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Flexural Behavior of Reinforced Concrete Beams with FRP Bars Exposed to Elevated Temperature

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Abstract
The present study aims to evaluate the performance of concrete beams with different Fiber Reinforced Polymer (FRP) and steel bars exposed to elevated temperatures through a detailed experimental investigation. Flexural behavior of beams is analyzed with Carbon Fiber Reinforced Polymer bars (CFRP), Basalt Fiber Reinforced Polymer bars (BFRP), Glass Fiber Reinforced Polymer bars (GFRP), and steel bars tests. Beams were exposed to elevated temperature 925 °C (1 hr) following standard fire curve, and subsequently cooled by either natural or forced water spraying. After the cooling, beam specimens were tested under four-point loading up to the failure load. Ultimate load and deflection profile of heated and unheated beams are evaluated. At higher temperatures (925 °C), the steel and GFRP specimens show a higher strength loss of about 60–80% with higher deformation values. The load carrying capacity of CFRP beams is found to be higher as compared to other types of beams. Specimens cooled by water shows higher strength loss of about 7–12% than air cooled specimens. The failure pattern of beams with FRP and steel beams are different, and it is based on heating cooling regime.
Keywords
FRP bars, reinforcement steel, elevated temperature, flexural behavior, failure mode

1 Introduction

In recent years, the construction industries have been focusing on the utilization of advanced building materials to extend the service life of the structure. Fiber-reinforced composites are highly demanded in increasing its application for the construction of concrete structures. It is due to the higher mechanical properties, lightweight, non-magnetic properties, and ease in fabrication than reinforcement steel [1]. In addition, fiber reinforcement bars, including CFRP, BFRP, GFRP, and aramid (AFRP), are widely used for structures in marine environment than reinforcement steel due to their better corrosion resistance [2]. Under service load conditions, the structural concrete members reinforced with FRP bars may experience to extreme fire temperatures. This should be a reliable and considerable factor in understanding and promoting FRP bars under elevated temperatures [3]. Due to this motive, the present investigation focuses to examine the flexural behavior of concrete beams reinforced with FRP bars exposed to high temperatures.

Many researchers have conducted detailed study on the physical and strength performance of concrete and FRP reinforcement steel under elevated temperatures. When concrete is exposed to a higher temperature, the weight loss, deformation changes in aggregate and damage of CSH gel, chemical changes, spalling, and decreases in mechanical properties occurs and lead to deterioration of the structural members [4]. Yield strength, ultimate strength, and modulus of elasticity of steel materials degrade when subjected to high temperatures [5]. At the temperature of 80 °C, the FRP bars does not showed any strength loss [6]. Temperature between 150 °C and 300 °C, a lower reduction of tensile strength with sudden fracture failure was

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observed [7]. With an increase in temperature from 300 °C to 400 °C, a sharp drop in the elastic modulus was observed as 45.7–52.2% [8]. When the temperature reaches between 500 °C and 700 °C, the GRFP bars exhibit a significant strength loss [9].

Beams are represented as flexural members, subjected to bending and shearing loads. Therefore, the residual flexural performance of reinforced concrete beams under elevated temperatures is considered as an essential factor for performing the structural fire design [10]. Flexural and shear strength of FRP reinforcement beams under elevated temperature degraded significantly [5]. FRP reinforced beams were less ductile but stiffer than steel-reinforced beams during the temperature exposure [6]. All the FRP-reinforced beams behave linearly until cracking and almost linearly between cracking and failure, with a considerable reduction in the slope. The FRP-reinforced beams failed by crushing of concrete and steel-reinforced beams were failed by yielding of steel reinforcement [11]. Deflections of beams with BFRP reinforcement were significantly higher than the reference beam due to the lower elastic modulus of BFRP bars than steel bars [12, 13]. However, the temperature test results indicated that concrete beams reinforced with GFRP rebar can meet the fire design requirements for the minimum fire resistance periods [7–9]. Hence assessment on the degree of deterioration of structures due to elevated temperatures is necessary to decide whether the structure needs to be repaired or demolished. This raises the need for studies on the behavior of reinforced concrete members at elevated temperatures [14].

The past literature reveals that the strength characteristics of the FRP rebar reduced drastically after being exposed to elevated temperatures. However, the behavior of FRP bars (CFRP, BFRP, and GFRP) may differ from that of the steel reinforcement bars used for construction. In addition, the effect of temperature on the flexural behavior of beams with different FRP bars is not reported in the earlier studies. Based on the literature, few studies have been undertaken on the behavior of beams with different reinforcements such as basalt, glass, and carbon under elevated temperatures. Therefore, the structural fire design can be performed with proper understanding to assess the post-fire behavior of FRP beams.

The present investigation focuses on the performance of concrete beams reinforced with FRP bars and reinforcement steel bars subjected to elevated temperatures. The concrete beam specimens were cast and exposed at a temperature of 60 minutes (925 °C) following standard fire curve [15]. The temperature response of concrete beams is monitored for FRP bars and steel bars with respect to time. The temperature exposed specimens are allowed to cool by air or water spraying. After the cooling phase, the beams are tested to evaluate ultimate load, load-deformation behavior, the tensile strength of FRP bars, and mode of failures.

2 Experimental program

2.1 Materials

The FRP bars used in this study are manufactured by the pultrusion technique and the textured surface. The FRP bar of 10 mm diameter and 1500 mm length reinforcement bar was obtained from the market. Fig. 1(a) illustrates different types of FRP rebars used in the experiments. Mechanical properties of the FRP bars and reinforcement steel are given in Table 1.

Cement of grade 53 was used, as per IS 12269 guidelines. In addition, crushed granite stone was used as a coarse aggregate with a maximum size of 12–20 mm. M sand conforming to Zone II as per IS 383 was used as fine aggregate in the concrete mixtures [16, 17]. The material properties of concrete ingredients are illustrated in Table 2.

2.2 Details of mix proportion and casting

Conventional concrete with a target compressive strength of 30 MPa was developed using the optimum cement content and aggregates with an appropriate water-cement ratio. The concrete mix design was carried out for moderate exposure conditions with a target slump of 100-125 mm as per [17]. Several trials were made to achieve the target workability and strength. The quantity of concrete ingredients are: 385 kg/m^3 of cement, 805 kg/m^3 of fine aggregate, 1045 kg/m^3 of coarse aggregate used to develop the concrete mix. Water to cement ratio of 0.5 was considered to attain

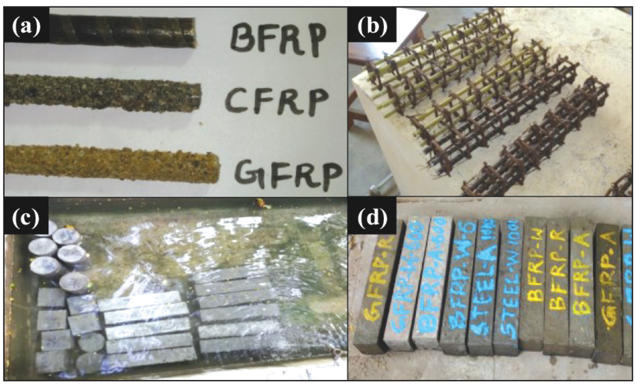

Fig. 1 View of (a) FRP reinforcement bars, (b)FRP and steel reinforcement cage, (c) Concrete specimens under water curing, (d) Beam specimens for testing

Table 1 Properties of reinforcement bars

Properties	CFRP	BFRP	GFRP	Steel
Yield strength (MPa)	1570	950	850	575
Elastic modulus (GPa)	122.29	68.23	47.15	227.38
Density(g/cm^3)	1.6	2.2	2.0	7.8
Poisson's ratio	0.45	0.29	0.22	0.3

Table 2 Material properties of concrete ingredients

Material	Density (kg/m^3)	Specific gravity	Water absorption (%)	Fineness modulus
Cement	1436	3.15	–	3.27
Fine aggregate	1684	2.70	0.54	2.60
Coarse aggregate	1775	2.96	1.14	5.13

the slump value. Twelve concrete beam specimens were cast with specimen dimensions of 700 × 150 × 150 mm. Each of these beams are reinforced with two longitudinal bars of 10 mm diameter each on the tension face (FRP bars for FRP reinforced beams and steel bars for steel-reinforced beams). The top reinforcement for all the beams consisted of two FRP/steel bars of 10 mm diameter. A clear cover of 25 mm was provided for the test specimens. Ties of 6 mm dia are used with a spacing of 50 mm for all the beams. Fig. 1(b) shows the FRP reinforcement cage used for the casting of beams. After the casting, all specimens were kept in a curing tank for 28 days, as shown in Fig. 1(c) and sufficiently dried before testing after target curing; the specimens were allowed to dry, as shown in Fig. 1(d).

2.3 Beam specimens with FRP/steel bar under elevated temperature

An electric furnace with an inner dimension of 700 × 400 × 400 mm was used to heat the specimens, as shown in Fig. 2(a). The electrical heating coils on the sides and the top of the furnace were fixed in the fire clay. The heating capacity of the heating instrument is 1250 °C. The beams were kept inside the furnace and heated up to 925 °C (60 minutes) following the standard fire curve. The actual rate of heating was recorded in an identified for all beams location. K-type thermocouples was used to record the time temperature in the beam specimen at various locations such as (furnace coil (T1), concrete surface (T2), FRP/rebar (T3), and at the core (T4) of the beam). The heating and schematic view of thermocouple position of the beam specimen is illustrated in Fig. 2(b), and Fig. 2(c), it shows the thermocouple setup inside the furnace of the concrete beam specimen. An integrated device attached with a urnace was used to record the actual rate of heating.

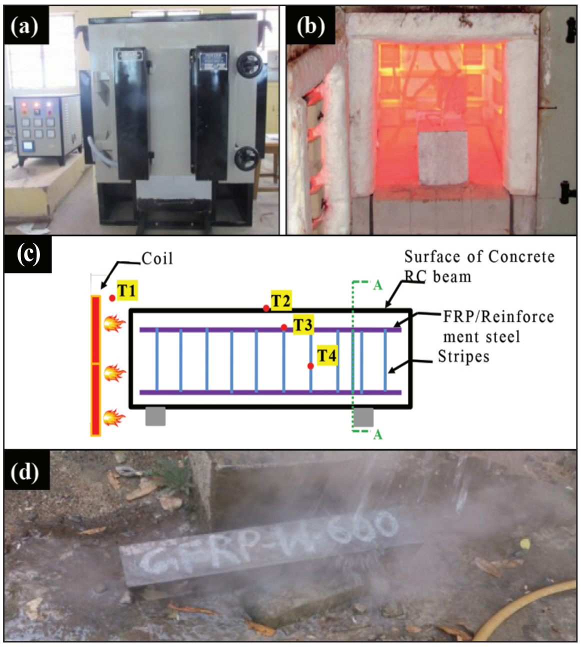

Fig. 2 (a) View of the electric furnace, (b) Heating of beams in the electrical furnace with thermocouple setup, (c) Location at the thermocouple setup in the beam specimens, (d) Water cooling

After exposing the specimens to the target temperature, the furnace was switched off automatically, and the specimens were taken out of the furnace in hot condition. Then, the specimens were cooled either by air or water spraying. Fig. 2(d) shows the water-cooling of the beam specimen after exposure.

2.4 Flexure test

After exposure to air and water cooling, an experimental investigation has been carried out to evaluate the flexural performance of beams with FRP/steel bar. Each beam specimen is tested with simply supported condition over a span of 600 mm and subjected to two-point loading. A computerized data acquisition system was used to continuously record the specimens load and mid-span deflection. A detailed schematic test setup of four-point loading beam specimens is illustrated in Fig. 3(a). A UTM of capacity 1000 kN is used for testing, as shown in Fig. 3(b). The specimens were tested till the failure.

2.5 Tension test on FRP/steel bars

After testing, the beam specimens are broken to examine the tensile strength of the FRP and reinforcement bars which are shown in Fig. 4(a). Twelve specimens are tested in which four are at room temperature, and eight are exposed to elevated temperature. The tensile strength of the FRP bars and reinforcement bars was tested as per

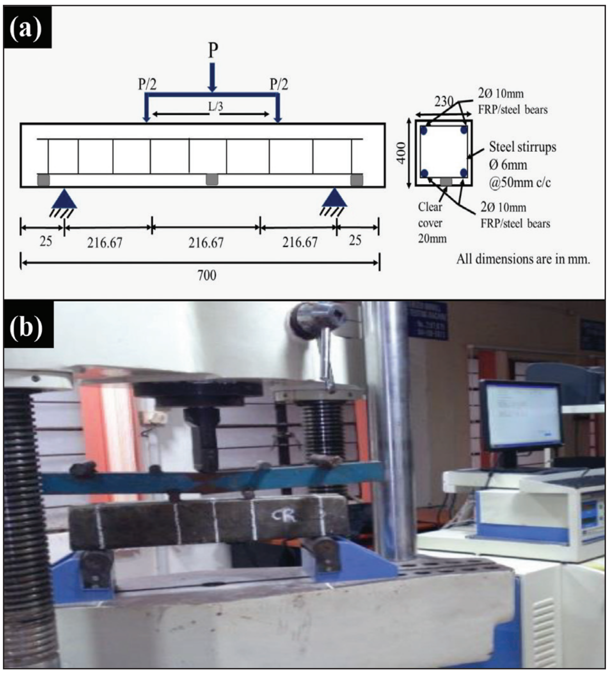

Fig. 3 View of (a) Schematic test setup, (b) Flexural test

Fig. 4 View of (a) FRP rebars specimens after loading, (b) Tension test of rebar/FRP

the guidelines of ASTM D7205/D7205M-06(2016) [18]. The tensile test setup used for testing FRP and steel rebar specimens is given in Fig. 4(b). Load-deformation and stress-strain behavior of specimens are recorded in the data acquisition system.

3 Results and discussion

3.1 Time-temperature curve

Fig. 5(a–d) shows the time-temperature response of concrete beams with FRP/steel rebar specimens. It is observed that, during the initial heating phase, the lesser magnitude of temperature rise was observed. For 16–25 minutes, the measured temperature in the coil is above 750 °C. Furthermore, at 45–60 minutes, the temperature exceeds between 850 °C and 915 °C. The temperature penetration at (T2) is almost the same as the coil temperature, with a minor difference of 5–10%. The measured concrete core temperature values at (T3) exhibited a temperature of 545 °C, 565 °C, 559 °C, and 554 °C for the GFRP, BFRP, CFRP, and steel rebar specimens. Moreover, at the core of the concrete beam specimens of GFRP, BFRP, CFRP, and steel rebar specimens (T4) are observed as 450 °C, 466 °C, 425 °C, and 456 °C, respectively.

The measured results showed that the temperature penetration at (T3) and (T4) shows lesser values when compared to applied temperature and coil temperature. It is due to the distance between the surface of the concrete beam to the measured beam positions, and the difference is 25 mm and 115 mm from the specimen surface. Regarding the temperature penetration for different FRP and steel bars, the temperature penetration is almost the same with minor temperature changes for both (T3) and (T4) positions. Similar test results are observed in the research studies by Thanaraj et al. [10].

3.2 Compressive strength of concrete

The compressive strength of concrete cube specimen was assessed following the guidelines of IS 516:2004 [19]. Cube specimens of size 150 × 150 mm are used in the study. Concrete cube specimens were tested in a computerized Compression Testing Machine (CTM) to determine the compressive strength. The residual compressive strength of concrete after the exposure was evaluated by the experimental results. The obtained compressive strength of reference cube specimen (unheated) is 34.5 MPa. In the case of heated specimens, at 925 °C (60 min) exposure a sharp strength loss was noted as 20.9% and 30.7% for air- and water-cooled specimens, respectively.

3.3 Ultimate load-carrying capacity of beam specimens

After heat exposure, the experiments are conducted to assess load-deflection behavior in the beams with FRP/steel bars. Fig. 6 shows the ultimate load-carrying capacity of the steel and FRP reinforced beam specimens. Steel beam specimens show a strength loss between 70.1% and 78.1% compared to reference steel beam specimens (unheated). Specimens of CFRP, BFRP and GFRP exhibited a significant strength loss of 69.1%, 70.1%, 74.1%for air cooled and 75.2%, 76.9%, 83.4% for water cooled specimens compared to FRP reference beam specimens.

The temperature exposure on beam specimens exhibits a significant effect on strength loss. However, the temperature exposure of CFRP and BFRP beam specimens retained the strength between 5–12% when compared with steel beam specimens under temperature exposure. The CFRP and BFRP beams show higher residual strength values

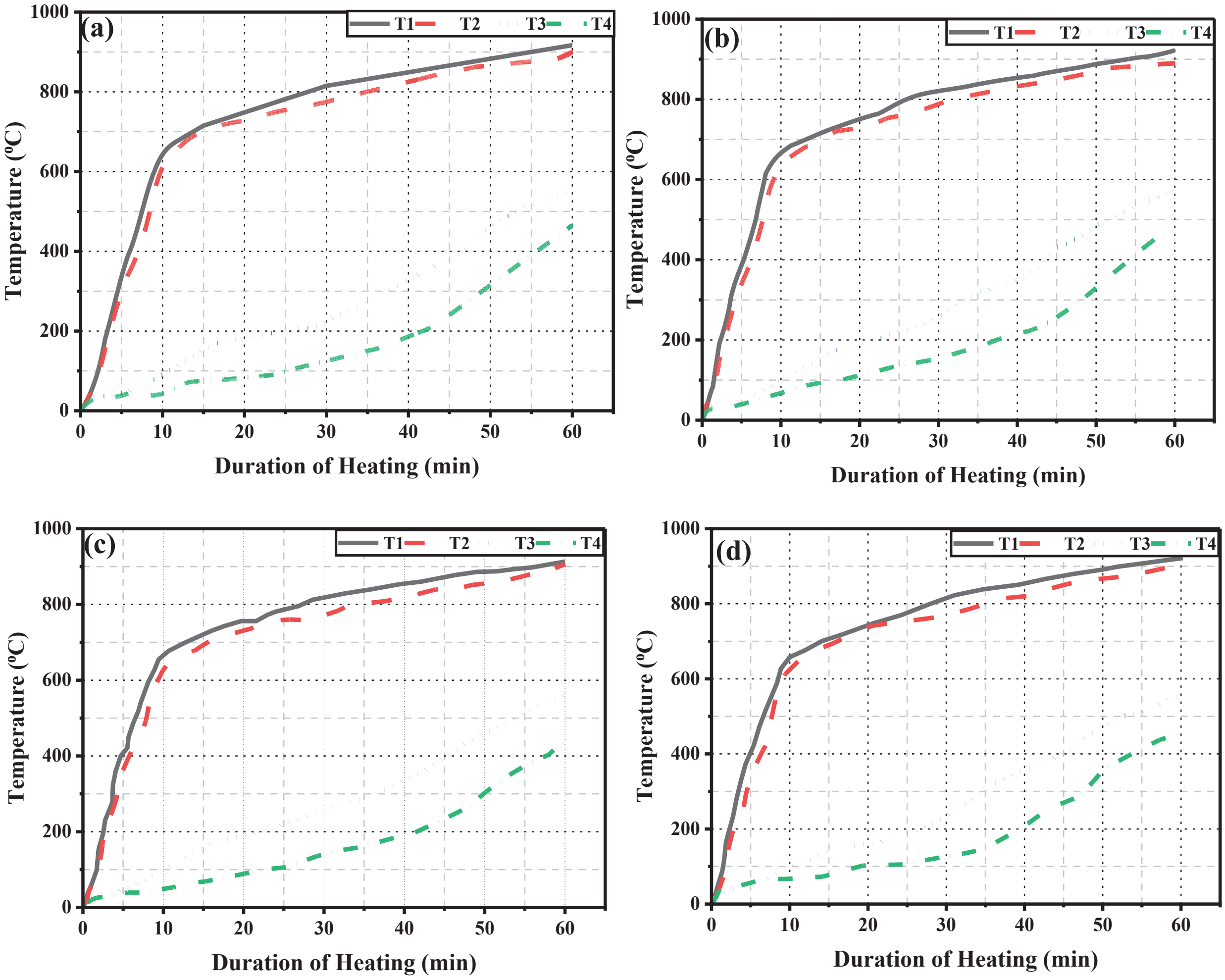

Fig. 5 Time-temperature response of concrete beam specimens (a) CFRP, (b) BFRP, (c) GFRP, (d) Steel reinforcement

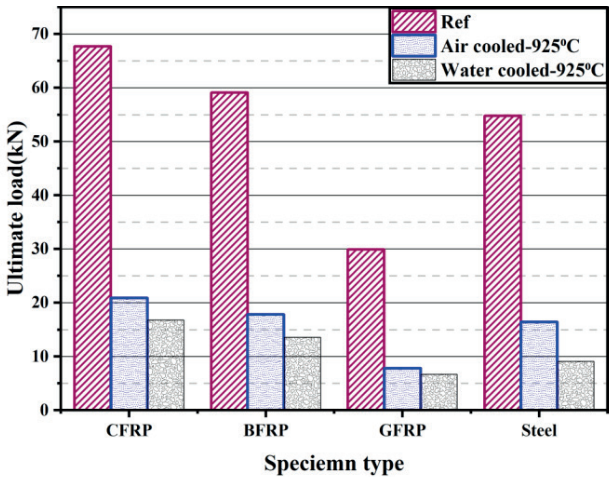

Fig. 6 Ultimate load of FRP/steel reinforced beams

than steel beam specimens. The CFRP and steel beam specimens perform better in air or water cooling than other beams. Also, the GFRP specimens exhibited a poor performance compared to all the other beam specimens. Moreover, the nature of cooling significantly affects the strength loss of all the beam specimens. All the water-cooled beam specimens showed efficient performance compared to air-cooled beam specimens, similar trend in the results were observed by Mathews et al [4].

3.4 Load-deflection behavior of beam specimens

The load-carrying capacity and deflection values were recorded with the aid of a data acquisition system in the UTM. The load-deflection behavior of FRP and steel beam specimens is shown in Fig. 7. In the case of all the reference beam specimens, the load values are initially increased linearly with lesser deformation. For all FRP and reference steel beam specimens, the load-carrying values were recorded as 67.7 kN, 59.8 kN, 29.7 kN, and 65.2 kN with deflection values of 14.3 mm, 10.1 mm, 9.3 mm, and 11.2 mm.

It is seen from the load-deflection graphs that the exposed beam specimens show a sharp strength loss with higher deflection. Concrete and steel materials lose their properties

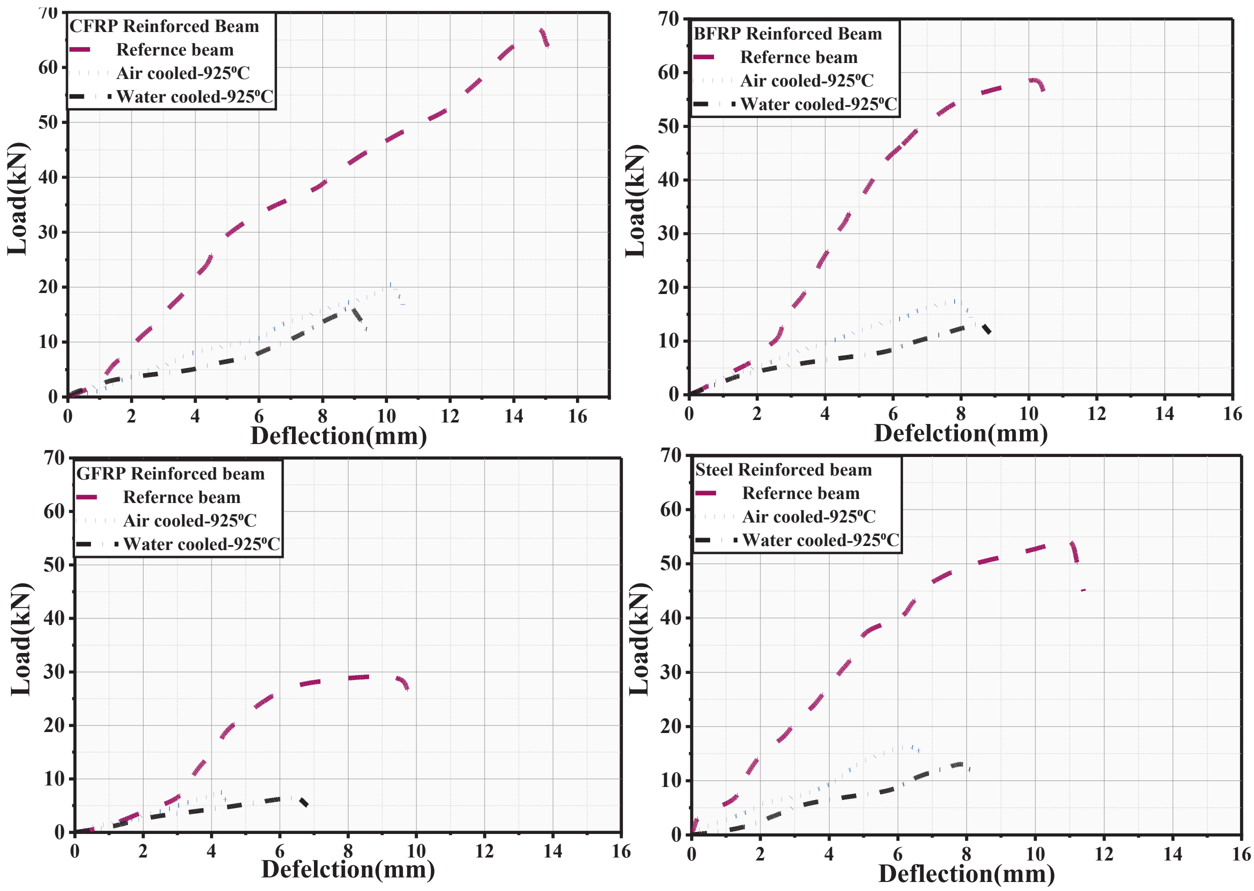

Fig. 7 Load-deflection of steel and FRP beam specimens with unheated and heated (925 °C)

and characteristics after the exposure to elevated temperature [20]. At ultimate load, the deflection values increased for both the type of cooled beams than the original unheated specimen. The load-carrying values of CFRP, BFRP, GFRP and steel air-cooled beam specimens are 20.9 kN, 17.8 kN, 7.8 kN and 16.4 kN and the deflection values are 10.2 mm, 8.1 mm, 4.2 mm, and 6.3 mm respectively. For all the water-cooled beam specimens, the load-carrying values are 16.8 kN, 13.6 kN, 9.1 kN, and 6.7 kN with the deflection of 9.1 mm, 8.4 mm, 6.3 mm, and 81 mm, respectively.

It was observed that all reference beam specimens exhibited a higher ultimate load with lesser deflection, and the failure pattern of the beam followed a pure flexure model. As a result, concrete cracking, rebar yielding, and plastic deformation were observed. Furthermore, the temperature exposed specimen shows poor load carrying capacity with a higher deflection. It is because of the temperature exposure on concrete and steel through the cross-section of the beam specimen. Also, the loss in bond between concrete and reinforcement bar after exposure to elevated temperature [10].

3.5 Tensile behavior of FRP/steel

A distinct tensile stress to tensile strain behavior is observed for FRP/steel bars extracted from both the cooled specimens. Fig. 8(a–d) presents the tensile stress to tensile strain behavior of all the specimens subjected to higher temperature. It is noted from the figure that, the ultimate tensile strength of FRP and steel bar varies due to its polymer properties [1]. The maximum tensile strength of CFRP, BFRP, GFRP, and steel is 1570, 950, 850, and 625 MPa. The stress-strain curve linearly increases to the ultimate stress with small strain values. Rebar exposed specimens, the AC specimens show low tensile strength values of about 510, 290, and 215 MPa for CFRP, BFRP, and GFRP respectively. A similar trend result was noted for WC specimens with higher strength loss. It was 350, 220, and 180 MPa, respectively. It is because of the decomposition of the polymer matrix in the FRP steel. It is stated that, the loss in bond between the different matrices of fibers which exhibits a lower tensile strength of FRP bars [6, 7]. However, at high temperature exposure on the steel bar specimens, the strength reduction was not seen for both

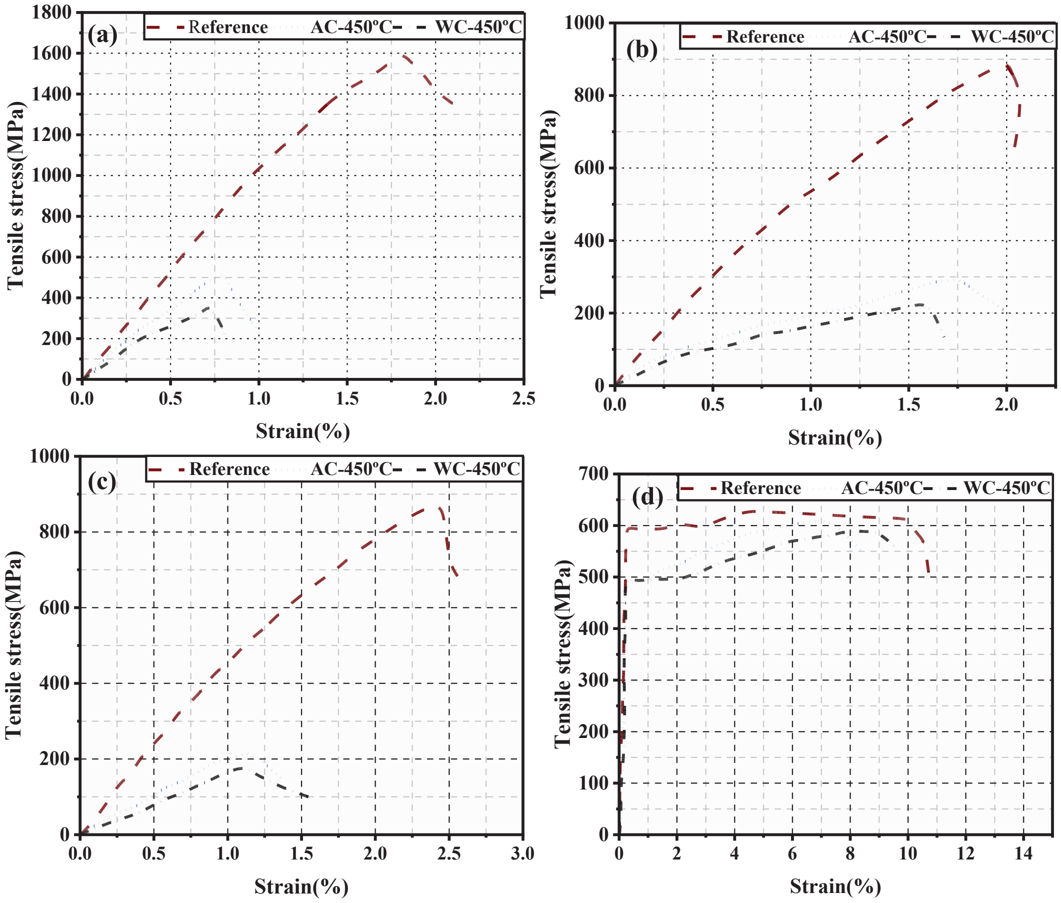

Fig. 8 Stress-strain behavior of different FRP and steel bars (a) CFRP, (b) BFRP, (C) GFRP, and (d) Steel rebar

the cooled specimens. As the ferrite content decreases in the microstructure of steel, it retains the tensile strength of steel rebar, as reported by Tariq and Bhargava [21].

3.6 Failure modes of beams

All the reference specimens failed in flexure mode whereas when the specimens are subjected to higher temperature, the failure pattern is observed with a combination of flexure, shear and bond. It is noted that, the ultimate failure of FRP reinforced unheated beams are due to sudden crushing of concrete, whereas the steel reinforced beams failed by yielding of steel along with flexural cracks. In the case of FRP heated beams, the failure is due to weakening of concrete and it is observed from the damaged concrete beams that the bond between concrete and FRP bar was completely lost. It is due to the higher ultimate strength of FRP bars with poor ductility under the effect of elevated temperature. The failure of both types of beams are due to the damage of concrete after the higher temperature exposure [1]. The type of cooling has a significant effect in the failure mode. The beams cooled by water cooling have shown a sudden failure with more damage. The concrete beam with steel reinforcement specimens failed by shear, and the bond loss was noticed between concrete and rebar. Also, it is observed that the effect of temperature has a significant effect on reduction in shear strength of concrete and it is more pronounced in the loading stage. The typical failure modes of beam specimens reinforced with FRP bars are depicted in Fig. 9. The effect of water cooling reduces the concrete strength significantly and it also depends on the type of cooling [22, 23].

4 Conclusions

An attempt has been made to conduct an experimental investigation to evaluate the load-deflection behavior and load-carrying capacity of FRP/steel reinforced concrete beams subjected to elevated temperatures. The load-deflection behavior of the beams under ambient and elevated temperatures was investigated. In addition, the strength properties and failure patterns of FRP/rebar samples were tested. Following are the primary conclusions of the research work.

Fig. 9 Typical failure mode of test beams and failure pattern

1. The exposed FRP/Steel reinforced concrete beams exhibited higher strength loss 60-80% compared to the reference beam.
2. The influence of temperature had a significant effect on load carrying capacity and failure mode of beam specimens. Also, the lower residual strength and higher deformation values was found to be more in specimens cooled by water than in the samples cooled by air.
3. It was observed from the results that the ultimate load of the CFRP, BFRP and steel heated beams exhibited a better temperature resistance than the GFRP specimens.
4. Strength reduction and increase in deflection was found to be dependent on the type of cooling, as the rate of cooling is different for both the cooling phases.
5. Beams reinforced with Steel bars showed the best performance in terms of load-carrying capacity, for both unheated and heated samples, whereas the performance of beams with GFRP bars are not remarkable. However, the cost of CFRP bars is higher than GFRP bars.
6. BFRP reinforced beams are observed with higher load-carrying capacity than GFRP beams.
7. At higher temperature, the FRP reinforced concrete beams failed by crushing of concrete with a de-bonding. Also, the failure depends on the exposure temperature and type of cooling.
8. An effective and suitable method to be formulated to protect the FRP bars under fire exposure in future studies.

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