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SHORT-TERM CRACKING IN BFRP RC BEAMS – EXPERIMENTAL AND THEORETICAL ANALYSIS

KRÓTKOTRWAŁE ZARYSOWANIE BELEK ZBROJONYCH PRĘTAMI BAZALTOWYMI BFRP – ANALIZA TEORETYCZNA I DOŚWIADCZALNA

Abstract

Basalt fiber-reinforced polymer (BFRP) bars can be a good alternative to traditional reinforcing steel. This type of reinforcement has low modulus of elasticity, hence deflections and cracking in BFRP RC flexural elements are larger than these found in typical RC members. As a result, the design of FRP RC beams is often governed by the serviceability limit states (SLS). This paper presents chosen results of a research programme in which 6 beams have been tested under four-point bending. The beams were varied in terms of the reinforcement ratio and diameter of rebars. The main goal of this paper was to investigate crack spacing and crack width of the beams. The results of experiments were compared with code formulations.

Keywords: BFRP bars, BFRP RC beams, cracking

Streszczenie

Bazaltowe pręty zbrojeniowe (BFRP) mogą być dobrą alternatywą dla klasycznej stali. Charakteryzują się one niskim modułem sprężystości, dlatego to SGU najczęściej decyduje o ostatecznej geometrii zginanego przekroju. W artykule przedstawiono wyniki badań laboratoryjnych zachowania się 6 belek zbrojonych prętami BFRP poddanych działaniu obciążenia statycznego. Głównym celem badań było określenie wpływu stopnia zbrojenia na rozstaw i szerokość rys. Rezultaty badań porównano z wynikami obliczeń teoretycznych.

Słowa kluczowe: zbrojenie bazaltowe BFRP, belki zbrojone BFRP, zarysowanie

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1. Introduction

Basalt fiber-reinforced polymer (BFRP) bars are a relatively new building material. On the one hand, this type of reinforcement has low modulus of elasticity and high tensile strength [1]. As a result deflections and cracking in BFRP reinforced concrete (RC) beams are larger than these found in traditional RC members [2]. Consequently, the design of BFRP RC flexural members is often governed by the serviceability limit states [3, 4]. On the other hand, BFRP bars have high corrosion resistance [5, 6]. Hence, building standards [7–9] for FRP RC structures allow relatively large crack widths of 0.5–0.7 mm.

The main aim of this study was to evaluate the crack widths in simply supported BFRP RC beams depending on the reinforcement ratio. This paper presents chosen results of a larger research programme in which 12 beams have been tested under static four-point bending. The results of experiments were compared with the results of theoretical analysis.

2. Experimental programme

Tests of 6 (3 pairs) simply supported BFRP RC beams subjected to four-point bending were carried out in the laboratory of the Institute of Structural Engineering at Poznan University of Technology. Three different amounts of BFRP reinforcement were used: 0.19% for beam BFRP 3#7, 0.32% for beam BFRP 3#9 and 0.52% for beam BFRP 5#9.

2.1. Test specimens

Fig. 1 illustrates the geometry and the reinforcement of test specimens. All the beams had a cross-section of 0.20 × 0.30 m^2, a total length of 3.05 m and a span of 2.70 m. The shear reinforcement consisted of 8 mm round steel stirrups placed at intervals of 100 mm.

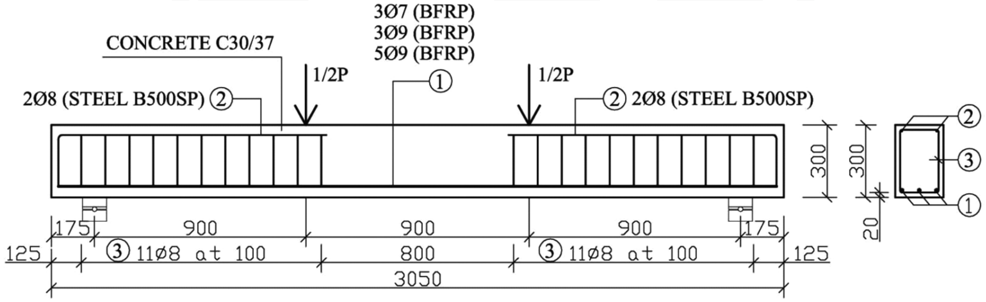

Fig. 1. Geometry and reinforcement of BFRP RC beams (dimensions in mm)

In the pure bending zone no stirrups were provided. Two 8 mm steel bars were used as top reinforcement to hold the stirrups. Reinforcing steel grade B500SP was used.

2.2. Materials properties

All the beams were made of C30/37 concrete. The properties of this material were evaluated from core samples taken from the beams after the tests had been carried out. BFRP ribbed bars were used as the flexural reinforcement. The experimentally determined mechanical properties of reinforcement [1] and concrete are shown in Table 1.

Table 1

Mechanical properties of concrete

Mechanical property	Material		
	concrete C30/37	reinforcement $\Phi = 7$ mm	reinforcement $\Phi = 9$ mm
Compressive strength $f_{ck,}$ MPa]	54.0	–	–
Modulus of elasticity E_{cm} [GPa]	38.450	–	–
Tensile strength f_{ctm} [MPa]	2.5	–	–
Age[days]	280	–	–
Equivalent diameter [mm]	–	6.7	8.7
Tensile strength f_u [MPa]	–	1185	1485
Modulus of elasticity E_f [GPa]	–	52.800	56.300
Ultimate strain ε_{fu} [‰]	–	22.5	26.2

3. Tests results

Detailed results of the tests are presented in the paper [10]. Table 2 shows the experimental maximum, average and minimum crack spacing measured in the pure bending zone at the height of the reinforcement. The crack spacing ranged between 35 and 223 mm. The average ratio minimum to average and maximum to average crack spacing is found to be 0.48 and 1.82, respectively. The load levels at which cracking stabilized were relatively high – they ranged between 45% and 80% of the ultimate load P_{max}. These values differ from those found in the literature [3, 11, 12].

Table 2

Experimental crack spacing and level at which cracking stabilizes

Beam designation	Maximum crack spacing $S_{r,max}$ [mm]	Average crack spacing S_{rm} [mm]	Minimum crack spacing $S_{r,min}$ [mm]	Force at which cracking stab. P_{sta} [% of P_{max}]
BFRP 3#7-1	180	107	55	56
BFRP 3#7-2	223	117	52	64
BFRP 3#9-1	151	88	43	45
BFRP 3#9-2	143	80	35	80
BFRP 5#9-1	178	93	45	73
BFRP 5#9-2	186	85	44	61

Table 3 presents the maximum crack widths at every load steps for all the beams. It is clear from the table that the reinforcement ratio has a considerable effect on the crack widths. For loads of 25-35 kN (loads for permissible deflections – equal to about L/250) the maximum crack widths were ca. 0.55 mm, 0.43 mm, 0.28 mm for BFRP 3#7, BFRP 3#9 and BFRP 5#9, respectively.

Table 3

Maximum crack width

Load [kN]	Maximum crack width w_{max} [mm]				
	BFRP 3#7-2	BFRP 3#9-1	BFRP 3#9-2	BFRP 5#9-1	BFRP 5#9-2
18	–	–	–	0.05	0.05
23	0.55	0.10	0.30	0.10	0.10
28	0.75	0.40	0.45	0.20	0.25
33	1.10	0.60	0.55	0.25	0.30
43	2.75	1.40	1.40	0.65	0.45
53	3.00	–	–	–	–
63	–	1.40	1.75	1.00	0.85
83	–	2.00	2.75	1.40	1.30

4. Theoretical analysis of crack widths

Table 4 presents four models for calculation the maximum crack widths of RC beams.

Table 4

Expressions for crack width

Expression	Procedure
$w_k = s_{rm}\left(\varepsilon_{sm} - \varepsilon_{cm}\right)$ (1) $s_{rm} = 3.4c + 0.425 k_1 k_2 \dfrac{\phi}{\rho_{p,eff}}$ (2) $\varepsilon_{\mathrm{sm}} - \varepsilon_{cm} = \dfrac{\sigma_s}{E_s} - \dfrac{k_t f_{ctm}\left(1+\alpha_e \rho_{p,eff}\right)}{E_s \rho_{p,eff}} \geq 0.6 \dfrac{\sigma_s}{E_s}$ (3)	EN 1992-1-1:2004 [13]
$w = 2 \dfrac{f_f}{E_f} \beta k_b \sqrt{d_c^2 + \left(\dfrac{s}{2}\right)^2}$ (4)	ACI 440.1R-06 [7]

$w = 2.2k_b \frac{f_{frp}}{E_{frp}} \beta \sqrt[3]{d_c A}$ (5)	ISIS Canada [14]
$w = k\left[4c + 0.7\left(c_f - \phi\right)\right]\frac{\sigma_f}{E_f}$ (6)	JSCE [9]

where w (w_k) is the maximum crack width, c is the concrete cover, k_1 is the bond coefficient (0.8 for high bond – assumed in the study, 1.6 for plain rebars), k_2 is the load coefficient (0.5 for bending, 1.0 for tension), Φ is a bar diameter, $\rho_{p,eff}$ is the effective reinforcement ratio, σ_s (σ_f) is the tensile stress in the reinforcement, E_s (E_f, E_{frp}) is the modulus of elasticity of the reinforcement, k_t is the load coefficient (1.0 for short-term loading, 0.5 for long-term loading), f_{ctm} is the mean value of the tensile strength of concrete, $\alpha_e = E_s/E_c$, f_f (f_{frp}) is the stress in the tension FRP reinforcement, k_b is the bond coefficient (1.0 for FRP bars with bond properties similar to steel, > 1.0 for bars with inferior bond behavior, <1.0 for bars with superior bond behavior, 1.4(ACI), 1.2(ISIS) in the absence of significant test data – assumed in the study), d_c is the concrete cover measured from the centroid of tension reinforcement to the extreme tension surface, s (c_f) is a bar spacing, $\beta = h_2/h_1$ where h_2 is the distance from the extreme tension surface to the neutral axis, h_1 is the distance from the centroid of tension reinforcement to the neutral axis, A is the effective tension area of concrete, k is the bond coefficient (1.0~1.30, 1.0 – assumed in the study).

Figs. 2-4 show experimental and theoretical load – maximum crack widths curves for beam BFRP 5#9, BFRP 3#9 and BFRP 3#7, respectively. Comparing theoretical predictions with the results of experimental tests (table 5), it can be observed that all the analytical approaches tend to significant overestimate the crack widths up to the load about $P = 2.5P_{cr}$ (P_{cr}~18 kN). For higher loads they move closer to the experimental data. Crack widths calculated according to EC2 [13] and ACI [7] present better estimate to the results of experiments than JSCE [9] and ISIS [14]. All the prediction models give better results for the bond coefficient k similar to that of steel reinforcement.

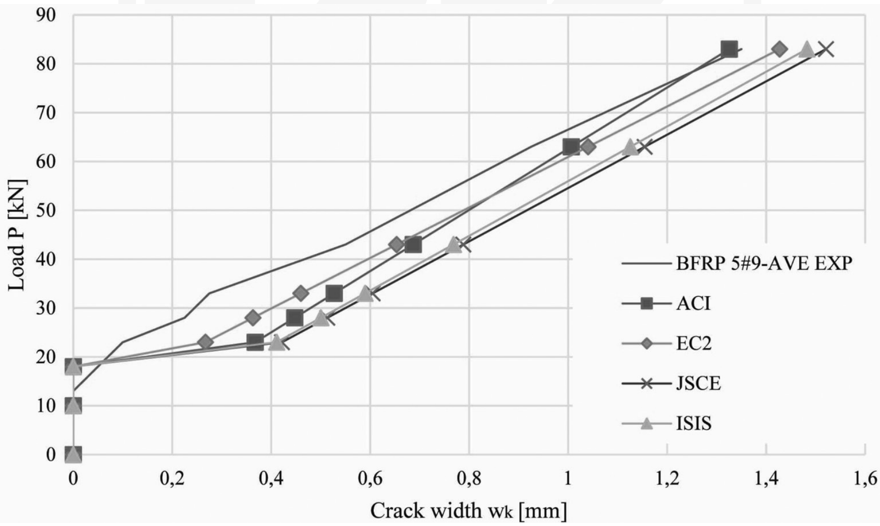

Fig. 2. Experimental vs. theoretical load – crack widths of BFRP 5#9

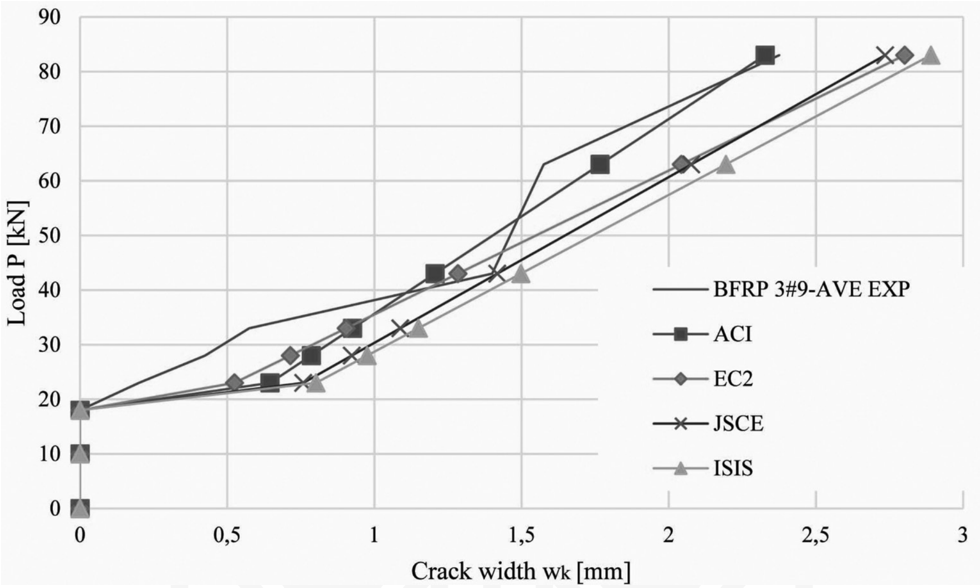

Fig. 3. Experimental vs. theoretical load – crack widths of BFRP 3#9

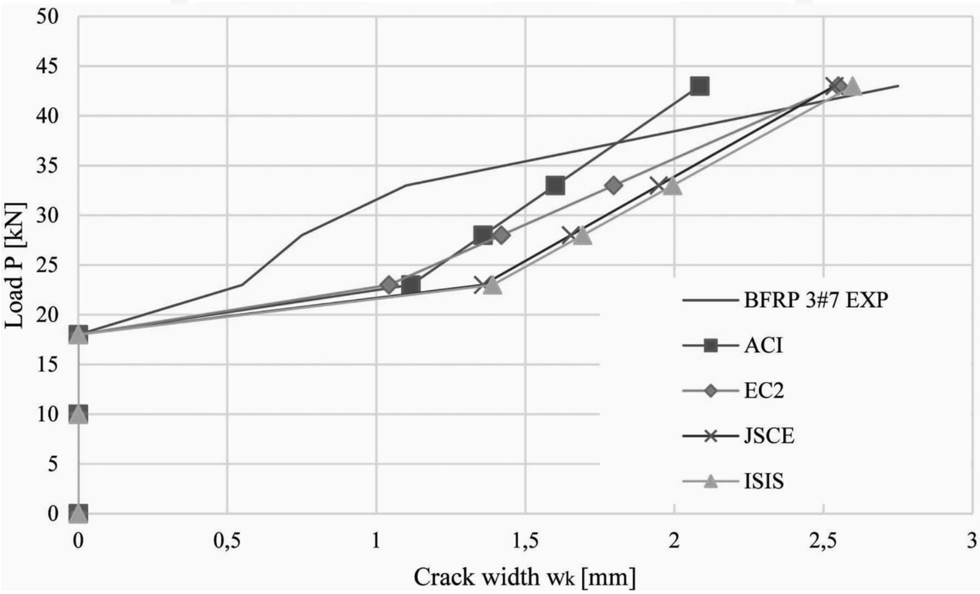

Fig. 4. Experimental vs. theoretical load – crack widths of BFRP 3#7

Table 5

Ratios w_{th}/w_{exp} for BFRP 3#7, BFRP 3#9 and BFRP 5#9

Load [kN]	Ratio w_{th}/w_{exp}											
	BFRP 3#7-2				BFRP 3#9-1 AVE				BFRP 5#9-1 AVE			
	EC2	ACI	ISIS	JSCE	EC2	ACI	ISIS	JSCE	EC2	ACI	ISIS	JSCE
23	1.90	2.03	2.53	2.47	2.62	3.23	4.01	3.79	2.67	3.68	4.11	4.22
28	1.89	1.81	2.26	2.20	1.68	1.85	2.30	2.17	1.61	1.99	2.22	2.28
33	1.63	1.45	1.81	1.77	1.57	1.61	2.00	1.89	1.67	1.92	2.14	2.20
43	0.93	0.76	0.94	0.92	0.92	0.86	1.07	1.01	1.19	1.25	1.40	1.43
63	–	–	–	–	1.30	1.12	1.39	1.32	1.12	1.09	1.22	1.25
83	–	–	–	–	1.18	0.98	1.22	1.15	1.06	0.98	1.10	1.13

5. Conclusions

This paper presents the results of an experimental and theoretical study of the flexural behaviour of BFRP RC beams. Based on these results, the following conclusions may be drawn:

- The reinforcement ratio has a significant effect on the crack widths of BFRP RC beams. An increase in the reinforcement ratio results in a decrease in the crack widths.
- The load levels at which cracking stabilize range between 45% and 80% of the ultimate load. These values are higher than those obtained for traditional RC members.
- The average ratio maximum to mean crack spacing equals 1.86 and the average ratio minimum to mean values is 0.48. The first value is higher and the second one is lower than those found in the literature.
- Crack widths for loads for permissible deflections (equal to about L/250) of the beams are lower than the maximum allowed ones (0.7 mm).
- Crack widths calculated according to EC2, ACI, JSCE and ISIS are significantly overestimated up to the load P=2.5P_{cr}. For higher loads they move closer to the experimental data.

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