WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.149858

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 2 2024

pp. 179 –193

Research paper

Study on the fire resistance of RC beams reinforced with BFRP and HFRP bars

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Abstract: For non-metallic reinforcement to be successfully integrated into residential and commercial construction, extensive research is required to understand the structural performance of Fiber Reinforced Polymer (FRP) reinforced concrete (RC) elements in various conditions, including the effect of elevated temperatures on structural performance. To accomplish this, a full-scale investigation was performed on the structural performance of FRP-RC elements subjected to elevated temperatures. The study involved conducting fire tests on beams, where the midsection was heated from below (tension zone) and the sides while being simultaneously loaded with 50% of their ultimate loads. The beams were reinforced with Basalt FRP (BFRP) bars and a hybrid composite of Carbon and Basalt Fibers (HFRP) bars. The HFRP-RC beams showed better resistance to the combined effect of loading and elevated temperatures compared to BFRP-RC beams. This study provides insights into the behavior of FRP materials in RC structures subjected to high temperatures, and contributes to the advancement of knowledge in this field.

Keywords: fiber reinforced polymers FRP, FRP bars, FRP reinforced concrete members, fire resistance of FRP-RC beams, basalt FRP, hybrid HFRP

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1. Introduction

The implementation of Fiber-Reinforced Polymer (FRP) composite materials has grown in various industries due to their versatility in the rehabilitation and strengthening of concrete and masonry structures, as well as their use in the design of new structures [1, 2]. Extensive research is currently being conducted on FRP materials for their potential use as internal reinforcement in reinforced concrete (RC) structures. This choice of reinforcement is primarily driven by its potential as a viable alternative to conventional steel reinforcement. The studies have revealed numerous benefits, these include improved corrosion resistance, reduced weight, immunity to electric and magnetic fields, as well as a high strength-to-weight ratio [3–8].

With the aim of creating a material that combines the best properties of its components, the idea of Hybrid Fiber-Reinforced Polymer (HFRP) bars was developed. This material offers improved and adjustable characteristics by utilizing the strengths of each constituent part. The development of Hybrid Fiber Reinforced Polymer (HFRP) bars primarily aimed to enhance the rigidity of FRP composite reinforcement. Compared to steel bars, FRP bars, particularly Glass Fiber Reinforced Polymer (GFRP) and Basalt Fiber Reinforced Polymer (BFRP) bars, exhibit relatively low stiffness, which has been a significant disadvantage of FRP bars [9–13]. In this study, BFRP and HFRP bars were used as internal reinforcement. HFRP bars are manufactured in the pultrusion process in a similar manner to those made of other types of FRP bars. As part of the production process of HFRP (HC/BFRP) bars, portion of basalt roving is being replaced with carbon roving to increase mechanical properties over BFRP bars while maintaining the cost lower than Carbon Fiber Reinforced Plastic (CFRP) [14].

Fire resistance of FRP bars is determined by the properties of the polymer matrix and the type and amount of fibers contained in them. Polymeric matrices employed in FRP bars are commonly characterized by low fire resistance, as they exhibit diminished strength and structural degradation when subjected to elevated temperatures [15–17]. The fiber type and content in the composite, as well as the thickness and density of the composite, are also important factors influencing its fire resistance [18]. In RC structures, the thickness of the concrete cover has a significant impact on the protection of FRP bars from elevated temperatures. A thicker cover can provide more insulation for FRP bars, which can help delay the onset of thermal degradation of fibers and maintain the bond strength between the FRP bars and the concrete [19, 20].

However, a limited number of studies have been conducted specifically on the performance of FRP bars when exposed to fire conditions, making this a relatively under-researched area. Due to that, the application of FRP reinforcement is currently limited to cases where fire resistance is not a major consideration, hindering the widespread implementation of FRP bars in construction [21].

This study focuses on evaluating the structural behavior of FRP-RC flexural elements under elevated temperatures. To achieve this, experimental fire resistance testing was conducted on FRP-RC beams. The beams underwent specific fire actions, with gradual heating applied to the mid-sections from below (in the tension zone) and from the sides.

The primary objective of this research was to expand upon the results of previous studies, specifically investigating the behavior of FRP-RC beams reinforced with BFRP and HFRP, while also exploring the effects of a larger concrete cover, ranging from 30 to 60 mm. Unlike prior research, which used a heating time of 80–100 minutes [22], during this study the heating time was extended to 120 minutes.

2. Materials and experimental program

2.1. General overview of experimental program

In the experimental program, 12 full-scale FRP-RC beams were designed and constructed, without any fire protection system. Six of these beams were subjected to a simultaneous application of gradual temperatures and sustained loads for a period of 120 minutes. These beams were divided into two sets: Set 1.1, consisting of three beams reinforced with BFRP, and Set 1.2, consisting of three beams reinforced with HFRP bars. The mid-sections of these beams were heated according to a standard heating curve ISO-834 (1999) [23], in order to simulate fire temperatures. The remaining six beams were used as reference samples, consisted of three samples of each type: three beams reinforced with BFRP bars (Set 2.1-ref) and three beams reinforced with HFRP bars (Set 2.2-ref). In addition to the experimental program, the results were compared with the beams from a previous study [22] (Set 3.1-prev for BFRP-RC sample, and 3.2-prev for HFRP-RC sample). Table 1 outlines the descriptions of the considered sets, while Table 2 provides a detailed description of the specimens used in the current and previous studies.

Table 1. Additional descriptions with regard to considered sets

Set No.	Description
1.1	BFRP-RC beams subjected to simultaneous exposure to elevated temperatures and loading
1.2	HFRP-RC beams subjected to simultaneous exposure to elevated temperatures and loading
2.1-ref	BFRP-RC beams that were only subjected to flexural tests
2.2-ref	HFRP-RC beams that were only subjected to flexural tests
3.1-prev	BFRP-RC beam subjected to simultaneous exposure to elevated temperatures and loading (one sample from previous study)
3.2-prev	HFRP-RC beam subjected to simultaneous exposure to elevated temperatures and loading (one sample from previous study)

Table 2. Descriptions of specimens and loading protocols

Set No.	Beam Designation	Dimensions	Concrete Cover	Number of Samples	Reinforcement Type (Tension Zone)	Heating duration
		l/*h*/*b*[1] (mm)	(mm)		Number/Ø/type	(minutes)
1.1	B2Ø14	3220/280/140	60 mm from bottom, 40 mm from other sides	3	2/14/BFRP[2]	120
1.2	H2Ø14			3	2/14/HFRP[3]	120
2.1-ref	B2Ø14			3	2/14/BFRP	–
2.2-ref	H2Ø14			3	2/14/HFRP	–
3.1-prev	B2Ø14	3200/260/140	30 mm from all the sides	1	2/14/BFRP	approx. 95
3.2-prev	H2Ø14			1	2/14/HFRP	approx. 83

Note: [1] *l/h/b* refer to length/height/width; [2]BFRP means basalt-fiber-reinforced polymers; [3]HFRP means hybrid-fiber-reinforced polymers.

2.2. Materials

For both study programs, the standard C40/45 concrete mixture was used, consisting of ordinary Portland cement (CEM III/A, Castorama, Warsaw, Poland), ash, and crushed stone with a nominal maximum size of 16 mm. The beams underwent a 28-day curing period in the laboratory before being subjected to testing. The concrete class was verified by performing compressive strength tests on 100 mm cube specimens, in compliance with the guidelines specified in PN-EN 12390-3 [24]. The mechanical characteristics of the concrete utilized in both the current and previous study programs are presented in Table 3.

Table 3. Mechanical characteristics of concrete used for the specimens

Set No.	Period	Compressive Strength	Tensile Strength	Modulus of Elasticity
		f_c (MPa)	f_{ct} (MPa)	E_{cm} (GPa)
1.1; 1.2; 2.1-ref; 2.2-ref	28 days	49.85	4.50	38.91
3.1-prev; 3.2-prev		48.75	4.23	37.83

The tension zone of the beams in both research programs was reinforced with two types of FRP bars: BFRP and HFRP bars. Different volume fractions of carbon and basalt fibers as well as their location were examined in order to determine the effects on the mechanical properties of hybrid composites. Detailed information regarding the characteristics and configurations of the bars can be found in these companion papers [25–27].

The results of the tensile tests on the BFRP and HFRP bars are summarized in Table 4, which includes the mean values for the maximum tensile force (F_u), limit tension stress (f_u), longitudinal modulus of elasticity (E_1), and limit strain (ε_u). These values were determined from five samples of each bar type and are consistent with the bars used in references samples (Set 2.1-ref and set 2.2-ref) and previous studies (set 3.1-prev and set 3.2-prev).

Table 4. Mechanical properties of FRP bars

Type of bars	Maximum Tensile Force	Tensile Strength	Tensile Strength at Rupture	Modulus of Elasticity
Type/Ø	F_u (kN)	f_u (MPa)	ε_u (%)	E_1 (GPa)
BFRP Ø6	37.07	1148.81	2.48	46.47
BFRP Ø8	60.03	1103.30	2.52	43.87
BFRP Ø14	179.26	1101.94	2.39	46.02
HFRP Ø14	206.57	1160.06	1.61	72.12

3. Test setup

The current study involved testing of beams with identical dimensions of 140 mm in width, 280 mm in height, and 3220 mm in length. The concrete cover on each of the specimens was 60 mm from the bottom and 40 mm from the remaining sides. The upper zone of each beam was reinforced with longitudinal reinforcement in the form of BFRP bars with a diameter of 8 mm and shear reinforcement in the form of stirrups made of BFRP bars with a diameter of 6 mm. The stirrup spacing was fixed at 100 mm. The middle section of the beam between the application of forces was without stirrups. This allowed for the investigation of the performance of different types of FRP bars in the tensile zone. Fig. 1 presents a schematic representation of the tested specimens.

Each of the specimens was equipped with type K thermocouples to monitor temperature during the fire exposure, with a maximum measurement range of 1200°C. For each beam, eight thermocouples were positioned at various depths, with seven being embedded in the concrete and one placed on the surface of a bar. The midsection of the beams was also equipped with three dial gauges on their top faces, to measure deflections. The arrangement of the thermocouples, dial gauges, and the overall test setup is depicted in Fig. 2.

In the current study, the beams of sets 1.1 and 1.2 were subjected to 4-point bending tests with an initial load of 50% of their ultimate capacity. The ultimate capacities were determined for the reference beams (set 2.1-ref and 2.2-ref) through a similar 4-point bending test. Fig. 3a shows a beam that was subjected to the load. As the next step, the furnace was positioned so that the middle third of each beam was exposed to heating, as depicted in Fig. 3b. Ceramic and rock wool insulation was applied to prevent heat loss at

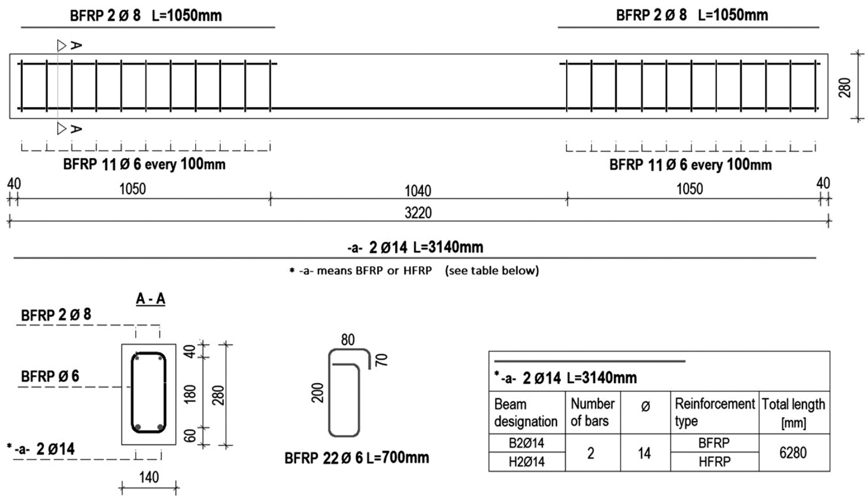


Fig. 1. Reinforcement scheme of the tested specimens

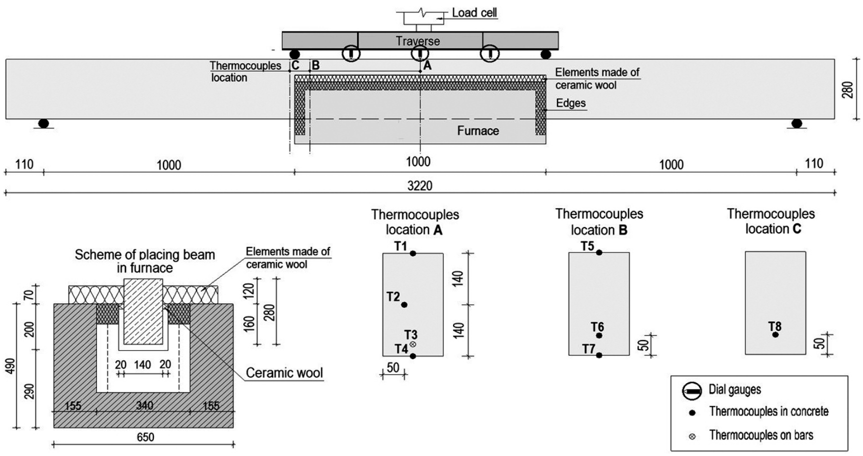


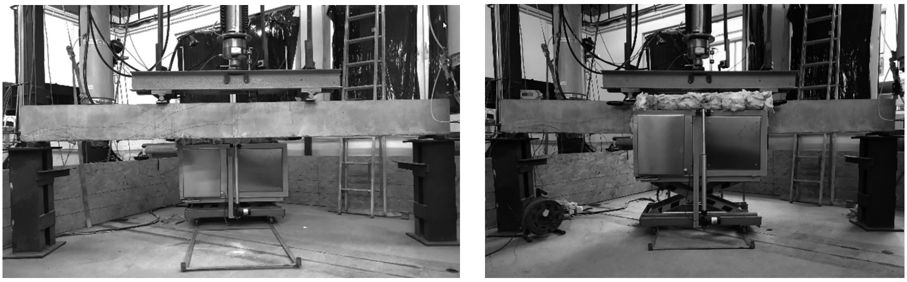
Fig. 2. Test setup

the interface between the beams and the edges of the furnace. During the heating phase, the specimens were subjected to a sustained load while exposed to heating from below and the sides for a total period of 120 minutes.

In this study, the beams were subjected to heating in accordance with a standard heating curve from ISO-834 (1999) [23], which was utilized to initiate the elevated temperature as specified by the formula in equation 3.1:

$$T_{\mathrm{ISO}} = T_0 + 345 \times \log(8t + 1) \tag{3.1}$$

where T_{ISO} is the temperature (°C), T_0 is the room temperature (assumed to be 20°C), and t is the time (min).



(a) (b)

Fig. 3. Test setup (a) subjected to loading (b) subjected to both loading and heating

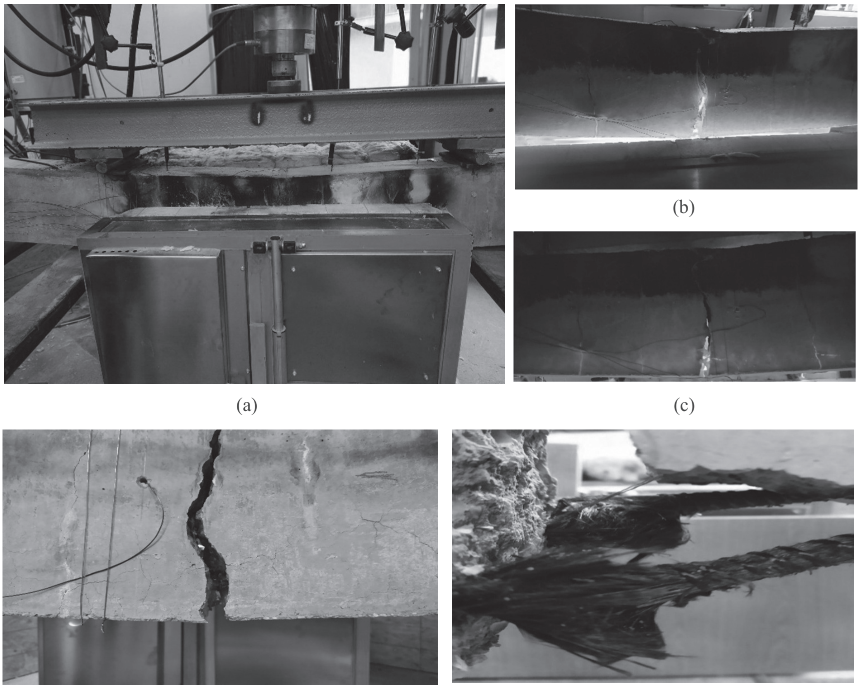
Following the two-hour heating phase, the specimens were allowed to cool for approximately 24 hours before undergoing a 4-point bending test to evaluate their residual flexural strength.

4. Results and discussion

In the current study, two samples from Set 1.2 (HFRP-RC beams) were able to withstand the simultaneous effect of loading and elevated temperatures for a duration of 120 minutes. In contrast, all the beams from the previous sets failed to endure the loading and temperature conditions, with the maximum recorded duration of one sample being 97 minutes. These observations suggest that increasing of the clear cover in HFRP-RC beams has a positive effect and enhance the resistance of the beams to the simultaneous effect of loading and elevated temperatures.

The samples from Set 1.1 (reinforced with BFRP bars) underwent destruction during the loading and heating phase, resulting from the failure of their reinforcing bars. At the moments of rupture, the temperature recorded at the bars surface was in the range of 670–750°C, causing a noticeable increase in the deflection of the samples, implying failure. Upon removing the insulation, it was observed that all the specimens had encountered an open fire, and it was presumed that the ignition of the epoxy resin contributed significantly to the degradation of the reinforcing bars. The Fig. 4a–4c depicts the progression of the experiment and the final stage for Set 1.1, demonstrating the manner in which the BFRP-RC beams experienced destruction.

The BFRP-RC beams were destructed within 90–100 minutes due to reinforcement failure. It is presumed that this failure was caused by a combination of the evaporation of the epoxy matrix and the degradation of the fibers, Fig. 4d. Upon the precise removal of the concrete cover, it was observed that some fibers ruptured and shifted slightly, Fig. 4e. These two issues led to a loss of bonding between the bar surface and the concrete, resulting in displacements within the middle portion of the beam. In contrast, the side portions of the



(a) (b) (c) (d) (e)

Fig. 4. Destruction of the samples from the Set 1.1 (a) B2Ø14 (sample 1) immediately after removing the ceramic insulation, (b) burning of epoxy resin caused by elevated temperatures, (c) post-removal of the beam from the furnace, (d) destruction of the sample B2Ø14 (sample 2) (e) view of bars after removing the cover

beam that were not subjected to elevated temperatures showed that the bond between the bars and concrete remained intact.

In a previous study, a sample from Set 3.1-prev experienced failure of its reinforcement, this failure mode is similar to that observed in the current study for Set 1.1 samples. The samples from the previous study and the reference beams of the current study (2.1-ref) were destroyed as a result of concrete crushing. This indicates that elevated temperatures have a significant impact on the strength capacity of FRP bars.

One of the samples from Set 1.2 (reinforced with HFRP bars) failed during simultaneous loading and heating at approximately 108 minutes of the heating period. The deflection significantly increased, the temperature recorded on the surface of the bars at that time of failure was approximately 650°C.

The remaining two HFRP-RC beams were able to withstand the entire heating duration and were subsequently subjected to a cooling phase lasting 24 hours. It is worth noting that in a previous study of similar beams (Set 3.2-prev), samples were only able to withstand a period of approximately 83 minutes under similar conditions. In comparison to the reference samples 2.2-ref, which were destroyed due to concrete crushing, the beams in the current study failed as a result of reinforcement failure, as depicted in the Fig. 5a. This suggests that load-bearing capacity of FRP-beams strongly depends on the type of bars used. Fig. 5b and 5c depict the character of the reinforcement failure.

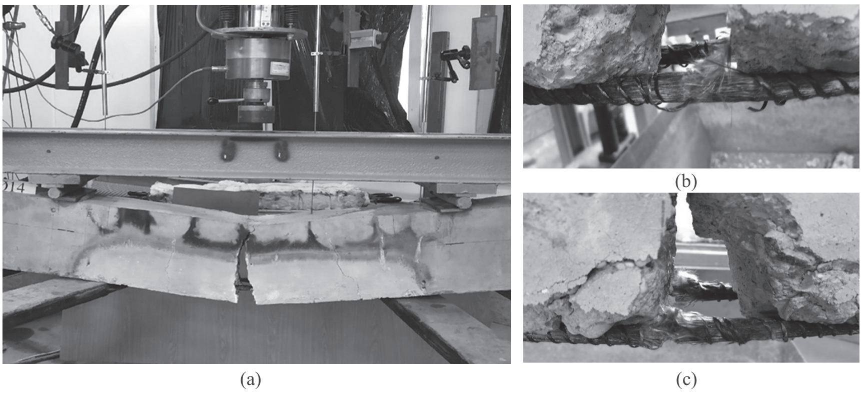


Fig. 5. Destruction of the beam from Set 1.2 (H2Ø14 sample 2) (a) the destruction mechanism, (b) significant rupture of a large portion of bars, (c) another view

Fig. 6 displays the maximum deflection measured by the central gauge (U2) and the ultimate load for the two beams from Set 1.2. The residual strength capacities of these beams are compared to the average result for the reference beams (Set 2.2-ref). The beams from Set 1.1 were destroyed during the heating period and, therefore, are not included in the summarizing graph. The reference samples were loaded until 12.5 kN, then reduced to 5 kN, and loaded again in an analogous cycle until failure. The cyclic loading was employed to reduce the effects of plastic strains.

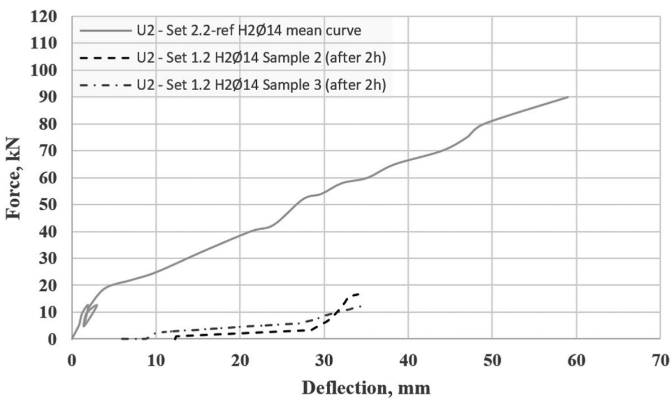


Fig. 6. Comparison of the ultimate strength capacity values for the tested HFRP-RC beams from the current study (Set 1.2) with the outcomes obtained for the reference beams (Set 2.2-ref)

Under the influence of elevated temperatures and sustained loads, the ultimate load capacity of the HFRP-RC beams subjected to testing was observed to be approximately five times lower than that of the reference beams. During the cooling phase, the deflection values for samples 2 and 3 from Set 1.2 remained, which resulted in the curve not commencing from a zero deflection value.

In both the current and previous studies, similar trends were observed for BFRP-RC beams, with deflections increasing with elevated temperatures, as it is common for beams reinforced with steel bars [28,29]. In the current testing, where the beams had larger concrete cover, the deflections were initially a bit smaller for the first 40–50 minutes, and then the deflections became higher or similar to those of the previous study (Set. 3.1-prev) until approximately 80 minutes. After that point, the deflections in the previous study became higher than in the current study. For the current study, the maximum deflections were measured for sample 3, which reached 91 mm at a temperature of 720°C measured on the bar surface at the time of failure. The heating time for this sample was the shortest (90 minutes), while the longest duration of heating was measured for sample 1 in comparison to the other samples of the current study, lasting 98 minutes.

Fig. 7a–7c displays the deflection-heating time relationship obtained in the current study, compared to the previous sample, Fig. 7d. The BFRP-RC beam in the previous study was also unable to withstand sustained loading and temperatures for the period of two hours. However, the sample from Set 3.1 endured the longest time (heating period was 97 minutes) and larger deflections, measuring 162 mm.

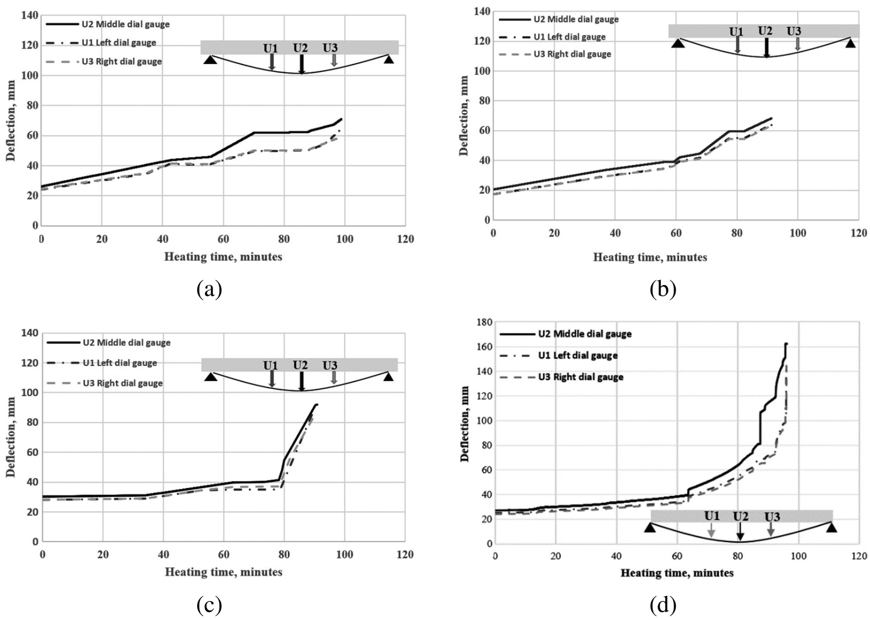


Fig. 7. Heating time vs. deflections measured by three dial gauges for set 1.1: (a) B2Ø14-beam 1; (b) B2Ø14-beam 2; (c) B2Ø14-beam 3; (d) set 1-prev: B2Ø14

In Set 1.2, Samples 2 and 3 were able to withstand the full 120 minutes heating duration, unlike Sample 1, as shown in Fig. 8a–8c. HFRP-RC beam from the previous study, as shown in Fig. 8d, was only able to withstand 83 minutes. Sample 2 had a maximum deflection of 53 mm, while the maximum deflection for the sample from the previous study was 70 mm, indicating a 24% lower deflections in the current research.

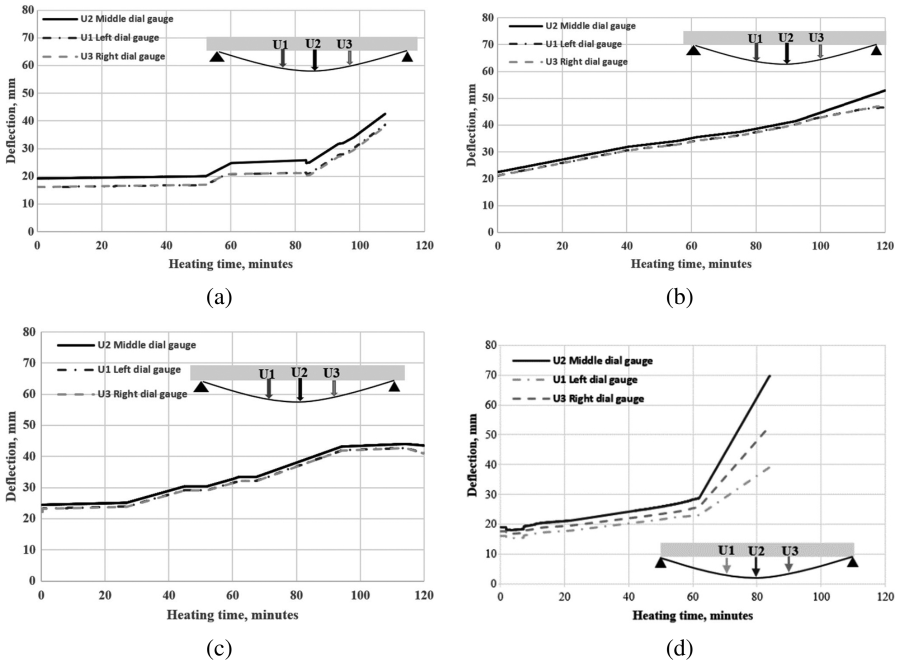
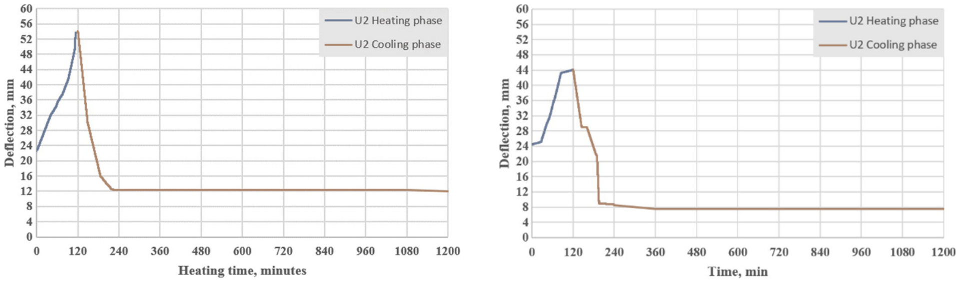


Fig. 8. Heating time vs. deflections measured by three dial gauges for set 1.2: (a) H2Ø14-sample 1; (b) H2Ø14-sample 2; (c) H2Ø14-sample 3; (d) set 1-prev: H2Ø14

Sample 1 failed at 108 minutes with a measured temperature of approximately 700°C at the bar, the temperatures for Samples 2 and 3 at 120 minutes were similar, ranging from 710–750°C. Following the heating period, the samples were allowed to cool for a duration of 24 hours. The corresponding deflection-heating time curves during heating and cooling periods are presented in Fig. 9.

In Set 1.1, the deflections of the beams were approximately 2.5 to 3.4 times higher than those of the corresponding reference beams, Set 2.1-ref. Specifically, the deflections ranged from 69 mm to 91 mm for Set 1.1, while the corresponding reference Set 2.1-ref had deflections of 27 mm. Similarly, in Set 1.2, the deflections of the beams were higher than the corresponding reference beams, Set 2.2, by approximately 2.5 to 3.1 times. The deflections ranged from 43 mm to 53 mm for Set 1.2, while the corresponding reference Set 2.2 had deflections of 17 mm. Summarizing table on the maximum deflections obtained during and after heating as well as for the reference beams is shown in the Table 5.



(a) (b)

Fig. 9. Mid-span deflections measured by U2 dial gauge for (a) set 1.2 (H2Ø14 sample 2); (b) set 1.2 (H2Ø14 sample 3)

Table 5. Comparison of maximum deflections for different samples at different phases

Current and previous research					Reference beams (mean)	
Set No.	Beam designation	Deflections [mm]			Set No.	Deflections* (mm)
		H	*C*	*After C*		
1.1	B2Ø14 (1)	72	–	–	2.1-ref (B2Ø14)	27
	B2Ø14 (2)	69	–	–		
	B2Ø14 (3)	91	–	–		
3.1-prev	B2Ø14	162	–	–		
1.2	H2Ø14 (1)	43	–	–	2.2-ref (H2Ø14)	17
	H2Ø14 (2)	53	12	33		
	H2Ø14 (3)	44	8	35		
3.2-prev	H2Ø14	70	–	–		

Note: *Deflections were measured at 50% of ultimate load, mm;
H refers to heating phase, *C* refers to cooling phase.

5. Conclusions

This paper presents the results of experimental study on the behavior of FRP-RC flexural members when exposed to elevated temperatures. Based on the research that has been carried out, the following conclusions can be made:

1. The BFRP-RC beams were destroyed within 90–100 minutes due to reinforcement failure. The failure was caused by the evaporation of the epoxy matrix and the degradation of the fibers, which led to a loss of bonding between the bar surface and the concrete.

2. One of the beams reinforced with HFRP bars (Set 1.2) failed during simultaneous loading and heating, while the remaining two HFRP-RC beams were able to withstand the entire 120 minutes heating duration and were subsequently subjected to a cooling phase.
3. The residual ultimate load capacity of the HFRP-RC beams was found to be approximately five times lower than that of the reference beams, clearly indicating the significant influence of elevated temperatures on the performance of HFRP-RC beams. However, it was observed that an increase in the concrete cover from 30 mm to 60 mm positively affected the load-bearing capacity of HFRP-RC beams under simultaneous loading and elevated temperature conditions. This was substantiated by the extended endurance period and decreased deflections noticed in the present study in HFRP-RC beams.

The results of the experimental fire resistance tests highlight the potential of newly developed HFRP bars in reinforcing concrete flexural members subjected to elevated temperatures.

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Badanie nośności ogniowej belek betonowych zbrojonych prętami BFRP i HFRP

Słowa kluczowe: polimery wzmacniane włóknami (FRP), pręty FRP, elementy żelbetowe zbrojone przez FRP, odporność ogniowa belek FRP-RC, pręty bazaltowe FRP, pręty hybrydowe HFRP

Streszczenie:

Dla skutecznego stosowania niemetalicznego zbrojenia w obiektach mieszkalnych i komercyjnych konieczne jest przeprowadzenie obszernych badań mających na celu zrozumienie zachowania strukturalnego elementów betonowych zbrojonych prętami FRP (ang. Fibre-Reinforced Polymers) w różnych warunkach, w tym wpływu podwyższonych temperatur na ich nośność. W tym celu przeprowadzono badania w skali rzeczywistej dotyczące elementów zginanych poddanych podwyższonym temperaturom. Badania obejmowały przeprowadzenie testów ogniowych na belkach, gdzie środkowa część była podgrzewana od dołu oraz ze stron bocznych, jednocześnie obciążając je 50% siły niszczącej (siła niszcząca została wyznaczona na bazie próbek referencyjnych – bez wpływu temperatury). Ponieważ głównym celem było zbadanie wpływu rodzaju zbrojenia FRP na odporność ogniową belek, zastosowano różne rodzaje prętów w strefie rozciągania (dolna część belek): zbrojenie na bazie włókien bazaltowych BFRP (ang. Basalt FRP) oraz hybrydowe zbrojenie HFRP (ang. Hybrid FRP) z włóknami węglowymi i bazaltowymi. Belki zbrojone prętami HFRP nie uległy zniszczeniu w zakładanym czasie i zostały poddane testowi w celu określenia ich rezydualnej nośności w przeciwieństwie do belek ze zbrojeniem BFRP. Badania te przedstawiają zachowanie elementów zginanych ze zbrojeniem FRP poddanych działaniu wysokich temperatur i przyczyniają się do poszerzenia wiedzy w tym obszarze.

Received: 2023-08-15, Revised: 2023-09-19