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AN EXPERIMENTAL AND THEORETICAL STUDY OF DEFLECTIONS OF BFRP RC BEAMS

UGIĘCIA BELEK ZBROJONYCH PRĘTAMI BAZALTOWYMI BFRP – BADANIA LABORATORYJNE I ROZWAŻANIA TEORETYCZNE

Abstract

Basalt fiber-reinforced polymer (BFRP) bars are a new material used in reinforced concrete (RC) structures. They present such properties as high tensile strength, low modulus of elasticity and shear strength. Due to these mechanical properties, flexural behavior of BFRP RC elements is significantly different to that of traditional steel RC. This paper presents the results of an experimental and theoretical study of the short-term flexural behaviour of a series of simply supported BFRP RC beams. The beams were tested under four-point bending. The main objective of this paper was to investigate deflections of the beams depending on reinforcement ratio. The results of experiments were compared with code formulations and prediction models.

Keywords: composite materials, BFRP bars, BFRP RC beams, deflections

Streszczenie

Bazaltowe pręty zbrojeniowe (BFRP) są stosunkowo nowym materiałem stosowanym w budownictwie. Charakteryzują się one wysoką wytrzymałością na rozciąganie, niskim modułem sprężystości oraz niską wytrzymałością na ścinanie. W artykule przedstawiono wyniki badań laboratoryjnych zachowania się belek zbrojonych prętami BFRP poddanych działaniu obciążenia statycznego. Głównym celem badań było określenie wpływu stopnia zbrojenia na ugięcia zginanych elementów. Rezultaty badań porównano z wynikami obliczeń teoretycznych.

Słowa kluczowe: materiały kompozytowe, zbrojenie bazaltowe, belki zbrojone BFRP, ugięcia

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1. Introduction

Fiber-reinforced polymer (FRP) bars present such properties as corrosion resistance, electromagnetic neutrality, light weight and high cutability [1, 2]. As a result they can be a good alternative to traditional steel for reinforced concrete (RC) elements, especially used in aggressive environments (e.g. offshore constructions, bridges), when electromagnetic neutrality is needed, or in temporary structures.

Basalt fiber-reinforced polymer (BFRP) bars are a relatively new type of FRP reinforcement. They have low modulus of elasticity and high tensile strength [3]. Moreover, they do not present any yielding before failure and behave almost linearly up to tensile rupture. Due to their mechanical properties, deflections and cracking in BFRP RC beams are larger than these found in traditional RC members [4]. Consequently, the design of BFRP RC flexural members is often governed by the serviceability limit states [5, 6].

The main aim of this study was to evaluate the stiffness of 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.

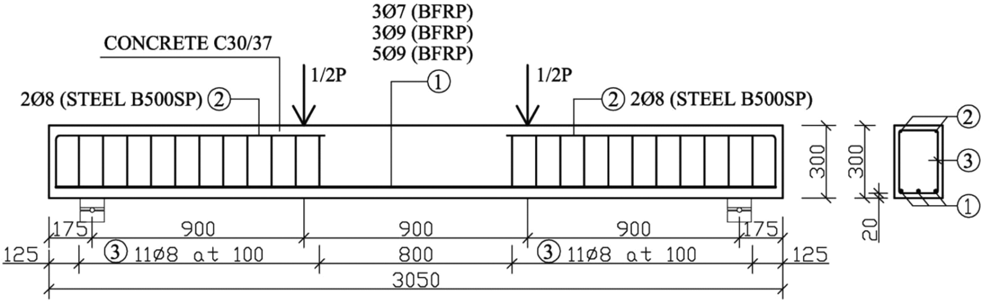

Fig. 1. Geometry and reinforcement of BFRP RC beams (dimensions in mm)

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

2.2.1. Concrete

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. Table 1 presents the mechanical properties of concrete.

Table 1

Mechanical properties of concrete

Compressive strength $f_{ck,}$ [MPa]	Modulus of elasticity E_{cm} [GPa]	Tensile strength f_{ctm} [MPa]	Age [days]
54.0	38.450	2.7	280

2.2.2. BFRP bars

BFRP ribbed bars were used as the flexural reinforcement. The experimentally determined mechanical properties of reinforcement [3] are shown in Table 2. According to the results of experiments [7, 8] the bond strength of these rebars is similar to that of steel bars.

Table 2

Mechanical properties of BFRP bars

Equivalent diameter [mm]	Tensile strength f_u [MPa]	Modulus of elasticity E_f [GPa]	Ultimate strain ε_{fu} [‰]
6.7	1185	52.800	22.5
8.7	1485	56.300	26.2

More details of the experiments (instrumentation and test procedure) are presented in the paper [9].

3. Tests results

Fig. 2 shows evolution of the concrete strain along the depth of the section of beam BFRP 5#9 for different load levels. As can be observed in this figure, the neutral axis before cracking is located at the mid-height of the section. After cracking the neutral axis depth increases and then its value is constant.

Fig. 3 shows load – midspan deflection curves for all considered elements. All the beams behaved almost linearly until failure. This is the result of the mechanical properties of BFRP bars, which present a linear elastic behaviour under tensile loading. Because of the low modulus of elasticity of BFRP reinforcement, ultimate deflections of the beams were more than six times greater than these permissible (SLS graph in Fig. 2 – deflection limit = L/250).

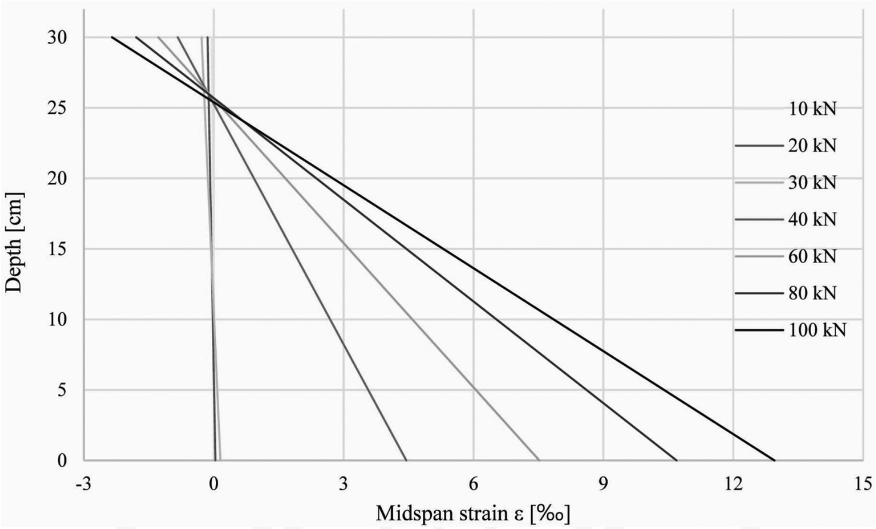

Fig. 2. Strain along midspan depth of beam BFRP 5#9

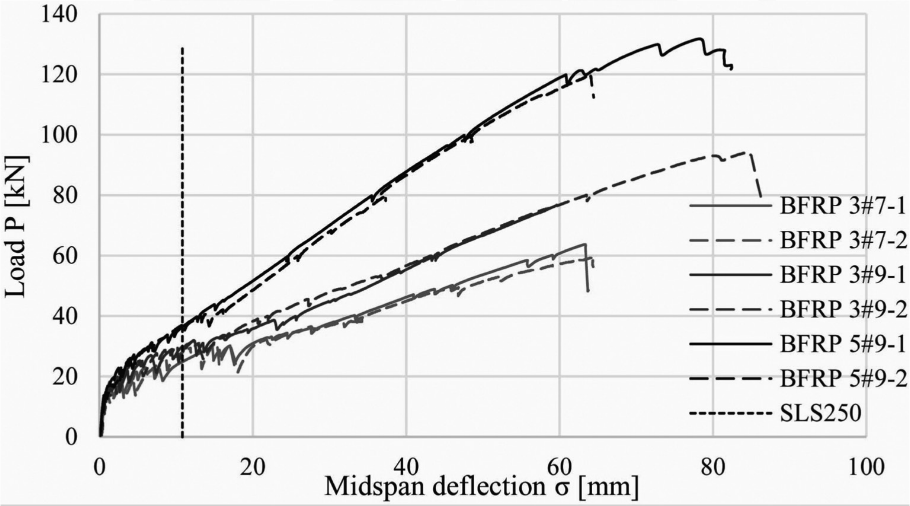

Fig. 3. Experimental load – midspan deflections

It is clear from Fig. 3 that the reinforcement ratio had a considerable effect on the stiffness of the beams. Loads for permissible deflections (equal to about L/250) of the beams were about 28%, 36% and 39% of the limit loads for BFRP 5#9, BFRP 3#9 and BFRP 3#7, respectively. These values correspond well with the values obtained for RC elements with other types of FRP reinforcement [5, 10, 11].

4. Theoretical analysis of deflections

Table 3 presents seven models for calculation deflections of BFRP RC beams.

Table 3

Expressions for the effective moment of inertia/deflections of FRP RC beams

Expression	Procedure
$\delta_{\max} = \left[1-\left(\frac{M_{cr}}{M_a}\right)^2\right]\delta_2 + \left[1-\left(1-\left(\frac{M_{cr}}{M_a}\right)^2\right)\right]\delta_1 \quad (1)$	EN 1992-1-1:2004 [12]
$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d I_g + \left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \le I_g \quad (2)$ $\beta_d = \frac{1}{5}\frac{\rho_f}{\rho_{fb}} \le 1 \quad (3)$	ACI 440.1R-06 [13, 14]
$I_e = \frac{I_T I_{cr}}{I_{cr} + \left[1-0.5\left(\frac{M_{cr}}{M_a}\right)^2\left(I_T - I_{cr}\right)\right]} \quad (4)$	ISIS Canada [15]
$\delta_{\max} = \frac{P \cdot L_a}{48 E_c \cdot I_{cr}}\left[3L^2 - 4L_a^2 - 8\left(1-\frac{I_{cr}}{I_g}\right)\left(\frac{M_{cr}}{M_a}\right)^3 \cdot L_a^2\right] \quad (5)$	CSA S806-02 [16, 17]
$I_e = \frac{I_{cr}}{1-\left(1-\left(\frac{I_{cr}}{I_g}\right)\right)\left(\frac{M_{cr}}{M_a}\right)^2} \quad (6)$	Bischoff [18]

$I_e = \dfrac{I_{cr}}{1-\left(1-\left(\dfrac{I_{cr}}{I_g}\right)\right)\left(\dfrac{M_{cr}}{M_a}\right)^2}$ (7) $\gamma = \dfrac{3\left(\dfrac{L_a}{L}\right)-4\left[4\left(\dfrac{M_{cr}}{M_a}\right)-3\right]\left(\dfrac{L_a}{L}\right)^3}{3\left(\dfrac{L_a}{L}\right)-4\left(\dfrac{L_a}{L}\right)^3}$ (8)	Bischoff and Gross [19]
$I_m = \dfrac{23 I_e I_{cr}}{8 I_{cr} + 15 I_e}$ (9)	Faza and GangaRao [20]

where M_{cr} is the cracking moment, M_a is maximum service moment, d_1 is uncracked-state deflection, d_2 is fully cracked-state deflection, I_e is the effective moment of inertia, I_g is the moment of inertia of gross section, I_{cr} is the moment of inertia of the cracked transformed section, ρ_f is the reinforcement ratio, ρ_{fb} is the balanced reinforcement ratio, I_T is the moment of inertia for uncracked section, P is the total force acting on the tested beam, L is the span of the beam, L_a is the distance from the force to the support of the beam, E_c is the modulus of elasticity of concrete.

Figs. 4 and 5 show experimental and theoretical load-deflection curves for beam BFRP 5#9. Comparing theoretical predictions obtained based on Eq. (1), Eq. (6) and Eq. (7), with the results of experimental tests, it can be observed that up to the service load (deflection σ<L/250) there is good agreement between theoretical and actual values of deflections. Deflections calculated according to ACI (Eq. 2) are underestimated, whereas deflections calculated according ISIS (Eq. 4), CSA (Eq. 5) and Faza and GangaRao (Eq. 9) are overestimated up to the service load. For higher loads all the theoretical approaches underestimate deflections.

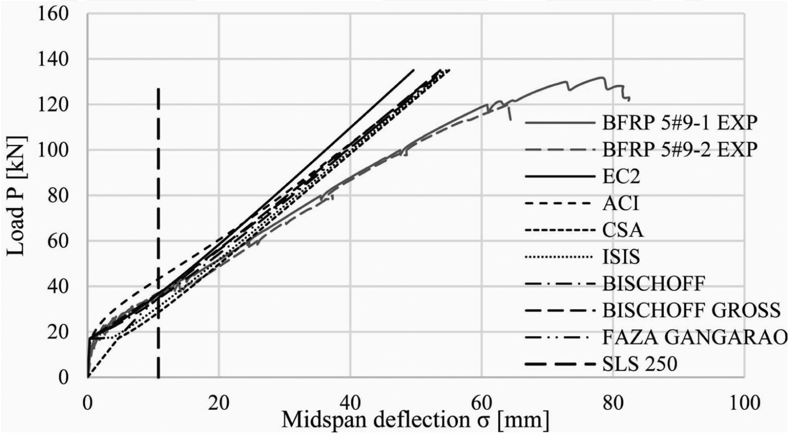

Fig. 4. Experimental vs. theoretical load – midspan deflections of BFRP 5#9

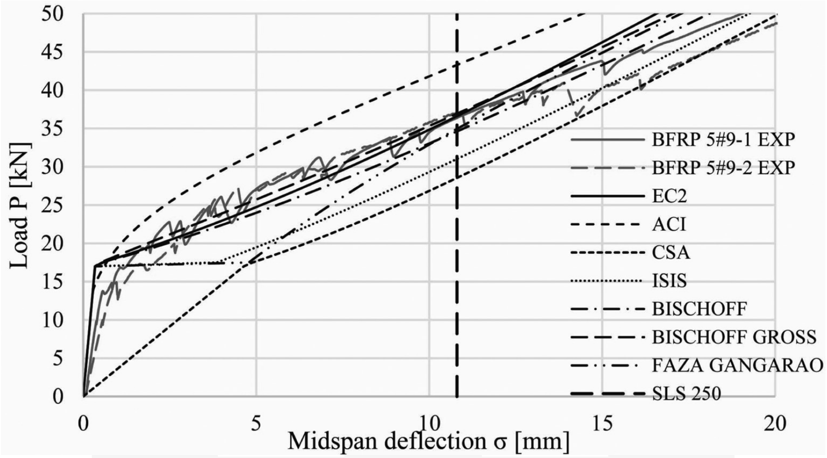

Fig. 5. Experimental vs. theoretical load – midspan deflections of BFRP 5#9 for loads less than service load

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:

- Due to the mechanical properties of BFRP bars, the beams behave almost linearly until failure, which takes place at relatively large deflections.
- Design of the beams is governed by the serviceability limit states.
- At the service load level, deflections calculated according to Eurocode 2 and Bischoff approaches are in close agreement with the results of the experiments. For higher loads these approaches underestimate deflections.
- Deflections calculated according to ACI are underestimated, whereas deflections calculated according to ISIS, CSA and Faza and GangaRao are overestimated up to the service load. For higher loads these theoretical approaches underestimate deflections.

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