TECHNICAL TRANSACTIONS 11/2018
MECHANICS

DOI: 10.4467/2353737XCT.18.170.9426
SUBMISSION OF THE FINAL VERSION: 29/10/2018

Kinga Brózda
Jacek Selejdak
kbrozda@bud.pcz.pl
Department of Concrete Structures and Geotechnics, Faculty of Civil Engineering, Czestochowa University of Technology

Peter Koteš
Department of Structures and Bridges, Faculty of Civil Engineering, University of Žilina

Analysis of the crack width of beams reinforced with FRP bars

Analiza zarysowania belek zbrojonych prętami FRP

Abstract

The paper investigates and compares a selected issue of Serviceability Limit State (SLS) of simply supported reinforced concrete (RC) beams subjected to various values of flexural stresses. Characteristic crack widths of beams reinforced with various types of bars were calculated. Beams reinforced with Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP) and Aramid Fiber Reinforced Polymer (AFRP) were examined. The computational analysis of beams reinforced with FRP bars was based on Italian guideline for the design (CNR-DT 203/2006) and in accordance with the EC2 (EN 1992-1-1:2004). Based on the conducted analysis, the effect of changing the service live load on the increase in crack width was presented.

Keywords: FRP reinforcement, RC beam, crack width, design recommendations, CNR-DT 203/2006

Streszczenie

W artykule omówiono i porównano wybrane zagadnienie Stanu Granicznego Użytkowalności (SLS) swobodnie podpartej jednoprzęsłowej zbrojonej belki betonowej, poddanej różnym wartościom naprężeń zginających. W celu przeprowadzenia analizy dokonano obliczeń szerokości rozwarcia rys prostopadłych do osi belek zbrojonych prętami kompozytowymi. Do obliczeń przyjęto pręty zbrojeniowe polimerowe wzmocnione włóknem szklanym (GFRP –*Glass Fiber Reinforced Polymer*), węglowym (CFRP – C*arbon Fiber Reinforced Polymer*) oraz aramidowym (AFRP – *Aramid Fiber Reinforced Polymer*). Obliczenia wytrzymałościowe belek zbrojonych prętami FRP (*Fiber Reinforced Polymer*) wykonano zgodnie z włoskimi zaleceniami projektowymi (CNR-DT 203/2006) oraz w oparciu o obowiązującą normę europejską Eurokod 2 (PN-EN 1992-1-1:2008). Na podstawie przeprowadzonej analizy przedstawiono wpływ zmiany obciążenia użytkowego na wzrost szerokości rozwarcia rysy.

Słowa kluczowe: zbrojenie FRP, belka zbrojona, szerokość rozwarcia rysy, zalecenia projektowe, CNR-DT 203/2006

1. Introduction

Recently, an increased interest in the use of the fiber reinforced polymer (FRP) materials in building and engineering structures can be observed [1–4]. Among other things, the use of FRP rebar as the main reinforcement of concrete structures is increasingly common. This interest arises due to very good physical and mechanical characteristics of this material. Especially, low self-weight, good fatigue properties (parallel to the fibers orientation) due to the production method (pultrusion) [5, 6], very high resistance to the impact of aggressive environmental factors and high corrosion resistance generate intensified research of possibility to use FRP bars [1–3, 7–11]. Such material characteristics of a FRP rebar as strength and stiffness properties depend on the type of used fiber. There are FRP bars reinforced with the following types of fibers [2]: glass (GFRP), carbon (CFRP), aramid (AFRP) and basalt (BFRP).

The main purpose of this paper is to determine the possibility of using FRP reinforcement. Accordingly, a computational analysis of simply supported reinforced concrete beams affected by various values of flexural stresses was performed. The analysis consists in the comparison of results obtained for RC beams reinforced with FRP rebars. During the research, crack widths were taken into consideration. The results of the analysis allow for the specification of the most effective reinforcement under assumed conditions.

2. Computational analysis

It is worth noting that there is no available standard for strength calculations of sections reinforced with FRP rebars [11–13]. As a result of long-term experience of many researchers and designers, guidelines for the design of structural elements reinforced with FRP bars were elaborated. Among the available recommendations for design, four most popular guidelines could be distinguished: the Italian [14], the American [15], the Canadian [16] and the Japanese ones [17]. These design recommendations have been developed on the basis of analytical solutions and empirical equations, which are supported by experimental tests carried out on FRP bar samples and structural RC elements reinforced with FRP rebars [1–4, 12, 13]. The computational analysis of beams was made on the basis of applicable standards and design recommendations.

2.1. Calculation model

Simply supported beams with a rectangular cross-section were assumed. The outline of the static scheme and cross-section of the investigated beams are presented in Fig. 1. The dimensions of the cross-section are the following: b = 180 mm, h = 350 mm, and the effective length of the span is L_{eff} = 4.0 m. The beams are reinforced with 3Φ12 of the following bars: CFRP, ARFP and GFRP. The used concrete is specified by C20/25 compressive strength class and the concrete cover thickness is assumed as c = 35 mm. The material characteristics of concrete were as follows: the characteristic compressive strength f_{ck} = 20 MPa, the mean value of axial tensile strength of concrete f_{ctm} = 2.2 MPa, the ultimate compressive strain in the concrete ε_{cu} = 0.0035 and the modulus of elasticity of normal weight concrete E_{cm} = $30 \cdot 10^3$ MPa. The strength properties of the rebar are reported in accordance with the bar manufacturer's material data [18, 19]. The beam is designed to carry a service dead load equal to w_{SDL} = 3.0 kN/m and a various value of a service live load equal to w_L = {0.5; 2.0; 3.5; 5.0; 6.5; 8.0; 9.5; 11.0} kN/m. The limitation of the crack widths is assumed as $w_{k.,lim}$ = 0.4 mm, in accordance with the EC2 standard [20]. The beam is not exposed to the moisture.

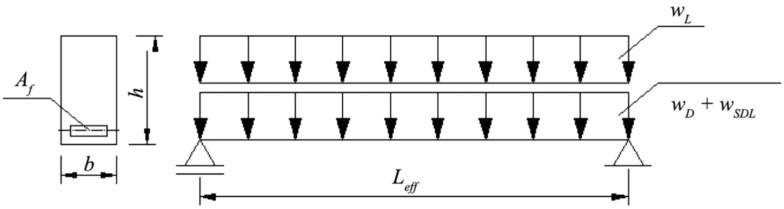

Fig. 1. The outline of the static scheme and cross-section of the investigated beams

2.2. Calculation method

The calculation method of beams reinforced with FRP was chosen in accordance with the Italian design recommendations [14], because of similarity thereof to the EC2 [20]. The material characteristics and environmental conversion factors of FRPs are specified by the manufacturer [18, 19] and shown in Table 1.

Table 1. The FRP's material characteristics

Type of rebar	The characteristic tensile strength of FRP f_{tk} [MPa]	The modulus of elasticity of FRP E_f [MPa]	The design strain of FRP ε_{fd} [–]	The environmental conversion factor η_a [–]
CFRP	2 300	$130 \cdot 10^3$	0.018	1.0
AFRP	1 400	$60 \cdot 10^3$	0.023	0.9
GFRP	1 300	$55 \cdot 10^3$	0.022	0.8

The characteristic crack widths w_k [mm] of the FRP reinforced element were calculated according to the Italian guidelines [14] using the following equation:

(1)

and compared with the ultimate value of the crack widths $w_{k.,lim}$. The non-dimensional coefficient β is relating the average crack width to the characteristic value and is assumed according to the design recommendation [14]. The final average distance between cracks s_{rm} [mm] was calculated using Eq. 2. It depends on bond properties of the FRP bars (non-dimensional coefficient k_1) and the strain diagram (non-dimensional coefficient k_2). The suitability of the relationships provided by the EC2 standard [20] for computations of the distance between cracks was assumed.

$$s_{rm} = 50 + 0.25 \cdot k_1 \cdot k_2 \cdot \frac{d_b}{\rho_r} \tag{2}$$

where:

d_b – the equivalent diameter of the FRP reinforcement, in mm;

ρ_r – the effective reinforcement ratio, equal to $\frac{A_f}{A_{c,eff}}$, where $A_{c,eff}$ is the effective concrete area in tension defined according to the EC2 standard [20] (the area around the tensile FRP reinforcement, which has a depth equal to the distance between FRP's centroid and tension fiber of concrete multiplied by 2.5).

The average strain accounting for tension stiffening, shrinkage, etc. is defined by ε_{fm} (Eq. 3). It depends on non-dimensional coefficients β_1 (accounting for bond properties of FRPs) and β_2 (accounting for the duration of loading).

$$\varepsilon_{fm} = \varepsilon_f \cdot \left(1 - \beta_1 \cdot \beta_2 \cdot \frac{\sigma_{fr}^m}{\sigma_f^m}\right) \tag{3}$$

where:

ε_f – the strain of FRP reinforcement;

σ_f – the FRP reinforcement stress in tension of the cracked cross-section, in MPa;

σ_{fr} – the FRP reinforcement stress in tension of the cracked cross-section (when the first crack is observed), in MPa;

m – the coefficient, which equals 2.

2.3. The results of the analysis

The results of the characteristic crack widths w_k of the beams obtained during the theoretical analysis were compared in Table 2.

Table 2. The results of crack widths w_k depending on the type of rebar and live load level w_L

The live load level w_L [kN/m]	**0.5**	**2.0**	**3.5**	**5.0**	**6.5**	**8.0**	**9.5**	**11.0**
Type of rebar	w_k [mm]							
CFRP	0.006	0.182	0.259	0.299	0.322	0.337	0.347	0.355
AFRP	0.025	0.753	1.069	1.235	1.332	1.394	1.436	1.465
GFRP	0.034	1.020	1.448	1.673	1.804	1.888	1.945	1.985

Assuming that the limitation of the crack widths equals 0.4 mm, only beams reinforced with CFRP bars satisfied the condition. The beams reinforced with AFRP and GFRP bars

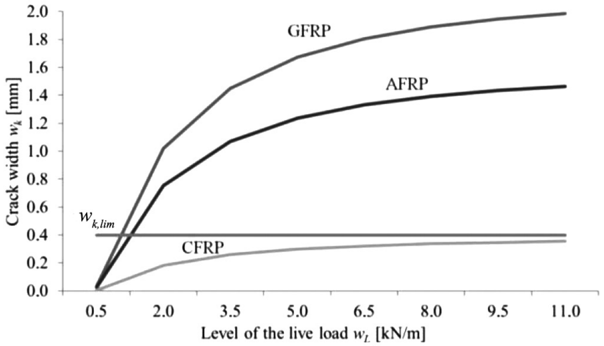

Fig. 2. The increase in value of the crack widths depends on the acting level of live load

exceed the limit value already at live load level equal to w_L = 2.0 kN/m. The reason of this phenomena is low values of modulus of elasticity of polymer rebar (AFRP and GFRP). The modulus of elasticity of CFRP is about two times higher than the ones of the other FRPs.

Interestingly, the increase in crack width of the beams reinforced with FRP seems to change as the logarithmical function. It means that the crack width growth at the initial load increase is more dynamic.

3. Summary

In this paper, an attempt to determine the most effective FRP reinforcement of a RC beam under assumed conditions was made. The characteristic crack widths which depend on the various level of service live load were calculated and compared. The calculations were done in accordance with the applicable standards and design recommendations [14-17, 20].

As it was suspected, during the computational analysis it was observed that the value of modulus of elasticity of the FRPs has the greatest impact on the growth of crack widths. Only beams reinforced with CFRP bars satisfy the condition of crack width limitations. It was noticed that the crack widths growth increased logarithmically as far as the intensity level of the acting live load increased. This is interesting due to the fact that in the case of steel reinforcement, as indicated by calculations made in accordance with EC2 [20], the crack width increased linearly. The obtained results will allow us to understand the flexural behavior of FRP RC members within SLS. In order to fully determine the effectiveness of FRP reinforcement under the SLS, further analysis is recommended.

References

[1] Brózda K., Major M., Selejdak J., *Computational Analysis of Serviceability Limit State of Beams Reinforced with FRP Bars*, 23th International Conference Engineering Mechanics, Svratka, 15–18 May 2017, 218–221.

[2] Brózda K., Selejdak J., Koteš P., *The Analysis of Beam Reinforced with FRP Bars in Bending*, Procedia Engineering, vol. 192, 2016, 64–68.
[3] Bywalski C., Drzazga M., Kamiński M., *Obliczanie zginanych elementach zbrojonych prętami FRP*, Materiały budowlane, vol. 6, 2014, 72–73.
[4] Drzazga M., Kamiński M., *Pręty kompozytowe FRP jako główne zbrojenie zginanych elementów betonowych – przegląd zaleceń i efektywność projektowania*, Przegląd budowlany, vol. 3, 2015, 22–28.
[5] Brózda K., Selejdak J., *Analysis of FRP Bars Used as Reinforcement in Concrete Structures*, Production Engineering Archives, vol. 12(3), 2016, 2–4.
[6] Ulewicz R., Mazur M., *Fatigue testing structural steel as a factor of safety of technical facilities maintenance*, Production Engineering Archives, vol. 1(1), 2013, 32–34.
[7] Selejdak J., Ulewicz R., Ingaldi M., *The Evaluation of the Use of a Device for Producing Metal Elements Applied in Civil Engineering*, 23rd International Conference on Metallurgy and Materials, Brno, 21–23 May 2014, 1882–1888.
[8] Lipinski T., *Corrosion effect of 20 % NaCl solution on basic carbon structural S235JR steel*, 16th International Scientific Conference Engineering for Rural Development, Jelgava, 24–26 May 2017, 1069–1074.
[9] Pliszka I., Radek N., *Corrosion Resistance of WC–Cu Coatings Produced by Electrospark Deposition*, Procedia Engineering, vol. 192, 2017, 707–712.
[10] Szczotok A., Nawrocki J., Pietraszek J., *The Impact of the Thickness of the Ceramic Shell Mould on the $(\gamma + \gamma')$ Eutectic in the IN713C Superalloy Airfoil Blade Casting*, Archives of Metallurgy and Materials, vol. 62(2), 2017, 587–593.
[11] Barris C., Torres L., Miàs C., Vilanova I., *Design of FRP reinforced concrete beams for serviceability requirements*, Journal of Civil Engineering and Management, vol. 18(6), 2012, 843–857.
[12] Gravina R.J., Smith S.T., *Flexural behavior of indeterminate concrete beams reinforced with FRP bars*, Engineering Structures, vol. 30, 2008, 2370–2380.
[13] Toutanji H., Deng Y., *Deflection and crack–width prediction of concrete beams reinforced with glass FRP rods*, Construction and Building Materials, vol. 17, 2003, 69–74.
[14] CNR-DT 203/2006. Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars.
[15] ACI 440.1R-06. Guide for the design and construction of concrete reinforced with FRP bars.
[16] CSA-S806-02. Design and Construction of Building Components with Fibre Reinforced Polymers.
[17] JSCE, Recommendation for design and construction of concrete structures using continuous fiber reinforcing materials, Concrete Engineering Series No. 23, 1997.
[18] Polprek Sp. z o.o. product data sheet, available at: www. polprek.pl (22.12.2016).
[19] Sireg Geotech S.r.l. product data sheet, available at: www.sireggeotech.it/en (22.12.2016).
[20] EN 1992-1-1:2004. Design of concrete structures. General rules and rules for buildings.

If you want to quote this article, its proper bibliographic entry is as follow: Brózda K., Selejdak J., Koteš P., *Analysis of the crack width of beams reinforced with FRP bars*, Technical Transactions, Vol. 11/2018, pp. 163–168.