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# Behavior and Failure Mode of GFRP bars RC Beams under Elevated Temperature

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**Abstract.** The presented work is providing the results of experimental study to investigate the impact of elevated temperature on load resistance related to the concrete beams that are reinforced via the glass fibre reinforced polymers (GFRPs). There are four GFRP reinforced concrete beams with width (250mm) and height (160mm) as cross-sectional dimensions, also (1250mm) as total length have been designed according to ACI440.1R-15[1], cast using normal weight concrete and considered in the experimental tests. One specimen has been put to test at ambient temperature, while other three specimens were firstly exposed to increased temperatures (350, 500, and 600 °C), after that subjected to a monolithically increased one point load up to failure. The effect of increased temperature on load displacement relationships as well as the failure modes regarding tested beams were discussed and put to comparison with the results related to the control beam (20°C). The experimental tests results have indicated that the shear failure is the pre-dominate failure mode with regard to all the tested GFRP-beams before and after exposing to elevated temperature. Results have also shown that in comparison to the control beam (20°C), reduction in loading capacity of heated reinforced concrete beams have been 4%, 15.5% and 19% when exposing to temperature of 350°C, 500°C and 600°C respectively.

Keyword: RC beams, Elevated temperature, thermal properties, GFRP bars, Fire resistance

## 1. Introduction

FRP material possesses good properties compared to the primarily used steel reinforcement like high durability, resistance to corrosion, as well as tensile strength. Because of the elevated tensile strength, using the GFRP bars might be of high importance in a lot of structural applications like offshore structures and bridges, in which the steel reinforcement's corrosion happens. A lot of studies were indicated on fire resistance that is related to the GFRP reinforced normal-weight concrete members. Also, such researches investigated a lot of aspects for helping in developing the design codes with regard to the FRP reinforced concrete member. For instance, a study conducted by Tanano et al. [2] provided experimental study for examining the residual strength related to FRP reinforced concrete beams following being exposed to increased temperature. The test results specified that decreasing the bond strength in addition to the stiffness regarding epoxy matrix in FRP reinforced concrete beams elevated with the increase in heating temperature. While the beams that are reinforced with inorganic matrix FRP exposed to not much loss in the residual strength in the case when subjected to heating up to 250 Celsius. Majorly, residual tensile strength related to all the types of FRP reinforcement has been decreasing with the increase in temperature. A study conducted by Sakashita[3] examined the impact of fire on the concrete beams that are reinforced via various FRP bars with many surface textures as well as fiber orientations. All the specimens have been pre-heated up to 100Celsius for

3hrs, after that subjected to heating for up to 1000Celsius under loading. Furthermore, the results showed that no failure related to GFRP reinforced beam specimens happened up to 180mins of heating with temperature on beam's bottom face reaching 680Celsius. A study conducted by Sadek et al. [4] put to comparison (in experimental program) fire resistance as well as concrete compressive strength related to the RC beams that are reinforced via steel with that which is reinforced via the GFRP bars. RC beams specimens have been loaded up to 60% regarding their ultimate load throughout the fire test. Results have revealed that the wide cracks developed during testing are the dominant failure mode. In addition, major decrease in the fire resistance because of using GFRP bars has been indicated in comparison to beam that is reinforced with the steel bars. It must be indicated that the study of Sadek et al.[4] utilized concrete cover of (25mm) for flexural reinforcements, that might be contributing to low fire performance regarding RC beams specified in experimental program. A study conducted by Abbasi and Hogg [5] specified that experimental investigation on fire resistance related to the concrete beam that is reinforced with the GFRP bars. All RC beams designed according to ACI440.1R-15 [1] with different shear reinforcement. Steel bars have been utilized in the second beam as shear reinforcement (stirrup), whereas GFRP bars have been utilized in the first beam as shear reinforcement (stirrup). A 40 KN load has been used to beams inside the furnace at four points and this load is maintained constant during the entire test. It was observed that the load-deflection curves became non-linear above 60 KN and the maximum deflection was exceeded at 90 KN. Failure time and mid-span deflection of first beam was found to be higher than that for second beam. Such difference might be because of the weak bond strength between rebar and concrete that is related to second beam in comparison to the first one. Rafi and Nadjai [6] have also investigated the fire resistance regarding the concrete beams that are reinforced with the CFRP bars and exposed to ISO 834 standard fire curve [7]. Experimental test results have indicated that the ultimate load and the mid-span deflection related to the CFRP-beams have been great in comparison to that of the steel-beams with the failure mode being tension failure in steel-beams and compression failure in CFRP-beams as expected according to ACI440.1R-15 [1].

It can be seen from the above previous studies that the fire resistance that is related to FRP RC beams has been high in comparison to that related to conventional steel RC beams with greater deflection. However, most of these studies have only considered fire resistance regarding FRP RC via specifying the time of fire at which failure of the concrete beams occurs. Whereas, the impact of increased temperatures on load-deflection behavior regarding the FRP RC beams was not majorly examined neither numerically or experimentally. Thus, the major aim of this work is experimental investigation of the effect of elevated temperatures on the performance regarding the concrete beams which are reinforced with GFRP bars involving failure modes and load deflection relationships. To full fit this objective, four RC beams were cast, cured, heated, also put to test under single static point load at beam mid-span. Degradation in beams capacity after exposing to various increased temperatures was considered, also discussed in the current experimental study.

## 2. Experimental program

The presented section is providing the specification regarding experimental program used in this work for examining the impact of increased temperatures on response of GFRP RC beams. This includes describing the material and geometrical properties of RC specimens used in the tests along with the test setup in addition to furnace's technical details, test machine and measurement devices used to collect and record the experimental test results.

### *2.1. RC beam specimens*

Four RC beams with width of 250mm and height of 160 mm, also 1250mm as total length, have been prepared and put to test in the presented work. RC beam specimens have been designed according to ACI 440.1R-15 [1] also casted utilizing the normal weight concrete with equivalent compressive

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strength regarding the concrete cylinder of 46 MPa. The following section describes the material and geometrical of the RC beams.

*2.1.1. The material properties***.** used material properties in current experimental test was described below:
Normal concrete**:** The normal weight concrete mixture with mix proportions of (1.0:1.26:2.45) was designed according to the procedure suggested by ACI code 211.1-91 [1] and used to cast the RC beams. Three concrete cubes with dimensions of( 150mm× 150mm×150 mm ), also 3 concrete cylinders with the dimensions (20×10mm) have been casted cast, cured in addition to being tested for determining tensile and compressive strengths of the concrete at ambient temperature on the basis of ASTM specifications [8]. Test results have shown that the average concrete tensile and compressive strengths have been 2.4 and 46MPa. Knowing that results of concrete cubes' compressive strength has been converted to equivalent concrete cylinder's compressive strength through an equation indicated via Eurocode 4 [9].

GFRP bars: Deformed GFRP bars with (16mm) as diameter have been utilized as major (i.e. tension) reinforcement in all RC beam specimens used in experimental tests. GFRP bars were supplied by the Nanjing Fenghui Company located at China. The thermal and mechanical properties related to GFRP bar were provided from the manufactured data sheet and listed in table 1.

Steel bars: Grade 60(G60) deformed steel bars with (8mm) as diameter have been utilized a shear reinforcement (stirrups) with regard to all the RC-beam specimens specified in experimental tests. A uniaxial tensile test has been implemented for determining the mechanical properties of (8mm) steel bar as can be seen in the table 2.

**Table 1.**Properties of GFRP bar applied in the experimental tests of the study**.**

| | |
|---|---|
| Density (G/cm^3) | 1.9-2.2 |
| Tensile strength (MPa) | 724 |
| Elastic modulus (GPa) | 46 |
| Bond strength (MPa) | 12.2 |
| Thermal conductivity (W/mk) | <0.5 |
| Specific resistance (μΩcm) | >1012 |
| Coefficient of thermal expansion | 0.6×10-5 |

**Table 2.**Properties of 8 mm steel bar applied in the experimental tests of this study.

| | |
|---|---|
| Yield stress $F_y$ (MPa) | 318 |
| $\epsilon_y=F_y//Ec$ | 0.00159 |
| Ultimate strength $F_u$ (MPa) | 447 |

2.1.1. *Geometrical properties and reinforcement details*. Table 3 and figure 1 showing the geometrical and reinforcement details regarding RC beams specimens used in the present experimental tests. All GFRP-RC beams have been supported and developed on the basis of ACI-440 [1] to fail at ultimate load of 180kN under ambient temperature by concrete crushing because it is the more favorable failure model related to GFRP RC beams [1]. The beams have been reinforced via 3ϕ16mm GFRP bars in tension and 1ϕ6mm steel bars in compression which is also used as a hanger for the shear reinforcement which consists of ϕ8mm spaced at 130mm center to center as shown in figure 1. One of the beams was tested under ambient temperature and it is considered as control beams (NC ºC), while the other three beams (N350ºC, N500ºC and N600ºC) were exposure to three different elevated temperatures which are 350ºC, 500ºC and 600ºC before testing under one point static load at beams mid span as can be seen in the fig 1. Beams were firstly tested thermally in the electric furnace up to the desired temperature then the beams were taken out of the furnace to cool down naturally to room temperature. Afterward, the beams were subjected load point static load up to failure.

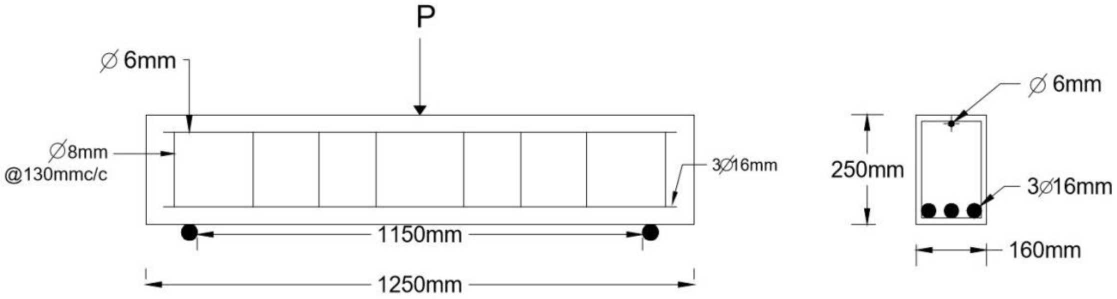



**Figure 1.** Dimensions and reinforcement details of GFRP RC beams specimens

**Table 3.** Details and Designation of GFRP RC beams specimens.

| Beam designation | Main reinforcement (bottom reinforcement) | Shear reinforcement | $T_{max.}$ |
|---|---|---|---|
| N 20 ˚C | 3 Ø 16 | Ø8mm @130mm c/c | 20 ˚C |
| N350 | 3 Ø 16 | Ø8mm @130mm c/c | 350 ˚C |
| N500 | 3 Ø 16 | Ø8mm @130mm c/c | 500 ˚C |
| N600 | 3 Ø 16 | Ø8mm @130mm c/c | 600 ˚C |

## 3. Thermal and structural tests

### *3.1. Thermal tests*

With regard to the heating cooling phase related to experimental tests, three GFRP RC beams have been exposed to various increased temperatures, namely 350 ºC, 500 ºC and 600 ºC using almost similar heating rate or temperature time history for each beam. After reaching the desired value, the temperature of the beams has been kept constant for approximately half of an hour in furnace for allowing the temperature for efficiently transfer to GFRP bars. Also, electric furnace has been developed, manufactured as well as calibrated in this work (fig 2) and applied for generating controlled elevated temperature and heat up GFRP RC beams specimens before applying static load. The designed electrical furnace consists of eight electrical heaters; each heater has a maximum temperature of about 100ºC. Two heaters are located at each side of the furnace chamber to ensure uniform distribution of the temperature along the beam length and around the beam section. The RC beams are supported on three steel rods inside the furnace to enable the movements of the beam inside and outside the furnace. Furnace's average heating rate has been controlled for being about 10ºC/min at the beginning of the heating then reduced gradually up to the end of the heating process. In the case when reaching the target increased temperature, RC beams have been naturally cooled down to ambient temperature. Furthermore, there are 2 Type - K thermocouples have been utilized for monitoring and recording the rise in temperature with time. One of the thermocouples were attached to the concrete surface while the second one was embedded inside the beam and attached to the surface of GFRP bar reinforcement. Furthermore, these thermocouples were attached to a digital reading to record time-temperature rise manually (see figure 3).

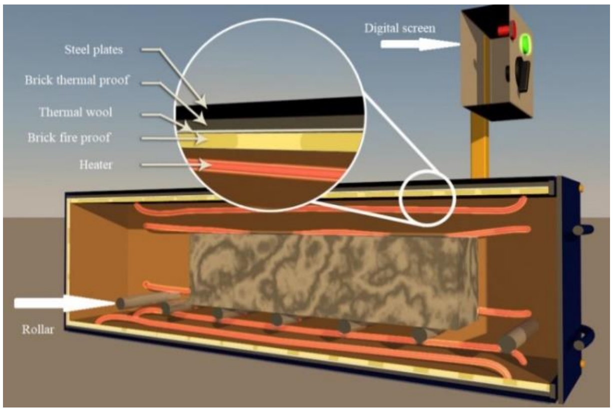
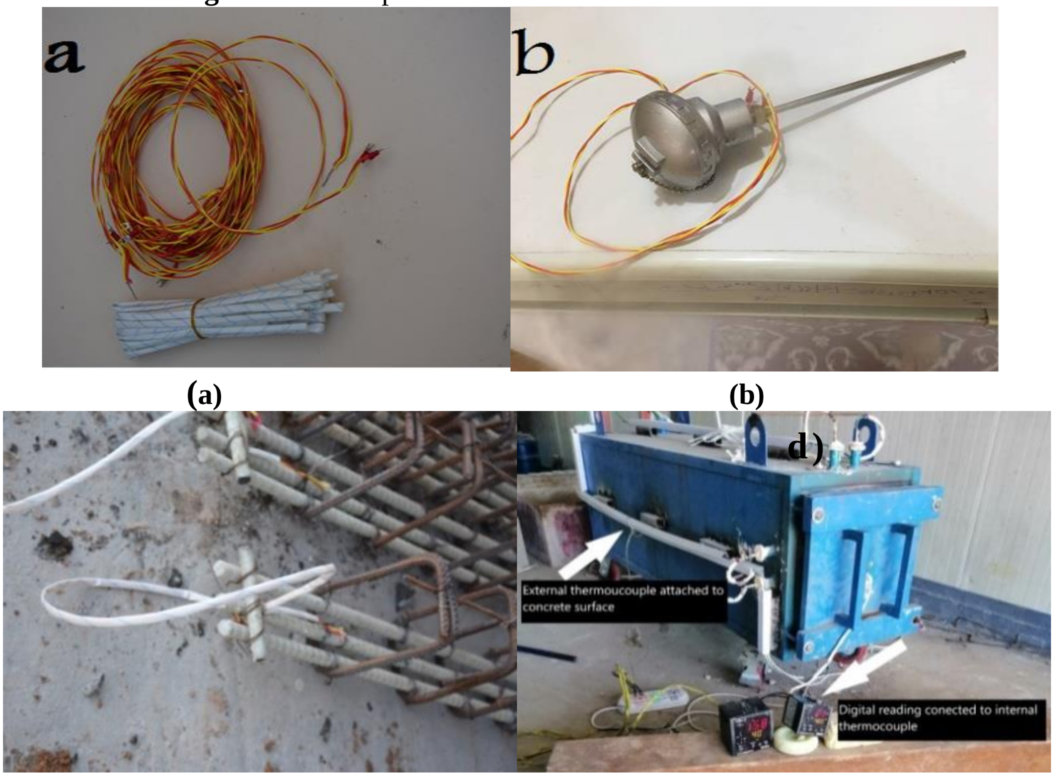



**Figure 2.**Close-up details of the electric furnace




(a) (b)

(c) (d)

**Figure 3.** Positions of thermocouples and digital monitor; (a): Thermocouples used for GFRP bars ;(b): Thermocouples used for concrete; ( c): Thermocouple at -GFRP bars; (d) Thermocouples connected to the digital monitor

*3.2. Mechanical tests*

With regard to structural tests, control specimen as well as heated GFRP-RC beam specimens have been exposed to gradually increasing concentrated static point load at beams mid-span up to failure with the use of universal test machine provided at College Engineering/University of Al-Qadisiyah/ Iraq as can be seen in fig 4. Maximum capacity regarding universal test machine has been approximately 2000 kN with least loading increase of 5 kN. As can be seen in the fig4, the load cell has been inserted between hydraulic jack and bearing I section steel beam for measuring and recording the load value at each of the load increments. Single linear variable displacement transformer (LVDT) has been placed under the middle of beam cross-section for the purpose of measuring and monitoring the lateral displacement which correspond to each of the load increments as can be seen in the fig 4.

The results that are acquired from LVDT at each one of the load increments in addition to recorded load values have been utilized for capturing load-displacement relationships regarding GFRPRC beams under various elevated temperature.

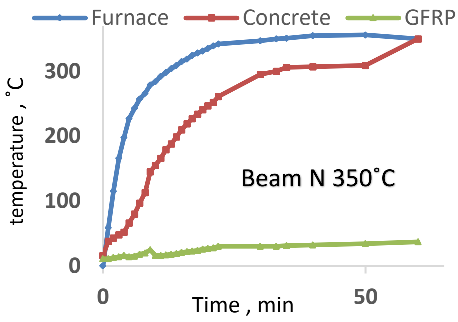

**Figure 4**. Test setup of GFRP-RC beam specimens.

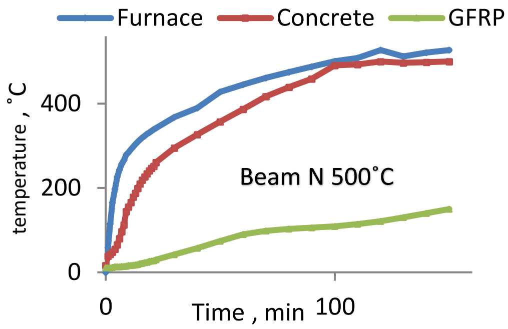
## 4. Tests results

### *4.1. Temperature–time histories*

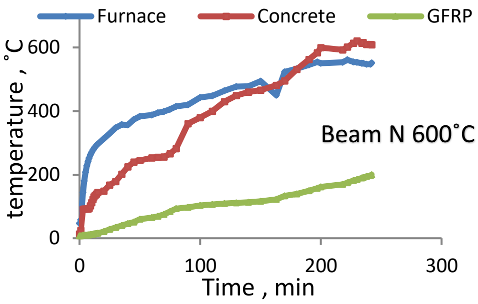
As mentioned before, the GFRP RC beam specimens were firstly exposed to elevated temperatures in a specially designed electric furnace (see figure 2). The electric furnace was designed to heat up unloaded reinforced concrete beams. For each beam, time-temperature histories during heating process were monitored and recorded at the concrete's surface and at surface of the GFRP bars using thermocouples attached to digital reading. The time-temperature histories of all hated GFRP RC beam under different target temperatures are indicated in the fig5, as it might be specified that heating rate in furnace was is almost similar for all GFRP-RC beam which might be specified via drastic rise in the temperature up to 300 Celsius then the rate of heating was significantly reduced to 8 ˚C/min up to 400˚C/min. Finally, the rate of heating was additionally reduced to be 4˚C /min and kept fixed during the rest the test. All beams were cooled down by natural air. Further, fig 4 (a) showing that the temperature value at the surface of GFRP RC beam reached 210 ˚C after 15 minutes of heating, and reached 350 ˚C at 60 minutes which means that the concrete surface exposed to high rate of temperature at the early stages of the heating following the heating rate of the furnace. This heating trend may be conforming to the ISO 834 standards heating curve wherein the temperature value reaches about 800 ˚C at the first 15min of the heating. However, the GFRP bars gain a small increase in temperature which is approximately about 1˚C per minute at the beginning of the test and continued to increase at this rate up to the end of the heating process. This has been majorly because of low thermal conductivity property regarding GFRP bars as reposted by previous researches [10] .In addition, effect of the concrete cover which reduce the temperature imparted to the GFRP bar. Also, Figure 4 shows that the GFRP bars reached a maximum temperature of 200 ˚C when testing RC beams under 600 ˚C. In addition, the results have shown that in the case when temperature at GFRP bars exceeded glass transition degree of temperature (60 ˚C to 82 ˚C) [11], the resin of the GFRP bars was firstly melted and then evaporated as shown in figure 7. Nevertheless, the glass fibers of the GFRP bars were undamaged and could resist the tension force at tension zone related to concrete beam section as can be seen in the fig 7.

Further, fig 6 showing the differences in temperature between concrete surface and GFRP bars in tested GFRP RC beams for the three elevated temperatures considered in this study. It can be seen from this figure that even at the at high elevated temperatures, the temperature differences between concrete surface and GFRP bars is high which confirm the low temperature transferred from the concrete to the GFRP bars because of low thermal conductively regarding GFRP bars in comparison to steel bars [10] .




a) T=350 ˚C b) T= 500 ˚C




c) T=600 ˚C

**Figure 5.** Temperature- time-temperature histories of heated GFRP-RC beams under different elevated temperatures

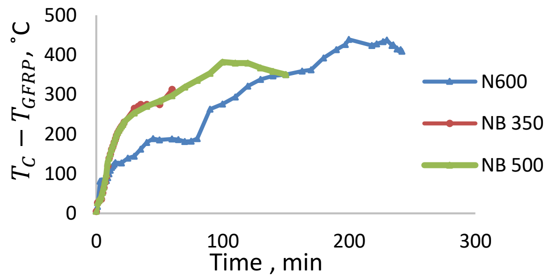



**Figure 6.** Differences in temperature between concrete and GFRP bar in tested beams

**Figure 7.** GFRP bars reached a temperature of 200˚C in beam (N 600 ˚C)

*4.2. Load–displacement relationships*

The load- mid-span displacement relationships of all tested GFRP RC beam under different elevated temperatures along with failure modes have been displayed in the fig7 and fig8. Ultimate load bearing capacity, and the maximum deflection at failure of each tested GFRP-RC beam were obtained from the experimental tests and tabulated in table 4. Test results have shown that the failure regarding reinforced GFRP-RC beam was mainly due to concrete crashing and shear failure as shown in figure 7 along with the crack patterns. Test results of the control beam (N 20 ˚C) have been applied as reference for evaluating the performance of the GFRP RC beams exposed to elevated temperature. Test results of all beams show that flexural cracks have been initiated at tension zone of beam mid-span at load value of 20 kN with (0.075mm) as average width. Afterward, the another set of inclined cracks were developed as well as propagated form the beam's end (for instance at beam's tension zone) toward the loading point with increasing in width until failure occurs eventually by pure shear failure combined with concrete's crushing at beam's compression zone in mid-span region. The control beam's failure happened at 174kN as ultimate load with 10.6mm as corresponding deflection as can be seen in the fig 7, figure 8 and Table 4. For the purpose of examining the impact of increased temperature on deformation characteristics of GFRP-RC beams, load-lateral displacement relationship of tested GFRP-RC were recorded and presented in Figure 8. It can be clearly shown in Figure 8 that each beam exhibit three different zones of behavior which are: elastic behavior, plastic behavior, failure behavior. Also figure 9 shows that the maximum bearing load resistance of GFRP-RC beams have dropped by 4%, 15.5% and 19% in comparison to load resistance regarding the control beam after exposing to temperature values of 350 ºC, 500 ºC and 600 ºC respectively. In addition, figure 9 and table 4 show the impact of temperature on the decrease in ultimate load related to tested GFRPRC beams. This reduction in the load resistance of the beam might be due to degradations in concrete's strength and reinforcing GFRP bars in the case when being exposed to high temperature. Also, it has been indicated from figure 8 that the lateral displacement of the beams decreases with increasing the temperature because of the thermal expansion and cracking expansion of concrete exposed to high temperature. Furthermore, it has been indicated that there is increase in the first crack's width by increasing exposed temperature because of the existing thermal cracks that was formed during the heating of the beams and developed under the applied loads. Further, table 4 shows the ductility index related to GFRP -RC beams under various elevated temperatures investigated in this study. It can be seen from this figure that the ductility index has been decreased under increasing of exposed temperature.

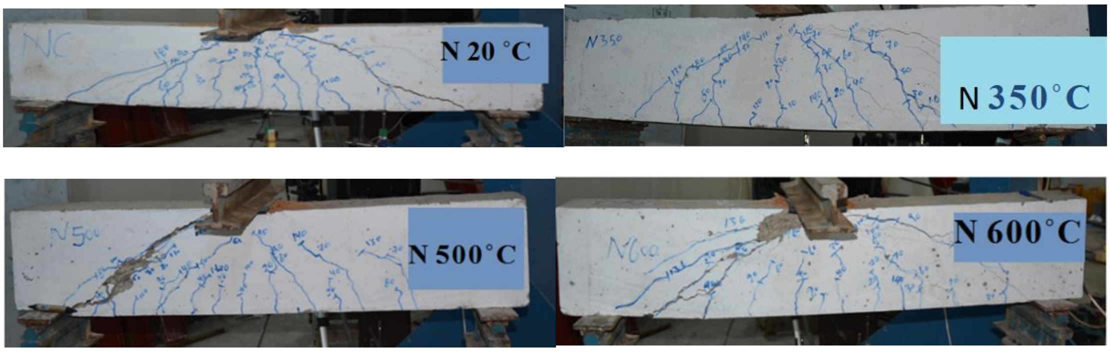
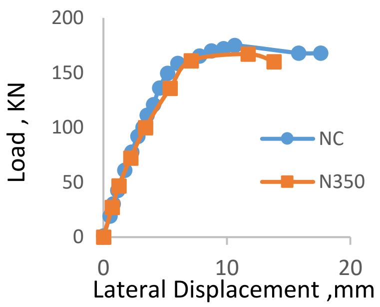
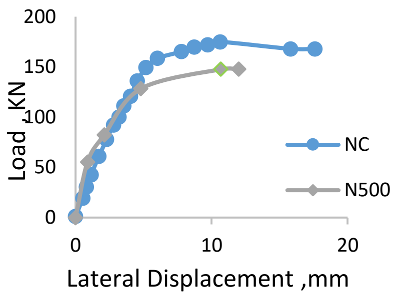
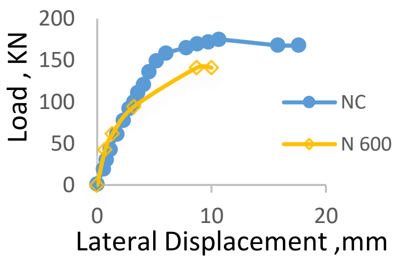


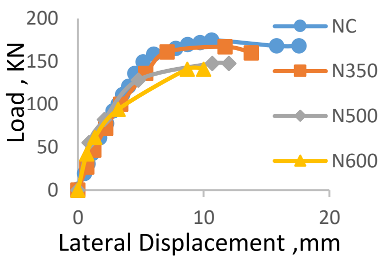

**Figure 7.**Shear failure of all tested GFRP-RC beams




a) T=350 ºC b) T=500ºC




c) T=600 °C d) All tested GFRP-RC

**Figure 8**. Load-displacement relationships of tested GFRP-RC beams under various temperatures

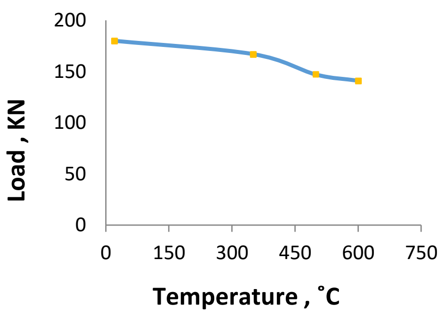



**Figure 9.** Effect of temperature on the ultimate loads of GFRP-RC beams under different temperatures

**Table 4.** Summary of the tests results.

| Beam designation | T max. ˚C | P cracking KN | P ult. KN | Max. disp. mm | Ductility index | Failure mode |
|---|---|---|---|---|---|---|
| NC | 20 ˚C | 20 | 174 | 17.6 | 0.91 | shear failure |
| N350 | 350 ˚C | 10 | 167 | 13.8 | 0.906 | shear failure |
| N500 | 500 ˚C | 20 | 147 | 12 | 0.902 | shear failure |
| N600 | 600 ˚C | 20 | 141 | 10.5 | 0.90 | shear failure |

## 5. Conclusions

The presented study provided and examine the experimental test results on investigating the behavior in addition to the failure modes of normal weight concrete beams that are reinforced with GFRP bars and exposed to elevated temperature. There are four GFRP-RC beams have been specified in experiment test, also three of RC specimens were subjected to increased temperatures of (350, 500 and 600 Celsius). These elevated temperatures were maintained constant for 30 minutes. Thereafter, all RC beams spacemen have been put to test under one lateral point load up to failure. The behavior regarding tested RC beams with regard to cracking patterns, ultimate load-carrying, load-deflection, and failure modes have all been recorded and discussed in the paper. A number of conclusions can extracted from the study which may be help to suggest more accurate approaches and equations of the design of RC beam reinforced with GFRP under elevated temperature. These conclusions may be summarized as follows

1. The flexural capacity that is related to GFRP RC beam considerably reduced when exposing to high elevated temperature. Results have shown that the maximum reduction in the flexural capacity of GFRP RC beam upon exposed to 600 ˚C was equal to 19% compared with an ultimate flexural capacity of GFRP RC beam at ambient temperature.
2. GFRP RC beams exhibit large deflection when exposing to high elevated temperature. The ductility index of the GFRP- RC beams was decreased under increasing of exposed temperature.
3. GFRP bars show a low rise in temperature with a rate of approximately 1 ºC /minute in spite of exposing GFRP- RC beams to high temperatures. The GFRP bars reached a maximum temperature of 200 ºC after 242 minutes of heating the beams under 600 ˚C.
4. Shear failure was the predominate failure mode for GFRP-RC beams under ambient and elevated temperature. Therefore, in designing RC beams reinforced with FRP bars having high tensile strength, shear failure criteria must be considered and addressed.

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## References

[1] ACI 440.1R-15 2015 Guide for the design and construction of structural concrete reinforced with FRP bars, vol. **440**. *ACI Committee*.
[2] ]Tanano H, Masuda Y, Kage T, Fukuyama H, Nishida I and Hashimoto T 1995 Fire resistance of continuous fibre reinforced concrete in non-metallic (FRP) reinforcement for concrete structures. Edited by L. Taerwe. E&FN Spon, London, UK, pp. 368.

[3] Sakashita M, Masuda Y, Nakamura K and Tanano H 1997 Proc. Int. Conf. on Deflection of continuous fiber reinforced concrete beams subject to loaded heating in non-metallic (FRP) reinforcement for concrete structures vol 2 (Japan Concrete Institute) pp. 51-58.

[4] Sadek, A, El-Hawary M and El-deeb A 2006 Fire resistance testing of concrete beams reinforced by GFRP rebars. European Journal of Sci. Res., Vol.15, No.2, (2006), pp. 190-200, 2006.

[5] Abbasi A , Hogg PJ 2006 Fire testing of concrete beams with fiber reinforced plastic rebar. Composites: Part A 37 (2006) 1142–1150

[6] 6] Rafi MM, Nadjai A F 2008 Fire resistance of carbon FRP reinforced concrete beams. Adv. Concr. Technol., vol. 6, no. 3, pp. 431–441.

[7] ISO 834 1975 Fire resistance tests – elements of building construction. International Organization for Standardization.

[8] ASTM E119 2008 Standard test methods for fire test of building construction and materials .Pennsylvania: American Society for Testing and Materials; 2008.Applied Mechanics and Materials, pp. 623-627, ASTM Int. West Conshohocken, PA, vol. 552, no. 1.

[9] Eurocode 4 2005 Design of composite steel and concrete structures–EN 1994.Part 1-2: General rules - Structural fire design, (August), pp. 1-109, Eurocode 4, vol. 2.

[10] Alnahhal W, Chiewanichakorn M, Are A and Alampalli S 2006 Temporal thermal behavior and damage simulations of FRP deck. Journal of Bridge Engineering, ASCE. 2006; 11(4):452-465.

[11] ACI 440.2R-08 2008 Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures .American Concrete Institute, Farmington Hills.