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Experimental Investigation of Heat-Damaged RC Slender Spiral Columns Repaired with CFRP Rope

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Abstract: Carbon fiber-reinforced polymer (CFRP) is widely used in construction to extend the service life of building structures through the repair and rehabilitation of reinforced concrete (RC) columns. However, due to the difficulty of wrapping CFRP strips spirally around an RC spiral column, a flexible CFRP rope material has been developed as an alternative, which will be used as a spiral hoop for repairing circular columns. In this study, 12 RC spiral columns were constructed and tested under concentric load, considering slenderness ratio and spacing between CFRP rope and heat temperature, to investigate the RC spiral column's behavior. These RC columns had three slenderness ratios with 17.75, 26.65, and 33.34 and were exposed to heat temperature of 600 °C for 3 h, then tested under compression. The results showed that as the slenderness ratio increases, the load capacity of RC spiral column decreases. The repaired specimens with a CFRP rope-with-slenderness ratio of 33.35 and 26.65 exhibited an increase in strength about (36% to 97%) and (30% to 88%), respectively. In all repaired specimens with a CFRP rope-of-slenderness ratio of 26.65 and 33.35, they showed a slight increase in ductility of about 2% compared with the heated specimen. However, they did not recover the ductility of the unheated specimen. Also, the specimens with a low slenderness ratio and repaired with CFRP at 300 mm showed a greater decrease in toughness and modulus of elasticity than in the specimens with a high slenderness ratio and repaired with CFRP at 150 mm. The repaired specimens with rope at 150 mm of spacing exhibited an increase in load capacity more than the repaired specimen with rope at 300 mm of spacing and reached a load capacity that was greater than what the unheated specimen reached in all groups. It can be shown that there is a significant effect of temperature on the behaviour of the RC spiral column. Adding rope at 300 mm of spacing restores the capacity and allows for a greater reach than the unheated load capacity of the specimens (about 4% to 11%). However, the specimens repaired with rope at 150 mm increased the load capacity by approximately 27.4% to 36.8% more than the unheated specimens in each group.

Keywords: confinement; carbon fiber-reinforced polymers; rope; RC column; slenderness ratio; temperature; strength; ductility

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1. Introduction

Reinforced concrete (RC) columns play a pivotal role as primary load-bearing elements in buildings, which are responsible for transferring both vertical and lateral forces and ensuring the overall vertical loads of structures are effectively transferred to the soil. However, the RC columns remain vulnerable to harm from earthquakes, fire, and flaws arising from outdated design codes. This study investigates the effect of heat temperature on the behaviour of RC spiral columns. These vulnerabilities pose risks of significant structural damage. Repairing or reinforcing existing concrete structures is often more environmentally and economically viable than complete replacement, particularly with the availability of simple, rapid, and effective strengthening methods. Because of this, catastrophes may occur if this is not provided sufficient consideration since structures may be unable to support their designed loads [1]. In addition, the RC column damage is a serious problem that has to be resolved right once in order to adhere to the most recent design standards and code. Before starting the repair or retrofitting procedure, it is essential to quickly restore the RC column to its maximal strength due to all of the aforementioned factors. Hence, prompt action is essential to restore the functionality of critical structural systems after significant damage.

There are two types of RC columns based on their slenderness ratio: short and slender columns. Short RC columns typically fail due to material strength limitations, whereas slender RC columns predominantly fail due to buckling, leading to a notable decrease in load capacity compared to short columns. Nevertheless, slender columns are increasingly favoured, driven by advancements in high-strength concrete. Several studies were conducted on fiber-reinforced polymer and FRP materials to repair short RC columns [2–12]. Based on the findings of this experimental study [13], circular columns exhibit greater ductility and axial strength compared to square or rectangular columns. One of the aforementioned reasons for damage caused in RC columns is elevated temperatures. Different techniques have been used to strengthen and repair RC columns, such as using steel or concrete jacketing [1,8]. However, these methods have shown limited efficiency due to their need for unwanted section enlargement and added weight, labour-intensive processes, and constraints during construction [14,15]. Furthermore, they elevate the stiffness of the columns, consequently drawing more seismic forces toward the reinforced columns [16,17].

Carbon fiber-reinforced polymer (CFRP) has recently increased in popularity due to its strengthening or repairing structural elements, especially in RC columns due to its low weight, high stiffness and tensile strength, and ease of installation [17–20]. The two main techniques to strengthen the reinforced concrete structure using FRP are externally bonded (EB) FRP sheets or near-surface-mounted (NSM) FRP techniques, which have been used in the flexural strengthening of RC columns or joints. Many researchers have used the externally bonded reinforcing (EBR) technique for repairing and strengthening reinforced concrete structures [21–24].

Hassan et al. [23] conducted a study on high-strength concrete (HSC) columns under eccentric loading, reinforced with FRP laminates. Their experimental results clearly indicate that FRP laminates substantially enhance the flexural capacity of uniaxially loaded HSC columns. The study reported strength improvements of up to 23% for specimens loaded with small eccentricities and up to 59% for those with large eccentricities. In a related investigation, Madupu [25] focused on short, reinforced concrete (RC) rectangular columns with rounded edges, which were strengthened using bi-directional glass fiber-reinforced polymer (GFRP) cloth bonded with epoxy resin under an axial load. The findings demonstrated a significant increase in the axial load capacity of the RC rectangular columns when wrapped with GFRP fabric and bonded with epoxy resin.

One significant limitation of the externally bonded reinforcement (EBR) technique is premature debonding, which hampers its ability to fully utilize the tensile strength of FRP materials. To address these issues, the near-surface mounted (NSM) technique has gained prominence in recent years. In NSM, FRP bars or strips are embedded within grooves cut into the concrete cover near the surface of the RC member. These grooves are then filled with cement mortar or epoxy paste [26]. NSM involves inserting FRP strips or rods into pre-cut grooves on the concrete surface of structural elements requiring reinforcement. Subsequently, the CFRP strip is bonded to the concrete using an epoxy adhesive. This method has been employed by several researchers for strengthening and repairing concrete structures.

Saeed et al. [27] investigated the effectiveness of EB-FRP and NSM-FRP systems in strengthening columns through the fabrication and testing of six specimens. Their findings underscored that both EB-CFRP and NSM-CFRP techniques notably enhanced the flexural resistance of RC columns. The findings from Saeed et al. suggest that both EB-FRP and NSM-FRP techniques could be adapted or serve as a benchmark for evaluating the performance of CFRP ropes, as CFRP materials in any form tend to significantly improve the strength and durability of compromised concrete structures. These insights are particularly valuable in guiding the selection of appropriate repair techniques that can mitigate the loss of flexural capacity caused by heat exposure while ensuring long-term reliability and performance.

In the last 30 years, there has been growing interest in repairing and rehabilitating structural concrete members damaged by heat [28,29]. When addressing the repair of a heat-damaged reinforced concrete (RC) column, several factors must be carefully considered, including the column's configuration, extent of damage, construction and repair costs, feasibility, and time constraints. However, there remains a noticeable lack of research in the literature specifically focused on repairing heat-damaged RC columns [30,31].

Yaqueb [30] studied how the cross-sectional shape influences the performance of post-heated reinforced concrete columns strengthened with FRP composites. The research highlighted that the original cross-sectional shape significantly impacts the load-carrying capacity of columns reinforced with post-heated FRP. Abadel et al. [31] investigated the effectiveness of various strengthening methods using carbon fiber-reinforced polymer (CFRP) jackets and near-surface mounted (NSM) steel bars for repairing circular and square RC columns damaged by high temperatures. Their findings indicated that exposure to elevated temperatures reduces the load-carrying capacity of columns. Combining CFRP strips with NSM steel bars proved more effective in restoring the initial stiffness of columns post-heating compared to using CFRP strips alone.

One of the primary challenges identified is the lack of sufficient research and precise guidelines for repairing slender RC columns using FRP. Design codes such as ACI 440.2-23 [32] and ISIS Canada [33] restrict the use of fiber-reinforced polymer (FRP) for strengthening short columns with minimal slenderness or secondary effects. Consequently, many slender RC columns in older buildings now require reinforcement or restoration. Numerous studies have explored the behavior of reinforced and repaired slender (RC) columns using (FRP) materials, considering various factors such as FRP configurations, concrete strength, and slenderness ratio.

Mirmiran et al. [34] examined the behavior of concrete-filled fiber-reinforced polymer tubes (CFFT) for confined slender columns, noting a decrease in load capacity with increasing slenderness ratio. Pan et al. [35] observed that higher slenderness ratios in RC columns reduce the efficiency of FRP strengthening. They highlighted that the slenderness ratio significantly affects the load capacity of FRP-strengthened columns compared to unstrengthened ones, primarily due to increased confinement rather than enhanced bending stiffness. Gajdosova and Bilcik [36] investigated two methods for strengthening RC columns: longitudinal (NSM) CFRP strips and sheet wrapping. Their research findings concluded that longitudinal strips were more effective in increasing slender column capacity, whereas transverse sheet wrapping demonstrated greater effectiveness in increasing the strength of short RC columns. Tao and Han [37] found that the beneficial effect of CFRP confinement on RC column strength diminishes with increasing eccentricity of load and slenderness ratio. Fitzwilliam and Bisby [38] experimentally studied slender RC columns subjected to equal eccentricity. They discovered that longitudinal CFRP reinforcement increased the load capacity of slender columns and reduced lateral deflection. In summary, these studies collectively contribute to understanding how various parameters influence the performance of FRP-strengthened and repaired slender RC columns, offering insights into optimizing their design and reinforcement strategies.

From the literature review, it is clear that not much research was previously done on slender RC columns repaired with CFRP rope. Most of the research on repaired or strengthened RC columns has concentrated on short columns reinforced with circular hoops made of NSM strips and FRP sheets [39,40]. As a result, there is a knowledge gap that necessitates further experimental studies on the behavior of RC columns reinforced with ropes, considering their slenderness ratios, in order to address this deficiency. Moreover, the majority of CFRP rope for the confinement of the RC slender column used in the previous studies was in the form of circular hoops. However, in this study, the CFRP rope is used to confine the RC slender column with different slenderness ratios, which allow it to form in a spiral fashion. Also, the RC specimens were exposed to a heat temperature of 600 °C.

Pul et al. [41] investigated the structural behavior of RC columns exposed to a high temperature of 1150 °C while under axial load, subjected to various heating and cooling scenarios. They tested 16 RC square columns considering different concrete strengths (13.7 MPa and 41.4 MPa), heating durations (30, 60, and 120 min), and cooling methods (water-cooling and air-cooling). The results showed that after 120 min of high-temperature exposure, the column's load capacity decreased by 9.5% with air-cooling and by 35% with water-cooling. In a related study, Liu et al. [42] examined the impact of using a Textile-Reinforced Engineered Cementitious Composite (TRE) system on the axial compressive behavior of fire-damaged square RC columns. They tested 13 specimens under axial compression, considering variables such as fire-exposure duration (2 h or 3 h), type of cementitious matrix, number of TRE layers (two layers or three layers), and thickness of the concrete cover (20 mm or 40 mm). The study concluded that employing the TRE system significantly increased the load capacity, secant stiffness, and ultimate displacement resistance of fire-damaged RC columns.

Therefore, the objective of this study is to investigate the influences of slenderness ratio, CFRP rope spacing, and heat temperature on the behavior of RC spiral columns subjected to concentric load. Twelve RC spiral columns were exposed to temperature and tested in this study, and nine of them were repaired using CFRP rope as spiral hoops. This work investigates a novel spiral FRP–rope approach for repairing RC circular columns. The spiral–rope system and the heat temperature are the main subjects of this study. One advantage of the technique is that the rope can be arranged at any spacing, shaped, and put as spiral confinement. The study's conclusions might be useful in developing design suggestions for how FRP-enhanced RC columns behave.

2. Experimental Program

The scope of this study is to evaluate experimentally the effectiveness of CFRP rope confinement on the strength and ductility of RC short and slender spiral columns exposed to high temperatures with different slenderness ratios. The axial compression performance of heat-damaged RC spiral columns was investigated considering three slenderness. All the tested RC spiral columns used in this study had the same cross-sectional areas that were designed using ACI 440.2-23 [32] code requirements. The RC spiral columns confined with one layer of spiral CFRP rope with different spacing were studied. Twelve RC spiral columns that had a circular cross-section with a diameter of 185 mm were considered, out of which six RC spiral columns (three heated control specimens and three unheated control specimens) were tested as control RC specimens without CFRP rope. However, the remaining nine RC spiral specimens were repaired with CFRP rope confinement with different spacing. All control and repaired RC spiral columns were tested under a concentric load.

2.1. RC Spiral Column Description

Twelve RC spiral columns were constructed for this investigation. All RC spiral column had the same size, with a circular cross-section with a diameter of 180 mm and different heights. Three heights were used in this study, with 800 mm, 1200 mm, and 1500 mm representing three slenderness ratios (klu/r) of 17.75, 26.65, and 33.34, respectively. The k in the expression is the effective length factor, Lu is the unsupported height, and r is the radius of gyration. In, $r = \sqrt{(I/A)}$, I and A are the moment of inertia and the gross area of the RC spiral column section. The tested specimens were divided into three groups based on the height and slenderness ratio. Each group had four specimens: the first one had RC columns with 800 mm of height (UH-80-Control, H-80-control, H-80-R30, and H-80-R15), the second one had RC columns with 1200 mm of height (UH-120-Control, H-120-control, H-120-R30, and H-120-R15), and the third one had RC columns with 1500 mm of height (UH-150-Control, H-150-control, H-150-R30, and H-150-R15). The UH and H in specimen names denote unheated and heated, respectively. The numbers 80, 120, and 150 represent the height in specimens in cm. Finally, R15 and R30 denote repaired specimens with spiral CFRP rope at 15 cm and 30 cm, respectively. Table 1 shows the details of test specimens of this study. Based on the ACI 318-11 [43], for the sway or non-sway frames of RC columns with equal moments at the ends, the slenderness limit is 22 and the RC spiral column with a height of 800 mm is classified as a short column, whereas the RC spiral column with 1200 mm and 1500 mm is classified as a slender/long column. All of the RC spiral columns were reinforced longitudinally by 5 Ø 10 mm rebars and transversally in terms of hoops by Ø 8 mm rebar at a spacing of 100 mm center-to-center (c/c). The cover of concrete was 25 mm to the main steel bars. The percentage of steel reinforcement of 1.55% was used for all specimens. Figure 1 shows the detailing of the RC spiral column's reinforcement.

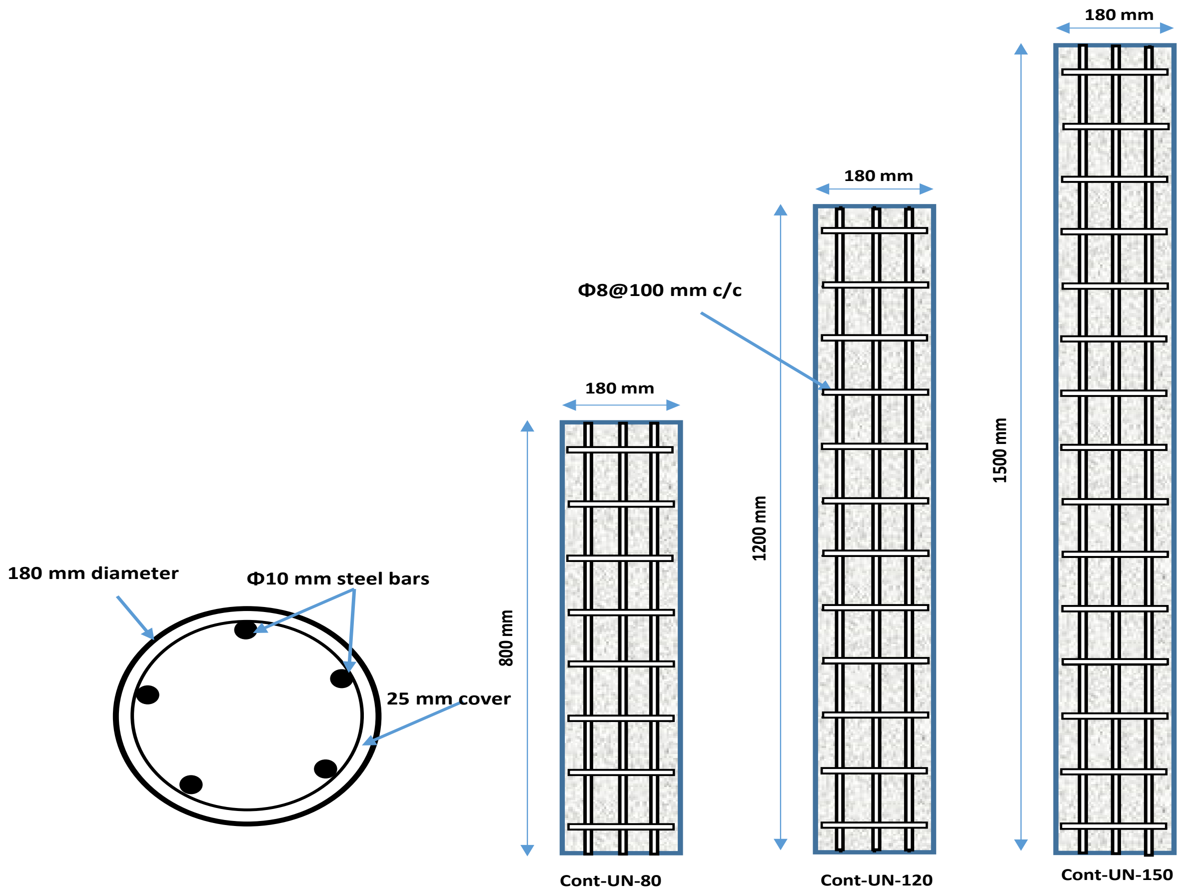


Figure 1. Details of the control unheated column specimens (Cont-UN).

Table 1. Details of test RC spiral column specimens.

Category	Sample Identification	Height of Column (mm)	Slenderness Ratio, KL/r	CFRP Shape	CFRP Rope Spacing, (mm)	Heat Temperature (°C)
1	UH-80-Control	800	17.75	-	-	-
	H-80-Control			-	-	600
	H-80-R15			Spiral	150	600
	H-80-R30			Spiral	300	600
2	UH-120-Control	1200	26.65	-	-	-
	H-120-Control			-	-	600
	H-120-R15			Spiral	150	600
	H-120-R30			Spiral	300	600
3	UH-150-Control	1500	33.34	-	-	-
	H-150-Control			-	-	600
	H-150-R15			Spiral	150	600
	H-150-R30			Spiral	300	600

2.2. Construction of Test Specimens and Material Properties

All tested RC spiral columns' specimens were constructed using one ready mix-concrete batch. Six cylinders with 150 mm × 300 mm of concrete were cast to measure 28 days of compressive strength. Then, the specimens were demolded for 24 h. Afterwards, the specimens were cured in a laboratory at room temperature for 28 days, covered by moist burlap sheets to achieve full capacity. The reinforcement cage of the column and footing was prepared first then fixed and fastened to formwork. The longitudinal steel bars were extended into the bottom and top footings. The footings used in this study were used to prevent stress concentrations and to ensure the failure at the instrument region (Figure 2).

In order to cast the RC spiral column specimens, a special circular PVC pipe was used. These pipes had internal diameters of 180 mm and a height of 800 mm, 1200 mm, and 1500 mm respectively. Ready mix concrete was poured into the wooden formwork in three. The three layers of concrete were compacted utilizing an electric vibrator.

(a) Preparing cage of reinforcement **(b)** Preparing formwork and placing the PVC

(c) Placing the cage of reinforcement in the formwork **(d) Pouring of the concrete**

Figure 2. Fabrication of RC spiral column: (**a**) Preparing cage of reinforcement, (**b**) preparing formwork and placing the PVC, (**c**) placing the cage of reinforcement in the formwork, (**d**) pouring of the concrete.

The same ready concrete mix was used to construct and cast all of the RC spiral columns, with a water/cement ratio of 0.50, a 90 mm slump, and an average compressive strength of 25 MPa after 28 days. The cage reinforcement consists of longitudinal and transverse reinforcement. The longitudinal reinforcement was 5 bars of 10 mm, and the transverse reinforcement, in terms of hoops, was 8 mm at 100 mm. The steel reinforcement used in the construction of specimens had a yield stress 420 MPa. The columns were strengthened and repaired using SIKA's unidirectional NSM-CFRP rope (Figure 3). The rope was first impregnated with Sikadur-52 adhesive. Then, the groove on the concrete cover was filled with Sikadur-330, and the CFRP rope was inserted into the groove. The characteristics of CFRP rope, Sikadur-330 adhesive, and Sikadur-52 are listed in Tables 2 and 3. Sikadur-52 adhesive comprises two parts: hardener (Part B) and resin (Part A), mixed two to one. However, CFRP ropes are bonded with Sikadur-330. Two chemicals, hardener (Part B) and resin (Part A), are combined in a 4:1 weight ratio to create it. In Figure 3, we see the CFRP-rope.

Table 2. Physical and mechanical Properties of SikaWrap® FX-50 C ropes.

Product Type	SikaWrap®FX-50C Ropes
Fiber Type	Mid-strength carbon fibers
Technical Data	
Areal Weight	50 g/m (carbon fibers only)
Fabric Thickness	2.98 mm (based on fiber content).
Fiber Density	1.82 g/cm^3
Mechanical/Physical Properties (Dry Fiber)	
Tensile Modulus	240,000 N/mm^2
Tensile Strength	4000 N/mm^2
Elongation at break	1.6%
Mechanical/Physical Properties (ropes)	
Tensile Modulus	230,000 N/mm^2
Tensile Strength	2100 N/mm^2

Table 3. Experimental results of all RC spiral columns.

Specimens	Stress (MPa)	Stress Increase (%) as Unheated Specimen	Increase in Peak Stress (%) as Heated Specimen	Peak Strain	Increase in Peak Strain % as Heated Specimen	Failure Strain	Increase in Failure Strain (%) as Heated Specimen	Ductility at Failure ($\mu_u = \Delta_u/\Delta_y$)	Increase in Ductility	Toughness (MPa)	Modulus of Elasticity MPa
UH-80-Control	28.21	-	33.179	0.004	−12.195	0.006	4.412	1.659	14.802	0.12	6880.48
H-80-Control	18.85	−33.179	0	0.0046	0	0.0065	0	1.413	0	0.081	4097.826
H-80-R30	26.68	−5.424	41.539	0.0053	15.217	0.0081	24.615	1.528	8.157	0.163	5033.962
H-80-R15	32.88	16.554	74.430	0.0054	17.391	0.011	69.231	2.037	44.16	0.222	6088.889
UH-120-Control	23.5	0	29.678	0.0044	−9.091	0.0056	7.143	1.273	14.881	0.103	5306.818
H-120-Control	16.42	−30.127	0	0.0048	0	0.0052	0	1.083	0	0.045	3420.833
H-120-R30	24.32	3.490	48.113	0.0055	14.583	0.0063	21.154	1.145	5.734	0.088	4421.818
H-120-R15	29.93	27.362	82.277	0.0057	18.750	0.0088	69.231	1.544	42.510	0.156	5250.877
UH-150-Control	19.2	0	36.311	0.0043	−3.926	0.0061	16.393	1.409	19.552	0.080	4833.718
H-150-Control	13.33	−30.573	0	0.0045	0	0.0051	0	1.133	0	0.038	2962.222
H-150-R30	21.33	11.094	60.015	0.0052	15.556	0.0064	25.490	1.231	8.597	0.08	4101.923
H-150-R15	26.26	36.771	97	0.0053	17.778	0.0083	62.745	1.566	38.18	0.135	4954.717

Figure 3. CFRP-rope.

2.3. Exposing RC Spiral Column to Elevated Temperatures

An electrical oven in a structural laboratory at the University of Jordan was used in exposing RC spiral column specimens to elevated temperatures (Figure 4). The RC spiral columns were divided into two groups based on the exposed temperature. The first group was exposed to room temperature and the second group was exposed to an elevated temperature of 600 °C. The second group, with different slenderness ratios, was placed into the oven with the desired temperature. All the specimens in this group maintained the necessary temperature for 3 h. The rate of heating is displayed in Figure 5 to reach the desired elevated temperature. Because some publications utilized this heat temperature, and because the available oven had a maximum heat temperature of 650 °C [28,43,44], the specimens in this investigation were exposed to 600 °C. Moreover, the intensity, fuel type, and ventilation conditions of the fire can all have a significant impact on the temperature that is structurally impacted on the concrete building. However, temperatures can vary from 300 °C to 500 °C in the early phases of a fire. Even though there may not be any significant structural damage at this time, the temperatures are still high enough to change the characteristics of the materials. On the other hand, especially in small areas like buildings, a well-affected fire can reach temperatures of 600 °C to 1100 °C or more. The most severe heat damage to structural elements, such as RC beams, slabs, and columns, occurs during this period. Since 600 °C is within the standard range for severe fire conditions in structural elements, it is relevant to the research of RC spiral columns, since it is the point at which material characteristics are anticipated to undergo significant changes.

Figure 4. RC columns in oven.

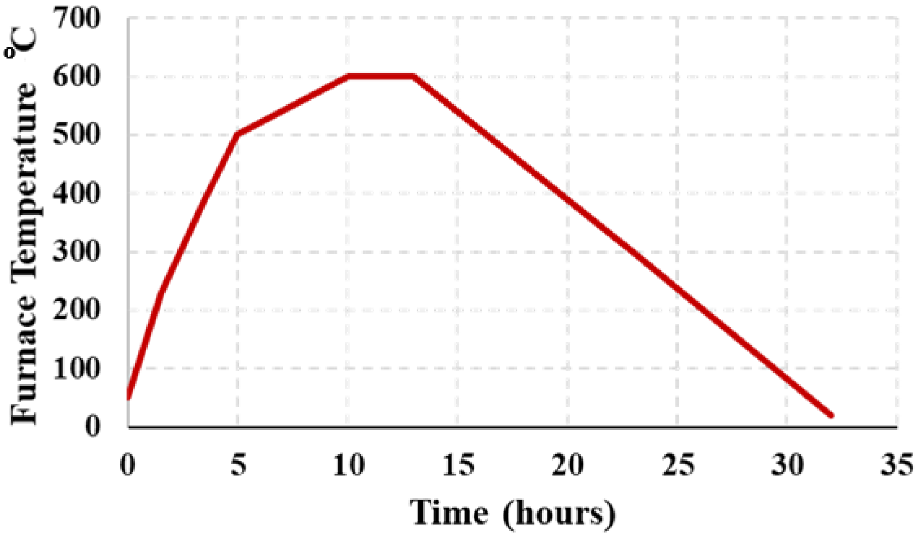


Figure 5. Heating rate.

2.4. Installation CFRP Ropes in RC Spiral Column

In this study, some of the tested RC spiral columns' specimens were strengthened and repaired with CFRP ropes. The procedure for installing Sika Wrap-FX 50 C CFRP rope in the groove is listed in the following steps:

1. Cleaning the surface of the RC column before installing the Sika Wrap-FX 50 C.
2. Accordance with the configurations, producing the groove of 10 mm in width and 25 mm in depth along the RC spiral column. After that, the RC spiral column is cleaned of dust.
3. The components of Sikadur-52 were mixed to produce the saturated mixture.
4. The Sika Wrap-FX 50 C rope was cut to necessary measured length and then saturated with the Sikadur-52 mixture.
5. The components of Sikadur-330 were mixed to create the mixture, which was inserted into the groove.
6. Finally, the saturated Sika Wrap-FX ropes were inserted into the grooves. The groove was filled with the Sikadur-330 mixture and then smoothed over by the blade (Figure 6).
7. The Sikadur-330 is used for incorporating the cord into the grooves, and another resin Sikadur-52 is for impregnating the fibers.

Figure 6. Installing of CFRP rope.

2.5. Test Setup and Instrumentation

The required details about the instrumentation and test setup are explained in this section. Before the start of testing, and in order to ensure the concentricity, the RC spiral column specimen was held at a desired position under the actuator using the crane and holding it manually as well until the initial compression. The test was done using the accessible universal testing machine at the Jordan University of Science and Technology (Figure 7). All the concrete spiral column samples were tested under compression until they failed.

Figure 7. Two-point load test setup.

The compression load gradually increases by a rate of 1.5 kN using the load-control tool in the testing machine. The test data, including the load, were recorded using the data-acquisition system at a rate of five readings per second. However, the axial displacement was recorded using two linear variable-displacement transducers (LVDT) attached at mid-height of the RC column.

3. Results and Discussions

3.1. Failure Modes

In this study, three unheated control specimens (UH-80-Control, UH-120-Control, and UH-150-Control) and three heated control specimens (H-80-Control, H-120-Control, and H-150-Control) with different slenderness ratios were tested. At the beginning of the applying load, there was no observed cracking. In addition, the relationship between the applying load and deformation was directly proportional. As the load increased, the cracks started appearing in the concrete at the mid-span of RC columns in all slenderness ratios. Moreover, the axial displacement of the RC spiral column increased with the load increasing. Finally, as shown in Figure 8, the three control columns failed due to spalling of the concrete and splitting failure of concrete observed, which occurred at the mid-height of the RC spiral column. Figures 8 and 9 show the modes of failure observed in control RC spiral columns of 800, 1200, and 1500 mm heights for unheated and heated specimens. The axial crushing of concrete is the failure mode of the (UH-80-Control and H-80-Control) 800 mm control RC columns, whereas, due to the high slenderness ratio, the ((UH-120-Control and H-120-Control) and (UH-150-Control and H-150-Control) 1200 mm and 1500 control columns failed somehow in flexure and were followed by slight outward buckling of the longitudinal reinforcement. The heated control specimens (H-80-Control, H-120-Control, and H-150-Control) with different slenderness ratios failed with the similar modes of unheated control specimens (UH-80-Control, UH-120-Control, and UH-150-Control), but with a lower load capacity due to the elevated temperature. The high temperature had a major impact on the heated specimens because it caused the concrete to deteriorate because of water evaporation and weakened the column cores. This results from the amount of the CFRP rope ratio provided and the increased amount of the spiral CFRP ratio and lateral pressure generated by spiral CFRP rope. Also, there are other contributing factors, such as reduced lateral expansion of the concrete. One of the primary advantages of using CFRP ropes for strengthening concrete structures is their capacity to decrease the concrete's lateral expansion under lateral stress. Concrete may crack or expand laterally when exposed to internal or external stresses, which cause structural failure. The use of CFRP ropes, which have a high tensile strength, decreases the concrete's lateral expansion. This provides a number of advantages, including enhanced durability, where the concrete's overall durability is increased by delaying lateral cracking. This increases the structure's durability and reduces the need for maintenance. Additionally, it improves the load distribution, while safety and delayed failure are achieved by the CFRP ropes, which decrease stress concentrations that might cause failure by distributing the applied load more uniformly throughout the concrete. Until repairs or reinforcements are completed, the concrete structure may safely support loads due to its delay failure mechanism. Additionally, specimens confined by CFRP ropes at 150 mm spacing experienced more confinement than those confined by CFRP ropes at 300 mm spacing. This finding emphasizes the benefits of using CFRP ropes to wrap the RC columns.

Figure 8. Failure modes of unheated control specimens (UH-80-Control, UH-120-Control, and UH-150-Control).

Figure 9. Failure modes of heated control specimens (H-80-Control, H-120-Control, and H-150-Control).

Figures 10 and 11 display the mode of failure in repaired columns with CFRP rope at a spacing of 300 mm and 150 mm of 800, 1200, and 1500 mm of height, respectively, as well as (H-80-R30, H-120-R30, and H-150-R30) and (H-80-R15, H-120-R15, and H-150-R15) specimens. The columns repaired with spiral ropes at a spacing of 300 mm showed the crushing concrete between the CFRP rope. Also, the failure load was delayed due to the presence of CFRP rope. The area of crushing concrete in specimens repaired with 150 mm was less than the specimens repaired with CFRP rope at 300 mm. Formation of ripples in CFRP rope, which were less dominant in 900 and 1200 mm columns. Unlike the CFRP sheet, no debonding of the CFRP rope was observed during the test. The failure mode of the repaired specimens of the 800 mm column was crushing, and the splitting of concrete was followed by the buckling of steel rebars. However, the repaired specimens of 1200 mm and 1500 mm columns were the crushing of concrete and the outward buckling of columns, followed by the buckling of steel rebars. The use of spiral CFRP ropes significantly delayed the failure modes of columns repaired with the CFRP rope. Additionally, the spiral CFRP rope increases the capacity of the repaired column by preventing or delaying the spalling of the concrete cover, which delays column failure.

Figure 10. Failure modes of repaired heated column with rope at 300 mm spacing (H-80-R30, H-120-R30, and H-150-R30).

Figure 11. Failure modes of repaired heated column with rope at 150 mm spacing (H-80-R15, H-120-R15, and H-150-R15).

3.2. Stress–Strain Response

The stress–strain response is extensively utilized to study the performance of the RC column. The influence of changing slenderness ratios of RC column on the stress–strain performance of the control and strengthened and repaired columns is studied by displaying the results of experimental test under four groups (i.e., control without CFRP ropes, strengthened column with rope at 300 mm of spacing, repaired columns with rope at 300 mm of spacing, and repaired columns with rope at 150 mm of spacing), Figure 12. Table 3 lists the summary of experimental results, including the peak stress, peak strain, failure strain, ductility at failure, toughness, and modulus of elasticity. The strain at failure and the strain at the peak ratio were used to calculate the ductility. The toughness was calculated by measuring the area under the stress–strain curve. Finally, the slope of the line at the elastic range is from the origin to the intersection of the stress–strain curve at 50% of the axial stress. Also, Table 3 presents the change in peak stress, peak strain, failure strain, toughness, modulus of elasticity, and ductility, with the change of the slenderness ratio comparing to the control specimen (unrepaired specimen in each category).

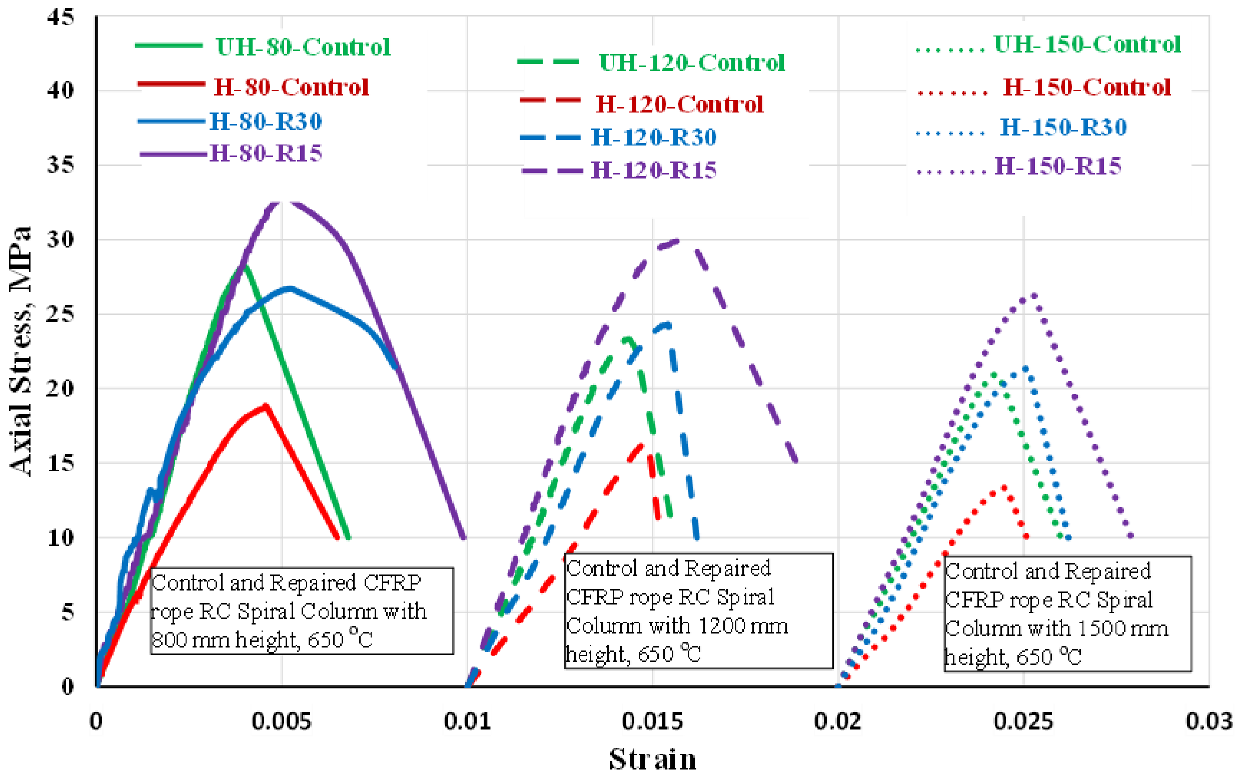


Figure 12. Axial stress vs. axial strain for all specimens with different slenderness ratios showing influence of CFRP.

The effect of the changing slenderness ratio and heat temperature were evaluated based on the stress–strain behavior of the tested RC spiral column specimens. Figure 12 shows the axial stress–strain curves of control and repaired RC spiral columns. The stress–strain curve in Figure 12 consists of three stages. Stage 1 is the first stage of the curve, which is extended from zero to 0.75 of maximum stress. As can be seen, this stage in all curves is quite similar, and the axial load did not cause a big lateral expansion yet and is still somewhat small. Additionally, during the test, the cracks are not obvious at this stage. Stage 2 (part of the curve from 0.75 to almost 95% of peak stress) began with small cracks between the spiral ropes and sound in the rope. As axial stress causes lateral expansion, it increased the rope stresses and strains. Stage 3 represents the part of the stress–strain curve that starts after 95% of the peak stress.

This stage showed an increase in the crack width between the rope, a slight increase in stress, and a substantial increase in axial strain. Eventually, the RC spiral column failed because of concrete crushing between the spiral ropes.

3.3. Effect of Slenderness Ratio of RC Spiral Column

To study the effect of the slenderness ratio on the RC spiral column behavior, twelve RC spiral columns were constructed with three different slenderness ratios (17.75, 26.65, and 33.35). The impact of using a variable slenderness ratio on the stress–strain behavior of both control and repaired RC spiral columns is displayed in Figures 13 and 14. It can be seen that as the slenderness ratio increases, the load capacity of the RC spiral column decreases. As shown in Table 3 and Figure 14, there is an enhancement in the capacity in repaired RC spiral specimens with NSM-CFRP rope. It is clear from Table 3 and Figure 13 that the load capacity and axial strain, corresponding to the peak stress and failure strain, increase as the slenderness ratio increases in control and repaired specimens. Moreover, the repaired RC column with rope at 150 mm showed (small spacing or a higher amount of CFRP rope) the most effect on the behavior of spiral columns as the slenderness ratio changes. It can be concluded that the slenderness ratio influences the load capacity of FRP-strengthened reinforced concrete columns more significantly than that of unstrengthened columns because the strength is increased due to the confinement, not bending stiffness. This is similar to the conclusion of Obaidat [43]. This is clarified by the fact that buckling governs the behavior of RC columns at high loads because the stiffness of RC columns is not significantly affected by the repairing of the CFRP rope. Therefore, the engineer must verify that the greater service loads that are expected will not cause the RC column to become unstable. The repaired specimens with CFRP rope with a slenderness ratio of 33.35 (H-150-R30 and H-150-R15) exhibited an increase in strength about (60% and 97%), respectively, compared with the heated control specimen (H-150-Control). However, repaired specimens with a slenderness ratio of 26.65 (H-120-R30 and H-120-R15) showed an increase in strength of about (48% and 88%), respectively, compared with the heated control specimen (H-120-Control). As seen in Figure 15, the most repaired specimens with CFRP rope with slenderness ratios of 26.65 and 33.35 had a 2% enhancement in ductility when compared to heated specimens but failed to recover the ductility of unheated specimens. Compared to heated and re-paired specimens with CFRP at 150 mm and a slenderness ratio of 26.65, the toughness and modulus of elasticity of heated and repaired specimens with CFRP at 300 mm and a slenderness ratio of 26.65 were reduced further. However, as seen in Figures 16 and 17, the repaired specimens with CFRP at 150 mm of slenderness ratio of 33.35 in certain ways exhibited fewer decreases in toughness and modulus of elasticity than the repaired specimens with CFRP at 300 mm. The number of CFRP ropes per unit length increases as the distance between CFRP ropes decreases. As a result, the ropes and the load they are supporting have a larger overall contact area. By improving the overall load distribution across more ropes, the larger contact area reduces the strain on each individual rope and increases the total load-bearing capacity. Moreover, higher distances between ropes in specific applications may cause the rope system to become unstable or buckle locally. Because the ropes provide each other more support, these problems are reduced when the ropes are placed closer together. When the ropes are spaced closer together, they are less likely to bend or buckle under stress. Finally, the system's total stiffness can be increased by decreasing the spacing between the ropes. Higher load-bearing capacity may result from a stiffer system's enhanced capacity to withstand deformation under load. By decreasing localized deformations that might otherwise limit capacity, a higher rope amount may participate in the more efficient distribution of applied forces.

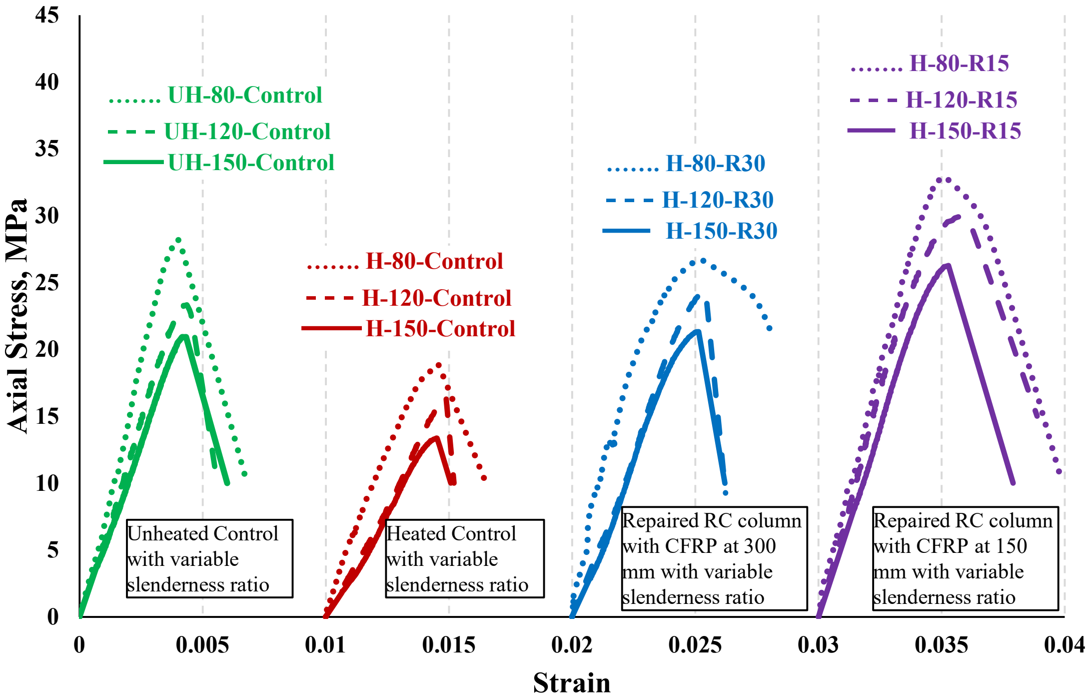


Figure 13. Axial stress vs. axial strain for all columns showing effect of CFRP slenderness ratio.

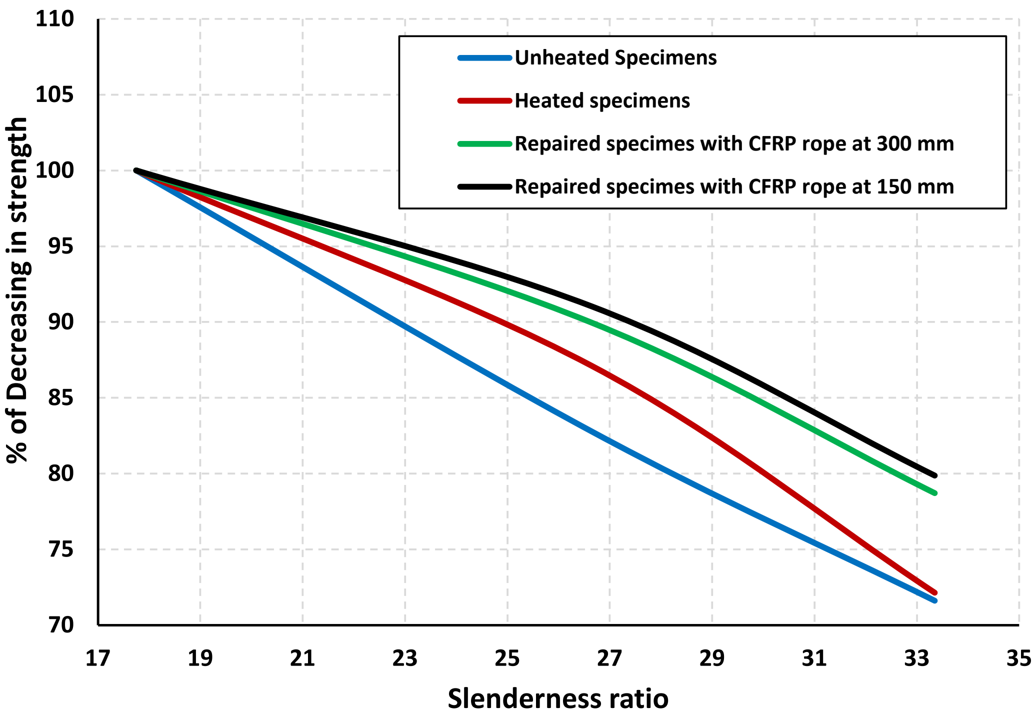


Figure 14. Effect of slenderness ratio on load capacity of RC spiral column.

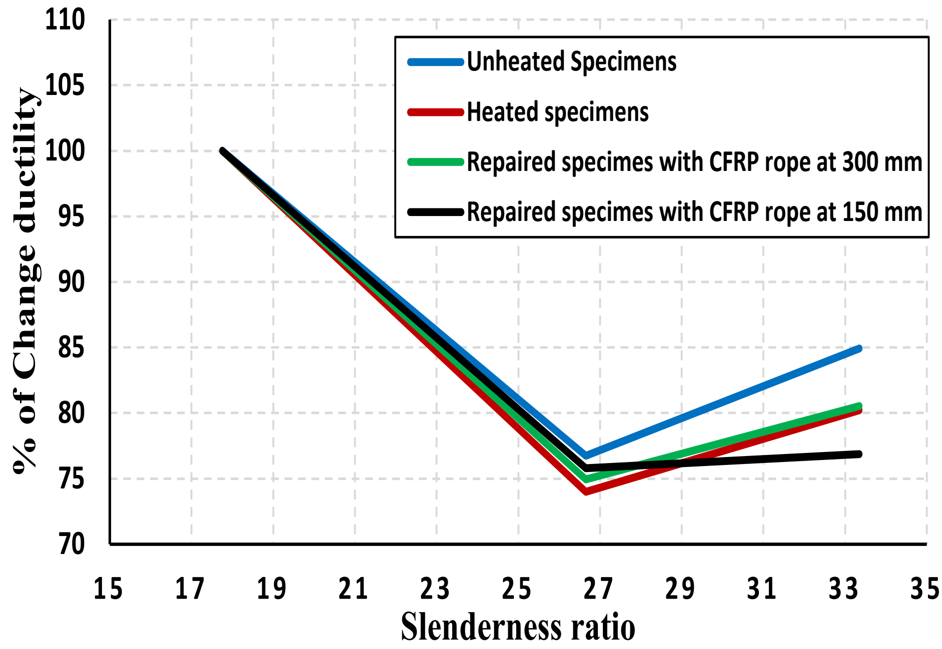


Figure 15. Effect of slenderness ratio on ductility of RC spiral column.

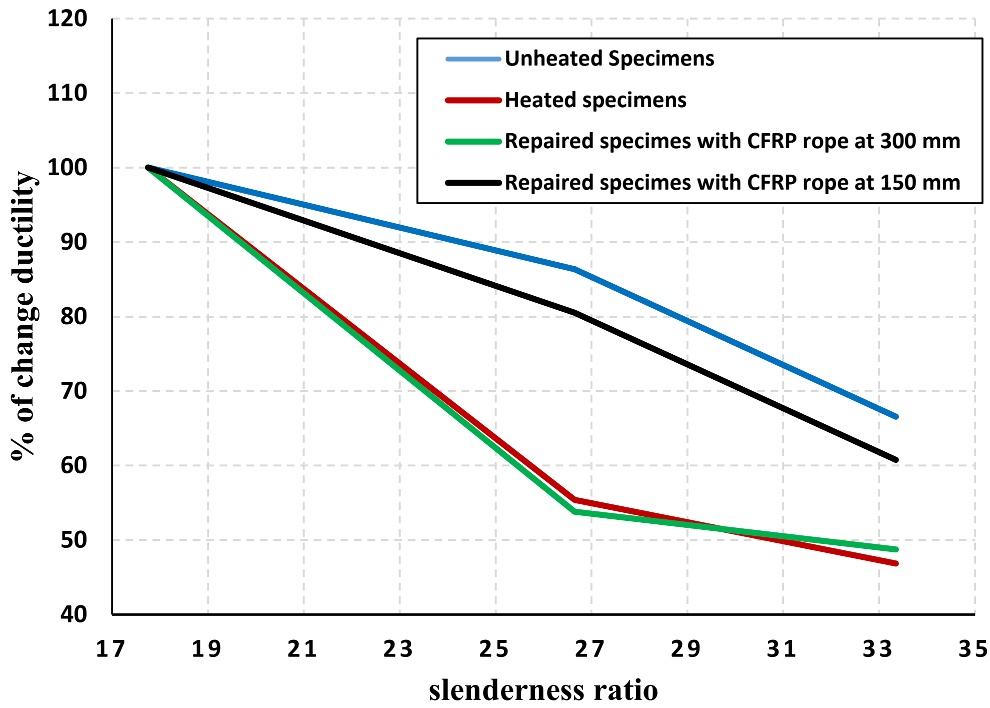
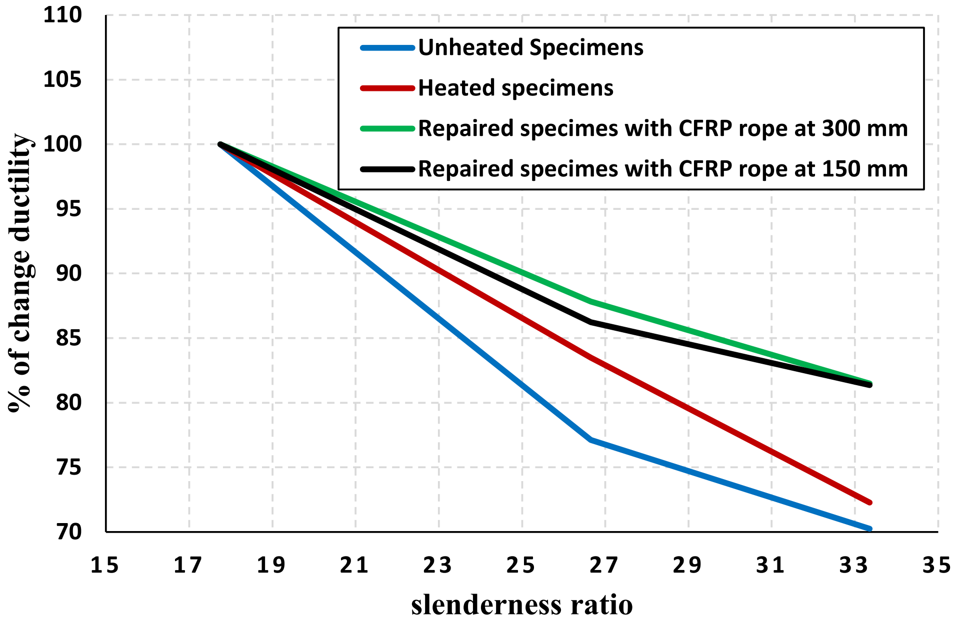


Figure 16. Slenderness ratio effect on toughness of RC spiral column.



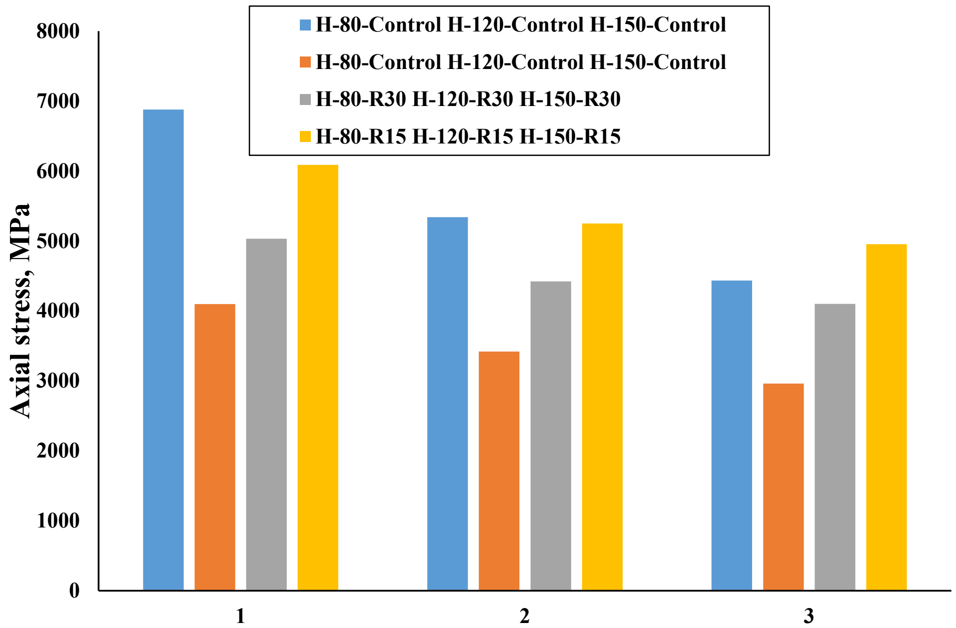
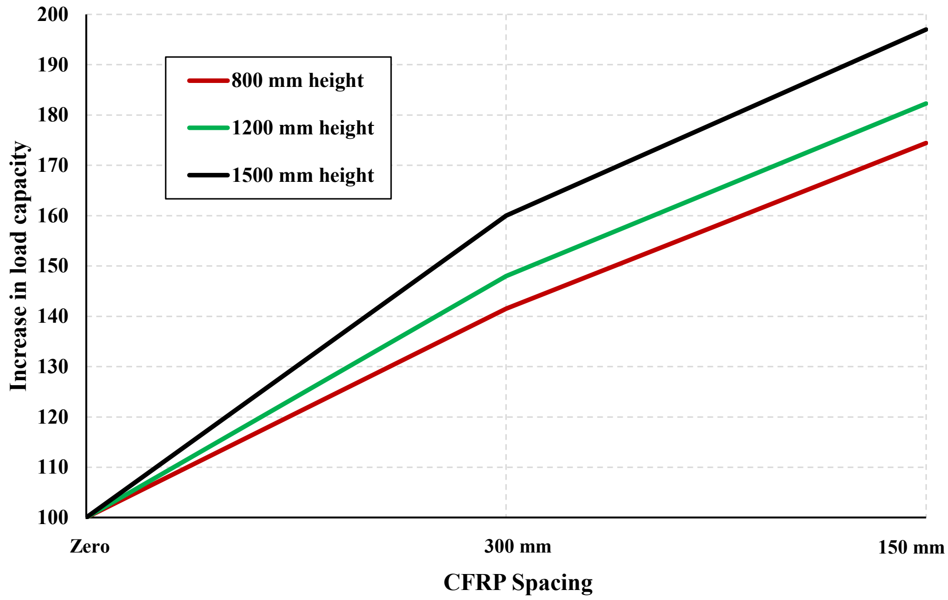


Figure 17. Effect of slenderness ratio on modulus of elasticity of RC spiral column.

3.4. Effect of Spacing Between CFRP Spiral Ropes

Figure 12 shows that in each group, with the same slenderness ratio, the load capacity increased as the spacing between CFRP ropes decreased. It can be seen that the repaired specimens with CFRP rope with a spacing of 150 mm exhibited an increase in load capacity more than the repaired specimens with rope at 300 mm spacing and reached a capacity more than the unheated specimen reached in all groups. The increase in load capacity exhibited by repaired specimens with CFRP rope with a spacing of 150 mm (H-80-R15, H-120-R15, and H-150-R15), about 74%, 83%, and 96%, respectively, as the control heated specimen of each group, whereas the specimens repaired with CFRP at 300 mm (H-80-R30, H-120-R30, and H-150-R30) exhibited an increase in load capacity of about 42%, 48%, and 61%, respectively, compared to the control heated specimen of each group as shown in Figure 18. It can be seen that the effect of CFRP spacing is more noticeable in the highest slenderness ratio. This means the slenderness ratio increases as the effect of spacing increases. Regarding the ductility, toughness, and modulus of elasticity, the CFRP rope at 150 mm on specimens with

1500 mm of height exhibited an increase in load capacity of about 38–34%, 248–256%, and 54–68%, respectively, as the control heated each group, as shown in Figure 19, whereas the specimens with CFRP rope at 300 mm showed an increase in load capacity less than the ones with CFRP at 150 mm about 5.5–8.5%, 96–110%, and 29–39%, respectively, as the control heated of each group as shown in Figure 19. It can be concluded that as the CFRP spacing decreases the ductility, the toughness and modulus of elasticity increase, while the load capacity also increases. This is a similar conclusion to [11,17,44]. This is because columns confined by ropes at 150 mm of spacing experience a higher lateral pressure from rope confinement than from columns confined by ropes at 300 mm of spacing. This finding demonstrates the benefits of using ropes to wrap the RC columns because a stronger "confinement" of the concrete is produced by more CFRP ropes. By performing this, the concrete is prevented from expanding or cracking under strain, which may otherwise cause failure immediately. In order to keep the concrete from experiencing excessive lateral expansion under load, CFRP rope efficiently "holds" it. Higher overall strength results from the material's ability to maintain its integrity due to its confinement, particularly under compression.



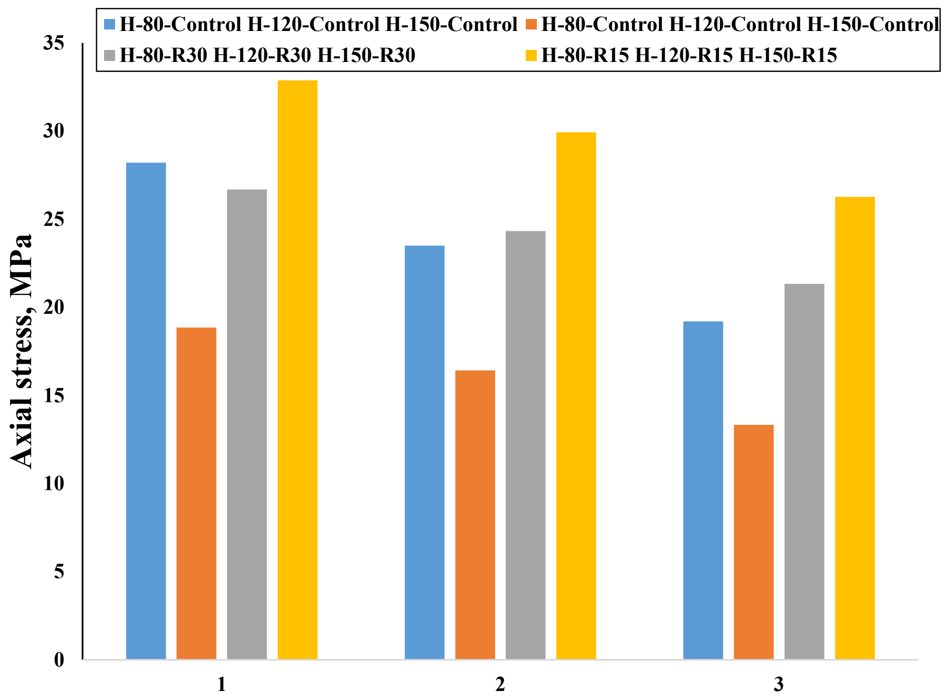


Figure 18. Effect of CFRP spacing on load capacity of RC spiral column.

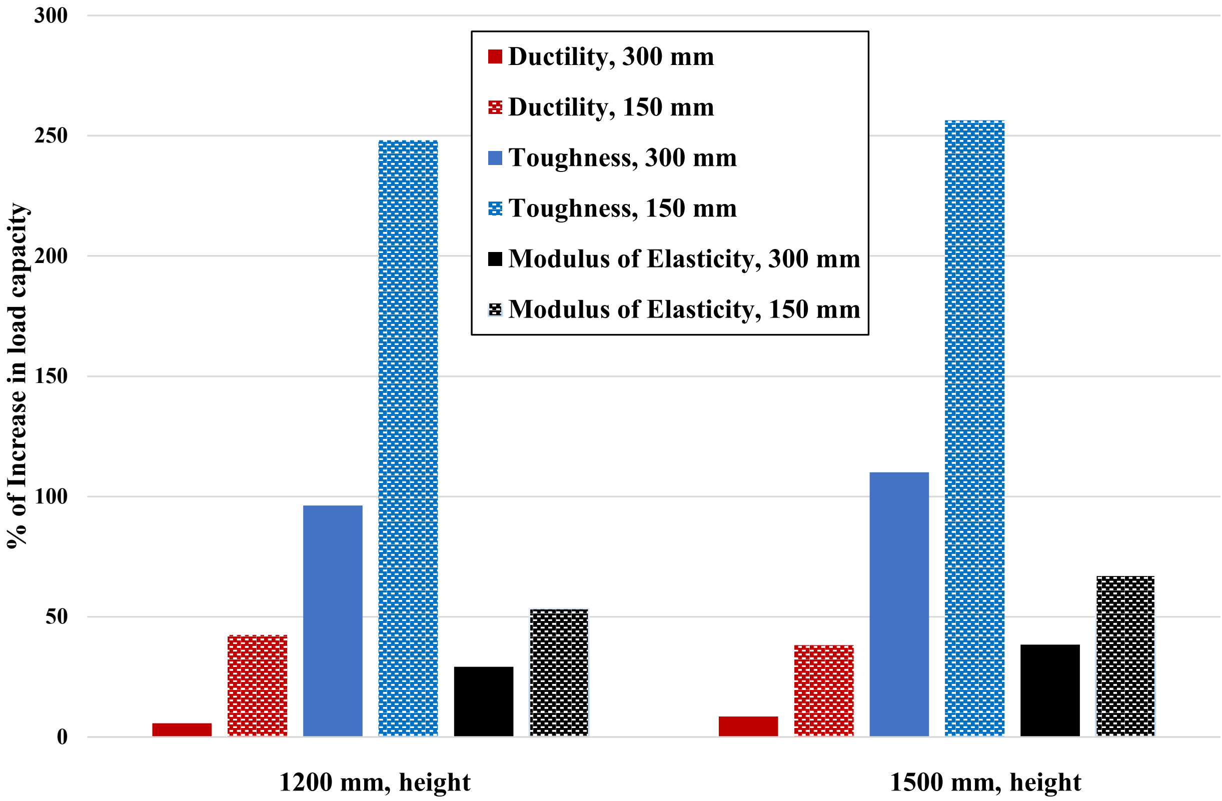


Figure 19. Effect of CFRP spacing on ductility, toughness, and modulus of elasticity of RC spiral column.

3.5. Effect of Elevated Temperature

The main objective of this study is to investigate the effect of heat temperature on the behaviour of RC spiral columns repaired with CFRP rope. Nine RC spiral column specimens were exposed to heat temperatures up to 600 °C, and the other three were kept at ambient temperature for comparison. Figures 20 and 21 display the effect of heat temperature on the RC spiral column performance. It can be shown that there is a significant effect of temperature on the behaviour of the RC spiral column. RC column specimens H-80-Control, H-120-Control, and H-150-Control exhibited a decrease in load capacity due to exposure to the heat temperature level of 600 °C, about (33%, 30.1%, and 30.5%), respectively, compared to the unheated specimen in each group. This is because of developing hair cracks in concrete due to heating, which cause the evaporation of water in concrete. This, in turn, results in a weakness in concrete and leads to a reduction in the load capacity of RC columns. Meanwhile, adding rope at 300 mm of spacing restores the capacity and reaches more than the unheated load capacity of the specimens (H-80-R30, H-120-R30, and H-150-R30) of about (−6%, 4%, and 11%), respectively. However, the specimens repaired with CFRP rope at a spacing of 150 mm (H-80-R15, H-120-R15, and H-150-R15) restore a load of about (16.6%, 27.4%, and 36.8%), respectively, more than the unheated specimen from each group as shown in Figure 22.

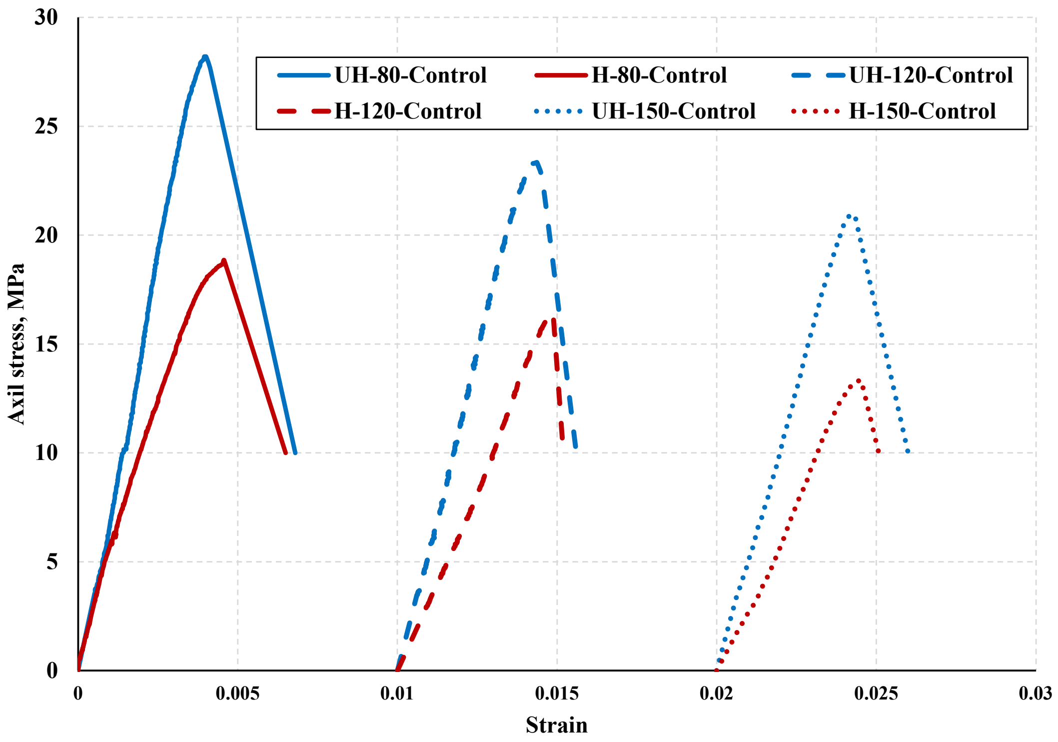


Figure 20. Effect of heat temperature on load capacity of RC spiral column.

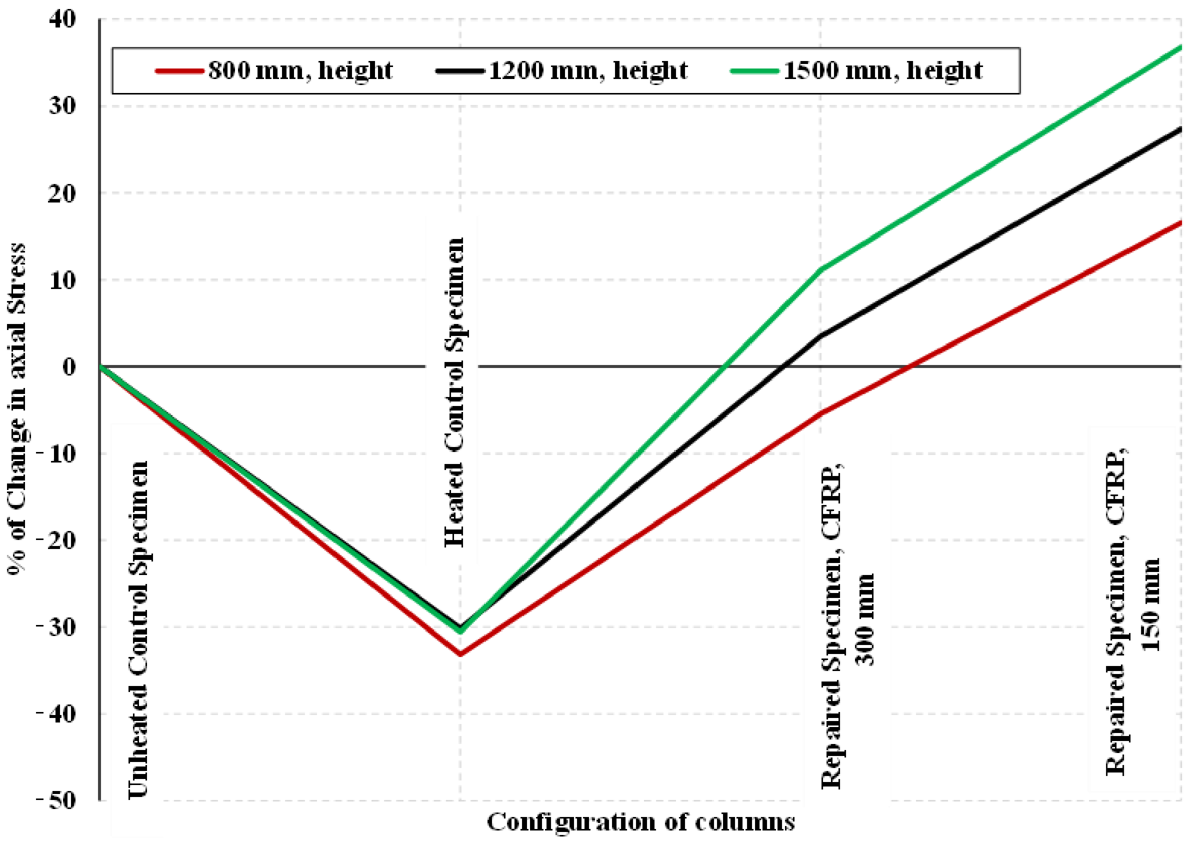


Figure 21. Effect of CFRP rope and heat temperature on load capacity of RC spiral column.

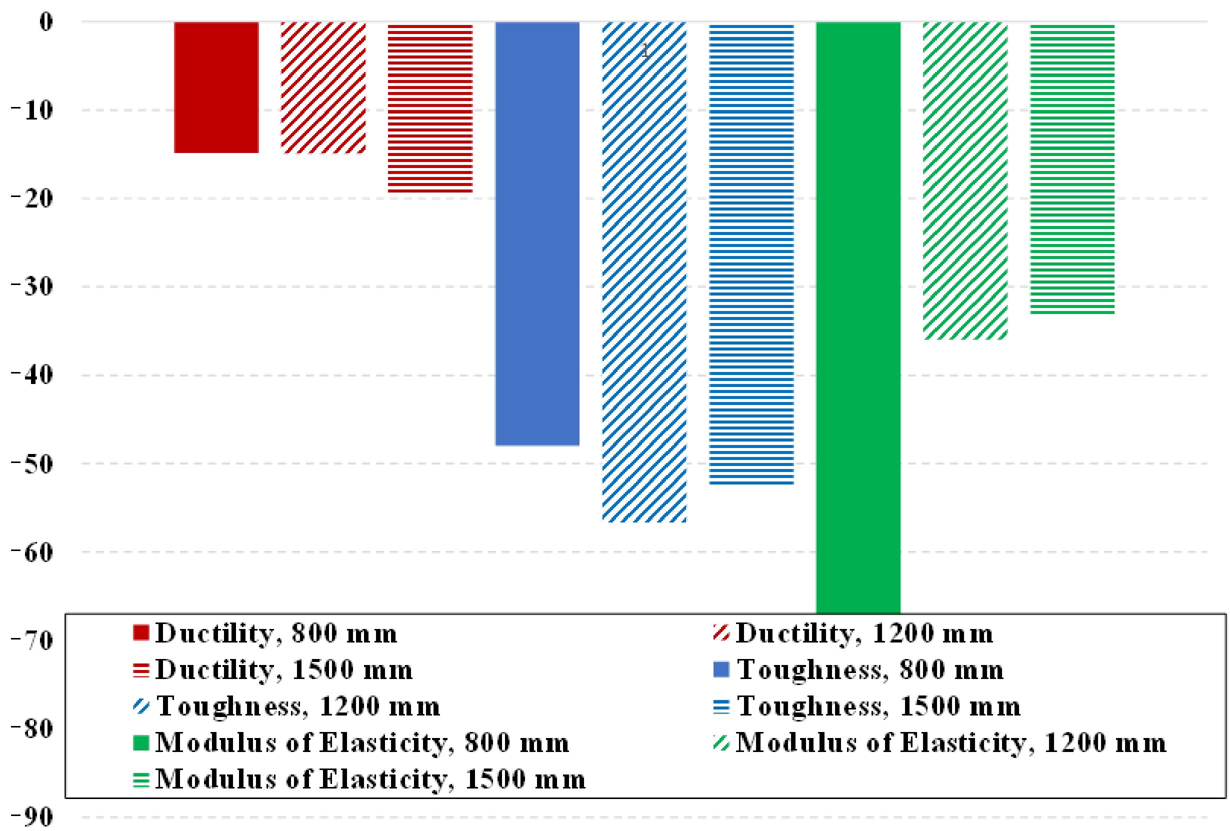


Figure 22. Effect of heat temperature on ductility, toughness, and modulus of elasticity of RC spiral column.

On the other hand, the temperature had an impact on the ductility, toughness, and modulus of elasticity. In general, specimens exposed to heat showed a reduction in these properties. When exposed to the temperature, all specimens ranging in slenderness ratios had a 12–20% reduction in ductility. Nevertheless, the toughness drops from around 58% to 48%. Ultimately, as Figure 21 illustrates, the modulus of elasticity decreased by approximately 65% to 32%. It is evident that the modulus of elasticity, toughness, ductility, and load capacitance are all reduced by the elevated temperature. It can be seen that the load capacity and the modulus of elasticity aspects are most significantly impacted by temperature.

Although it is not the sole reason, degradation from water evaporation is the main cause of concrete's decreased load capacity following exposure to high temperatures, such as 600 °C. Concrete deterioration at high temperatures is a complex combination of several processes that affect the inserted steel reinforcement, as well as the matrix of concrete. The chemically bonded water in the hydrated cement starts to evaporate at temperatures higher than 400 °C. In particular, the dehydration of calcium silicate hydrates (C-S-H), the primary bond phase in concrete, begins to accelerate from around 500 °C to 600 °C. The C-S-H structure breaks down as a result of the loss of this bonded water, reducing the concrete's overall strength. Additionally, steel reinforcement is commonly utilized in concrete. Although it is sensitive to thermal deterioration at high temperatures, steel's strength begins to decrease significantly at temperatures over 400 °C, and its yield strength may decrease regardless of whether the reinforcement has a better heat conductivity than concrete. Concrete and steel expand in various ways. Internal strains and cracking may result from the steel reinforcement expanding more than the surrounding concrete, especially when the concrete is confined or the steel is not well connected to the concrete matrix. Furthermore, the composite action of the concrete and reinforcement can be compromised if the bond between the steel and concrete is weakened as a result of microcracking or the loss of hydration products in the concrete.

4. Conclusions

This study aims to investigate the effect of the slenderness ratio and heat temperature on the damaged RC spiral column stress–strain behaviour. Based on the test results, the following conclusions are drawn:

- Using CFRP rope in repairing the specimens delays or prevents quick and brittle failure, unlike the unrepaired specimens.
- The reality that the CFRP rope did not debond or rupture indicates that there was adequate contact between CFRP ropes and the concrete.
- The elevated temperature of 600 °C resulted in a decrease in the load capacity, ductility, modulus of elasticity, and toughness of the RC spiral columns. The reductions were 33%, 15%, 40%, and 32%, respectively.
- The result showed that the columns with a height of 1500 mm were damaged at 600 °C and repaired using CFRP rope at 150 mm, recovering load capacity more than the unheated specimen by about 35%.
- Reducing the spacing between CFRP ropes resulted in a greater effective lateral confining pressure and enhanced CFRP effectiveness. This reduction in spacing led to an increase in capacity of approximately 37% to 40%. It can be concluded that the spacing between the ropes significantly influences the effectiveness of the CFRP.
- The slenderness ratio has a more significant impact on the load capacity of FRP-strengthened reinforced concrete columns than on unstrengthened ones. The repaired specimens, strengthened with CFRP rope and a slenderness ratio of 33.35, showed a strength increase of approximately 60% to 97% compared to the heated control specimen. This increase in strength is attributed to the confinement effect rather than an improvement in bending stiffness.
- CFRP ropes can be considered good confinement for spiral columns under axial strain.
- The greatest axial stress' corresponding axial strain and bearing load capacity decrease as the slenderness ratio increases.

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