Tikrit Journal of Engineering Sciences (2024); 31(3): 18-31
DOI: http://doi.org/10.25130/tjes.31.3.3

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Residual Strength of Concrete Beams Reinforced with GFRP Bars Exposed to Elevated Temperatures

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Keywords:
Beam strength capacity; Deflection; GFRP bars; Fire exposure; Residual strength.

Highlights:

- *Residual strength and deformation of GFRP-reinforced concrete beams exposed to high temperatures.*
- *Temperature increases in GFRP reinforcing bars, concrete core, and furnace during fire exposure.*
- *Fire-related behavior of loaded beams reinforced with GFRP bars.*

ARTICLE INFO
Article history:

Received	30 May	2023
Received in revised form	05 Aug.	2023
Accepted	02 Nov.	2023
Final Proofreading	29 Jan.	2024
Available online	24 Sep.	2024

Citation: Abdullah AN, Kassim MM. **Residual Strength of Concrete Beams Reinforced with GFRP Bars Exposed to Elevated Temperatures**. *Tikrit Journal of Engineering Sciences* 2024; **31**(3): 18-31.
http://doi.org/10.25130/tjes.31.3.3

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Abstract: The results of an experimental work to explore the effect of elevated temperatures on load resistance of reinforced concrete beams with glass fiber-reinforced polymers (GFRP) bars are reported in this paper. Twenty beams with cross-sectional dimensions of (120 x 200 x 1600 mm) were designed. Two specimens were evaluated at room temperature as reference beams, while the remaining eighteen were treated to high temperatures (200, 400, 600, and 800 °C) for 30, 60, and 90 minutes before being subjected to a similarly increased four-point load-up to the failure. The influence of raised temperature on load-deflection relationships as the failure modes for tested beams was examined and compared to a control beam. Compression failure is the most frequent failure mechanism in all the analyzed GFRP beams before and after exposure to high temperatures, according to the experimental test data. However, as the temperature and exposure time increased, the failure mode shifted from compression to balance and tensile failure. The beam heating was done under elastic loading, making these results unique. After 60 minutes of exposure to temperatures of 200, 400, 600, and 800 ºC, the residual loading capacity of heated beams was reduced by 13%, 17.39%, 32.6%, and 41.3%, respectively, compared to the control beam.

المقاومة المتبقية للعتبات الخرسانية المسلحة بقضبانGFRP بعد تعرضها لدرجات حرارة عالية

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الخلاصة

نتائج الاختبار العملي لاستكشاف تأثير درجات الحرارة المرتفعة على مقاومة الحمل في العتبات الخرسانية المسلحة بقضبان البوليمرات المقواة بألياف زجاجية في هذا البحث. تم تصميم عشرين عتبة بأبعاد مقطعية (١٦٠٠x ٢٠٠ x١٢٠ مم) وتم فحص عينتين كنماذج مرجعية عند درجة الحرارة الغرفة، بينما تم فحص الثمانية عشر المتبقية بدرجات الحرارة مختلفة (٢٠٠, ٤٠٠ , ٦٠٠ , ٨٠٠ °م) لمدة ٣٠ , ٦٠ و٩٠ دقيقة قبل تعرضها لزيادة مماثلة في الحمل بأربع نقاط حتى الفشل. تم فحص تأثير درجة الحرارة المرتفعة وتأثيرها على مقدار التحمل النهائي، حيث تم فحص أوضاع الفشل للعتبات المختبرة ومقارنتها بنتائج النماذج المرجعية. ظهر فشل الضغط أكثر آليات الفشل شيوعا في العتبات المسلحة بقضبان البوليمرات المقواة بألياف زجاجية التي تم تحليلها قبل وبعد التعرض لدرجات حرارة متزايدة، وفقا لبيانات الاختبار التجريبية. ومع ذلك، مع ارتفاع درجة الحرارة ووقت التعرض، يتحول وضع الفشل من الضغط إلى فشل التوازن والشد. ان الحداثة في نتائج هذه الاختبارات هي تسليط حمل موزع مقارب للتحمل المرن للعتبات اثناء تعريضها بالكامل لدرجات الحرارة العالية، ومقارنة مع النماذج المرجعية قل مقدرة التحمل للعتبات المسخنة بنسبة ١٣,٠٤٪، ١٧,٣٩٪، ٣٢,٦٪ و٤١,٣٪ بعد ٦٠ دقيقة من التعرض لدرجات حرارة (٢٠٠, ٤٠٠ , ٦٠٠ , ٨٠٠ °م) على التوالي.

الكلمات الدالة: المقاومة المتبقية، تعرض للنار، قضبان GFRP، مقاومة العتبة، هبوط العتبة.

1.INTRODUCTION

Fiber-reinforced polymer (FRP) material has superior features to steel reinforcement, such as excellent durability, corrosion resistance, and tensile strength. Due to its increased tensile strength, using GFRP bars may be critical in various structural applications, such as bridges and marine structures, where corrosion of rebar steel will occur. Several studies have related fire resistance to normal-weight concrete members reinforced with GFRP. Furthermore, such research has considered various GFRP-specific issues to develop design codes for FRP-reinforced concrete members. Tanano et al. [1] conducted an experimental study to assess the FRP-reinforced concrete beams' residual strength after being subjected to high temperatures. The results showed that with the increase in heating temperature, the bonding strength of the epoxy matrix in the concrete beams of FRP decreases. The beams reinforced with FRP inorganic matrix suffer little loss in residual strength when exposed to elevated temperatures up to 250 °C. All types of FRP reinforcement exhibited a decrease in residual tensile strength after exposure to high temperatures. Sakashit et al. [2] used Various FRP bars with various surface roughness and fiber orientations to investigate the impact of fire on reinforced concrete beams. All samples were preheated to 1000 °C for 180 minutes and then heated for 1000 ^{0}C under loading. Furthermore, no failure was caused by the GFRP-reinforced beam samples for up to 3 hours of heating, with a temperature on the underside of the beam reaching 680°C. Sadek et al. [3] compared the concrete compressive strength and fire resistance of RC beams reinforced with GFRP to those reinforced with steel bars. RC beam samples were subjected to 60% of their final load during the fire test. The results showed that the large cracks formed during the experiment were the main failure mode. Furthermore, utilizing GFRP bars results in a significant drop in fire resistance compared to a beam reinforced with steel bars. It should be noted that the researcher used a concrete cover of (25 mm) for flexural reinforcements, which may contribute to low fire performance for RC beams specified in an experimental program. Abbasi and Hogg [4] examined the experimental investigation of fire resistance to concrete beams reinforced with GFRP bars with various shear reinforcements created by ACI440.1R-15 [5]. GFRP bars were used in the first beam, and steel bars were used as shear reinforcement (stirrup) in the second beam. Beams within the furnace were subjected to a load of 40 kN at four places. This load was distributed over the beam and remained constant during the testing. The load-deflection behavior showed nonlinear behavior up to 60 kN; the highest deflection was obtained at 90 kN. The first beam's failure load and mid-span deflection were recorded in the experiment to be greater than the second beam. This variation is because the second beams had a weaker rebar-concrete bond strength than the first beam. Rafi et al. [6] studied the fire resistance of reinforced concrete beams using CFRP bars according to the specification ISO 834 fire curve [7]. The results showed that concrete beams reinforced with CFRP bars were stiffer than equivalent steel-reinforced concrete beams and collapsed due to concrete compression crushing, according to ACI 440.1R-15 [5]. Humur and Çevik [8] investigated the effect of elevated temperatures up to 800 ^{0}C for one hour on the flexural strength and deflection response of engineered geopolymer composite (EGC) and engineered cementitious composite (ECC). After exposure to 400 ^{0}C and above, the flexural load and deformation capacity of all samples were significantly reduced due to the polyvinyl alcohol fiber (PVA) melting, burned entirely, and lost most of its mechanical properties at a heat exposure higher than 400 ^{0}C. Jomaa'h et al. [9] explore the effect of fire at extreme temperatures ranging from 450 °C to 750 °C. It has been proven that when the temperature increased within this limit, the compressive strength of normal-strength concrete decreased by 93%. According to previous studies, the FRP RC beams' fire resistance was greater than traditional steel-reinforced concrete beams but with a larger deflection. Most of these studies only considered fire resistance in terms of FRP RC by examining beam behavior from fire initiation time until concrete beam collapse. On the other hand, the influence of the elevated temperature on the FRP RC beams' load-deflection behavior has yet to be studied extensively, either experimentally or numerically. As a result, the fundamental purpose of this research is to:

1- Determine the influence of elevated temperatures and exposure duration on the residual strength capacity of GFRP-reinforced concrete beams.
2- Measure the temperature rise of the GFRP reinforcing bars, concrete core, and furnace during the fire exposure of reinforced concrete beams.
3- Present the load-deflection behavior for reinforced concrete beams with GFRP bars after high-temperature treatment (30, 60, and 90 minutes) at 200, 400, 600, and 800°C.

The new findings of this research were in taking new variables that have not been explored earlier for a beam totally exposed to fire when loaded within elastic range during the previous points and the rest of the. Understanding the beam reinforced with GFRP behavior at the initiation of cracking load, crack growth pattern, residual ultimate strength, and failure mode can be improved by studying under these conditions and understanding their influence. To accomplish this, twenty GFRP-reinforced concrete beams were cast, cured, heated, and tested under four static point loadings. The present experiment analyzed and investigated beam capacity degradation after exposure to varying rising temperatures.

2.EXPERIMENTAL PROGRAM

The following section specifies the experimental program utilized in this study to investigate the effect of increased temperatures and duration time on the GFRP-reinforced concrete beams' behavior. The test setup, equipment, and measurement tools used to record the test results are fully specified, as well as the geometric and material properties of the RC specimens used in the experiment are described. The compressive strength of used concrete was 46 MPa. RC beam's material and geometry are described in the following section.

2.1.Materials

The following material properties were used in the present experimental tests:

Normal-weight concrete: The normal-weight concrete mixture (cement = 400 kg, sand = 814 kg, coarse aggregate = 880 kg, and superplasticizer = 2.4 kg) was designed according to ACI code 211.1-91 [10]. Six concrete cubes with 100 mm dimensions were cast for each beam specimen and hardened for 28 days before being tested to determine the compression strengths of the concrete at room temperature using BS 1881-116:1983 specifications [11]. According to the test results, the average concrete compressive strength was 46 MPa.

- ***GFRP Bars:*** All experimental RC beam specimens are reinforced with GFRP bars with a diameter of 13 mm diameter as a main (tension) reinforcement. Table 1 lists the mechanical and thermal parameters of the GFRP bar, as reported by the manufacturing datasheet.
- ***Steel Bars:*** Grade 40 with a diameter of 6 mm deformed steel bars were used as shear-reinforced (stirrups) for all RC beam specimens. The results of a uni-axial tensile test conducted to ascertain the mechanical characteristics of the steel bar are shown in Table 2.

Table 1 Characteristics of the GFRP.

Property	Unit	Value
Thermal Conductivity	W/mk	< 0.5
Density	G/cm^3	1.9 - 2.2
Tensile Strength	MPa	758
Specific Resistance	μΩ cm	> 1012
Elastic Modulus	GPa	46
Bond Strength	MPa	13.7
Coefficient of Thermal	expansion	0.6×10^{-5}

Table 2 Characteristics of Steel Bar Used.

Property	Unit	Value
Ultimate Strength, f_u	MPa	477
$\varepsilon_y = f_y/E_c$	---	1.59x10^{-3}
Yield Stress, f_y	MPa	318

2.2.Reinforcement Details and Geometric Properties

Figure 1 shows the geometry and reinforcement of the RC beam specimens. Table 1 illustrates the designation and details of these specimens used in the present tests. All the GFRP reinforced concrete beams were designed according to ACI 440.1R-15 [5] to fail at the ultimate load of 92 kN when tested at room temperature (20 ⁰C) by concrete crushing, to achieve a safety failure mode for GFRP reinforced concrete beams. The concrete GFRP beams were reinforced with 2 Ø13 mm GFRP bars in tension and compression zones, which also work as the hanger for a shear reinforcement that includes Ø6 mm spaced at 80 mm. The beams were subjected to a static four-point load distributed at L/3, as illustrated in Fig. 1. The beams were first thermally exposed in the furnace to the required time and temperature with an applied uniform load of 10% of the ultimate load capacity. Then, the furnace cooled to the ambient temperature. After that, a four-point load was applied to the beams until they failed.

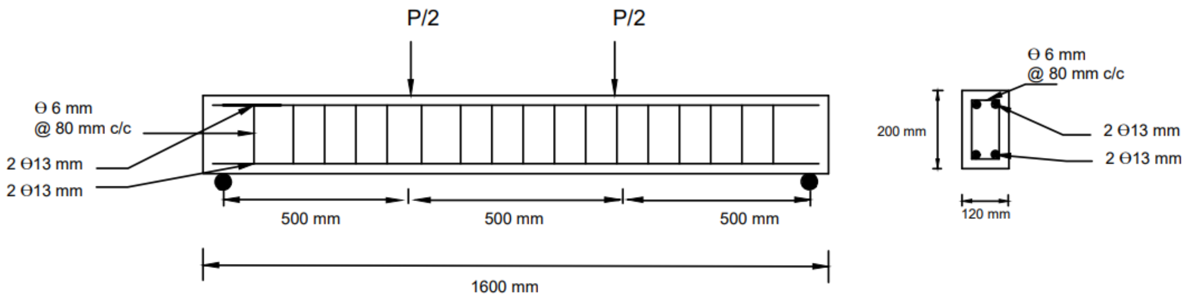


Fig. 1 Information About the Sample GFRP RC Beams.

Table 3 GFRP RC Beam Specimens Designation and Details.

Beam Series	Beam Designation	Max Temp. ˚C	Time, min
Control Beam	RB	20	--
Series 1	BT2.60	200	60
	BT4.60	400	60
	BT6.60	600	60
	BT8.60	800	60
Series 2	BT6.30	600	30
	BT8.30	800	30
Series 3	BT4.90	400	90
	BT6.90	600	90
	BT8.90	800	90

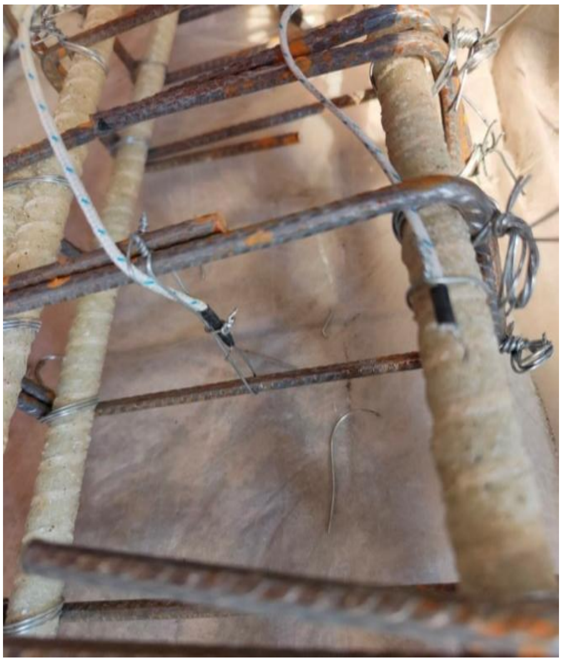
3.STRUCTURAL AND THERMAL TESTING

3.1.Thermal Test

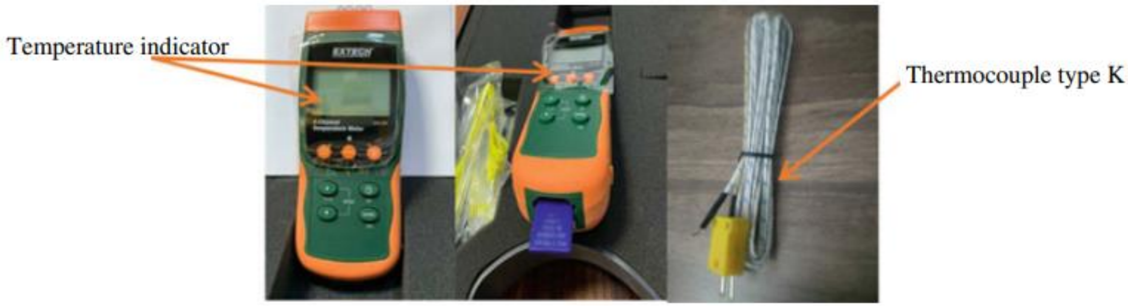
Twenty GFRP RC beams were heated and cooled in the heating-cooling phase of the testing at various elevated temperatures and duration time; two beams were tested for each variable, and the average was accepted for the results, which was (600 and 800 ⁰C) for 30 minutes; (200, 400, 600, and 800 ⁰C) for 60 minutes; and (400, 600, and 800 ⁰C) for 90 minutes duration using almost similar heating rates or temperature periods for each concrete beam. Additionally, a kerosene furnace was designed, built, and calibrated in this study and utilized to provide controlled heat to warm up GFRP RC beam specimens before applying static load. Outside the furnace, the beam specimens' end supports were fixed, and steel rods were welded beneath the beams' needed span length. These rollers allow the beam to expand freely at both ends outside the furnace while preventing the development of internal axial forces. The RC beams naturally cooled in the air to room temperature. Three K-type thermocouples (temperature multimeter) were also used to reflect and report rises in temperature over time. These thermocouples were used to measure the environment's temperature: one was fixed in the concrete core, another was attached to the GFRP bar reinforcement surface, and the third was enclosed inside the furnace. The time-temperature rise was manually recorded using these thermocouples, connected to a digital readout apparatus, as shown in Fig. 2 (b).

3.2.Mechanical Test

In terms of structural test, the reference beams and elevated temperature exposed GFRP-RC beam specimens were subjected to a gradual raising concentrated four-point static loads up to failure using a hydraulic jack on a steel frame, as shown in Fig. 3, with a loading increase interval of 2 kN. The load cell was fitted between the hydraulic jack and the load-distributing steel beam to measure and record the load value at each load increment. Under the mid-span of the beam, a single dial gauge with an accuracy of 0.01 mm was positioned to measure the vertical deflection corresponding to each load increment. To measure deformations in the tensile and compression zones, two dial gauges with 0.001 mm accuracy were also mounted, i.e., one in the tensile region and the other in the compression region. The load-deflection relationships for GFRP RC beams during fire exposure at various high temperatures were determined using a single dial gauge with an accuracy of 0.01 mm, placed over the mid-span of the beam.



(a)



(b)

Fig. 2 Heat Measurements (a) Thermocouple Positions, (b) Digital Monitor and Thermocouples.

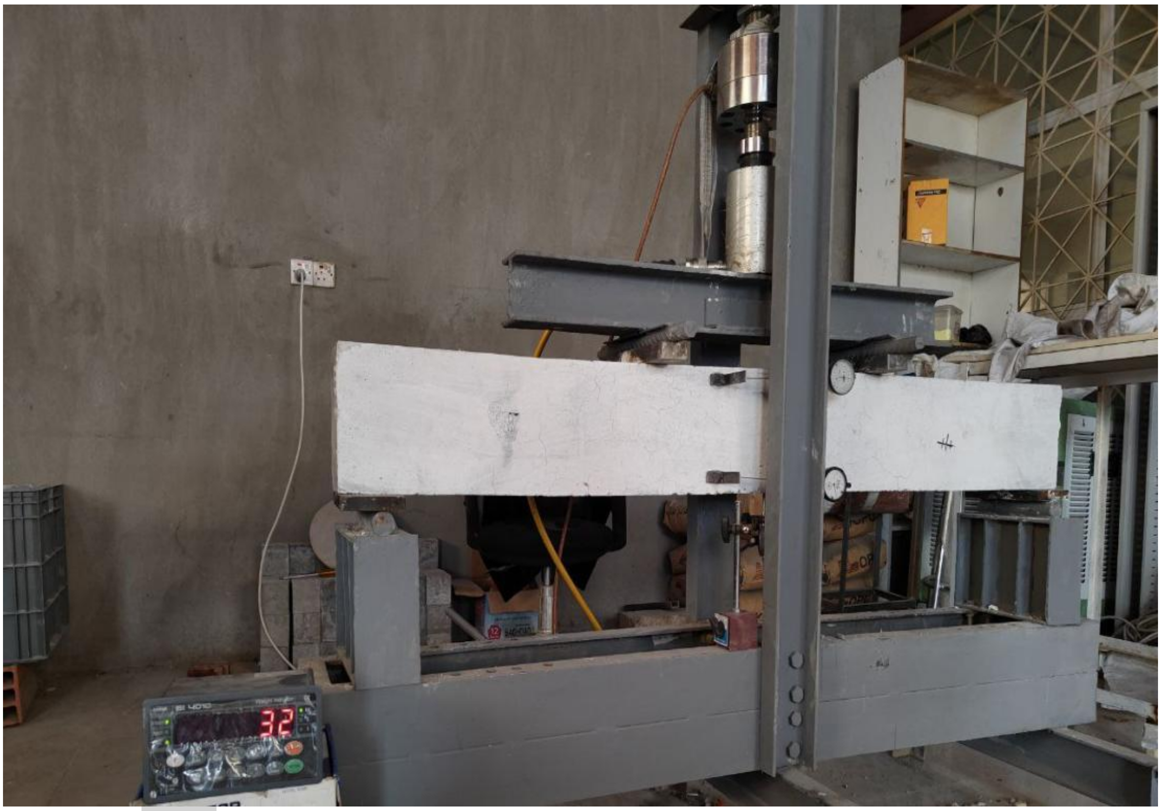
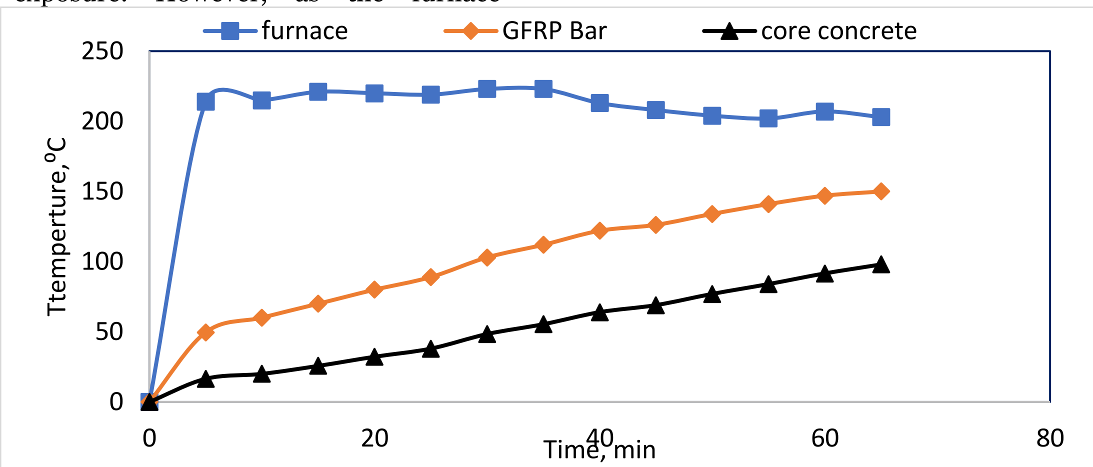


Fig. 3 The GFRP-RC Beam Specimen Test Setup Following Fire Exposure.

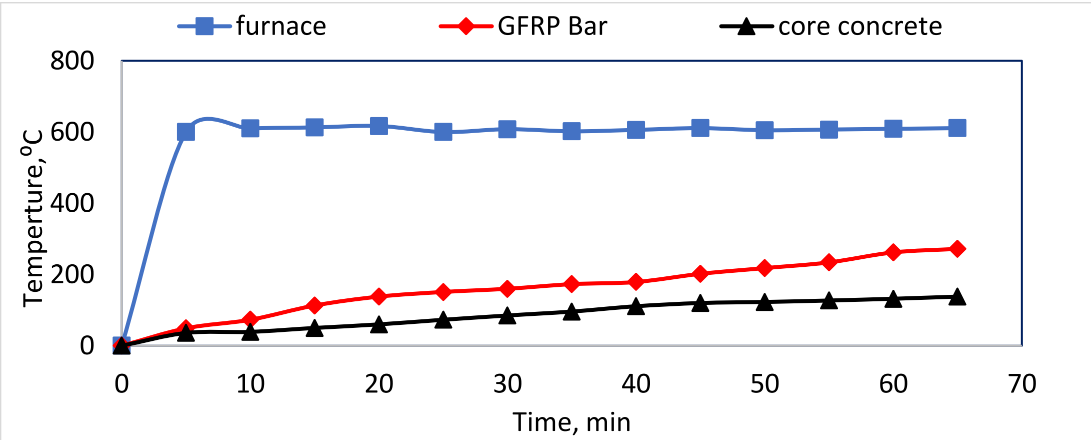
4. RESULTS AND DISCUSSIONS

4.1.Temperature-Time Histories

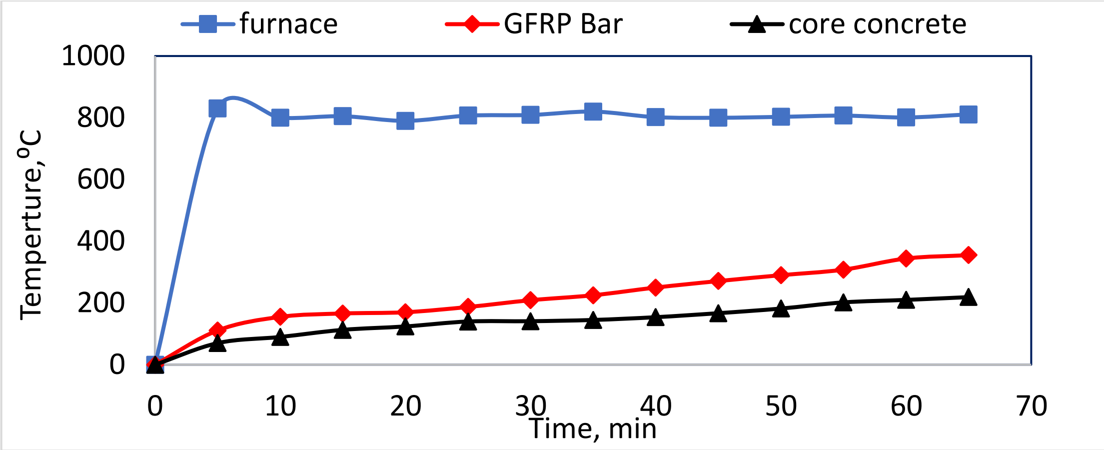
As was previously mentioned, the GFRP-reinforced concrete beam samples were heated in a specially constructed kerosene furnace. Ten percent of the ultimate load-bearing capacity of these RC beams designed after heating was applied as a distributed load on these beams initially before heating. Thermocouples connected to a digital reader were used to monitor and record time-temperature histories at the surface of the concrete and the surface of the GFRP bars for every beam as it heated up and the temperature change in the furnace. The temperature and time histories of all GFRP-RC beams at varied target temperatures are shown in Fig. 4. As it was possible to specify that the heating rate in a furnace was nearly the same for all GFRP-RC beams, which was shown by a sharp increase in temperature from zero to 800 ⁰C and stay constant during the rest test. All beams, after heating, underwent natural air cooling. Additionally, Fig. 4 demonstrates that the furnace's temperature value was the desired temperature shortly after 5 minutes of heating and stayed there for the test time, proving that the furnace's rapid heating caused the concrete surface to be exposed to a high temperature during the early phases of heating, simulating the condition of the building elements during fire exposure. However, as the furnace temperature increased, the heat gain rate for the concrete core and reinforcing bar varied, and the beam's temperature also increased. At the start of the test, these temperatures increased until the heating process finished. The GFRP bars' low thermal conductivity, as previously mentioned [12], is a critical contributor to this phenomenon. The concrete coating and cover help reduce the temperature conveyed to the GFRP bar. Fig. 4 (BT2.60) shows that when testing RC beams at 200 ⁰C, the GFRP bars reached a maximum temperature of 150 °C. Furthermore, the test results show that when the temperature at the GFRP bars surpassed the glass transition degree of temperature (60 ⁰C to 82 ⁰C) [13], the resin first melted and then evaporated [13]. On the other hand, the GFRP bars' glass fibers were unharmed and could carry tension strength at the concrete beam section connected with the tension zone. Fig. 6 depicts the temperature difference between the furnace and the GFRP bars utilized in GFRP RC beams for the elevated temperatures addressed in this work. Even at extremely high temperatures, the temperature differential between the furnace and the GFRP bars was large, demonstrating the low temperature conveyed from the concrete to the latter due to the latter's weaker thermal conductivity than steel bars [12].



BT2.60



BT6.60



BT8.60

Fig. 4 Time-Temperature Histories of Heated GFRP-RC Beams at Various High Temperatures.

Fig. 5 GFRP Bars Reached a Temperature of 300 °C in Beam (BT4.90).

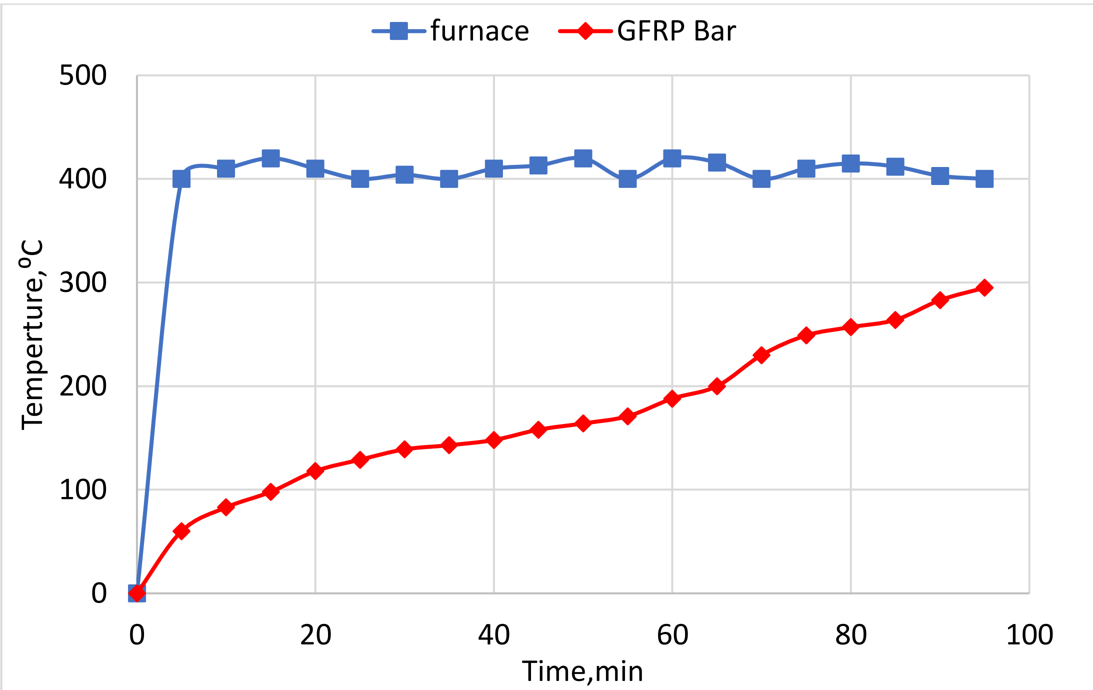


Fig. 6 Temperature Variations in the Tested Beam between the Furnace and the GFRP Bar.

4.2.Load–Deflection Relationships

At all evaluated temperatures, GFRP RC beams at different high temperatures are shown in Fig. 7 and Fig. 8 with the load-mid-span displacement correlations and failure modes. Table 4 provides an overview of each evaluated GFRP-RC beam's maximum deflection at failure and ultimate load-bearing capability based on the experimental test. Fig. 7 illustrates the concrete crushing, tension, and balancing failure modes that collapsed the reinforced GFRP-RC beam, along with the cracking patterns that resulted from these failures. Using the control beam (RB) test results as a benchmark, the performance of the GFRP RC beams subjected to high temperatures was evaluated. In all beam tests, flexural cracks with an average width of 0.07 mm started to appear in the tension zone of the beam's mid-span at a load value of 11 kN, representing about 11-20% of the ultimate load capacity. Then, a second set of inclined cracks developed and propagated from the beam's end at the tension zone in the loading point's direction. Enlarging until failure eventually occurred by compression failure, but as the temperature rose, switching the failure mode from compression to tension failure or balance failure. As shown in Figs. 7 and 8 and Table 4, the control beam failed at 92 kN as the ultimate load and 26.14 mm as the associated deflection. Fig. 8 shows the load-deflection relationship of the tested GFRP-RC beams used to examine the effects of higher temperatures on the deformation characteristics of GFRP-RC beams. Each beam exhibited three behaviors: elastic, plastic, and failure point. Fig. 8 further demonstrates how, following exposure to temperature values of 200, 400, 600, and 800 ⁰C for 60 minutes each, GFRP-RC beams' maximum bearing load resistance decreased by 13.04, 17.39, 32.6, and 41.3% respectively, compared to the control beams load resistance. The highest carries resistance to a load of GFRP-RC beams with change time at a fixed temperature dropped by 17.39% to 26.1% for beams (BT4.60 and BT4.90), 15.21% to 32.6% for beams (BT6.30 and BT6.60), and 17.4% to 41.3% to 50% for beams (BT8.30, BT8.60, and BT8.90) respectively, according to Fig. 9. The relationship between temperature and the reduction in ultimate load capacity for tested GFRP RC beams is also shown in Fig. 10 and Table 4. Due to deterioration in the strength of the concrete and reinforcing GFRP bars under high temperatures, the load resistance of the beams decreased. Fig. 8 also demonstrates how the ultimate load capacity decreased and the corresponding deflection of the beams also relatively decreased as the temperature increased, a similar result in Haitham Al-Thairy [14] because of thermal expansion and concrete cracking when exposed to high temperatures. Also, it was demonstrated that increasing the exposed elevated temperature increased the radius of the initial curvature due to existing thermal cracks created throughout the beam heating process and evolved under the applied load. The red colored cracks shown in Fig. 7 represent the thermal cracks produced in the furnace after 90 minutes at 800 °C and 10% of the Ultimate load.

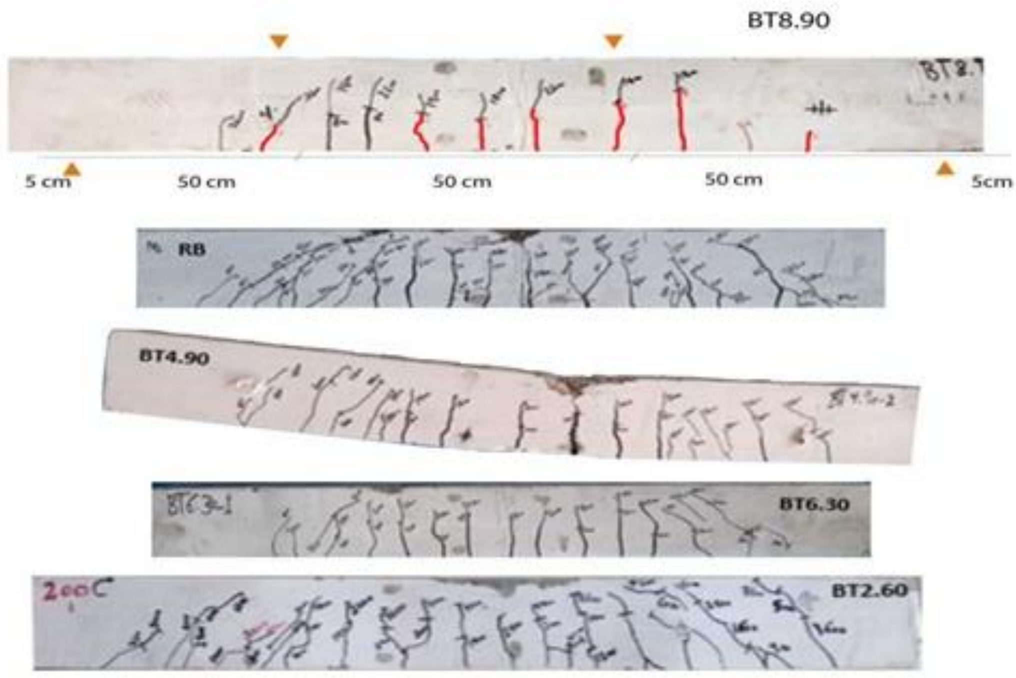


Fig. 7 Cracks and Failure Mode of Tested GFRP-RC Beams.

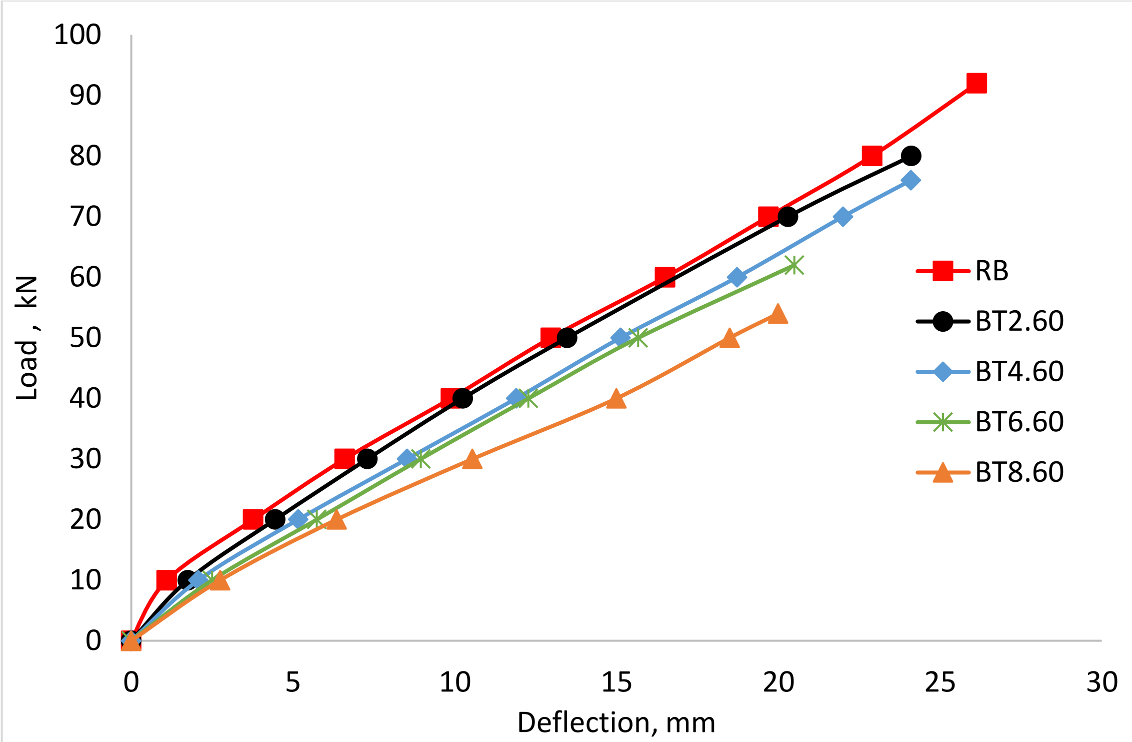
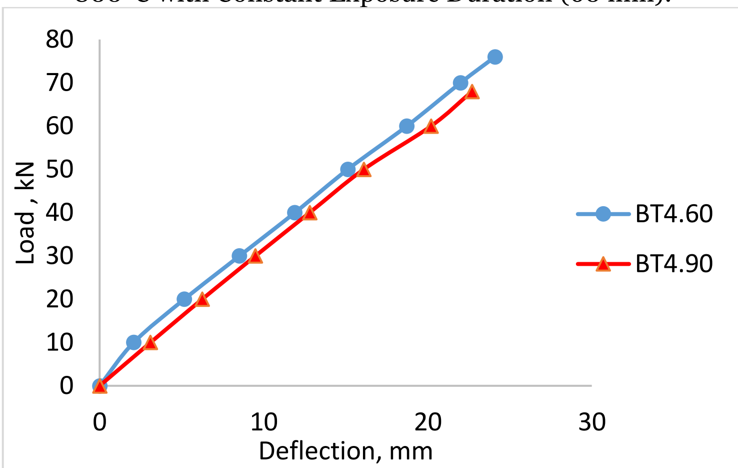
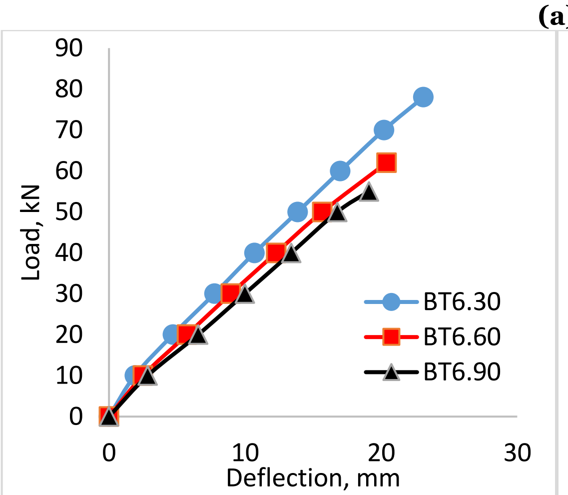


Fig. 8 Load-Deflection Characteristics of Examined GFRP-RC Beams at 200°C, 400°C, 600°C, and 800°C with Constant Exposure Duration (60 min).



(a)



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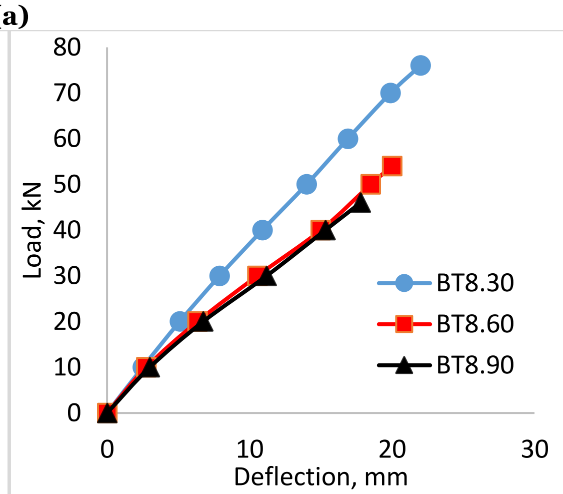
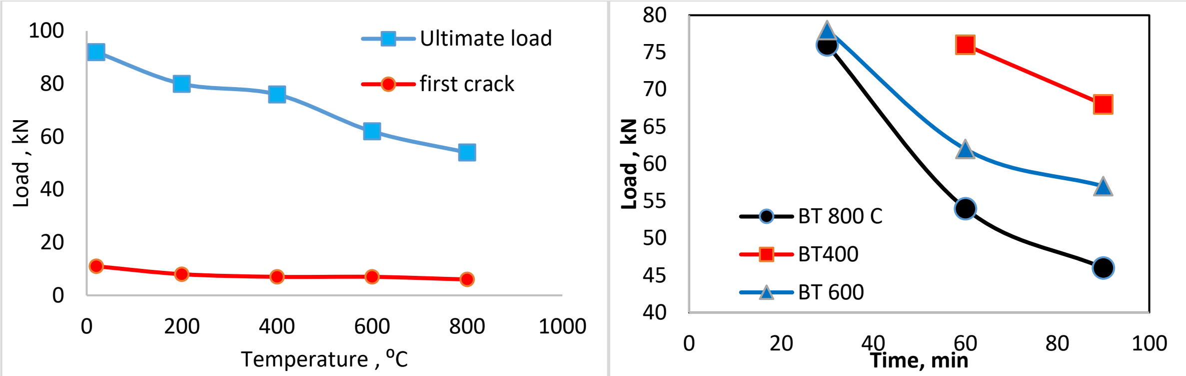


(c)

Fig. 9 Relationships between Load and Deflection for GFRP-RC Beams Tested Under Varying Time Exposure (a) 30 min., (b) 60 min., and (c) 90 min.



(a) At different temperatures (b) For different duration

Fig. 10 The Influence of the Time and Exposure Temperature on GFRP-RC Beam Ultimate Load Capacity.

Table 4 The Test Findings Summary.

Beam designation	Temp., ^{o}C	First crack Load, kN	Ultimate load, kN	Max. Deflection, mm	Failure Mode
RB	20	11	92	26.15	Compression
BT2. 60	200	8	80	24.11	Compression
BT4. 60	400	7	76	24.1	Compression
BT6 .60	600	7	62	20.4	Compression
BT8.60	800	6	54	20	Compression
BT4.90	400	6	68	22.1	Balance
BT6.30	600	6	78	23.10	Compression
BT6.90	600	6	80	19.2	Balance
BT8.30	800	6	76	22	Compression
BT8.90	800	8	46	17.8	Tension

5.BEAM LOAD-STRAIN RELATIONSHIPS

5.1.Strain in the Compression Zone Concrete

Mechanical dial gauges were mounted in the longitudinal direction to measure the deformations on the extreme compression and tension concrete fibers on both sides of the beams, as shown in Fig. 11. The maximum concrete compression strain in this direction was recorded with top dial gauges and the tension strain of the concrete at the GFRP bars level by bottom dial gauges in a length of 220 mm in the beam's mid-span. Fig. 12 depicts the effect of increased temperature and exposure duration on the strain values. The effect of increasing the temperature (200, 400, 600, and 800 ^{o}C) with a fixed exposure time of 60 minutes is shown in Fig. 12 (a). In this study, an increase in strain was identified with an increase in temperature to 200 ^{o}C; a similar finding was observed in the work of Humur et al. [15]. When the temperature increased, the amount of strain decreased. The temperature stabilization effect at 400 °C and increasing the exposure time from 60 to 90 minutes is seen in Fig. 12 (b). The tensile stress was alleviated by increasing the exposure period. Figs. 12 (c) and (d) illustrate the effect of increasing the exposure period (30, 60, and 90 minutes) at constant temperatures of 600 and 800 °C, revealing a significant effect on the strain, with increasing the exposure time decreasing the strain. Tao et al. [16] found that the strain decreased with compressive strength reduction.

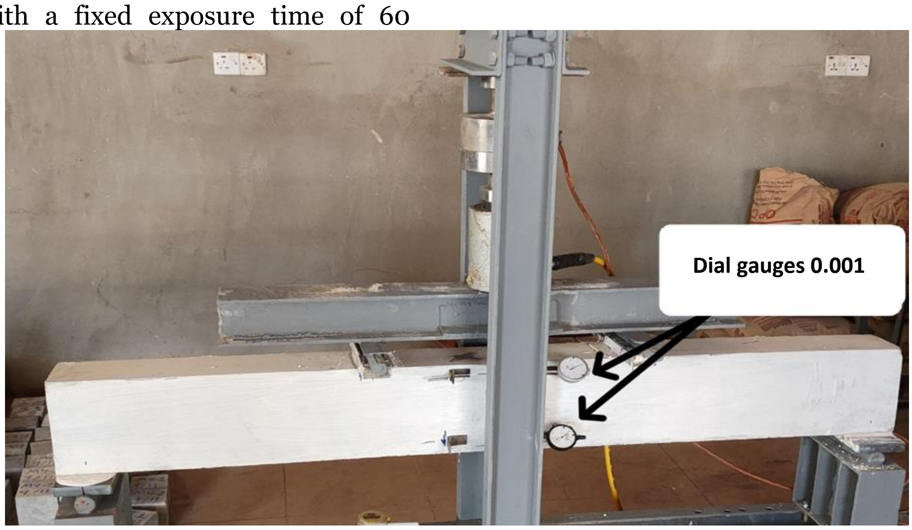


Fig.11 Dial Gauge Installation Positions.

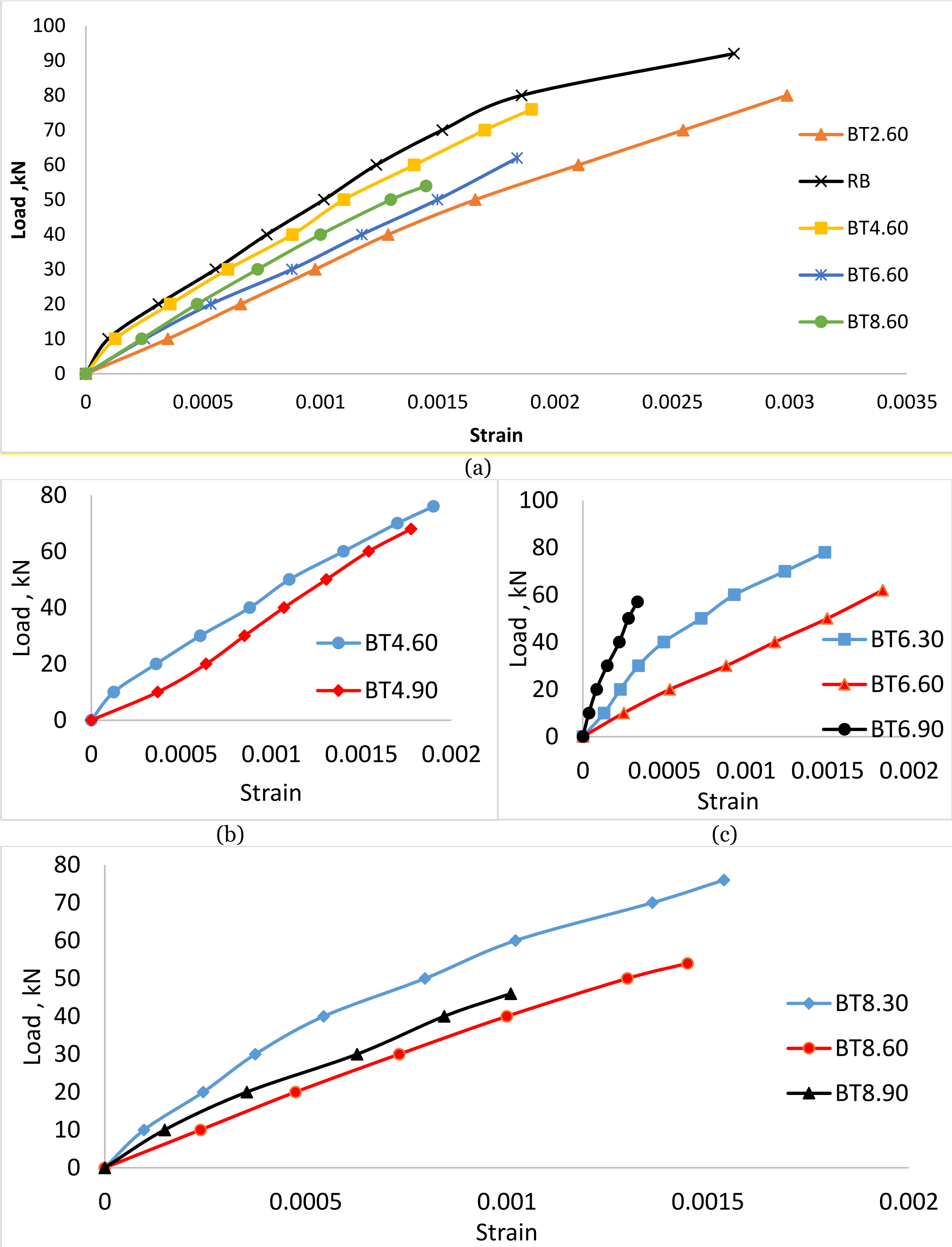
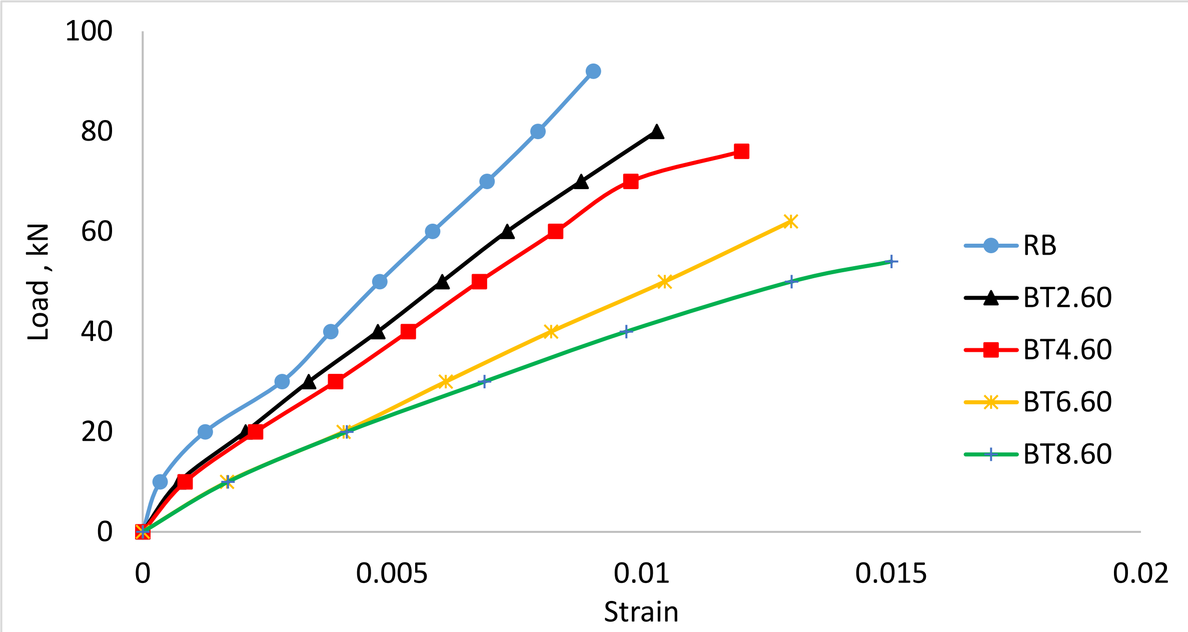


Fig.12 Load-Strain Relationships for Concrete, (a) Effect of Increased Temperature and Exposure Time, (b, c, and d) Effect of Increasing the Exposure Time at Stabilized Different Temperatures.

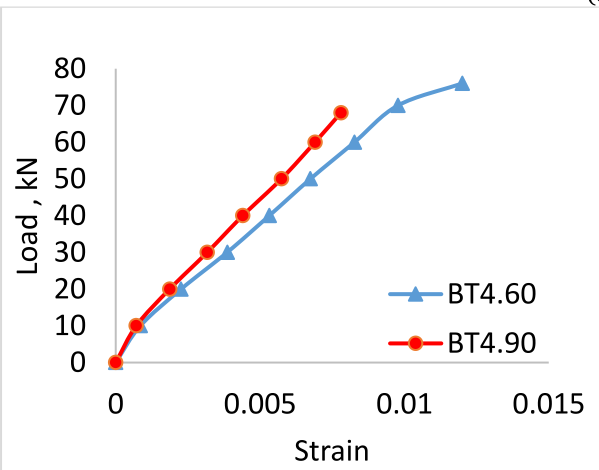
5.2.GFRP Reinforcement Strain

The tensile strain in the concrete and GFRP bars was measured using bottom dial gauges, as specified in section 5.1 and illustrated in Fig. 11. Fig. 13 depicts the effect of increased temperature and exposure duration on strain values. The effect of increasing the temperature (200, 400, 600, and 800 ⁰C) with a fixed exposure time of 60 minutes is shown in Fig. 13 (a). When the temperature was raised, there was an increase in strain [17]. Fig. 13 (b) shows the effect of maintaining the temperature at 400 °C and increasing the exposure time from 60 to 90 minutes. The strain was clearly lowered by increasing the exposure period. Meanwhile, Figs. 13 (c) and (d) indicate that increasing the exposure time (30, 60, and 90 minutes) at constant temperatures of 600 and 800 °C significantly affected strain, with increasing exposure time increasing strain.

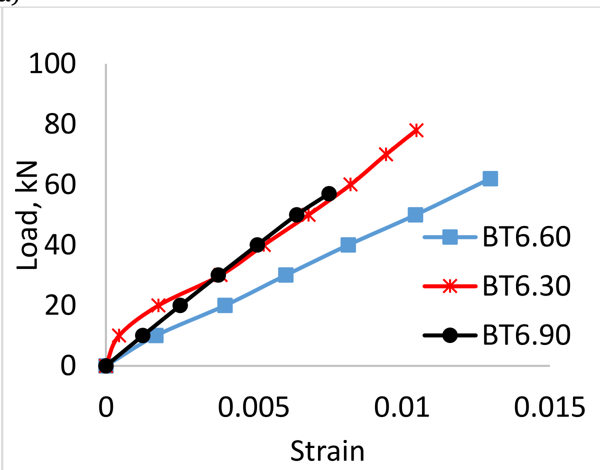
Increased strain for both groups was found by increasing the time from 30 to 60 minutes. However, when the same two groups were exposed to increased exposure time, the strain dropped considerably, as did the failure transfer from the concrete to the GFRP bars. As stated before, thermal insulation by surrounding concrete cover, isolating it from direct heat, is one of the most important causes for the high temperature of the GFRP growing with increasing duration time.



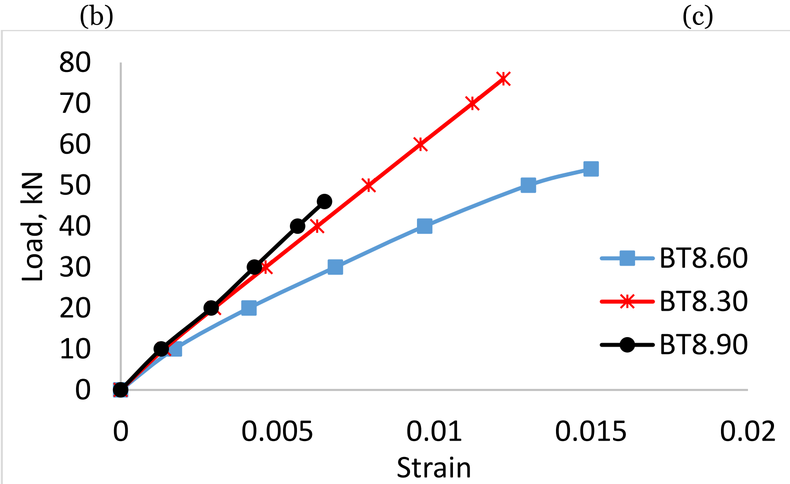
(a)



(b)



(c)



(d)

Fig.13 Load-Strain Relationships for GFRP.

5.CONCLUSIONS

The following is a description of the experimental test conclusions, the failure mechanisms, and the behavior of normal-weight concrete beams reinforced with GFRP bars and subjected to high temperatures:

- The GFRP RC beam flexural capacity is dramatically diminished when subjected to high temperatures over lengthy periods. Compared to the ultimate flexural capacity of GFRP-reinforced concrete beams not exposed to high temperature, the maximum drop in flexural capacity of the GFRP RC beam (BT8.90) when exposed to 800 ⁰C for 90 minutes was equivalent to 50%.
- GFRP RC beams deflected significantly when subjected to extremely high temperatures.
- When exposed to high temperatures, GFRP bars demonstrated a slow rate of temperature rise. The GFRP bar reached its maximum temperature of 355 ⁰C after 60 minutes of heating the beams at 800 ⁰C.
- Compression failure was the most common failure mode for GFRP-reinforced beams at ambient and higher temperatures. As a result, when constructing reinforced concrete beams reinforced with FRP bars with high tensile strength, tensile and balance failures must be considered, as occurred in beams BT8.90 and BT4.90, respectively, when the temperature drastically rose and time exposure was extended.
- Flexural cracks were developed when GFRP RC beams were exposed to high temperatures (more than 800 ⁰C) for an extended time (90 minutes), even if they were lightly loaded within the elastic range.

ACKNOWLEDGEMENTS

The authors are grateful for the technical and financial support towards this research by the staff of the Concrete Lab and the Department of Civil Engineering, College of Engineering, University of Kirkuk. Postgraduate Research Grant (PGRG) Kirkuk University Registration Order No./2021/HIR/MOHE/ENG/5637-7-28

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