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Research paper

Structural testing of compression members reinforced with FRP bars

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Abstract: The Fibre Reinforced Polymer (FRP) bars are increasingly used as an alternative to steel reinforcement in concrete structures. Their wide applicability is due to their properties such as high strength, resistance to corrosion, easy cutting, etc. For many years, research has been conducted on the identification of properties and the possibility of application of FRP bars in structural members as the alternative to steel reinforcement. This paper presents results of experimental tests of concrete columns reinforced with BFRP (Basalt Fibre Reinforced Polymer) and HFRP (Hybrid Fibre Reinforced Polymer) bars. Observed failure modes are presented along with comparison of the experimental and the predicted ultimate capacities of the regarded columns.

Keywords: results of experimental tests, concrete columns, reinforcement, basalt fibre reinforced polymer bars, hybrid fibre reinforced polymer bars, compression, resistance

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1. Introduction

Nowadays, the design process of new facilities is increasingly focused on environmental impacts and the impact of the environment on their durability. This is due to the global problem of environmental pollution, which is the result of ongoing socio-economic transitions. Such transitions have caused the destruction of local ecological systems due to use of natural resource, land, and energy. They also impact on the emission and spread of hazardous substances and increase of greenhouse gasses and waste pollution, and water pollution [1, 2]. Therefore, currently one of the aspects of design process is pointed to the sustainability of the structure. It is expressed, among other, by means of life cycle assessment of a building structure including cost as well as the risk and consequences of its destruction. The purpose of design for sustainability is to reduce impacts on the environment by selecting right materials resistant to adverse influence environment [3].

At the moment, we can see that in the surrounding area, the huge part of building structures is made of concrete, reinforced concrete or pre-stressed concrete.

Due to continuous exposure to environmental influences, polluted elements of structure undergo destruction. This destruction is most often caused by the carbonation of the concrete cover, which protects the steel reinforcement bars from corrosion [4–6]. A detailed analysis of this phenomenon was presented in the article [5] by L. Runkiwiecz. The author, in his study, analyses the years from 1962 to 2014. The analysis shows that the majority of catastrophes of concrete and reinforced concrete structural elements (about 45%) during the studied period occurred due to cracks or excessive displacement in areas with severe corrosion.

One of the methods of protecting construction building objects from catastrophe is strengthening with composite strips, which R. Kotynia [7] presented in her monograph in relation to bending elements. However, the collaboration between these materials has been discussed, among others, in [8] and [9].

The processes of aggressive environmental impact on the structure affect its safety, reliability and durability, which can be considered significant enough problem during its service life. Therefore, an alternative solution for steel reinforcement is being sought. One of the solutions is to use of FRP (Fibre Reinforced Polymer) bars. The bars have many desirable properties, such as high tensile strength and high corrosion resistance [10–12]. The FRP reinforcement bars, among other, due to the much longer service life and high tensile strength are a promising replacement for the steel reinforcement in concrete structures.

Currently, the use of FRP reinforcement bars has gone beyond the experimental tests, and they are in many concrete structures. For this reason, theoretical analyses of their proper use as well as experimental verification tests are necessary. For a dozen of years, research has been conducted on the properties and the possibility of using structural members reinforced with CFRP (Carbon Fibre Reinforced Polymerbars), GFRP (Glass Fibre Reinforced Polymerbars), BFRP (Basalt Fibre Reinforced Polymer) bars as an alternative to steel. FRP bars can incorporate various constituents to achieve desired properties, resulting in what are known as HFRP (Hybrid Fibre Reinforced Polymerbars) bars. Among others, A. Garbacz and his co-authors described the properties of HFRP bars on the basis of experiments carried out in works [13–15]. Analyses carried out by the authors have shown that replacing some of the basalt fibres in the HC/BFRP rod with carbon fibres has a beneficial effect on its mechanical properties. Just a 10 percent substitution with LS carbon fibres results in a 16.0 per cent increase in longitudinal modulus and 9.0% increase in tensile strength.

It is also worth to emphasise that the FRP composite bars came up to the requirements of environmental oriented design and sustainable development. During production of composite reinforcement bars, both carbon dioxide (CO_2) emission and energy usage are several times smaller than in the production process of conventional structural materials. During production of steel reinforcement bars, the emission of carbon dioxide is about 170% larger than during production FRP bars (according to report of Imperial College London for producer of MagmaTech bars from the Great Britain). Moreover, energy consumption in the steel production process ranges from about 140% of the energy needed to produce CFRP bars up to about 500% in case of GRFP bars.

Due to properties of composite bars (linear stress-strain diagram) the vast majority of research concerns bending beams [16–22] and concrete bending slabs [23, 24]. Håkan Nordin and Björn Täljsten [25], C.A. Neagow, L. Gil, and M.A. Pérez [26], as well as A. Koaik, S. Bel, and B. Jurkiewicz [27] conducted studies on hybrid composite beams consisting of a profile made of Glass Fiber Reinforced Polymer (GFRP) strengthened with carbon fiber and a concrete compression zone. The conducted studies and analyses have shown that it will be possible to create a technically and economically viable hybrid profile made of glass fibers in combination with carbon fibers. In addition to the studies and analyses of bending elements, research is also being conducted on compressed concrete columns externally reinforced with FRP strips [28–31]. In the areas where this reinforcement was applied, a reduction in the width of cracks in the concrete and an increase in load-bearing capacity were observed.

However, for compressed elements with FRP bars there is a lack of extensive research, with a few works [32–35]. In all of the studies, it was shown that the failure of the concrete element with FRP reinforcement primarily occurs due to excessive deformation of the longitudinal reinforcement bars under compression, which is a result of the inherent properties of this reinforcement. M. Urbański and K. Protchenko conducted studies on the compression behavior of BFRP reinforcement bars, and the results of their observations were published in [36] and [37]. Based on the conducted studies, the authors suggest that BFRP bars could be used as an alternative to steel reinforcement bars, after comprehensive investigations are carried out to assess the factors affecting their compressive load-bearing capacity [38].

However, there is an increasing requirement to assess the suitability of FRP reinforcement in compression elements. Application of FRP reinforcement in columns is more problematic than in beams because of higher fragility to compressive loading of FRP bars than steel bars.

This paper presents results of experimental tests of concrete columns reinforced with BFRP and HFRP bars. Observed failure modes are presented along with comparison of the experimental and the predicted ultimate capacities of the regarded columns.

2. Experimental testing

The carried out research included structural elements that were subjected to axial compressive force. The experimental tests of the columns were carried out in an EU 1000 hydraulic press (Fig. 1). The load was increasing continuously from zero to ultimate force. After reaching the limit point, the loading program was continued in order to obtain a full course of the static equilibrium path, also in the post-critical range.

Fig. 1. The test stand

During the experimental tests, the behaviour of each element was monitored depending on the level of the load applied, and the mode of damage was recorded. The deformation of the reinforcement bars, the vertical and horizontal deformation of the concrete, as well as the vertical shortening of the elements and their horizontal deviation at mid-span were also measured (Fig. 2). The deformations of the reinforcement and concrete were recorded using electric resistance wire strain gauges.

Fig. 2. Method of measuring concrete deformation and element shortening

2.1. Description of tested elements and materials utilized in the work

The experimental programme incorporated a preparation of 24 low columns with the cross-section dimensions 150 × 150 mm and height of 750 mm reinforced with BFRP, HFRP bars. Analysed HFRP bars were composed of fibres by 80% (carbon-basalt fibres ratio was assumed as 1:4) and epoxy resin was assumed to be 20%. Further information regarding the characteristics of HFRP bars can be found in the accompanying papers [36, 37, 39]. In each of the elements, the stirrups were made of bars with a diameter of 6 mm of the same material as bars of the longitudinal reinforcement.

The tensile strength for BFRP bars ranged from 1103 to 1153 MPa and the elastic modulus from 43.87 to 48.18 GPa. In case of the HFRP bars the tensile strength was between 1139 and 1278 MPa while the elastic modulus was between 73.57 and 73.89 GPa. The concrete with a compressive strength in the range from 45.64 to 60.94 MPa (Table 1), that was measured on cubic samples was used.

Table 1. Characteristic of concrete specimens

Series	**Compressive strength of concrete [MPa]**	**Elasticity modulus of concrete [GPa]**
Series 1 to 4	45.64	34.70
Series 5 to 8	60.94	37.83

Table 2. Description of the tested samples

Series	**Name of elements**	**Type of rein-forcement**	**Tensile strength/Elasticity modulus [MPa]**	**Bars**	**ρ [%]**	**s [mm]**
S1	B8S7.5_i	BFRP	$1103/43.87 \cdot 10^3$	$4\phi8$	0.89	75
S2	B8S15_i	BFRP	$1103/43.87 \cdot 10^3$	$4\phi8$	0.89	150
S3	B10S7.5_i	BFRP	$1153/48.18 \cdot 10^3$	$4\phi10$	1.40	75
S4	B10S15_i	BFRP	$1153/48.18 \cdot 10^3$	$4\phi10$	1.40	150
S5	H8S7.5_i	HFRP	$1139/48.18 \cdot 10^3$	$4\phi8$	0.89	75
S6	H8S15_i	HFRP	$1139/48.18 \cdot 10^3$	$4\phi8$	0.89	150
S7	H10S7.5_i	HFRP	$1278/73.89 \cdot 10^3$	$4\phi10$	1.40	75
S8	H10S15_i	HFRP	$1278/73.89 \cdot 10^3$	$4\phi10$	1.40	150

Where i denotes number of element, B means a bar of BFRP, H – a bras of HFRP, S7.5 means a stirrup spacing of 75 mm, a S15 spacing of 150 mm, ρ is percentage of reinforcement and s is distance between stirrups.

The eight series of reinforced concrete columns differing in type, dimeter of longitudinal reinforcement bars, and spacing of stirrups were examined. Each of the series consisted of three elements. For columns of series 1 and 2, four BFRP bars (one in each corner) with a diameter of 8 mm were used, while for series 5 and 6, HFRP bars of the same diameter were applied. The total reinforcement ratio for these elements was 0.89%. For series 3 and 4, four BFRP longitudinal reinforcement bars with a diameter of 10 mm were used, while for series 7 and 8, HFRP bars were applied. In this case, the total reinforcement percentage was 1.40%. For the odd-numbered series, stirrups were spaced at 75 mm intervals, while for the even-numbered series, they were spaced at 150 mm intervals. Table 2 presents material and geometrical characteristics of the samples used in the carried out experimental tests.

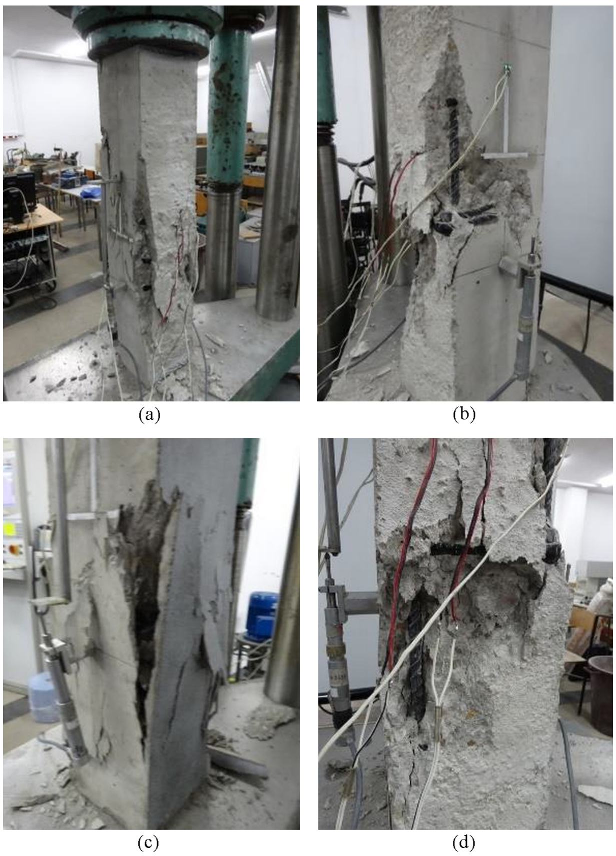

Fig. 3. Images of the collapse modes of columns loaded with axial force with reinforcement BFRP; (a) B8S7.5, (b) B8S15, (c) B10S7.5, (d) B10S15

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

Fig. 4. Images of the collapse modes of columns loaded with axial force with reinforcement HFRP; (a) H8S7.5, (b) H8S15, (c) H10S7.5, (d) H10S15

2.2. Results of experimental test

In the performed tests it was observed that all compression members collapsed by concrete crushing failure under the applied compression load. The destruction modes of the selected, exemplary compressed elements are shown in Figure 3 and Figure 4.

For elements with BFRP bars the experimental ultimate force (N_n) ranged from 906 kN to 1001.50 kN, while for the elements with HFRP bars from 905.50 kN to 972.20 kN. The predicted theoretical ultimate force (N_R) was 1026.90 kN for columns with BFRP bars and 1371.15 kN with BFRP bars, respectively.

The theoretical bearing capacity (N_R) of columns with BFRP and HFRP bars, was calculated according to the recommendations in the literature [10–12, 40], contribution of the compression reinforcement was neglected. The difference in the calculated capacities depends on the compressive strength of concrete, for individual batches of the concrete.

To determine the bearing capacity of elements under compression, the equations of the resultant force and moment in the cross-section should be used:

$$N = \sum_{i=1}^{n} A_{si}\sigma_{si} + \iint_{A_{cc}} \sigma_c \mathrm{dA_{cc}}, \tag{2.1}$$

$$M = \sum_{i=1}^{n} A_{si}\sigma_{si}(v_2 - d_i) + \iint_{A_{cc}} \sigma_c \mathrm{dA_{cc}}(v_2 - \mathrm{d_c}) \tag{2.2}$$

where: A_{si} – an area of the reinforcement in cross-section, n – number of the reinforcement groups, each with area of A_{si}, with spacing of d_i from the most compressed or the most tensioned section edge (here d_i for reinforcement A_{s2} equals to d), v_2 – the distance from the centre of gravity of the concrete cross-section to the most compressed edge, d_c – the location of resultant force of the compressive stress block taken from the area A_{cc}, measured from the compressed edge of the cross-section, which is expressed as:

$$d_c = x - \frac{\iint\limits_{A_{cc}} A_{cc} y \sigma_c \mathrm{dA_{cc}}}{\iint\limits_{A_{cc}} A_{cc} \sigma_c \mathrm{dA_{cc}}} \tag{2.3}$$

where: x – the depth of compression zone, y – the location of stresses σ_c – relations to neutral axis of the section.

Table 3 summarises the experimental and theoretical predictions of limit capacity of columns for individual series.

Based on the performed analysis, the recorded values of the experimental ultimate forces N_n, and calculated capacities, it can be concluded that for all elements the experimental ultimate force is smaller than the theoretical bearing capacity N_R (Table 3).

Table 3. Experimental and theoretical predictions of limit capacity of columns

Series	**Name of elements**	**Average experimental ultimate force, N_n [kN]**	**Theoretical ultimate force, N_R [kN]**	**$(N_n/N_R)\cdot 100$ [%]**
S1	B8S7.5	1001.00	1026.90	97
S2	B8S15	906.00	1026.90	88
S3	B10S7.5	1001.50	1026.90	98
S4	B10S15	1020.70	1026.90	99
S5	H8S7.5	1152.50	1371.15	84
S6	H8S15	905.50	1371.15	66
S7	H10S7.5	980.60	1371.15	72
S8	H10S15	972.20	1371.15	71

Analysing the results presented in Table 3, it can be observed that the differences between the estimated theoretical force N_{Rd} and the experimentally obtained force N_n range from approximately 66% (elements of series 6) to approximately 99% (elements of series 4). One of the lowest compressive strengths recorded during the experimental tests was achieved by the elements from series 6 (reinforcement bars 4ϕ8, HFRP, and stirrup spacing of 150 mm), for which the average value of the destructive force was $N_n = 905.5$ kN. At this stage of the experimental studies, it is not possible to clearly identify the causes of the obtained values of the destructive forces.

However, the difference between the results is less prominent if a larger diameter of the longitudinal reinforcement bars were used or for the elements in which the stirrup spacing was reduced. The use of 10 mm diameter reinforcement bars (except in one case, HFRP reinforcement bars) as longitudinal reinforcement in the tested columns increased the experimental ultimate force. The largest increase was observed for columns with HFRP reinforcement and the smallest with BFRP reinforcement, at the same stirrup spacing. The use of a smaller stirrup spacing (75 mm) with a longitudinal reinforcement bar diameter of 8 mm for BFRP bars increased the experimental ultimate force by approximately 10% and for HFRP bars by approximately 27%.

3. Results and discussion

The axial compressive force and longitudinal deformation (strain) in the reinforcement bars were recorded during the carried out experiments. Strains were measured in bars located on the opposite sides of columns. The representative results for the tested columns are shown in Figure 5 and Figure 6. Force versus strain diagrams for the tested columns with BFRP bars are shown in Figure 5, while for the columns with HFRP reinforcement are presented in Figure 6. In the graphs (Fig. 5), TBFRP1 and TFRP2 represent the strain gauge measurement results for BFRP bars, while THFRP1 and THFRP2 represent the results for HFRP bars (Fig. 6).

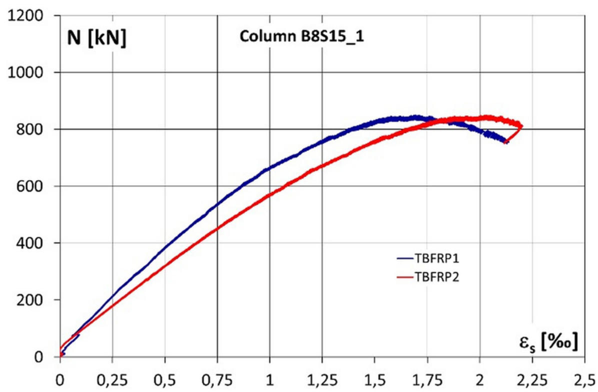

Fig. 5. Axial force vs strain measured in the main reinforcement bars for the columns with BFRP

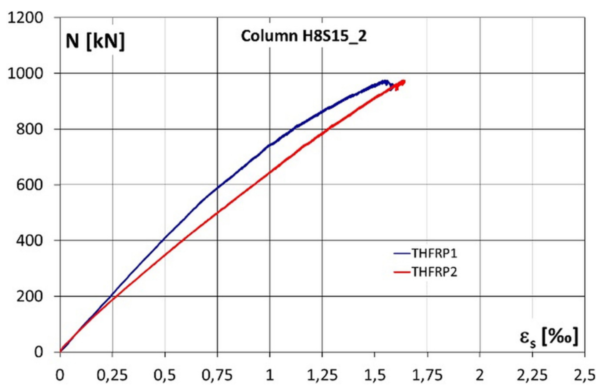

Fig. 6. Axial force vs strain measured in the main reinforcement bars for the columns with HFRP

The ultimate capacity is about 15% higher for columns with HFRP reinforcement bars than for columns with BFRP reinforcement bars. However, reported strains at the ultimate load (reflecting ductility) are slightly larger for columns with BFRP bars than in case of columns with HFRP reinforcement. The observed difference is caused predominately by difference in the compressive strength of concrete used, compare in Table 1.

4. Summary and conclusions

The performed tests confirm the applicability of the FRP bars in compression elements, although a further testing is required needed to investigate the possible range of their application. As a result of the analysis based on the experimental tests, it was observed that the largest difference between the theoretical force and the experimental ultimate force was for the series 6 columns and was 43%, and the smallest for the series 4 columns was 1%. Reported discrepancy between the measured and the predicted ultimate load requires additional research on formulation of the calculation procedures and reinforcement detailing. Based on the observed failure mechanisms, the stirrup spacing seems to be very important in the regarded structural elements.

The use of a stirrup spacing of 75 mm with a BFRP longitudinal reinforcement bar diameter of 8 mm increased the ultimate force by approximately 10% and for HFRP bars by approximately 27%. Using 10 mm diameter longitudinal reinforcement bars for both BFRP and HFRP bars, stirrup spacing did not have a significant effect on the increase in experimental failure force. When using 10 mm diameter bars as longitudinal reinforcement for both BFRP and HFRP bars, the spacing of stirrups had no significant effect on the increase in experimental ultimate force.

Comparing the test results shown in the graphs (Fig. 5 and Fig. 6), it can be observed that the load capacity of the columns with HFRP reinforcement is about 15% higher than with BFRP reinforcement. Whereas, the measured deformations at ultimate load are larger (about 30%) for columns with BFRP bars than for columns with HFRP reinforcement. The observed difference may be due to the difference in compressive strength of the concrete used (Table 1).

Another noticed problem in more successful application of FRP bars, is their high ductility (straining) compared to concrete. Lateral deformation (elongation) developed in columns during increase of compressive loading causes premature splitting of concrete cover.

Additional research is supposed to be conducted on application of the distributed reinforcement or the use of wound reinforcement [41] instead of horizontal stirrups to avoid premature cover splitting. Technological solution to the problem of too low experimental ultimate capacity should be found. Increase of compatibility of the reinforcement and concrete matrix along with the beneficial confinement effect should be regarded as further steps in the enhancement of FRP bars usage in compression elements. Based on comparisons of the experimental and the predicted capacities there is a need for validation of the design procedures on a larger population of typical compression structural elements.

However, the use of FRP-based composite reinforcement bars (BFRP and HFRP) as an alternative to steel reinforcement in compressed elements requires an individual approach, practical engineering experience, as well as further experimental research.

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Badania strukturalne elementów ściskanych zbrojonych prętami FRP

Słowa kluczowe: wyniki badań doświadczalnych, słupy betonowe, zbrojenie, pręty BFRP (Basalt Fibre Reinforced Polymer), pręty HFRP (Hybrid Fibre Reinforced Polymer), ściskanie, nośność

Streszczenie:

Pręty FRP (Fibre Reinforced Polymer) są dynamicznie rozwijającym się produktem na rynku budowlanym. Pręty FRP są coraz częściej stosowane jako alternatywa dla zbrojenia stalowego w konstrukcjach betonowych. Ich szerokie zastosowanie wynika z ich właściwości, takich jak wysoka wytrzymałość, odporność na korozję, łatwość cięcia itp. Od wielu lat prowadzone są badania nad identyfikacją właściwości i możliwością zastosowania prętów BFRP (Basalt Fibre Reinforced Polymer), GFRP (Glass Fibre Reinforced Polymer), CFRP (Carbon Fibre Reinforced Polymer), HFRP (Hybrid Fibre Reinforced Polymer) w elementach konstrukcyjnych jako alternatywy dla zbrojenia stalowego. Ze względu na liniową zależność naprężenie-odkształcenie dla prętów kompozytowych zdecydowana większość badań i analiz dotyczy elementów zginanych, podczas gdy dla elementów ściskanych ze wzmocnieniem kompozytowym brakuje obszernych badań. Istnieje jednak coraz większe zapotrzebowanie na ocenę przydatności tego zbrojenia w elementach ściskanych. W artykule przedstawiono wyniki badań eksperymentalnych niskich słupów betonowych zbrojonych prętami BFRP i HFRP.

Badaniami objęto elementy konstrukcyjne poddane działaniu osiowej siły ściskającej. Program eksperymentalny obejmował słupy o wymiarach przekroju poprzecznego 150 mm $\times$ 150 mm i wysokości 750 mm wzmocnione prętami BFRP, HFRP. W każdym z elementów strzemiona zostały wykonane z prętów o średnicy 6 mm, z tego samego materiału, co pręty zbrojenia podłużnego. Wytrzymałość na rozciąganie prętów BFRP wynosiła od 1103 MPa do 1153 MPa, a moduł sprężystości od 43,87 GPa do 48,18 GPa. W przypadku prętów HFRP wytrzymałość na rozciąganie wynosiła od 1139 MPa do 1278 MPa, a moduł sprężystości od 73,57 GPa do 73,89 GPa. Zastosowano beton klasy C35/45 o wytrzymałości na ściskanie w zakresie od 45,64 MPa do 60,94 MPa, którą zmierzono na próbkach sześciennych. Podczas badań zaobserwowano, że elementy ściskane ze zbrojeniem BFRP i HFRP uległy zniszczeniu przez zgniecenie betonu. Dla elementów z prętami BFRP eksperymentalna siła niszcząca (N_n) wynosiła od 906 kN do 1001,50 kN, natomiast dla elementów z prętami HFRP od 905,50 kN do 972,20 kN. Przewidywana teoretyczna siła nośności granicznej (N_R) wynosiła odpowiednio 1026,90 kN dla słupów z prętami BFRP i 1371,15 kN z prętami BFRP. Na podstawie przeprowadzonej analizy zarejestrowanych wartości eksperymentalnych sił niszczących Nn można stwierdzić, że dla wszystkich elementów siła ta jest mniejsza niż obliczona teoretyczna nośność N_R. Jednak różnica między wynikami jest mniej widoczna, jeśli zastosowano większą średnicę prętów zbrojenia podłużnego lub dla elementów, w których zmniejszono rozstaw strzemion. Podczas przeprowadzonych eksperymentów rejestrowano osiową siłę ściskającą oraz odkształcenia wzdłużne prętów zbrojenio-

wych. Odkształcenia mierzono w prętach znajdujących się po przeciwnych stronach naroży słupów. Porównując uzyskane wyniki można stwierdzić, że nośność graniczna jest o około 15% wyższa dla słupów ze zbrojeniem HFRP w porównaniu do słupów z prętami BFRP. Jednak odnotowane odkształcenia przy obciążeniu granicznym (plastyczność) są nieco większe w przypadku słupów z prętami BFRP niż w przypadku słupów ze zbrojeniem HFRP. Przeprowadzone testy potwierdzają możliwość zastosowania prętów FRP w elementach ściskanych, chociaż potrzebna jest większa liczba testów w celu zbadania możliwego zakresu ich zastosowania. Odnotowana rozbieżność między zmierzonym a przewidywanym obciążeniem granicznym wymaga dodatkowych badań nad sformułowaniem procedur obliczeniowych i szczegółami zbrojenia (np. rozstaw strzemion) w rozpatrywanych elementach konstrukcyjnych. Procedury projektowe powinny być walidowane na dużej populacji typowych elementów konstrukcyjnych.

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