Rehabilitation of Prestressed Concrete Bridges by FRP Composites in the Light of in Situ Testing

Arkadiusz Mordak
Opole University of Technology, Poland

Zbigniew Mańko
The International University of Logistics and Transport in Wroclaw, Poland

The article presents the analysis of FRP composite materials strengthening systems for pre-stressed bridge structure elements. Displacements and strains of main beams of bridges were investigated before and after the strengthening executed by FRP composite materials. Test load field and theoretical analysis were performed after bridge structure repair. The results of bridge structures after strengthening in field load tests allowed for an assessment of the efficiency of the strengthening, as well as establishment of guidelines for future reference concerning this type of maintenance in the engineering practice.

Keywords: concrete bridges, FRP composites, displacements, strains, bridge structure repair.

1. INTRODUCTION

A lot of engineering structures connected with communication need to be rebuilt or strengthened to adapt them to actual traffic requirements. In Poland there are many structures, still in operation, which require intervention due to different reasons. They include both the bridge structures [6], [7], [8], [11], [13] as well as road pavements [14].

Traditional methods of concrete bridge structures strengthening, which are generally applied in Poland, are: an additional reinforcement (steel ribs or flat steel bars), steel flat bars gluing as an external reinforcement, external pre-stressed elements, reinforced concrete cross-sections. An alternative method is gluing FRP components to the tension concrete elements.

For a relatively short period of time, bridges in Poland were strengthened by carbon fiber strips, attached on the outer surfaces of concrete structural elements [1], [3], [11], [13]. This method requires a relatively simple technology and devices. For that reason, engineers become increasingly interested in applying this type of solution. As a result of an increasing interest and the efficiency of applying FRP (*Fiber Reinforced Polymers*) strips in bridge strengthening and still relatively high costs, there exists a need of their good and efficient usage. Thus, it is then purposeful to conduct appropriate experimental research on the strengthened, real objects to determine the behavior of such structures under known static and dynamic load.

The article presents the analysis of FRP composite materials strengthening systems for pre-stressed bridge structure elements. Displacements and strains of main beams of bridges were investigated before and after the strengthening executed by FRP composite materials. Test load field and theoretical analysis were performed after bridge structure repair.

The results of bridge structures after strengthening in field load tests allowed for an assessment of the efficiency of the strengthening, as well as establishment of guidelines for future reference concerning this type of maintenance in the engineering practice.

2. BRIEF DESCRIPTION OF THE BRIDGE

The tests were carried out on the five-span road bridge. Each span consists of six main girders integrated with the new reinforced concrete deck slab of B30 ($f_{cc} = 22.5$ MPa) concrete class. The total width of the individual spans is constant along the bridge length and it is 9.94 m (Figures 1, 2). The total length of the bridge is 98.60 m. The effective length of each of the spans is 18.00 m.

The particular spans are simple-supported and made from *Plonsk* type prefabricated pre-stressed concrete girders of length, L, of 18.50 m and are integrated with the RC deck slab over interior supports. The bridge was designed to serve under the I class load (300 kN) in accordance with the PN-66/B-02015 [9] (or C according to the PN-85/S-10030 [10]). The span interior crossbeams are made as pre-stressed concrete. The tests covered spans I and II (Figure 2). The bridge supports are in the form of massive concrete piers and abutments on spread foundation, fixed in a reinforced concrete footing. The foundation rests directly on the virgin soil. The main beams rest always on steel single-roller and fixed bearings (Figure 1). The roadway was covered with bituminous pavement, 0.09 m thick, with incorporated insulation of an average thickness 0.01 m (Figure 2). The usable width of the bridge amounts to 9.50 m, which includes the 7.00 m wide roadway and a 1.25 m sidewalk on each side.

(a)

(b)

Fig. 1. General side view from the direction of the headwater of the road bridge: (a) localization of four trucks on tested span II (load scheme IIS) and (b) bottom view on the girders strengthening by CFRP strips.

The strengthening of the particular bridge spans was accomplished by gluing the CFRP strips made of carbon fibers (three for each girder) to the bottom flanges of the main girders similar as [7]. Additionally, a new reinforced concrete deck slab of variable thickness 0.12–0.185 m was used, and also the outer stirrups in the form of steel flats of 5×50 mm section were added, with axial base by every 0.35 m [4], [5], [6], [12].

3. THE AIM AND RANGE OF RESEARCH

The static field load tests of the bridge included the following measurements (Figure 2):

- six main girders deflections (load-carrying structure) at their mid-span by dial indicators with 1×10^{-5} m accuracy;
- vertical and horizontal displacements of the chosen expansion and fixed bearings by dial indicators with 1×10^{-5} m accuracy;
- strains (stresses) in the main girders, which were performed by strain gages (extensometers) and mechanical indicators;
- strains in the strengthening strips in half and 1/4 of the effective span of the main girders;
- strains in the outside stirrups in bearing zones and in mid-span, which were performed by strain gages;
- vertical displacements in selected intermediate supports and abutments, and
- confirmation dimensions of each element of the span structure taken during a general bridge inspection (the technical condition of the span and support structures was inspected prior to, during and after the finish of the testing).

The static load tests were conducted for two nonsymmetrical and one symmetrical load schemes. All the measurements specified by the test loading program were taken exclusively under a static load [6]. Four trucks of the *KAMAZ* 5511 type loaded by soil dump with the total weight of 191.50 kN, were used in the tests (Figures 3 and 4).

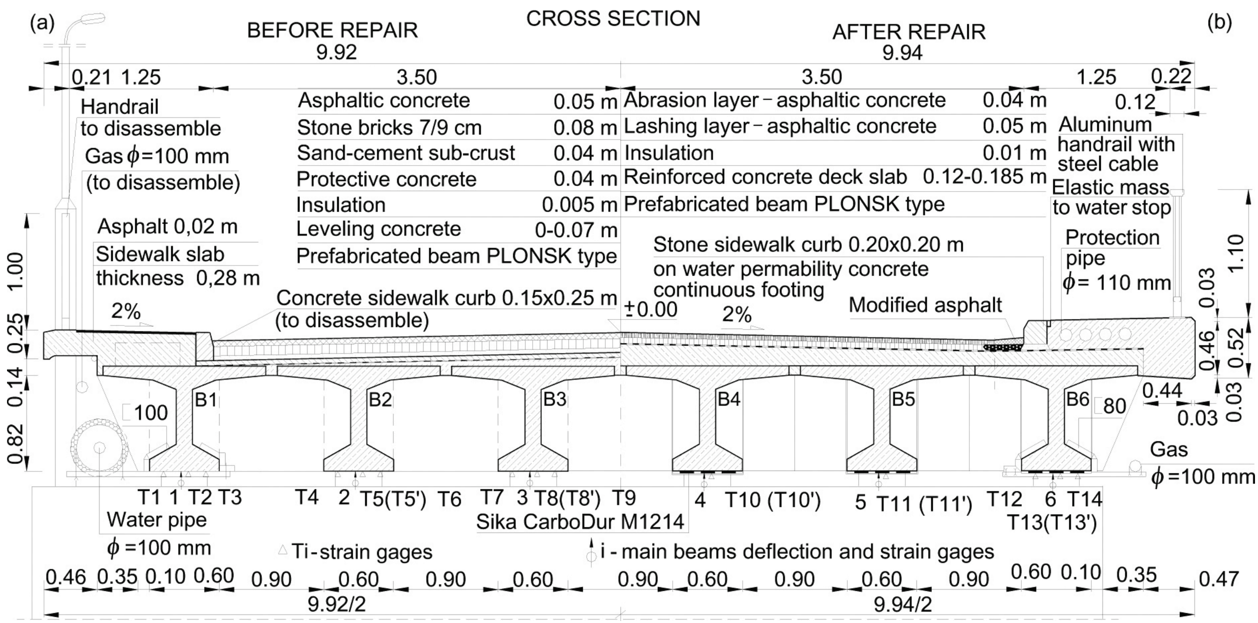


Fig. 2. Cross-section of spans and localization of measurement points: (a) before and (b) after, its repair.

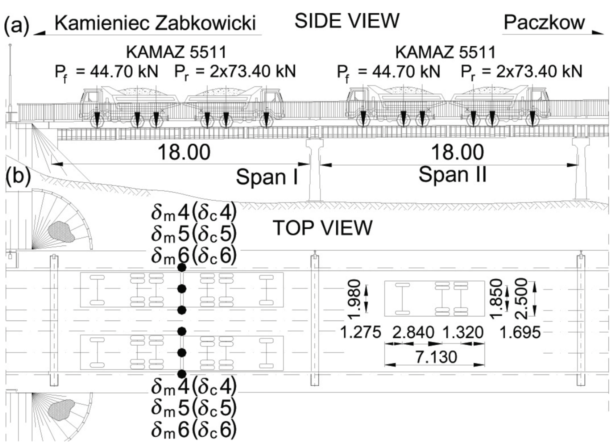


Fig. 3.Pre-stressed concrete road bridge and load cases distribution on bridge during field test: (a) side view from headwater, (b) top view – technical parameters of truck type KAMAZ 5511.

(b)

Fig. 4.Front view from Paczkow city centre on the span I loaded by: (a) two trucks (load scheme IN1) and (b) four trucks (load scheme IS) during field load tests.

(a)

4. CALCULATIONS

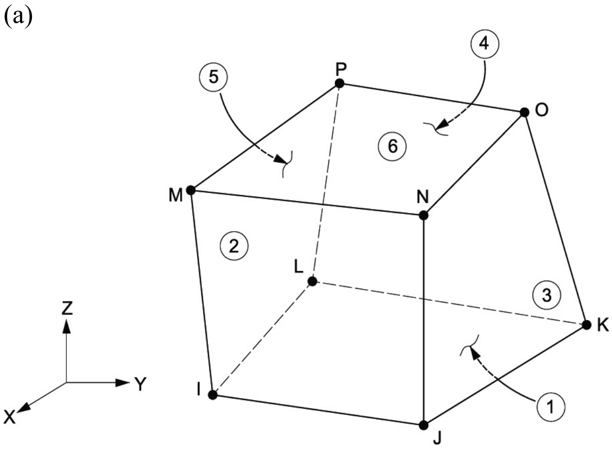
Numerical analysis of the structure, for example by using a computer with high computing power, is considered generally to be completely accurate. As it is known, no matter how accurate computer calculations are, the accuracy of the result, obviously, depends largely on the method used to define the mathematical structure and its boundary conditions to prepare input data for the calculations.

Two basic models of FEM calculation were used, executed with different types of elements, namely the grid model containing the rod elements with variable geometric characteristics and discreet 3D model composed of solid finite elements.

Typical elements (Fig. 5) available in the program COSMOS / M were used to create computational models of analyzed bridge span structures.

Constant material properties at each point of structural elements was assumed, which was modelled with isotropic and linear-elastic materials.

(a)



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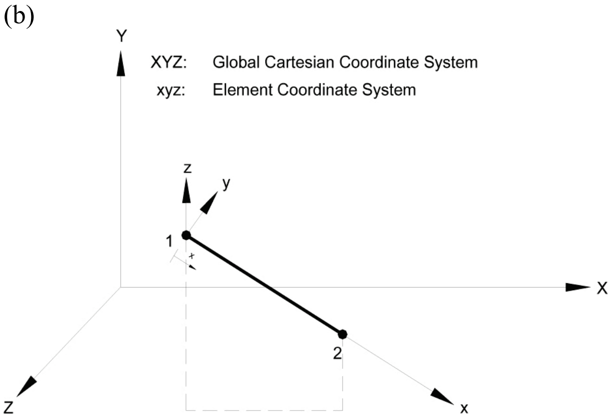
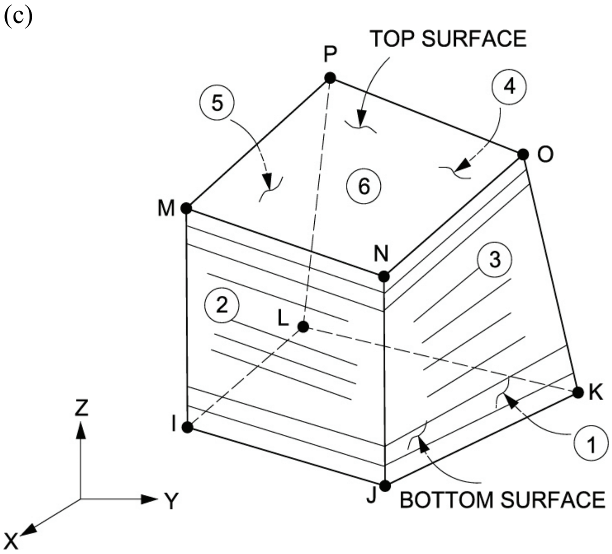


(c)



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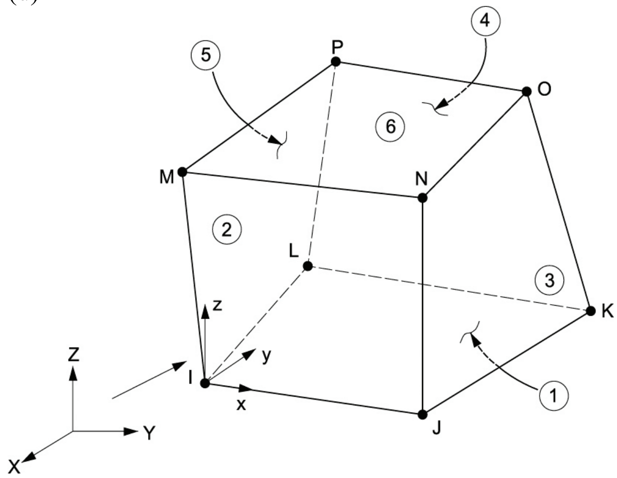

Fig. 5. Elements available in the program COSMOS / M used to create computational models of analyzed bridge span structures.

5. TESTS ORGANIZATION

The first two readings (zero readings) of all measurement devices had been made before introducing the load on the following examined spans. After introducing ballast on the span, the measurement devices gives the different readings every ten minutes, in at least 30-minute time. If the differences between the two following readings of deflections were lower than 1% of the total calculated deflection in 15 minutes, the measurements were aborted. On completion of all the measurements, there still occurred small differences in the values indicated by the measuring instruments, which was caused by regular traffic on the other lane of the road. Due to the lack of any possibility of stopping the traffic on the bridge during the research, the differences were included in the final result. In this way, four readings were made under the loaded span. Similarly, readings were made after unloading the span that is after every 10 minutes during the time of 20 minutes. Such readings were repeated at least three times.

The differences between the last readings of the dial gages (extensometers) after load removing and the first ones are the quantities of the permanent deflections (or strains), and between total deflections (strains) and permanent ones exists elastic values. The load had to stay on the span as long as the difference between two following readings was lower than 1%.

The measurements of the main beam support displacements were made in order to figure out if there were any substantial bearing or thin concrete layer settlements occurred. During the performed research of the particular bridge spans under the static load, also the research on supports settlement was made using the method of precise levelling.

Before the direct load of the bridge spans structure, the following actions were to be performed:

a) at the place of measurements of the displacements of the chosen load-carrying structure's elements (main beams), to set a special fixed scaffolds where tripods were placed to which dial or induction gages were attached,
b) to stick on the bottom surfaces of the main girders the strain gages (or to set displacement mechanical indicators based on the bars of 400 mm),
c) to stick on the bottom surfaces of the strengthening strips and on the bottom and sides surfaces of the outside stirrups strain gages,
d) to pull out the cables and connect them to measuring instruments, which were installed in the support truck,
e) to install all the gages and check correctness of their performance,
f) to weight the loading truck used in research,
g) to prepare documents (measurement logs) for recording readings from the measuring instruments and to instruct a personnel involved in the measurements.

6. EVALUATION OF MEASUREMENTS ACCURACY

The results of the strains and deflections measurements may be subject to some errors. The possible total maximal error of slow-variable strain ($t < 0.1$ s) should be within ±10% of the measured range. The lowest value of strain (in other words sensitivity or instrument resolution) that was possible to intercept, with determined error, was $\pm 1\times10^{-6}$.

The probable error of the main girders structure deflection of the span Δ_f in the most unfavourable set of converters and apparatus was determined from the formula (1):

$$\Delta_f = \sqrt{\Delta_1^2 + \Delta_2^2 + \Delta_3^2 + \Delta_4^2} = 3.39\% \qquad (1)$$

where, adequately $\Delta_1 = \pm 2.0\%$ – displacement converter error; $\Delta_2 = \pm 1.0\%$ – switch compensating unit error; $\Delta_3 = \pm 2.5\%$ – measurement amplifier (bridge) error; $\Delta_4 = \pm 0.5\%$ – calibration error.

The probable strain's measurement error Δ_ε (normal stress Δ_σ) in the element of the span's structure in the most unfavourable set of the apparatus is (expression 2):

$$\Delta_\sigma = \sqrt{\Delta_5^2 + \Delta\delta_6^2 + \Delta_7^2 + \Delta_8^2} = \pm 3.91\% \qquad (2)$$

where $\Delta_5 = \pm 2.0\%$ – extensometer (or mechanical indicator) error; $\Delta_6 = \pm 1.0\%$ – switch compensating unit error; $\Delta_7 = \pm 2.5\%$ – measurement amplifier error; $\Delta_8 = \pm 2.0\%$ – assumed concrete elasticity modulus error.

7. TESTS RESULTS AND ANALYSIS

The final results of bridge tests, conducted after the complete repair under the static load, allowed for a comprehensive evaluation of the efficiency of the main girders strengthening by applying CFRP strips (Figure 3). The maximal total main girders deflections measured during the research under static load oscillate between 1.37×10^{-3} m and 5.99×10^{-3} m (Table 1). The average deflection values of span cross-sections were smaller than calculated ones in all cases and did not exceed permissible values ($\delta_{perm.} = L / 800 = 18.00 / 800 = 22.50\times10^{-3}$ m). For the possible three load schemes to execute after the repair works average measured correspond to calculated elastic deflection relations were as follow: IS – 0.629, IN2 – 0.560, IN1 – 0.517 for the span I, and IIS – 0.598, IIN2 – 0.540, IIN1 – 0.508 for the span II. The measured main girder deflection distributions in span cross-sections were different than calculated ones (Table 1). It is proved that a real torsional stiffness of the bridge was higher than assumed in the static calculations [2]; [15].

The measured permanent deflections of the particular main girders differ inconsiderably among each other and are not proportional to elastic deflections as well as they do not exceed permissible values (less than 20% of elastic deflections or strains). The relations of the main girders permanent deflections to their total deflections and strains were established based on diagrams shown in report by Manko and Mordak [6]. The differences between the initial and the final readings found in measurements were approximately the same in all spans and examined main girders cross-sections. It may prove that they were rather a result of new bearings settlements or

Table 1. Results of total δ_m and ε_m (upper row) and calculated δ_c and ε_c (bottom row) deflections and strains of main girders of studied spans at the mid-span for all load schemes by measurement and calculation.

Span no	Load scheme number		Deflections δ_m and δ_c in (10^{-3} m)						Strains ε_m and ε_c in (10^{-6})					
			Main girder number											
			B1	B2	B3	B4	B5	B6	B1	B2	B3	B4	B5	B6
I	IS	measured	4.77	4.95	5.08	5.16	5.14	5.16	315	350	310	340	190	185
		calculated	504	5.47	5.74	5.77	5.55	5.18	347	334	324	326	337	351
	IN1	measured	3.81	3.55	2.79	2.21	1.58	1.06	180	130	160	175	10	100
		calculated	5.33	4.54	3.52	2.26	1.00	0.17	211	163	138	115	91	77
	IN2	measured	5.99	5.81	5.45	5.04	4.35	3.65	455	410	325	300	160	120
		calculated	6.93	7.26	7.06	5.93	4.14	2.08	401	377	355	333	308	266
II	IIS	measured	4.68	4.83	4.90	4.88	4.88	4.88	230	200	345	370	115	335
		calculated	5.04	5.47	5.74	5.77	5.55	5.18	347	334	324	326	337	351
	IIN1	measured	3.65	3.19	2.63	2.06	1.37	0.88	180	120	160	150	20	75
		calculated	5.33	4.54	3.52	2.26	1.00	0.17	211	163	138	115	91	77
	IIN2	measured	5.78	5.53	5.17	4.69	4.08	3.53	315	270	355	355	100	290
		calculated	6.93	7.26	7.06	5.93	4.14	2.08	401	377	355	333	308	266

under bearing joints and possible insignificant reading errors of the measurement instruments, and only to a minimal rate of the permanent strains of the pre-stressed main girders. This might have resulted in the occurrence of some insignificant settlements and differences in readings under proportionally heavy static load.

8. CONCLUSIONS

The practical experience gained from the testing of the road bridge and the observations concerning the behaviour of the structure of post-tensioned pre-stressed concrete girders of the *Plonsk* type made during the tests, as well as the comprehensive analysis of the results obtained from the tests and their comparison with the calculated values leads to specific conclusions as to the real behaviour of the structure of the individual spans of the bridge and allows one to form the following general conclusions [6]:

1. In the light of the tests that were carried out, the structures of the bridge span and supports did not raise any doubts. The deflections of the main girders are principally elastic. The minimal permanent displacements that were discovered are in part residual deflections of the main girders and partly caused by the bearings settlement of piers.
2. A satisfactory agreement of main beam deflections in all of tested spans was obtained in comparison with calculated ones in all cases for each structure element (stiffness of elements, layers thickness, etc.). This shows a correctness of assumptions taken for calculation and static-strength analysis of these spans or also the correctness of assumed analytical structure model with their real behaviour.
3. In most cases of tested main beams sections and elements of superstructure (deck plate) deflection and strains (and normal stresses which was calculated on their basis) during field load tests have had an elastic nature and even without consideration of bearing settlements and displacements have appeared mostly smaller than the calculated ones.
4. The grid model of variable load-capacity structure which was assumed for calculation in dependence of layers and strengthening strips seems to be sufficient tool to determine the deflections and strains in tested structures on an engineering level (what it shows also in the presented results) .
5. Small differences between the results obtained both from calculations and measurements, in range for deflections 11.74–24.32% and for strains 7.24–20.27%, shows correctness of assumed computational model.
6. Normal stresses in strips (which they were calculated on the basis of strain values) show unambiguously their load-capacity was used only in about 5–10%. However any strains were noticed in outer stirrups.
7. Application of additional concrete deck slab in pre-stressed concrete bridges is a more efficient strengthening solution than the CFRP strips gluing.
8. The differences in the expected deflections and strains of main beams in a relation to the obtained from measurements after the repair

of one half of bridge span provides that it was well interaction between a new bridge deck layer and pavement layers of roadway. However the applied of strengthening of main beams with CFRP strips and outer stirrups did not call out the significant changes in deflections and strains values of main beams.

In the fact, above summary and conclusions refer to the structures of the tested span elements of preset geometric characteristics, particular element stiffness, and determined effective spans. However, it may be stated that spans strengthening constructed by lamels and steel outer stirrups is not the best solution as far as this type of structures are concerned, mostly from the economical point of view. In order to use expensive CFRP strips to a higher extent, one should install on the girders already known pre-stressing devices for CFRP strips [4], [7].

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Arkadiusz Mordak
Opole University of Technology, Poland
a.mordak@po.opole.pl