كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (53),Issue (1)
January 2024, pp:56-63
https://erjsh.journals.ekb.eg

Effectiveness of Insulation Layers for Fire Protection of FRP Reinforced Concrete Flexural Members

Mustafa Abdullah [1,*] , Osama O. El-Mahdy [1], Gehan A. Hamdy [1]

[1] *Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.*
**Corresponding author*

E-mail address: mustafa.ismael@feng.bu.edu.eg, osama.alhenawy@feng.bu.edu.eg , gehan.hamdy@feng.bu.edu.eg

Abstract: This paper investigates experimentally the efficiency of thermal insulation layers in preserving the flexural capacity of fiber-reinforced polymer (FRP) reinforced concrete beams subjected to elevated temperature. FRP rebars are innovative alternatives to conventional steel reinforcement rebars in reinforced concrete structures. There is a need to identify the performance of those beams under fire scenario. Four concrete beams reinforced by different FRP rebars were investigated under elevated temperature exposure up to 800 °C for two hours. Two of those beams were thermally insulated by a 25 mm thick thermal insulation layer from perlite mortar. Experimental tests showed that the insulation layer enhanced the flexural performance of the concrete beams compared to the uninsulated beams. Moreover, the thermally insulated beams showed that the major failure mode is the crushing concrete at the top substrate of tested beams as recommended by the design guidelines. The thermal progression, failure load, failure mechanism and mid-span deflection of the tested beams are presented and discussed.

Keywords: RC beams; FRP bars; thermal insulation; flexure performance; experimental investigation.

1. Introduction

FRP is an innovative alternative to traditional steel reinforcement for multiple factors such as the ability of FRP to resist corrosion, high strength, and high stiffness in addition to the ease of handling to facilitate the construction time and process [1, 2]. Generally, the design guidelines recommend the design of FRP reinforced concrete beams to be an over-reinforced beam to depend on the nonlinear behavior of concrete in compression zone which may preserve a limited degree of deformability which can lead to a less catastrophic failure [3]. However, the behavior of the fiber reinforced polymer rebars subjected to elevated temperatures is a problem that needs to be investigated to ensure the capability of the FRP reinforced concrete beams to sustain the expected structural loads in case of fire occurrence. Thus, the experimental tests are required to set limitations and ascertain the safety margin of FRP-reinforced beams in fire events. Studies in the literature reported that the stiffness and strength of FRP bars degrade rapidly under elevated temperatures especially when the temperature exceeds the critical temperature level [4-8]. [6] reported a degradation in the tensile strength of glass and carbon FRP bars by about 50% to 70% under elevated temperature exposure up to 450°C. [7] reported degradation of BFRP bars tensile strength by 19%, 30%, 45% and 87% under high temperatures exposure up to 125 °C, 250 °C, 325 °C and 375 °C, respectively, and stiffness modulus degradation by 4%, 12%, 21% and 53% under the same thermal exposure. Lu et al [8] concluded that with the increase in temperatures from ambient normal temperature up to 200 °C, the tensile strength and modulus of elasticity of BFRP plates were degraded by 37.5% and 31%, respectively. Limited studies are found in the literature to investigate the degradation level in the ultimate flexural capacity of FRP reinforced concrete beams [9-18]. Degradation level up to 19% in flexural capacity of GFRP reinforced concrete beams under 600 °C and up to 53% under 700 °C [9,10], where the authors reported that the temperature level measured at FRP bar level exceeded the critical temperature causing a rapid reduction in strength and stiffness of those beams. Using a thick insulation layer from calcium silicate boards, an ultra-thin coating system and PC embedded ceramic fiber blanket enabled the insulated beams to have a satisfactory fire endurance for two hours [11-13]. Kamal, et al. [14] reported that a 50 mm thick PC embedded ceramic fiber blanket protected the insulated FRP strengthened beam and nearly preserved the flexural capacity to the same level as the control beam tested under ambient temperature. [15] tested BFRP-RC beams under elevated thermal exposure up to 925 °C for one hour. The beams were left to cool and then were tested in flexure up to failure. The authors reported that the heated beams showed strength degradation in the range of 60% to 80% compared to the control beam tested under normal temperature. [16] exposed the tension zone of concrete specimens reinforced by the BFRP bars and with hybrid FRP reinforcement under fire exposure according to ISO-834 [17] for two hours. The recorded failure of the BFRP reinforced beams occurred after 108 minutes due to reinforcement failure while the hybrid FRP beams showed 70 % strength reduction after two hours of exposure and with a recorded concrete crushing failure. [18] reported that the thermal insulation layers reduced the degradation in compressive strength of FRP strengthened concrete cylinders up to 24% under 400°C thermal exposure. This paper aims to investigate experimentally the effect of using a thermal insulation layer of an innovative material that is locally produced and available in the Egyptian market to protect the FRP reinforced concrete beams under elevated temperatures up to 800 ^{o}C. In this research, an experimental program is conducted in which four concrete beams reinforced by different FRP bars were exposed to elevated temperature and then tested under a four-point flexural test. The experimental procedures are explained and the experimental results are presented and discussed.

2. EXPERIMENTAL PROGRAM

The experimental program consists of four concrete beams reinforced with different FRP rebar. Two of those beams were thermally insulated by innovative perlite mortar of 25mm thick to study the efficiency of that material in protecting the tested FRP reinforced concrete beams. The typical section of the prepared concrete beams is 120x240 mm. Two of those beams were reinforced by two glass FRP (GFRP) bottom reinforcement of 10 mm diameter while the other two beams were reinforced by two basalt FRP (BFRP) bottom rebars of 8 mm diameter, as shown in Table 1. Traditional top steel reinforcement of 8 mm diameter along with two branch stirrups of 8mm diameter of steel reinforcement spaced at 100mm within the beam shear span was used for all beams. The experimental work was performed in Concrete Laboratory at the Housing and Building Research Centre (HBRC), Cairo, Egypt.

2.1 Materials

A concrete mix with a target cube compressive strength of 40 MPa was designed according to the mix proportions shown in Table 2. The constituent materials of the used concrete mix are: Portland cement conforms with the Egyptian standard specification ES 4756-1[19] with a washed-crushed limestone coarse aggregate of a nominal maximum size of 20 mm, and clean natural siliceous sand conforms with the Egyptian specification ES 1109 [20], and drinkable clean water in addition to a high range water reducer and slump retaining concrete admixture (Sikament®-R4PN) to improve the concrete mix workability and compressive strength at early stages. Moreover, the used Glass FRP rebar had 950 MPa tensile strength and 0.02 mm/mm tensile strain, while Basalt FRP rebar had 1100 MPa tensile strength and 0.022 mm/mm tensile strain. Stirrups and two longitudinal top reinforcements were 8 mm diameter mild steel bars with yield stress 240 MPa and ultimate strength 520 MPa conforming with the Egyptian Specification ES: 262-2 [21]. Table.3 shows the mix proportions of the perlite mortar as recommended by the manufacturer [22]. An important note is that Sika Aer, which is an air-entrained admixture was added to create an air bubble that works as a thermal barrier and increases the efficiency of the perlite thermal insulation layer.

TABLE 1. Experimental program

Beam No. / ID.	Cross-Section Dimensions (mm)	FRP Bottom Rebar	FRP Rebar Type	ρ_f%	Steel Top Rebar	Steel Shear Stirrups	Thermal Insulation Layer
B1: GBT	120 x 240	2T10	GFRP[a]	0.64	2Ø8	Ø8-100	-
B2: GBTP	120 x 240	2T10	GFRP[a]	0.64	2Ø8	Ø8-100	25 mm of Perlite Mortar
B3: BBT	120 x 240	2T8	BFRP[b]	0.41	2Ø8	Ø8-100	-
B4: BBTP	120 x 240	2T8	BFRP[b]	0.41	2Ø8	Ø8-100	25 mm of Perlite Mortar

[a] GFRP: Glass fiber-reinforced polymer rebar.

[b] BFRP: Basalt fiber-reinforced polymer rebar.

TABLE 2. Mix constituents per 1 m3of concrete.

Cement (kg)	Sand (kg)	Coarse aggregate (kg)	Water (L)	HRWR[a] (L)
450	690	1120	190	10

[a] HRWR: High range water reducer (Sikament®-R4PN).

TABLE 3. Thermal insulation mortar mix proportions per 1 m3.

Thermal Insulation Layer	Cement (kg)	Perlite (kg)	Water (L)	Glass Fiber (g)	Sika Aer (L)
Perlite Mortar	500	150	330	900	4

2.2 Beams preparation

Four concrete beams reinforced with different FRP bars. Two beams reinforced by two glass FRP rebars of 10 mm diameter. The other beams were reinforced by two basalt FRP rebar with a diameter of 8 mm are designed according to ACI 440.1R guidelines [3]. All beams were designed with a rectangular cross-section of (120x240) mm and with two traditional steel rebars of 8 mm diameter as a top reinforcement. Shear stirrups are spaced at 100mm with a diameter of 8 mm mild steel, over the beam shear span. Dimensions and reinforcement details of the tested concrete beams are shown in Fig. 1. Wooden moulds and reinforcement cages were prepared as shown in Figs. (2,3). For tracing the thermal progression in the cross-section of the beams, three thermocouples of type (k) protected with small ceramic fiber rings were located in the beam mid-depth, at bar level and in between the thermal layer and the beam bottom soffit as shown in Fig. 3. Concrete constituents were mixed using a mechanical mixer and all beams specimen were allowed to set for 24 hours inside the formwork, then the beams were left and placed in the curing water-filled tank for 28 days before conducting the thermal and flexural tests. A perlite mortar was cast in prepared wooden formwork at the bottom soffit of the hardened concrete beams as shown in Fig. 4.

2.3 Tests to determine material properties

Three standard concrete cubes of (150x150x150) mm were cast from the same concrete mix, cured under the same conditions and tested after 28 days in compression; the average concrete cube compressive strength was 41 MPa. Figure 5 shows the concrete cubes. Moreover, three basalt FRP bars and three glass FRP bars were tested in tension using the universal testing machine of 1000 kN capacity and to avoid bar slippage or local failure of the bar in the anchorage zone, a steel pipe 250 mm long with outer diameter of 55 mm was used at each end of the tested FRP rebar adhered using epoxy resin and hardener. The testing procedure followed the ASTM D7205 standard [23]. The average tensile strength of the GFRP rebar was 950 MPa with a corresponding ultimate tensile strain was 0.02 mm/mm, while the BFRP rebar had 1100 MPa as an average tensile strength with an ultimate tensile strain of 0.022 mm/mm. Testing machine and rebar tests are shown in Fig.6.

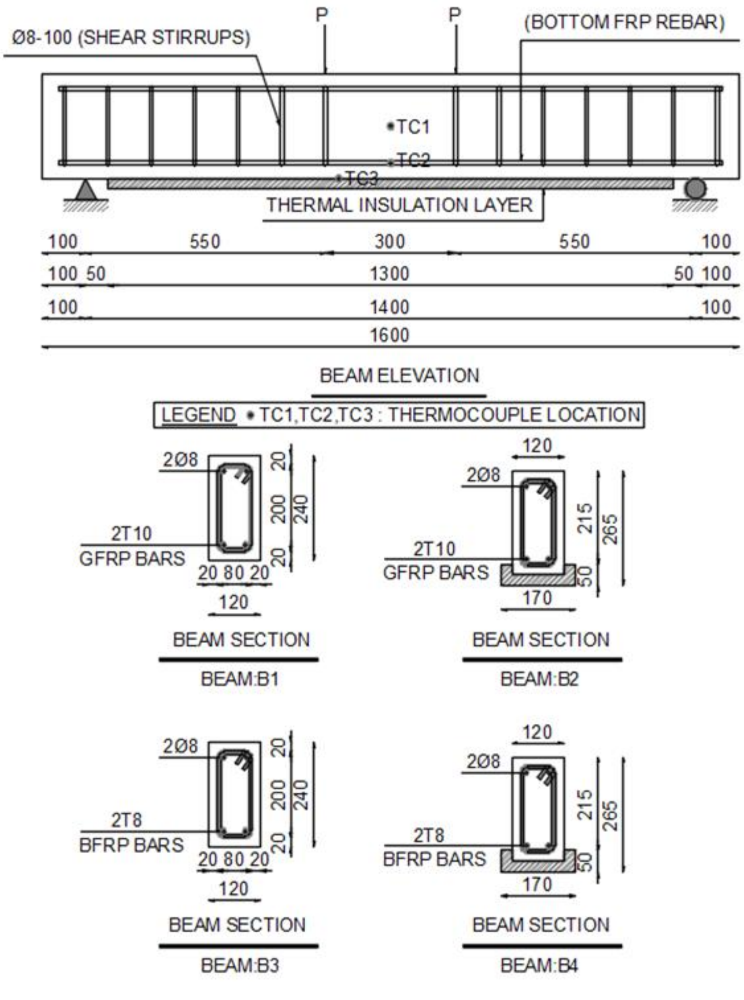


FIGURE 1. Beam elevation and cross-section details (dimensions in mm).

FIGURE 2. Typical beam preparation and casting.

FIGURE 3. Beams reinforcement cage with bottom GFRP or BFRP bars

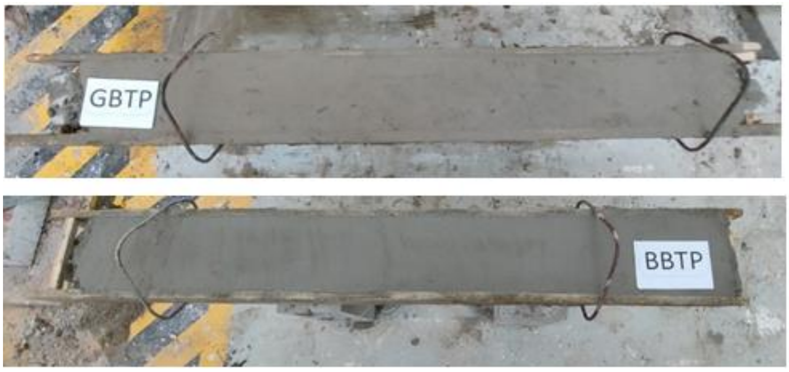


FIGURE 4. Perlite mortar insulation layer in beams B2: GBTP and B4: BBTP

FIGURE 5. Concrete cubes.

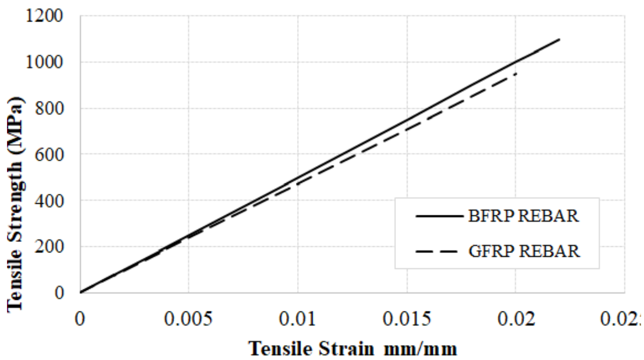


FIGURE. 6. Tensile stress-strain curve of used FRP rebars.

2.4 Fire exposure for beams

The beams were tested under fire exposure in the fire lab under elevated temperature exposure up to 800 °C. The beams were tested as simply supported at ends with an unsupported length of 1400 mm and located on top of the furnace, such that the beams bottom soffits were exposed to the elevated temperature. The temperature was increased according to ASTM E119 [24] rate up to 800 ºC due to technical limitations of the furnace and remained constant for two hours. The beam arrangement and the testing furnace are shown in Figs. (7,8). Thermal progression was measured via the thermocouples TC1, TC2 and TC3 placed at beam mid-height, FRP bar level and in between the thermal insulation layer and beam bottom side, respectively.

2.5 Bending test for beams

The beams were left to cool down at ambient temperature for one day, then tested in flexure, where the specimens were subjected to a four-point flexural test up to failure through a universal testing machine of 1000 kN capacity. The beams were supported as simple along with an effective span of 1400 mm and loaded through a hydraulic actuator and steel spreader beam to distribute the load into two equal loads spaced at 300 mm and 550 mm from beam supports. This was performed to ensure the flexural failure of all beams. A typical beam testing set-up is shown in Fig. 9. The load was increased at a uniform rate up to beam failure. Mid-span deflection of the tested beams was measured using a dial gauge of least count 0.01mm at the center of the specimen. Three Linear Variable Differential Transformers (LVDTs) were used to measure mid-span deflection, one at the center of the beam and two under applied loading points. The data acquisition system was connected to record the corresponding applied load along with the mid-span deflection.

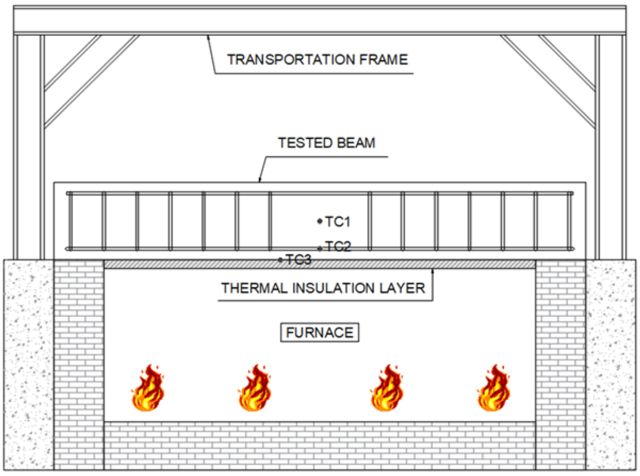


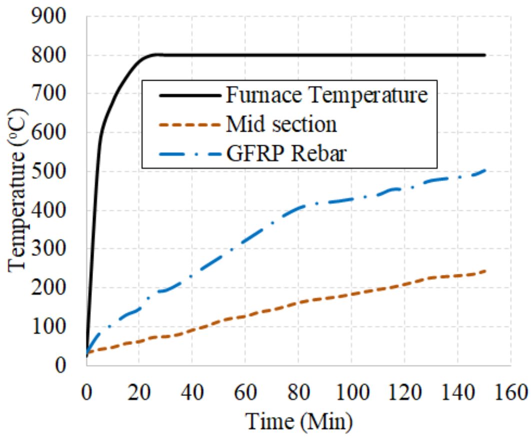
FIGURE 7. Test setup in fire.

FIGURE 8. Testing furnace in HBRC fire lab

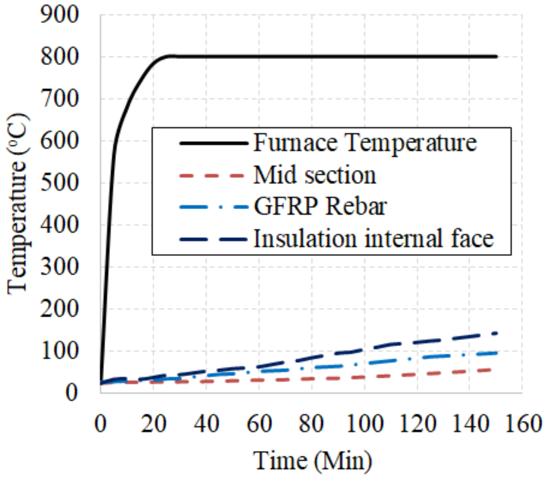
FIGURE 9. Test setup for four-point bending test of beams.

3. EXPERIMENTAL RESULTS and DISCUSSION

Thermal progression within the tested beam section was measured with the data logger via the connected thermocouples specified earlier. A higher temperature rise at a faster rate was measured for the uninsulated beams B1 and B3, where the temperature at GFRP and BFRP bars reached 500 ^{o}C and 396 ^{o}C after two hours, respectively which exceeds the critical glass transition temperature of FRP bars as reported by Kodur et al. [4], while the insulated beams with 25mm of perlite mortar recorded a temperature rise at low rate, this is due to a low thermal conductivity of the perlite insulation layer, where the temperature at GFRP and BFRP bars reached 96^{o}C and 114^{o}C after two hours exposure, respectively, which indicates that the flexural capacity of the beams shall not degrade at the same behavior of the uninsulated beams. The measured thermal progression for all tested beams is shown in Figs. 10 and 11. Moreover, the temperatures at the FRP bar, beam mid-height and insulation layer are listed in Table.4.

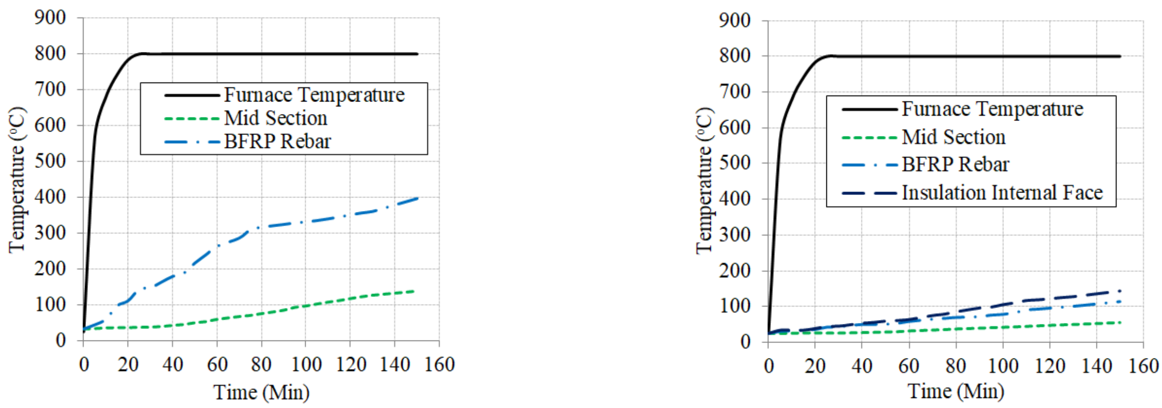


(a) Beam B1: GBT



(b) Beam B2: GBTP

FIGURE 10. Temperature variation in GFRP beams B1: GBT and B2: GBTP



(a) Beam B3: BBT **(b) Beam B4: BBTP**

FIGURE 11. Temperature variation in BFRP beams B3: BBT and B4: BBTP

TABLE 4. Measured temperatures during the thermal test.

Time	Measured temperature location	Beam (B1)	Beam (B2)	Beam (B3)	Beam (B4)
30 min.	Temp. at FRP bar °C	191	36	147	44
	Temp. at beam mid-height °C	74	28	38	27
2 Hours	Temp. at insulation layer °C	-	145	-	144
	Temp. at FRP bar °C	500	96	396	114
	Temp. at beam mid-height °C	242	58	139	56

The load-deflection curves for all tested beams are shown in Fig.12. The uninsulated beams were observed to exhibit early failure due to the high temperature directly affecting the FRP bar strength, where the major failure mode was the FRP bar rupture. The thermally insulated beams showed the failure recommended by design guidelines [3]. The concrete beam showed starting cracks within the mid-span and extended towards the supports until the beam was crushed at the top substrate indicating a compression failure as shown in Fig.13. Similar beam behavior was reported in the literature by Al-Thairy et al. [9]. Table 5 summarizes the ultimate load of all concrete beams at failure with the corresponding mid-span deflection, where the thermal insulation layer of perlite mortar enhanced the ultimate load carrying capacity of insulated beams by 202% and 180% compared to the uninsulated beams reinforced by GFRP beam and BFRP beams, respectively.

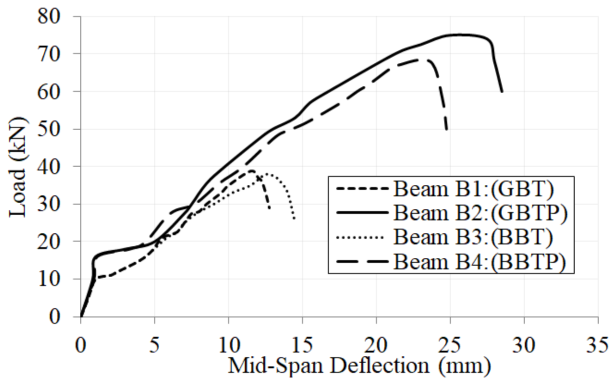


FIGURE.12. Load-deflection curves of all tested beams

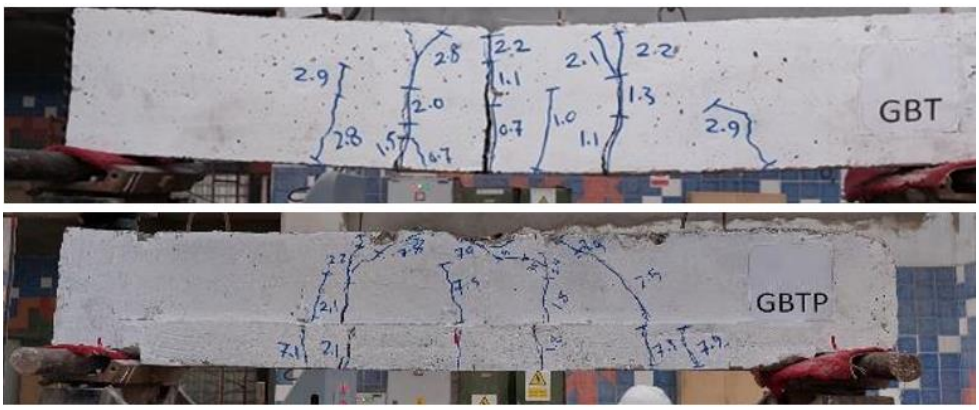


FIGURE 13. The cracking pattern of beams tested in bending until failure

TABLE 5. Experimental results of the tested beams.

Beam No.	Experimental Test Results		Failure Mode
	P_u (kN)	δ_u (mm)	
B1: GBT	38.80	12.45	GFRP bar Rupture
B2: GBTP	78.50	25.25	Concrete crushing
B3: BBT	37.90	12.50	BFRP bar Rupture
B4: BBTP	68.25	23.75	Concrete crushing

4. Conclusions

The present research investigated experimentally the efficiency of the thermal insulation layer of perlite mortar to maintain the flexural performance for concrete beams reinforced by different innovative FRP bars and exposed for two hours to elevated temperatures up to 800^{o}C. The thermal progression, load-deflection curves, failure loads and failure mechanisms were presented and discussed. Based on the experimental results and observations, the following conclusions may be drawn.

- Exposing FRP RC beams to high temperatures without thermal insulation causes severe degradation in flexural strength which may lead to catastrophic failure.
- The major failure mode for the tested FRP reinforced concrete beams subjected to fire conditions without thermal insulation was controlled by FRP bar rupture.
- Thermal insulation layer of perlite mortar transformed the failure mode of the tested beams to be concrete crushing as specified by design guidelines.
- The adopted innovative thermal insulation layer of perlite mortar enhanced the ultimate load carrying capacity of RC beams reinforced by GFRP and BFRP by 202% and 180%, respectively, compared to similar uninsulated beams.
- Exceeding the critical glass transition temperature of FRP bars caused early and sudden failure of the uninsulated beams.
- The thermal insulation layer maintained the temperatures at FRP bars below the critical temperatures.

5. References

[1] Nanni A., De Luca A., Jawaheri Z. H., Reinforced concrete with FRP bars: Mechanics and Design, CRC Press, Boca Raton, FL, 2014.

[2] Urbanski M., Lapko A., Garbacz A. Investigation on concrete beams reinforced with basalt rebars as an effective alternative of conventional RC structures, Procedia Engineering 57: 1183–1191, 2013.

[3] American Concrete Institute ACI 440.1R-15, Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars, American Concrete Institute, Farmington Hills, MI 48331, 2015.

[4] Yu B., Kodur V., K., Factors governing the fire response of concrete beams reinforced with FRP rebars, Composite Structures100: 257-269, 2013.

[5] Yu, B., Kodur V., K., Fire behavior of concrete T-beams strengthened with near-surface mounted FRP reinforcement, Engineering Structures 80: 350-361, 2014.

[6] Ashrafi H., Bazli M., Najafabadi E., Oskouei A.V., The effect of mechanical and thermal properties of FRP bars on their tensile performance under elevated temperatures, Construction and Building Materials 157: 1001-1010, 2017.

[7] Hamad R.J.A., Johari M.A., Haddad R.H., Mechanical properties and bond characteristics of different fiber reinforced polymer rebars at elevated temperatures", Construction and Building Materials 142: 521-535, 2017

[8] Lu Z., Xian G., Li H., Effects of elevated temperatures on the mechanical properties of basalt fibers and BFRP plates, Construction and Building Materials 127: 1029-1036, 2015.

[9] Al-Thairy, H., Al-Hasnawi, N., H., Behavior and failure mode of GFRP bars RC beams under elevated temperature, IOP Conference Series: Materials Science and Engineering 888, 2020.

[10] Albu-Hassan N., Al-Thairy H., Experimental and numerical investigation on the behavior of hybrid concrete beams reinforced with GFRP bars after exposure to elevated temperature, Structures 28: 537-551, 2020.

[11] Dong K., Hu K., Gao W., Fire behavior of full-scale CFRP-strengthened RC beams protected with different insulation systems, Journal of Asian Architecture and Building Engineering 15(3): 581-588, 2016.

[12] Rafi M.M., Nadjai A., Ali F., Finite element modeling of carbon fiber-reinforced polymer reinforced concrete beams under elevated temperatures, ACI Structural Journal 105(6): 701-710, 2008.

[13] Salama A.E., Ghanem G.M., Abd-Elnaby S.F., El-Hefnawy A.A., Abd-Elghaffar M., Behavior of thermally protected RC beams strengthened with CFRP under dual effect of elevated temperature and loading, Housing and Building National Research Center Journal (HBRC Journal) 8(1): 26-35, 2012.

[14] Kamal O.A., Hamdy G.A., Abou-Atteya M.A., Efficiency of coating layers used for thermal protection of FRP strengthened beams," Housing and Building Research Center Journal (HBRC Journal) 10(2): 183-190, 2014.

[15] Anand N., Kiran T., Lubloy E., Mathews M.E., Kanagaraj B., Andrushia D., Flexural behavior of reinforced concrete beams with FRP bars exposed to elevated temperature, Periodica Polytechnica Civil Engineering, 2022

[16] Protchenko K., Residual fire resistance testing of basalt- and hybrid-FRP reinforced concrete beams, Materials 15: 1509, 2022.

[17] ISO 834, Fire Resistance Tests – Elements of Buildings Construction – Part I – General Requirement, International Organization for Standardization, 1999.

[18] Altunişik A.C., Akbulut Y.E., Adanur Sü., Kaya A., Günaydin M., Mostofi S., Mosallam A., Evaluating the high-temperature endurance of FRP-strengthened concrete using an innovative insulation system: Experimental investigation, Journal of Building Engineering 73(15): 106444, 2023,

[19] ES 4756-1: Cement – Part 1: composition, specifications and conformity criteria for common cements, Egyptian Organization for Standards and Quality (EOS), Cairo, Egypt, 2022.

[20] ES 1109: Aggregates for Concrete, Egyptian Organization for Standards and Quality (EOS), Cairo, Egypt, 2021.

[21] ES: 262-2: Steel for the Reinforcement of Concrete, Egyptian Organization for Standards and Quality (EOS), Cairo, Egypt, 2015.

[22] The Egyptian company for manufacturing Perlite, [Online]. Available: Expanded Perlite Construction | E.C.P. www.perlite.com.eg

[23] ASTM D7205/D7205M-06 (Reapproved 2011), Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, USA, 2011, pp. 13.

[24] ASTM E119, Standard Test Methods for Fire tests of Building Construction and Materials," ASTM International, West Conshohocken, 2015.