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RESEARCH ON THE NEW CFRP PRESTRESSING SYSTEM FOR STRENGTHENING OF RC STRUCTURES

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Abstract
The paper presents a research on the new Polish CFRP prestressing system for strengthening of reinforced concrete structures. The system is called Neoxe Prestressing System II (NPS II). NPS II consists of two main elements: a special steel anchorages mounted on both ends of a single CFRP strip and a tensioning device. The anchorage is made of two steel plates. CFRP strip end is fixed between steel plates through bonding by epoxy resin and gripping by bolts. The tensioning device compatible with anchorages can generate maximum prestressing force of 170 kN. The research on NPS II comprised a series of static and fatigue tests on anchorages themselves, system mounted on strengthened beams as well as on-site, i.e. on actual RC bridge. The system has been examined, its efficiency has been confirmed in laboratory and in field tests and now it is ready to use in strengthening purposes.

Streszczenie
W artykule opisano badania nowego polskiego systemu do wzmacniania konstrukcji za pomocą wstępnie naprężanych taśm CFRP. Głównymi elementami systemu Neoxe Prestressing System II są: specjalne zakotwienia mechaniczne, montowane na obu końcach taśmy kompozytowej oraz urządzenie naciągowe. Zakotwienia zbudowane są z dwóch blach stalowych, pomiędzy które taśma jest wklejona za pomocą żywicy epoksydowej. Skleina jest wzmocniona połączeniem śrubowym. Urządzenie naciągowe, kompatybilne z zakotwieniem czynnym, pozwala na naprężenie taśmy siłą 170 kN. Prace nad rozwojem systemu NPS II obejmowały serie statycznych i zmęczeniowych testów zakotwień, badania belek żelbetowych wzmocnionych systemem w laboratorium oraz wdrożenie systemu do wzmocnienia istniejącego mostu żelbetowego. System został sprawdzony, jego efektywność została potwierdzona badaniami laboratoryjnymi oraz in-situ i aktualnie jest on gotowy do stosowania w budownictwie.

Keywords: **Anchorages; CFRP strips; Prestressing; Strengthening; Tensioning device.**

1. INTRODUCTION

One of the best method to increase load bearing capacity and stiffness of reinforced concrete structures subjected to bending is the external prestressing with CFRP strips. Thanks to great mechanical parameters of CFRP strips and high efficiency of prestressing effects, this technology can be a good alternative to conventional strengthening methods and it has recently been more often used for practical application. Tensioning of CFRP strips allows to increase load bearing capacity and stiffness of strengthened structural elements and enhances composite material utilisation in comparison with passive externally bonding technique. The first externally bonded prestressing system has been developed by Leonhardt, Andrä & Partners. This system is known as Sika Leoba

Carbodur II. The first on-site application of externally bonded prestressed CFRP strips was carried out using this system on a prestressed concrete bridge in Germany in 1998 [1]. Nowadays we can observed a dynamic development of CFRP prestressing systems worldwide. There is a lot of systems available on the market, for instance Sika StressHead [2] , S&P systems [3, 4] or Tenroc [5]. Still a great number of solutions have been currently testing and developing in laboratories all over the world [6, 7]. This technology is also fast developing in Poland. The first Polish system has been developed in Road and Bridge Research Institute based on Sika Leoba Carbodur II idea [8]. The next Polish system, Neoxe Prestressing System (NPS), has been developed by Neoxe company and tested in laboratories of Rzeszow University of Technology [9]. This paper presents the results of a research programme on the second generation of the Neoxe Prestressing System (NPS II). The main goal of creating a new system was increasing of tensioning force, which could be applied on the strips. For this purpose many research have been conducted. During this study the new types of anchorages and tensioning device have been developed.

2. DESCRIPTION OF THE NEW SYSTEM

The Neoxe Prestressing System II consists of two main elements: a special steel anchorages mounted on both ends of a single CFRP strip and a relevant tensioning device. The system uses high-strength UHS 614 strips of cross-section 1.4×60 mm with the ultimate tensile strength 3200 MPa, modulus of elasticity 160 GPa and the strain at failure about 2%. There are two kinds of anchorages: an active anchorage combining with a tensioning device and a passive one. The strips with determined length are delivered on site as ready-to-install, i.e. with two steel anchorages mounted on both strips ends. The anchorage is made of two 2 mm thick steel plates welded together along edges to create a pocket, in which CFRP strip end is fixed. The end of the strip is placed in the steel anchorage pocket and bonded with special epoxy-based glue. It is followed by gripping of both materials (steel plates and CFRP strip in-between) with small high-strength bolts with 6 mm diameter. The anchorages transfer the tension force from tensioning device to the strip by internal bonding, screw gripping and friction 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 small holes for attaching the plate to the concrete surface by anchors and threaded holes for mounting the tensioning device (in the active anchorage only).

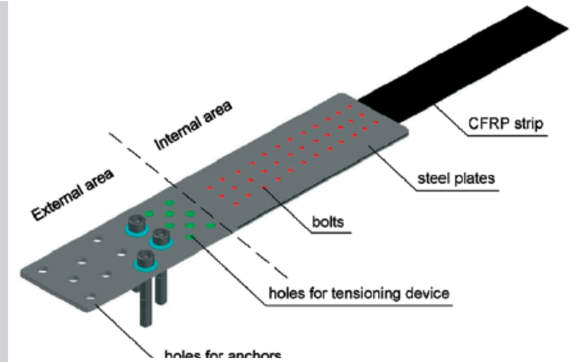

Figure 1.
Active anchorage

The tensioning device comprises three separately installed components: guide rails, carriage (bolted to the active anchorage) and hydraulic jack (Fig. 2). The hydraulic jack can generate maximum prestressing force of 170 kN. Thanks to device body division to three small and light parts (the heaviest element weights 37 kg) its installation on-site is very fast and easy.

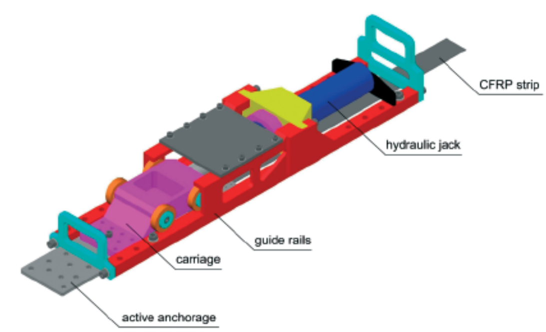

Figure 2.
Tensioning device

3. TESTS OF ANCHORAGES

In order to develop steel anchorages with required carrying capacity many research have been conducted. In the first phase tests on small specimens have been performed in order to find optimal method of preparing steel surface, composition of epoxy-based glue and type and arrangement of mechanical fasteners. The second phase concerned full scale anchorage specimens. Technology of performing anchorages was developed based on first phase tests. The tests of static carrying capacity were conducted in five series (two or three specimens in each of them). Specimens

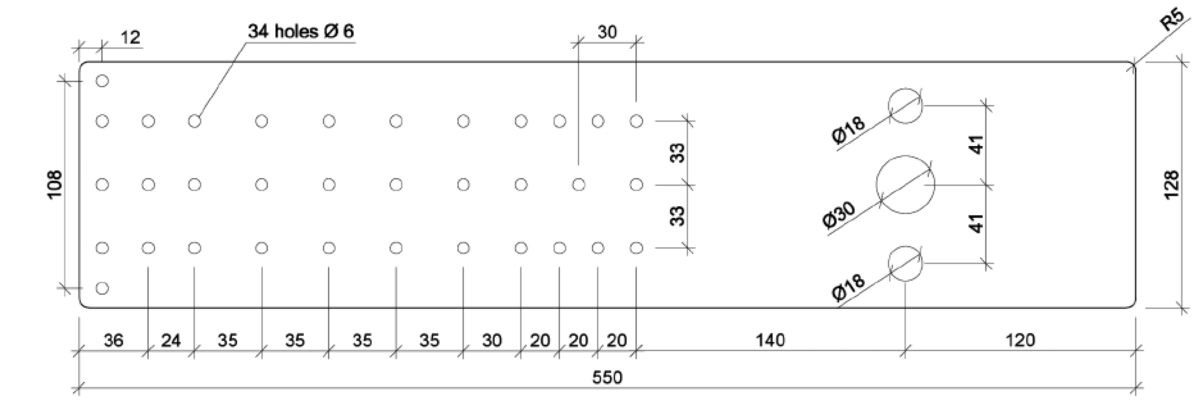

Figure 3.
Final arrangement of the holes in the anchorage

tested in subsequent series were subjected to small modifications aimed at increasing the carrying capacity of anchorages. The modifications mainly comprised several attempts to enhance the bonding shear capacity of both glued steel surfaces and to check the different arrangement small bolts. In the final solution CFRP strip is overlaid by epoxy adhesive before mounting between steel plates and the arrangement of bolts as presented in the Fig. 3 is used. All specimens were made as a one-sided anchorage and the free ends of strip were protected by aluminium plates and placed in the jaws of the testing machine (Fig. 4).

The anchorage specimens were subjected to axial tensile test in testing machine Instron J1D 1200 kN. The tests were conducted under displacement control at a rate of 2 mm/min. During the tests increment of force and displacement were measured. The measurement of these values was provided by using the set of sensors built in the testing machine.

Fig. 5 shows the load – displacement plots for the maximum value of the failure force of each series. Thanks to successive modifications in manufacturing anchorages the noticeable increase of failure force was obtained. Still development of anchoring technology for followed specimens allowed to obtain value of failure force of almost 200 kN in the last two series.

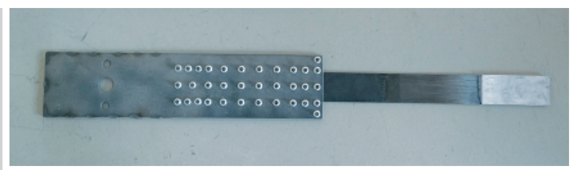

Figure 4.
Anchorage specimen view

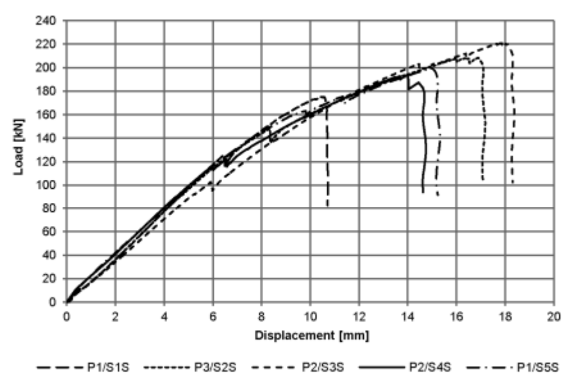

Figure 5.
Maximum load – displacement plots for five series

Variability coefficients equal to 1.7% and 0.4% in the last two series indicate that the tested anchorage specimens had a high level of homogeneity. The collected results of static tests were presented in Tab. 1.

Table 1.
Collective testing results of five series of anchorages

Series No.	Failure load of each specimen:			Mean failure load	Standard deviation	Variability coefficient	CFRP efficiency
	P1	P2	P3				
	[kN]	[kN]	[kN]	[kN]	[kN]	[-]	[-]
S1S	175	174	166	171	5.2	3.0%	62%
S2S	147	161	208	-	-	-	-
S3S	177	221	-	199	31.3	15.7%	72%
S4S	189	194	188	190	3.2	1.7%	69%
S5S	199	198	-	199	0.8	0.4%	72%

Table 2.
Specification of tested beams

Beam	Prestressing level	Prestressing force	Initial CFRP strain	Initial CFRP stress	Anchorages
	[-]	[kN]	[-]	[MPa]	[-]
B1	-	-	-	-	-
B2	-	-	-	-	No
B3	0% f_{fu}	-	-	-	Yes
B4	30% f_{fu}	81	6.0‰	960	Yes
B5	40% f_{fu}	108	8.0‰	1280	Yes
B6	50% f_{fu}	134	10.0‰	1600	Yes

f_{fu} – CFRP tensile strength (for the Neoxeplate UHS 614 strips f_{fu} = 3200 MPa)

Table 3.
The results of tested beams

Beam	Cracking moment	Yielding moment	Ultimate moment	Strengthening efficiency	CFRP strain at failure	CFRP utilization	Ductility
	[kNm]	[kNm]	[kNm]	[-]	[-]	[-]	[-]
B1	55	266	272	-	-	-	1.84
B2	70	318	332	22%	5.9‰	30%	1.35
B3	72	321	361	33%	7.8‰	39%	2.78
B4	111	371	424	56%	15.8‰	79%	3.52
B5	120	394	415	53%	16.4‰	82%	2.17
B6	136	419	428	57%	16.7‰	84%	1.15

The value of the failure force is applied to establish the efficiency of the anchorages defined as ratio of maximum failure force of the anchorage to the CFRP characteristic tensile strength (force), which is 276 kN for the UHS 614 CFRP strips. Thanks to applied modifications repeatable anchorage efficiency higher than 70% could be obtained. It is a sufficient value for post-tensioning system for strengthening concrete structures because optimal strengthening effects are obtained with strip prestressing level equals about 60% of CFRP tensile strength [10].

4. TESTS OF STRENGTHENED RC BEAMS

In order to verify of system efficiency tests on the strengthened reinforced concrete beams were conducted. Beams had a rectangular cross-section with dimensions of 0.50×0.42 m and 6.0 m length. They were made of C45/55 concrete and B500SP steel. Longitudinal reinforcement bars were the 25-mm-diameter and stirrups the 12-mm-diameter. The scope of the study included six beams. The first of them was the reference beam (B1). The second beam (B2) was strengthened with two CFRP strips with dimensions of 60 × 1.4 mm, which were passively glued to beam's tensioned surface. The third beam (B3) was strengthened with the same strips but additionally anchored by system anchorages. The next three beams (B4-B6) were strengthened with pre-tensioned strips with various prestressing level and anchored by system anchorages (Tab. 2).

The studies were conducted on a special test stand. The span length of beams was 5.6 m. Loading was carried by a hydraulic actuator Instron Schenck with maximum pressure force 630 kN. Four point bending scheme was applied by means of spreading the load from the actuator by steel traverse beam. During the tests continuous measurement of load, displacements of beams, strains of upper and lower surfaces of concrete and steel bars in the constant bending moment range, as well as strains along CFRP strips, were measured. In the subsequent steps of loading cracking of concrete was controlled. The failure modes were checked and identified in detail.

The results of beam tests were collected in Tab. 3. For each beam values of cracking, yielding and ultimate load as well as strengthening efficiency were noted. The strengthening efficiency is defined as ratio of increase of ultimate load of strengthened beam to ultimate load of reference beam. The ultimate load is defined as the maximum value of bending moment occurred during the test. In the strengthened beams ultimate load is connected with failure of strengthening system. Moreover, in the table maximum CFRP strains at failure and CFRP utility level were given. CFRP utility level is ratio of maximum stress occurred in CFRP strip to ultimate strength of CFRP. In the last column ductility of the beams was presented. Ductility is calculated as ratio of deflection at failure to deflection at yielding.

Strengthening of the beams caused increasing of cracking and yielding moment as well as ultimate moment. It influences the improving of serviceability parameters of beams: a reduction of deflection and cracking. Deflection reduction can be observed in Fig. 6, where load-deflection plots in the middle of span for each beam were presented.

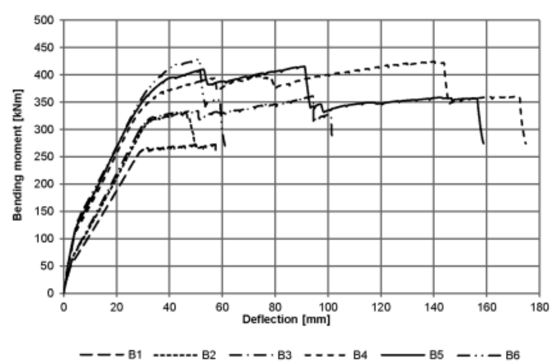

Figure 6.
Load- deflection plots for all tested beams

Beams strengthening by the passive strips resulted in a small reduction of deflection of the beams and increase of these ultimate load by 22% and 33% for beams B2 and B3 respectively. The usage of the anchorages in beam B3 effects on appearance of additional, emergency phase of work (after debonding up to failure). The anchorages caused increasing the ultimate load of 9% compared to beam without anchorages, increasing the CFRP utilities level and changing the failure mode. Thanks to the use of tensioned CFRP strips ultimate load of tested beams was increased about 55% in relation to reference beam. Value of ultimate load was similar for each prestressed beam. Prestressing level has therefore no important effect on increase of ultimate carrying capacity. However, it significantly affects the yielding moment (Tab. 3) and ductility of the beams. With increasing prestressing level increases the value of yielding moment. Increase of this value compared to reference beam was 39% and 58% for beams B4 and B6, respectively. Beams with higher prestressing level exhibited lower ductility. It is connected with behaviour of beam during failure. When the prestressing level is higher, then failure is more abrupt. Failure mode of each prestressed beam was similar. Failure was caused by debonding of CFRP strips from concrete surface followed by slipping from anchorages. In certain cases slipping CFRP strips from anchorages was accompanied by CFRP failure.

The most important results from the point of view of strengthening system are significant increase of ultimate load (strengthening efficiency about 55%) and improving of serviceability: reduction of deflection and cracking. The system is characterized by a high level of utilization of the composite material. In the prestressed beams utilization of CFRP strips was about 80%. The results of the tests of beams, strengthened by Neoxe Prestressing System II, confirm generally known conclusions about the behaviour of reinforced concrete beams strengthened with prestressed CFRP strips. Therefore, they proved that the new system works properly.

5. APPLICATION ON-SITE

The last stage of research on the new strengthening system was practical on-site application at the existing RC bridge. The bridge is simply supported beam with cantilevers. The length of the middle span is 16.0 m and the length of both cantilevers is 5.5 m. Superstructure consists of four main RC beams braced by crossbeams and deck slab, all of them cast monolithically. The girders have a rectangular cross section with dimensions of 0.5×1.2 m. An angle between longitudinal axis of the bridge and the river is 50°.

In order to increase the bridge carrying capacity, the strengthening by prestressed CFRP strips of main RC beams in tension regions was designed. The strips were located at the bottom surfaces of beams in the main span and at the top surfaces of slab deck above beams over the supports and in the cantilevers. The location of strips in both cross-sections was presented in Fig. 7. Each strip was tensioned with force of 75 kN, which corresponded to strains equal about 5.6‰. A total of 48 CFRP strips were used to strengthen of the bridge.

The strips with the anchorages were prepared at the factory and delivered for the construction site in a bobbins. Installation was started following preparation of concrete and strips surfaces. For each strip at first passive anchorage was mounted to the concrete

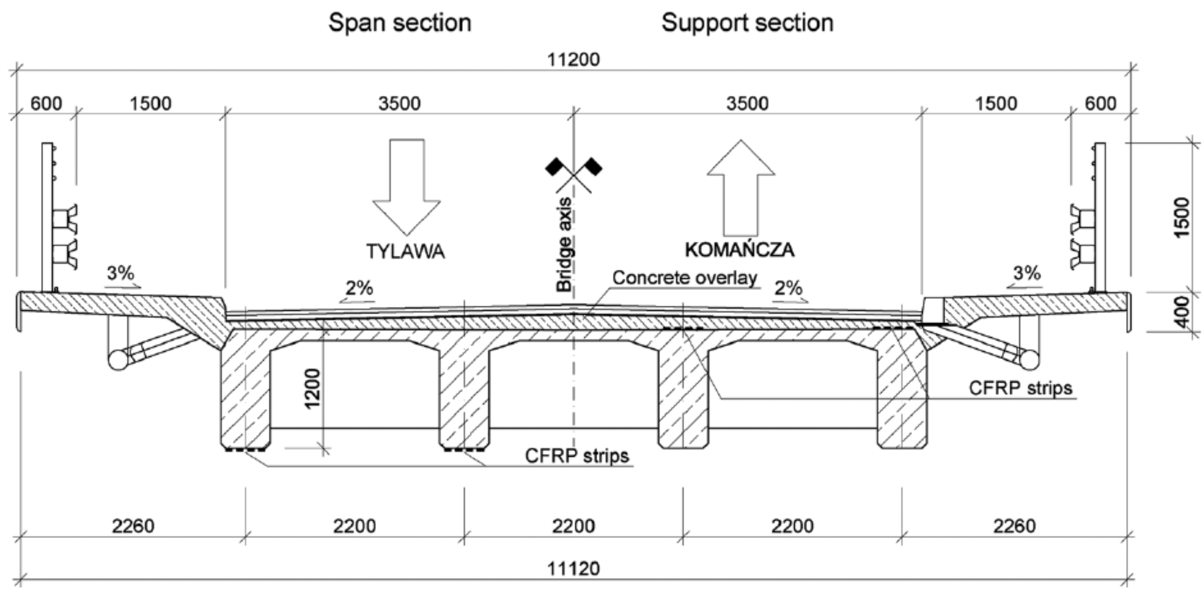

Figure 7.
Cross-section of strengthened bridge

surface, then the tensioning device was installed at active side, adhesive was applied on the CFRP strip and the strip was tensioned up to designed value of prestressing force. After tensioning, active anchorage was mounted and the tensioning device could be removed. In the last step strip was pressed to the concrete surface and excess of adhesive was removed.

The bridge was subjected to static load tests before and after strengthening works. The aim of the test was to evaluate the efficiency of strengthening the existing RC bridge using the NPS II system. During the tests beam's deflection in the middle span were measured along with strains of concrete, reinforcing bars and CFRP strips in the middle section of the span. Two trucks with a weight of 38 tons each were used for the tests.

There were no significant changes of the beam deflections due to strengthening with prestressed strips. The deflection in the first stage (performed before strengthening) and the second stage (after strengthening) was equal to 2.0 and 1.8 mm for beam B1 (outer) and B2 (inner) respectively. Such a result could be expected, because strengthening of RC beams (with quite large cross-section) by CFRP strips has negligible effect on their stiffness. The strip in fact cannot improve beam's moment of inertia and thus the stiffness of the beam. No reduction of beam deflection could be explained by the fact that the capacity utilization of the beams under applied load was very small. The beams were not cracked and in I phase of RC beam work the deflection change may be imperceptible. However, inducing a larger utilization of the beams was unreachable due to bridge geometry (span length of 16.0 m and angle 50°). The detailed analysis of the results was performed by comparison of the strains (stresses) measured under load. The effectiveness of the strengthening of the bridge beams can be checked based mainly on reducing the stress in the reinforcing steel. The mean value of tensile stress in the steel reinforcement bars obtained in the first stage was on average 28.3 MPa. In the second stage this stress was reduced to 21.8 MPa. Therefore, the average reduction of the stresses in the reinforcing steel due to strengthening was equal 23%.

The test results indicate that despite a slight utilization of the beam's carrying capacity, it was possible to observe the effects of the strengthening. In the second stage, after beams prestressing by the CFRP strips, there were significantly lower stresses in reinforcing bars than before strengthening. Moreover, strains noted in CFRP strips indicate that the strips were effectively incorporated into the cooperation in carrying loads. Based on the results it can be concluded that the strengthening of the bridge by NPS II system was performed properly, and its use was quite effective (at least at the expected level). The installation of the strips on the bridge was performed very efficiently. All elements of the system, both anchorages and tensioning device, passed the exam on the construction site. Strengthening was carried out at a rate of approximately 4 strips daily.

6. CONCLUSIONS

The new Polish CFRP prestressing system for strengthening reinforced concrete structures was shortly presented in the paper. After examination on RC beams in the laboratory and practical application on-site the system is ready to use for strengthening purposes.

Comparing the NPS II system to another CFRP prestressing solutions available on the market authors observe the following advantages of the new system thanks to applied strip anchorage method:

- the method comprises adhesive bonding with bolt gripping and friction action and thus sums up the advantages of these three joining methods;
- effects of prestressing are transferred to the strengthened structure just after mounting of active anchorage, without need to wait for adhesive curing;
- anchorages are mounted in factory and fully tested before delivering to construction site;
- geometry of steel anchorages can be designed to suit existing rebar layout and strip type;
- cutting the grooves in concrete is not required with this method;
- the method eliminates risk of the strip slippage during strengthening on-site and guarantees constant strip tension during setting of adhesive.

7. ACKNOWLEDGEMENTS

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