SMAR 2015

# Pioneering strengthening of bridge girders with pretensioned CFRP laminates in Poland

Renata Kotynia[1], Michal Staskiewicz[1], Julien Michels[2], Christoph Czaderski[2], Masoud Motavalli[2]

[1] Lodz University of Technology, Lodz, Poland
[2] Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

ABSTRACT: The Polish-Swiss TULCOEMPA project between the Lodz University of Technology (TUL, Poland) and EMPA (Switzerland) showed a research collaboration in development of innovative methods for structural strengthening of existing bridge infrastructure and subsequent long-life monitoring using advanced wireless systems. The main aim of the project was a pioneer application of the innovative strengthening system with pretensioned carbon fibre reinforced polymer (CFRP) laminates of an existing bridge over the Pilsia River in Szczercowska Wieś (central Poland). The joint team from EMPA and TUL with technical support of S&P Switzerland and S&P Poland carried out the structural strengthening of five existing bridge girders in flexure and shear. The paper describes a full process of the bridge reconstruction and strengthening from the surface preparation through girders levelling and finally strengthening with anchorage by the gradient method.

## 1 INTRODUCTION

The road bridge over the Pilsia River located in Szczercowska Wieś (about 66 km southwest of Lodz) was built in 196. The bridge is located on the road connecting two new bridges, hence in order to increase the full road class, the bridge needed reconstruction and strengthening to upgrade the bridge load class. The existing structure of the bridge consisted of five 18.4 m long post-tensioned precast concrete I-girders supporting a reinforced concrete deck of 160 mm depth (Fig. 1). Three rectangular cross-beams were situated in the midspan and over the supports, connecting all five girders and the deck in transverse direction. The whole bridge was supported on two solid concrete abutments on both sides of Pilsia river. Modernization of the bridge consisted of two steps. In first, the existing deck was removed. As the bridge required widening, two new rectangular-section posttensioned concrete girders were installed on the widened abutments (in green on Fig. 2). Then a new concrete deck of 210 mm height was casted on the girders. Overall width of the bridge and road width increased from 7.4m and 6.0m to 9.7m and 8.4, respectively. After this reconstruction the flexural strengthening of the existing I-girders with externally bonded (EB) pretension carbon fibre reinforced polymer (CFRP) strips (in red on Fig. 2) was performed with the shear strengthening by using of EB CFRP vertical wrapping sheets (in blue).

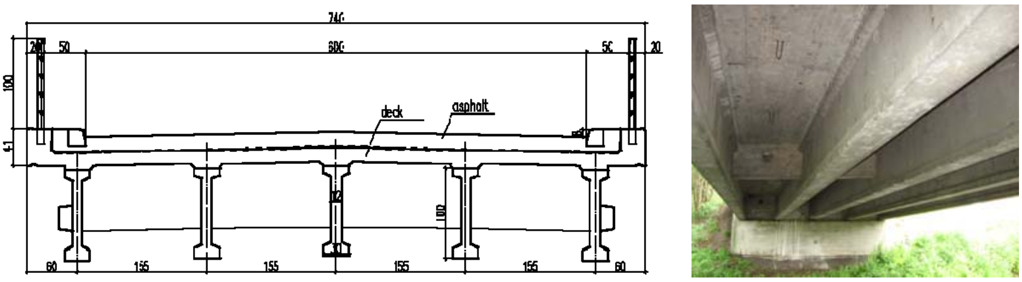


Figure 1. Bridge cross-section and bottom view of the bridge before reconstruction.

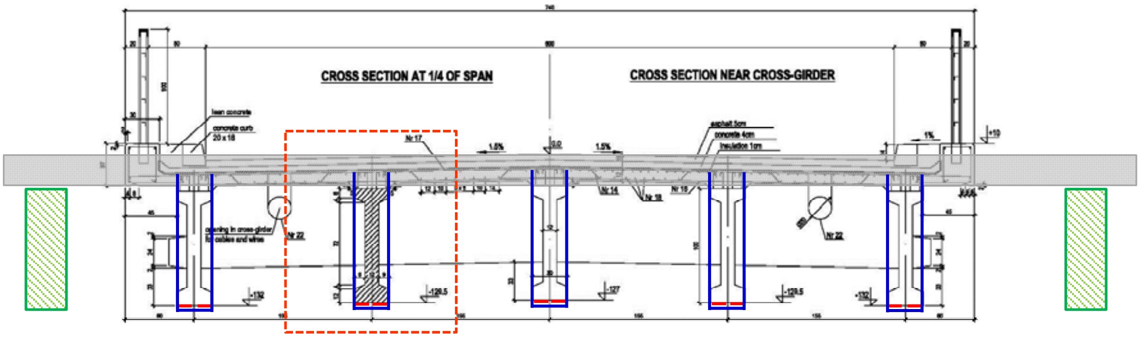


Figure 2. Range of bridge reconstruction.

Two 18.4 m long and 1000 mm deep full-scale girders based on the original 1965 Szczercowska Wieś bridge plans were fabricated and casted with class C35/45 self-compacting concrete following the drawings of the existing bridge construction. The first girder was served as a reference and the second one was strengthened with two prestressed CFRP strips. The initial negative cambering of the second girder was levelled out by a layer of dry shotcrete before the flexural strengthening. This girder was strengthened with the innovative, gradient anchorage method Stoecklin et al. (2003), Czaderski et al. (2007) and Michels et al. (2013).

The non-mechanical anchorage system avoided installation of steel bolts and plates, with the exception of a temporary support frame. The ends of the CFRP strips were anchored by sequential epoxy curing and force releasing in three steps, which reduced the prestressing force to zero at the strip ends. This allowed faster adhesive curing and the possibility of a stepwise transfer of the shear stress by gradually releasing the prestressing force at different curing stages. Two 100 mm wide and 1.2 mm thick CFRP strips ($E_f$ = 158 GPa) were pretensioned with 120 kN force to an initial pre-strain of 0.006. The gradient anchorage was applied over a length of 800 mm, with the force releasing in three steps. Shear strengthening required the installation of trapezoid-shaped concrete bolsters (ribs) in order to locally change the I-shaped girder to a rectangular section. The CFRP sheets of 75 mm wide and 0.9 mm thick with the modulus of 240 GPa were applied at a spacing of 1000 mm on the concrete ribs (see Fig. 3). The strengthened girder exhibited a ductile behavior up to strip rupture with a distinct steel yielding and a subsequent pronounced increase of the load carrying capacity. Comparison of experimental results of the strengthened and nonstrengthened girders indicated 24% ultimate load gain, 16% cracking load gain and 20% steel yielding load gain. Strengthened girder failed due to rupture of the prestressed CFRP laminates. No damage to the CFRP shear strengthening occurred. The maximum measured CFRP strain at failure was 0.010, corresponding to an ultimate strain of 0.016 including the prestressing strain. The transversal CFRP shear loops effectively held back debonding of longitudinal CFRP strips.

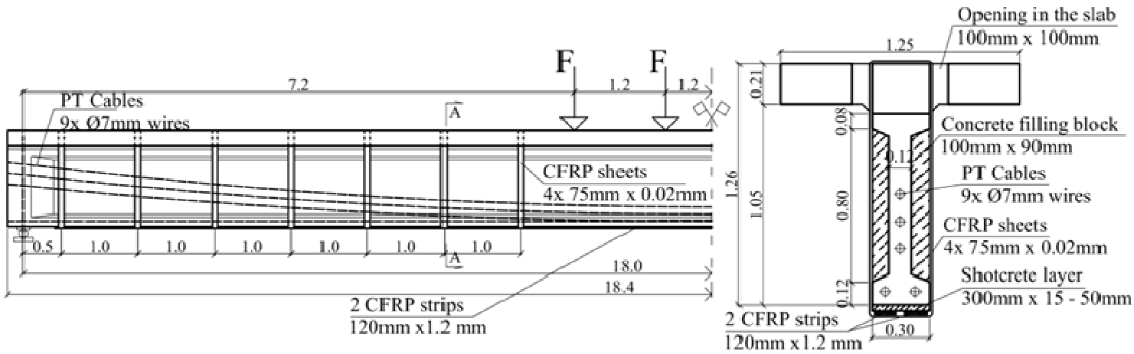


Figure 3. Scheme of laboratory girders, internal steel cables and strengthening configurations.

## 2 BRIDGE STRENGTHENING

Modernization of the bridge started with removing of the existing slab and the bridge widening with two new posttensioned concrete girders installed on both lateral sides of the bridge (Fig. 4). Then the new concrete slab was casted combining seven beams of the whole bridge structure.

Figure 4. Concrete bridge deck casting (top  and side view).

Bridge strengthening started with water-jet treatment of their bottom surface subjected to a stream of water under 2500bar pressure using the Trail Jet 100 device (Fig. 5).

Figure 5. Process of water-jet surface preparation, bottom surface after water-jetting.

Figure 6. Mounting of steel frames and L-shaped pieces mechanically fastened with bolts.

The process was repeated in support areas of all five girders, at the length of 2.5m on each side, to guarantee good bond properties in the gradient area. A total of ten U-shaped steel frames and sixty L-shaped pieces were installed on the bridge. In the first step longitudinal axis was set to mount the frames on both sides parallel to each other, against the curvature of the girder (Fig. 6). Following, holes were drilled along the axis and both U-shaped and L-shaped frames were glued and mounted with mechanical steel bolts.The reprofilation was performed with dry-shotcrete PCC mortar in one layer at the whole length of the girders (Fig.7) with the thickness equal to 15-20mm near the steel frames, up to 50mm in the midspan. Nearly 4.5 tons of mortar was used for the reprofilation, what equals to 900kg per one girder.

Figure 7. Reprofilation of bridge girders with dry-shotcrete, view the bottom girders.

### *2.1 Flexural strengthening*

The existing 5 bridge girders were strengthened in order from B1 to B5 (Fig. 8) similar to the Girder 2 in EMPA laboratory. For each application a strip of ca. 17.25m length was covered with epoxy resin (except for the last 50cm on each side) and glued to bottom concrete surface (Fig. 8). Two CFRP laminates S&P CFK 150/2000 of 100x1.2mm cross-section, prestressed with 120kN force were designed for application on each girder. The laminates were anchored with a gradient method. The prestressing force in the CFRP laminates was gradually reduced at the end sections by consecutive steps of accelerated epoxy curing and force releasing in hydraulic jacks. A total of 4 steps of reduction were done, each on 30cm long section of the laminate. After holding the ends of the strip in the prestressing devices, the heating boxes were installed on the girder, prestressing force was introduced and the curing procedure began. Heating and cooling process took 30 and 10 minutes, respectively. The prestressing force was reduced every 40min. Halfway through the process the heating boxes removed and mounted in different position, to extend the gradient zone.


Figure 8. Application of prestressed CFRP laminates with the gradient method.

Application of the prestressed strip resulted in an additional camber on the order of 0.15 – 0.30 mm. No loss of initial prestressing force in the CFRP laminate was observed during the strengthening of the first girder. During application of the first laminate on the second girder (2A), its debonding occurred approximately 1 hour after the application was finished, the debonding initiated in the first and second gradient sector of the laminate, on the southern side of the bridge. The CFRP detachment occurred due bond loosing between concrete and shotcrete mortar layer. The pull-off tests proved enough tensile strength of the materials, exceeding 1.5MPa at average. The deboning occurred due to unforeseen concentration of the shear stress in one of the gradient sectors, rather than material imperfections. After the CFRP strip debonding the girder B1 was repaired with the new PCC mortar and then strengthened. To avoid similar problems on other girders, the prestressing force was reduced from 120kN to 75kN, what corresponded to ca. 3.75‰ of prestrain.

## 2.2 *Shear strengthening*

For the shear strengthening 180 pieces of concrete filling elements casted at the laboratory of Lodz University of Technology were glued to the lateral sides of the girders for the purpose of the shear strengthening to make the rectangular cross-section at the respective locations (Fig. 9). The CFRP sheet wrappings were made with S&P C-Sheet 240 400g/m2. Sheets of 2.8m length and 75mm width were glued in four layers in designated places with the S&P Epoxy Resin 55. One layer of the flexible sheet had the original width of 300 mm and thickness of 0,13mm. It was folded four times to obtain a final width of about 75 mm and the thickness ca. 1 mm. The sheets were subsequently bonded to the concrete by wet-lay-up procedure around the total cross section. The CFRP ends were anchored in the sockets made in concrete deck. After the strengthening the sockets were filled with shotcrete mortar. Inside the socket longitudinal bars were mounted to hold the ends of the CFRP sheets. The bottom girders' corners were rounded to avoid the CFRP sheets rupture (Fig. 10).

In the last phase both CFRP laminates and CFRP sheets were covered with epoxy and quartz sand, for the purpose of finishing entire surface of the girders with plaster skimming and painting (Fig. 11).

Figure 9. Preparation of concrete trapezoid-shaped filling elements for shear strengthening.

Figure 10. Shear strengthening.

Figure 11. Bridge after strengthening and painting.

## 3 BRIDGE MONITORING DURING STRUCTURAL STRENGTHENING

To evaluate the effect of prestressing on the bridge deformability, deflections and concrete strains of the girders were measured continuously during flexural strengthening of each girder. The measurements consisted of: girders' deflection performed with a special laser interferometer, concrete strains measured with the electronic extensometer of 1290mm base length, concrete strains measured with the eddy-current-extensometer and CFRP strain registered by the electric strain gauges. All the measurements were situated in the girder midspan.

Concrete strains of the girders were measured out with two systems: a dial extensometer on 1290mm base length and a concept eddy-currents (Foucault-currents) extensometer developed by TUL team (Fig. 12). Results of the measurements showed that the thermal expansion of concrete had much higher influence on the concrete strains than prestressing of the CFRP laminates. Concrete strains changed by up to 0.15‰ due to the temperature changes. While the concrete strain changes due to CFRP prestressing were very small and even immeasurable. Moreover, in certain instances the strain changes had the opposite signs, depending on time of a day, what made the results more difficult to compare. High-precision measurements by the laser interferometer showed that girder's deflection reduced by 70-90μm during prestressing of the first CFRP strip and by additional 50-70μm during prestressing of second one. Thermal expansion of concrete had also a big influence on girders' deflection. Changes of deflections due to the temperature changes reached up to 230μm (Fig. 13).

Figure 12. Vertical deflections, concrete and CFRP strain measured during strengthening

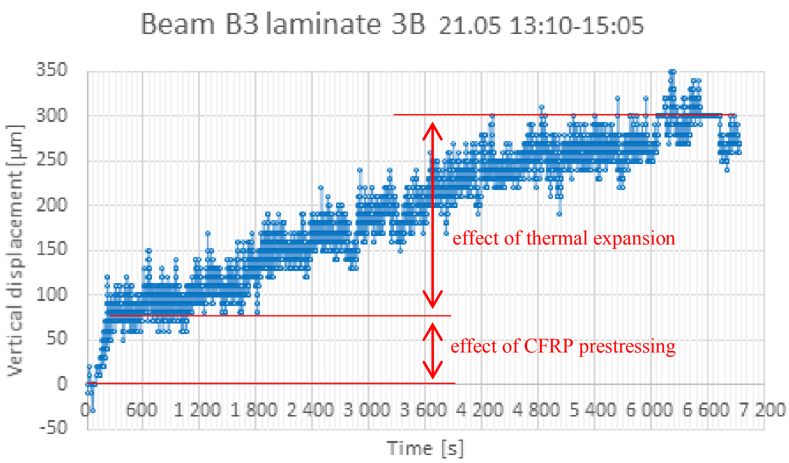

Figure 13. Vertical deflections of the girder B3 due to strengthening with prestressed laminates and thermal expansion.

A prestressing level of the CFRP laminates was measured with the strain gauges situated in the mid-span. Measurements were registered by two systems: classic data acquisition system paired with the computer and the wireless acquisition system sending collected data directly to servers via GSM network. Direct measurements of the CFRP strain confirmed proper designed pre-tensioning level and no loss of the CFRP pre-strain during the force-releasing steps in the gradient method. Wireless measurements system also registered environment temperature and humidity during the bridge strengthening.

### *3.1 References*

Stoecklin, I, Meier, U, 2003. *Strengthening of Concrete Structures with Prestressed and Gradually Anchored CFRP Strips*. Proceedings of FRPRCS-6, Singapore.

Czaderski, C, Motavalli, M, 2007. *40-Year-old Fullscale Concrete Bridge Girder Strengthened with Prestressed CFRP Plates Anchored Using Gradient Method*. Composites Part B: Engineering, 38(7–8), 878–86.

Michels, J, Sena Cruz, J, Czaderski, C, Motavalli, M, 2013. *Structural Strengthening with Prestressed CFRP Strips with Gradient Anchorage*. ASCE Journal of Composites for Construction 17(5), 651-661.

## 4 ACKNOWLEDGEMENTS

The authors acknowledge the financial contribution of the Polish-Swiss Research Programme (PSRP) for the financial contribution to the joint research TULCOEMPA project. Furthermore, the invaluable help of EMPA and TUL staff for related experimental tests were highly appreciated. Finally, the contribution to the strengthening application of the Swiss and Polish S&P Clever Reinforcement is acknowledged.