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STRUCTURAL RESPONSE OF REINFORCED CONCRETE BEAMS STRENGTHENED IN FLEXURE WITH NEAR SURFACE MOUNTED FIBRE REINFORCED POLYMER COMPOSITE STRIPS
EXPERIMENTAL RESULTS

BY

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Abstract. This paper presents the results obtained from a series of tests performed on reinforced concrete (RC) beams strengthened in flexure with near surface mounted (NSM) carbon fibre reinforced polymer (CFRP) composite strips. In order to determine the overall stiffness and flexural capacity of the strengthened specimens, four-point bending tests were carried out under monotonic loading. For the beam strengthened with two CFRP strips, with the cross section of 1.2 × 18 mm, an increase in the load carrying capacity of 164% and a reduction of the deflection up to 12% was achieved, in comparison with the reference beam. For the specimens strengthened with three CFRP strips, with the cross section of 1.2 × 12 mm and 1.2 × 24 mm, an increase of the bearing capacity of 158% and 202% is obtained, in comparison with the control specimen. Failure mode for all the tested beams occurred by debonding in the form of concrete cover separation (CCS).

Key words: reinforced concrete; near surface mounted; carbon fibre reinforced polymer; concrete cover separation.

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1. Introduction

Over the past three decades, the CFRP composites have been used in the flexural strengthening of RC structures, due to the fact that they offer significant advantages when compared to conventional materials like steel. These benefits include high tensile strength to weight ratio, better resistance to corrosion and easy application.

In order to increase the flexural resistance of RC structural elements, the CFRP laminates are generally applied on the faces of the elements, according to the so called *externally bonded reinforcement technique*. The research work carried out until now has revealed the fact that mobilizing the full tensile strength of the FRP material is almost impossible, mainly due to their premature debonding. To overcome this drawback, many attempts have been made in order to conceive new strengthening techniques (NSM) for RC structural elements based on FRP composites (Hollaway *et al.*, 2008). The NSM FRP strengthening technique involves bonding FRP bars/strips, with an appropriate binding agent (epoxy paste or cement grout), into pre-cut grooves in the concrete cover of the structural elements to be strengthened (Barros *et al.*, 2005).

In order to assess the effectiveness of the NSM technique for the flexural strengthening of RC beams, an experimental program was carried out. In this paper the strengthening procedure and the results of the flexural tests are presented and discussed.

2. Experimental Program

To appraise the effectiveness of the NSM technique, four-point bending tests were carried out under monotonic loading on four RC beams (A1, B1, C1, D1) with a length of 3000 mm and a rectangular cross section of 200 × 300 mm (Ciobanu *et al.*, 2012). The geometric characteristics of the unstrengthened beams are presented in Fig. 1.

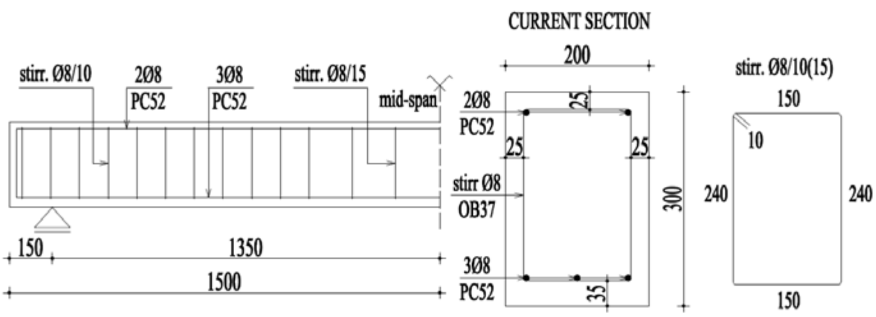

Fig. 1 – Geometric characteristics of the beams, [mm].

The tension and compression reinforcements used are steel bars with 8 mm diameter. The transverse reinforcement consists of steel stirrups of 8 mm diameter with 100/150 mm spacing, in order to avoid shear failure. The thickness of the concrete cover is 25 mm on the lateral and upper faces of the beams and 35 mm on the bottom one.

The concrete compressive strength of 47.6 MPa was determined as the average strength of three values obtained on cube specimens, taken during the pouring of concrete into the beams formworks. The longitudinal steel reinforcement (PC52) and the shear reinforcement (OB37) have the yield strength of 355 MPa and 255 MPa, respectively.

During the experimental program, the NSM strengthening technique was used for the strengthening of the RC specimens. Slits of 5 mm width and 15/25/30 mm depth were cut in the concrete cover on the tension face of the beams with a diamond blade cutter, and were then cleaned with compressed air to remove dust and debris (Fig. 2).

Fig. 2 – Slits preparation

Each groove was filled halfway with epoxy adhesive, prepared according to the supplier recommendations. The CFRP strips were mounted into slits and the excess epoxy adhesive was removed as shown in Fig. 3.

The unidirectional CFRP laminates (Carboplate E170) used for the strengthening of the RC specimens have the ultimate tensile strength equal to 3100 MPa and the modulus of elasticity equal to 170 GPa. The adhesive is a two component product (Adesilex PG1) based on epoxy resin, selected fine-grain aggregates and special additives according to a formula developed by the producing company. In order to enhance the adherence between concrete and FRP composites, a primer (MapeWrap Primer1) was used.

The geometric characteristics of the beams tested during the experimental program are presented in Fig. 4.

Fig. 3 – Applying of the CFRP strips.

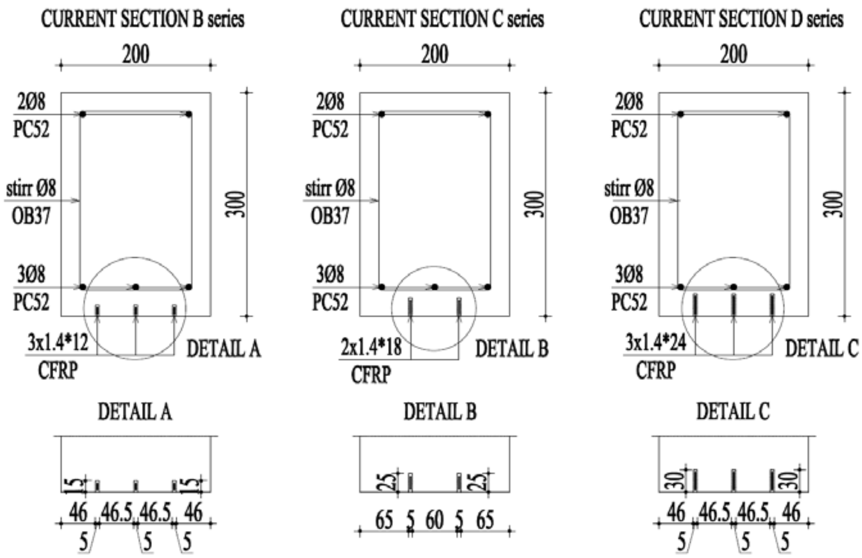

Fig. 4 – Geometric characteristics of the beams B1, C1, D1, [mm].

The beams B1, C1 and D1 were strengthened with CFRP strips having the dimensions 1.4 × 12 mm, 1.4 × 18 mm and 1.4 × 24 mm, respectively. The FRP laminates were placed into 5 mm wide and 15/25 /35 mm deep grooves on the bottom side of the beams. Beam A1 was tested without any strengthening in order to be used as a control specimen.

Table 1 presents the main geometric characteristics the tested beams.

Table 1
Geometric Properties of Tested Beams

Beams	b mm	h mm	L mm	A_s mm^2	A_{s2} mm^2	A_f mm^2	ρ_s %	ρ_{s2} %	ρ_{eq} %
A1	200	300	3,000	150.72	100.48	–	0.3	0.19	–
B1	200	300	3,000	150.72	100.48	50.4	0.3	0.19	0.3714
C1	200	300	3,000	150.72	100.48	50.4	0.3	0.19	0.3714
D1	200	300	3,000	150.72	100.48	100.8	0.3	0.19	0.44

The following parameters for the beams were used in Table 1: b – width of the cross section, [mm]; h – height of the cross section, [mm]; d – effective depth of the concrete transversal section, [mm]; L – length of the beam, [mm]; A_s – area of steel in tension, [mm^2]; A_{s2} – area of steel in compression, [mm^2]; A_f – area of FRP strip, [mm^2]; ρ_s – reinforcement ratio in the tension zone, [%]; ρ_{s2} – reinforcement ratio in the compression zone, [%]; ρ_{eq} – equivalent reinforcement ratio, [%]; E_f – Young's modulus of FRP, [MPa]; E_s – Young's modulus of steel reinforcement, [MPa].

Eqs.

$$\rho_s = \frac{A_s}{db}; \tag{1}$$

$$\rho_{s2} = \frac{A_{s2}}{db}. \tag{2}$$

define the reinforcement ratio in tension and in compression zone.

The equivalent longitudinal reinforcement ratio is defined by

$$\rho_{eq} = \rho_s + \frac{E_f}{E_s} \cdot \frac{A_f}{bh}. \tag{3}$$

Four point bending tests under monotonic loading were carried out for all RC beams, as presented in Fig. 5.

During testing, the RC beams were considered to be simply supported, with the span between the supports equal to 2,700 mm. The load was applied monotonically, with two concentrated forces in the central one third of the span.

The deflections were measured during the experiment by using five linear variable differential transducers (LVDT), which were mounted at midspan, located at 450 mm and 900 mm, respectively, from midspan on each side.

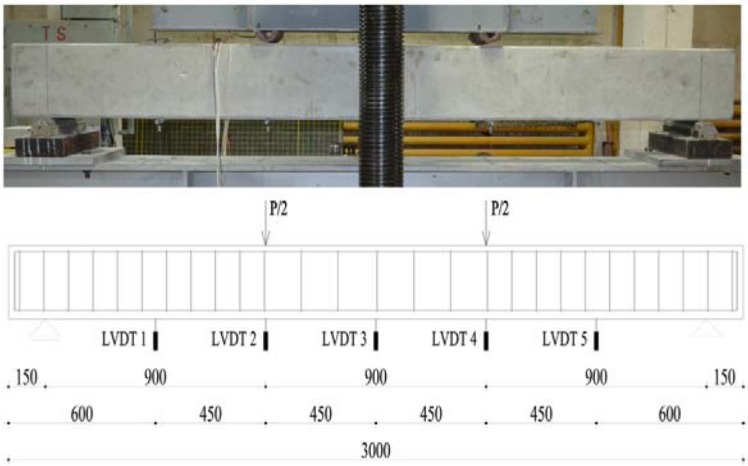

Fig. 5 – Experimental stand and LVDT positions, [mm].

3. Experimental Results

During the testing of the RC beams, the following parameters were monitored: the value of the applied load, crack appearance and development, and the transversal displacement which was measured in the five points previously established.

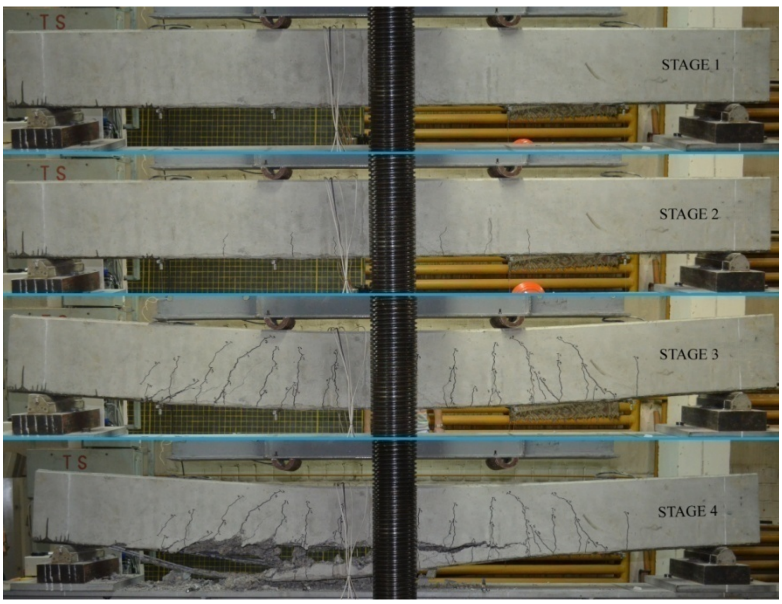

Fig. 6 – Crack stages for the tested beams.

Fig. 6 shows different cracking stages for all tested RC beams. In stage 1, the beams have a perfectly linear behaviour up to the appearence of the first flexural cracks (stage 2). After cracking and until the yielding of the steel bars, the external load is primarily carried by the steel reinforcement. Once the steel starts to yield, deflection increases rapidly with every little increase in load (stage 3). Failure mode (stage 4) for all tested strengthened beams occurred by debonding in the form of concrete cover separation (CCR).

Beam A1, with no external strengthening, failed at a load of 58.5 kN after yielding of the steel reinforcement. The strengthened specimens B1, C1 and D1 failed at a load of 151 kN, 154.2 kN, and 176.5 kN, respectively. For beam C1, strengthened with two CFRP strips, an increase in the load carrying capacity of 164% and a reduction of the deflection up to 12% are achieved, in comparison with the control specimen. For beams B1 and D1, strengthened with three CFRP strips, an increase of the bearing capacity of 158% and 202%, respectively, and a reduction of the deflection of 9% and 49%, respectively, were recorded, in comparison with the control specimen.

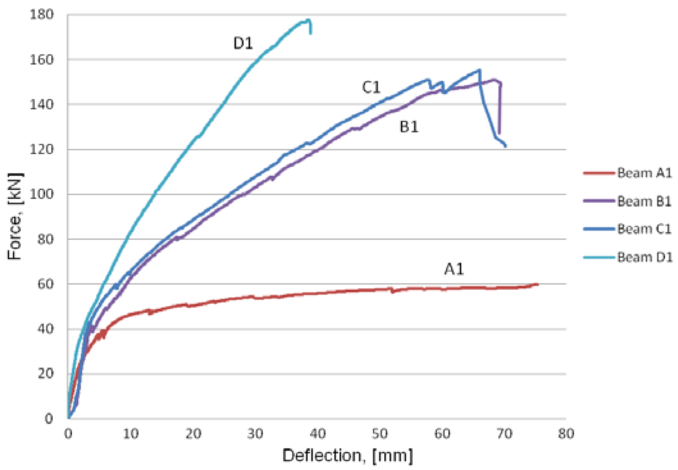

Fig. 7 – Force *vs*. mid-span deflections for the tested RC beams.

Table 2

Experimental Results for the Tested Beams

Beam	First crack		Steel yielding		Ultimate force		Failure mode
	F_{cr} kN	d_{cr} mm	F_y kN	d_y mm	F_{max} kN	d_{max} mm	
A1	27	2.65	45	9.85	58.5	75	RY
B1	40.5	4	–	–	151	68.5	CCS
C1	41.6	3.6	–	–	154.2	66	CCS
D1	46.8	3.6	–	–	176.5	38.6	CCS

Table 2 summarises the main results of the tested RC beams. In this table, F_{cr}, F_y, and F_{max} represent the loads at concrete crack initiation, yield of the steel reinforcement (RY) and at the failure of the specimens, respectively, and d_{cr} , d_y and d_{max} are the corresponding vertical displacements at the mid-span.

For the purpose of comparative analysis, the forceversus mid-span deflection diagrams obtained from the tested RC beams are shown in Fig. 7.

4. Conclusions

This paper presents the experimental results obtained from a series of flexural tests performed on RC beams strengthened in flexure with NSM CFRP reinforcement. For all the tested specimens, the load carrying capacity increased and the corresponding maximum transversal displacement decreased. Failure mode for all tested beams was concrete cover separation. The bearing capacity of the strengthened beams increased by 158% for beam B1, 164% for beam C1 and 202% for beam D1, in comparison with reference beam A1. The corresponding maximum displacements were reduced by 9%, 12% and 49%, respectively, as compared to the reference beam.

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RĂSPUNSUL STRUCTURAL AL GRINZILOR DIN BETON ARMAT CONSOLIDATE CU FÂŞII COMPOZITE APLICATE LÂNGĂ FEŢELE EXTERIOARE

Rezultate experimentale

(Rezumat)

Sunt prezentate rezultatele experimentale obţinute în urma unor teste, la încovoiere efectuate pe grinzi din beton armat consolidate cu ajutorul fâşiilor compozite

armate cu fibre, montate lângă feţele exterioare (NSM). Pentru grinda consolidată cu două fâşii compozite având secţiunea transversală de 1,2 × 18 mm, s-a observat o creştere a capacităţii portante de 164% şi o reducere a deplasării transversale de până la 12%, în comparaţie cu grinda de control. Pentru probele consolidate cu trei fâşii compozite, având secţiunea transversală de 1,2 × 12 mm şi 1,2 × 24 mm, s-a obţinut o creştere a capacităţii portante de 158% şi respectiv 202%, în comparaţie cu grinda de control. Cedarea elementerlor consolidate s-a produs prin desprinderea acoperirii de beton de la partea tensionată a acestora