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Damage investigation of pre-stressed cables in segmental box girder concrete bridge ev. No. 324-018 in Pardubice, Czech Republic

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Abstract. Complete reconstruction of the reinforced pre-stressed bridge Pavel Wonky in Pardubice was carried out in 2006. During this reconstruction specialists of the Klokner Institute made a complete revision of linear free external cables in bridge chambers, namely from the aspect of corrosion. During the ordinary visual inspection of the bearing structure of this bridge, in July 2017 [1], the SUS Pardubice staff members found out that in the places above both the pillars in the right-hand chamber of the Pavel Wonka bridge central beam in Pardubice, the blocks of deviators on the left-hand side of the chamber were deflected against the direction of stationing, towards Hradec Kralove. Some of the findings obtained during this revision are presented in this article.

1. Brief data concerning the bridge under study

Bridge ev. No. 324-018 was built between 1956 and 1959. The load-bearing structure of the bridge is composed of a continuous beam with a field length of 50, 70 and 50 m, shown in figure 1. In the cross-section, the bridge's load-bearing structure consists of three chamber beams interconnected with transverse pre-stressing at the level of the bridge board. Each beam has three chambers. The height of the cross-sectional area of the load-bearing structure is variable and ranges from 1.6 m in the field to 2.9 m above the support. The load-bearing structure is pre-stressed both longitudinally and transversally.

The longitudinal pre-stress is induced by cohesion cables placed in the chamber ribs as well as by free pre-stressed cables. The cohesion cables are made of 12 x P7 mm patent wire and are positioned and injected in 42 mm diameter armored tubes or 36 mm flexible tubes. The free pre-stressed cables originally consisted of 168 profiles of P7 mm patent wire. During the reconstruction in the early 1980s, drawbars were replaced by loose cables of 42 ropes with 15.5 mm in diameter. There are two free pre-stressed cables in each chamber, one on each side of the chamber. Each rope is covered by a guard made of PVC pipe segments with a diameter of 330 mm along the length of the bridge. The tube is filled with PUR foam inside. In the area of the bridge ends where the rope bundle is branched for anchoring, the protection is made of PVC boards forming a rectangular chamber filled with PUR foam again. All free pre-stressed cables are anchored to the cross member at the head of the bridge beams. Each cable is composed of 42 ropes with Lp 15.5 mm with a length of about 175 m. Due to the implementation and leading of the cables in deviators, the cables were divided into three-rope bundles which are lead separately and anchored into the anchor sleeve in the crosspieces at the end of the bridge.



Each three-chamber beam is pre-stressed across both the top and bottom plates. At the pre-stress in the top plate, some cables run through the boards of all three beams. Transverse pre-stressing is ensured by 16 x P4.5 mm cables lead in injected armored tubes.

2. History of the diagnostic survey

The Klokner Institute was surveying the bridge in 2006 [2], the aim of which was an assessment of the corrosion condition of the system of steel free pre-stress cables. The level of corrosion attack of the cables was assessed by using the scale:

- 1 - Reinforcement without any signs of corrosion,
- 2 - Reinforcement with starting surface corrosion of local nature to a small extent,
- 3 - Reinforcement with developed surface corrosion of local nature without peeling off of the corrosion products,
- 4 - Reinforcement with developed all-area surface corrosion and possibly with the peeling off of corrosion products.

The following conclusions were stated at that time by the visual inspection of free pre-stress cables carried out:

- ✓ The corrosion condition of the pre-stress reinforcement is at the level of degrees 1 and 2 in free length (i.e., out of the untwisting areas), which means without corrosion or with minimal symptoms. The existing protection system of the PVC conduits filled with PUR foam fulfills its anti-corrosion function sufficiently.
- ✓ A problematic area is formed virtually of all untwisting areas which are valued, from the corrosion point of view in 1/2 with the degree 3, and in 1/6 they are valued with the corrosion degree 4. It is evident that the existing implementation of the anticorrosion protection of untwisting areas with foam wrapping of PUR foam and protection of PVC panels is not systematic and fails to fulfill its protective function sufficiently. The most problematic aspect from the corrosion point of view seems to be the area of transition of cables from the cross-beam to the chamber and immediately downstream of this transition where the climbing-down holes are situated. For this reason, it is necessary to ensure the complete major repair of these untwisting areas (see the recommendations).
- ✓ On the whole, it is possible to state that besides the local issues in the untwisting areas the system of free cables is attacked in a relatively small extent and after implementation of additional anticorrosion measures it will continue to fulfill its function.

Another visual diagnostic inspection was carried out by the Klokner Institute in 2015 [3] intending to assessing a possible change in the corrosion condition of the steel free pre-stress cables against the previous visual inspection from July 2006 [2]. The following was stated from the survey carried out:

- ✓ There were carried out altogether four probes – 3 probes in the untwisting areas and one probe in the free-length cable, i.e., out of the untwisting area. The probes were carried out in the places where the corrosion of cables of the degree 3 or 4 was stated during the visual inspection in 2006.
- ✓ The same degree of corrosion like the one discovered during the previous visual inspection in 2006 was diagnosed in all the implemented probes after the removal of the existing protection (PVC conduits or PVC panels and PUR foams).
- ✓ During the visual inspection of the pre-stress cables in the entire length of chambers 1 – 9 there were not discovered any spots where it would be possible to register any significant visible degradation of the existing protection of cables or leakage into the area of chambers, or onto the protective elements of pre-stressing cables.
- ✓ On the whole, it was stated that the attacking of the system of free cables from the viewpoint of corrosion in the place of the probes carried out for nine years has not changed since the initial visual inspection of 2006.

3. Inspection of the position of deviators and the state of rope corrosion

Within the framework of the survey, an investigation was carried out for deviators in the right-hand chamber of the central beam, and a change in their position and shifts of the plastic cover of cables were found out. In this chamber, there are seven deviators on each side, two deviators above the pillars, and two deviators in the first and third spans (each) of the bridge. The marking of their position and numerical identification of the cables are shown in figure 2.

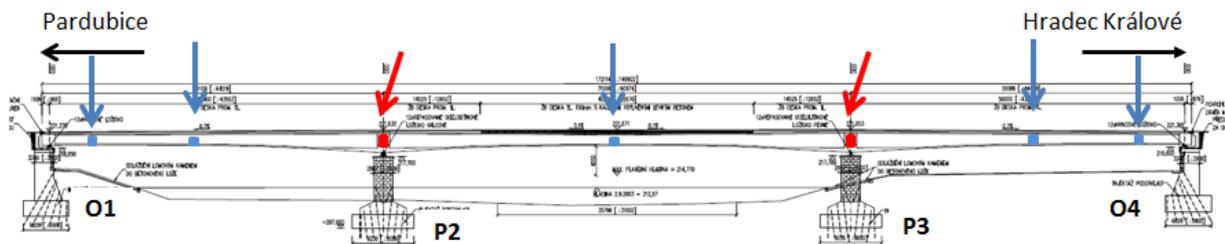


Figure 1. Chart of the placement of deviators

The deviators in the place above pillars P2 and P3 were not anchored to the crossbeams in any way, and therefore they may have deviated from their original condition. According to the data provided, this deviation was not discovered during the previous regular inspections.

Above the P2 pillar, plastic protection of the cable was cut out, and PUR foam was partly removed. No symptom of rope damage by corrosion was found out on the ropes uncovered.

In the next step, PUR foam was gradually removed above the O1 support on both the right-hand and left-hand sides of the chamber in the place of the untwisting areas. According to the expert report [3], there was found out a corrosion level at the cable No.7 in a small extent, at the cable no. 8 with developed corrosion of local nature. After the uncovering, there has not yet been found out any corrosion damage to an increased extent.

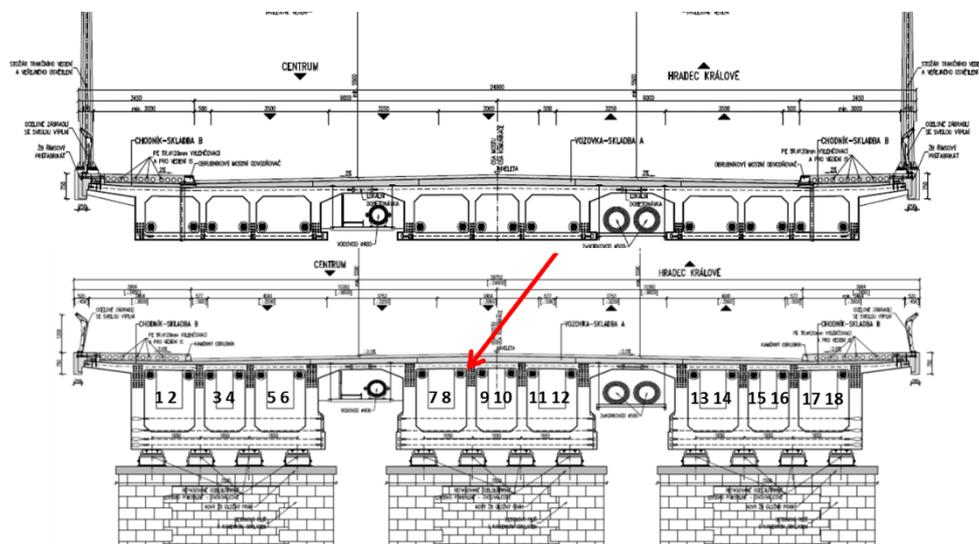


Figure 2. Cross-sections in the bearing structure with numerical marking of the cables: a view from the stationing direction. Stress deviators inclined to the right (Hradec Kralove) side of the bridge are marked by the red arrow.

Some rope strands of cable No. 8 are partly or entirely released. This finding was confirmed by the tapping with a hammer on the strand. At damaged and undamaged strands, different acoustic responses are apparent. A logical explanation of this fact is that a partial or complete failure of this cable has occurred.

The edge of the cross-beam above the P2 pillar was damaged, it was broken off in a width of approx. 80 mm under the shifted block of deviators, figure 3.

From the above-stated findings, it is possible to conclude that the cable failure probably occurred in the first bridge span.

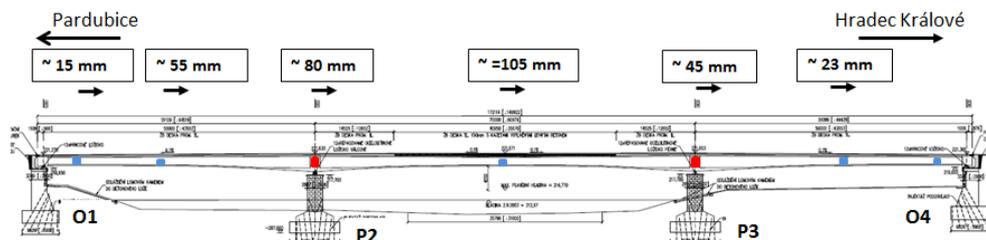


Figure 3. The approximate shift of the cable found out in the direction against the stationing

At the request of the customer, only the visual inspection of the cables was performed at the first phase. The extension of the diagnostic range was considered at the second phase, based on the results of the first phase. At the second phase, a stress analysis on the cables as a function of the separation between the pillars to determine the susceptibility to fail by corrosion-fatigue was planned.

4. Additional Inspection of the rope corrosion

Two inspections were carried out in February-March 2018 after the strands of the ropes were made accessible, and these inspections were focused on their corrosion state.

The following conclusions were found out from the survey carried out:

- ✓ At the support no. O1: 35 ropes out of the total number of 42 ropes were damaged by fracture.
- ✓ At the support no. O4: 1 rope was damaged, and one rope was heavily corroded, out of the total number of 42 ropes.
- ✓ In the places of failure, massive corrosion of pre-stressing ropes was identified, with peeling-off layers of corrosion products.
- ✓ The massive corrosion of pre-stressing ropes in the places of failure is in the areas of the original assembly holes in the bridge deck of the chamber at the O1, and O4 supports. At a certain distance (several meters) from this place, the reinforcement was without any corrosion, or with significantly lower surface corrosion. This evaluation must also be confirmed for other cables.
- ✓ The damage of the pre-stressed ropes was called out without any doubt by the localized form of the corrosion damage caused by moisture and stimulated by chloride anions. The damage was further supported by the mechanism of the diameter weakening due to ordinary electrochemical corrosion, and partly also the corrosion under stress stimulated again by the presence of chloride anions.
- ✓ According to the preliminary evaluation by the staff members who ensure the removal of the PUR foam, similar rope failures are also registered in other chambers, in connection with assembly holes.
- ✓ No visible signs of corrosion were found on the ropes in the area in front of the deviator at the O1 support, and no symptoms of corrosion in the ropes are registered behind the deviator either.

5. Passport of the corrosion state of the ropes of all the cables

At the next phase, it was recommended to verify the corrosion state of the pre-stressing ropes in all the places where the so-called historical handling holes are situated above the untwisting areas of the cables and where they could be affected by long-term water leakage [4, 5]. Another visual inspection in all the chambers on both sides of the bridge was held in March 2018. Within the framework of this visual

inspection, the corrosion state of the ropes was photographically documented and visually assessed in the places where technological holes were made in the upper slab of the chambers, providing access for the assembly of the free pre-stressing cables. These holes are at a distance of approx. 7-9 m from the internal front of the cross-beam. It was clear that long-term leakage must have occurred in this area before the repair. The testing place was described through localization of the place assessed, by means of the position of the exposed cable from the front part of the cross-beam, through existence of the concrete-covered breakdown above the test place, number of damaged ropes and subjective evaluation of the corrosion state according to the scale selected (corrosion degrees).

The following can be stated from the results of visual inspections and corrosion state assessment:

- ✓ In the untwisting area at the O1 support the ropes were characterized:
 - Sixty-four ropes were damaged, i.e., approx. 8.5 %,
 - 14 % rope corrosion state 2,
 - 26 % rope corrosion state 3,
 - 59 % rope corrosion state 4.
- ✓ In the untwisting area at the O4 support the ropes were characterized:
 - Forty-nine ropes were damaged, i.e., approx. 6.5 %,
 - 9 % rope corrosion state 2,
 - 24 % rope corrosion state 3,
 - 67 % rope corrosion state 4.
- ✓ It is clear that in the place of the original assembly holes, through which water leakage into the structure and onto the ropes was very likely to occur in the past, there is a local area in a length of approx. 2 m, in which the pre-stressing cables and their ropes are affected by massive corrosion (corrosion degree 4) which is already manifested through the peeling-off of the corrosion products and diminishing of the area of the pre-stressing reinforcement. Already 2/3 of all pre-stressing ropes of the free pre-stressing system are affected by corrosion this way.
- ✓ The very unfavorable corrosion state which was detected, even though in a local scale only, must be considered, from the viewpoint of the further identified influence on mechanical characteristics of the pre-stressing reinforcement as highly risky and hardly acceptable on a long-term basis.

6. Non-destructive determination of the reinforcement position

The HILTI PS 1000 radar was (figure 4) used for determination of the thickness of the pre-stressing reinforcement in the walls of the chambers (external surface). The instrument works on the principle of transmission of electromagnetic impulses into the structure. The output of the registration of reflections of the electrical impulses from non-homogeneities of the material is the area scanning with a cross section of the structure in question. The orientation determination of the position and thickness of coverage on external surfaces of individual structures was made with the use of the Hilti PROFIS PS 1000 software interface. The HILTI PS 1000 instrument works with a maximum detection depth of 300 mm. The precision of indication of a depth smaller than 100 mm is ± 10 mm. At a depth exceeding 100 mm, the accuracy is $\pm 15\%$. The localization precision is ± 10 mm.

It was selected for execution of individual area scanning operations that always one area image would be scanned with a spacing of approximately 3 m. Scanning was carried out in the direction from the O4 support to $\frac{1}{2}$ of the middle span. This was justified by the presumption of the bridge symmetry. The non-destructive diagnostics presumed that it would make it possible to determine the courses of the pre-stressing reinforcement for individual structural assessments.

The illustration output from the HILTI PROFIS PS 1000 graphics interface is provided for in figure 5. For the reason of thick reinforcement using soft reinforcement material as well as because the cables of the pre-stressing reinforcement are conducted in as many as four layers it was always possible to identify the first reinforcement layer (considered from the external face of the structure).

The aim of the additional diagnostics was that a structural analysis of the load-bearing capacity of the bridge would be subsequently drawn upon the basis of the information found out about the course of the cohesion reinforcement, corrosion state, and corrosion risks at free ropes.



Figure 4. Non-destructive determination of the reinforcement position by radar HILTI PS 1000

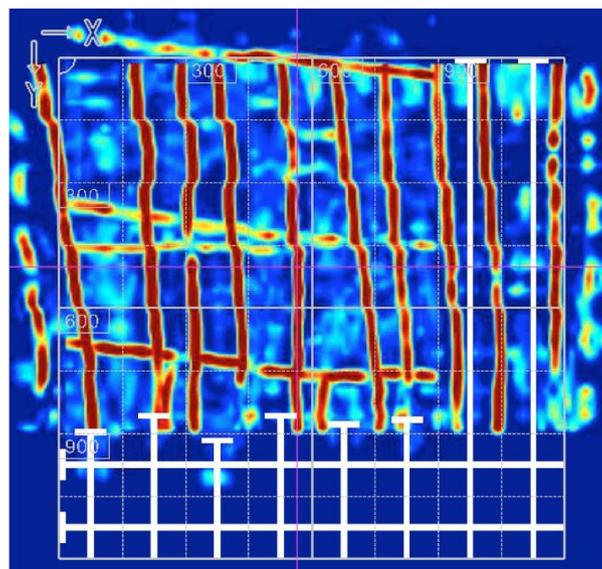


Figure 5. Illustration output from the HILTI PROFIS PS 1000 graphics interface

7. Conclusions

The visual inspections and laboratory analyses carried out in this study made it possible to state:

- ✓ It is evident that in the place of original assembly holes, through which water leakage into the structure and onto the ropes was very likely to occur in the past, there is a local area in a length of approx. 2 m, in which the pre-stressing cables and their ropes are affected by massive corrosion (corrosion degree 3-4) which is already manifested through the peeling-off of the corrosion products and diminishing of the area of the pre-stressing reinforcement. Already 2/3 of all pre-stressing ropes of the free pre-stressing system are affected by corrosion this way.
- ✓ From the above-mentioned findings, it is, therefore, possible to derive and basically it is not possible to exclude that the mechanical strength of the free pre-stressing ropes is approximately (for 2/3 of ropes) lower than at the time of installation by as much as 1/3, and at the same time they do not have ductile capacity in the case of damage.
- ✓ The damage of the pre-stressed ropes was called out, without any doubt, by the localized form of the corrosion damage caused by moisture and stimulated by chloride anions. The damage was

further supported by the mechanism of the diameter weakening due to ordinary electrochemical corrosion and partly also the corrosion under stress, stimulated again by the presence of chloride anions.

- ✓ PUR foam is not a source of contamination of the rope surface with corrosion stimulants (chloride and sulfate anions). With high probability, these are chloride anions originating from road salts used during winter maintenance of roads.
- ✓ The very unfavorable corrosion state which was detected, even though in a local scale only, especially under the assembly holes, must be considered, from the viewpoint of the further identified influence on mechanical characteristics of the pre-stressing reinforcement as highly risky and unacceptable on a long-term basis.
- ✓ If the condition identified in 2018, as well as the condition of the corrosion of the ropes, detected already at the time of renovation (2006), but in entirely different places, are taken into consideration, then from the viewpoint of corrosion of the pre-stressing ropes the entire untwisting operation is risky. The ropes are protected from corrosion with PUR foam, it is true, but as it implies from visual inspections, the actual packing of the foamed area is not tight. It is clear that where effects of moisture can be observed and where moisture gets to the PUR foam, then moisture further penetrates closer to the ropes and causes local corrosion. This means that the anticorrosion system used (protection with PUR foam) has its certain limits. In the existing structural arrangement, it is not possible to verify the corrosion state of the ropes along the entire length. A failure and therefore also the loss of the functionality of a rope or even of a whole cable can appear anywhere, even though (of course) the riskiest place is the untwisting area at the O1 and O4 supports.
- ✓ In this situation, when already relatively small surface corrosion leads to "fragile" behavior, it is virtually possible to exclude any coupling of the ropes with surface corrosion at the level of degrees 3 and 4.
- ✓ Concerning the possibility of pit corrosion, which forms a bordered "groove" on the surface also the degree 2 can be risky from the viewpoint of coupling.

Acknowledgments

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