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The vibration-based assessment of the influence of elevated temperature on the condition of concrete beams with pultruded GFRP reinforcement

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A B S T R A C T

Concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars subjected to elevated temperature have been experimentally studied. The influence of high temperatures on GFRP-reinforced concrete beams condition has been check both, destructively and nondestructively. The nondestructive tests foresaw vibration-based tests to obtain the natural frequency values after exposure to varying temperatures. The vibration-based tests allowed for the indirect observation of beams stiffness reduction after exposure to elevated temperature. The approach based on frequency response function (FRF) turned out to be efficient even in the case of relatively low temperatures (120 °C). The investigation involved also destructive tests which were conducted in various conditions: once the bending load and elevated temperature were applied at the same time and in the next case, the destructive tests were conducted after heating and cooling down the experimental objects. The study proved that the increase of the temperature causes the reduction of characteristic mechanical parameters, regardless the beams were cooled down or not. However, the simultaneous action of bending load and elevated temperature resulted in a greater reduction of the ultimate strength of tested objects.

1. Introduction

Glass fibre reinforced polymer (GFRP) materials have several advantages over traditional steel reinforcement, which make them an attractive alternative for various applications in civil and mechanical engineering fields. Composite rods are characterized by high durability and strength, they are not susceptible to the corrosive environment. Their application may lead to a significant reduction of construction costs because of relatively low-cost transport, fast preparation and application. Their storage is also easier than steel reinforcement. Although all these superior attributes over metallic alloys, the composite reinforcement has one serious drawback which significantly limits its common applicability. Despite the worldwide acceptance of the composite bars currently available [1–3], they cannot be used in structures supposed to elevated temperatures. Despite the low thermal conductivity of composite rods, their resistance to high temperatures is much lower than in the case of steel reinforcement.

The experimental studies have been conducted by Lobanov et al. [4] to investigate the influence of increased temperatures on fatigue life, relative stiffness and residual strength of structural fiberglass specimens. They proved that the increase in temperature adversely affects the mechanical properties of the GFRP specimens. Sherkarchi et al. [5] examined the compressive mechanical behavior of a composite specimen consisting of square steel or pultruded GFRP tubes and timber infill which were exposed to elevated temperatures. Their study indicated the significant influence of temperature on GRFP-composed specimens. The pultruded GFRP exposed to an elevated temperature greater than the glass transition temperature in which the resin softened, the strength and stiffness of specimens respectively decreased noticeably. Xu et al. [6] presented the results of the investigation of the influence of elevated temperatures on the strength and modulus degradation of pultruded high-temperature resistant (HTR) carbon fiber reinforced polymer (CFRP) tendons. Despite the fact the temperature resistance has been significantly improved over traditional CFRP materials, the rapid strength decrease was observed in the temperature of 200-300 °C, which is typical for composite materials [7–9]. Benmokrane et al. [10] proved that even the temperature of 60 °C affects the predicted service life of composite tendons, while the maximum service temperatures in Northern climates are equal to 70 °C. The deterioration of the mechanical properties of composite bars may be observed even in lower temperatures. Moreover, one should take into account climatic changes, sunlight exposure, as well as other unforeseen factors, e.g. fire conditions, which

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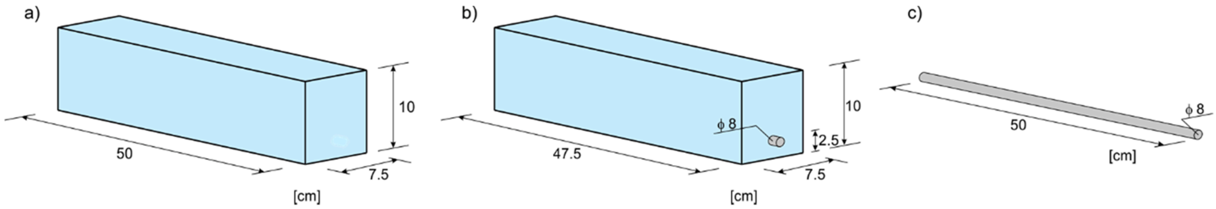

Fig. 1. Geometric parameters of tested specimens: (a) concrete beam, (b) concrete beam reinforced with GFRP rod and (c) single GFRP rod.

may adversely affect the strength of the composite reinforcement. Another drawback may be the difference in transverse coefficients of thermal expansion for concrete and GFRP rods. Changes in bars diameter may results in an increase of stress in the radial direction and consequence, concrete cracking and deterioration of adhesive connection between concrete cover and reinforcement. The proper condition assessment of the reinforcing bars, which is crucial for the safety of the structure, is not a trivial issue, because they are covered with concrete, so the standardly applied approaches based on visual inspection do not provide sufficient and detailed information about the current state of the composite inserts. For this reason, the development of non-destructive methods of condition assessment is of significant importance nowadays.

The possibility of the use of nondestructive vibration-based methods in diagnostics of composite structures has been proved in many studies ([11–14]) however, their utilization in the detection of temperature-induced degradation has not been considered in detail yet. The high temperature is especially dangerous in the cases of reinforcement which cannot be assessed visually. Because the deterioration of the GFRP reinforcement takes place in relatively low temperatures, the degradation of the reinforcement may occur even if the concrete cover remains undamaged.

The article presents the results of nondestructive vibration-based testing of concrete beams with composite reinforcement subjected to high temperatures (>240C). The research was conducted to analyze the dynamic behavior of composite material during and after exposure to elevated temperatures. The research includes the vibration tests of concrete beams with and without composite reinforcement, which allowed for indirect measurement of the stiffness reduction of both concrete and composite part.

The original elements of the paper are the comparison of the results of destructive tests conducted in ambient conditions after cooling down the experimental object as well as in the conditions of elevated temperatures. The deterioration of the mechanical properties of GFRP-reinforced specimens has been also assessed non-destructively using the vibration-based method, which allowed to indicate the relationship between the natural frequency and the applied temperature. Even though it is recommended to use the GFRP bars to reinforce the structures subjected to hire hazard, the study proves that the deterioration of the mechanical properties of GFRP bars is observable only in conditions of the elevated temperature, while after cooling down the stiffness reduction not observed, regardless the applied temperature.

2. Materials and methods

2.1. Experimental models

Experimental studies were conducted on GFRP rods, concrete beams and concrete beams with GFRP reinforcement. Within each group at least 12 specimens have been subjected to high temperature and next tested during destructive and nondestructive tests. Carrying out the analysis separately for concrete, composite rods and then for objects composed of both concrete and composite allowed to analyze the high-temperature influence on the degradation of each of these materials. For the same reason, the structure of the investigated beams is relatively simple. The beams were performed by using specially prepared steel forms which allowed for omitting the additional transverse reinforcement. The composite reinforcement (Fig. 1b) in the form of a single rod with a diameter of 8 mm was placed in the form and covered with concrete. The reinforcement was cast 2.5 cm from the lower edge of the beam. The dimensions of the beam cross-section were 7.5 cm × 10 cm and the length was 47.5 cm (Fig. 1). The total length of the GFRP rods, as well as the concrete beam without the reinforcement, was equal to 50 cm (Fig. 1c).

Table 1
Material parameters of concrete and GFRP reinforcement.

Material	Mechanical properties	
Concrete	density	2010 kg/m^3
	elastic modulus	25.1 GPa
	cube compressive strength	14 MPa
GFRP	density	1890 kg/m3
	elastic modulus	45 GPa
	glass transition temperature	120C
	fracture strain	2.2%

2.2. Materials

The material parameters of the concrete and composite rods were the same within each group. All experimental specimens were performed in the laboratory using ready-mix concrete. The mixture was made of Portland cement type CEM I 42R, with sand (0–2 mm), and fine aggregates (2–8 mm). Because of the relatively small dimensions of the beams, the aggregates with a larger diameter mm were not used in the concrete mix. The beams and their companion cubes dedicated to material compressive tests were left to cure at least for 28 days in wet and next in dry conditions to obtain the full strength. Then, concrete parameters were determined during the destructive of cube concrete samples conducted in the machine Zwick Roell 400 according to European standards [15]. The averaged parameters obtained for 15 concrete samples are summarized in Table 1.

The GFRP rods are comprised of epoxy resin and continuous strands of pultruded fibre glass. The tension strength of the GFRP profiles and the elastic modulus presented by the manufacturer was 1 GPa and 43–54 GPa, respectively. The value of elastic modulus was also examined during tension extensometric tests conducted according to European standards [16]. The parameters of GFRP are presented in Table 1. Experimentally determined elastic modulus during tension tests was equal to 45 GPa, which was consistent with manufacturer declaration [17]. The GFRP reinforcement can be used in temperature from −60 °C to 90 °C, while the low glass transition temperature (120 °C) excludes the possibility of using the GFRP reinforcement in structures subjected to fire hazards.

2.3. Experimental procedure

The experimental tests were divided into three main stages. In the first stage, the specimens were tested non-destructively (Fig. 2). The first step allowed to determine the dynamic characteristics of the undamaged beams. The free-free end support conditions were provided by using the suspension system. The distance between strings was 36 cm. The

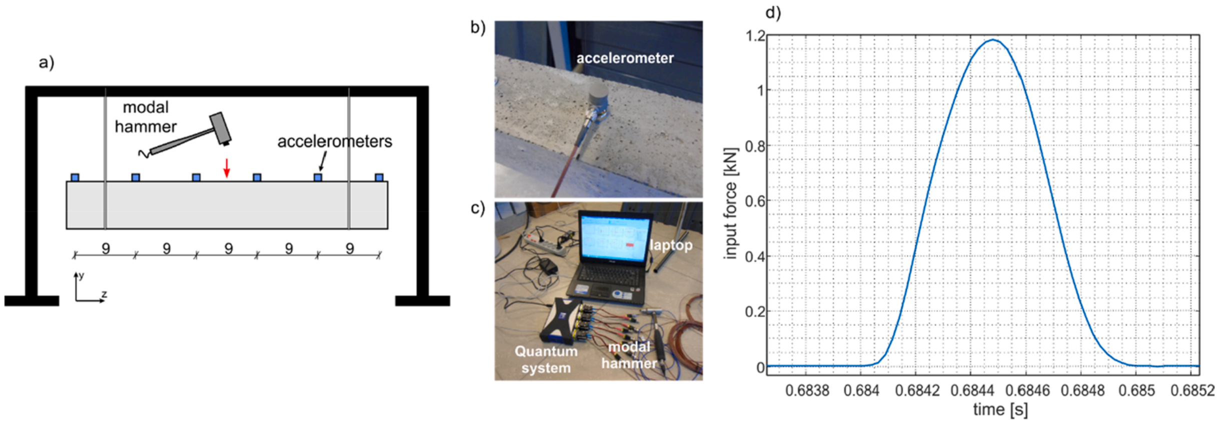

Fig. 2. Experimental investigation: (a) suspended beam, (b) accelerometer attached at the beam surface and (c) equipment used during experimental tests and (d) input force applied by the hammer.

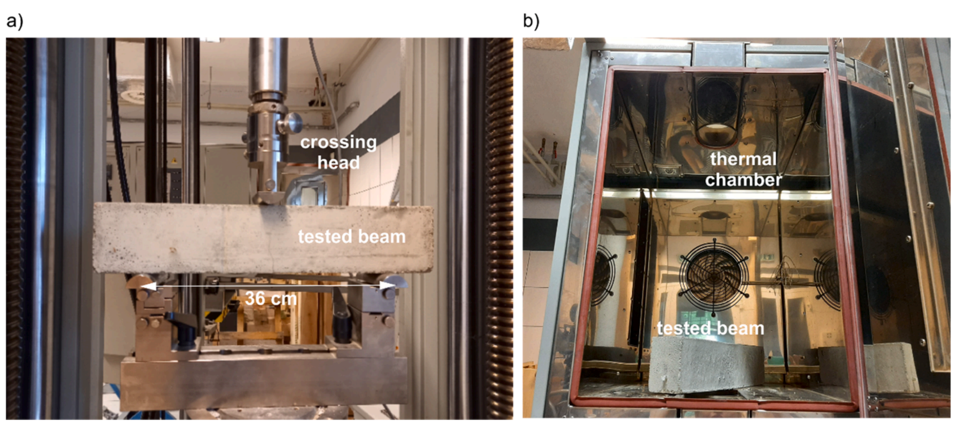

Fig. 3. Experimental test: (a) three-point bending tests and (b) beam in a thermal chamber.

dynamic tests were carried out using an impact hammer (PCB Piezotronics 086D05) connected to an acquisition system (Quantum MX840B). The acceleration signals were registered in the vertical *y*-direction by six single-axis accelerometers (ASC P101A15 – T51) attached at the beam surface. The sampling frequency was 38.4 MHz. All investigated specimens were subjected to the impact force applied in the middle point of the beam. The exemplary impact force is presented in Fig. 2d. The vibration tests were repeated five times for each beam and the results obtained were averaged.

After dynamic tests, beams were placed in a thermal chamber with constant airflow. The temperature inside was monitored. When it reached the desired value, the tested beams were left for 24 h in the chamber. Several different temperatures were investigated (120, 160, 200, and 240 °C). The temperature range taken into consideration was established based on the recommendations for the GFRP reinforcement, which says that composite reinforcement should not be used in structures exposed to temperatures higher than 80 °C. Moreover, the main research was preceded by destructive tests of composite rods subjected to both high temperature and external load, which are described in the next section (Section 4.1). Based on the results obtained as well as the manufacturer recommendations the temperature range for further research has been established.

After cooling down, the nondestructive vibration-based tests were conducted on concrete and GFRP-reinforced concrete beams again and the signals for damaged specimens were collected and processed. Finally, the specimens were destroyed during destructive bending tests. The destructive three-point bending tests, which allowed to determine the load-carrying capacity of particular specimens, were conducted on the testing machine (Fig. 3). To avoid the dynamic effects the velocity of the machine crosshead was equal to 1 mm/min. Three stages of the experimental investigation allowed for the assessment of the influence of variable elevated temperature on the condition of the concrete specimens and to compare the results of both destructive and non-destructive tests.

2.4. *Methods of results analysis*

Within the study, the experimental test results characterizing the dynamic behavior of healthy and damaged beams were obtained through frequency response function (FRF) which is a relation between the output spectrum of the structure in response to input force. Both modal parameters and FRFs can be efficiently used to assess the condition of the structure, however, the modal data are difficult to obtain. The main advantage of FRF is that it is the non-model-based method [18] and thus, the FRF data is more and more often used in diagnostic applications ([19–22]). The main assumption of this approach is that the occurrence of the damage influences the dynamic characteristics of the object. The research hypothesis says that the elevated temperature should affect the stiffness of the GFRP-concrete specimens. Thus, the changes in FRFs should be observed.

3. Experimental results

3.1. *The influence of the high temperature on composite rods*

3.1.1. *Simultaneous action of load and temperature*

At the first step of the investigation, the influence of the temperature on composite GFRP rods was tested. According to manufacturer

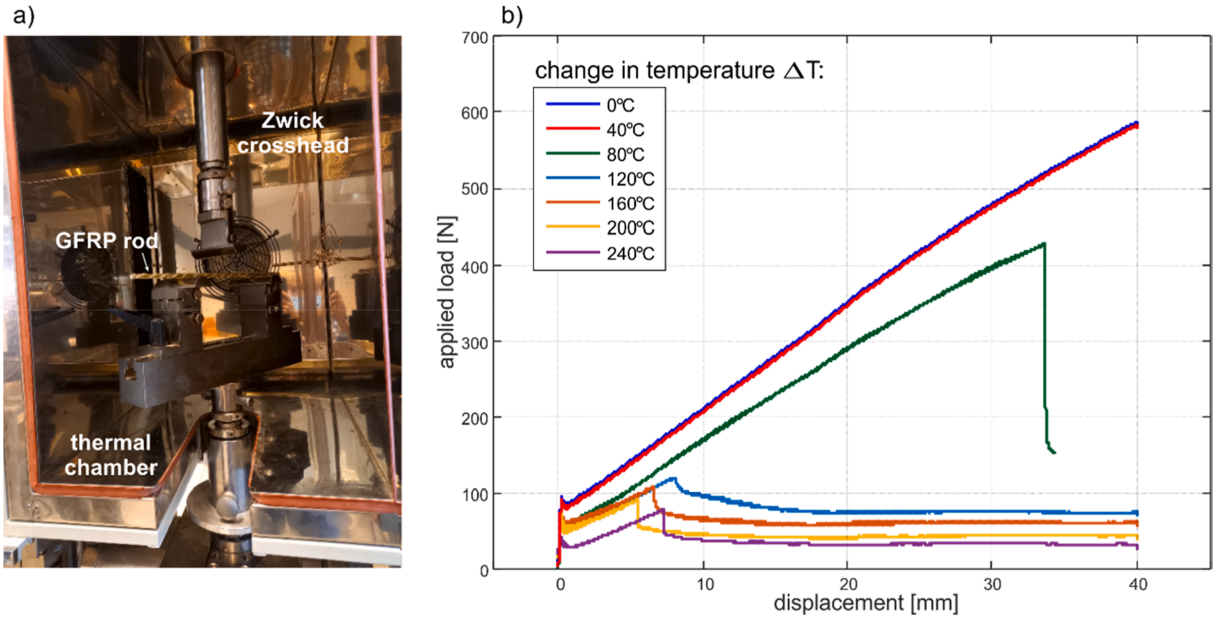

Fig. 4. (a) Composite rod in the thermal chamber during bending tests, (b) results of the destructive tests.

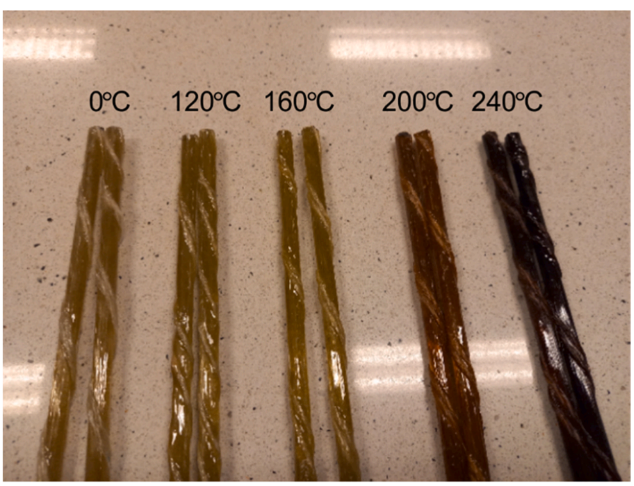

Fig. 5. The photograph of GFRP bars subjected to high temperatures.

recommendations, the GFRP rods should not be exposed to temperatures higher than 90 °C. The GFRP rods were placed in the thermal chamber and subjected to variable changes in temperature concerning the temperature in the laboratory (0 °C, 40 °C, 80 °C, 120 °C, 160 °C, 200 °C, 240 °C). Temperature $\Delta T = 0$ °C means that the rod was tested in ambient temperature, which was equal to about 20 °C. After one hour each rod was subjected to destructive bending tests. Bending tests were conducted in a thermal chamber, so we could observe the effects of simultaneous action of temperature and external load. The results in the form of displacement-force curves are presented in Fig. 4. The initial force was equal to 50 N, the velocity was 10 mm/min. The tests were conducted until the displacement was equal to 40 mm.

The effect of the high temperature of the GFRP rod behavior is visible: the inclination of particular curves, as well as the maximum value of the applied load differs, which suggests that both elastic modulus and composite resistance were affected by the temperature. Because for the higher temperatures even the insignificant load caused large deformations, in some cases it was difficult to apply the initial force at the start of the test. Thus the curves are shifted relative to each other. In two cases (0 and 40 °C) the test finished without damaging the GFRP sample. After removing the load, the bar regained its initial shape. Moreover, the visual inspection did not reveal any damage. In the case of the temperature of 80 °C we can observe the sudden drop of the curve – it indicates the fracture of the rod, which was also clearly visible and was associated with sound effects. In temperatures higher than 80 °C, even a relatively small load resulted in significant bar deflection, which stays in agreement with the specification of GFRP bars. The load drop was also visible but it was not such significant as in the previous case. Based on the obtained results, in further research we decided to investigate the influence of the temperatures of 120 – 240 °C on concrete - composite behavior because for the lower temperatures the deterioration of mechanical properties of the composite was not observed.

3.1.2. *The influence of temperature on the behavior of cooled GFRP bars*

Within this stage, the experimental analysis of single uncovered GFRP bars has been conducted. The GFRP bars were subjected to high temperatures in a thermal chamber for 24 h, cooled down and next were damaged during destructive bending tests in ambient conditions. The state of the damaged bar could be easily assessed visually. After heating and cooling the clear changes in color from the original are visible to the naked eye, but all rods retained luster and straight shape (Fig. 5). The shape of the ribs also remained unchanged even though the applied external temperature was much higher than allowed.

After cooling down (about 24 h) the bars were placed in the testing machine and subjected to bending tests. The load–displacement curves for particular rods are presented in Fig. 6. The distance between supports was equal to 36 cm, which was too short to induce to observe the fracture of the bar. The tests were finished when the displacement of the machine crosshead was 40 mm. The results obtained indicate that the temperature did not influence the elastic modulus of the GFRP rods. The difference in angle of inclination for particular curves is negligible and does not depend on the temperature. The one deviation from the linear load–displacement relationship was observed for the rod subjected to 120 °C. However, the load drop observed for about 12 mm was probably associated with fracture of several fibers or “arrangement” bar in the machine because after the bending test the rod was carefully assessed visually and we did not observe any defect.

Based on the results of the first experimental stage, one can conclude that GFRP bars are sensitive to high temperatures, but it is especially dangerous only in cases of simultaneous action of load and high temperature.

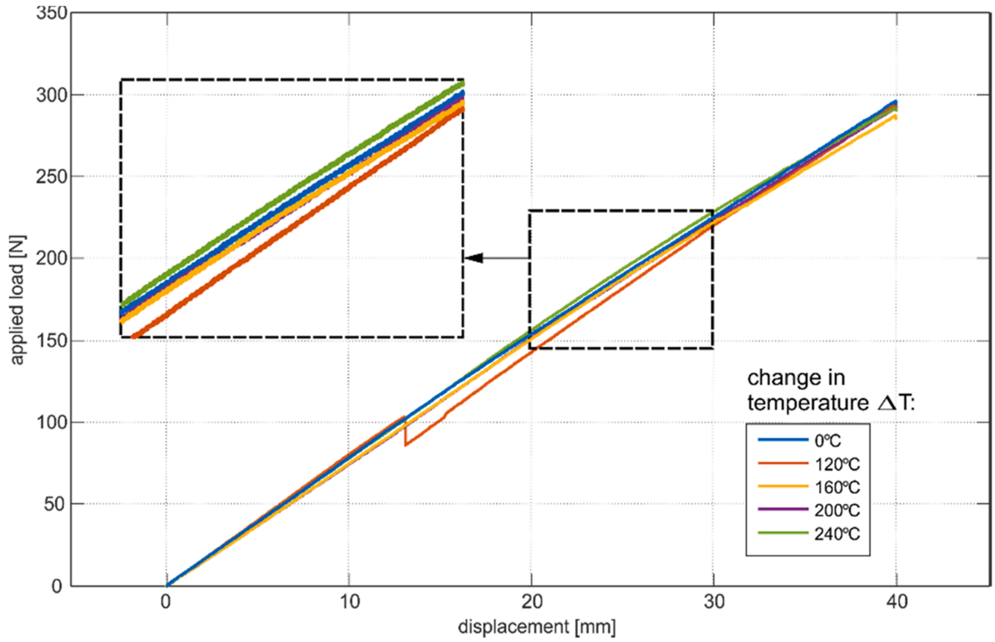

Fig. 6. Results of bending tests of cooled GFRP bars: load–displacement curves.

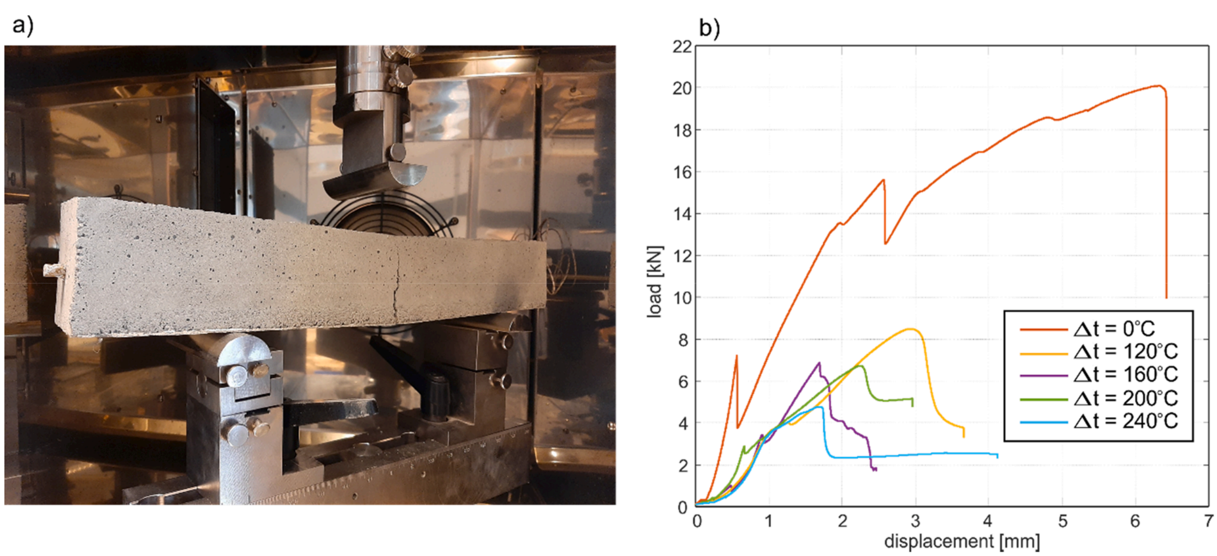

Fig. 7. Destructive tests in elevated temperature: (a) concrete beam loaded in the thermal chamber, (b) load–displacement curves for concrete beams with GFRP rod subjected to elevated temperatures and external load.

3.2. The influence of the high temperature on concrete beams reinforced with GFRP rods

3.2.1. Simultaneous action of load and temperature

In the next stage, the concrete beams reinforced with GFRP bars were subjected to high temperatures in a thermal chamber for 24 h and at the end of the heating process, they were damaged during destructive bending tests (Fig. 7a). The results of destructive tests in the form of displacement of crosshead versus applied load are presented in Fig. 7b. The load-carrying capacity of the beams tested in ambient conditions was significantly higher than other tested beams. The load capacity drop is associated with a significant reduction of load capacity of the GFRP reinforcement with temperature increase (Fig. 7b), which was also presented during the first stage of experimental investigation (compare Fig. 4).

The first peak indicates the moment when the cracks in concrete start propagating. For a healthy, undamaged beam the first peak was observed for the load value of 7.2 kN. In the rest of the cases, the load causing concrete damage did not exceed 3.4 kN. Despite that the clear decrease of the first peak is observable, there is no clear relationship between its value and the applied temperature.

The most important conclusion resulting from this stage of investigation is the high sensitivity of GFRP reinforcement to high temperatures. In fact, in elevated temperatures, the load capacity of the GFRP – reinforced concrete is reduced to the load capacity of the concrete. It is noteworthy that the considered temperature range is not an extreme case and the fire hazard is related to exposure to temperatures of even 1000 °C [8].

3.2.2. The influence of temperature on the behavior of cooled concrete beams with GFRP bars

The second step was devoted to assessing the influence of elevated

Table 2
Natural frequency values for undamaged GFRP-reinforced concrete beams

Frequency values of undamaged specimen	f_1 [Hz]	f_2 [Hz]
Euler - Bernoulli beam	1089.7	1453
FEM analysis	1096.8	1394
Experimental averaged values	1083.6	1394.8

temperature, but this time the GFRP-reinforced beams were cooled down before destructive tests. Moreover, before and after beams exposure to high temperature in the thermal chamber, the nondestructive vibration-based tests were performed.

The undamaged specimen can be considered as a slender uniform Euler-Bernoulli beam. If the gravity forces, shear deformation, damping and the influence of rotary inertia are neglected the natural vibration of the beam can be described by the following equation:

$$EI\frac{\partial^4 w}{\partial x^4}+\rho A\frac{\partial^2 w}{\partial t^2}=0 \tag{1}$$

where w is the lateral deflection of the beam, x is the spatial coordinate, t denotes time, EI is flexural stiffness and ρA is the mass per unit length. The solution of the above equation can be presented in the form:

$$\omega_n=\left(\alpha_n\frac{n\pi}{l}\right)^2\sqrt{\frac{EI}{\rho A}} \tag{2}$$

where ω_n denotes n-th natural circular frequency. The value of the coefficient α_n depends on the number of considered frequency and for the first mode of the beam with free-free boundary conditions is equal to 1.5056 [23].

By taking into account the vibrations in two different directions, the first two natural frequencies have been calculated and summarized in Table 2. Additionally, the theoretical calculations were supported with a numerical campaign performed in the commercial FEM-based program Abaqus.

The acceleration signals were collected and processed in a MATLAB environment according to the procedure described in Section 3. Fig. 9 presents the FRFs obtained for all experimental models. Each graph contains the FRF determined for all signals collected by six accelerometers. As we can see, the characteristic peaks were registered for the same frequencies, regardless of the sensor position. Insignificant peak shifts registered for various beam models may result from material and geometric imperfections. Two characteristic peaks were identified and indicated in the figures. The first peak characterized by a relatively small amplitude coincides with the first vibration mode. The beam stiffness is smaller in the x-direction (Fig. 2), and thus the first natural frequency corresponds to the vibration in the x-direction.

The small amplitude of the first peak results from the fact that the excitation load was applied in a perpendicular y-direction. Nevertheless, based on the obtained results the natural frequencies corresponding to the first and second vibration mode can be determined.

The experimental values have been averaged and presented in Table 2. A high agreement between theoretical, numerical and experimental values has been obtained.

Next, the dynamic analysis was repeated for specimens that were subjected to high temperatures for 24 h. Beams were cooled down to the ambient temperature (about 20 °C) and next tested nondestructively. The comparison of the envelope diagrams of FRFs obtained before and after heating suggests that the high temperature influenced the condition of the beams (Fig. 9). After exposure to the elevated temperature, the FRF peaks were registered at lower frequencies, which indicates the stiffness reduction (Fig. 10). Moreover, the FRFs obtained for heated beams are characterized by multiple peaks, observed especially in the higher frequency range, which results in decreasing the illegibility of the obtained results. The deterioration of FRFs smoothness is visible in all cases and is clearly related to the temperature: the higher temperature, the greater number of additional peaks in FRF. Exposition to high temperature probably caused microcrack propagation and nonlinear behavior of the excited beams. One can conclude that the identification of the higher vibration modes would be difficult in the case of specimens exposed to elevated temperatures.

Fig. 10 presents the changes in the second natural frequency, for which the peak with the highest amplitude has been registered. Even the influence of the temperature of 120 °C was detected using the dynamic approach meanwhile, this temperature is considered safe for concrete [24]. Each beam after thermal tests was subjected to careful visual inspection and in any case it revealed the visible cracks. The results collected within this stage of the study suggest that a dynamics-based approach can be successfully used in the detection of even insignificant changes in stiffness caused by temperature influence.

After dynamic tests, the concrete-composite members were destroyed in the testing machine. Again, the distance between supports was equal to the distance between strings used in the suspension system (see Fig. 2a). The concentrated force was applied in the middle of the beam. After bending tests the GFRP rods were uncovered and the change in color caused by elevated temperature could be observed by a naked eye (Fig. 8). The results of the destructive tests are presented in Fig. 11 as load–displacement curves. The destructive tests indicated the interesting behavior of the concrete beams with GFRP rods over concrete reinforced traditionally with steel rods, which was not observed in the case of simultaneous action of temperature and external load. The elastic modulus of GFRP is significantly lower than the modulus of steel (45–55 GPa over about 200 GPa). Thus the stresses, and in consequence, the load which is carried out by the composite reinforcement is considerably lower than by steel reinforcement. The GFRP bars started “cooperating” with concrete only after the concrete was cracked. The fracture moment was mainly determined by the concrete tensile strength, which is manifested by the first local peak. In general, the character of all curves is similar and in each case, two distinct ranges and two characteristic values can be distinguished in the charts.

In the first range, the load was mainly carried out by the concrete. The first characteristic peak indicates the damage of the concrete part and the occurrence of the crack propagating usually in the middle part of the beam. Next, the applied load increased despite the increasing width

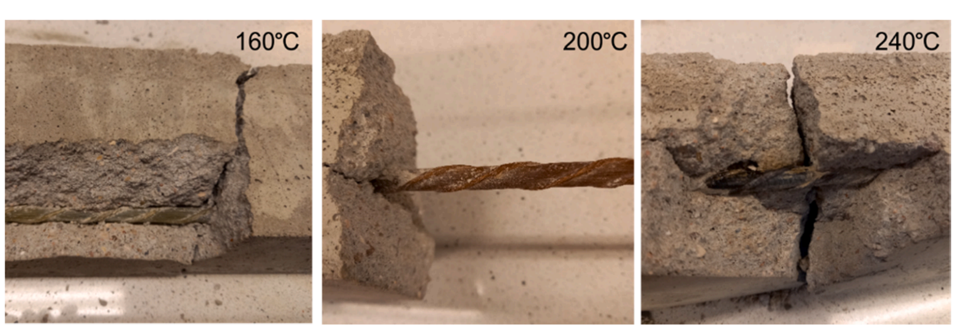

Fig. 8. Uncovered GFRP reinforcement after destructive bending tests.

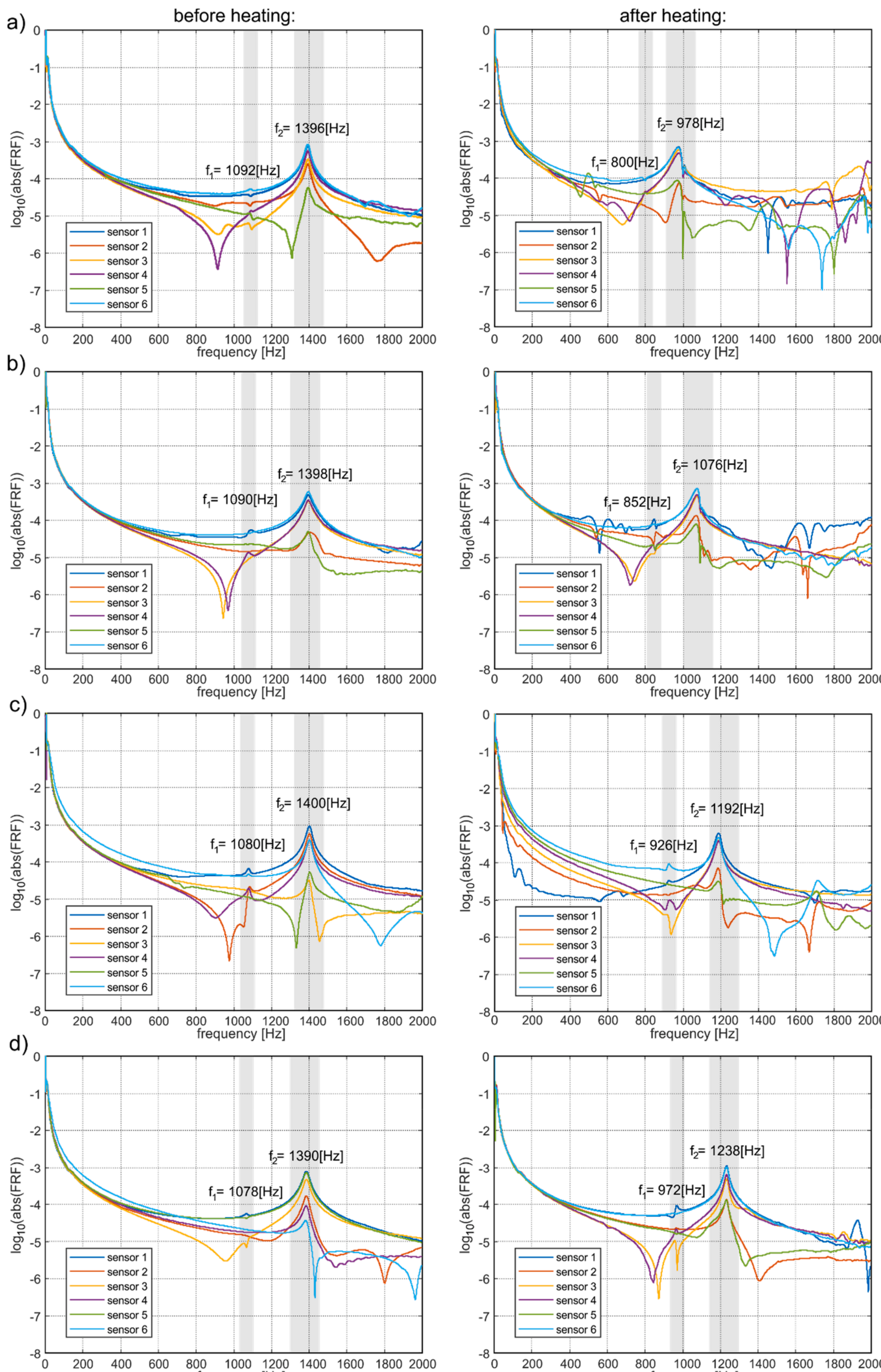

Fig. 9. Envelope diagrams of FRFs for GFRP-reinforced concrete beams subjected to high temperature: (a) 240 °C, (b) 200 °C, (c) 160 °C and (d) 120 °C.

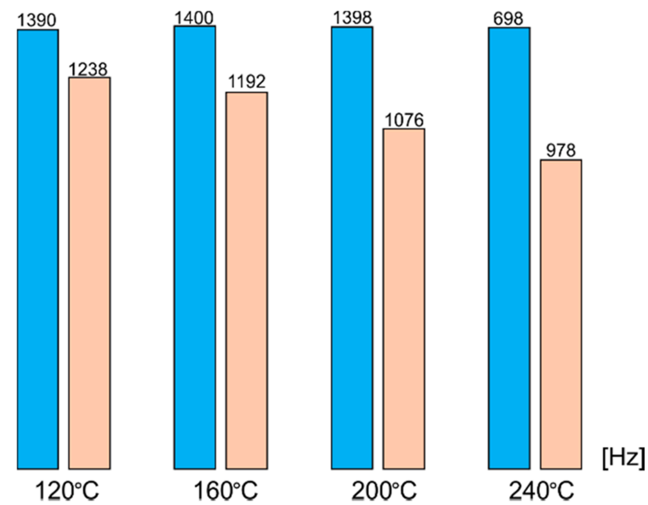

Fig. 10. Comparison of the second natural frequency in damaged and undamaged GFRP – reinforced beams.

of the crack, and the next characteristic point, which is the maximum value of the applied load, indicates the ultimate strength of the concrete specimen. In the second range, the load was carried out by the composite reinforcement and undamaged compressed concrete part. The increase of the applied load after concrete cracking was not clearly observed in the case of simultaneous action of external load and high temperature because the heated GFRP bars were characterized by negligible stiffness and were unable to carry the load.

The values of the first peak (concrete cracking) and the ultimate strength of the beams were plotted in the charts (Fig. 12). The simultaneous action of temperature and external load caused the decrease of both, load capacity and concrete tensile strength. Moreover, the clear decrease with increasing temperature is visible in both cases. The deviation from the downward trend was observed for tensile concrete strength but is usually neglected in design, mainly due to its unpredictability and insignificant value.

For completeness, the relation between the ultimate strength of concrete beams and the natural frequency is presented in Fig. 13. The graph presents only one set of data (for beams heated and cooled down) because as mentioned the destructive tests conducted in a thermal chamber under the simultaneous action of the elevated temperature were not preceded by the vibrational tests.

3.2.3. Concrete beams subjected to high temperatures

The next stage of the analysis concerns concrete beams without any reinforcement. This stage of the investigation is crucial because the changes in stiffness observed in the previous section for concrete beams with GFRP rods can be the result of concrete damage, damage of the reinforcement, as well as the damage of the adhesive connection between concrete and composite inserts.

This stage of investigation is limited to nondestructive tests in ambient conditions. The destructive tests of beams without any reinforcement would only allow for monitoring the variation of tensile concrete strength, which is not the aim of the study.

The comparison of FRFs obtained for pristine beams and beams subjected to varying, high temperatures are presented in Fig. 14. Also in the case of concrete, the natural frequencies decreased with increasing temperature, which indicates that the concrete stiffness reduces with temperature. The increase of the temperature is also associated with nonlinear effects manifested by multiple peaks visible in FRFs, especially for higher frequencies. It is also visible that concrete beams are characterized by lower frequencies than concrete reinforced with GFRP. The first reason is the possible difference in the concrete mixture. Moreover, manufacturing the concrete beams did not demand using specially prepared spacers and thus the concrete part has been about 2.5 cm longer (Fig. 1).

The comparison of natural frequencies of concrete beams with and without composite reinforcement is presented in Fig. 15. The graphs present the difference in frequencies of the two first modes calculated according to the following formula:

$$\Delta f = \frac{f_H - f_D}{f_H} \tag{3}$$

where f_H denotes the natural frequency of the healthy, undamaged beam, while f_D is the frequency of the damaged beam. Next, the results were approximated by a linear function using regression analysis based on the least square method. The obtained data were approximated using the linear function described by equation $y = ax$. Because from the physical point of view the change of temperature $\Delta T = 0$ °C (ambient conditions) cannot cause the change in natural frequencies, it was assumed that the approximating function passes through the point (0,0). The correlation coefficient *R*-squared has been calculated to assess qualitatively the approximation. The strength of the correlation is high:

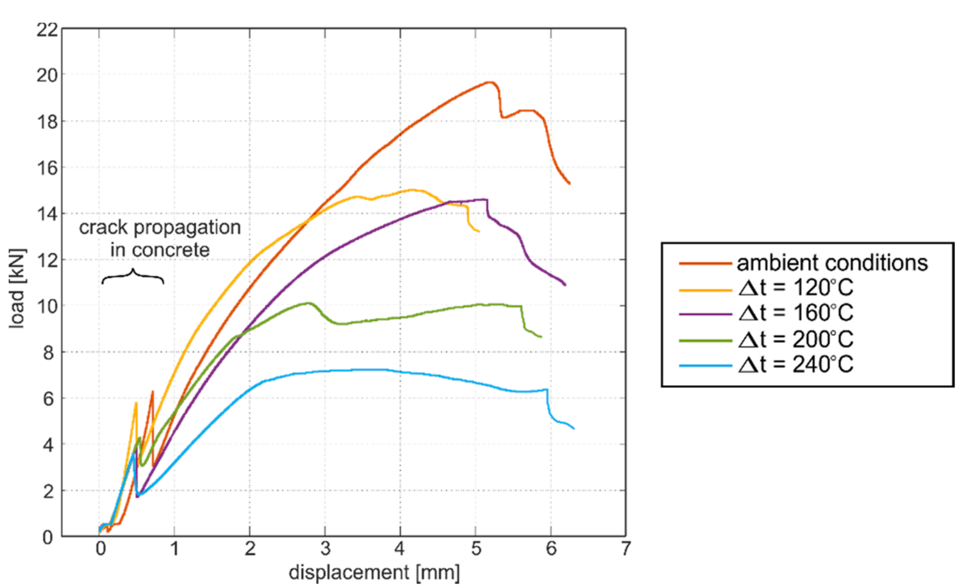

Fig. 11. Load – displacement curves for beams exposed to elevated temperatures.

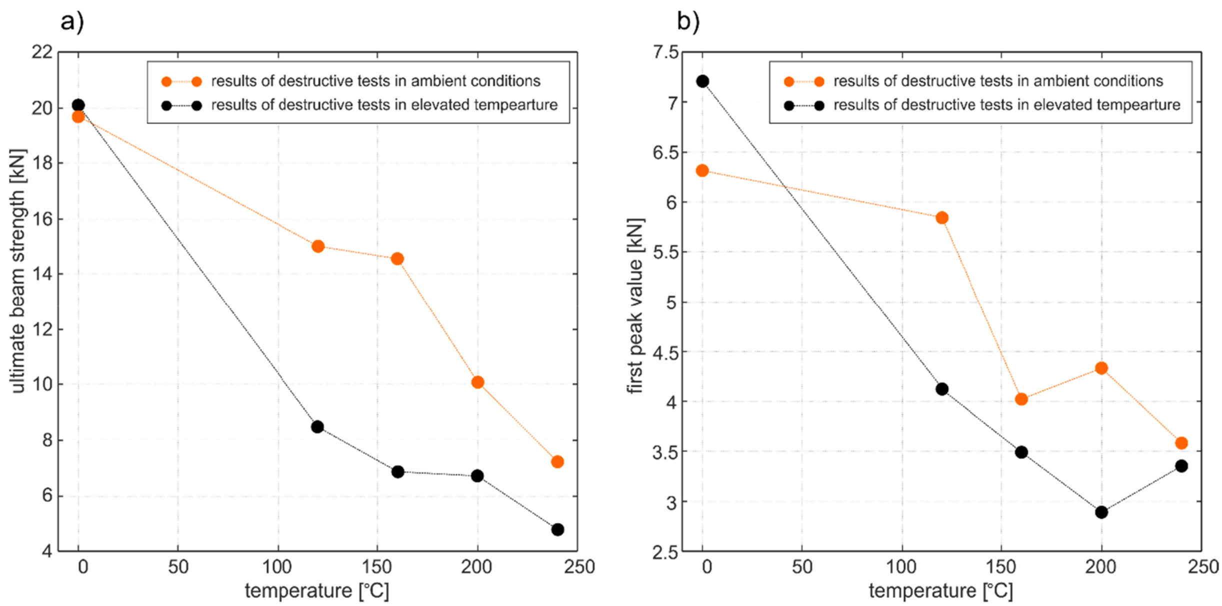

Fig. 12. The influence of high temperature on (a) ultimate beam strength and (b) load causing first crack propagation in GFRP-reinforced concrete beams in ambient conditions and in elevated temperatures.

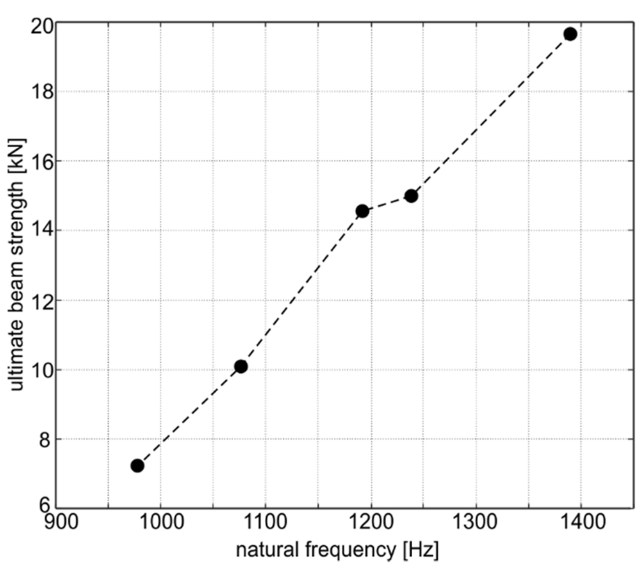

Fig. 13. The relationship between ultimate beam strength and the second natural frequency.

the value of the correction coefficient varies from 0.945 to 0.967.

First of all, in all cases (for both frequencies and beams with and without reinforcement) the influence of external temperature on the results of the non-destructive analysis is visible. Obtained results demonstrate that the stiffness of concrete beams also varies for various temperatures and, what is crucial, the damages caused by the elevated temperature are permanent. We can observe even insignificant changes (about 10%) in natural frequency for the temperature which is considered safe for the concrete (120 °C), which proves the efficiency of the nondestructive vibration-based method.

Second of all, the stiffness reduction of the GFRP-reinforcement beams results from not only damage of the GFRP bars, but also concrete degradation. The slope of the approximating function has been denoted as ϕ in the figures. The greater the slope, the greater change in natural frequency caused by the temperature. In both cases, the slope was greater for concrete with GFRP which indicates that these beams were more sensitive to high temperatures, even that the GFRP bars after cooling down were characterized by the same elastic modulus as pristine bars. The possible explanation may be the influence of the quality of the adhesive connection between the cover and the reinforcement. The difference in thermal expansion coefficients might cause the microcrack propagation and deterioration of the reinforcement and concrete connection. Moreover, the difference obtained for specimens with and without GFRP bars might result from the differences in the evolution of the temperature distribution in investigated specimens caused by the presence of the reinforcement.

4. Discussion of the results

The first stage of investigation concerning destructive tests of uncovered GFRP bars in the thermal chamber in elevated temperatures and ambient conditions after cooling down indicated both advantages and disadvantages of the composite reinforcement. The ability GFRP stiffness decreased significantly when the temperature was higher than 80 °C, which is in line with reinforcement specification. Above the melting temperature, the reinforcement is unable to carry on the external load. However, when the GFRP bars were cooled down before bending tests, their stiffness was the same regardless of the applied temperature. Moreover, during bending tests, we did not observe the development of any damage, fibre cracking, etc. After removing the external load, the rods regained their initial shape and the only effect of the temperature load as well the bending tests was the color change.

The second stage was devoted to concrete beams with GFRP reinforcement. The destructive tests conducted in the thermal chamber in elevated temperatures resulted in similar outcomes as for uncovered GFRP bars. A significant reduction of the load capacity was observed with increasing temperature. When the beams were cooled down before destructive tests, the reduction of the maximum applied load was also observed but the reduction was smaller than in the case of the simultaneous action of temperature and external loading.

Because the GFRP bars are characterized by relatively low elastic modulus (about 45 GPa) the destructive tests could be divided into two main stages. Within the first stage, the external load is carried out mainly by the concrete. The strains of the reinforcement are insignificant and in consequence, the load carried by the GFRP bars is also small. Within the next stage which takes part after concrete cracking

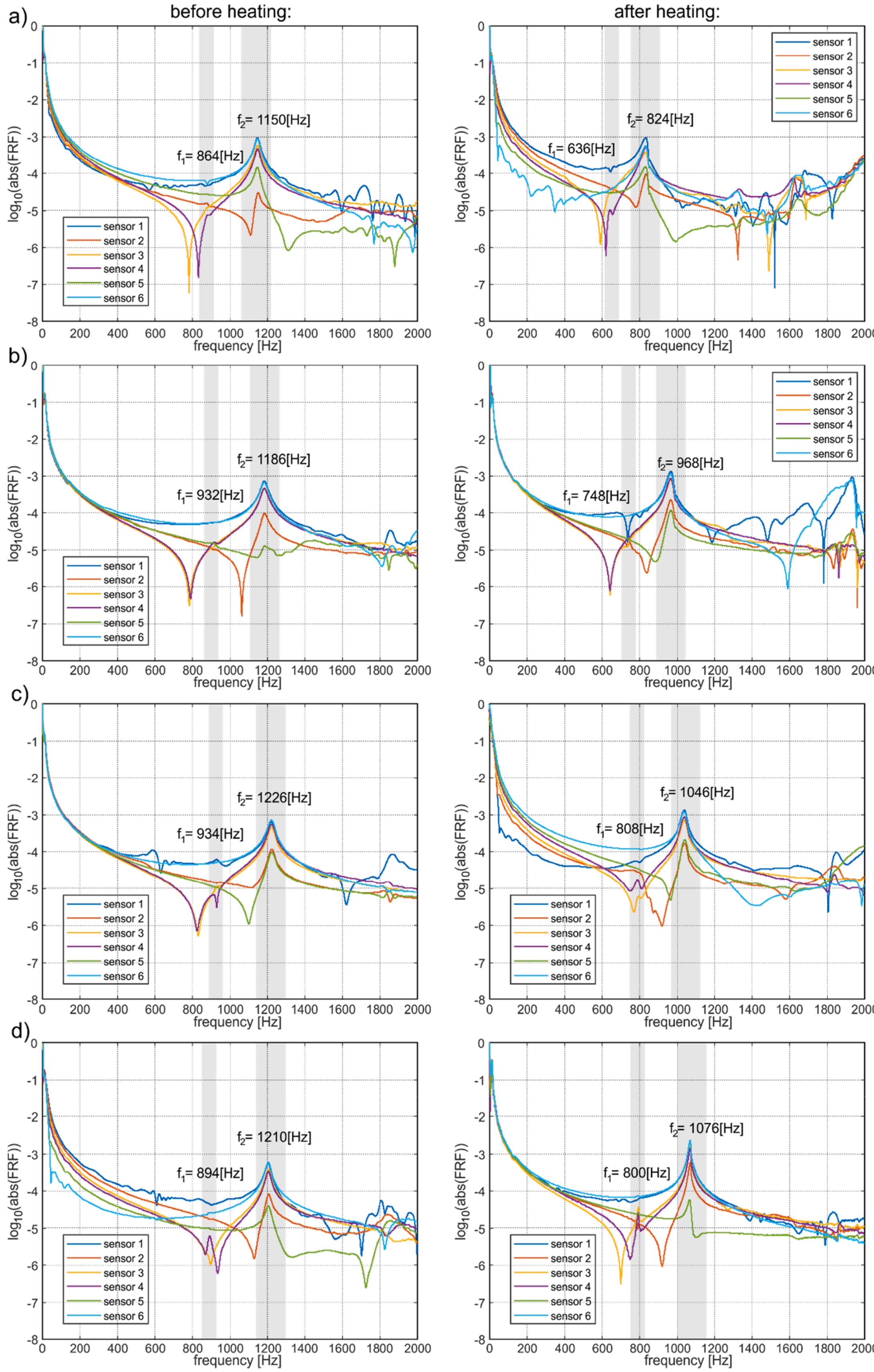

Fig. 14. Envelope diagrams of FRFs for concrete beams subjected to high temperature: (a) 240 °C, (b) 200 °C, (c) 160 °C and (d) 120 °C.

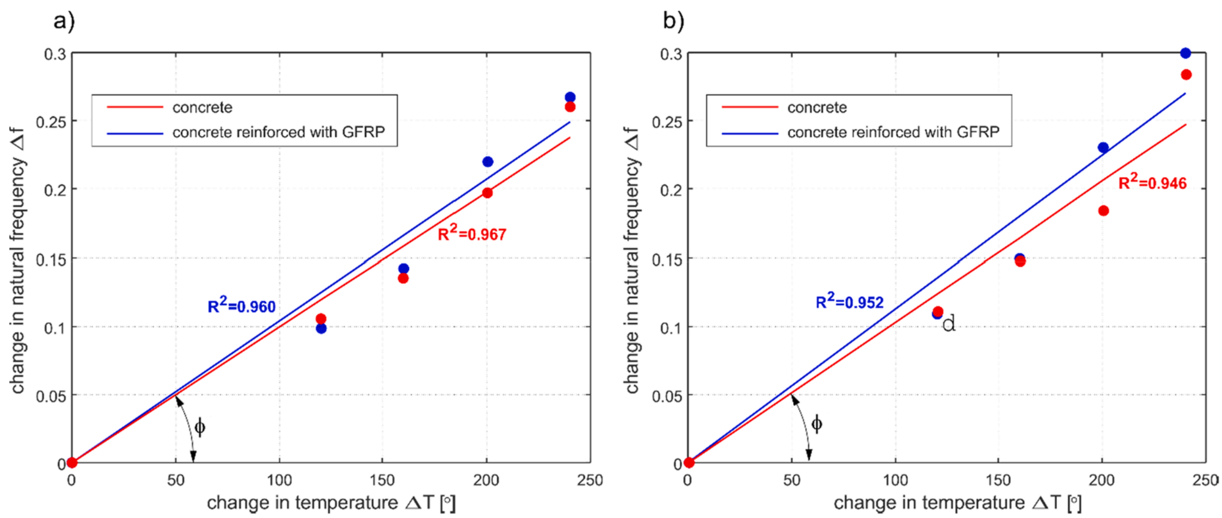

Fig. 15. The comparison of the changes in (a) first natural frequency and (b) second natural frequency of concrete and concrete with GFRP for various temperatures.

manifested by the sudden load drop, the applied load is mainly carried out by the reinforcement. The increase of the temperature caused the reduction of both characteristic values (strength of the concrete and ultimate strength of the beam), which clearly indicated that mechanical properties of the specimens have deteriorated, regardless the beams were cooled down or not. Despite the first stage of investigation concerning bending tests of uncovered bars did not reveal stiffness reduction of GFRP after heating and cooling down, in the case of GFRP - reinforced beams the deterioration of their condition can be suspected within this stage, which is manifested by a significant drop in maximum applied load. One can conclude that the elevated temperature caused the deterioration of the adhesive connection between GFRP rods and concrete which resulted in a general load capacity decrease. This conclusion is additionally supported by the results obtained for concrete beams without any reinforcement, for which the non-destructive vibration-based tests were conducted. The results of the vibration-based tests revealed that FRF can be efficiently used in the assessment of stiffness reduction of concrete-composite specimens subjected to elevated temperatures. Regardless the concrete was reinforced with GFRP or not the natural frequencies clearly decreased with increasing temperature. The linear model of approximation the relationship between the temperature and frequency was characterized by the high values of correlation coefficients. The decrease of frequency indicated the decrease of stiffness in both cases, however, the reduction of stiffness was higher in the case of beams with GFRP reinforcement. Possibly, the difference in thermal expansion coefficients might cause the microcrack propagation and deterioration of the reinforcement and concrete connection.

5. Conclusions

The study presents the results of the non-destructive and destructive evaluation of the influence of elevated temperatures on the condition of concrete specimens reinforced with GFRP bars. The experimental vibration-based and destructive bending tests were preceded by testing uncovered GFRP bars. Their stiffness strongly depended on the applied temperature. However, after cooling down the GFRP reinforcement regain its initial mechanical parameters, which is an important advantage of the composite reinforcement.

The conducted investigation proved that the vibration-based method can be efficiently applied in the assessment of stiffness of the GFRP-reinforced concrete subjected to elevated temperature. The natural frequencies decreased with increasing temperature. A similar trend was observed also for concrete beams with no reinforcement so one can conclude that not only the damage of GFRP bars but also the concrete damage was the reason for the stiffness reduction of GFRP-reinforced concrete beams.

CRediT authorship contribution statement

Beata Zima: Conceptualization, Methodology, Software, Visualization, Investigation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Marcin Krajewski:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical Statement:

Authors state that the research was conducted according to ethical standards.

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