

Influence of static long-term loads and cyclic freezing/thawing on the behaviour of concrete beams reinforced with BFRP and HFRP bars

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Abstract. The purpose of this study was to define the influence of static long-term loads and cyclic freezing/thawing on the deflections and cracking of concrete beams with non-metallic reinforcement. The rods made of basalt fiber reinforced polymer (BFRP) and hybrid fiber reinforced polymer (HFRP) were used as non-metallic reinforcement. Four series of single span beams were loaded with a single static force in a three-point bending test, then specimens were subjected to 150 freezing/thawing cycles in a large-size climatic chamber. The experimental test results were compared to those obtained from prior carried out short-term tests and theoretical calculations based on ACI 440:1R-06 standard concerning concrete element with non-metallic reinforcement.

1 Introduction

Fiber reinforced polymer (FRP) bars are made of continuous fibers (carbon, basalt, glass) as well as of epoxy or polyester resins using the pultrusion method. This technology is based on dragging the material through a set of nozzles producing the fiber strands, which are later immersed in the resin and formed in the shape of smooth bars, and then wrapped with a roving to create ribbing, in the same way as in case of conventional steel reinforcing bars [1].

The composite bars have become a useful substitute for conventional reinforcement in civil engineering structures for which load capacity and resistance to environmental factors influences are required [8, 9, 15]. Considering the requirements of responsible design of engineering structures with particular emphasis on durability, the use of non-metallic reinforcement in structural reinforced elements allows reducing the costs related to buildings' erection, as well as the costs of buildings' maintenance and renovations. Non-metallic bars are characterized by high resistance to corrosion, which allows to extend the life cycle of the object [3, 5, 18]. They are often used in concrete structural elements exposed to strong environmental aggression, such as foundations, breakwaters and other seaside structures and tanks in sewage treatment plants [8, 18].

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The use of FRP bars allows to reduce the thickness of the concrete cover of reinforcement, which also makes it possible to reduce the dimensions and weight of structural element. Higher tensile strength of composite bars, in comparison to typical steel ones, makes it possible to reduce the diameter of bars, and lower bulk density of a composite material also causes the reduction of total weight of the structure [6, 7].

In spite of dissemination of different types of non-metallic bars and numerous investigations of elements reinforced using these bars [4, 16, 17], this type of reinforcement is still treated as an unconventional construction material. One of the barrier of non-metallic bars application is the lack of standards and clear guidelines for the design of structures reinforced with FRP bars. No standards have been developed for determining the mechanical parameters of FRP reinforcing bars, and thus the separate mechanical properties tests should be carried out for each application of this type of reinforcement.

The relatively least amount of research on structures with non-metallic reinforcement concerns the use of basalt fiber reinforced polymer (BFRP) bars. The basalt fibers included in their composition are characterized by high chemical and thermal stability [11]. The basalt fiber retains the basalt structure and features, such as corrosion resistance, ideal thermal insulation, sound absorption and low moisture absorption. In addition, the fiber has a higher tensile strength than steel and a relatively high modulus of elasticity, however, lower than the elasticity modulus of steel. According to [12], basalt fibers show higher tensile strength than type E glass fibers, higher limit deformations at destruction than carbon fibers, as well as good resistance in conditions of chemical aggressiveness and fire temperatures [11, 13]. BFRP bars can be an alternative to conventional reinforcement due to the favorable functional properties of basalt fibers, therefore research works should be undertaken to disseminate their use. Even fewer studies concern the use of hybrid fiber reinforced polymer (HFRP) rods in which, besides basalt fibers, also carbon fibers have been introduced to increase the modulus of elasticity [16].

The aim of the research presented in the work was to assess the behavior of model beams made of concrete reinforced with basalt (BFRP) bars and hybrid (HFRP) bars, subjected to bending. The mechanical parameters of composite bars were determined. Deflection values and cracking of the element in three-point bending conditions were analyzed.

2 Experimental programme

2.1 Materials and model beams' preparation

The tests were carried out on model beams with dimensions of $80 \times 120 \times 1100$ mm made of C30/37 concrete with $w/c = 0,50$. The composition of the concrete mix was shown in Table 1.

Table 1. Composition of concrete mix

Component	Density (kg/m ³)	Content (kg/m ³)
Cement CEM I 42,5R	3,10	320
Water	1,00	160
Fine aggregate 0-2 mm	2,65	732
Coarse aggregate 2-16 mm	2,65	1203
Superplasticizer	1,07	5,49

Two types of composite BFRP bars and HFRP bars were used as the reinforcement of model beams. The first one is based on rovings with basalt fibers, the other is based

on rovings with basalt and carbon fibers. All bars were made using pultrusion method with appropriate fibers immersed in a polyester matrix. The material was formed into smooth bars wrapped with an additional braid increasing their adhesion to concrete. The appearance of both types of products makes them impossible to distinguish with the naked eye. During the preparation of reinforcing frameworks and concrete casting, it was necessary to use labels with a description on each used bar.

The results of strength tests of reinforcing bars carried out in accordance with the guidelines [2] were shown in Table 2. They correspond to the values which must be provided by the producer of composite bars:

- f_{ju}^* - guaranteed tensile strength, defined as the mean tensile strength $f_{u,ave}$ minus three times standard deviation σ_s ,
- E_f - design or guaranteed modulus of elasticity of FRP defined as mean modulus of test specimens ($E_f = E_{f,ave}$),
- ϵ_{ju}^* - guaranteed rupture strain of FRP reinforcement defined as the mean tensile strain at failure of test specimens minus three times standard deviation σ .

Table 2. Mean values of basic strength parameters of HFRP and BFRP bars

Bar type	$f_{u,ave}$	σ_s	f_{ju}^*	E_f	$\epsilon_{u,ave}$	σ	ϵ_{ju}^*
BFRP	1190,0	14,3	1147,1	47,6	2,6 %	0,20	2,0 %
HFRP	1190,0	14,3	1147,1	64,3	2,2 %	0,02	2,1%

Despite the addition of carbon fibers, the mean tensile strength of HFRP bars did not increase, while the modulus of elasticity increased by as much as 35% compared to BFRP bars.

The reinforcement system of the test elements was based on four main FRP bars with a diameter of 6 mm in each of the corners of the cross-section and evenly spaced stirrups with a diameter of $\varnothing 3$ mm every 50 mm made of steel type A-0. The test elements have been designed in accordance with the guidelines of ACI 440: 1R-06 [1], assuming the crushing of the compression zone of concrete as their destruction mechanism.

The division into individual groups with the encoded sample names was shown below:

- HFRP FT: beams reinforced with HFRP bars, subjected to static load and cyclic freezing and thawing,
- BFRP FT: beams reinforced with BFRP bars, subjected to static load and cyclic freezing and thawing,
- HFRP C: reference beams reinforced with HFRP bars, subjected to static load,
- BFRP C: reference beams reinforced with BFRP bars, subjected to static load.

2.2 Test method

The assumptions of the experiment were based on a comparison of the behavior of beams subjected to three point bending test under the influence of a long-term static load and at the same time to cyclic freezing and thawing in the temperature range from -20°C to $+20^\circ\text{C}$. In addition, reference beams loaded in the same way, were tested at constant temperature of $+20^\circ\text{C}$. The midspan deflections of beams, strains of concrete at the level of the top and bottom reinforcement as well as the spacing and the opening widths of cracks were measured.

For simulating the conditions during the ordinary test procedure of frost resistance of concrete and limiting the drying of beams surface, all samples were pre-soaked with water and then they were tightly wrapped with plastic cover and periodically the water losses were supplemented.

The value of the static load in the midspan of beam was taken as the equivalent of 20% of the beam bearing capacity determined when testing the elements under the short term load. The assumed level of the research elements effort corresponded to their reaching the ultimate limit state of deflection. Thus, the beams reinforced with BFRP and HFRP bars were loaded with different values of forces, which were equal to 5,60 kN and 7,00 kN, respectively.

The deflections were controlled using the moisture resistant dial gauges, with an accuracy of 0,01 mm and a measuring range of 10 mm. The strains were measured through benchmarks previously fixed on beams' surface. In the further part of the study, the pair of benchmarks will be referred to as line 1 and line 2, respectively. The contactless device with an accuracy of 0,001 mm with a measuring base of 150 mm was used for strains determination. The crack opening was measured by a Brinell loupe with an accuracy of 0,01 mm.

Specially designed test stands were placed in a freezing chamber, the task of which was to simulate the above-mentioned temperature regime. The 150 cycles were accepted as the period of test, with each cycle lasting 8 hours.

Inverted static scheme (beam bending upwards) allows full exposure of the tensile edges of tested elements, and thus the current registration of crack morphology. The view of stands placed in the freezer chamber was shown in Fig. 1.



Fig. 1. Testing equipment in freezing chamber

3 Test results

The predicted deflection values for beams with composite reinforcement were determined based on the procedures described in ACI 440: 1R-06 [1] on the basis of obtained material properties of FRP bars and concrete used. The obtained results of calculations were compared with the results of deflection measurements under conditions of long-term (50 days) load

of beams not subjected to cyclic freezing and thawing. Fig. 2 shows the theoretical levels of beam deflections predicted for the assumed materials and the average test results of deflection for each series.

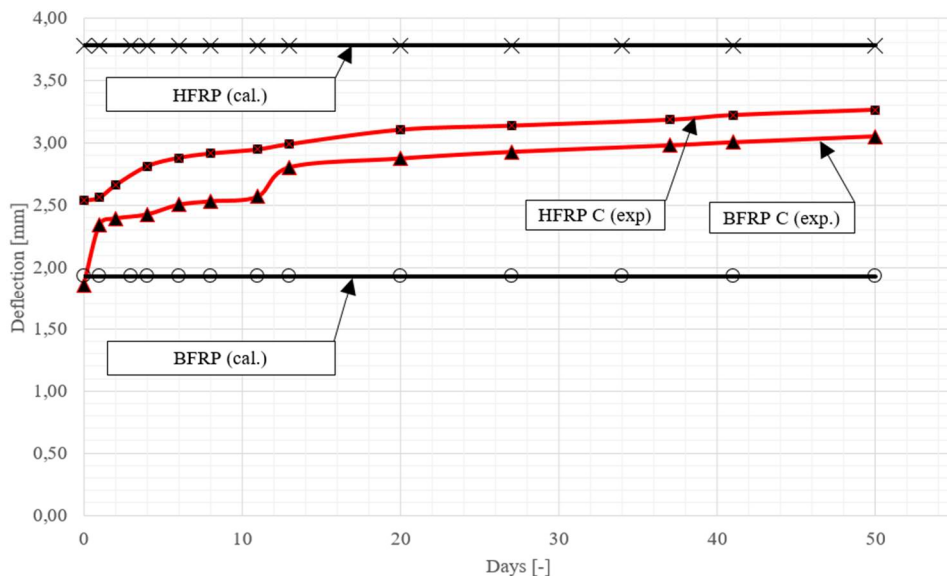


Fig. 2. Comparison of experimental and calculated values of midspan deflections of beam with composite reinforcement

The midspan deflection of beams with both types of reinforcing bars slightly increased during the test. The results of deflection values calculations for BFRP beams represent values smaller than those recorded during the tests for series BFRP C. The difference was 1.12 mm. In the case of analogous comparison for HFRP C, the obtained theoretical results were higher than the results of measurements at test, and the difference achieved 0.73 mm.

The above mentioned differences in the value of deflections should not disqualify the calculation methods proposed in [1] due to previously published [16] possible discrepancies in the levels of effort of test elements in the ranges of 0-20% and 80-100%.

Fig. 3 presents the relationships of beam deflection versus number of freeze/thaw cycles in comparison to the results obtained for reference beam specimens tested under static load at the temperature of +20 °C. The mean strains in tensile zone of concrete beams subjected to freeze/thaw cycles and reference ones were presented in Fig. 4.

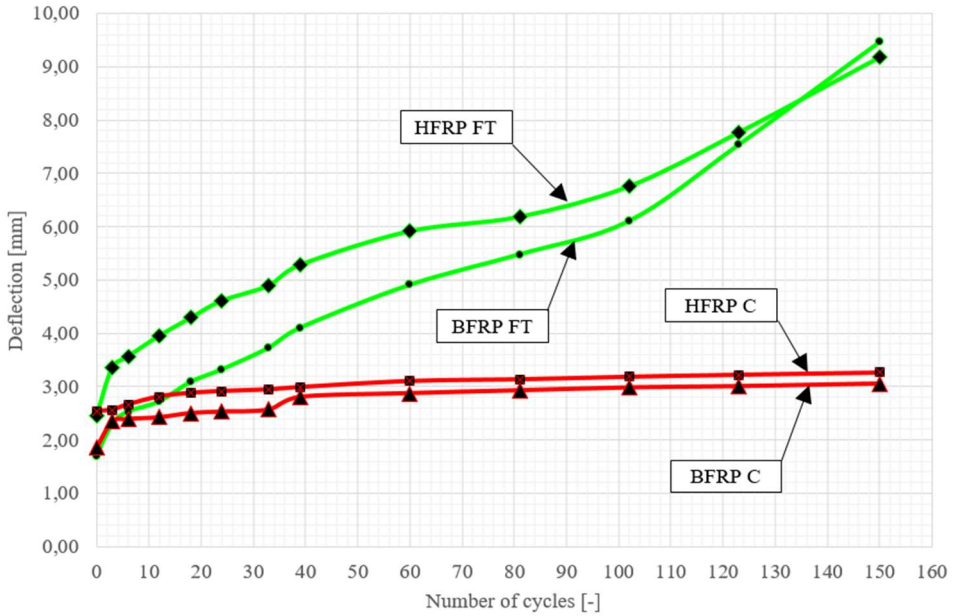


Fig. 3. Experimental relationships of number of cycles - midspan deflection of beams with composite reinforcement

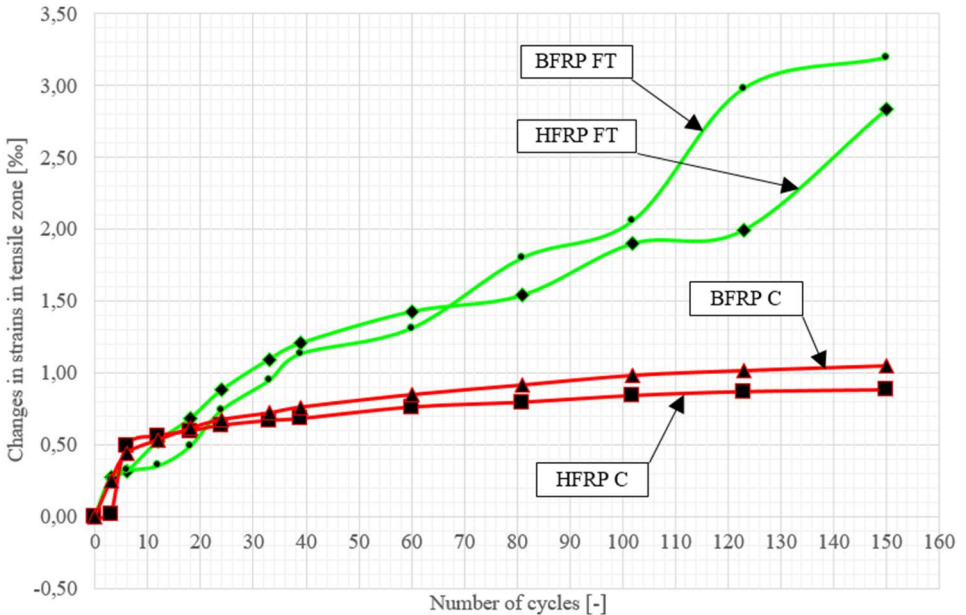


Fig. 4. Strains in tensile zone of beams in comparison to initial state

Cyclic freezing and thawing of beams under controlled moisture conditions, subjected to sustained load, caused a significant increase in deflection over the entire test period. After 150 cycles the mean values of deflections of beams with different types of composite reinforcement were comparable, although the absolute values of the load for both types of beams were different. The significant influence of cyclic freezing and thawing on beam deformations has also been confirmed by the analysis of strains in tensile zone. In the case

of HFRP C and BFRP C beams subjected to load at constant temperature, after initial slight increase, the deformations increased very slowly. The increase in strains in beams under freeze/thaw cycles (FT) was almost linear throughout the test period and the values recorded were even three times greater in comparison to the strains in beams at constant temperature.

Table 3 contain the analysis of crack formation in beams subjected to cyclic freezing and thawing and in reference beams.

Table 3. The values of number and width of cracks in beams subjected to cyclic freezing and thawing (FT) and in reference beams (C)

Cycle	HFRP FT		BFRP FT		HFRP C		BFRP C	
	Number of cracks [-]	Crack width [mm]	Number of cracks [-]	Crack width [mm]	Number of cracks [-]	Crack width [mm]	Number of cracks [-]	Crack width [mm]
0	4	0,00	2	0,00	5	0,00	4	0,00
3	5	1,10	3	0,70	5	0,79	4	0,72
6	5	1,11	3	0,74	5	0,85	4	0,75
12	5	1,22	3	0,83	5	0,98	4	0,88
18	5	1,32	4	1,03	5	1,02	4	1,00
24	5	1,34	4	1,07	5	1,04	4	1,03
33	5	1,45	4	1,11	5	1,11	4	1,05
39	6	1,48	5	1,18	5	1,12	5	1,17
60	6	1,48	5	1,32	5	1,15	5	1,19
81	9	1,52	7	1,36	5	1,21	5	1,23
102	15	1,62	11	1,45	5	1,21	5	1,23
123	17	1,66	14	1,60	5	1,25	5	1,25
150	17	1,67	14	1,61	5	1,25	5	1,25

The mean values of cracks width in statically loaded elements were respectively 0.138 mm and 0.114 mm for samples from the HFRP C and BFRP C series. The results were respectively 0.040 mm and 0.026 mm, higher, than those measured after 150 test cycle.

It can be seen in Fig 3 and in Table 3 that for the beams tested at a constant temperature, the stabilization of the deflection increments and total crack width took place after 39 freeze/thaw cycles.

In contrast, for elements subjected to variable temperature conditions, the values of the mentioned parameters are constantly increasing along with the number of freeze/thaw cycles. In the final phase of the test, specimens subjected to freeze/thaw cycles, reinforced with BFRP and HFRP bars, achieved 180% and 210% higher deflections, respectively, and were characterized by 34% and 29% higher values of the total crack width compared to reference specimens C. In addition, elements reinforced with hybrid bars showed greater number of cracks, and thus a smaller value of the average cracks width, e.g. 0.098 mm for HFRP reinforced beam, and 0.115 mm for BFRP reinforced beam. In addition, within 150 cycles of freezing and thawing, elements with hybrid bars were characterized by 71.3% lower strain increase in relation to initial state, than those based only on basalt fiber bars.

4 Conclusions

The insertion of additional rovings of coal fiber into the original basalt fiber bars significantly improved the mechanical properties of the reinforcing bars. It also had a beneficial effect on deformation characteristics of beams subjected to cyclic freezing and thawing conditions.

Based on the tests conducted, it was found that in the aspect of long-term work, considering the atmospheric factors, simple beam elements reinforced with hybrid (HFRP) bars show the ability to carry 25% higher loads in comparison to those reinforced with basalt (BFRP) bars. Mainly, this is due to the higher modulus of elasticity of HFRP bars, and hence the higher stiffness of the elements.

In the case of beam elements subjected to freezing and thawing cycles, the results of deflections differ significantly from the theoretical estimates. In order to obtain comparable results, it is necessary to introduce an additional parameter taking into account the destruction of concrete under sustained load and freeze/thaw cycles.

The algorithms proposed in the design guidelines for structures reinforced with composite bars can be pre-applied for theoretical estimation in order to determine the behavior of beams reinforced with BFRP and HFRP.

This research work was financially supported by National Centre for Research and Development, Poland; project number PBS3/A2/20/2015 (ID 245084).

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