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Post-heating behavior of concrete beams reinforced with fiber reinforced polymer bars

Mohammad R. Irshidat*, Rami H. Haddad[a] and Hanadi Almahmoud[b]

Department of Civil Engineering, Jordan University of Science and Technology,
P.O. Box 3030, Irbid 22110, Jordan

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Abstract. The present paper investigates the post heating behavior of concrete beams reinforced with fiber reinforced polymer (FRP) bars, namely carbon fiber reinforced polymer (CFRP) bars and glass fiber reinforced polymer (GFRP) bars. Thirty rectangular concrete beams were prepared and cured for 28 days. Then, beams were either subjected (in duplicates) to elevated temperatures in the range (100 to 500^{o}C) or left at room temperature before tested under four point loading for flexural response. Experimental results showed that beams, reinforced with CFRP and GFRP bars and subjected to temperatures below 300^{o}C, showed better mechanical performance than that of corresponding ones with conventional reinforcing steel bars. The results also revealed that ultimate load capacity and stiffness pertaining to beams with FRP reinforcement decreased, yet their ultimate deflection and toughness increased with higher temperatures. All beams reinforced with FRP materials, except those post-heated to 500^{o}C, failed by concrete crushing followed by tension failure of FRP bars.

Keywords: RC beams; elevated temperatures; fiber reinforced polymer; flexural behavior

1. Introduction

The combination of concrete with relatively high compressive strength and reinforcing steel bars has made reinforced concrete (RC) the most common used material for construction in the world. However, there has been a lot of concern with regard to corrosion of steel reinforcement in concrete structures located in chloride saturated environments; because steel corrosion may result in significant deterioration and possibly failure of these structures. Therefore, several methods were tried during the past two decades to delay or prevent concrete structures including the replacement of traditional steel with stainless, galvanized, or epoxy coated steel bars, or the implementation of corrosion prevention techniques such desalination and cathodic protection. Unfortunately, none of these methods has totally solved the steel corrosion problem. Recently, fiber reinforced polymer (FRP) bars had been suggested to substitute steel reinforcement due to their high resistance to corrosion, high tensile capacity, and low weight in comparison with steel.

*Corresponding author, Ph.D., E-mail: mrirshidat@just.edu.jo
[a]Professor, E-mail: rhaddad@just.edu.jo
[b]Master Student, E-mail: hanadyhanady13@yahoo.com

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Experimental studies on the flexural and shear behavior of FRP reinforced concrete beams had been carried out during the past decade with emphasizes on the effect of concrete section inherent properties such as reinforcement ratio, bar size and type, and concrete type and strength as well as type of loading (static and dynamic). The results from works that investigated the effect of FRP reinforcement ratio and concrete strength on the flexural behavior of beams revealed that higher values of both variables had contributed to promoting ultimate moment capacity and lowering the deflection at service load limit (Alkhrdaji *et al*. 2001, Ospina and Bakis 2006, Thériault and Benmokrane 1998). In another study, Almusallam *et al*. (1997) concluded that compression reinforcement with FRP bars has insignificant influence on the behavior of beams. Later, other studies reported that the incorporation of short steel fibers in flexural concrete elements with FRP reinforcement contributed to enhancing their ductility and reducing width of static or dynamic-induced cracks (Alsayed and Alhozaimy 1999, Wang and Belarbi 2005, Yang *et al*. 2012). Kara *et al*. (2013) presented an analytical model to predict deflection of concrete structures reinforced with FRP bars based on the stiffness matrix method. They showed that bottom FRP reinforcement at mid-span section of the beams has a significant effect on the reduction in deflections.

Concrete structural facilities are susceptible to fire attack. Previous experience indicated satisfactory resistance of steel reinforced concrete elements to temperatures of up to 500^{o}C with exposure periods of up to four hours (Bazant and Kaplan 1996). It has been stipulated that the extend of resistance to fire was dependent upon inherent factors such as concrete strength grade, aggregate type, and concrete internal moisture content, concrete cover over reinforcing steel as well as upon external factors related to fire intensity and distribution (Bazant and Kaplan 1996, Bisby and Kodur 2007, Yu and Kodur 2013). As expected, fire endurance of concrete flexural elements with FRP bars would be different than that with conventional steel owning to the failure criterion adopted in the design of corresponding elements (ACI 318M-11 2011). This fact directed research ideas over the past decade towards understanding fire endurance of FRP concrete elements in much depth (Abbasi and Hogg 2006, Bisby and Kodur 2007, Katz *et al*. 1999, Kodur and Bisby 2005, Lin and Zhang 2013, Nigro *et al*. 2011, Rafi and Nadjai 2011, Rafi *et al*. 2011, Saafi 2002, Sadek *et al*. 2005). The results of works conducted to investigate the shear and flexural behavior of FRP reinforced concrete beams revealed significant degradation in shear and flexural strengths capacity of these elements upon exposure to fire (Saafi 2002, Sadek *et al*. 2005). Sadek *et al*. (2005) concluded that using GFRP instead of steel bars had resulted in reducing fire resistance and fire endurance of the concrete beams. Saafi (2002) developed an analytical method for estimating the residual flexural and shear strengths of RC beams with FRP bars that have been exposed to fire. The results revealed that beams with FRP reinforcement displayed significant degradation in flexural and shear strengths under fire. Rafi and Nadjai (2011) studied the behaviors of beams with CFRP only and hybrid (steel- CFRP) bars at elevated temperatures. They concluded that beams reinforced with hybrid bar were more ductile compared to those with CFRP. They also found that the CFRP reinforced beams showed higher strength and stiffness compared to that of hybrid ones. In another work, Rafi *et al*. (2011) investigated the behaviour of beams with FRP reinforcement at elevated temperatures. Their findings indicated that the reduction in stiffness upon heating was the least in CFRP beams and was similar for beams with GFRP and conventional steel reinforcement. The impact of fire on bond strength between FRP bars and concrete of flexural members was also investigated (Katz *et al*. 1999, Rafi and Nadjai 2011). The findings demonstrated that beams, reinforced with FRP bars, experienced more reduction in bond strength than those reinforced with steel ones. Other studies (Abbasi and Hogg 2006, Rafi *et al*. 2011) concluded that beams, reinforced CFRP bars, had shown better strength and stiffness than those with steel or GFRP bars.

The capability of FRP bars to substitute conventional steel bars in concrete beams subjected to elevated temperatures is thoroughly investigated in this paper. For this, two types of FRP rebars namely, carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), along with commercial reinforcing steel bars were used in reinforcing typical concrete beams having dimensions of (100×150×1550 mm). Those were cured to 28 days, subjected to elevated temperatures of up to 500℃ and then tested under four-point loading setup of flexural response. Post-heating and loading cracking patterns were also determined for all beams.

2. Experimental program

2.1 Test specimens

Thirty simply supported beams with rectangular cross section and dimensions of (100×150×1550 mm) were designed according to American Concrete Institute recommendations (ACI 318M-11 2011) as shown in Fig. 1. Beams reinforced with traditional reinforcing steel (BS) were designed as an under-reinforced whereas those with CFRP and GFRP bars (BC and BG, respectively) were designed as an as over-reinforced flexural elements. In fact, experience has proven that concrete sections with CFRP and GFRP show compression failure regardless of whether sections were under or over-reinforced because FRP bars do not yield prior to compression concrete failure. All beams had the same top and bottom reinforcements of 2Φ10 and 2Φ12 mm, respectively; with a concrete clear cover of 15 mm. Steel stirrups of 7 mm diameter were used as shear reinforcement for all beams at spacing of 50 mm along the length of the beams to avoid shear failure. Reinforcement details are shown in Fig. 1.

2.2 Materials properties

Different concrete flexural beams were prepared using the same normal strength concrete mixture, made using locally available ingredients. Detailed descriptions of the properties of materials used are as follow.

2.2.1 Concrete

A normal strength concrete mixture was prepared from ordinary Portland cement, a mixture of crushed limestone and silica sand, and coarse limestone with a maximum size of 12.5 mm. The physical properties of aggregates used were obtained according to ASTM C33 standards (C09 Committee 2013a) and are listed in Table 1. The mixture was proportioned to achieve required workability and 28-day compressive strength according to ACI recommendations (ACI 318M-11 2011). The different ingredients were mixed using a titling drum mixer according to ASTM method C192 (C09 Committee 2013b). Initially, a small amount of water was poured in the mixer to wet its inside surface, then the entire quantity of coarse aggregate were placed in the mixture and their surface were wetted with water under continuous mixing. After that, significant amount of cement was added to coat the aggregates surface, followed by an alternative addition of fine aggregates, cement, and water. The last one-third of water quantity was added with the super plasticizer. Each batch of concrete was used in casting four beams with six concrete cylinders. The cylinders were tested for determination of compressive and tensile strengths at 28 days of curing

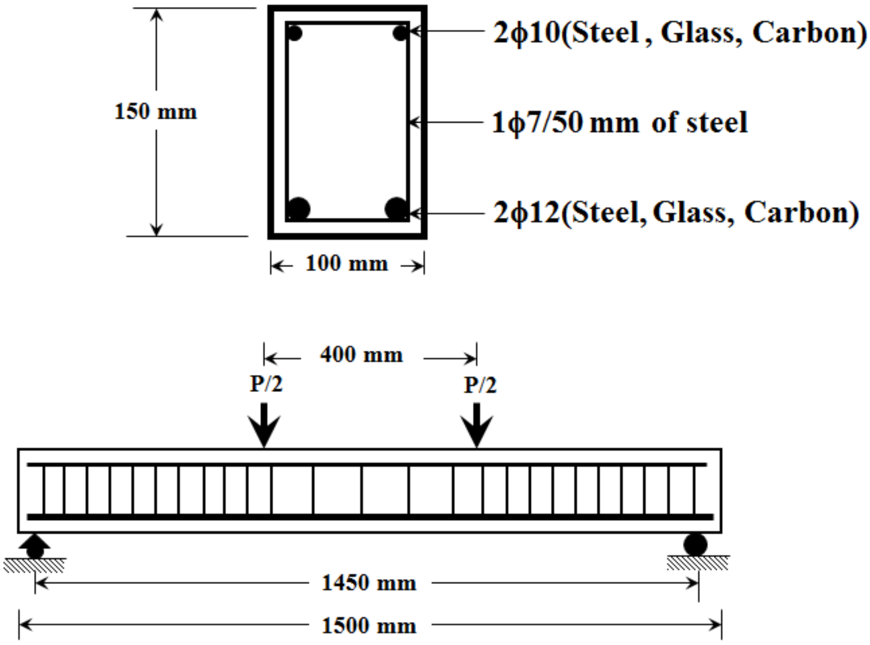


Fig. 1 Concrete dimensions and reinforcement details of tested beams

Table 1 Physical properties of aggregates used in the concrete mix

Material	Specific Gravity	Absorption
Coarse limestone	2.5	2.4%
Crushed limestone	2.4	5.4%
Silica sand	2.6	0.5%

Table 2 Concrete mix design

Material	Weight (kG/m^3)
Cement	371
Silica sand	173
Coarse aggregate	807
Fine aggregate	693
Water	200

according to ASTM method C192 (C09 Committee 2013b). The casted beams were demolded after 24 hours, covered with wet burlap and stored under the laboratory conditions for 28 days ready for heat-treatment and later flexural testing under four-point loading.

2.2.2 Reinforcing materials

CFRP and GFRP bars, produced by Aslan FRP Ltd, Hong Kong and shown in Fig. 2, were used for longitudinal reinforcement. The geometrical and mechanical properties of FRP bars, as either measured in the laboratory or provided by the remanufacturer are listed in Table 3. Grade 40

Table 3 Mechanical properties of FRP bars

FRP type	Bar diameter (mm)	Modulus of elasticity (GPa)	Strain at rupture	Tensile strength (MPA)
CFRP	10	139.8	0.0179	2274
	12	137.2	0.0141	1868
GFRP	10	47.4	0.0225	952
	12	42.3	0.0248	1020

Fig. 2 Reinforcing bars: CFRP (top) and GFRP (bottom)

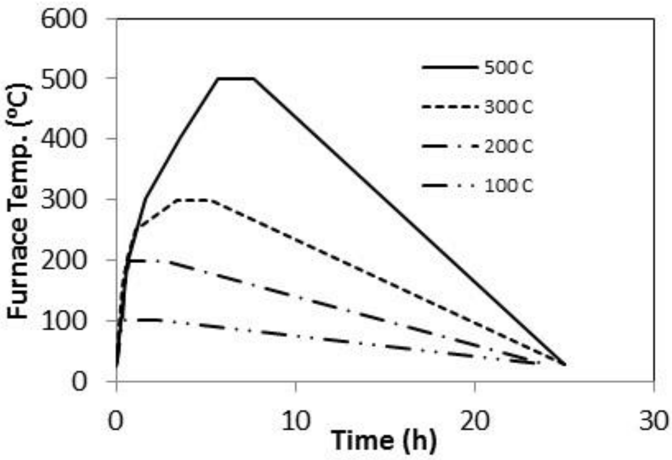
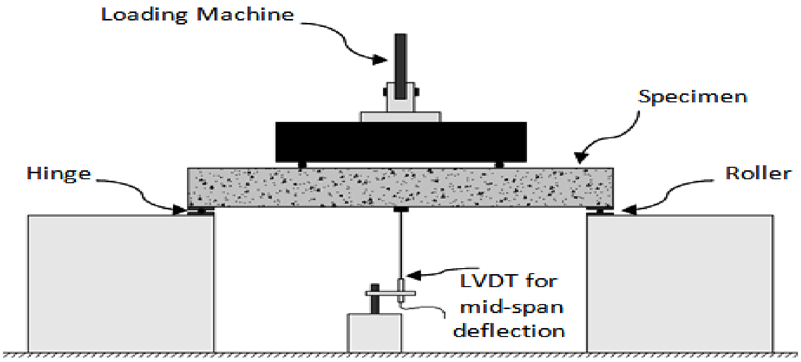


Fig. 3 Temperature history

reinforcing bars of Φ7 mm were used as transverse reinforcement and for all beams.

2.3 Heat treatment

Beam specimens, designated for heat treatment, were exposed to elevated temperature using a special electrical furnace that is equipped with an electronic panel to control automatically the temperature and time of exposure. The beams (in duplicates) were subjected to four different levels of heating, namely 100℃, 200℃, 300℃, and 500℃. Of course, duplicate beams from each group were kept at room temperature, as controls. The heat region adopted for all beams is depicted in Fig. 3.



(a)

(b)

Fig. 4 Test set-up: (a) schematic drawing (b) real picture.

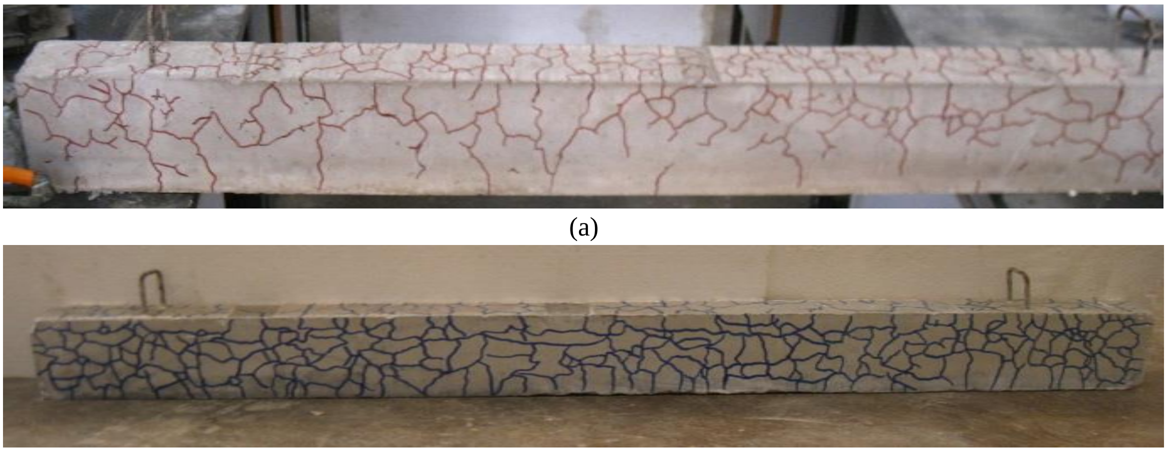
2.4 Test set up

All beams were tested in the structural laboratory via Civil Engineering Department at Jordan University of Science and Technology. The tested beams were simply supported with a clear span of 1450 mm, as shown in Fig. 4. Two point loads were applied to the beams under displacement-controlled condition. The load was applied at the center of rigid steel plate which transmitted the load on two bearings, spaced 400 mm, and resting on the beam's top surface. The deflections were measured at the mid-span of the beams using two linear variable differential transducers (LVDTs). Load versus deflection measurements were collected electronically using a data acquisition system then analyzed to obtain load-deflection curves. Cracking load was monitored during testing and recorded on the bottom of each beam.

3. Experimental results

3.1 Cracking patterns due to elevated temperatures

The post-heating cracking patterns as marked on the surfaces of different beams were determined. No cracks were generated when specimens were subjected to temperature at 100℃, whereas few hairy cracks appeared after heating to 200℃. Exposure to a higher temperature of 300℃ resulted in creating any interconnected short hairy cracks on surfaces of corresponding beams. The intensity of these cracks increased as temperature approached 500℃, as shown in Fig. 5.



(a)

(b)

Fig. 5 Cracking patterns of the tested beams at temperatures of (a) 300℃; and (b) 500℃.

It is important to mention that the cracking patterns on heated beams were not affected by the type of the FRP reinforcement used.

3.2 Cracking patterns and mode of failure

In this part, the modes of cracking and failure for control and heat-treated specimens pertaining to different types of reinforcement are presented and discussed in details.

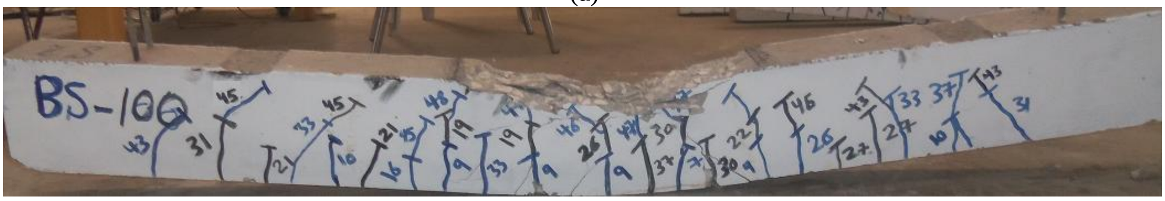
3.2.1 Beams reinforced with conventional steel bars

The mode of cracking and failure for the beams with steel bars were described to set a reference for comparison with those reinforced with FRP bars. As shown in Fig. 6, beams of this group showed flexural failure under transverse loading. As load was increased, flexural cracks initiated in the high moment zone region before extended towards the compression zone and spread in the shear span with further load increase. Prior to failure, these cracks extended deeper into the compression zone, which resulted in beams failure by yielding of steel reinforcement followed by crushing of the compression zone. Generally, differences in cracking patterns and modes of failure of beams of this group heated at different temperature levels below 500^{o}C were unnoticeable. For beams reinforced with steel bars, the cracks were first observed at a load of (9, 9, 10, 8, and 1 kN) for control and those heated at 100℃, 200℃, 300℃ and 500℃; representing (20, 20, 22, 18, and 3%) of their ultimate load capacity, respectively. The cracking loads for different test beams are summarized in Table 3 along with the characteristics of load-deflection diagrams.

3.2.2 Beams reinforced with GFRP and CFRP bars

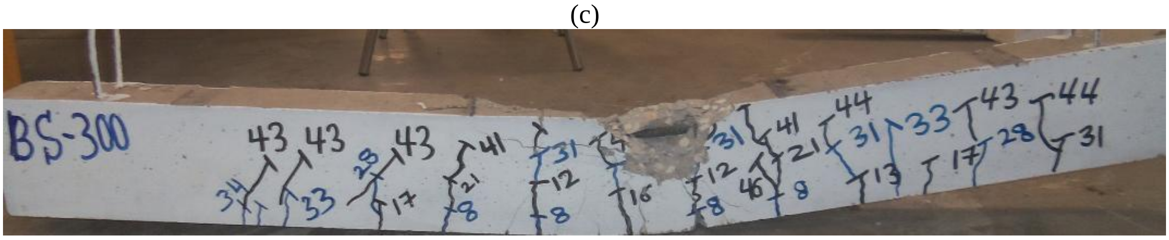
The beams reinforced with GFRP and CFRP bars, except those post-heated to 500^{o}C, showed concrete crushing failure followed by tension failure of FRP bars. Flexural cracks initiated in the high moment zone region, then extended towards the compression zone and spread in the shear span with further load increase. Finally, the cracks extended deeper into the compression zone leading to crushing of concrete, prior to FRP bars failure in tension, as shown in Figs. 7 and 8. Those heated at 500℃ failed by a single flexural crack initiated at their center then extended

(a)



(b)

(c)



(d)

(e)

Fig. 6 Crack patterns at failure for heat-damaged concrete beams reinforced with steel bars at temperature of (a) unheated (b) 100℃ (c) 200℃ (d) 300℃ (e) 500℃

towards the compression zone, causing crushing of concrete, as shown in Fig. 7(e) and 8(e). These failure modes suggested that GFRP and CFRP bars had lost their tensile strength partially to fully upon heating.

Generally, for temperatures greater than 300℃, the propagation of cracks and following failure modes of heat-damaged beams depended on the type of the FRP reinforcement used, whereas differences in cracking patterns and modes of failure between the different types of specimens were unnoticeable below 300℃. The cracking loads for different test beams are summarized in Table 3 along with the characteristics of load-deflection diagrams. For beams reinforced with GFRP, the cracks were first observed at a load of (5, 7, and 6 kN) for control and those heated at 200℃ and 300℃; representing (10, 15, and 14%) of their ultimate load capacity, respectively. The corresponding cracking loads and percentages of ultimate load for those reinforced with CFRP bars were (6, 10, and 6kN), and (8, 15, and 10%), respectively.

Table3 Cracking loads and mechanical characteristics for various beams

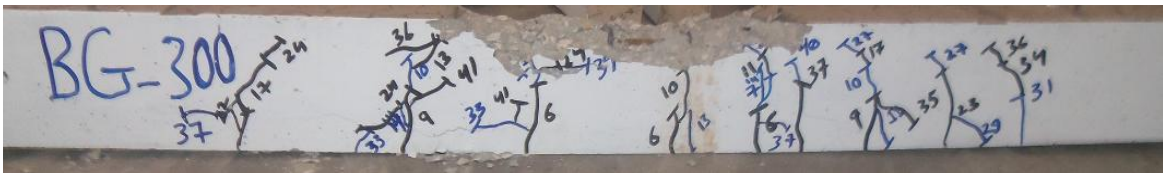
Beam designation	Cracking load (kN)	Ultimate load (kN)	Deflection at ultimate load (mm)	Deflection at failure (mm)	Toughness (J)	Stiffness (MN/m)
BS-C	9	45.1	8.1	18.4	668.9	10.4
BS-100	9	46	11.1	49.7	1855.7	8.4
BS-200	10	44.8	14.0	51	1818.4	7.9
BS-300	8	44.1	15.9	50	1789.8	7.3
BS-500	1	29.6	9	47.1	1181.7	6.9
BC-C	6	74	11.2	14.5	713.3	8.0
BC-100	7	77.2	18.5	29.4	1528.1	6.3
BC-200	10	67.2	24	25.1	1614.1	5.8
BC-300	6	60	30.0	35.7	1607.9	4.8
BC-500	1	4.4	8.4	60.4	158.3	2.8
BG-C	5	48.1	32.1	32.1	1072.1	3.7
BG-100	5	50.8	42.6	42.6	1461.8	2.1
BG-200	7	47.5	38.8	39.8	1250.6	2.8
BG-300	6	44	46.4	46.4	1368.5	1.8
BG-500	2	3	9.8	56.9	499.2	0.4

(a)

(b)

(c)

Fig. 7 Crack patterns at failure for heat-damaged concrete beams reinforced with GFRP bars at temperature of (a) unheated (b) 100°C (c) 200°C (d) 300°C (e) 500°C

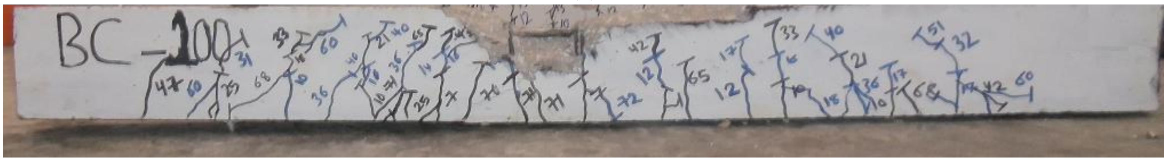


(d)

(e)

Fig. 7 Continued

(a)



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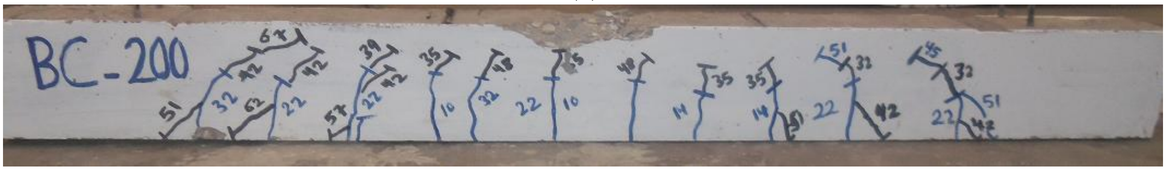

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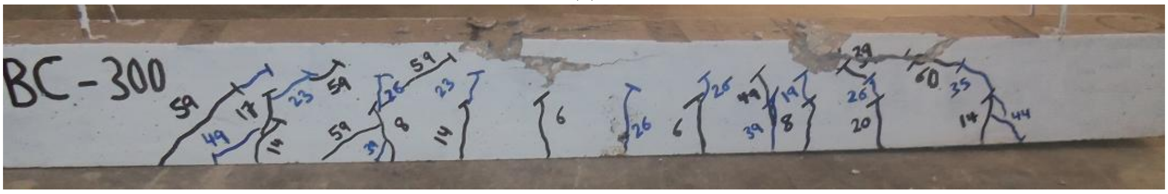

(d)

(e)

Fig. 8 Crack patterns at failure for heat-damaged concrete beams reinforced with CFRP bars at temperature of (a) unheated (b) 100℃ (c) 200℃ (d) 300℃ (e) 500℃

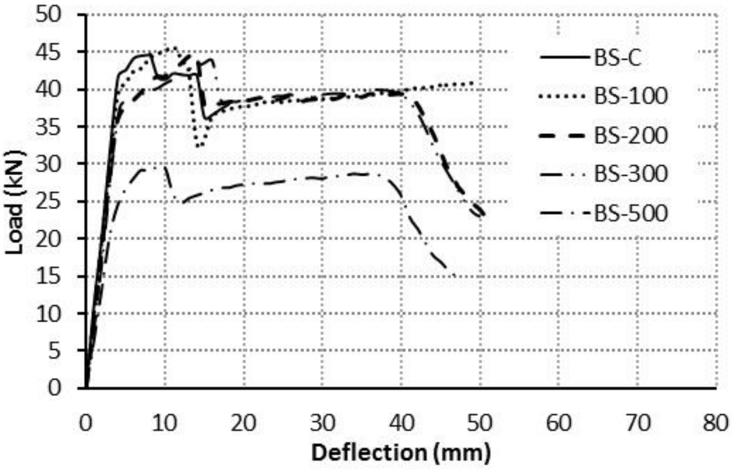

Fig. 9 Load-deflection curves of heat-damaged beams reinforced with steel bars.

3.3 Effect of elevated temperature on flexural behavior of RC beams

Fig. 9 shows the load–deflection behavior of heat-damaged beams reinforced with steel bars. It is clear that the heating process did not affect the overall behavior of the tested beams. The load-deflection curves for all beams reinforced with steel bars comprised from straight line portion (pre-cracking stage) followed by a nonlinear behavior up to failure; diagnostic of reduction in stiffness due to concrete cracking. Results from Table 3 showed that the ultimate loads experienced insignificant reduction when subjected to temperatures below 300℃, yet were significantly reduced when subjected to 500℃ at about 34% of the original value. Contrariwise, the central deflection at ultimate load was increased by 37%, 73%, and 96% for beams corresponding to exposure temperatures of 100, 200, and 300℃, respectively.

The load-deflection behavior of heat-damaged beams reinforced with GFRP and CFRP are shown in Figs. 10 and 11, respectively. It is clear that the heating process had insignificantly influenced the overall behavior of the tested beams for exposure temperature less than 300℃. The load-deflection curves for all beams reinforced with CFRP and GFRP bars comprised from a straight line portion (pre-cracking stage) followed by another softened straight lines with multiple peaks up to failure; diagnostic of reduction in stiffness and appearance of multiple concrete cracking, respectively. Results from Table 3 showed that the ultimate loads experienced insignificant reduction when subjected to temperatures below 300℃, yet were significantly reduced when subjected to 500℃ at about 93% and 94% of the original value for beams reinforced with CFRP and GFRP bars, respectively. This drastic reduction is mainly attributed to the reduction in mechanical properties of FRP bars: FRP bars lost approximately 90% of its strength at 500℃ as a result of polymer melting. As may expected the central deflection at ultimate load for beams reinforced with GFRP bars and CFRP bars were increased by (33, 21, and 45%) and (65, 114, and 168%) corresponding to exposure temperatures of (100, 200, and 300℃), respectively. Significant reduction in beams stiffness is also noticed due to heating process as indicated by the results of Table 3. Moreover, the slight increase in the ultimate load of tested beams heated at 100℃ is attributed to the enhancement in compressive strength of concrete; owing to the reduction in concrete moisture content.

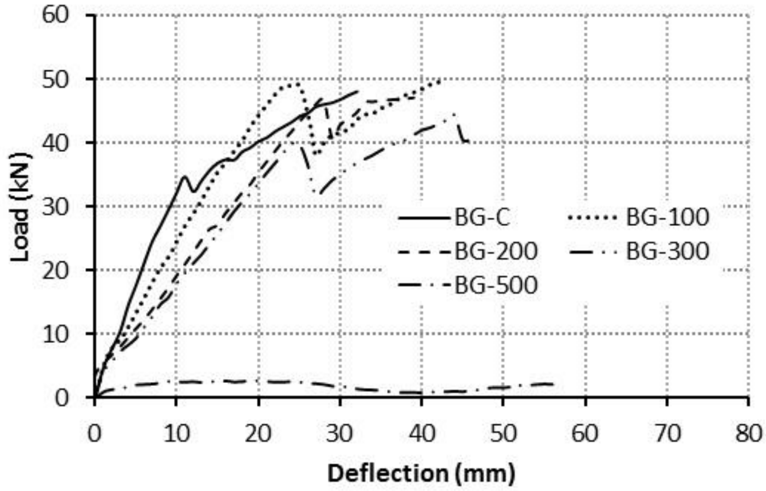

Fig. 10 Load-deflection curves of heat-damaged beams reinforced with GFRP bars

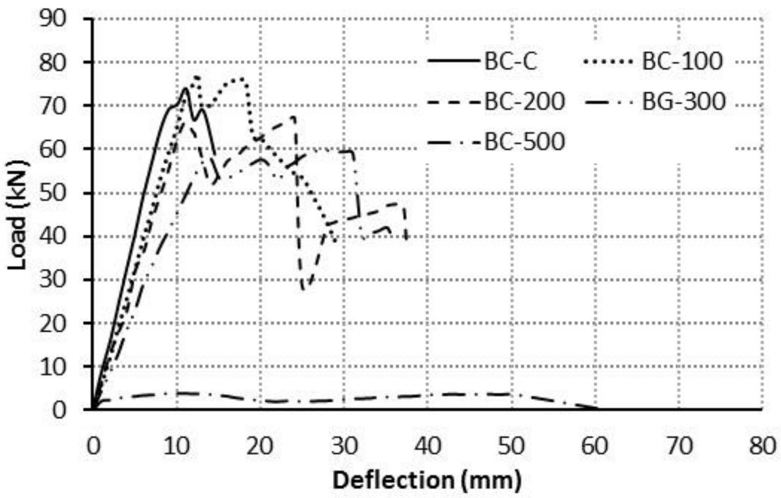

Fig. 11 Load-deflection curves of heat-damaged beams reinforced with CFRP bars

3.4 Effect of reinforcement type on flexural behavior of heat-damaged beams

In order to understand the effect of the FRP reinforcement on the flexural behavior of concrete beams under elevated temperatures, the load-deflection curves pertaining to beams with steel, CFRP, and GFRP bars were depicted in Figs. 12-16. The load-deflection curves pertaining to beams with CFRP and GFRP bars experienced significant post-cracking softening proportional to temperature level with higher extent for those of beams with GFRP bars; because of the latter's relatively lower stiffness. Moreover, Figs. 12-16 show that the beams with CFRP bars have higher flexural load capacity than those with GFRP and conventional steel bars for exposure temperature less 300°; owning to the higher tensile strength of the former bars at this temperature range. As expected, the deflection behavior was inversely proportion to the modulus of elasticity of the

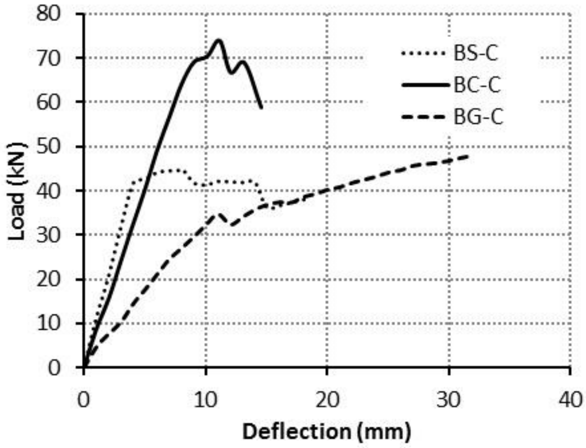

Fig. 12 Load-deflection curves of unheated beams

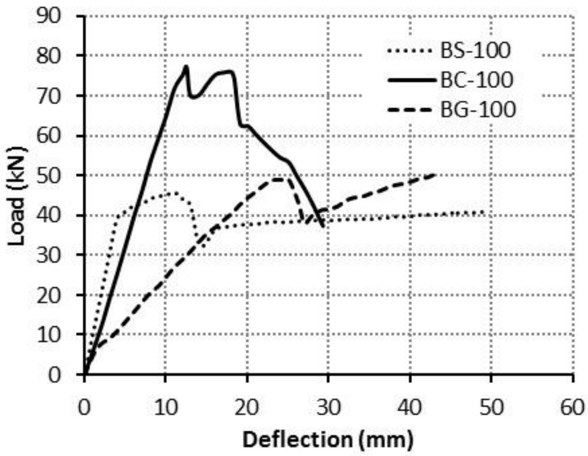

Fig. 13 Load-deflection curves of beams heated at 100°C

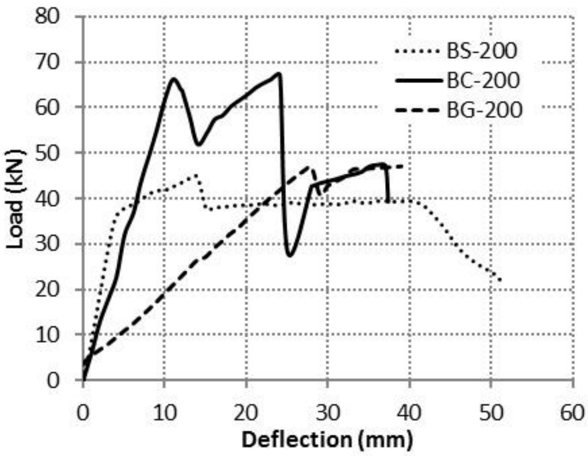

Fig. 14 Load-deflection curves of beams heated at 200°C

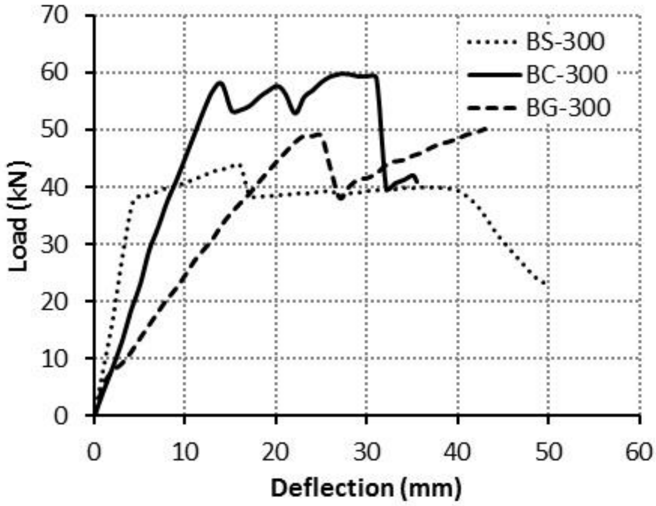

Fig. 15 Load-deflection curves of beams heated at 300°C

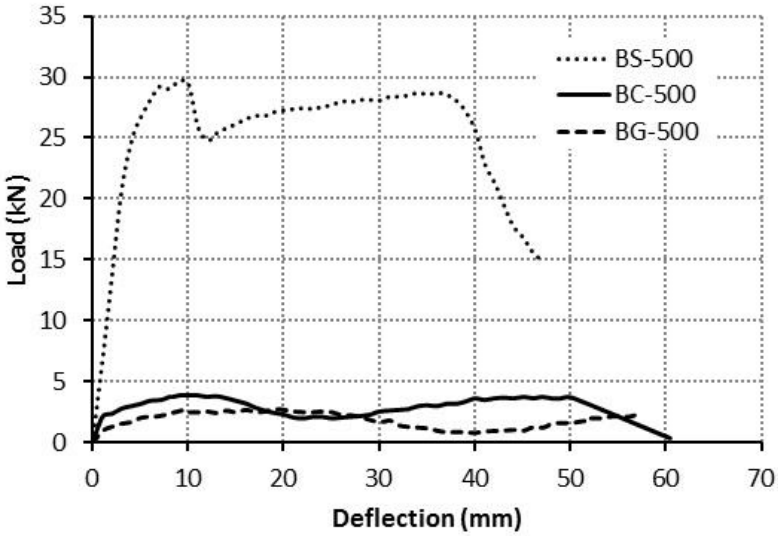

Fig. 16 Load-deflection curves of beams heated at 500°C

reinforcement.

The variation of normalized ultimate load and the corresponding normalized deflection with temperature for each group of tested beams are plotted in Figs. 17 and 18, respectively. It is clear from Fig. 17 that beams with steel bars have shown superiority over those with FRP bars in terms of resistance to heating. Moreover, beams with CFRP bars showed more sensitivity to heating than those with GFRP bars; owning to the former higher ultimate load prior to heating. Fig. 18 shows that deflection of the beams with CFRP bar was less affected by heating followed, in sequence, by those of beams with steel and GFRP bars, respectively. This referred to the higher modulus of elasticity of CFRP bars, prior to heating, as compared to those with steel and GFRP bars.

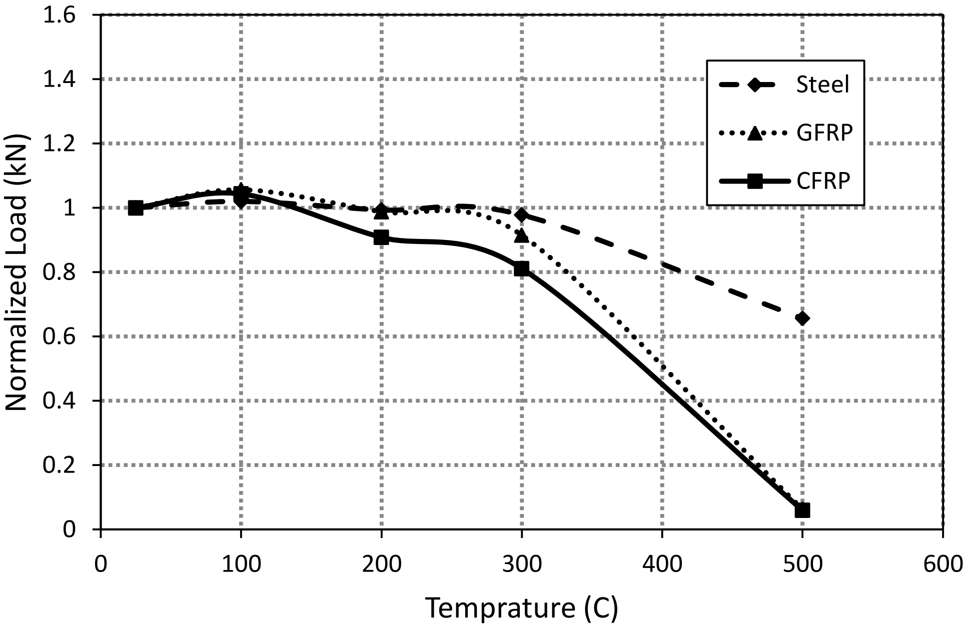

Fig. 17 Normalized ultimate load versus heating level for beams with different reinforcement

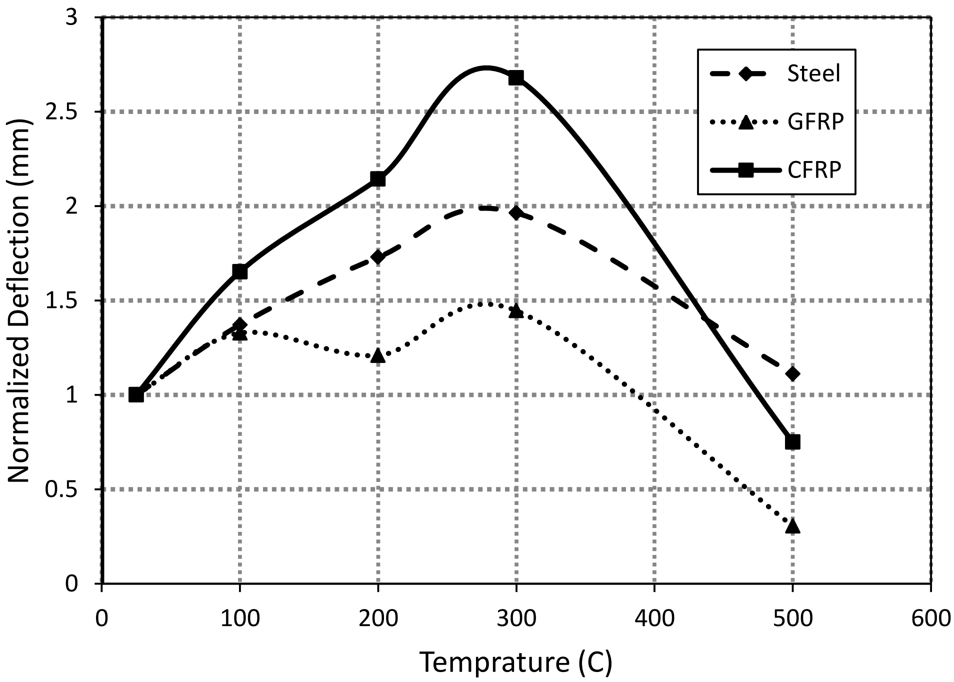

Fig. 18 Normalized deflection corresponding to ultimate load versus heating level for beams with different reinforcement

4. Conclusions

The current article studies the flexural behavior of concrete beams, reinforced with FRP bars and subjected to elevated temperatures. Thirty rectangular concrete beams reinforced with either steel, GFRP, or CFRP bars were casted, subjected to elevated temperatures in range of 100^{o}C-500^{o}C, then tested under four-point loading condition. For the parameters studied herein, the following conclusions can be stated:

• Exposing concrete beams with CFRP bars to elevated temperatures of up to 500^{o}C resulted in significant reduction in their flexural load capacity and stiffness and an increase in maximum deflection and toughness. The percentage reduction in load capacity and stiffness reached as high as 19%, 40% at temperature of 300^{o}C and 94%, 65% at 500^{o}C, respectively.

• Concrete beams reinforced with CFRP and GFRP bars showed higher ultimate load than those with steel bars for temperatures range from 23 to 300^{o}C. Beyond 300^{o}C, both CFRP and GFRP lost their load resistance hence corresponding beams showed sudden type brittle failure.

• The load-deflection curves for beams reinforced with CFRP and GFRP bars showed a typical load-deflection curves comprised from a straight line portion (pre-cracking stage) followed by another softened straight lines up to failure.

• Beams with CFRP bars showed higher sensitivity to heating with respect to load capacity than those with GFRP bars; owning to the former higher ultimate load prior to exposure to heating.

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