrete. As shown in Fig. 9, almost every type of concrete, ranging from 32 to 90 MPa, has been considered by different researchers. Jia Xu [82] also studied the impact of fire on high-performance concrete and how CFRP confinement affects the repaired strength.

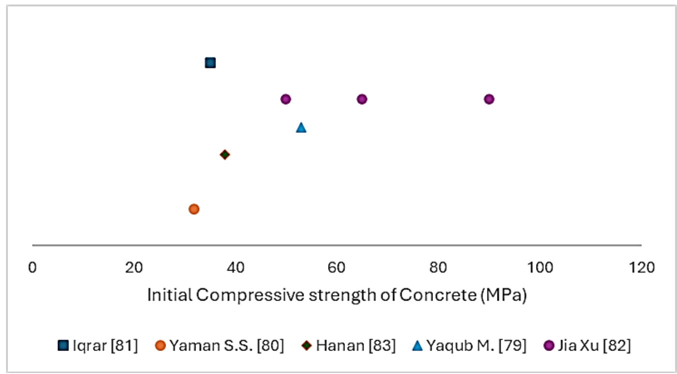

Fig. 9. Variation of initial compressive strength of concrete in the current literature for circular columns.

Different researchers covered a wide range of fire durations. As illustrated in Fig. 10, Iqrar Hussain [81] performed experimentation with fire durations as low as 1 hour (60 Minutes), while Yaqub M. [79] kept the fire duration as high as 3.5 hours (210 minutes). Still, the literature is quite limited regarding experimental programs that extend to fire durations of more than 3.5 hours.

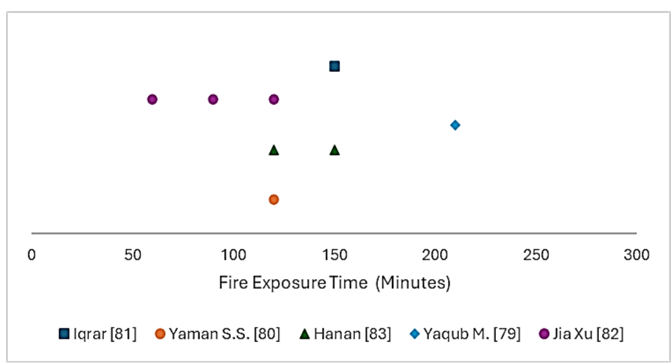

Fig. 10. Fire exposure time in the existing investigations for circular columns.

Numerous finite element models are present in the literature to predict the effect of CFRP confinement on heat-damaged circular columns. Moreover, a regression analysis by Iqrar [81] is also available, providing an equation to predict the repaired strength of fire-damaged columns using CFRP. As technology advances, machine learning and artificial intelligence are increasingly being utilized; however, there are no machine learning models available in the literature to predict the axial strength of fire-damaged circular columns repaired with CFRP. Therefore, future researchers should be encouraged to follow this course.

6.2 Research gap for fire-damaged rectangular/Square Columns:

In comparison to circular columns, the research available in the literature about rectangular columns is limited, as CFRP is most effective in circular columns. Since most buildings nowadays have rectangular or square columns, additional research is recommended. Fig. 11 shows that the temperature range of the available experimentation programs is very low. Only three investigations are available, varying around 500 °C. Therefore, future researchers should investigate the effects of CFRP on temperatures below 500 °C.

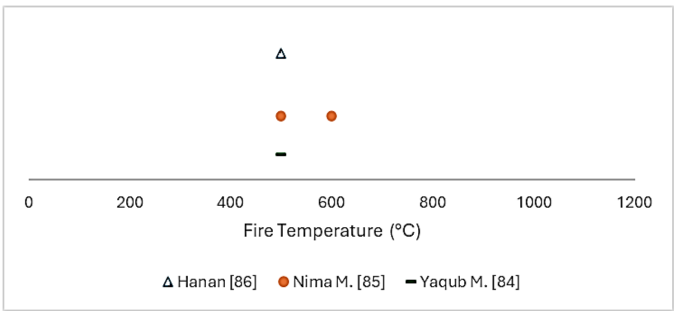

Fig. 11. Fire temperature range in the current literature for square/rectangular columns.

The same is true for the initial compressive strength of concrete, as shown in Fig. 12. In the case of circular columns, the research was very detailed, considering different types of concrete, even up to 90 MPa. However, in the case of rectangular/square columns, the variation of initial compressive strength of concrete is minimal. Hence, it is suggested that the effects of fire and CFRP confinement on high-performance concrete be examined, while maintaining the square cross-sections of the specimens.

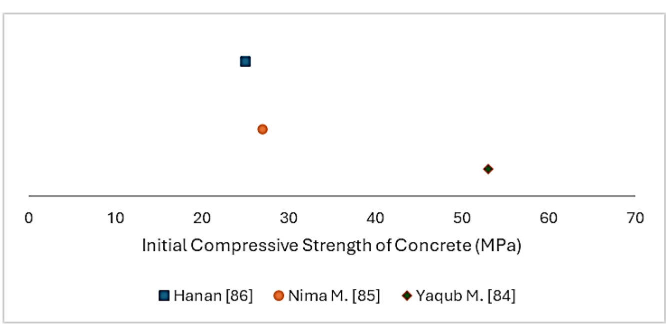

Fig. 12. Initial compressive strength of concrete in the existing studies for square/rectangular columns.

Regarding the fire duration for rectangular/square columns, again, the range of experiments is very minimal. The available literature only shows the effects of fire extending from 180 to 240 minutes, as outlined in Fig. 13. It is highly encouraged to expand the research and investigate how fire with a duration of less than 3 hours (180 minutes) impacts the effect of CFRP confinement.

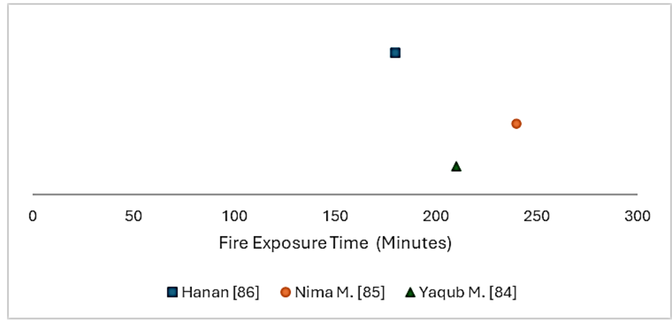

Fig. 13. Variation of fire exposure time in the current literature for square/rectangular columns.

Moreover, it's proven that the corner radius of square columns plays a vital role in affecting the impact of CFRP confinement on square columns [15]. In the case of fire damage repair, scientists have only studied columns with a radius of up to 25mm. Therefore, it's also recommended to investigate the impact of different corner radii on the confinement of square columns. In addition to experimental programs, the literature is also limited on available models to predict the effects of CFRP on rectangular/square columns. Only Nima M. [85] performed a Finite element (FE) analysis for Short rectangular columns; hence, future researchers can focus on preparing FE models, performing regression analysis, and developing neural network analytical models to ease the design process for the rehabilitation of structures after a fire activity.

6.3 General recommendations for researchers:

As recommended by Aref A. [87], the hybrid technique of using CFRP and NSM is only exposed to a temperature of 600 °C. To identify the conditions under which strengthened RC columns can be utilized safely and to assure a greater comprehension of the fire response of such columns, additional testing across a broader temperature range would be necessary. Moreover, other hybrid techniques suggested by Iqrar [81] and Hanan [86] should also be explored at a different range of temperatures and fire duration.

On the other hand, Ala Taleb [88] also used a combination of CFRP ropes and CFRP sheets to repair heat-damaged columns. From the results, it was concluded that columns heated up to 600 °C and rehabilitated using NSM and one or two layers of CFRP rope can recover their strength to about 88% and 64%, respectively. These positive results indicate that this composite technique should also be further investigated by using different spacings between CFRP ropes and studying the effect on the column's stiffness.

6.4 Recommendation for designers and practitioners:

The results of experimental investigations are scattered in the literature; therefore, it's difficult for practitioners to plan to use CFRP composites effectively under different types of damage due to fire exposure. This section suggests the most optimal measures for various scenarios and conditions of damage.

1. For repairing circular columns that were exposed to fire for more than 3 hours, two layers of CFRP with a thickness of 0.227 mm should be used. [80] This would fully recover the lost axial strength. Meanwhile, if the duration of fire is less than 2 hours, one layer of CFRP would suffice and restore the lost axial strength. [80]
2. On the other hand, as Section 3.2 illustrates, fire exposure would decrease the stiffness of circular columns by 60–70%. [82] Therefore, it's also essential to recover the lost stiffness if the exposure to fire is around 2 hours. To fully recover the lost stiffness and axial strength of circular columns, the hybrid technique proposed by Aref A. [87] to use near-surface-mounted (NSM) steel bars and CFRP sheets should be considered, as described in Section 5.
3. For rectangular columns, the behavior of CFRP is very different from that of circular columns. It's because the circular cross sections contain entirely effective confined concrete regions, whereas square cross sections include some inefficiently confined concrete areas and stress amplification at their corners. Moreover, the knife action of the sharp edges of rectangular columns would also reduce the efficacy of CFRP Sheets. Therefore, only 17.2-29.2% of the lost axial capacity was restored. Practitioners are recommended to use the hybrid technique proposed by Hanan Al-Nimry [85] to combine CFRP plates with CFRP sheets. This would not only restore the lost axial capacity but would also restore 40.8% of the lost stiffness.

VII. CONCLUSIONS

After a detailed state-of-the-art review of repairing fire-damaged circular and square columns with CFRP composites, the following conclusions can be drawn.

1. Using CFRP sheets as a repair technique is substantially effective in restoring the axial capacity of fire-damaged circular columns. From experimental investigations present in the literature, it is evident that when fire-damaged circular columns are repaired with CFRP, 33.1–169.2% of the lost axial load capacity was restored.
2. For rectangular columns, due to their sharp edges and the amplification of stresses at the corners, CFRP sheets were not as effective and were only able to restore 17.2–29.2% of the lost axial strength.
3. All experimental investigations agreed that solo CFRP sheet confinement is unable to recover the lost stiffness of the columns. This is because after fire exposure, the concrete exhibits increased porosity; hence, the post-heated columns undergo a substantial reduction in stiffness, which is challenging to recover solely by confining with CFRP jackets. 0–29.2% of the lost stiffness was restored in rectangular columns, while the number is 0–11.1% in circular columns.
4. The lost stiffness of the fire-damaged columns can be regained or repaired by using several hybrid or composite techniques, including the use of NSM and SWM, in addition to CFRP sheets, as summarized in the article.
5. Gaps in the literature that require attention from future researchers are highlighted; it is highly encouraged that special attention should be given to rectangular columns. It's because nowadays, most constructed columns are rectangular in cross-section, so more research in the suggested areas should be carried out to utilize this valuable material effectively for repair.

REFERENCES:

[1] Z. Tao, M. Ghannam, T.-Y. Song, and L.-H. Han, "Experimental and numerical investigation of concrete-filled stainless steel columns exposed to fire," J. Constr. Steel Res., vol. 118, pp. 120–134, 2016, doi: https://doi.org/10.1016/j.jcsr.2015.11.003.

[2] A. T. Obaidat, "Repairing of Circular Reinforced Concrete Columns Damaged by Heat Using Carbon Fiber Reinforced Polymers (CFRP) (Rope) Technique," IOP Conf. Ser. Earth Environ. Sci., vol. 498, no. 1, 2020, doi: 10.1088/1755-1315/498/1/012042.

[3] X. L. Zhao, "Recent Developments in FRP Strengthening of Metallic Structures," in First Middle East Conference on Smart Monitoring, Assesment and Rehabilitation of Civil Structures, Dubai, UAE, 2011, pp. 2–9.

[4] K. V. K. R., C. Fu-Ping, W. Tien-Chih, and S. M. A., "Effect of Strength and Fiber Reinforcement on Fire Resistance of High-Strength Concrete Columns," J. Struct. Eng., vol. 129, no. 2, pp. 253–259, Feb. 2003, doi: 10.1061/(ASCE)0733-9445(2003)129:2(253).

[5] D. Cree, E. U. Chowdhury, M. F. Green, L. A. Bisby, and N. Bénichou, "Performance in fire of FRP-strengthened and insulated reinforced concrete columns," Fire Saf. J., vol. 54, pp. 86–95, 2012, doi: https://doi.org/10.1016/j.firesaf.2012.08.006.

[6] E. E. Etman, "Rehabilitation and Strengthening of Fire Damaged Reinforced Concrete Beams Using CFRP Plates," no. April 2002, 2002, [Online]. Available: https://www.researchgate.net/publication/300098953

[7] Z. Tao, Z. Bin Wang, L. H. Han, and B. Uy, "Fire performance of concrete-filled steel tubular columns strengthened by CFRP," Steel Compos. Struct., vol. 11, no. 4, pp. 307–324, 2011, doi: 10.12989/scs.2011.11.4.307.

[8] S.-W. Yoo and J. F. Choo, "Behavior of CFRP-reinforced concrete columns at elevated temperatures," Constr. Build. Mater., vol. 358, p. 129425, 2022, doi: https://doi.org/10.1016/j.conbuildmat.2022.129425.

[9] E. Ahmed and A. Atorod, "Behavior of Circular Concrete-Filled Steel Tube Columns," in Composite Construction in Steel and Concrete IV, in Proceedings. 2012, pp. 573–583. doi: doi:10.1061/40616(281)50.

[10] L. H. Han, Y. Q. Zheng, and J. G. Teng, "Fire resistance of RC and FRP-confined RC columns," Mag. Concr. Res., vol. 58, no. 8, pp. 533–546, Oct. 2006, doi: 10.1680/macr.2006.58.8.533.

[11] Z. Cui and Z. Yang, "Study on the Fire Resistance of Reinforced Concrete Structures Strengthened with Carbon Fiber Fabric," vol. 5, no. 8, pp. 1–5, 2025.

[12] A. Salameh, R. Hawileh, M. Assad, and J. Abdallah, "Bond Slip Behavior for CFRP-to-Concrete Joints at Room Temperature," Key Eng. Mater., vol. 1004, no. December, pp. 3–12, 2024, doi: 10.4028/p-CiE4bW.

[13] A. U. Rehman, Z. A. Siddiqi, M. Yasin, H. M. S. Aslam, S. Noshin, and H. M. U. Aslam, "Experimental study on the behavior of damaged CFRP and steel rebars RC columns retrofitted with externally bonded composite material," Adv. Compos. Mater., vol. 34, no. 1, pp. 93–139, 2025, doi: 10.1080/09243046.2024.2358262.

[14] A. Akhtar, S. Saleem, M. Salman, M. Noman, M. Zulqarnain, and T. Jirawattanasomkul, "Performance of square masonry columns retrofitted with NSM steel and GFRP reinforcement under axial compression," Constr. Build. Mater., vol. 458, Aug. 2024, doi: 10.1016/j.conbuildmat.2024.139534.

[15] M. Yaqub and C. G. Bailey, "Cross sectional shape effects on the performance of post-heated reinforced concrete columns wrapped with FRP composites," Compos. Struct., vol. 93, no. 3, pp. 1103–1117, 2011, doi: https://doi.org/10.1016/j.compstruct.2010.09.012.

[16] J. Liu, P. Gao, X. Lin, X. Wang, X. Zhou, and Y. F. Chen, "Experimental assessment on the size effects of circular concrete-filled steel tubular columns under axial compression," Eng. Struct., vol. 275, p. 115247, 2023, doi: https://doi.org/10.1016/j.engstruct.2022.115247.

[17] B. Chen and Z. Yang, "Axial compressive behavior of CFRP reinforced concrete filled steel tube short columns with a circumferential gap," E3S Web Conf., vol. 490, 2024, doi: 10.1051/e3sconf/202449001013.

[18] Z. Tao and L.-H. Han, "Behaviour of fire-exposed concrete-filled steel tubular beam columns repaired with CFRP wraps," Thin-Walled Struct., vol. 45, no. 1, pp. 63–76, 2007, doi: https://doi.org/10.1016/j.tws.2006.11.004.

[19] C. Jing, L. Zhao, S. Chen, T. Wu, Z. Chen, and B. Liu, "Experimental and numerical simulation of reinforced concrete-filled GFRP pultruded tubular columns under axial compression," Constr. Build. Mater., vol. 462, 2025, doi: 10.1016/j.conbuildmat.2025.139914.

[20] G. Y. Y. K. Y. L. Lingying, "High-Temperature Mechanical Properties of Carbon Fiber Reinforced Polyimide Resin Composites MT300/KH420 (I)—Tensile and Interlaminar Shear Properties," J. Compos. Mater., vol. 06, 2016, doi: http://dx.doi.org/10.13801/j.cnki.fhclxb.20160122.001.

[21] C. Zhang, Y. Li, and J. Wu, "Mechanical Properties of Fiber-Reinforced Polymer (FRP) Composites at Elevated Temperatures," Buildings, vol. 13, no. 1, pp. 1–17, 2023, doi: 10.3390/buildings13010067.

[22] C. E. U., B. L. A., G. M. F., and K. V K., "Residual Behavior of Fire-Exposed Reinforced Concrete Beams Prestrengthened in Flexure with Fiber-Reinforced Polymer Sheets," J. Compos. Constr., vol. 12, no. 1, pp. 61–68, Feb. 2008, doi: 10.1061/(ASCE)1090-0268(2008)12:1(61).

[23] V. K. R. Kodur, L. A. Bisby, and M. F. Green, "Experimental evaluation of the fire behaviour of insulated fibre-reinforced-polymer-strengthened reinforced concrete columns," Fire Saf. J., vol. 41, no. 7, pp. 547–557, 2006, doi: https://doi.org/10.1016/j.firesaf.2006.05.004.

[24] E. U. Chowdhury, L. A. Bisby, M. F. Green, and V. K. R. Kodur, "Investigation of insulated FRP-wrapped reinforced concrete columns in fire," Fire Saf. J., vol. 42, no. 6, pp. 452–460, 2007, doi: https://doi.org/10.1016/j.firesaf.2006.10.007.

[25] J. P. Firmo, J. R. Correia, and L. A. Bisby, "Fire behaviour of FRP-strengthened reinforced concrete structural elements: A state-of-the-art review," Compos. Part B Eng., vol. 80, pp. 198–216, 2015, doi: https://doi.org/10.1016/j.compositesb.2015.05.045.

[26] M. F. Green, L. A. Bisby, A. Z. Fam, and V. K. R. Kodur, "FRP confined concrete columns: Behaviour under extreme conditions," Cem. Concr. Compos., vol. 28, no. 10, pp. 928–937, 2006, doi: https://doi.org/10.1016/j.cemconcomp.2006.07.008.

[27] V. Kodur, L. A. Bisby, M. F. Green, and E. C. Chowdhury, "Fire endurance of insulated FRP-strengthened square concrete columns," Am. Concr. Institute, ACI Spec. Publ., vol. SP-230, no. January, pp. 1253–1267, 2005, doi: 10.14359/14892.

[28] R. T. Terms, "Fire endurance of FRP-strengthened reinforced concrete columns," NRC Publ. Rec., pp. 1–15, 1963.

[29] E. U. Chowdhury, L. A. Bisby, M. F. Green, N. Bénichou, and V. K. R. Kodur, "Fire behaviour of FRP wrapped squarereinforced concrete columns," Third Int. Conf. Durab. F. Appl. Fibre Reinf. Polym. Compos. Constr., no. June 2014, pp. 83–90.

[30] S. G. Wesnousky, "Earthquakes, quaternary faults, and seismic hazard in California," J. Geophys. Res. Solid Earth, vol. 91, no. B12, pp. 12587–12631, Nov. 1986, doi: https://doi.org/10.1029/JB091iB12p12587.

[31] D. Vamvatsikos et al., "Structural vulnerability assessment under natural hazards: A review," COST ACTION C26 Urban Habitat Constr. under Catastrophic Events - Proc. Final Conf., no. April 2018, pp. 711–723, 2010.

[32] V. Janssens, D. W. O'Dwyer, and M. K. Chryssanthopoulos, "Assessing the Consequences of Building Failures," Struct. Eng. Int., vol. 22, no. 1, pp. 99–104, Feb. 2012, doi: 10.2749/101686612X13216060213473.

[33] Malalgoda, C., Amaratunga, D. and Haigh, R., "Challenges in creating a disaster resilient built environment." Procedia Economics and Finance, 18, pp.736-744, 2014.

[34] Z. Wang, D. Wang, S. T. Smith, and D. Lu, "CFRP-Confined Square RC Columns. I: Experimental Investigation," J. Compos. Constr., vol. 16, no. 2, pp. 150–160, 2012, doi: 10.1061/(asce)cc.1943-5614.0000245.

[35] R. Kotynia, H. Abdel Baky, K. W. Neale, and U. A. Ebead, "Flexural Strengthening of RC Beams with Externally Bonded CFRP Systems: Test Results and 3D Nonlinear FE Analysis," J. Compos. Constr., vol. 12, no. 2, pp. 190–201, 2008, doi: 10.1061/(asce)1090-0268(2008)12:2(190).

[36] A. H. Al-Abdwais and A. K. Al-Tamimi, "Evaluation of Bonding Properties Between CFRP Laminate and Concrete Using Externally Bonded Reinforcement on Transverse Grooves (EBROTG) Method," J. Compos. Sci., vol. 8, no. 12, 2024, doi: 10.3390/jcs8120488.

[37] L. Wang, D. Cheng, and X. Wang, "Experimental Research on Mechanical Properties of Carbon Fiber-Reinforced Reactive Powder Concrete after Exposure to Cryogenic Temperatures.," Mater. (Basel, Switzerland), vol. 15, no. 12, Jun. 2022, doi: 10.3390/ma15124240.

[38] C. Wu, Y. Su, P. Zhang, H. Zhu, D. Gao, and S. A. Sheikh, "Experimental Study of GFRP Reinforced Concrete Beams With U-Shaped CFRP Grid-Reinforced ECC Stay-in-Place Formwork," Front. Mater., vol. 9, no. March, pp. 1–15, 2022, doi: 10.3389/fmats.2022.872232.

[39] Qiang Wang, Hong Zhu, Bai Zhang, Yixuan Tong, Fei Teng, and Weiqiang Su, "Anchorage systems for reinforced concrete structures strengthened with fiber-reinforced polymer composites: State-of-the-art review," J. Reinf. Plast. Compos., vol. 39, no. 9–10, pp. 327–344, Mar. 2020, doi: 10.1177/0731684420905010.

[40] J. Zhou and L. Wang, "Repair of Fire-Damaged Reinforced Concrete Members with Axial Load: A Review," Sustain., vol. 11, no. 4, pp. 1–16, 2019, doi: 10.3390/su11040963.

[41] B. J. Bett, R. E. Klingner, and J. O. Jirsa, "LATERAL LOAD RESPONSE OF STRENGTHENED AND REPAIRED REINFORCED CONCRETE COLUMNS," Aci Struct. J., vol. 85, pp. 499–508, 1988, [Online]. Available: https://api.semanticscholar.org/CorpusID:137430349

[42] B. Hasan and S. Ullah, "a Review on Frp Repairing of Fire Damaged Rc Members," no. September, pp. 0–8, 2021.

[43] Marina Alkess Kerllos Ibrahim and Khaled Farouk Omar El-Kashif, "'Behavior of strengthened reinforced concrete columns after exposure to elevated temperature'," Adv. Struct. Eng., p. 13694332251334838, Apr. 2025, doi: 10.1177/13694332251334838.

[44] A. Gholampour, R. Hassanli, J. E. Mills, T. Vincent, and M. Kunieda, "Experimental investigation of the performance of concrete columns strengthened with fiber reinforced concrete jacket," Constr. Build. Mater., vol. 194, pp. 51–61, 2019, doi: https://doi.org/10.1016/j.conbuildmat.2018.10.236.

[45] L. Wang and R. K.-L. Su, "Repair of Fire-Exposed Preloaded Rectangular Concrete Columns by Postcompressed Steel Plates," J. Struct. Eng., vol. 140, no. 3, 2014, doi: 10.1061/(asce)st.1943-541x.0000884.

[46] L. Wang and R. Kai-Leung Su, "Theoretical and Experimental Study of Plate-Strengthened Concrete Columns under Eccentric Compression Loading," J. Struct. Eng., vol. 139, no. 3, pp. 350–359, 2013, doi: 10.1061/(asce)st.1943-541x.0000659.

[47] R. K. L. Su and L. Wang, "Axial strengthening of preloaded rectangular concrete columns by precambered steel plates," Eng. Struct., vol. 38, pp. 42–52, 2012, doi: https://doi.org/10.1016/j.engstruct.2012.01.003.

[48] L. Wang and R.K.L. Su, “Experimental Investigation of Preloaded RC Columns Strengthened with Precambered Steel Plates under Eccentric Compression Loading,” Adv. Struct. Eng., vol. 15, no. 8, pp. 1253–1264, Aug. 2012, doi: 10.1260/1369-4332.15.8.1253.

[49] R. K. L. Su and L. Wang, “Flexural and axial strengthening of preloaded concrete columns under large eccentric loads by flat and precambered steel plates,” Struct. Infrastruct. Eng., vol. 11, no. 8, pp. 1083–1101, Aug. 2015, doi: 10.1080/15732479.2014.936879.

[50] R. K. L. Wang. L,Su, “Strengthening of preloaded RC columns by post compressed plates-a review,” Struct. Eng. Mech., vol. 65, no. 4, pp. 477–490, 2018, doi: https://doi.org/10.12989/sem.2018.65.4.477.

[51] L. Wang, R. K. L. Su, B. Cheng, L. Z. Li, L. Wan, and Z. W. Shan, “Seismic behavior of preloaded rectangular RC columns strengthened with precambered steel plates under high axial load ratios,” Eng. Struct., vol. 152, pp. 683–697, 2017, doi: https://doi.org/10.1016/j.engstruct.2017.09.048.

[52] A. P. Michael, H. R. Hamilton, and M. H. Ansley, “Concrete confinement using carbon fiber reinforced polymer grid,” Am. Concr. Institute, ACI Spec. Publ., vol. SP-230, pp. 991–1009, 2005, doi: 10.14359/14877.

[53] T. Turgay, Z. Polat, H. O. Koksal, B. Doran, and C. Karakoç, “Compressive behavior of large-scale square reinforced concrete columns confined with carbon fiber reinforced polymer jackets,” Mater. Des., vol. 31, no. 1, pp. 357–364, 2010, doi: https://doi.org/10.1016/j.matdes.2009.06.008.

[54] B. Doran, H. O. Koksal, and T. Turgay, “Nonlinear finite element modeling of rectangular/square concrete columns confined with FRP,” Mater. Des., vol. 30, no. 8, pp. 3066–3075, 2009, doi: 10.1016/j.matdes.2008.12.007.

[55] M. N. S. Hadi, “Behaviour of eccentric loading of FRP confined fibre steel reinforced concrete columns,” Constr. Build. Mater., vol. 23, no. 2, pp. 1102–1108, 2009, doi: https://doi.org/10.1016/j.conbuildmat.2008.05.024.

[56] S. Rocca, N. Galati, and A. Nanni, “Interaction diagram methodology for design of FRP-confined reinforced concrete columns,” Constr. Build. Mater., vol. 23, no. 4, pp. 1508–1520, 2009, doi: https://doi.org/10.1016/j.conbuildmat.2008.06.010.

[57] G. Promis, E. Ferrier, and P. Hamelin, “Effect of external FRP retrofitting on reinforced concrete short columns for seismic strengthening,” Compos. Struct., vol. 88, no. 3, pp. 367–379, 2009, doi: https://doi.org/10.1016/j.compstruct.2008.04.019.

[58] T. El Maaddawy, “Strengthening of Eccentrically Loaded Reinforced Concrete Columns with Fiber-Reinforced Polymer Wrapping System: Experimental Investigation and Analytical Modeling,” J. Compos. Constr., vol. 13, no. 1, pp. 13–24, 2009, doi: 10.1061/(asce)1090-0268(2009)13:1(13).

[59] I. M. A., A. R. Z., and I. M. A., “Experimental and Parametric Study of Circular Short Columns Confined with CFRP Composites,” J. Compos. Constr., vol. 13, no. 2, pp. 135–147, Apr. 2009, doi: 10.1061/(ASCE)1090-0268(2009)13:2(135).

[60] Y.-C. Wang and K. Hsu, “Design of FRP-wrapped reinforced concrete columns for enhancing axial load carrying capacity,” Compos. Struct., vol. 82, no. 1, pp. 132–139, 2008, doi: https://doi.org/10.1016/j.compstruct.2007.04.002.

[61] R. Benzaid, N. E. Chikh, and H. Mesbah, “Behaviour of square concrete column confined with GFRP composite WARP,” J. Civ. Eng. Manag., vol. 14, no. 2, pp. 115–120, 2008, doi: 10.3846/1392-3730.2008.14.6.

[62] T. El Maaddawy, “Behavior of corrosion-damaged RC columns wrapped with FRP under combined flexural and axial loading,” Cem. Concr. Compos., vol. 30, no. 6, pp. 524–534, 2008, doi: https://doi.org/10.1016/j.cemconcomp.2008.01.006.

[63] M. M. Mia, “Retrofit of slender square reinforced concrete columns with glass fiber-reinforced polymer for seismic resistance,” Iran. J. Sci. Technol. Trans. B Eng., vol. 32, no. 5, pp. 437–450, doi: 10.22099/ijstc.2013.723.

[64] Y. A. Al-Salloum, “Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates,” Compos. Part B Eng., vol. 38, no. 5, pp. 640–650, 2007, doi: https://doi.org/10.1016/j.compositesb.2006.06.019.

[65] S. A. Sheikh and Y. Li, “Design of FRP confinement for square concrete columns,” Eng. Struct., vol. 29, no. 6, pp. 1074–1083, 2007, doi: https://doi.org/10.1016/j.engstruct.2006.07.016.

[66] M. F. Green, L. A. Bisby, A. Z. Fam, and V. K. R. Kodur, “FRP confined concrete columns: Behaviour under extreme conditions,” Cem. Concr. Compos., vol. 28, no. 10, pp. 928–937, 2006, doi: 10.1016/j.cemconcomp.2006.07.008.

[67] R. Kumutha and M. S Palanichamy, “Investigation of Reinforced Concrete Columns Confined using Glass Fiber-reinforced Polymers,” J. Reinf. Plast. Compos., vol. 25, no. 16, pp. 1669–1678, Nov. 2006, doi: 10.1177/0731684406068409.

[68] M. N. S. Hadi, “Behaviour of FRP wrapped normal strength concrete columns under eccentric loading,” Compos. Struct., vol. 72, no. 4, pp. 503–511, 2006, doi: https://doi.org/10.1016/j.compstruct.2005.01.018.

[69] K. Galal, A. Arafa, and A. Ghobarah, “Retrofit of RC square short columns,” Eng. Struct., vol. 27, no. 5, pp. 801–813, 2005, doi: https://doi.org/10.1016/j.engstruct.2005.01.003.

[70] A. P. Michael, H. R. Hamilton, and M. H. Ansley, “Concrete confinement using carbon fiber reinforced polymer grid,” Am. Concr. Institute, ACI Spec. Publ., vol. SP-230, no. January 2005, pp. 991–1009, 2005, doi: 10.14359/14877.

[71] Z. Yan, C. P. Pantelides, and L. D. Reaveley, “Shape modification with expansive cement concrete for confinement with FRP composites,” Am. Concr. Institute, ACI Spec. Publ., vol. SP-230, pp. 1047–1066, 2005, doi: 10.14359/14880.

[72] S. P. Tastani and S. J. Pantazopoulou, “Experimental evaluation of FRP jackets in upgrading RC corroded columns with substandard detailing,” Eng. Struct., vol. 26, no. 6, pp. 817–829, 2004, doi: https://doi.org/10.1016/j.engstruct.2004.02.003.

[73] K. A. Harries and S. A. Carey, “Shape and ‘gap’ effects on the behavior of variably confined concrete,” Cem. Concr. Res., vol. 33, no. 6, pp. 881–890, 2003, doi: https://doi.org/10.1016/S0008-8846(02)01085-2.

[74] K. A. Harries and G. Kharel, “Experimental investigation of the behavior of variably confined concrete,” Cem. Concr. Res., vol. 33, no. 6, pp. 873–880, 2003, doi: https://doi.org/10.1016/S0008-8846(02)01086-4.

[75] R. Realfonzo and A. Napoli, “Concrete confined by FRP systems: Confinement efficiency and design strength models,” Compos. Part B Eng., vol. 42, no. 4, pp. 736–755, 2011, doi: https://doi.org/10.1016/j.compositesb.2011.01.028.

[76] M. Demers and K. W. Neale, “Confinement of reinforced concrete columns with fibre-reinforced composite sheets - an experimental study,” Can. J. Civ. Eng., vol. 26, no. 2, pp. 226–241, Apr. 1999, doi: 10.1139/l98-067.

[77] M. Amir, S. Mohsen, S. Michel, E. H. El, M. J. Carlos, and P. Odell, “Effect of Column Parameters on FRP-Confined Concrete,” J. Compos. Constr., vol. 2, no. 4, pp. 175–185, Nov. 1998, doi: 10.1061/(ASCE)1090-0268(1998)2:4(175).

[78] H. Saadatmanesh, M. R. Ehsani, and M. W. Li, “Strength and ductility of concrete columns externally reinforced with fiber composite straps,” ACI Struct. J., vol. 91, no. 4, pp. 434–447, 1994, doi: 10.14359/4151.

[79] M. Yaqub and C. G. Bailey, “Repair of fire damaged circular reinforced concrete columns with FRP composites,” Constr. Build. Mater., vol. 25, no. 1, pp. 359–370, 2011, doi: https://doi.org/10.1016/j.conbuildmat.2010.06.017.

[80] Y. S. S. Al-Kamaki, “Strengthening of fire-damaged RC columns using CFRP fabrics,” Swinburne University of Technology, 2015. doi: 10.25916/sut.26286337.v1.

[81] I. Hussain, M. Yaqub, M. Mortazavi, M. A. Ehsan, and M. Hussain, “Study of fire-damaged circular RC columns repaired using composite confinement techniques,” Proc. Inst. Civ. Eng. - Struct. Build., vol. 177, no. 3, pp. 222–234, Jun. 2022, doi: 10.1680/jstbu.21.00017.

[82] J. Xu, “Circular reinforced concrete columns damaged by fire and retrofitted with CFRP and Steel Jacketing,” Syracuse University, 2022. [Online]. Available: https://surface.syr.edu/etd/1573

[83] H. S. Al-Nimry and A. M. Ghanem, “FRP Confinement of Heat-Damaged Circular RC Columns,” Int. J. Concr. Struct. Mater., vol. 11, no. 1, pp. 115–133, 2017, doi: 10.1007/s40069-016-0181-4.

[84] M. Yaqub, C. G. Bailey, and P. Nedwell, “Axial capacity of post-heated square columns wrapped with FRP composites,” Cem. Concr. Compos., vol. 33, no. 6, pp. 694–701, 2011, doi: https://doi.org/10.1016/j.cemconcomp.2011.03.011.

[85] N. Moghtadernejad, M. Jamshidi, M. R. Maheri, and C. K. Keong, “Repair of post-heated short rectangular reinforced concrete columns with FRP jackets,” Structures, vol. 34, pp. 4269–4283, 2021, doi: https://doi.org/10.1016/j.istruc.2021.10.038.

[86] H. Al-Nimry, R. Haddad, S. Afram, and M. Abdel-Halim, “Effectiveness of advanced composites in repairing heat-damaged RC columns,” Mater. Struct. Constr., vol. 46, no. 11, pp. 1843–1860, 2013, doi: 10.1617/s11527-013-0022-8.

[87] A. A. Abadel, M. I. Khan, and R. Masmoudi, “Axial capacity and stiffness of post-heated circular and square columns strengthened with carbon fiber reinforced polymer jackets,” Structures, vol. 33, pp. 2599–2610, 2021, doi: https://doi.org/10.1016/j.istruc.2021.05.081.

[88] A. T. Obaidat, A. M. Ashteyat, S. Hanandeh, and A. Y. Al-Btoush, “Behavior of heat damaged circular reinforced concrete columns repaired using Carbon Fiber Reinforced Polymer rope,” J. Build. Eng., vol. 31, p. 101424, 2020, doi: https://doi.org/10.1016/j.jobe.2020.101424.