SWISS CONTRIBUTION | Polish-Swiss Research Programme | OPI OŚRODEK PRZETWARZANIA INFORMACJI PAŃSTWOWY INSTYTUT BADAWCZY

PROJECT COMPLETION REPORT
WITHIN THE POLISH-SWISS RESEARCH PROGRAMME
Part 1 – Scientific aspects

SPRAWOZDANIE KOŃCOWE
W RAMACH POLSKO-SZWAJCARSKIEGO PROGRAMU BADAWCZEGO
Część 1 – Aspekty naukowe

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SCIENTIFIC PROGRESS OF THE PROJECT/ POSTĘP NAUKOWY PROJEKTU

1. Scientific abstract/Abstrakt naukowy

The TULCOEMPA project based on the Swiss-Polish cooperation between the Lodz University of Technology (TUL) and the Swiss Federal Laboratories for Materials Science and Technology - Empa, in research and development of the innovative methods for monitoring in the civil engineering infrastructure. This multidisciplinary project lasting from 2011 to 2016, focused on sustainable development of civil engineering (CE) activities in increasing the load carrying capacity of bridges and their long-life monitoring with advanced wireless systems (ICT). The CE activities were expressed by the pioneer worldwide application of the innovative strengthening method using unanchored prestressed carbon fiber reinforced polymer (CFRP) laminates called "gradient system" on the existing Polish bridge. The system before the field application was successfully tested on the real scale replicas of concrete post-tensioned cable girders built and strengthened in the laboratory. The ICT part contained monitoring of multi-point system consisted of sentinel nodes, which were responsible for detecting events (upcoming trucks) and for triggering alert messages, and of monitoring nodes mounted on the bridge, which only upon receiving an alert message recorded and processed data of the event. A low power event driven structural monitoring system for bridges based on a wireless sensor network was developed. The monitoring system was tested under realistic operation conditions with several field tests on bridges in Switzerland and Poland. Initially simultaneous use of solar and wind energy was assumed, but due to vibrations introduced by the wind turbines on the bridge the system was powered only by the energy delivered from solar panels.

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2. Lay summary/Uproszczone streszczenie

Polska wersja uproszczonego streszczenia

Aspekty naukowe projektu obejmują trzy pakiety prac: WP3: ICT – Długotrwałe monitorowanie mostu; WP 4: CE - Eksperymentalne badania laboratoryjne; WP 5: CE – Wdrożenie - Demonstrator

WP3: ICT - Długotrwałe monitorowanie mostu

Systemy monitoringu oparte na sieciach bezprzewodowych czujników umożliwiają szybką instalację zmniejszając w ten sposób koszty monitoringu obiektów budowlanych. Ta zaleta, jednak może być w pełni wykorzystana tylko wówczas, gdy te sieci czujników zasilane z baterii mogą być używane przez wystarczająco długi okres czasu, ponieważ zbyt częste ich wymiany byłyby kosztowne i mogłyby obniżyć inne korzyści tego systemu. Energooszczędny tryby pracy jest zatem kluczowym problemem do rozwiązania, mającym znaczenie w konkurencyjności sieci czujników bezprzewodowych. W wielu systemach, zapis danych może być wymagany w bardzo krótkim czasie np. gdy oczekuje się istotnych rejestracji (np. przejazdu pociągu albo samochodu przejeżdżającego przez most). Taki system monitoringu sterowanego zdarzeniem ma szczególną potrzebę znaczącego oszczędzania energii. Aby zbadać wykonalność i skuteczność takiego systemu monitorowania, opracowano energooszczędny system monitoringu konstrukcji mostów oparty na sieciach czujników. System monitorowania składała się z węzłów, które są odpowiedzialne za wykrywanie zdarzenia (np. nadjeżdżającej ciężarówki lub pociągu) i wyzwalanie komunikatów – rozkazów dla odpowiednich węzłów systemu monitoringu zamontowanego na moście, który dopiero po otrzymaniu komunikatu ostrzeżenia, rejestruje i przetwarza dane zdarzenia. System monitorowania został przetestowany w rzeczywistych warunkach pracy w kilku badaniach poligonowych na mostach w Szwajcarii i Polsce. Opracowany system jest niezawodny pod względem wykrywania zdarzeń (powyżej 99%), a ponadto wskazuje, że procedura monitoringu sterowanego zdarzeniami pozwala osiągnąć znaczną oszczędność energii. Początkowo panowano jednoczesne wykorzystanie energii słonecznej i wiatrowej. Zrezygnowano z tego, gdy ze względu na drgania wywołane przez turbiny wiatrowe na słupach, system ulegał wzbudzeniom i zakłócał rejestrację obrazu. Z tego względu zrezygnowano z zasilania z turbin wiatrowych i pozostawiono zasilanie wyłącznie energią dostarczaną z paneli słonecznych.

WP 4: CE – Doświadczalne badania laboratoryjne;

Dwa rzeczywistej skali (1:1) dźwigary zostały wykonane wspólnie przez zespół TUL i Empa, następnie zabetonowane zgodnie z oryginalnymi archiwalnymi rysunkami mostu we Wsi Szczercowskiej. Jeden z dźwigarów wzmocniono naprężonymi taśmami CFRP metodą bezkotwową - zwaną również metodą gradientową z wagi na stopniowy spadek siły sprężającej na długości zakotwienia. badanie dźwigar został następnie instalowane przez dwie sprężonych taśm CFRP z kotwicowiska gradientu. Ze względu na dużą smukłość przekroju poprzecznego i obecność dwóch wewnętrznych stalowych cięgien w dolnej części przekroju belki, wykluczone było montowanie jakichkolwiek systemów wymagających zakotwień mechanicznych. „Zakotwienie gradientowe" polega na przyspieszonym wiązaniu kleju na skutek działania wysokiej temperatury (przyspieszone utwardzanie w wysokiej temperaturze). Siła sprężająca jest obniżana w kolejnych krokach, na kolejnych segmentach – odcinkach zakotwienia, co właśnie zapewnia redukcję sprężenia taśmy i bezpośrednio nawiązuje do metody gradientowej. Po wzmocnieniu na zginanie, wykonano wzmocnienie dźwigara na

ścinanie (rys. 1). Następujące wnioski można wyciągnąć z wyników badań doświadczalnych: użycie torkretu na sucho do wyrównywania ujemnej strzałki ugięcia przed wzmocnieniem okazało się skutecznym rozwiązaniem reprofilacji dźwigara, wzmocnienie przy użyciu naprężonych taśm CFRP wykazało wyraźną poprawę obciążenia wywołującego zarysowanie, uplastycznienie zbrojenia stalowego i nośności na zginanie, ponadto uzyskano odpowiednią plastyczność wzmocnionego dźwigara. Zainstalowane wzmocnienie na ścinanie spełniło swój cel, ale ponadto, ograniczyło zapewniło nieplanowany postęp odspojenia tej części taśmy, która została na zerwana w chwili zniszczenia elementu (rys. 2). Ta obserwacja jest niewątpliwie bardzo ważnym wnioskiem, w stronę zapewnienia bezpieczeństwa dźwigara w chwili jego zniszczenia i z całą pewności podnosi walory techniczne zaproponowanej metody wzmocnienia.
Badania doświadczalne rozszerzonej części projektu dotyczące sieciowania żywic epoksydowych w różnych warunkach termicznych przyniosły następujące efekty: a) potwierdzony został spadek wytrzymałości zaprawy na skutek zmiennego termicznie sieciowania b) wytrzymałość na rozciąganie nie zmniejsza się na skutek zmiennych procesów starzenia żywic, c) temperatura zeszklenia Tg po takich procesach nieznacznie maleje, ale nie ma to negatywnego efektu na połączenie kompozyt-beton.

WP 5: CE – Wdrożenie - Demonstrator

Pionierskie zastosowanie wzmacniania dźwigara na zginanie przy użyciu naprężonych taśm CFRP metodą bezkotwową (ze stopniowym spadkiem siły sprężającej na długości zakotwienia taśmy) z sukcesem przeprowadzone w badaniach laboratoryjnych WP 4, zaaplikowano po raz pierwszy w świecie na istniejącym moście w Szczercowskiej Wsi (centrum Polski). Przed reprofilacją dolnej powierzchni dźwigara przy użyciu suchego torkretu PCC, dolną powierzchnię dźwigara przygotowano metodą strumienia wodnego, co oczyściło idealnie tę powierzchnię z luźnych części betonu. 5 istniejących dźwigarów mostowych wzmocniono dwiema taśmami CFRP sprężonymi siłą 120kN. Wzmocnienie wykonano metodą bezkotwową zwaną też gradientową (od redukcji siły sprężającej). Po wzmocnieniu na zginanie wykonano wzmocnienie na ścinanie przy użyciu mat CFR (Fig. 3). Aby ocenić wpływ sprężania dźwigarów na odkształcalność mostu, w trakcie wzmacniania wykonano badania ugięć – metodą bezprzewodowego czujnika laserowego ugięć a pozostałe dźwigary monitorowano w sposób ciągły podczas procesu wzmocnienia każdego dźwigara. Pomiary są jeszcze zarejestrowane przez dwa systemy: klasyczny system zbierania danych i bezprzewodowej systemu gromadzenia i wysyłania zebranych danych bezpośrednio do serwerów za pośrednictwem sieci GSM. Ten drugi pozwala na bieżące monitorowanie odkształceń mostu.
Przed i po wzmocnieniem mostu wykonano próbę obciążeniową wymaganą, jako test dopuszczenia mostu do użytkowania (rys. 4 – wygląd mostu po rekonstrukcji).

<u>English version of Lay summary</u>

Scientific aspects covered three work packages:WP3: ICT - Structural health monitoring of the bridge; WP 4: CE - Experimental laboratory tests; WP 5: CE – Demonstrator

WP3: ICT - Structural health monitoring of the bridge

Monitoring systems based on wireless sensor networks enable a rapid deployment thus reducing the costs of structural monitoring. This advantage, however, can only be fully exploited if these battery powered sensor networks can be operated during a sufficiently long period of time since a too frequent battery replacement would increase the maintenance costs and nullify the advantages of rapid deployment. Power efficient operation modes are therefore paramount for the competitiveness of wireless sensor networks. In many applications, data recording can be limited to those short periods of time when relevant data is expected (e.g. a train or truck passing a bridge). Such an event driven monitoring policy has the potential for a significant power saving. To investigate the feasibility and performance of this monitoring policy, a low power event driven structural monitoring system for bridges based on a wireless sensor network was developed. The monitoring system consisted of sentinel nodes, which were responsible for detecting events (e.g. upcoming trucks or trains) and for triggering alert messages, and of monitoring nodes mounted on the bridge, which only upon receiving an alert message recorded and processed data of the event. The monitoring system was tested under realistic operation conditions with several field tests on bridges in Switzerland and Poland. It performed very reliable in terms of event detection (hit rate greater than 99%) and demonstrated that the event driven monitoring policy enables to achieve a significant power saving. Initially simultaneous use of solar and wind energy was assumed, but due to vibrations introduced by the wind turbines on the bridge the system was powered only by the energy delivered from solar panels.

WP 4: CE - Experimental laboratory tests;

Two real scale (1:1) girders were performed in accordance with the original archival drawings of the bridge in Szczercowska Wies by the common team from TUL and Empa. One of the girders was strengthened with two pretensioned CFRP laminates according to the unanchored gradient method. This method based on a gradient reduction of the prestressing force along the anchorage length of the laminate. Due to the high slender cross-section and the presence of two internal steel rods in the lower part of the beam section, installation of systems requiring any mechanical anchorage were not permitted in order not to cut the existing cables. Anchorage gradient method referred to the special curing of adhesive, accelerated by the action of heat (accelerated curing at high temperature). Prestressing force was reduced in the following steps, on the following anchorage segments. After flexural strengthening with the prestressed laminates, the shear strengthening with vertical wraps was applied (Fig. 1). Several conclusions can be drawn from the test results: using dry shotcrete for levelling of a negative cambering due to internal prestressing was an efficient solution, using prestressed CFRP strips for structural retrofitting showed a clear enhancement of the cracking load, yielding load and ultimate load carrying capacity with a sufficient ductility. Tensile failure of the carbon fibres was the final failure mode, indicating the most efficient use possible of the material (Fig. 2). The installed CFRP shear reinforcement seemed to have a positive effect on the overall bond behavior between the flexural strips and the shotcrete substrate by prohibiting an end-anchorage debonding or a progressive delamination close to the ultimate load and thus allowing to further profit of the composite's tensile capacity.

Experimental studies in the extended part of the project related to the long-term behavior of epoxy resins used for structural engineering. The main results are the following: a) reduction in the tensile strength when an initial accelerated epoxy curing was confirmed, b) tensile strength does not decrease after the mentioned ageing processes, c) glass transition temperature is slightly reduced, but not in a relevant way for structural purposes.

WP 5: CE – Demonstrator

The pioneering application of strengthening method successfully tested in WP 4, was performed on the bridge in Szczercowska Wies (centre of Poland) in the same way and by the same team as in the laboratory. Strengthening started with water-jet treatment of their bottom surface subjected to a stream of water, then reprofilation was performed with dry-shotcrete PCC mortar. The existing 5 bridge girders were strengthened with two CFRP laminates prestressed with 120kN force. The laminates were anchored with a gradient method. Then shear strengthening was applied (Fig. 3). To evaluate the effect of prestressing on the bridge deformability, deflections and strains of the girders were measured continuously during flexural strengthening of each girder. Measurements are still registered by two systems: classic data acquisition system and the wireless acquisition system sending collected data directly to servers via GSM network. Before and after strengthening the trial loading tests were performed required, as a test of admission bridge to the public usage (Fig. 4 – view of the bridge after reconstruction).

3. Scientific report/Raport naukowy

Scientific Report followed the main structure of the project that covers three work packages:WP3: ICT - Structural health monitoring of the bridge; WP 4: CE - Experimental laboratory tests; WP 5: CE – Demonstrator

WP3: ICT - Structural health monitoring of the bridge

The goal of the ICT part of the project was to develop and investigate the performance of a low cost and power event driven structural monitoring system for bridges based on a wireless sensor network. The monitoring system consisted of sentinel nodes, which were responsible for detecting events (e.g. upcoming trucks or trains) and triggering alert messages, and of monitoring nodes mounted on the bridge, which only upon receiving an alert message recorded and processed data of the event.
The work addressed 4 main topics.

First, a low power strain sensing hardware was designed and implemented. Strain sensing occurs very often in structural monitoring applications. The predominantly used sensors, strain gages, however, have a power consumption (ca. 60 mW) that is ten times greater than the typical power consumption of sensors used with wireless sensor networks. Such power consumption would quickly deplete the batteries and therefore dramatically reduce the competitiveness of wireless sensor networks. By modifying the signal conditioning circuit, the power consumption of the novel hardware is a factor 3 to 6 smaller than existing hardware. The power saving could be achieved without impairing the signal to noise ratio (ca. 1 μm/m rms). A low power 24 bit analog to digital converter enables to achieve a high resolution (0.5 μm/m) without penalizing the amplitude range (±15'900 μm/m) [2] .
Second, an algorithm for strain cycle identification was developed which enable to reduce the data that has to be transmitted over the network to a few % of the original recorded data size. Indata intensive applications, such as vibration or strain cycle monitoring, transmitting all the recorded data would exceed the data throughput capacity of the network and also quickly deplete the batteries since data transmission is very expensive in terms of power consumption. The novel algorithm identifies strain cycles within a record that are greater than a given threshold since in fatigue assessment of metallic structures small amplitude cycles below the endurance limit are neglected. The embedded data processing is very fast. A

record of 2048 samples is processed in less than 100 ms. [2]
Third, sentinel nodes were developed for detecting events for railway and road bridges. For railway bridges rail vibrations were used to detect upcoming trains. The sentinel node senses permanently vibrations with a low power MEMS accelerometer (0.6 mW) and analyses the recorded data by embedded data processing. The event detection algorithm checks the data for exceedance of an amplitude threshold. If the threshold is exceeded in two consecutive data records the sentinel node identifies an event and broadcasts an alarm message [1].
The event detection situation is much more complex on road bridges. On these bridges only trucks or busses are generating effects on bridges that require to be recorded. Cars, delivery vans and delivery trucks are too lightweight to produce effects that are of interest. Therefore, sentinel nodes must have the ability to discriminate trucks and busses from all other vehicles. This discrimination has to be performed nearly in real time and with sensing devices that are sufficiently low cost and low power and quickly deployable. Truck recognition is performed by estimating the size of a vehicle. The height of the vehicle is detected with a sonar and the length with three magnetic field sensors (Figure 1a). The sonar enables to identify cars by mounting it at a certain height (e.g. 2.5 m) over the road pavement. All vehicles reflecting back the sonar signal are considered as potential heavy vehicles. Cars, which represent the majority of vehicles, are thus sorted out. Three magnetic sensors detect changes of the magnetic field induced by passing vehicles (Figure 1b). By comparing the detection time of the magnetic sensors the speed and the length of the vehicle can be estimated. Short and light vehicles like delivery vans and trucks can be sorted out by using a length threshold. Vehicles that exceed both the height and length threshold are considered as heavy trucks and originate an alarm message.
Fourth, a novel flooding protocol was developed for notifying the monitoring nodes about the upcoming event by using alarm messages. The notification by the sentinel node must be fast and reliable in order to avoid data loss due to late reception of the alarm message. An alarm message is broadcasted by the sentinel node each time an event is detected. Network nodes receiving the alarm message rebroadcast it several times in order to increase the likelihood to be received by all nodes of the network. Tests showed that a reception rate of more than 99% can be achieved by repeating the message three times [1].

a)

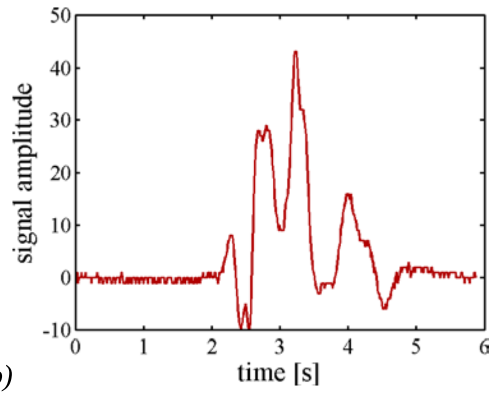
b)


Figure 1: Truck recognition system deployed on the road. Detail of a magnetic field sensor (top left) and of the sonar mounted on a pole (bottom right). b) Magnetic field sensor signal induced by a passing truck.

Several field tests were performed to assess the performance of the monitoring system and in particular the novel components under realistic operation conditions. A first field test on a railway bridge was performed to evaluate the strain sensing hardware and strain cycle identification algorithm [2]. The strain sensing hardware worked reliably and was able to provide high quality data (resolution about 1 μm/m rms) which completely complies with the requirements of fatigue assessment. Embedded data processing performed *reliably as well. In this test, train detection was not performed with sentinel nodes but by embedded data processing. The failure rate of train detection was failure rate was about 0.6%. The estimated operation lifetime of monitoring nodes with a set of batteries was about 25 days since strain sensing was performed permanently. A similar test was performed on the retrofitted road bridge in Poland which confirmed the results regarding data quality and reliability that were obtained with the previous test.*

A third test on a railway bridge was performed to evaluate the performance of train detection by sentinel nodes and the alarm messages notification mechanism [1]. During the test 3728 events occurred. Train detection by sentinel nodes was completely safe. The alarm messages notification was fast. 99.9% of the alarm messages were received by the monitoring nodes in less than 0.5 s. The alarm messages average reception rate of the monitoring nodes was 98.7%. The expected operation lifetime of monitoring nodes was about 100 days. Four times more than when monitoring nodes are recording data permanently. Currently, an additional field test with an improved alarm messages notification mechanism is ongoing. This mechanism synchronises communication of the monitoring nodes with the sentinel nodes to increase the alarm messages reception rate of monitoring nodes and to reduce the power consumption of the alarm message delivery process. The results are so far promising since the alarm messages average reception rate of the monitoring nodes was better than 99. 8%.

The field test for evaluating the truck detection system on road bridges is also ongoing. The hit rate for detecting potential heavy trucks with the sonar is 100%. Cars are therefore sorted out very reliably. The discrimination between large trucks and small delivery trucks by length estimation with magnetic field sensors is less reliable. At low vehicle speeds (20-40 km/h) the hit rate is about 80%. A better performance above 90% is achieved at higher vehicle speeds (60-80 km/h). Additional optimisation steps and tests will be performed to achieve higher hit rates. Since small delivery trucks represent about 20% of trucks the truck detection could be operated only based on sonar data with limited effect on power efficiency since the majority of vehicles, cars (90% of vehicles), are sorted out safely.

Apart from various types of sensors deployed by Empa there was the image analysis utilization proposed, as the most reliable and the least invasive method by TUL. To deliver appropriate solution, the dedicated hardware platform with a sufficiently high computing power was developed and the image processing and analysis algorithms were implemented. In the observed image the contours of the moving objects have been detected. Their overall sizes have been analysed and thresholder in order to identify trucks. During the algorithm development the changes in the image background changes caused for example by wind blast occurred to became significant problem. However, the suitable algorithms allowed to eliminate this problem.

Initially simultaneous use of solar and wind energy was assumed. Unfortunately, the vibrations introduced by the wind turbines caused problems with the correct identification of vehicles by the vision system. Utilization of more complex image analysis methods did not lead to the expected improvement. Finally, the system is powered only by the energy delivered from solar panels.

The implementation of the vehicle weighing subsystem occurred to be complicated task. The typical weighing platform installed in the road surface was unstable in terms of generated signals. There was developed a dedicated measurement system which process them and performs a preliminary analysis. In the case of heavy vehicle detection, the obtained measurement data is sent for further analysis. Due to the interferences observed, at present the system classify the weight of vehicles which goes through the bridge.

The measurement data together with the information about the heavy vehicle detection goes through GSM network to the server database (Fig. 2). Due to the variety of systems monitoring of the bridge condition, it was necessary to implement different communication interfaces. In order to visualize the measurement results the user interface was prepared. It ensures remote access to information through a Web browser and their export for further analysis.

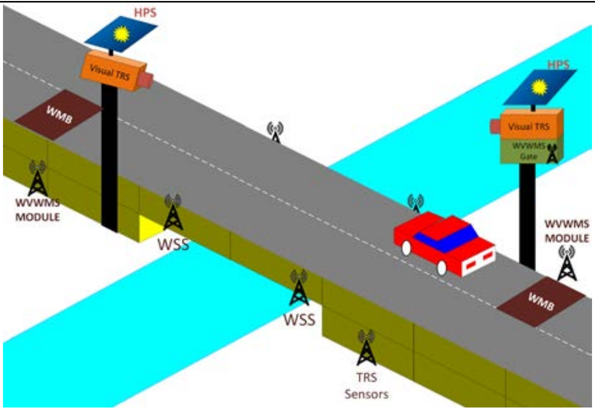


Figure 2: Subsystems deployed on the bridge – Wireless Strain Sensors, Truck Recignition System and Wireless Veight Measurement System

After some time of the whole system operating some problems occurred. Lack of system responsibility caused the need to its main component disassembly. It occurred that there were different reasons of the situation. First of all, the SD memory cards delivered with the OMAP platforms has failed. These cards are used to store the firmware of the OMAPs and locally store the acquired data. Probably the problem was caused by data storage system (EXT3) used in Linux based embedded systems. The issue is to use such memories of industrial grade. The second problem has been arisen from very deep discharge of the batteries in the system void of wind turbines. This problem was resolved by implementation of additional protection routines implemented in battery monitoring software. Additionally, because the cameras are useless at night, they are introduced in the suspend mode. After these modifications and some component replacement system was tested in the laboratory. In the nearest future it will be again installed on its destined place.

The vision system tests lead to a conclusion that huge impact on TRS have vibrations coming from the wind turbines of supply system. Because of this some additional image processing complex methods were implemented to solve this problem. The further tests showed that none of them improved the system quality – the distance to the tested objects is too long. What is more the new algorithms significantly increased the power consumption. Finally the wind turbines were dismounted.

In summary, this work demonstrates for the first that event driven monitoring with wireless sensor networks is feasible. It could be operated with high reliability and it was demonstrated that a significant power saving could be achieved. Since even for strain monitoring operation lifetimes of up to 6 months are achievable, wireless sensor networks have a great potential to reduce significantly the costs structural monitoring.

WP 4: CE - Experimental laboratory tests (common research work of EMPA and TUL);

Experimental research contains two main parts: Experimental tests of the bridge girders and Experimental tests of epoxy resins behaviour

WP 4.1 Experimental tests of the bridge girders

Two 18.4-m-long large-scale prestressed concrete girders were produced following the drawings of the existing Polish bridge construction. After casting, the second fabrication step comprised the prestressing of three parabolic and two straight steel tendons. Initial negative cambers at a midspan of approximately 33 mm were measured for both girders. Last, a part of the new upper concrete deck with a width of 125 cm and a thickness of 21 cm was casted. The complete cross section is shown in Fig. 3.

Flexural strengthening performed with two laminates made of carbon fibre reinforced polymer (CFRP) bonded to the bottom surface of the girder with two component epoxy resin. The CFRP strips had a width of 100 mm and a thickness of 1.2 mm. According to the distributor, the strips have a nominal elastic modulus of 165GPa, which was used later for deriving the total prestressing force from the measured pre-strain. Tensile tests on small strip specimens were performed according to DIN-EN-ISO-527-5 (DIN 1997) and revealed a unidirectional tensile strength of 2,795 (6115) MPa at an average failure strain of 1.6%. CFRP wraps with an elastic modulus above 240 GPa and a strain at failure of 1.7% were installed as shear reinforcement.

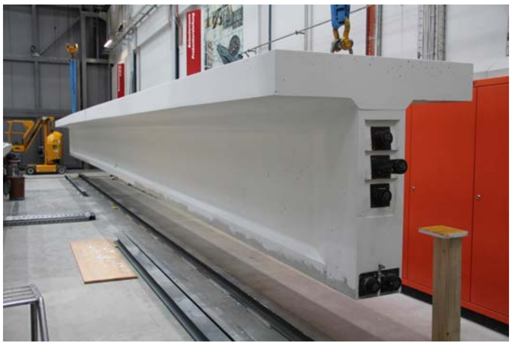


Figure 3: Posttensioning of the concrete girder with steel cables (left) and the full T-section girder after slab concreting(right) [3].

The surface-levelling procedure was chosen according to a preceding experimental investigation on the bond behavior of CFRP strips with various cementitious substrates [4]. Subsequently, dry shotcrete was applied. The maximum camber level at midspan was approximately 60 mm. Each CFRP strip was prestressed to a strain level of 0.58%, which corresponds to a prestressing force of approximately 115 kN. The gradient anchorage at the strip ends was realized according to [4], three consecutive force releases (DF) of 50, 35, and 35 kN over 300-, 200-, and 200-mm bond lengths, respectively (Fig. 3). Prior to the application of the shear strengthening, concrete filling elements were installed to dispose of a regular cross-section geometry at the respective locations. The shear strengthening with CFRP wraps were subsequently bonded to the concrete by a wet-lay-up procedure around the total cross section to include the compression zone (Fig. 4).

Figure 4: Flexural and shear strengthening of the posttensioned concrete girder with prestressed CFRP Laminates (left) and CFRP wraps (right) [3].

The reference and strengthened girders were tested in the test setup presented in Fig. 5 with the span of 18.0 m. The applied loads consisted of total four actuators at a distance of 1.2 m (Fig. 5). Deflections were *measured at several locations by LDVTs, strain gauges were used to assess the concrete compressive strain at the top plate as well as the CFRP strain in tension on both strips at the bottom side.*

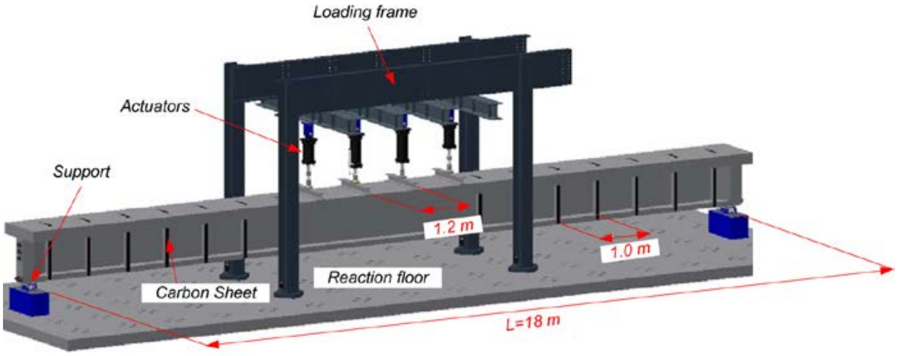


Figure 5: Test set up [4]

Test results indicated increase in: the cracking load by 16%, in the yielding load by 19%, and in the ultimate load by 24% (Fig. 6). A ductile behavior of the strengthened girder was observed with the tensile failure of the CFRP strips. Several conclusions can be drawn from the test results: using dry shotcrete for levelling of a negative cambering due to internal prestressing was an efficient solution, using prestressed CFRP strips for structural retrofitting showed a clear enhancement of the cracking load, yielding load and ultimate load carrying capacity with a sufficient ductility. Tensile failure of the carbon fibres was the final failure mode, indicating the most efficient use possible of the material. The installed CFRP shear reinforcement seemed to have a positive effect on the overall bond behavior between the flexural strips and the shotcrete substrate by prohibiting an end-anchorage debonding or a progressive delamination close to the ultimate load and thus allowing to further profit of the composite's tensile capacity.

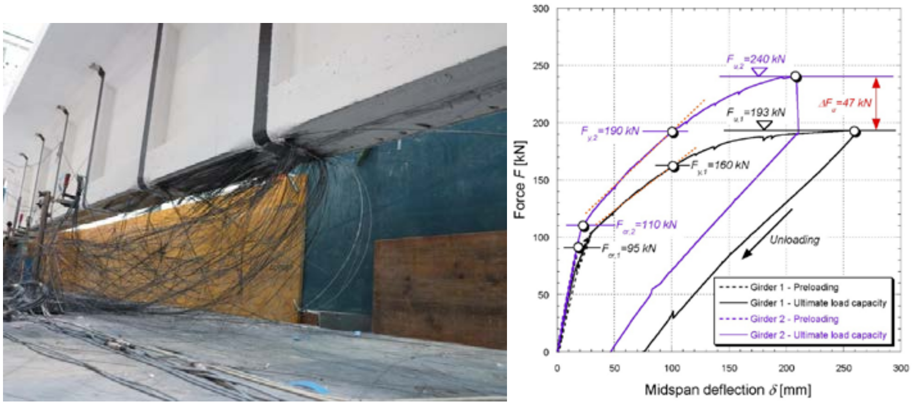


Figure 6: Failure mode of the strengthened girder (left) and measurements of deflection in the reference and the strengthened girder (right) [4]

WP 4.2 Experimental tests of epoxy resins behaviour

Nowadays, many existing constructions need reparations due to their age and the related deterioration due to environmental exposure. One commonly used practice are composite materials in shape of laminates or fabrics that are applied on the existing structure to upgrade the structure's load carrying capacity. Normally, these composite materials are bonded to the substrate by means of epoxy resins. One key question currently strongly discussed deal with the question about the epoxy resins' mechanical and physical characteristics on the long-term. In case of a decrease, the retrofitting itself would not be able to fulfil its purpose anymore. The investigation in the framework of this project specifically deal with the remaining mechanical (strength) and physical (resistance to high temperatures) of such epoxy resins in *civil engineering. Material specimens were tested before and after three different ageing categories, namely exposure to freeze-that cycles and immersion to water and water with chlorides. Results indicated that the strength and temperature resistance ('glass transition temperature') remain almost unchanged even after severe ageing processes. Special attention has to be paid however to potential interface (epoxy/concrete) problems.*

Another research referred to variable curing temperature and curing time indicated the following conclusions: initial accelerated curing (IC) under temperature 70 / 100 degrees reduces the time of curing but the time of curing is absolutely decisive parameter influencing the shear strength of the epoxy; the presence of high thermomechanical properties of tested epoxy adhesives indicated significant exothermic effect of curing process, however, the presence of the greater exothermic effect reduces considerable the cross-linking time and technical service life, it makes the use of such adhesives unavailable for practical conditions.

WP 5: CE – Demonstrator

The road bridge over the Pilsia River located in Szczercowska Wieś 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. 7). Three rectangular cross-beams were situated in the midspan and over the supports, connecting all five girders and the deck in transverse direction. 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. 7). 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. 7) was performed with the shear strengthening by using of EB CFRP vertical wrapping sheets (in blue).

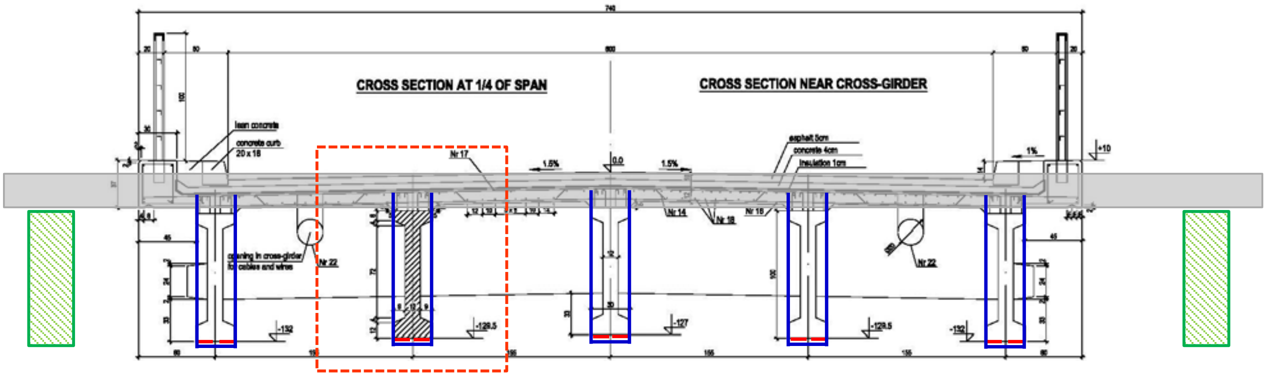


Figure 7. Range of bridge reconstruction.

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. 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 (Fig. 8). A total of ten U-shaped steel frames and sixty L-shaped pieces were installed on the bridge.

Figure 8. Process of water-jet surface preparation, bottom surface after water-jetting.

The existing 5 bridge girders were strengthened in order from B1 to B5 similar to the Girder 2 in the laboratory tests. 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. 9). 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 (Fig. 9). A total of 4 steps of reduction were done, each on 30cm long section of the laminate. 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.

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.

Figure 9. Application of prestressed CFRP laminates with the gradient method and shear strengthening

To evaluate the effect of prestressing on the bridge deformability, deflections and 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, concrete strains measured with the eddy-current-extensometer and CFRP strain registered by the electric strain gauges.

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. 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. 10).*

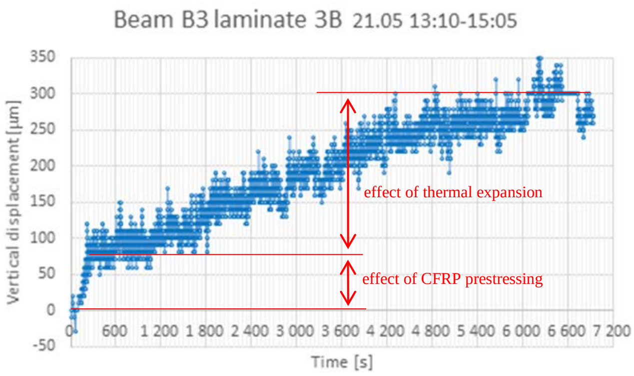


Figure 10. Vertical deflections of the girder due to strengthening with laminates and thermal expansion.


Figure 11. Bridge after reconstruction.

Literature:

1. Popovic N, Feltrin G, Khash-Erdene J and Wojtera M. Event driven strain cycle monitoring of railway bridges using a wireless sensor network with sentinel nodes. Structural Control and Health Monitoring. 2016. (accepted).

2. Feltrin G, Popovic N, Flouri K and Pietrzak P. A Wireless Sensor Network with Enhanced Power Efficiency and Embedded Strain Cycle Identification for Fatigue Monitoring of Railway Bridges. Journal of Sensors. 2016.

3. Julien M., Michal S., Christoph C., Lasek K, Kotynia R., Motavalli M. "Anchorage resistance of CFRP strip.s externally bonded to various cementitious substrates", Composites Part B-Engineering, Vol. 63 July 2014, pp. 50-60; p-ISSN: 1359-8368.

4. Kotynia R., Michal Staskiewicz, Christoph Czaderski, Masoud Motavalli 2016, ASCE Journal of Bridge Engineering BEENG-2042R3, ASCEE; Journal of Bridge Engineering, 2016, 21(5): 04016003-(1-14), ISSN 1084-0702 "Prestressed CFRP strips for concrete bridge girder retrofitting - application and static loading test "

4. Dissemination of results/Rozpowszechnienie wyników
Description should cover the following issues:

1. List of the joint Polish-Swiss publications as well as the ones written separately.

Publications

Year	*Title of Journal / Book*	*Title of paper*	*Authors*	*Score*
2014	***Composites Part B-Engineering, Vol. 63 published July 2014, , pp. 50-60; p-ISSN: 1359-8368***	*"Anchorage resistance of CFRP strips externally bonded to various cementitious substrates"*	*Michels J., Staskiewicz M., Czaderski C., Lasek K., Kotynia R., Motavalli M.*	*International Journal, ISSN 1359-8368, (Polish List A, score:40)*
2014	***Journal of Composites for Construction, Vol. 18, No. 3, ISSN 1090-0268***	*"Flexural Behavior of Preloaded RC Slabs Strengthened with Prestressed CFRP Laminates"*	*Kotynia R., Lasek K., Staśkiewicz M.*	*International Journal, ISSN 1090-0268 (Polish List A, score:40)*
2014	***Journal Polymers, 6 (1) (2014), pp. 114–131,*** *ISSN 2073-4360*	*"Prestressed CFRP strips with gradient anchorage for structural concrete retrofitting: experiments and numerical modeling"*	*Michels J., Martinelli E., Czaderski C., Motavalli M.*	*International Journal, ISSN 2073-4360 (Polish List A, score:35)*
2015	***PRZEGLĄD BUDOWLANY 7-8/2015***	*„Przyczepnościowe metody wzmacniania konstrukcji żelbetowych przy użyciu naprężonych kompozytów polimerowych"*	*Kotynia R.*	*National Journal, (Polish List C)*
2015	***Design Procedures for the Use of Composites in Strengthening of Reinforced Concrete Structures. State-of- the- Art.. Report of the Rilem, Technical Committee 234-DUC, C. Pellegrino, J. S. Cruz, Springer, ISBN 978-94-017-7335-5; pp. 392.***	*"Chapter 7: Prestressed FRP Systems"*	*Michels J., Barros J., Costa I., Sena-Cruz J., Czaderski C., Giacomin G., Kotynia R., Lee J., Pellegrino C., Zile E.*	*International book, published by Springer, ISBN 978-94-017-7335-5*
2016	***ASCE Journal of Bridge Engineering BEENG-2042R3, ASCEE; Journal of Bridge Engineering, 2016, 21(5): 04016003-(1-14), ISSN 1084-0702***	*"Prestressed CFRP strips for concrete bridge girder retrofitting - application and static loading test "*	*Michels J., Staśkiewicz M., Czaderski C., Kotynia R., Harmanci Y., Motavalli M.*	*International Journal, ISSN 1084-0702 (Polish List A, score:25)*
2016	***Composites Part B: Engineering, Volume 98, 1 August 2016, Pages 434–443, ISSN: 1359-8368***	*"Mechanical performance of cold-curing epoxy adhesives after different mixing and curing procedures"*	*Michels J., Sena Cruz J., Christen R., Czaderski C., Motavalli M.*	*International Journal, ISSN 1359-8368, (Polish List A, score:40)*
2016	***Journal of Sensors, Article ID: 4359415 (14 pp.) , ISSN 1687-725X***	*"A Wireless Sensor Network with Enhanced Power Efficiency and Embedded Strain Cycle Identification for Fatigue Monitoring of Railway Bridges"*	*Feltrin G., Popovic N., Flouri K. And Pietrzak P.*	*International Journal, ISSN 1687-725X , (Polish List A, score:25)*
2016	***Journal of Structural Control and Health Monitoring, (John Wiley & Sons, Inc. , ISSN 1545-2255***	*" Event driven strain cycle monitoring of railway bridges using a wireless sensor network with sentinel nodes. Structural Control and Health Monitoring"*	*Feltrin G., Popovic N., Khash-Erdene J., Wojtera M.*	*International Journal, ISSN 1545-2255 (Polish List A, score:25)*
2016	***„Structural Health Monitoring in Sustainability of Civil Engineering Infrastructure"/ „Nowoczesne systemy monitoringu w strategii zrównoważonego rozwoju infrastruktury budowlanej".***		*Kotynia R., Staśkiewicz M., Michels J., Czaderski C., Motavalli M.*	*Publication (book) in progress.*

2. List of the conferences/workshops/seminars where Project results were presented.

Conferences

Date	*Topic of Conference /Workshop/Seminar*	*Title of Presentation*	*Prelegent*
18.10.2011	*Meeting of Polish Group of International Institute for FRP in Construction, Lodz (in English)*	*Polish-Swiss TULCOEMPA Project „Innovative Structural Health Monitoring In Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
24-25.11.2011	*Kompozyt EXPO 2011, Kraków (in Polish)*	*Polish-Swiss Project TULCOEMPA „Innovative Structural Health Monitoring In Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
16-18.05.2012	*XII Conference : Naukowo-Techniczna Warsztaty Pracy Rzeczoznawcy Budowlanego, Organizator Polski Związek Inżynierów i Techników Budownictwa Oddział Kielce, Miejsce Kielce (in Polish)*	*Projektowanie wzmocnień belek żelbetowych przy użyciu kompozytów polimerowych*	*R. Kotynia*
12.06.2012 r.	*fib International Federation for Structural Concrete Task Group 9.3 (27th Meeting), Roma, (in English)*	*Polish-Swiss TULCOEMPA Project „Innovative Structural Health Monitoring In Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
12.06.2012 r.	*RILEM TC 234-DUC – Design procedures for the use of composites in strengthening of reinforced concrete structures, Roma (in English)*	*Polish-Swiss TULCOEMPA Project „Innovative Structural Health Monitoring In Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
13-15.06.2012	*CICE 2012 Roma The 6th International Conference on FRP Composites in Civil Engineering, Roma, (in English)*	*Polish-Swiss TULCOEMPA Project „Innovative Structural Health Monitoring In Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
22-23.11.2012	*CECOM 2012 1st International Conference on Civil Engineering Infrastructure Based on Polymer Composites, Kraków (in English)*	*1. The TULCOEMPA project „Innovative Structural Health Monitoring in Civil Engineering Infrastructure Sustainability"*	*R. Kotynia*
		2. *"Advanced structural strengthening and innovative monitoring in Polish-Swiss "Tulcoempa" project"*	*R. Kotynia*
9-11.09.2013	*Second Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR 2013 (in English)*	***1.*** *Structural monitoring of the bridge in Szczercowska Wieś (Poland) under trial loading*	*M. Staśkiewicz*
		2. Lap shear tests of PCC reprofilation mortars	*M. Staśkiewicz*
22-24.04.2013	*III TUL External PhD Seminar (in English)*	*Struktura węzła w systemie bezprzewodowego monitorowania odkształcenia mostu z wykorzystaniem standardu IEEE 802.15.4*	*A. Andrzejczak; A. Napieralski*
12.2013	*CEN-TC250-SC2-WG1 "Strengthening and reinforcing with fibre reinforced polymers" Committee Meeting(in English)*	*Tulcoempa project*	*R. Kotynia*
16-18.06.2014	*8th International Conference AMCM 2014 – Analytical Models and New Concepts in Concrete and Masonry Structures. (in English)*	*"Analytical models for reinforced concrete members shear strengthened with FRP composites"*	*R. Kotynia*

20-22.08.2014	*7th international Conference on Fiber Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2014). (in English)*	*Strengthening and large-scale static testing of two pretensioned concrete girders*	*R. Kotynia M. Staśkiewicz*
8.09.2014	*Łódzkie - kopalnia nowych możliwości (in Polish)*	*Projekt TULCOEMPA - Innowacyjne systemy monitoringu w strategii zrównoważonego rozwoju infrastruktury budowlanej*	*R. Kotynia*
17-19.09.2014	*60 Konferencja Komitetu Inżynierii Lądowej i Wodnej PAN oraz Komitetu Nauki PZiTB Lublin-Krynica 2014 (in Polish)*	*Badania doświadczalne kablobetonowych dźwigarów wzmocnionych materiałami kompozytowymi CFRP*	*R. Kotynia M. Staśkiewicz*
30.09-1.10.2014	*„The 10th Central European Congress on Concrete Engineering LIBEREC 2014”. (in English)*	*First application of prestressed CFRP laminates with gradient anchorage in strengthening of post-tensioned concrete bride in Szczercowska Wieś*	*M. Staśkiewicz*
7-9.09.2015	*Third Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR 2015, Antalya TR 7– 9 September 2015 (in English)*	*Pioneering strengthening of bridge girders with pretensioned CFRP laminates in Poland*	*R. Kotynia, M. Staśkiewicz, M. Motavalli, C. Czaderski, J. Michels*
4-6.04.2016	*International Conference COST Action TU1207, Next Generation Design Guidelines for Composites in Construction (in English) Industry Seminar (in English)*	*Effect of epoxy resins cross-linking parameters on mechanical properties of adhesive joints Renata Kotynia, Anna Strąkowska, Marcin Masłowski, Kinga Adamczewska*	*R. Kotynia,*
		First application of gradient anchorage for pretensioned CFRP laminates on the concrete bridge in Poland. Renata Kotynia (TUL), Julien Michels (Empa) , Michal Staskiewicz (TUL), Christoph Czaderski (Empa), Masoud Motavalli (Empa), Martin Hüppi (S&P Clever Reinforcement Company AG), Marek Makarewicz (S&P Polska Sp. z o.o.), Tomasz Bartosik (Euro-Projekt)	*R. Kotynia,*

3. Other forms of dissemination (if applicable).

Presentations

Date	***Meeting/Seminar/Conference/Newsletters***	***Presentation***	***Presenting person***
6.12.2012	*PhD and MSC Student Seminar Politechnika Lubelska, Lublin (in Polish)*	*The TULCOEMPA project „Innovative Structural Health Monitoring in Civil Engineering Infrastructure Sustainability”*	*R. Kotynia,*
13-15.03.2013	*Konwent Dyrektorów Zarządów Dróg Wojewódzkich, Hotel Grzegorzewski, Tuszyn k.Łodzi, (in Polish)*	*Realizacja polsko-szwajcarskiego projektu "Tulcoempa" na przykładzie przebudowy mostu w Szczercowskiej Wsi w ciągu drogi wojewódzkiej nr 480"*	*R. Kotynia,*
4.12.2013	*Engineering Seminar ETH, Zurich, 4 grudnia 2013 r., (in English)*	*„Event driven monitoring with wireless sen-sor networks”*	*G. Feltrin*
5.12.2013	*University of Applied Research Rapperswil (in English)*	*„Event driven monitoring with wireless sen-sor networks”*	*G. Feltrin*
20.06.2014	*21st. International Conference Mixdes 2014, Lublin, Poland, 19-21 June 2014 (in English)*	*„Sensor Reliability Evaluation Method in Multi-Sensor Control Systems”*	*Łęczycki P., Andrzejczak A., Pietrzak P., Pękosławski B., Napieralski A.;*
		"A Low-Power Embedded System for Visual Vehicle Detection"	*Grabowski K., Clapa J.,*

		"Hybrid Power System for Truck Recognition System"	*Pękosławski B., Pietrzak P., Andrzejczak A., Łęczycki P., Topiłko J., Napieralski A.,*
3.07.2014	*FRP INTERNATIONAL the official newsletter of the International Institute for FRP in Construction (in English)*	*Polish-Swiss team demonstrate the first application of prestressed CFRP laminates with gradient anchorage for strengthening post-tensioned concrete bridge - The TULCOEMPA Project*	*R. Kotynia*
8.09.2014	*Łódzkie - kopalnia nowych możliwości (in Polish)*	*Projekt TULCOEMPA - Innowacyjne systemy monitoringu w strategii zrównoważonego rozwoju infrastruktury budowlanej*	*R. Kotynia*
3.12.2014	*ETH Seminar, Zurich, (in English)*	*"Monitoring with wireless sensor networks",*	*G. Feltrin*
29-30.06 2015	*Cambridge, UK (in English)*	*Event driven monitoring with wireless sensor networks, Cambridge Conference on Wireless Sensor Network for Civil Engineering and Infrastructure Monitoring*	*N. Popovic*
23-25.09.2015	*Providing Solutions to Global Challenges, Geneva, Switzerland (in English)*	*Monitoring of strain cycles on a railway bridge with a wireless sensor network. In IABSE Conference – Structural Engineering:*	*Feltrin, G. Popovic, N.*
16.11.2015	*Tulcoempa final conference Łódź, Poland (in English)*	*Event driven monitoring with wireless sensor networks: concepts, implemen-tations and field tests,*	*G. Feltrin, N. Popovic*
		Load-Carrying Capacity Assessment of a prestressed CFRP-strengthened bridge girder by static loading tests	*J.Michels*
18.11.2015	*Seminar for guests of King Fahd University, Saudi Arabia. (in English)*	*Event driven monitoring with wireless sensor networks*	*G. Feltrin*
2.12.2015	*Seminar ETH Zurich, Switzerland (in English)*	*Structural Monitoring with Wireless Sensor Networks*	*G. Feltrin*
3.12.2015	*Seminar FH Rapperwil, Switzerland (in German)*	*Bauwerksmonitoring mit drahtlosen Sensornetzen*	*G. Feltrin*
25-26.04.2016	*FRP Training Course (in English)*	*FRP for prestressed applications - new and strengthening*	*R. Kotynia*
3-4.03.2016 r.	*Konferencja Łódzkiej Okręgowej Izby Inżynierów Budownictwa „Nowoczesne technologie w budownictwie – wybrane zagadnienia" (in Polish)*	*Nowatorskie zastosowania materiałów kompozytowych w realizacjach budowlanych*	*R. Kotynia*
4-6.04.2016	*International conference COST Action TU1207, Next Generation Design Guidelines for Composites in Construction Industry Seminar (in English)*	*First application of gradient anchorage for pretensioned CFRP laminates on the concrete bridge in Poland. Renata Kotynia (TUL), Julien Michels (Empa), Michal Staskiewicz (TUL), Christoph Czaderski (Empa), Masoud Motavalli (Empa), Martin Hüppi (S&P Clever Reinforcement Company AG), Marek Makarewicz (S&P Polska Sp. z o.o.), Tomasz Bartosik (Euro-projekt)*	*R. Kotynia*
5-8.04.20016	*Third International Conference on Railway Technology: Research, Development and Maintenance, Cagliari, Sardinia, Italy, Cagliari, Sardinia, Italy, (in English)*	*Strain Cycles Monitoring of Metallic Railway Bridges using a Wireless Sensor Network. In Civil-Comp Press.*	*Feltrin, G., Popovic, N., Jalsan, K. Wojtera, M.*

5. Progress in research career/Postęp w karierze naukowej

Progress in research career of persons engaged in the Project during its realisation, i.e. PhD thesis, dr hab/D.Sc. thesis, professorial titles obtained.

Person	***Year***	***Progress in research career***
Renata Kotynia (TUL)	*2012*	*Dr hab. inż.*
Renata Kotynia (TUL)	*2013*	*Prof. nadzw. Politechnika Łódzka*
Krzysztof Lasek	*2016*	*PhD thesis defence; Dr. inż.; Supervisor: Prof. R. Kotynia*
Michał Staśkiewicz	*2012-2016*	*PhD in progress; Supervisor: Prof. R. Kotynia*
Kinga Adamczewska	*2016*	*Started PhD in Tulcoempa Project; Supervisor: Prof. R. Kotynia*
Yunus Emre Harmanci(Empa)	*2016*	*PhD in progress; Supervisor: Prof. Dr. E. Chatzi (ETHZ) and Dr. Julien Michels (Empa)).*
Marcin Piasecki	*2012*	*MsC Thesis; I Award in the Student Competition for the Best MSC Thesis in Civil Engineering in memory of Prof.*

6. Sustainability of the results and Project follow-up/Trwałość wyników oraz kontynuacja Projektu

Description should clearly outline the sustainability of Project results, their transferability and potential follow ups.

The results concerning event driven monitoring with wireless sensor networks represent a scientific breakthrough and an important milestone towards the practical application of this technology since this work demonstrates the feasibility of the concept not only with laboratory tests but with field tests under realistic operation conditions.
With suitable minor optimisations, the results are ready for a technology transfer to industry. The strain sensing hardware has been already transferred to industry and is now commercialized by the company Decentlab GmbH. The hardware is currently in use in more than 50 monitoring deployments worldwide (mostly environmental monitoring).
The results concerning civil engineering part is the successful application of the strengthening with the gradient method of the prestressed CFRP laminates on existing bridge. Dissemination of this method on other bridges is recommended.
Bridge is under on-going monitoring that will be continued with the registration of the measured parameters.

7. Other relevant information concerning Project realisation/Inne istotne informacje dotyczące realizacji Projektu

Please, contain other relevant information concerning Project realisation (not mandatory).

COLLABORATION/WSPÓŁPRACA

1. Meetings:

2012 year

There were several meetings in EMPA of Polish staff implementing planned tasks of Work Packages 3, 4 and 5.

1. Michał Staśkiewicz 03.01.2012 - 29.02.2012
Preparation of the workplace for the building of the girders. Production of the pads for the support of prestressing tendons. Construction of the reinforcement skeletons for the girders. Trial concreting of the sample of the girder and selection of concrete type. Casting of the girders. Preparation of the concept of a formwork for the slabs. Preparation of the project of test set-up
2. Krzysztof Lasek, Jacek Łapiński 16.01.2012 - 29.02.2012
Construction of the reinforcement skeletons for the girders. Trial concreting of the sample of the girder and selection of concrete type. Casting of the girders.
3. Renata Kotynia 11.03.2012 - 13.03.2012
Supervising of the post-tensioning of the tendons in the first girder
4. Sławomir Wróblewski , Bartosz Pękosławski, Artur Andrzejczak, Paweł Łęczycki, Michał Wojtera -- 13.03.2012 - 28.03.2012
Discussion of strain gauge device's location on concrete beam ; Deployment of strain gauge device on concrete beam ; Strain measurements of concrete block during prestressing ; Calibration measurements of strain gauge device ; Discussion of communication method between OMAP platform and TRS sensors, and wireless strain measurement module; Discussing communication protocol; Designing application architecture
5. Michał Staśkiewicz 16.03.2012 - 30.04.2012
Supervising of the post-tensioning of the tendons in the second girder. Measurements on the girders after post-tensioning. Modelling of the girder for numerical analysis. Preparation of the rebars for the slabs. Building of the formwork for the slabs. Construction of the reinforcement skeletons for the slabs. Casting of the slabs
6. Krzysztof Lasek, Jacek Łapiński 11.04.2012 - 02.05.2012
Preparation of the reinforcement for the slabs. Building of the formwork for the slabs Construction of the reinforcement skeletons for the slabs. Casting of the slabs
7. Michał Staśkiewicz 02.06.2012 - 10.07.2012
Preparation of the formwork for the filling elements (for shear strengthening). Casting of the filling elements. Surface treatment for the reprofilation of the girder's surface. Installation of the filiing elements on the second girder. Static tests of the first girder
8. Krzysztof Lasek, Jacek Łapiński 01.07.2012 - 14.07.2012
Preparation of the filing elements for installation. Installation of the filling elements on the second girder. Static tests of the first girder. Preparation of the second girder for structural strengthening
9. Michał Staśkiewicz 13.08.2012 - 14.08.2012
First attempt to strengthen the girder with prestressed CFRP laminates
10. Michał Staśkiewicz 03.09.2012 - 07.09.2012
Second attempt to strengthen the girder with prestressed CFRP laminates. Preparation of the concept of test program for the reprofilation mortars

2013 year

1. Michał Staśkiewicz 11.06.2013 - 16.06.2103 Empa
Reprofilation of the laboratory girder with use of dry shotcrete, for the purpose of the girder's flexural strengthening. Performed with help of S&P Polska and SPB Torkret employees.
2. Michał Staśkiewicz 15.07.2013 - 29.08.2103 Empa
Preparation of the laboratory girder for strengthening, trial applications of the strengthening on additional concrete slabs. Development of the strengthening procedure before application on the girder.
3. Michał Staśkiewicz 30.09.2013 - 04.10.2013 Empa
Strengthening of the girder for flexure and shear with use of prestressed CFRP laminates and CFRP sheet wrappings. Performed with help of S&P Polska employees.
4. Renata Kotynia 30.09.2013 - 01.10.2013 Empa
Strengthening of the girder for flexure and shear with use of prestressed CFRP laminates and CFRP sheet wrappings. Performed with help of S&P Polska employees.
5. Michał Staśkiewicz 27.10.2013 - 29.10.2013 Empa
Participation in the flexural tests of the strengthened girder in Empa laboratory.
6. Renata Kotynia 28.10.2013 - 29.10.2013 Empa
Participation in the flexural tests of the strengthened girder in Empa laboratory.
7. Andrin Herwig (from Empa) 09.12.2013 -14.12.2013 - TUL
Cooperation in 3D modelling of the bridge for the evaluation of its load capacity and stiffness; analysis of the girders' shear load capacity. Comparison of the numerical model and real bridge structure.

2014 year

1. PhD student Michal Staśkiewicz (TUL) held in the EMPA research internship in January 2014. The purpose of the visit was the final definition of strengthening condition by using the gradient method.
2. In May 2014, Julien Michels (EMPA) and employees of the S & P Switzerland: Martin Hueppi, William Saxer and Bernhard Schuler took part in strengthening the bridge in Szczercowska Village. Strengthening work was directly performed by employees of EMPA, Switzerland S & P and S & P Poland. Strengthening involved bending and shear of bridge girders.
3. In April 2014 Glauco Feltrin and Nemanja Popovic (Empa) as well as Renata Kotynia, Michał Wojtera and Arthur Andrzejczak (TUL) participated in a two-day (7-8.04.2014) conference on "Conference Polish-Swiss Research Programme".
4. May 19-21, 2014 N. Popovic (Empa), visited the bridge in order to implement a wireless monitoring system of the bridge, in cooperation with the TUL's employees.

2015 year

16.-17. 11. 2015 Final conference in Łódź - visit G. Feltrin, N. Popovic, and J. Michels (Empa)

2016 year

4-6.04.2016 International conference COST Action TU1207, Next Generation Design Guidelines for Composites in Construction Industry Seminar organized by TUL. visit of. C. Czaderski (from EMPA) *and Martin Hüppi (S&P Clever Reinforcement Company AG), Marek Makarewicz (S&P Polska Sp. z o.o.), Tomasz Bartosik (Euro-projekt)*

2. Project integration, knowledge and technology transfer.
25-26.04.2015 - FRP Training Course (in English) - Knowledge transfer by presentation of the Tulcoempa project results by R. Kotynia and C. Czaderski
25-26.04.2016 - FRP Training Course (in English) Knowledge transfer by presentation of the Tulcoempa project results by R. Kotynia and C. Czaderski

3. Collaboration with other institutions.

- *Marshall Office – the bridge administrator*
- *Road and Bridges Office – Institution performing the tasks of the Regional Board of Lodz in the governance of regional roads on the planning, construction, reconstruction, repair, maintenance and protection of roads; Polish acronym – ZDW managed the bridge in Szczercowska Wieś reconstruction process*
- *S&P Swiss and Poland - The S&P Group is one of the key partners of Tulcoempa project. S&P delivers solutions and materials crucial for the completion of the project. S&P Clever Reinforcement Company AG, Switzerland, is co-author of the gradient strengthening method and supports all the laboratory works carried out in EMPA laboratories. S&P Polska takes part in research works at Lodz University of Technology and is responsible for the preparation of structural strengthening of the bridge in Szczercowska Wieś, which is the main goal of Tulcoempa project.*
- *TORKRET Sp. z.o.o - SPB Torkret company collaborated with Lodz University of Technology during preparations for reprofilation of the bridge girders. SPB Torkret representatives helped to select the most appropriate materials and technology for the reprofilation and performed a dry-shotcrete application on the laboratory girder at EMPA laboratories.*
- *Stahlton AG - A Swiss company Stahlton AG supported Tulcoempa project during the production of post-tensioned laboratory girders. Stahlton AG representative took part in the design of the girders' reinforcement. The company delivered custom made post-tensioning cables with anchor heads and performed the post-tensioning of the both girders.*
- *SKB - SKB company delivered a set of custom made steel elements necessary for the structural strengthening of the bridge girders. Products delivered by SKB were of top quality and outstanding precision.*

PROMOTIONAL ACTIVITIES/DZIAŁANIA PROMOCYJNE

Description should cover the following issues:

1. Project website: www.tulcoempa.com
2. Promotion materials:
1. Bags with Logo Swiss Contribution and logo TULCOEMPA's project.
2. Calendar with Logo Swiss Contribution and logo TULCOEMPA's project(2014, 2015)
3. CD with Logo Swiss Contribution and logo TULCOEMPA's project contains audio-visual materials about the results of project

4. Roll up which contains Logo Swiss Contribution and logo TULCOEMPA's project
5. Signs and stickers with Logo Swiss Contribution and logo TULCOEMPA's project
6. Official paper of the project with Logo Swiss Contribution and logo TULCOEMPA's project
7. Leaflets of the project with Logo Swiss Contribution and logo TULCOEMPA's project
8. Movies about the project

http://lodz.tvp.pl/20044154/13052015-1830
https://youtu.be/q8SrTAWgQfo
https://youtu.be/xhr0Gu8tzwA
https://youtu.be/5fVUkt0BBn0
https://youtu.be/5EPS--OLqo0
https://youtu.be/ECAag4Fh_n8
https://youtu.be/G6GFHlqw6pQ
https://youtu.be/0gkPQOnq9_A
https://youtu.be/3UIMGl7hcGU
https://youtu.be/8g9AQH1X2vw

9. Links to press information about TULCOEMPA project:

1. *http://tinyurl.com/znvug4p*
2. *http://tinyurl.com/j2f7uhp*
3. *http://tinyurl.com/gwe4bw6*
4. *http://tinyurl.com/jr44ea5*
5. *http://tinyurl.com/jry8jva*
6. *http://stooq.pl/n/?f=701604&c=0&p=0*
7. *http://tinyurl.com/henpqzo*
8. *http://tinyurl.com/jkzo2gg*
9. *http://tinyurl.com/zshtls6*
10. *http://tinyurl.com/hasxzes*
11. *http://tinyurl.com/j6weog4*
12. *http://tinyurl.com/hvxqnsm*
13. *http://tinyurl.com/hdzlgcz*
14. *http://tinyurl.com/hvxqnsm*
15. *http://tinyurl.com/z5bha3j*
16. *http://tinyurl.com/j4k2r92*
17. *http://tinyurl.com/zzmsy6m*
18. *http://tinyurl.com/hwnrtc7*
19. *http://tinyurl.com/jg94ucp*
20. *http://tinyurl.com/hxgk4h9*
21. *http://stooq.pl/n/?f=851696&c=0&p=4+18+22*
22. *http://tinyurl.com/jngtxtv*
23. *http://tinyurl.com/hg9d2m4*
24. *http://tinyurl.com/h38mg4d*
25. *http://tinyurl.com/h5gvfxv*
26. *http://tinyurl.com/jezb7c2*
27. *http://tinyurl.com/gmpnzud*
28. *http://tinyurl.com/zq27arp*
29. *http://tinyurl.com/hls2rum*

30. *http://tinyurl.com/gtr8e9c*
31. *http://tinyurl.com/h6cxsf5*
32. *http://tinyurl.com/h9kfxbb*
33. *http://tinyurl.com/hj57eh4*
34. *http://tinyurl.com/hratprc*
35. *http://tinyurl.com/jy8b8jh*
36. *http://tinyurl.com/hks34fs*

Signatures/Podpisy

I hereby certify that I am duly authorised to sign this Project Completion Report. I confirm that I have thoroughly reviewed the information provided in this report and that the information is correct and accurate and reflects correctly Project realization, including the incurred expenses. I confirm that this project was carried out in line with the Financial Agreement.
I confirm that the Beneficiary undertakes to provide information ex-post; to maintain the Project for the period of 2 years after the completion of Project realisation, including making the results of the Project available free of charge to all interested entities, with the observance of the principle of free access to the said results as well as to maintain the documentation for the period of 10 years following the conclusion of the Project realisation.

Zaświadczam, że jestem w pełni upoważniona/y do podpisywania Sprawozdania końcowego z realizacji projektu. Potwierdzam, że przeczytałam/em uważnie podane w sprawozdaniu informacje i są one poprawne, rzetelne oraz prawidłowo odzwierciedlają realizację projektu, w tym poniesione wydatki. Potwierdzam, że projekt był realizowany zgodnie z Umową finansową.
Potwierdzam, że Beneficjent zobowiązuje się do udzielania informacji ex-post, utrzymania trwałości Projektu w okresie 2 lat po zakończeniu realizacji Projektu (w tym do nieodpłatnego udostępnienia wszystkim zainteresowanym podmiotom wyników uzyskanych w efekcie realizacji Projektu, z zachowaniem równego dostępu do ww. wyników) oraz do przechowywania dokumentacji przez 10 lat po zakończeniu realizacji.

	Project Coordinator/ Kierownik Projektu
Place/Miejsce:	Lodz University of Technology / Politechnika Łódzka
Date/Data:	01.07.2016
Name and Surname/ Imię i Nazwisko	Renata Kotynia
Signature/ Podpis:	
Position/ Stanowisko Służbowe:	Prodziekan ds współpracy z zagranicą / Vice Dean for Collaboration with Industry