Flexural Behaviour of RC Beams Strengthened with Post-tensioned CFRP Strips with Various Prestressing Level

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Abstract. The paper presents the results of the research on a series of reinforced concrete beams strengthened with the new Polish CFRP post-tensioning system with various prestressing levels (force). The tests included four RC beams with a rectangular cross-section of 0.50 m × 0.42 m and a length of 6.0 m. The first beam was a reference (control) beam. The next three beams were strengthened by prestressing with two CFRP strips. Prestressing level is defined as a ratio of prestressing force to the characteristic ultimate tensile strength of CFRP strip. Tested beams were prestressed with 30%, 40% and 50% of CFRP tensile strength which corresponds to a force of 162 kN, 216 kN and 268 kN for subsequent beams. The beams were investigated in a full range of flexural behaviour, including post-debonding phase. The results indicate that changing of prestressing level has a significant influence on behaviour of prestressed beams. The beams strengthened with higher prestressing level exhibited a higher cracking, and steel-yielding moments as well as slightly higher level of CFRP utilisation. Changing the strip prestressing level did not affect the load-bearing capacity of the beams. Beams with different prestressing levels exhibited similar flexural behaviour until strip debonding. Differences occurred in post-debonding phase of work. The higher prestressing level, the failure mode of the beams was more sudden. On the basis of the failure mode of the tested beams, the optimal prestressing level of the CFRP strip in the new prestressing system was determined.

Keywords: CFRP strips · Prestressing level · RC beams · Strengthening system

1 Introduction

Strengthening of reinforced concrete structures with post-tensioned CFRP strips is a highly effective method to improve the load carrying capacity and to reduce cracking as well as deflection of the elements under service loads. Thanks to their advantages such as high strength to weight ratio, light weight, ease of transport and installation, excellent fatigue characteristics and resistance to corrosion, CFRP strips can be a good alternative for conventional strengthening methods. Flexural strengthening with externally bonded CFRP strips has been developed for about 30 years (Saadatmanesh and Ehsani 1991,

Triantafillou et al. 1992). Currently, it is a widely used method for retrofitting reinforced concrete structures throughout the world (Hollaway and Teng 2008).

The most common way to strengthen the structure with CFRP material is passive bonding to the external concrete surface. However, passively bonded CFRP strips have some limitations. Research proved that only approximately 20–50% of CFRP tensile strength can be utilised before the failure of strengthening, caused in most cases by the debonding of the strip due to concrete cover failure (Meier 1995, Kotynia et al. 2008). Moreover, passive strengthening has hardly any influence on the stiffness of RC elements. It could be effectively applied only when reducing the deflection or cracks width is not required (Hollaway 2010).

In order to obtain the best strengthening effects and increase utilisation of CFRP material, the strips can be tensioned before bonding and fixing to the strengthened structure. Prestressing allows for increasing the load-bearing capacity and stiffness of strengthened structural elements and thus enhances the composite material utilization in comparison with a passive external bonding technique (Garden and Hollaway 1998, Michels et al. 2016). Currently, all over the world, intensive research is being undertaken for better understanding static, fatigue and long-term behaviour of RC elements strengthened with this technology (Amran et al. 2018, Ali et al. 2012, Chalot et al. 2019). During last 20 years wide research in this field has been conducted around the world as a result of which several CFRP post-tensioning systems were developed. One of these systems has already been implemented on-site and now they are used in practical applications, others are in the research phase (Aslam et al. 2015). The paper presents the new Polish CFRP post-tensioning system (Piątek and Siwowski 2017) and the results of the research on series of reinforced concrete beams strengthened using this system with various prestressing level.

1.1 CFRP Prestressing System

The newly developed system is the second version of the solution developed in Poland in 2008 (Siwowski, Żółtowski, 2012). It consists of two main elements: special steel anchorages (Fig. 1, 2) mounted on both ends of a single CFRP strip and a relevant tensioning device (Fig. 3). There are two kinds of anchorages: an active anchorage (Fig. 1a) combined with a tensioning device and a passive one (Fig. 1b). The system uses ultra-high strength CFRP strips with a cross-section of 60 mm × 1.4 mm, with the ultimate tensile strength $f_{fu} = 3200$ MPa, a modulus of elasticity $E_f = 160$ GPa and the strain at failure ε_{fu} of approximately 2%. The strip with a specific length is delivered on site as ready-to-install, i.e., with two prefabricated steel anchorages mounted on both strip ends. The anchorage is made of two thin steel plates welded together along the edges to create a pocket, in which the CFRP strip end is fixed and bonded with a special epoxy-based adhesive. Prior to welding the inner surfaces of the plates are sandblasted and cleaned with acetone. It is followed by gripping both materials (steel plates and CFRP strip in-between) with high-strength bolts (Fig. 2). The anchorages transfer the tension load from the tensioning device to the strip by internal bonding, friction and gripping, simultaneously. The anchorage has two functional areas: external and internal (Fig. 1). The strip is clamped, bonded and gripped within the internal area. The external area comprises threaded holes for mounting the tensioning device (in the active anchorage

only) and anchor holes for attaching the anchorage to the strengthened element. The load carrying capacity of the anchorages obtained in one-sided specimens (Fig. 2) in axial tensile tests was 200 kN (Piątek et al. 2020). The tensioning device is the second key part of the strengthening system. The tensioning device consists of three separately installed components: guide rails, carriage (bolted to the active anchorage) and hydraulic jack with resisting block (Fig. 3a).
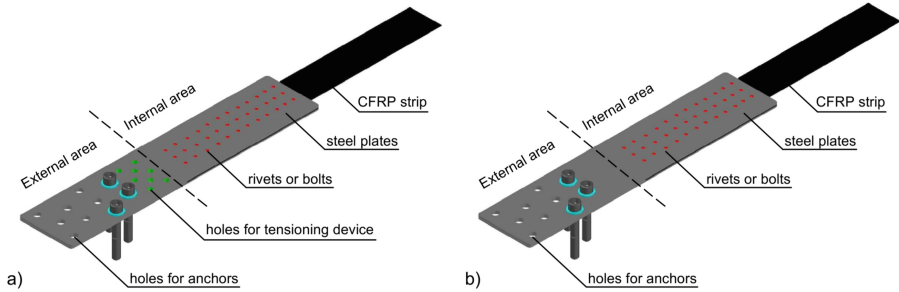

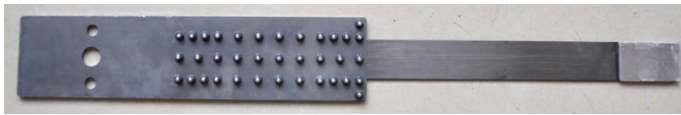**Fig. 1.** Mechanical anchorages, a) active, b) passive.

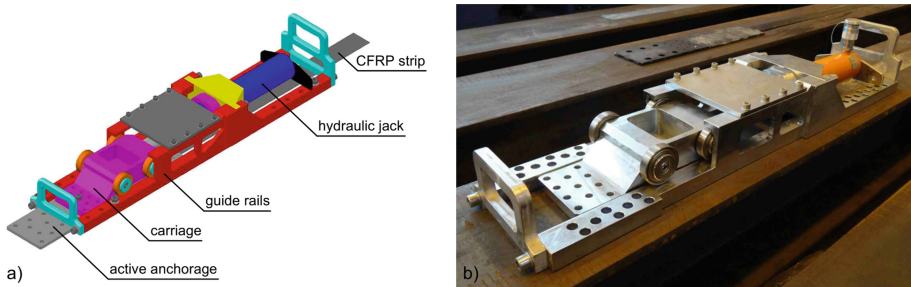**Fig. 2.** Specimen of the anchorage used in the tests.

Fig. 3. Tensioning device, a) scheme, b) prototype.

2   Experimental Program

In order to verify effectiveness of the newly developed system as well as to determine optimal prestressing level of this system the tests on series of RC beams were carried out.

2.1   RC Beams

The tests were carried out on four identical reinforced concrete beams which were similar, in terms of dimensions and reinforcement, to small precast bridge beams. Tested beams had a rectangular cross-section with dimensions of 0.50 m × 0.42 m and length of 6.0 m reinforced with longitudinal bars with a diameter of 25 mm and stirrups with a diameter of 12 mm (Fig. 4). The concrete cover was 25 mm and the steel reinforcement ratio $\rho_s = 0.79\%$. All beams were manufactured with C45/55 concrete (maximum aggregate size of 16 mm) with the mean value of compressive strength $f_{cm} = 62$ MPa (obtained in the tests of cubic specimens). The B500SP reinforcing steel was used with the mean value of yield strength $f_y = 522$ MPa and tensile strength $f_u = 628$ MPa as well as the characteristic strain at maximum load $\varepsilon_s = 10.9\%$ and modulus of elasticity $E_s = 192$ GPa.
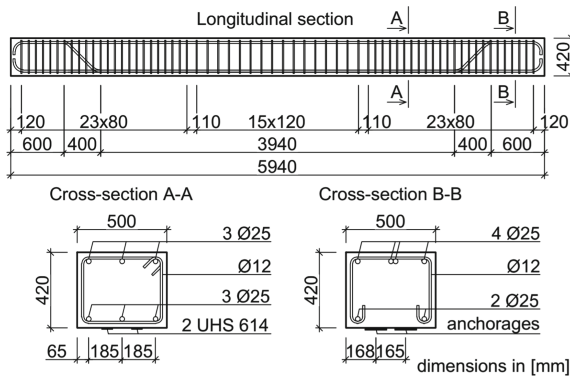

Fig. 4.   Reinforcement layout of the beams.

2.2   Strengthening Procedure

The beams were strengthened using novel CFRP prestressing system. Before the strips installation, RC beams were set on the assembly station in the same scheme as during the tests. Strengthening was carried out on the bottom surfaces of the beams to take into account dead load of the beams. The concrete surfaces were grinded, dedusted and degreased. The CFRP strips equipped with anchorages were fabricated in a precast workshop. At first, the passive anchorage was mounted to the concrete surface, then the tensioning device was installed at the active side. The installation of the tensioning device consists of mounting the guide rails to the concrete surface (Fig. 5a), inserting the active anchorage between the two rails (Fig. 5b), bolting the movable carriage to the active anchorage (Fig. 5c) and installing the hydraulic jack with the resisting block (Fig. 5d). When the tensioning device was ready, the strip was tensioned up to the designed value of prestressing force (trial tensioning), the holes for mounting the active anchorage were drilled and the prestressing force was released. Then the adhesive was prepared and applied to the CFRP strip. After application of the adhesive, the CFRP strip

was tensioned again, it was fixed to the beam with mechanical anchors bolted in pre-drilled holes (Fig. 6) and the tensioning device could be removed. In the last steps, the CFRP strip was pressed to the concrete surface, and the excess adhesive was removed. The whole installation of one CFRP strip takes about 2 h.
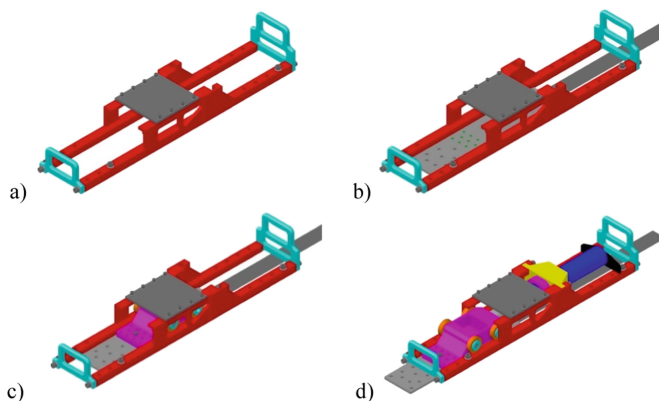

a)   b)   c)   d)

Fig. 5. Installation of CFRP strip, a) mounting the guide rails, b) inserting the CFRP strip, c) bolting the carriage, d) installation of hydraulic jack.

Fig. 6. Strengthening of the beams.

2.3 Test Setup

The tests were carried out at a special adjustable lab stand. Loading was carried by an Instron Schenck hydraulic actuator with a maximum load force of 630 kN. A four-point bending scheme was applied by means of a steel traverse beam, spreading the load from the actuator (Fig. 7). The span length of beams was 5.6 m. The beams were supported pointwise on roller bearings. The tests were conducted with a force-controlled rate of 1 kN/s up to steel yielding and then manually with a displacement control.
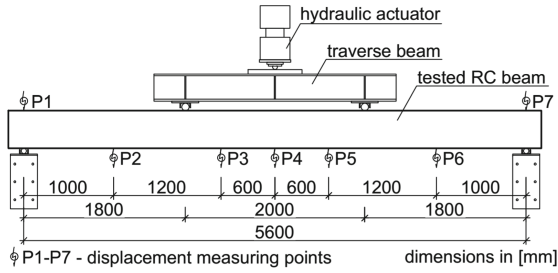
Fig. 7. Test setup.

The first beam (B0) was not strengthened and served as a reference beam. Next three beams (B30, B40 and B50) were prestressed and strengthened with the new system with different prestressing levels, amounting 30%, 40% and 50% of the composite tensile strength (f_{fu}). The detailed strengthening parameters of all tested beams are listed in Table 1.

Table 1. Parameters of beam strengthening

Beam	Prestressing level [-]	Prestressing force [kN]	Initial CFRP strain [‰]	Initial CFRP stress [MPa]
B0	0	0	0	0
B30	30% f_{fu}	2×81	6.0	960
B40	40% f_{fu}	2×108	8.0	1280
B50	50% f_{fu}	2×134	10.0	1600

2.4 Instrumentation

During the tests, the load, the displacements of the beams, the strains of concrete and the steel in the bars as well as the strains along the CFRP strips were measured continuously. The displacements were measured using linear variable displacement transducer (LVDT) gauges with a 100 mm range with an accuracy of 0.01 mm, while strains were measured using 10 mm electric strain gauges with an accuracy of 0.001‰. All gauges were connected via a set of QuantumX MX840A amplifier modules to a computer with Catman Easy data acquisition software. The cracking of beams was controlled during loading visually along with a width measurement. The failure modes were also identified in detail by means of a video camera.

3 Test Results

The results of the beam tests were collected in Table 2. For each beam, the values of cracking, yielding, debonding and ultimate moment (load-bearing capacity) were

noted. The ultimate moment is defined as the maximum value of bending moment that occurred during the test. In the reference beam, the ultimate moment was achieved when the testing load stopped increasing (after steel yielding). In the strengthened beams, ultimate moment is connected with a failure of the strengthening system. Moreover, the maximum CFRP strains at failure (including the initial strains equalled 6‰, 8‰ and 10‰ for beams B30, B40 and B50, respectively) and description of failure modes were presented in the table.

Table 2. Test results

Beam	Cracking moment	Yielding moment	Debonding moment	Ultimate moment	Ultimate deflection	CFRP strain at failure	Failure mode
	M_{cr} [kNm]	M_y [kNm]	M_d [kNm]	M_u [kNm]	Δ_u [mm]	ε_f [‰]	[-]
B0	55	266	–	272	66,2*	–	Steel yielding
B30	111	371	393	424	147,6	15.8	Debonding, slipping from anchorages and rupture
B40	120	394	400	415	97,5	16.4	Debonding, slipping from anchorages and rupture
B50	136	419	428	428	57,6	16.7	Simultaneous debonding and slipping from anchorages

Note: test of the reference beam was stopped after steel yielding without increase of load.

Strengthening of the beams caused an increase of the cracking and yielding moment as well as the ultimate moment. Due to the use of the tensioned CFRP strips, the ultimate moment of tested beams was increased by about 55% in relation to the reference beam. In cases of cracking and yielding moment, the increases were equal to 102–147% and 39–58%, respectively, depending on the value of prestressing level. Strengthening with CFRP strips influences also the improvement of serviceability parameters of the beams: a reduction of deflection and cracking. Deflection reduction can be observed in Fig. 8, where load-deflection (M-Δ) relationships in the middle of the span for each beam were presented. Changes of cracking pattern for each beam under the load of 200 kNm (approximately equal to the characteristic load for the strengthened beams) are presented in Fig. 9. Under this load, maximum crack width for beam B0 was 0.3 mm, while for strengthened beams crack widths did not exceed 0.2 mm. Total crack width (measured

as a sum of widths of single cracks) was over twice lower for strengthened beams in comparison with beam B0 (Fig. 9).

Failure modes of strengthened beams were associated with damaging of the strengthening system. In case of beams B30 and B40, failure occurred gradually. It was initiated by debonding of the strip from the concrete surface followed by slipping from the anchorages. Subsequent steps of failure are visible on the plots in Fig. 8, where discontinuities of load-displacement curves occurred. These discontinuities are caused by the subsequent debonding of the first and second strips as well as the slipping of these strips from anchorages. The failure of beam B50 (with highest prestressing level) had a different character, because the debonding and slipping from the anchorages of both strips occurred at the same moment. In this case, only one discontinuity of the plot in Fig. 8 was recorded – in the moment of failure of the beam. Subsequent phases of failure modes of the beams are shown in Fig. 10. In each strengthened beam the failure was concerned the strengthening system, there was no concrete crushing at the top surface of the beams.
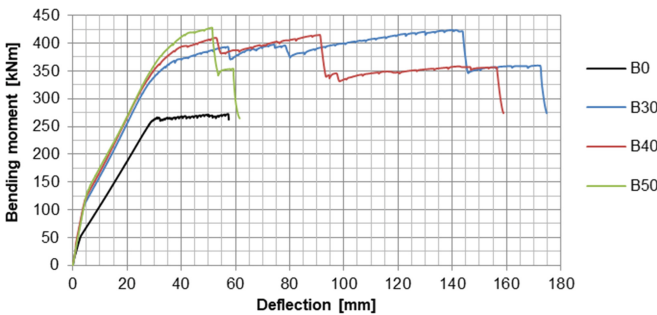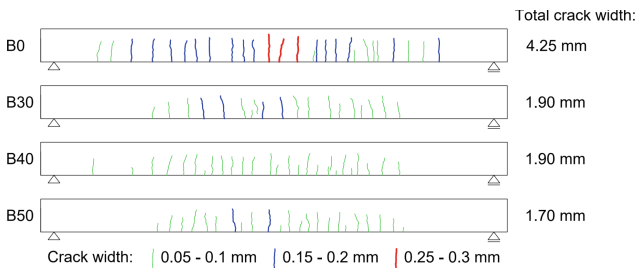

Fig. 8. Load-deflection plots for all tested beams.

Fig. 9. Cracking patterns of all tested beams under the load of 200 kNm.

4   The Results Analysis

Prestressing level had significant influence on behaviour of strengthened beams (B30-B50). The cracking moment was increased following the increasing of prestressing level. The increase of cracking moment of the B40 and B50 beams in comparison with the
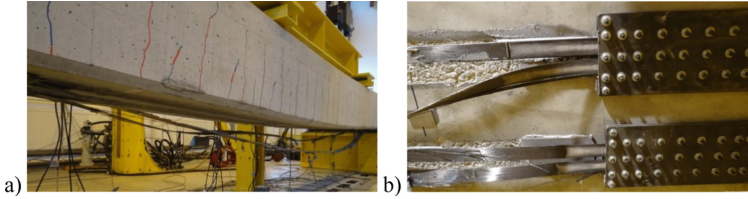
Fig. 10. Subsequent phases of failure modes, a) debonding of CFRP strips, b) slipping from anchorages.

B30 beam was 8% and 23%, respectively. The yielding moment also increased when prestressing level increased. However, the increase of this parameter of the B40 and B50 beams in comparison with the B30 beam was lower – 6% and 13%, respectively. A similar relationship was noted in the case of debonding moment. In the B40 and B50 beams, it was higher of 2% and 9% in comparison with the B30 beam. Prestressing level had a minor effect on the ultimate moment. All strengthened beams have been damaged under similar value of testing load equal to 415–428 kNm (differences between the ultimate moments of prestressed beams did not exceed 2%). Moreover, ultimate moment of the beam B30 (with the lowest prestressing level) was higher than in case of beam B40. Due to that, the strengthening efficiency defined as a ratio of increase of ultimate moment of strengthened beam to ultimate moment of reference beam in all strengthened beams was similar and amounted about 55%. The relationships between cracking, yielding, debonding as well as ultimate moments depending on the value of prestressing level are presented in Fig. 11.
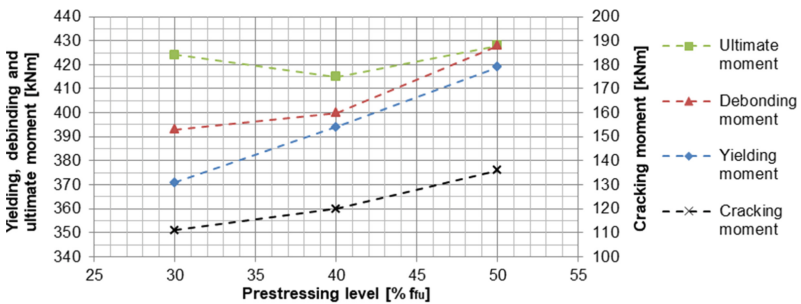

Fig. 11. Influence of prestressing level of cracking, yielding, debonding and ultimate moments.

The influence of prestressing level on changes in the stiffness of prestressed beams is visible in Fig. 8, showing the load-displacement (M-Δ) relationships. In the non-cracked phase, this influence is negligible. However, in the cracked phase, the slope of M-Δ curves for each prestressed beam is different, which results in a reduction of deflections in subsequent prestressed beams under similar load levels. For example, in the case of testing load of 200 kNm, the reduction of deflection of the B40 and B50 beams against the B30 beam amounted 7% and 12%, respectively. The prestressing level affects also the cracking mode. However, no clear relationship between the prestressing level

and beam cracking was observed during the tests. The maximum crack width under the load of 200 kNm in the case of the B30 and B50 beams was the same and amounted to 0.15 mm. In the case of the B40 beam, the width of particular cracks was smaller and did not exceed 0.1 mm. However, in this beam a larger number of cracks were noted, giving the same total crack width along the beam as for the B30 beam (1.90 mm). In the case of B50 beam, the total crack width was slightly lower (1.70 mm). After the load was increased to 250 kNm, the cracks in the B30 beam were wider compared to the beams with a higher prestressing level and the total crack width along all the beams was slightly decreasing once the prestressing level was higher. Therefore, it can be concluded that the increase of the strip prestressing level results in limiting the beam cracks, but in the analysed example this impact is small and hardly visible.

In subsequent prestressed beams the total strains of the CFRP strips $\varepsilon_p + \varepsilon_l$ (initial strains caused by prestressing + strains from testing load) increased with increasing prestressing level and before failure they were equal to 15.8‰, 16.4‰ and 16.7‰ for B30, B40 and B50 beams, respectively. In the case of these beams, the CFRP material was therefore utilised in 79% (B30), 82% (B40), and 84% (B50). Thus, there was a slight increase of the CFRP strip utilisation level along with the increase of prestressing level. However, CFRP strains under testing load ε_l (excluding the initial strains) decreased with increasing prestressing level. This is related to the higher stiffness of the beams with higher prestressing level. Strains distributions along the CFRP strips under the load of 400 kNm (close to failure) are presented in Fig. 12.
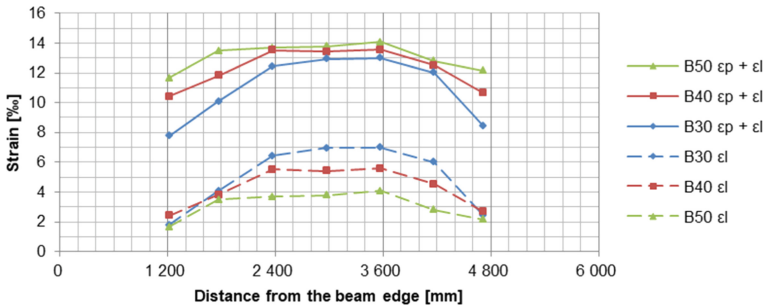

Fig. 12. Strains distributions along the CFRP strips under the load of 400 kNm.

Prestressing level of the CFRP strips had a significant influence on the failure modes of the strengthened beams. In the case of B30 and B40 beams, the failure modes had long-lasting, gradual character. After debonding of the CFRP strips, an additional phase of work occurred and then failure was due to slipping the strips from the anchorages. During post-debonding phase CFRP strains were approximately equal along the strip because of debonding and loss of adhesive joint between the strip and concrete surface. The CFRP strip worked then like a tie. The failure mode of beam with the highest prestressing level (B50) was different. The B50 beam was suddenly damaged due to the strips slipping from anchorages, without any previous debonding signs. These two phenomena, debonding and slipping from the anchorages of both strips, occurred at the same moment. This was due to the higher initial strains induced by prestressing.

The ratio of ultimate moment to debonding moment (M_u/M_d) in the B30 beam with the lowest prestressing level was 1.08. In beams with higher prestressing level this ratio decreased to 1.01 for the B40 beam and 1.00 for the B50 beam, in the case of which strip debonding occurred at the same time as the failure of strengthening. Increasing the strip prestressing level up to 50% f_{fu} resulted in the loss of an additional safety margin related to the post-debonding phase of work. A similar dependence occurred in the case of a ratio of beam deflections after strip debonding Δ_u/Δ_d. The higher the value of this ratio, the behaviour of the beam after debonding is more ductile and the failure signs are more visible. In the case of the B30 and B40 beams, the ratio was 2.48 and 1.73, respectively. However, in the B50 beam, in the case of which the sudden failure occurred, the ratio was 1.00. The ductility of prestressed beams was decreased as the strip prestressing level was increased.

Due to a significant change in the failure mode of the B50 beam (with strips prestressed up to 50% f_{fu}), which was abrupt and did not show any prior signs, it is recommended to apply the strips maximally prestressed up to 40% f_{fu} to strengthen the reinforced concrete elements by means of the novel prestressing system. This value corresponds to the initial strains of 8‰ and the prestressing force of 108 kN for one CFRP strip. However, a higher prestressing level could be applied, but then sudden failure mode can occur and this fact should be taken into account at the design stage. These conclusions concern only the particular system which was used to strengthen the tested beams. In case of this system optimal prestressing level is connected with limited efficiency of anchorages.

5 Conclusions

Strengthening the beams with prestressed strips caused a considerable increase of load-bearing capacity (by more than 50%). Prestressing caused also an increase of the cracking moment, the yielding moment as well as stiffness of the beams. Changing the strip prestressing level did not affect the load-bearing capacity of the beams, but it had a significant influence on other beam parameters. Once the strip prestressing level was increased, there was an increase of the cracking, yielding and debonding moments, as well as a reduction of deflection and cracking of the beams. The level of CFRP utilisation also increased slightly.

On the basis of the failure mode of the tested beams, the optimal prestressing level of the CFRP strip in the novel system was determined, equalling 40% f_{fu}. Up to this level, a ductile failure mode of strengthening occur, which allows to early identify the possible damage caused by overloading the strengthened structure. The system (efficiency of the anchorages) enables to use a higher prestressing level of 50% or even 60% f_{fu}. However, sudden failure mode of strengthening should be taken into account during designing. In general conclusions of the tests in terms of behaviour of RC beam strengthened with CFRP strips under static load are similar to other research described in the literature, which means that the system works properly. The system have been already implemented on-site to strengthen several RC bridges in Poland.

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