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Expert report:

EVALUATION OF THE WORK AND ASSESSMENTS CARRIED OUT TO DATE TO THE LISTED RAILWAY BRIDGE AT KM 3.706 POD VYŠEHRADEM WITH THE PARTICIPATION OF A FOREIGN EXPERT

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ANNOTATION

The report presents an expert evaluation of the work and assessments carried out so far on the listed railway bridge at km 3.706 Pod Vyšehradem by the foreign expert prof. Brühwiler (Annex 1). The assessment focuses on the evaluation of practical and economic possibilities of the rehabilitation of the bridge in question. This report also presents the results of the experimental verification of the cleaning methods of the segmented elements of the steel load-bearing structure of the bridge Pod Vyšehradem (Annex 2). Experimental verification of the cleaning methods was carried out under the supervision of doc. Ryjáček from the Faculty of Civil Engineering of CTU in cooperation with the Institute of Mechanical Engineering Technology / Surface Treatment Group, Faculty of Mechanical Engineering of CTU represented by Ing. Kudláček Ph.D., Applus and Klokner Institute. This report also summarises information on the reconstruction of similar bridges in the Czech Republic and abroad. Finally, the results of both surveys are summarised and commented.

The report was compiled by the employees of the CTU in Prague, the Klokner Institute, which is registered in the list of institutes qualified for expert activities, according to the provisions of Section 21(3) of Act No. 36/1967 Coll. and Decree No. 37/1967 Coll., as amended, published in the Central Bulletin of the Czech Republic, year 2004, No. 2, dated 14 October 2004, annex to the Communication of the Ministry of Justice dated 13 July 2004, No. 228/2003-Zn.

Fig. 1: View of the railway bridge Pod Vyšehradem

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1 INTRODUCTION

1.1 DESCRIPTION OF THE WORK

An expert evaluation of the work and assessments carried out to date on the listed railway bridge Pod Vyšehradem at km 3.706 was carried out with the participation of a foreign expert on the basis of order 19/618000080, dated 11 February 2019.

The report presents an expert evaluation of the work and assessments carried out so far on the listed railway bridge at km 3.706 Pod Vyšehradem by the foreign expert prof. Brühwiler (Annex 1). The assessment focuses on the evaluation of practical and economic possibilities of the rehabilitation of the bridge in question. This report also presents the results of the experimental verification of the cleaning methods of the segmented elements of the steel load-bearing structure of the bridge Pod Vyšehradem (Annex 2). Experimental verification of the cleaning methods was carried out under the supervision of doc. Ryjáček from the Faculty of Civil Engineering of CTU in cooperation with the Institute of Mechanical Engineering Technology/ Surface Treatment Group, Faculty of Mechanical Engineering of CTU represented by Ing. Kudláček Ph.D., RTD Applus and the Klokner Institute. This report also summarises information on the reconstruction of similar bridges in the Czech Republic and abroad. Finally, the results of both surveys are summarised and commented.

As part of the expert evaluation, the following was carried out:

- Submission of documents [1–3] for expert evaluation to prof. Brühwiler
- Personal tour of the bridge by prof. Brühwiler 21 February 2019
- Presentation of prof. Brühwiler's concept at SZCZ 22 February 2019
- Supplementation of documents to the calculation assumptions by SUDOP [4–7]
- Recalculation of the bridge according to the Swiss standard SIA 269/3 "Existing steel structures" in the framework of the master thesis of Nikolaï Martin under the supervision of prof. Brühwiler
- Extract from the publications of prof. Brühwiler [8–10] on the reconstruction of riveted railway bridges, Summary of examples of reconstruction of similar bridges in the Czech Republic (Ing. Holý)
- Summary of examples of reconstructions of similar bridges in the Czech Republic and abroad (doc. Ryjáček)
- Expert report by prof. Brühwiler dated 1 July 2019 – see Annex 1
- Performing a test to verify the possibility of cleaning and repair of the segmented elements of the steel load-bearing elements of the bridge 11 – 12 July 2019 (doc. Ryjáček, FME CTU, KI)
- Evaluation of experimental verification of cleaning methods, report dated 10 August 2019 – see Annex 2.
- Summary of the conclusions of prof. Brühwiler's expert report and experimental cleaning.

1.2 UNDERLYING MATERIALS

[1] Reconstruction of railway bridges under Vyšehrad, Construction part E.1.4, SUDOP PRAHA a. s., Draft Design Documents (DD) for discussion 04/2020

[2] Expert Report No. 1800J329 "Evaluation of the Diagnostic Survey of the Bridge Structures at km 3.706 – Pod Vyšehradem", KÚ 11/2018

[3] Expert assessment of the static recalculation of the bridge "SO-20-20-05 Railway bridge at km 3.706 – Pod Vyšehradem, University of Žilina, 08/2018

[4] Archival documentation of the Pod Vyšehradem Bridge from 1900 and 1960

[5] Supplementing the SUDOP static calculation assumptions

[6] COST CZ – The Prediction of the Joint Stiffness in Riveted Steel Bridges, thesis of Marcos Bryan Flores Pazmiño under the supervision of doc. Ryjáček, CTU 01/2018

[7] COST CZ – Advanced methods for assessment of deteriorated steel structures, 12/2016

[8] Brühwiler, E., Hirt, M. A.; Umgang mit genieteten Bahnbrücken von hohem kulturellem Wert, Stahlbau 79 (2010), Heft 3, pp 209–219

[9] Meyer, Ch., Bosshard, M., Brühwiler, E.; Nachweis der Ermüdungssicherheit von Brücken – Teil1: Veranlassung, Ziel und Messkonzept des Monitoring-Projekts "Bahnbrücke Eglisau", Stahlbau 81 (2012), Heft 7, pp. 504-509

[10] Bosshard, M. et al; Nachweis der Ermüdungssicherheit von Brücken – Teil2: Nachweis basierend auf den Messwerten des Monitoring-Projekts "Bahnbrücke Eglisau", Stahlbau 81 (2012), Heft 11, p. 868–868

[11] Vlasák M., Konečný O.; Repair of the steel structure of the bridge at km 12.061 of the Chrást – Stupno line, Brno MOSTY 2004, 9th International Symposium, 2004

[12] Vlasák M., Bartaloš J.; Recalculation of the railway bridge at km 41.791 of the line Tábor – Písek, Červená nad Vltavou, SILNICE ŽELEZNICE 2016, http://www.silnice-zeleznice.cz/clanek/prepocet-zeleznicniho-mostu-v-km-41-791-trati-tabor-pisekcervena-nad-vltavou/

[13] https://de.wikipedia.org/wiki/Hohenzollernbrücke

[14] Marek, L., Lojík, O.; Bridge at km 1,429 of the Pňovany – Bezdružice line; Conference Bridges 2019, Brno, 2019

[15] Reconstruction of railway bridges under Vyšehrad, Technical certificates, SUDOP

[16] South Carolina Demonstration Project: Rapid Removal and Replacement of the SC 703 Ben Sawyer Bridge Over the Intracoastal Waterway in Charleston County, Federal Highway Administration, 2011

1.3 RECAPITULATION – BRIEF DESCRIPTION OF THE BRIDGE STRUCTURE

Railway bridge at km 3.706 (mark SO-20-20-05 in the SUDOP Preparatory Documentation [1]) bridges the Vltava River with three bridge openings. The supporting structures were manufactured in 1901. The load-bearing structures are designed as closed truss multiple systems with a curved upper chord with an identical span of 71.72 m. The individual profiles are graded according to the expected stresses. The bridge is double-lined with an elemental rail-track consisting of supporting cross bars and unconnected longitudinal trusses that are inserted between the supporting cross bars. The axial distance between the main beams is 8.80 m. The height of the main beam varies from 7.136 m at the portal to 12.347 m in the centre of the span. The shape of the upper chord is polygonally broken in the place of panel points. The main beam is divided into 16 trusses with lengths of 3.46 m + 4.00 m + 4.40 m and 5 x 4.80 m at mid-span. Pedestrian bridge cantilevers are attached to both main beams with a clear width between the railings of 1,820 mm.

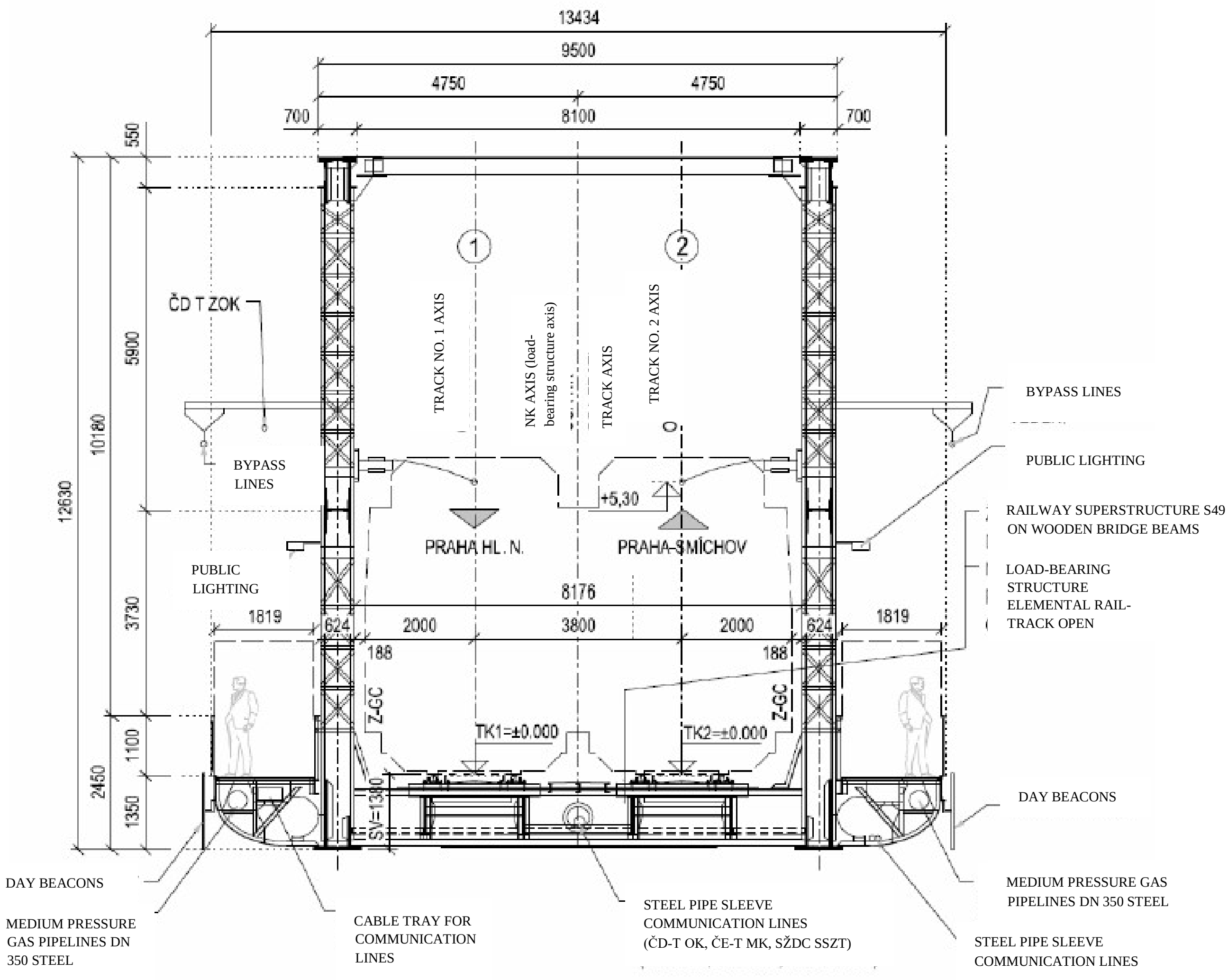

Fig. 2: Cross section in the centre of the span [1]

As part of the strengthening of the longitudinal trusses in 1987, the longitudinal trusses were supplemented with bridge stiffening and a brake stiffener. The stiffener was located in the centre of the load-bearing structure and to the edges of the 2nd truss. During the reconstruction, pavement plates and longitudinal trusses of the pavement plates were installed. The upper stiffening over the rail-track was comprehensively reconstructed in 1970 together with the electrification of the railway. The upper stiffening is formed by a rhombic system with mullions (perpendiculars). The original cross-section stiffening was completely removed and replaced with a mullion at the level of the upper chord made of welded asymmetrical I profile. The reconstruction included the outermost portals.

The load-bearing structures are supported on cast steel bearings. The dilatation movement of all constructions is from Smíchov towards Vyšehrad. The moving bearings are cylindrical roller bearings with five Ø 160 mm rollers and a bascule. Fixed bearings are rack mounted. The substructure is solid of coursed rubble, with concrete infill. The method of foundation in the case of abutment O01 and piers P01 and P02 is flat. The piers are based on steel riveted caissons. The Smíchov abutment O02 from 1871 is based on a wooden pile sleeve. As part of the installation of new structures in 1901, the upper part of the abutment was modified in place of the storage blocks and cornices on the wings.

Since December 2004 the set of bridge structures has been a cultural immovable monument “Railway Bridge – set of railway bridges on the line Praha hl. n. – Praha Smíchov”.

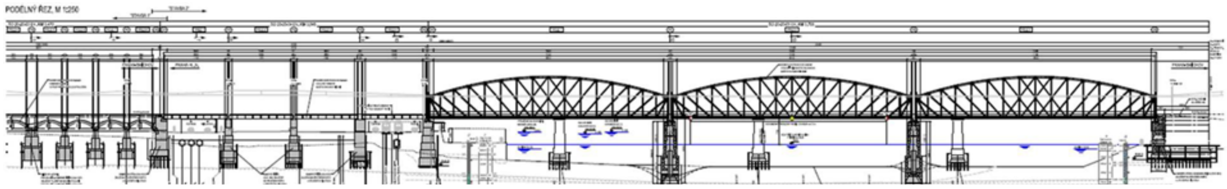

Fig. 3: Gradient profile through the bridge with the foreland

Apart from the addressed bridge with three bays over the Vltava River, the set of bridges consists of 4 other structures, in direct continuity there is a foreland formed by a beam steel bridge connected further to the stone arches.

2 SEARCHES FOR REPAIRS OF SIMILAR BRIDGES

In this chapter, a research summary of information concerning the reconstruction of steel riveted bridge structures similar to the Pod Vyšehradem Bridge at km 3.706 in the Czech Republic and abroad is made.

2.1 ACCESS TO EXISTING RIVETED RAILWAY BRIDGES OF HIGH CULTURAL VALUE ACCORDING TO [8]

The paragraphs below are based on a translation of the text of an article [8] by prof. Brühwiler, who has published on the subject in question. These paragraphs summarise the starting points for a possible evaluation of existing historic riveted bridge structures.

Riveted bridge construction structures flourished between 1880 and 1910. For their construction, welded (layered structure) or first plow steel (structure similar to contemporary steel) was used. The riveted truss structures made it possible to bridge larger spans at high slenderness and were more economical in terms of material consumption compared to contemporary commonly used structures. The disadvantage of these constructions is currently the high labour intensity of production due to the long-outdated riveting technology and inappropriate construction details in terms of corrosion protection and maintenance (segmented rods).

In the event of railway riveted bridges, in addition to technical and economic requirements, it is also necessary to take into account aspects of monuments preservation. The assessment/recalculation of historic riveted structures with the current level of knowledge and current computational capabilities, combined with structural monitoring, allows the life of the existing structure to be extended to the maximum extent possible.

The current standards for the design of new structures are in principle not or are only partially applicable for the structural analysis of a load-bearing structure – they impose high requirements in terms of durability and maintenance, and do not include rules for historical materials and previous construction methods.

U For existing riveted railway bridges it is usually necessary to:

- *Test the load capacity for higher traffic loads with higher traffic volumes compared to the original design*
- *If the structure complies with, the fatigue assessment and compliance with the requirements for serviceability limit states are usually decisive*
- *Extraordinary situations such as derailment, impact with piers, flood, earthquake were usually not taken into account or were insufficiently taken into account in the original bridge design – therefore they must be verified*
- *The durability of the bridge must be restored and improved by the corrosion protection coating (CPC)*

- *Operational and construction interventions must be optimised to have minimal impact on constraints.*

V in the event of reconstruction of existing riveted railway bridges it is usually necessary to carry out:

- *Meaningful static and dynamic load tests for model calibration*
- *Monitoring stresses in elements – important for fatigue assessment*
- *Maintenance/repair – replacement of loose rivets (high-tensile and prestressed bolts can be used)*
- *Maintenance/repair – replacement of steel elements at the open rail-track, modification of the rail-track*
- *Maintenance/repair – bearings*
- *Maintenance/repair – CPC renovation*

In the event of a need to replace the structure, the following options are offered:

- *Replicas – usually expensive, preserving maximum architectural and historical value, bridges are witnesses of engineering art that mirrors the spirit of that time*
- *Partial replica using modern construction technologies – also expensive, it is a "compromise" of architectural and structural design, historical value is questionable, from the architectural point of view it is a "hybrid" between the past and the present*
- *New construction – until now, each generation had the right to design structures freely according to the available technologies and materials of the time, and so the original structures were replaced in the past by, for example, the riveted truss structures that we can admire now*

2.2 EXAMPLES OF BRIDGE REPAIRS IN THE CZECH REPUBLIC

2.2.1 Road bridge over the railway station Praha-Vršovice on Bohdalecká Street

It is a road bridge with a lower rail-track with two trusses with an upper parabolic strip.

Fig. 4: Partial view of the bridge construction

The existing steel bridge from 1914 had severely corroded rail-track elements, which reduced its load capacity. During the repairs completed in 2005, some of the longitudinal trusses, the upper chords of the supporting cross bars and some other steel elements of the rail-track were replaced. The original steel bearings were cleaned and preserved. A new concrete rail-track slab was constructed using filigree slabs over the entire bridge ground plan. The main beams and upper stiffening remained original as they were in quite good condition. The main beams are of similar composite cross-sections as those of the Pod Vyšehradem Bridge. The entire steel structure was sandblasted and a new corrosion protection with a four-layer coating was applied. At present (almost 14 years after the completion of the repair), CPC defects on the main beams and corrosion leaching are already visible – it is obvious that the filled gaps between the profiles of the perpendiculars and lacings are leaking and corrosion of the steel bearing structure of the bridge is occurring.

Fig. 5: Defects 13 years after reconstruction (photo from 2018) [SUDOP photo]

2.2.2 Railway viaduct Chrást (Plzeň-sever) [11]

Fig. 6: Aerial view of the bridge

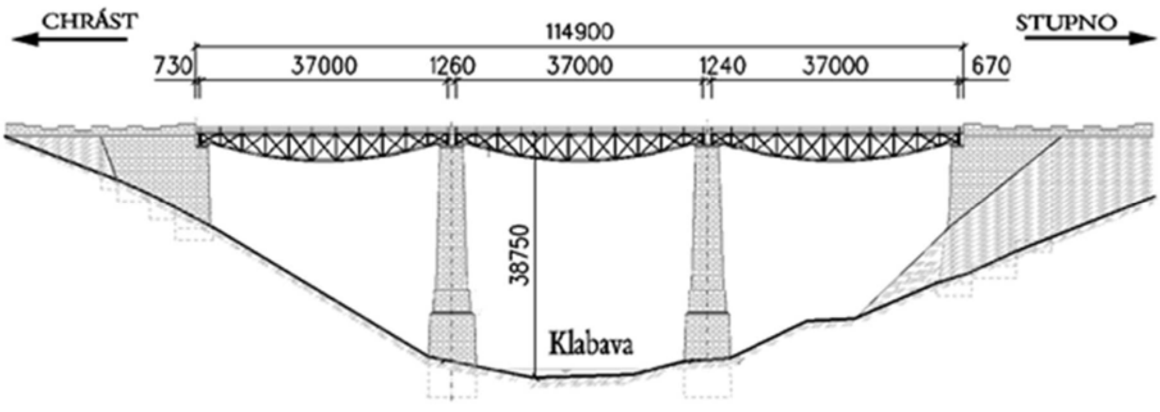

Fig. 7: Geometry of the bridge load-bearing structure

Description of the bridge

The single-track railway bridge from 1892 with three openings consists of a steel beam truss riveted load-bearing structure identical in all bridge openings, supported by two prismatic brick piers made of stone blocks. The span width of the main beams is 37 metres and their spacing is 2.8 metres. The trusses are composite systems with a straight upper chord and a parabolically curved lower chord. The height of the beam above the abutment is 1.5 metres and

4.5 metres at the centre of the span. The elemental rail-track is made up of supporting cross bars and longitudinal trusses, on which oak bridge beams are placed.

Description of defects

The structural condition of the bridge deteriorated over time due to degrading corrosion protection, which was last carried out in 1938, until it threatened to stop operation in 2003. The recalculation in 2000 established a crossing capacity of 80% of railway class A at a speed of 10 km/h. It was shown by recalculation of the load-bearing structure that repair of the load-bearing structure is necessary to eliminate the unsatisfactory load bearing capacity $Z_{UIC} = 0.38$.

Fig. 8: Details of the bridge structure before repair

Repair of the bridge

In 2002–2003, therefore, a total repair of the bridge was carried out, which included repair of the superstructure including replacement of rails, repair of the structure including reinforcement and corrosion protection and repair of the horizontal surfaces of the storage sills of the substructure. The following modifications were proposed for all three steel structures: reinforcement of the main beams and longitudinal trusses, replacement of the upper and lower stiffening including the revision footbridge, replacement of the railings including the pavement planks.

The gradual replacement of elements and the overall restoration of the CPC managed to repair the bridge at a very reasonable cost (about CZK 6.5 million per bay). The rescue of this unique construction helped to maintain the operation on the Chrást-Stupno line, which celebrated its 140th anniversary in 2003.

Fig. 9: Details of the bridge structure after repair

2.2.3 Railway bridge at km 41.791 of the line Tábor – Písek, Červená nad Vltavou [11]

Fig. 10: View of the bridge

Description of the bridge

The railway single-track bridge structure with five bridge openings has a total bridge length of 284.20 m. The bridge structure consists of a stone arch structure in bays 1 and 5, a riveted steel truss structure of rhombic system with perpendiculars with intermediate rail-track in bays 2, 3 and 4. The span of the trusses bays is 84.40 + 84.40 + 84.40 m = 253.2 m. Two joints are embedded in the middle bay, i.e. the structure acts as statically determined, the so-called "Gerber beam". The end beams are with overhanging ends with a lining of 3 × 8.44 = 25.32 m. The embedded bay has a span of 4 × 8.44 m = 33.76 m. The length of the trusses is identical along the length of the structure at 8.44 m. The intermediate perpendiculars are connected at the mid-span of the trusses to the panel point of lacing crossing. The bridge is made of plow steel.

The upper chord is a "Pi" section composed of plates and angles with a base height of 0.529 m. The lower chord consists of a pair of inverted T-sections. The perpendiculars are made of I profiles in the lower part of trusses and in the upper part of plate girders. The over-supporting perpendiculars and the perpendiculars at the embedded joint are trussed multiple plate girder closed rectangular cross-sections. The lacing cross-sections are usually of H truss or plate girder profile. The lacings in the centres of the bays, where the alternation of pressure and tension occurs, are made of closed rectangular truss cross sections. The rail-track is an intermediate elemental consisting of longitudinal trusses and supporting cross bars. The height of the upper chord above the TK is approx. 1.2 m. The 0.6 m high longitudinal trusses are plate girder riveted I-profiles with an axial distance of 1.8 m. The longitudinal trusses act as connected continuous. The supporting cross bars are of truss hight of 1.6 m. The supporting cross bars support the longitudinal trusses at a distance of 4.22 m and are connected to the perpendiculars and intermediate lacings via splice plates.

Description of defects

During a detailed inspection of the bridge (2014–15), significant failures were identified that were limiting to the remaining life of the bridge structure. In particular, the detail at the connection point of the truss coupling of the segmented rod between the pair of neck angles. Dirt settles in the narrow space of the crevice between the neck angles and the constant moisture causes corrosion of the entire neck angle flanges or significant corrosion loss. From the point of view of reparability, this is an unrepairable fault that can only be solved by replacing the entire element. The corrosion of these faults will worsen over time. From the point of view of load-bearing capacity, the detected defects are significant and significantly reduce the load-bearing capacity of the rods, which will be further reduced by the development of corrosion. The inspection revealed a large extent of these failures. It concerns virtually all pier perpendiculars and mostly all drawn lacings. In many cases, the corrosion damage was covered by a thick layer of paint, but the paint was hollow at the point of failure and a hammer could be used to completely remove the corroded neck angle flange. Replacing all these affected elements to the extent identified would essentially be equivalent to fabricating a replica of the entire load-bearing steel structure. Another element that is significantly weakened by corrosion are the supporting cross bars, where corrosion loss of the neck angles occurs at the heading joint in the placing at the upper chord of the supporting cross bar. The failure can only be repaired by replacing the longitudinal trusses. During the static recalculation it was found that the structure is not able to carry the current standard loads, especially wind loads and brake force loads, which induce enormous additional stresses in the elements under consideration, which is mainly due to the absence of stiffeners that would transfer the load to the global system.

Bridge replacement proposal

Considering the structural condition of the steel structure and after evaluating the possibility of structural modifications, only local repairs without renewal of the coating system were proposed. The maintenance of the operational capability on the line was conditioned by the replacement of the steel structure with a comprehensive rehabilitation of the substructure within 5 years.

Fig. 11: View of the bridge axis at the level of the lower chord

2.2.4 Railway bridge at km 1.429 of the Pňovany – Bezdružice (Hracholusky) line

The bridge was single-track with truss main beams of variable height from 3.9 m at the ends to 6.7 m in the middle of the span and an intermediate rail-track. The span of the steel riveted truss structure bays was 3 x 57 m. The bridge structure was manufactured in 1899–1900. The last major maintenance of the bridge was carried out in 1969–1973. It is a low-traffic line with about 7 trains per day. In 2015, an inspection found the bridge in a state of disrepair. Detailed corrosion inspection revealed uneven local corrosion losses, extensive corrosion weakening of the main load-bearing elements. On the basis of a static recalculation, it was shown that the bridge could no longer be kept in operation. It was decided to replace it with a new structure similar in shape, which was carried out this year.

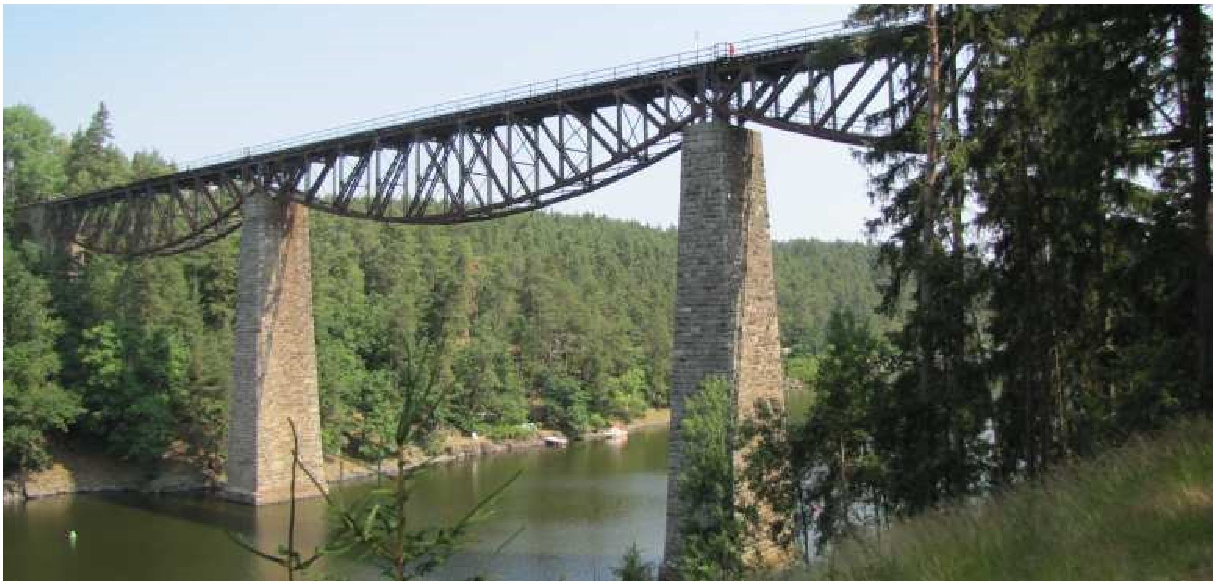

Fig. 12: View of the bridge before reconstruction

Fig. 13: Replacing the first arch

Fig. 14: Visualization of the bridge with a footbridge

2.3 EXAMPLES OF BRIDGES ABROAD

2.3.1 Hohenzollernbrücke (Germany, Cologne) [13]

The Hohenzollern Bridge (German: Hohenzollernbrücke) is a railway bridge over the Rhine River in
Cologne. It consists of 3 separate double-track bridges with three bays, total length 413 m and total width 40 m, see Fig. 11,12. The lengths of each bay and the maximum height of the structure in each bay are shown in Figure 15.

Fig. 15: Information boards at the bridge

Each of the bridges has a different structural design, see Figures 16–19. The bridge was built according to the design of architect Franz Heinrich Schwechten between 1907 and 1911; first in the form of two railway bridges and one road bridge. In 1945 it was blown up by the German army, after the end of the war it was rebuilt, with footbridges and a cycle path.

The Hohenzollern Bridge is structurally designed as a truss arch with the lower rail-track suspended on vertical rods. During the reconstruction, the drawn elements and the rail-track were completely replaced and the arch elements repaired. Although the Hohenzollern Bridge is visually similar to the Pod Vyšehradem Bridge, from the point of view of static action they are completely different structures (the Pod Vyšehradem Bridge acts as a truss).

The bridge is one of the most important transport links in the German transport network. Directly behind it on the Old Town side there is the main Cologne railway station, see Figure 12, so the speed of traffic on the bridge is limited. Approximately 1,120 trains cross the bridge every day, making it the most frequently used bridge in Germany. On the two left bridges, the rails are directly fixed to the bridge structure via the bridge beams, the maximum permitted speed there is 60 km/h, but the normal speed of trains entering the station is 20–30 km/h. On the newest right-hand bridge for SBahn there is a railway bed with a top train speed of 80 km/h or 50 km/h from the signal at the western end of the bridge towards the station.

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Fig. 16: Aerial view of the bridge

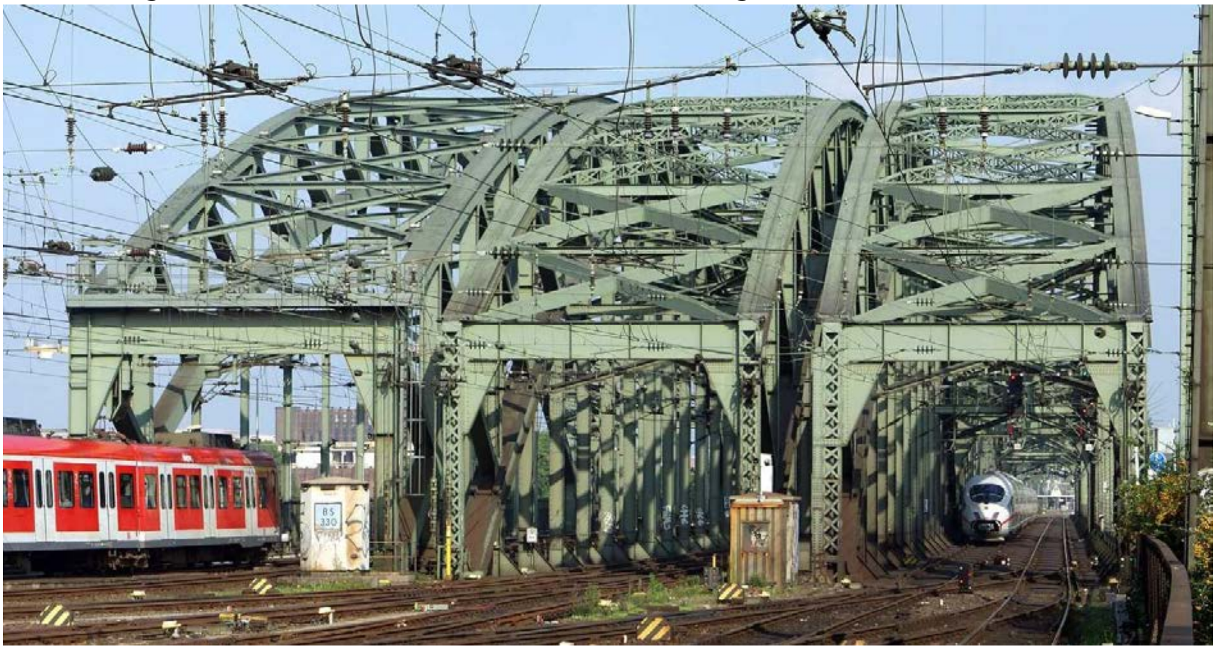

Fig. 17: Different structural designs of each of the three double-track bridges evident from the differences in the extreme portal frames

Fig. 18: Different rail-track structural designs for each of the three double-track bridges

Fig. 19: Different structural designs of arches. The arches are riveted and welded

Fig. 20: Detail of the arch area with a high concentration of riveted joints and scabs

2.3.2 Untere Limmatbrücke Wettingen, (Switzerland) [8–10]

- these are 3 parallel railway single-track bridges from 1922
- the load-bearing structure consists of a continuous truss over 3 bays with a total length of 133 m
- upper rail-track
- the bridge was made of plow steel
- the open rail-track was the weakest point of the bridge, so it was replaced by a similar one with improved structural details in terms of fatigue, the main beams were preserved, today the bridge is used for the railway class D3

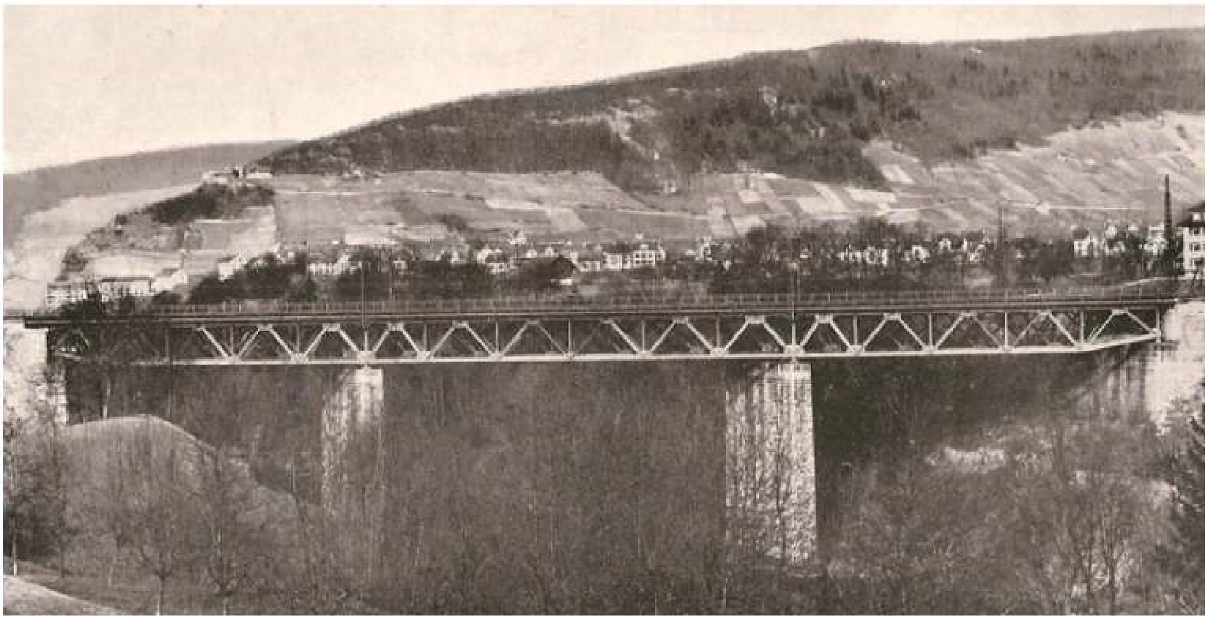

Fig. 21: View of the bridge

2.3.3 Bridge over the Rhine in Eglisau, (Switzerland) [8–10, Annex 3]

- single-track bridge with upper rail-track from 1897 made of plow steel
- bay over the river – a simple truss with a span of 90 m and a height of 9 m
- high historical value, part of a stone arched elevated road of 20 bays with vault spans between 12–15 m total length 457 m
- turbulent past, during operation problems with subsidence and horizontal shifts of the adjacent quay piers towards the steel bay, multiple readjustments of the sliding bearings, cracks + subsidence in the top of the adjacent vaults > subsequently in 1921 the vault was underpinned by prestressing, the prestressing introduced a force of approx. 1,000 kN into the bottom cord of the truss, measurements on the steel structure
- static recalculation 1980 -> in 1982/83 reinforcement of some elements of the structure (especially joints) + change of the open rail-track to a railway bed, complete CPC renewal
- the static recalculation from 2001–2003 did not comply with the fatigue -> calculation uncertainties, unsubstantiated estimates, preparation of extensive monitoring
- in 2010, monitored on a long-term basis with 137 meters
- results – by changing the type of rail-track the fatigue stresses were significantly reduced
- sophisticated detailed calculation of fatigue life based on measurements was carried out
- fatigue life predicted to be approximately another 50 years due to refinement of input information

Fig. 22: View of the Bridge across the river Rhine in Eglisau

The CPC restoration in 2019 was carried out in four stages. The blasting of the structure was carried out in an airtight canvas covering (with a slight subatmospheric pressure in the area of canvas covering). The sandblasting residues were transported to a tent under the first stone arch where the blasted corrosion products (containing lead) and sand were separated and the sand was reused for blasting, see Figure 23.

Fig. 23: Airtight canvas covering, right view inside the canvas covering

Fig. 24: View of the structure before the blasting – CPC on the surfaces is still functional, local corrosion is occurring, corrosion losses are still negligible

Fig. 25: View of the structure after application of the new CPC, on the right it is shown that it is possible to clean and apply CPC even in the narrow space between the plates without filling the joint

2.3.4 Ben Sawyer Bridge – Replacement of a bridge in the USA [16]

The Ben Sawyer Road Bridge forms the only direct link from the coastal town of Mount Pleasant to Sullivan's Island. The original steel bridge was opened in 1945 and is considered a cultural heritage site. It is a long complex of bridges with a main lifting truss bay across the navigation channel. The bridge was in poor condition and in need of repair. In 2005, it was therefore decided that the original structure should be preserved as much as possible. Due to the technical condition of the structure, the original substructure was retained. In the case of the steel structure, it was decided to replace it with a similar structure. The replacement was carried out with a bridge closure of only 10 days as follows: Mounting trestles were assembled on both sides of the structure. The new bridge was fabricated in the bridgeworks, transferred by ship and placed next to the existing structure on the assembly trestles. During the traffic closure, the lifting equipment (retractable supports) was replaced and the old structure was moved horizontally to the assembly trestles and the new bridge was moved to its final position.

Fig. 26: Replacement of the main truss bay – horizontal movement over the assembly trestles.

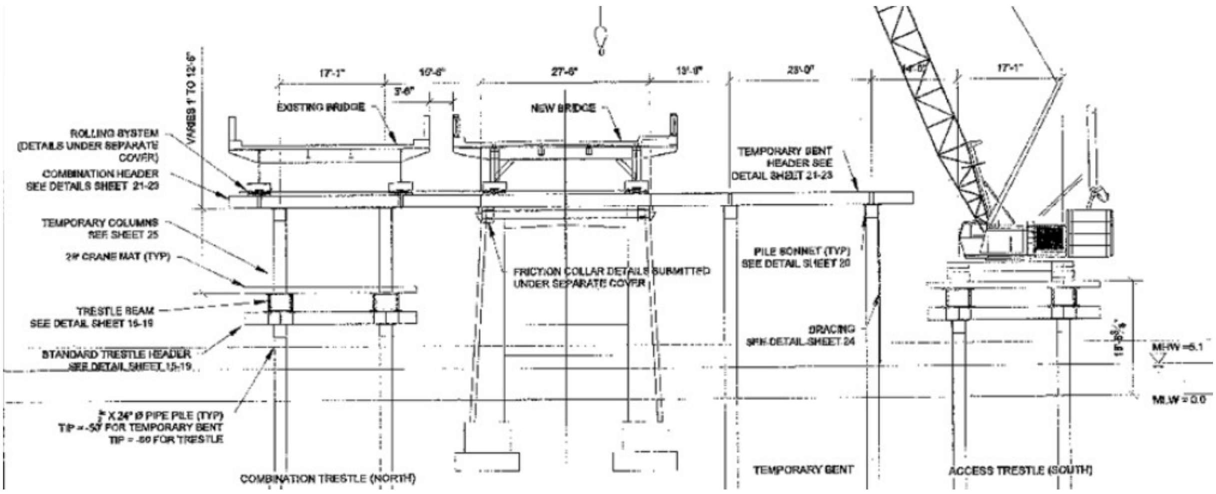

Fig. 27: Scheme of construction

3 RECAPITULATION OF THE SUDOP RECONSTRUCTION PROPOSAL

3.1 RECONSTRUCTION

On the basis of the analysis, SUDOP considered that 60–70 percent of the elements (rail-track, perpendiculars, lacings and partially lower chords) would have to be replaced, while only 30 years of life extension would be achieved.

Reconstruction of the steel structure to the extent proposed **requires the structure to be lightened** by supporting it on trestles. This would mean removing traffic from the structure and creating a replacement temporary bridge. For the reconstruction of the bridge it was therefore assumed:

a) The reconstruction of the bridges would take place on an assembly platform in a displaced position (along the river direction).

b) Ensuring single-track operation for about 4 construction seasons, i.e. 42 months, which represents a major limitation of the traffic capacity of this section. To ensure traffic during construction, a 3 x 72 m bridge temporary structure of type ŽM16 in 2p2sz configuration will be built.

c) The load-bearing structure of the Výtoň foreland would be reconstructed out of position in the contractor's bridgeworks.

A schematic representation of the construction process is shown in the following figures.

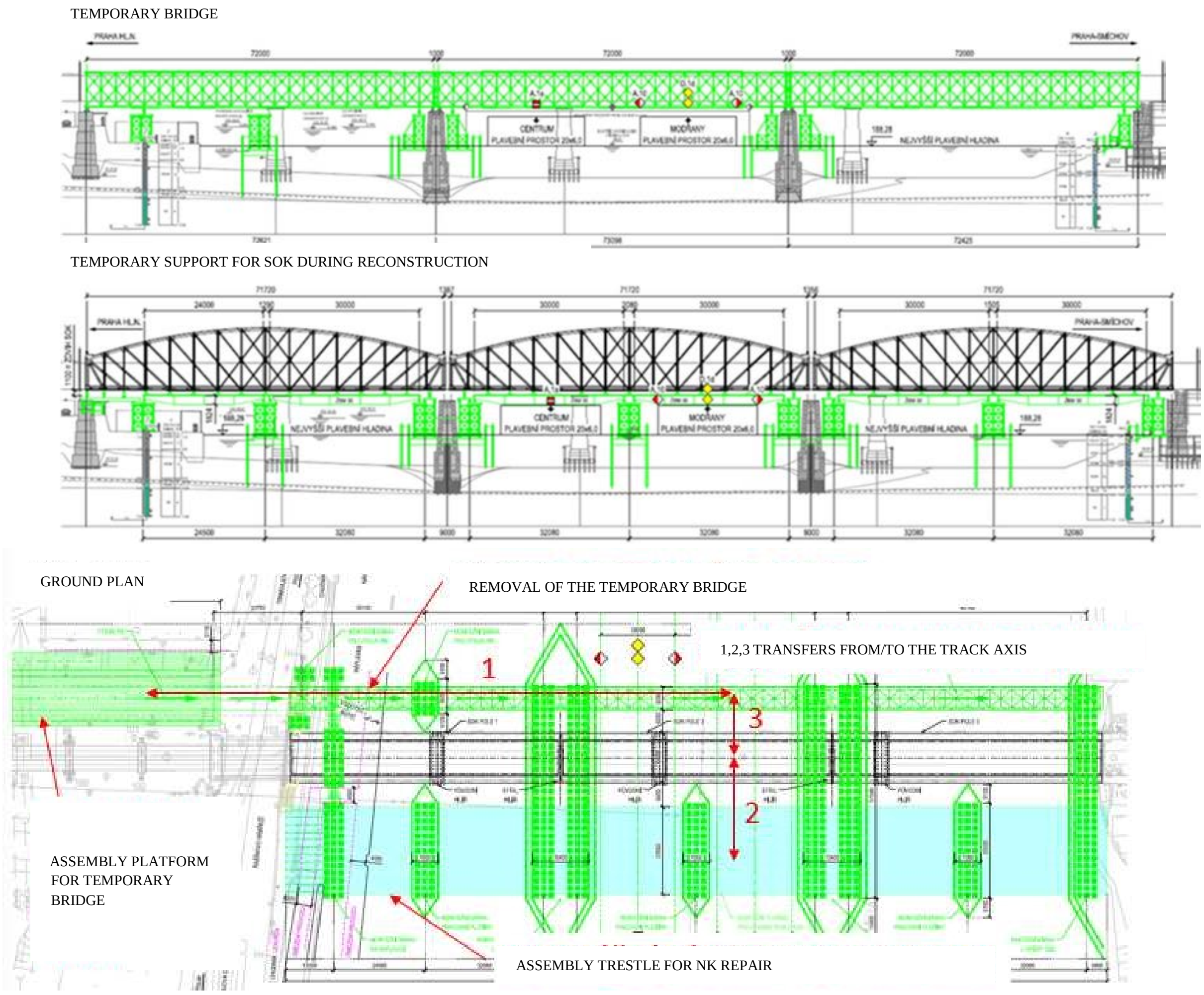

Fig. 28: Diagram of the construction repair procedure according to the SUDOP proposal

The quotation of the summary assessment and recommendations for further steps in the SUDOP [1] reconstruction proposal is as follows:

> After evaluating the scope of the proposed modifications, in relation to the investor's intention to reconstruct while maintaining the existing structure for the given SO, it is necessary to state that the proposed scope of reconstruction of the steel structures of the bridges at km 3.545 and km **3.706 is disproportionate to the overall implementation time, long-term limitation of operation, financial costs and the resulting parameters with a limited life of 30 years and we recommend the Client to reconsider the intention to reconstruct the steel structures of the bridges and to consider the replacement of the supporting structures** that will ensure a service life of 100 years for the bridge structure. However, this proposal would require the removal of the listed building protection on these affected parts of the bridge.

3.2 COMPARISON WITH THE NEW BRIDGE OPTION

In the case of a new bridge, the bridge would be replaced with a new one with the proviso that the substructure would have to be rehabilitated during operation with one of the tracks restricted at a time. In parallel, a new bridge would be constructed and then the replacement would be carried out by transverse movement.

In the framework of the preparation of the so-called Technical Status Certificates [15], time and financial analyses were carried out comparing the option of new construction of the steel structure and repair according to the SUDOP assumptions [1] with the replacement of elements. The Technical Status Certificates compared a new bridge alternative and a reconstruction alternative for the entire span of bridges. The part across the Vltava River is only structure 20-20-05. A comparison of the estimated costs is given in the following table.

Table 1: Comparison of assumptions

"Reconstruction of railway bridges under Vyšehrad"		
SO	**INVESTMENT COSTS**	
	PD – reconstruction	**N – new**
	[Thousand CZK]	**[Thousand CZK]**
SO 20-20-01	31,630	31,630
SO 20-20-02	9,961	16,177
SO 20-20-03	47,912	47,912
SO 20-20-04	75,718	92,989
SO 20-20-05	535,277	369,847
SO 20-20-05.1	14,151	18,362
SO 20-20-05.2	1,020	1,020
SO 20-20-05.3	32,948	32,948
SO 20-23-01	1,353	1,353
Only structures 05	**583,396**	**422,177**
TOTAL	**749,970**	**612,238**

CHANGE N x PD	**-137,733** **-18%**

PD reconstruction of the listed railway bridges under Vyšehrad – currently prepared planning procedure documentation of the construction "Reconstruction of railway bridges under

Vyšehrad” study of visually similar structures of a double-track bridge with a new

N

steel load-bearing structure on the rehabilitated existing substructure

From the analyses carried out in the Technical Status Certificates it can be stated:

a) Reconstruction with replacement of elements would take 4 construction seasons i.e. approx. 4 years approx. 48 months
b) The construction of the new structure would take place during the 2 construction seasons, i.e. about 20 months, i.e. about half the time of the reconstruction. This would mean significantly less impact on the operation on the existing bridge.
c) It is assumed that the repair of the substructure will be limited to single-track operation and then a virtually short time period for moving the structures to the new position.
d) According to SUDOP's assumptions, the life of the reconstruction will be a maximum of 30 years considering the retention of certain parts of the structures when increasing the operation from 19 million hr.t/year to 35 million hr.t/year.
e) The new bridge will have a designed life of at least 100 years.

4 CONCLUSIONS FROM THE STUDY OF PROF. BRÜHWILER

This chapter is based on prof. Brühwiler's report “Railway Bridge „Pod Vyšehradem” in Prague – Preservation of the existing bridge: Assessment and feasibility study for the restoration”, which is attached as **Annex 1** to this report. The specification of the assignment for prof. Brühwiler is given on page 3 of his expertise (see **Annex 1)** and included:

1) review of the reports established by the SUDOP company and the Klokner Institute regarding the current bridge condition, the calculated structural and fatigue safety of the riveted steel structure as well as the proposed remedial measures
2) comparison and benchmarking with similar cases of riveted steel railway bridges (in Switzerland)
3) proposal of an intervention concept with the objective to maintain the original bridge structure as far as possible, considering economic aspects and a long future service duration for future railway service.

The task of prof. Brühwiler was therefore to draw conclusions and recommendations from the surveys and calculations carried out by SUDOP within the preparatory documentation for the reconstruction of the railway bridge Pod Vyšehradem [1], the expert report of the Klokner Institute [2] dealing with the evaluation and supplementation of the original diagnostic survey of SUDOP and the expert report of the University of Žilina [3] dealing with the assessment of the static recalculation of SUDOP, based on his long experience with the reconstruction of railway riveted structures. Prof. Brühwiler also made a personal inspection of the bridge during his visit to Prague on 21 February 2019. During the visit, he presented partial conclusions to the staff of KI, SUDOP and SZCZ. He also involved his student Nikolaï Martin, who carried out a comparative recalculation of the bridge's load-bearing capacity according to the Swiss standard SIA 269/3 “Existing steel structures”.

It can be stated that prof. Brühwiler's opinion is clearly, comprehensibly and carefully prepared. In comparison to the existing view of the repair presented by the SUDOP documentation, the professor comes up with innovative but, from the Czech viewpoint, experimental and untested approaches that are not codified in the legal environment.

4.1 STATIC ANALYSIS

The static analysis was carried out by Nikolaï Martin under the supervision of the professor Brühwiler according to the Swiss standard SIA 269/3, taking into account the Eurocodes and CEN/TC 2050 M515 WG2.T1 Assesment of Existing Structures – final draft 04/2018.

Analysis assumptions:

- Load corresponding to railway class D4
- Damaged cross-sections of the main beams will be restored to their original dimensions.
- The rail-track will be converted to a fixed track using the Edilon system with prefabricated UHPFRC panels that will be welded to the existing longitudinal trusses via embedded anchor plates with spikes, glued with epoxy and then prestressed.
- Assumption of plastic joint formation in the panel points and elements, which leads to the elimination of secondary bending moments

Conclusions of the static analysis:

- If the cross-sections are restored to their original dimensions, the main beams will comply with the ultimate limit state assessment with a tolerance.
- When the cross-sections are restored to their original dimensions, the fatigue assessment is not critical because of the relatively small stress ranges, which are less than the fatigue limit.
- In the case of a rail-track modification to a fixed track, the existing rail-track elements will comply with ultimate limit state and fatigue stress with a tolerance.

Table 2: Comparison of SUDOP and EB assessment results – different assumptions – see below

Table 5.1: Structural safety verification at ULS (Type 2: ultimate resistance): Results obtained by SUDOP using UIC71 Load Model and EPFL using Line Class D4 Load Model for railway loading.

	SUDOP (UIC71)		EPFL (D4)
Structural member	"utilized capacity"	degree of compliance *n*	degree of compliance *n*
Lattice Girder			
Upper flange	78%	1.29	1.35
Lower flange	109%	0.92	1.42
Diagonal D7 (mid-span)	85%	1.18	2.08
Diagonal D2 (near support)	101%	0.99	1.16
Posts	117%	0.85	2.17
Track supporting structure			
Cross girder	146%	0.68	1.61
Floor beam	133%	0.75	1.16

Note on the table:
Utilised capacity – utilisation at ultimate limit state
Degree of compliance – degree of safety (load-bearing capacity / load)

Different input assumptions of the analyses

- SUDOP used UIC 71 – load model for bridge design x EB model for railway class D4 (UIC 71 is about 11% heavier than D4),
- SUDOP is considering placing the existing rails over the bridge beams x EB adjustment to a fixed track,

- SUDOP assessed the structure with the inclusion of corrosion weakening according to the applicable regulations in the Czech Republic x EB assessed the structure without corrosion weakening for the restoration of the sections to their original condition according to the Swiss standard SIA 269/3

4.2 DISCUSSIONS ON STATIC ANALYSES – SUDOP x EB

It should be noted that the assumptions of the static analysis of SUDOP and EB were quite different.

SUDOP carried out a detailed analysis according to the valid regulations in the Czech Republic, including the regulations of SZCZ. A linear analysis on a 3D-model was performed **taking into account corrosion weakening based on a detailed corrosion survey**. The fatigue assessment was carried out using modern approaches for fatigue reduction during corrosion [7]. The stiffness of the panel points was calculated using the latest analysis methods [6] and was further tuned based on load tests. It can be concluded that in terms of structural assessment, the SUDOP assessment was of a superior standard and SUDOP went to the limit of the normal and usual approach in the Czech Republic.

EB recalculation was performed on a structure **without corrosion weakening,** with **consideration of joints in the panel points and with a modified rail-track to a fixed track.** Overall, the EB approach leads to NK maximalist use. It must be stated, however, that the SIA approaches are not fully compatible with the EN standards and our practices stipulated in the SZCZ Methodological Guideline for Determining Load-Bearing Capacity. For example, EB allows plasticity in the panel points also at elements, which leads to the elimination of moments in the panel points and consequently to a "higher load-bearing capacity", i.e. a more optimistic view of the structure, which is not allowed in our regulations.

The results of the static analysis carried out by SUDOP according to the currently valid standards in the Czech Republic and supervised by prof. Brühwiler according to SIA 269 and CEN/TC 2050 M515 WG2.T1 would probably not differ much in principle, under the same input assumptions, i.e. especially considering the corroded structure and similar loads, in concluding that the bridge is in very poor condition. This is also the basis for the recommendations presented in prof. Brühwiler's study.

4.3 RECOMMENDATIONS FOR REPAIR DESIGN

Prof. Brühwiler confirms that the overall current condition of the bridge is poor, the bridge is heavily damaged by corrosion. **There is a clear need to urgently repair the bridge.** The bridge is still in operation, although the riveted steel structure of the bridge has probably shown severe localised corrosion damage for many years.

A table summarising the most relevant part of the design description is given below.

Table 3: The overall repair design specified in prof. Brühwiler's expert report

There are four main types of intervention summarized in the following table and discussed hereafter.

Element:	*Intervention:*	*Remarks:*
1. Rail-track	Renewal by adding a fixed track in R-UHPFRC or in steel	optional, but highly recommended
2. Riveted steel structure	Repair of severely corroded zones	mandatory, urgent
	Application of new corrosion protection coating	
3. Bearings	Rehabilitation and repair	mandatory
4. Piers and abutments	Rehabilitation of natural stone masonry	mandatory
	Rehabilitation of pier foundations (in the river)	

A translation of the contents of Table 3 is as follows
Interventions to be carried out in the case of bridge reconstruction

Element	**Intervention**	**Note**
Rail-track	Recommended to renew by adding a fixed track in UHPFRC or steel	Optional, highly recommended
Main beams	Repair severely corroded areas, apply new CPC	Mandatory, urgent
Bearings	Repair, restore	Mandatory
Abutments and piers	Rehabilitation of pier foundations (in the river) and rehabilitation of natural stone masonry	Mandatory

According to E. Brühwilerr: The existing rail-track is unsuitable in terms of transmission of brake forces and is a weak point in terms of fatigue (stress on some rivets for tension), is demanding for maintenance and is noisy. The application of the railway bed on the existing supporting cross bars is not possible because the grade line of the track would have to be increased (in addition to extensive modifications in front of and behind the bridge, the portals would also have to be modified) and in addition, the existing bridge would be significantly overloaded. The professor suggests replacing the bridge beams with a fixed track with the Edilon system. This modification would be an effective solution because:

a) the grade line of the track will be maintained,
b) there will be only a small overload on the existing structure,
c) significant improvement will occur in terms of statics (stiffening of the elemental rail-track for the transmission of brake and run-up forces, significant reduction of stresses on the supporting cross bars and longitudinal trusses),
d) the plate with a cog will ensure protection of the bridge NK in the event of a train derailment (reducing the load effects for the exceptional design combination),
e) rail-track maintenance requirements are reduced, noise levels are reduced.
f) As there is no need to dismantle the existing bridge rail-track elements, this modification of the rail-track would be significantly more cost-effective in terms of time and effort.

Quotation from the text of prof. Brühwiler's report – repair options and CPC

6.2. Repair and corrosion protection of the riveted steel structure

Repair of corrosion damaged riveted steel elements is known since the beginning of riveted steel structures in the 19th Century. Methods, techniques and materials have evolved over the decades. In the present case, in order to repair the corrosion damaged zones, the following methods may be applied:

– In case rivets need to be removed or are missing, they are replaced by bolts. Riveted joints may be strengthened by replacing rivets by post-tensioned bolts.

– Voids between plates and due to corrosion are filled with epoxy resin for sealing, in particular to (1) preclude the ingress of air and moisture which would lead to further corrosion and (2) provide a smooth, level surface on to which a new steel elements can be fitted.

– Interfaces and gaps between plates are sealed with a (single component) polyurethane sealant or mastic.

– Flanges and webs showing localized corrosion damage with significant section reduction or full loss of a part of the section are repaired using cover plates in steel bolted to the element to restore the original section. Sometimes filler or packer plates are needed for adjustments. Alternatively, glued carbon fiber lamellas may provide the same effect as steel plates.

The bridge bearings are in satisfactory condition. New corrosion protection coating of the massive steel parts and maintenance works of the mobile parts is required.

Corrosion protection coating is reinstalled on the overall surface of the steel structure using conventional techniques including:

1) sandblasting of the whole steel structure inside a tight tent allowing for complete collection of all residual products,

2) disposal of the residual products that most likely contain lead based paint (mineral red), and

3) application of several layers of protection coating.

Regarding the specific repair of the damaged parts of the main beams, the professor outlined the following possible solutions:

- In the case of missing or removed rivets, replace rivets with bolts. The joints can be strengthened by applying pre-tensioned bolts.
- Fill narrow gaps between plates with epoxy to prevent air and water from entering.
- Gaps, areas between parts of combined cross-sections to be filled with polyurethane or sealant
- Re-clad chords showing high corrosion losses with scabs or alternatively reinforce with carbon lamellas

Removal of corrosion products and CPC application:

- Sandblasting the structure in a “tight tent” ensuring that all residual blasting products are captured
- Removal of lead-containing minium base Application of several layers of corrosion protection

4.4 EB SUMMARY AND RECOMMENDATIONS

Quotation from the text of prof. Brühwiler's report – conclusions and recommendations

7. Conclusions and Recommendations

The condition and technical performance of the «Railway Bridge» in Prague, a riveted steel structure from 1901, resting on piers and abutments in natural stone masonry, has been investigated. The expertise relies on information, data and investigations provided by the Klokner Institute, SUDOP engineers as well as own investigations and benchmarking with similar cases of bridges, in particular in Switzerland.

The main conclusion is that preservation of the existing «Railway Bridge» is technically feasible while respecting current code provisions and allowing for a long future service duration:

– The structural safety at ULS Type 2 (ultimate resistance) and the fatigue safety at ULS Type 4 are verified for Line Class Model D4 (and tentatively also for UIC71 Load Model) provided that the riveted steel structure, in particular the members with severe corrosion damage, are restored and maintained in the future.

– Doubts regarding insufficient remaining fatigue duration are not justified. The fatigue relevant elements of the riveted main lattice girder are subjected to low fatigue stresses below the fatigue endurance limit such that it may be concluded that the riveted structure can be considered undamaged in terms of fatigue.

– The existing riveted structure has sufficient structural capacity in order to carry future train traffic including higher trainloads and higher train frequencies, without calling for systematic strengthening of most structural members. However, critical zones with severe corrosion damage must be repaired, and new corrosion protection painting is indispensable.

Preservation of the existing bridge implies some modifications, in particular related to the rail-track supporting system. These interventions will be of minor visual impact on the bridge aesthetics, and thus the restored bridge most likely will be still compatible with cultural values.

Based on these conclusions, it is recommended to estimate and update the cost for the following mandatory works:

– repair of damaged structural members: it is crucial to limit the cost for the repair of damaged structural members; effective and durable repair methods need to be implemented without calling for replacement of entire structural members. Such methods have been applied in similar cases.

– application of a new corrosion coating on the steel structure and maintenance of bearings

– rehabilitation of the natural stone masonry of the piers and abutments and consolidation of the foundations.

In addition, it is highly recommended to improve the rail-track supporting system by installing a new fixed track (in R-UHPFRC or steel construction) using the Edilon Track System.

<u>According to Professor Brühwiler, the bridge can be reconstructed in the following way:</u>

- **All severely damaged parts will have to be repaired.**
- It is necessary to eliminate the replacement of elements, the number of repair points. It will probably not be necessary to replace the elements in the area of the main beams, but it will not be easy to find an effective solution to repair all the damaged details.
- There is no need to reinforce the structure, the originally designed cross-sections have sufficient load-bearing capacity, but it is necessary to repair damaged parts with a serious loss of cross-sectional area.
- It is recommended that the rail-track be modified to a fixed track using a slab of ultra-high-value concrete or steel (rather than the otherwise necessary complete rail-track replacement, which is also unsuitable from a fatigue point of view).
- On the basis of his experience with similar bridges, prof. Brühwiler assumes that the reconstruction costs would be lower than replacing the bridge with a new structure if

the reconstruction is carried out in a way that the existing load-bearing elements are not dismantled, i.e. the structure does not have to be moved and the total closure would only take place for a short period of a few weeks.

- **The repair must be carried out efficiently to ensure the life of the structure for at least another 80 years.**

5 CLEANING CHECK TEST – VERIFICATION OF CORROSION CONDITION

5.1 DESCRIPTION OF THE WORK CARRIED OUT

Based on the agreement with the Client, the work solution was extended by checking the possibility of cleaning corroded parts and removing corrosion products in poorly accessible crevices between the elements of the segmented elements. A detailed report of this experimental programme is given in Annex 2.

The main objective of the experimental work was to verify the possibility of cleaning the surface of individual sections to the extent necessary for the application of protective coating systems. Furthermore, estimation of the total time and, if applicable, financial intensity of the surface pre-treatment prior to the application of corrosion protection.

At the same time, the aim was to verify the conclusions of a check measurement of the partially blasted outer side of the lower chord of the truss structure (carried out within the reconstruction of the side footbridge by STRABAG in 08-09/2018), when corrosion weakening of the cross-sections was found in several cases to be approximately 5% greater than that determined in the original SUDOP inspection [1], which was carried out on the unblasted structure.

In the experimental cleaning (surface blasting) programme, the usual designs for the pre-treatment of steel surfaces for the application of protective coatings were selected – i.e. blasting with the use of sand ("sandblasting") or with the use of steel grit as an abrasive. The experimental programme involved the application of a high-pressure water jet using radial (rotary) and direct (demolition) nozzle to guide the water jet. The experimental work was carried out by the team of the Faculty of Civil Engineering, Faculty of Mechanical Engineering and the Klokner Institute of the Czech Technical University in Prague. Blasting focused on these details:

- through crevice in the lacing
- impenetrable crevice in the lacing
- impenetrable crevice inside the lacing with difficult access,
- crevice under the lower chord

Several conclusions were drawn from the experimental procedures carried out for the pre-treatment of the surface and crevices of the steel structure:

5.2 CONCLUSIONS OF THE TEST CLEANING

1) Waterjet pre-treatment is suitable for the removal of delaminated coating systems and incoherent corrosion products. In the case of waterjet blasting, it is necessary to alternate the individual positions and angles of the blasting to ensure perfect removal of the above-mentioned impurities in the crevices, which also applies to other methods. The great advantage of this method is low time demand of the entire pre-treatment process compared to other commonly used pre-treatments. However, pre-treatment with a high-pressure water jet in the crevice area alone does not guarantee complete removal of previous corrosion protection in the form of coating systems with good adhesion in these crevices. In addition, this pre-treatment is not suitable for severe surface degradation of materials because the appropriate surface cleanliness according to ISO 8501-1, i.e. at least Sa 2.5, will not be preserved before the application of coating systems. It was also found that this pre-treatment method does not provide sufficient surface roughness for subsequent application of coating systems (see Table 4). The use of a demolition nozzle at maximum pressure (2,500 bar) proved to be more effective and allowed blasting down to the base material of the steel structure in some parts of the crevices. A nozzle with radial water jet transport is considerably less efficient. If the nozzle is modified, an increase in the efficiency of the pre-treatment itself could be achieved for these applications. Another limitation is the necessity of **100% wastewater capture** due to the capture of hazardous substances contained in the original coatings.

2) Water jetting and sand blasting is very time consuming. It is necessary to reposition the blast head, blast from 2 or more positions to achieve the desired quality. If we consider that it took about 22 minutes to blast a 0.5 m long site (specifically site 20 according to Annex 2), then about 1.5 h of blasting (total water and sand) is needed for 1 m of the entire rod length. The total length of the main beam rods is 3,600 m, then 450 working days are needed to blast them. Using 3 blasters, 7 months of the year with acceptable climatic conditions for the application of CPC (which must be applied immediately after blasting, no further blasting is allowed until drying, under the required humidity, no rain), **the blasting of the main beams alone will take 1 year.** In addition, the coating will also take 1–2 years, and both activities cannot be carried out simultaneously (they will follow each other in short intervals – blasting of the part and subsequent protection with CPC in one day). Both the blasting and CPC should be carried out when traffic is excluded, both because of traction and because of the resulting dispersion, it is impracticable to consider canvas covering in the middle of the bridge.

3) Using mechanical pre-treatments, i.e. light silica sand blasting and blasting with metallic abrasives, a favourable surface condition was achieved in many cases. Adequate surface cleanliness and roughness for application of the coating system was achieved at some test sites. Adequate pre-treatment quality of the crevices was achieved especially for those with smaller depths, as in the case of deep crevices there was a significant dispersion of abrasive on the walls of the steel elements of the structure.

4) Mechanical pre-treatment using hand-held power tools would only be appropriate for smaller size and complexity of the structure, especially to remove delaminated coating systems and corrosion products. The subsequent application of the coating system would require the use of additional machinery to pre-treat the surface, in particular to remove residual corrosion products, adhering coatings, etc.

5) A **combination of blasting** with a high-pressure **water jet** and subsequent pre-treatment with **silica sand** blasting or **steel grit** appears to be the most suitable current pre-treatment of the crevices and surface of this steel structure for adequate quality, surface finish and subsequent application of coating systems. Due to the complexity of the structure, it is necessary to carry out the pre-treatment with sufficient care before the actual application of the coating systems. In this case, it would be necessary to provide a qualified inspection supervisor to oversee the adequate quality of the PKO implementation itself in accordance with the specifications.

6) In the case of using these pre-treatment methods, it would be necessary to ensure **complete covering of the lower part of the structure, which would also be able to absorb blasting water with back-filtration** as a result of f**alling abrasives, corrosion products and paint residues** (including lead-containing minium base paint) into the Vltava River.

7) Another task will be to ensure the required corrosion protection of the cleaned surfaces, as it is very difficult to apply a uniform layer of paint into narrow crevices and thus achieve the required barrier protection.

8) In terms of corrosion weakening, a **strong form of localised corrosion damage** is evident after removal of corrosion products and deposits from the non-continuous crevices in lacings. The material loss on the flat sections in the crevice in the area of the splice plate reaches up to 70% of the original thickness at the monitored locations, i.e. a residual thickness of 30% of the original thickness (minimum of 2.8 mm detected). The observed weakening in terms of their average value corresponds approximately to the SUDOP corrosion survey.

Note: According to the inspection of the KI [2]: On the basis of a check measurement of the partially blasted outer side of the lower chord of the truss structure, corrosion weakening of the cross-sections was found in several cases to be approximately 5% greater than that determined in the original SUDOP inspection [1], which was carried out on the unblasted structure.

5.3 STATEMENT OF PROF. BRÜHWILER ON CLEANING CONCLUSIONS

Professor Brühwiler expressed his views by means of the Memorandum set out in Annex 3. The conclusions of his statement are as follows:

Locally measured corrosion losses are even greater than 50%, but the local losses must be related to the total cross-sectional area. The cleaning tests therefore correspond in principle to the SUDOP corrosion survey. Most of the sites showing visually significant damage have corrosion losses between 5% and 10% of the total cross-sectional area of the individual elements, with a maximum losses of 12% of the cross-sectional area.

Note: In terms of the load-bearing capacity of the structure and fatigue assessment, according to EB, corrosion losses of the main beam elements between 10–12% of the cross-sectional area are acceptable without reducing the required track class (traffic load magnitude). These locally damaged areas should also only be repaired locally. Current local damage does not require replacement of entire elements. (A complete replacement of the elements would be too invasive and costly.)

Proposals for the repair of local corrosion damage were not content/part of the work and surveys carried out so far. Professor Brühwiler recommends that a repair proposal be developed for specific type details with serious corrosion damage.

5.4 COMPLETION – EXPERIENCE FROM REPAIR OF BRIDGE SO 201 at km 59.126; Volary – Černý Kříž (Dobrá na Šumavě)

Annex 4 contains the complete report "Assessment of the condition of the crevices in the steel structure of the bridge SO 201 at km 59.126; Volary – Černý Kříž (Dobrá na Šumavě) after one year since the implementation of CPC". Structure SO 201 represents a steel riveted truss structure of a bridge over the Teplá Vltava River in the Šumava National Park. The length of the bridge is approximately 51.7 m. The structural design of the steel structure is based on two main trusses with a lower elemental rail-track. In the steel structure, due to the CPC defects in combination with the corrosiveness of the environment, corrosion of the base material and in some places also significant losses of thickness of some elements occurred. In order to prolong the life of the life of the steel structure of the bridge and to ensure safe operation on the line, reconstruction was carried out including the construction of a completely new corrosion protection in 2018. The report details the original condition of the structure and the methods of repair.

The following conclusions can be drawn from the assessment of the condition of the crevices after 1 year of exposure:

From the results of the site investigation and the photo documentation it is evident that in the case of the impermeable crevices, a suitable type of sealant was selected that meets the requirements for elasticity, adhesion and compatibility with the coating system used. No areas of undesirable sealant degradation or CPC defects caused by the behaviour or nature of the sealant were observed on the structure.

In the case of the through crevices that have not been sealed, it can be seen that the areas that could not be removed from corrosion products and old coatings by the surface pre-treatment and subsequently coated are unprotected and further exposed to the atmosphere (see photos below).

Well accessible areas, i.e. those where it was possible to implement a good surface pre-treatment and apply a complete coating system using blasting technology, do not show any signs of the degradation of CPC or steel structure.

It can therefore be concluded that the method and quality of cleaning of difficult to access narrow crevices in the case of a complete reconstruction is essential for reliable, durable and functional corrosion protection of the steel structure.

6 DISCUSSION OF THE APPROACH TO REPAIR

The approach to repair from the EB perspective is completely different from the SUDOP approach:

a) EB proposes less invasive interventions, with the expectation that the extent of repair would be reduced, relying on Swiss standards for existing structures, which allow for a higher utilisation of the structure.
b) SUDOP adheres to the valid regulations in the Czech Republic and emphasises the minimisation of risks in terms of the repair itself and in terms of the future durability and structural reliability of the structure.

The static analysis and assessment of the SUDOP is not in fundamental conflict with the EB assessment. They both recommend extensive and speedy repair. There is a different view on the repair of corroded parts, which we will try to comment on in more detail below.

In view of the possibilities and especially the scope of the authors' assignments, it is clear that they necessarily vary in detail and volume. The SUDOP documentation is at the preparatory stage and includes a large amount of detailed analyses and surveys. Prof. Brühwiler prepared a study based mainly on the structural part of this documentation.

In the event of the need to replace elements of the steel load-bearing structure, these elements can only be replaced when the associated parts of the structure are dismantled, and in principle only in the lightened state, which requires the need to support the load-bearing structure. Therefore, SUDOP proposes to move the structure to the assembly trestles where the structure would be gradually dismantled and then assembled. This is a costly solution in terms of time and money.

If the elements were left in the structure and only repaired (e.g. by means of scabs), the repair options are very limited in terms of design, both in terms of implementation and the design of the repair itself.

First of all, it is necessary to properly clean the load-bearing structure of corrosion products and prepare the surface for the application of the new CPC to comply with the regulations. For this reason, a cleaning check test was carried out, the results of which are presented in the previous chapter (and in detail in Annex 2). In particular, the following conclusions are important for the repair:

It is possible to clean the structure well, but:

The blasting of the main beams alone will take 1 year. In addition, the application of the coating will also take 1–2 years, and both activities cannot be carried out simultaneously (they will follow each other in short intervals – blasting of the part and subsequent protection with CPC in one day). Both the blasting and CPC should be carried out when traffic is excluded, both because of traction and because of the resulting dispersion, it is impracticable to consider canvas covering in the middle of the bridge.

it would be necessary to ensure complete covering of the lower part of the structure, which would also be able to absorb blasting water with back-filtration as a result of falling abrasives, corrosion products and paint residues (including lead-containing minium base paint) into the Vltava River.

In terms of corrosion weakening, a strong form of localised corrosion damage is evident after the removal of corrosion products and deposits from the non-continuous crevices in lacings. The material loss on the flat sections in the crevice in the area of the splice plate reaches up to 70% of the original thickness at the monitored locations, i.e. a residual thickness of 30% of the original thickness (minimum of 2.8 mm detected).

Repair of damaged parts is quite difficult to implement due to the very tight spaces around the joints. According to SUDOP assumptions from the planning procedure documentation:

- The application of additional scabs or their incorporation into the structure is virtually beyond the feasible possibilities of contractors in the Czech Republic for the given extent of damage in most cases.
- The high frequency of failures on the structure precludes efficient repair, as one repair follows another continuously.

It can be further stated:

- Based on experience with repairs of riveted structures in the Czech Republic, it is known and tested that currently in-situ rivets do not last more than 30 years of intensive operation.
- Prestressed bolts are not a compatible connection to rivets for shear force transfer because they have different deformation limits for activation of the connection (for bridges, category C is required for prestressed connections, i.e. no overlap in the ultimate limit state).

Thus the above reasons show that such a repair would be highly uncertain. Leaving the original elements in the structure would also mean with a strong probability that this solution will not guarantee the required long-term durability.

In terms of the implementation of fixed track on railway bridges in the Czech Republic, it should be mentioned that the Edilon continuous rail support system has not been used on railway bridges in the Czech Republic so far. This would therefore be the first application and would mean, among other things, to address the approval procedures and possible modifications of the SZCZ regulatory base.

6.1 COMPARISON OF ASSUMPTIONS AND APPROACH TO RECONSTRUCTION

Below there is an attempt to compile a summary table comparing the approach of SUDOP and EB to the reconstruction of the Pod Vyšehradem Bridge:

Table 4: Comparison of assumptions and approaches to bridge reconstruction

Item	**Reconstruction according to SUDOP**	**Reconstruction according to Brühwiler**	**Comment**
Static analysis			

1	Calculation assumptions – Rail-track model	Existing design solution assessed	Assessment of the rail-track modification to a fixed track = reduction of stresses on existing elements	Difference affecting the outcome of the assessment significantly in favour of EB
2	Calculation assumptions – Corrosion model	Taking into account corrosion weakening of the cross-sectional area based on a detailed corrosion survey (on average about 12%)	Cross-sections of the main beams restored to original dimensions	Difference affecting the outcome of the assessment significantly in favour of EB
3	Model assumptions – Load model	UIC-71 load approximately 11% heavier than D4. The assessment concluded that a reduction to railway class C3 (20 tonnes per axle + 7.2 tonnes/m') was necessary for a residual life of 5 years	Railway class D4 (22t+8 ton/m´), reduction of the constant load coefficient	Difference affecting the assessment result in favour of EB
4	Assessment according to regulations and standards	according to SZCZ standards and regulations valid in the Czech Republic	according to SIA 169/3 and CEN/TC 2050 M515 WG2.T1, taking into account EN	Difference affecting the outcome of the assessment in favour of EB. The Client would have to accept the use of regulations and procedures that are not standard in the Czech Republic.
5	Ultimate limit state – Type 2	The stiffness of the panel points is considered on the basis of detailed calculations of specific particularities in combination with verification by a load test. Internal forces include secondary bending moments.	The assumption of a formation of a plastic joint in the panel points and in the elements, which leads to the elimination of secondary bending moments, which is not in accordance with our regulations.	Difference affecting the outcome of the assessment significantly in favour of EB
6	Fatigue limit state – Type 4	Palmgreen-Miner fatigue accumulation, consideration of the effect of corrosion on fatigue capacity	Achieved stress ranges lower than the fatigue limit of details	Difference affecting the outcome of the assessment significantly in favour of EB. EB neglects the issue of local corrosion and relies on the previous satisfactory behaviour, where no fatigue cracks were found on the main beams
Repair design (scope of work)				
7	Rail-track	Total replacement including reinforcement of some rail-track elements	Retaining existing supporting cross bars and longitudinal trusses, replacing bridge beams with fixed track	A fixed track will improve the parameters of the rail-track. In the Czech Republic, however, this method of rail and track modification is not regulated
8	Main truss arch beams	Dismantling of the structure in the lightened state on the assembly trestles, replacement/repair of damaged elements in the bridgeworks, assembly of the structure and moving the structure back to the piers	Retaining existing elements, local repair of elements without dismantling them	EB automatically assumes the reparability of corroded elements and is not concerned much with feasibility. Based on a detailed knowledge of the corrosion condition, SUDOP recommends replacing the damaged elements, as it cannot imagine repairing them with the extent of the damage
9	Bearings	Repair, restore	Repair, restore	Same approach

10	Piers and abutments	Rehabilitation of pier foundations (in the river) and rehabilitation of the natural stone masonry	Rehabilitation of pier foundations (in the river) and rehabilitation of the natural stone masonry	Same approach
Details of the repair				
11	Restriction of traffic	For repair by replacement of elements, a general construction procedure is proposed. It includes a temporary bridge for 1 track for the period of 4 years. The traffic is therefore limited by the number of tracks.	It is not addressed in detail in the assessment. It is not described whether the anticipated actions can be done gradually while the bridge half is in operation or if a full closure is required for both cleaning and repair and for how long.	According to the SUDOP, the old bridge has to be moved to a lightened position to replace the elements. EB does not specify the construction process in its study. In the case of a new bridge, it can be fabricated outside the final location and only then the structures can be moved with a short closure of a few weeks.
12	Special measures	Assembly trestle, removal of the temporary bridge, bridge relocation, dismantling of the structure, repair/fabrication in bridgeworks	In the case of thorough cleaning of corrosion in the crevices, an ecological measure (bath) will be necessary to capture residual blasting products.	The assembly trestle for moving the existing and new or temporary structure is a significant expense.
Risks of the repair process				
13	Risk of change in technology and scope due to possible higher corrosion attack	It is proposed to replace approximately 2/3 of the elements (lower chords, lacings, perpendiculars) that are severely corroded, in a lightened state outside the existing position. This significantly reduces this risk.	The EB study is inconclusive on this point. The context implies that a thorough cleansing should first take place and only afterwards a decision should be made as to what and how will be repaired and supplemented.	SUDOP's proposal to replace about 2/3 of the elements is rather conservative. The process according to EB has a rational core in terms of implementation and approach, however, under the pressure of closures and the length of the repair, it poses a major risk in terms of unpredictable progress and impact on the works schedule.
14	Risk of faulty repair of damaged elements and reduced structural reliability	It is proposed to replace approximately 2/3 of the elements (lower chords, lacings, perpendiculars) that are severely corroded, in a lightened state outside the existing position. This significantly reduces this risk.	The EB study does not address this in detail. It is generally stated that cross-section repair methods are commonly known. Only a general conceptual solution is suggested.	SUDOP's proposal to replace about 2/3 of the elements is rather conservative. The course of action according to EB poses a risk in that the expected scope of local interventions is unusually large. There is a risk that the repaired elements will not be fully functional in terms of statics. Any malfunctions will only become apparent after commissioning and monitoring of the structure.

15	Risk of failure to meet the deadline for repair completion	It is proposed to replace approximately 2/3 of the elements (lower chords, lacings, perpendiculars) that are severely corroded, in a lightened state outside the existing position. This significantly eliminates and reduces this risk	The EB study does not address this in detail. In principle, it is not possible to decide in advance of the cleansing what will be repaired and how. The assumptions will need to be verified during the repair.	The repair procedure according to EB poses a significant risk of affecting the duration of the repair due to the indeterminate scope of work.
16	Risk of non-compliance with the repair price	The SUDOP assumptions are relatively comprehensive and specific in terms of specifying the repair procedure.	The EB study does not address this in detail. EB assumes that repair without dismantling the structure would be significantly cheaper. It would be necessary to prepare a more detailed repair project.	At the moment, SUDOP has prepared a clearer specification that can be reflected in the construction process and price. The EB study does not address this in detail.
17	Risk of reduced repair durability	It is proposed to replace approximately 2/3 of the elements (lower chords, lacings, perpendiculars) that are severely corroded, in a lightened state outside the existing position. This significantly reduces this risk.	Local repair of damaged elements poses a significant risk of reduced durability / future life of the structure.	If damaged elements are repaired without complete replacement, the real durability of the repair will certainly be lower. SUDOP assumes a repair life of 30 years when replacing damaged elements.
18	Risk when awarding a public contract	The solution enables to prepare a relatively detailed budget and time schedule and specifications for the contractor.	The study does not address this and has not even been assigned.	In the Czech Republic, it is not possible to award a public contract without clear financial and time requirements

Table 5: Comparison of some reconstruction design factors according to SUDOP, EB and new bridge design

Item	Reconstruction SUDOP	Reconstruction according to Brühwiler	New bridge
Historical value	+	++	-
Maintenance requirements	-	-	+
Security level (degree of use of elements)	-	- -	+
Restriction of operation due to POV	-	- **	+ *
Immediate investment costs	- -	+	-
Long-term costs	-	- -	+
Compliance with technical standards in the Czech Republic	+	-	++
Risks associated with implementation and operation	-	- -	+

*New bridge can be built next to and moved over existing piers
** The conclusions of the report according to Annex 2 show that the blasting should be carried out with complete exclusion of traffic on the bridge, prof. Brühwiler assumes traffic on 1 track.

Key:

A + sign means that a better result can be expected for the option within the evaluation point A - sign means that a worse result can be expected for the option within the evaluation point

Although from a simple assessment of the pros and cons for each option the "New Bridge" option appears to be more advantageous for several reasons, it is up to the discretion and decision of the Client and the investor of the construction as to what weight and importance to assign to the individual criteria, or whether not to choose additional new ones. It is one of a few possible ways how to arrive at a rational and defensible decision from a technical and cultural and social point of view.

6.2 THREE-TRACK OPTION AND RECONSTRUCTION

Information by the Client of this report has shown that the so-called three-track option is being seriously considered. In the case of the request to transfer three tracks over the Vltava River, prof. Brühwiler in his report comes up with a solution to install the third track on a parallel single-track bridge. As the photographs on the next page show, it is clearly based on the practice used in Switzerland. This single-track bridge could be implemented as a permanent bridge, the option of only a temporary structure is costly. The single-track bridge would be built first and would serve for the duration of the reconstruction of the original double-track bridge. The original double-track bridge could thus also be reconstructed according to SUDOP's proposal without moving it out of its current position. This would result in a significant cost reduction compared to the original assumption of moving the bridge to a secondary structure. However, this solution would also mean that both original tracks and both footbridges are left in their current position. If the bridge reconstruction is chosen, it is necessary to replace the rail-track (the current solution is inadequate) to ensure reliable operation on the bridge. The main beams must be reliably repaired.

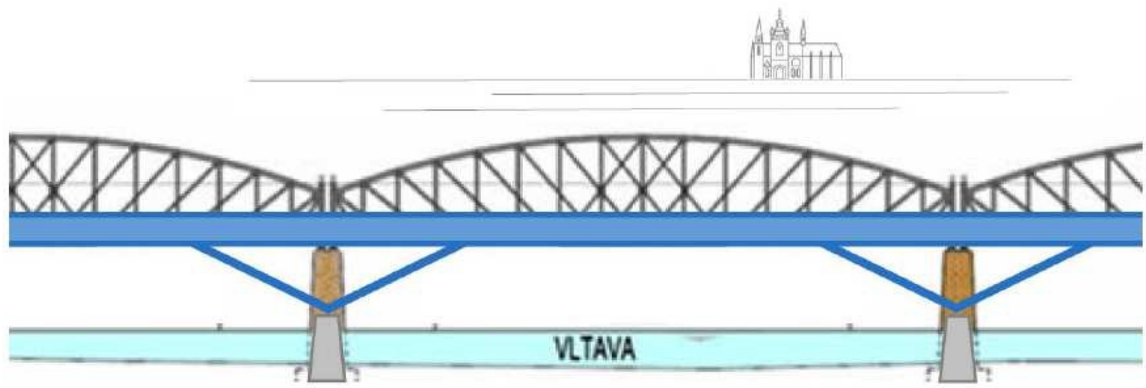

Fig. 29: Design of the third track on a parallel single-track bridge according to the EB report. It is a minimalist construction that does not go up in height and does not obstruct the view of the original listed bridge.

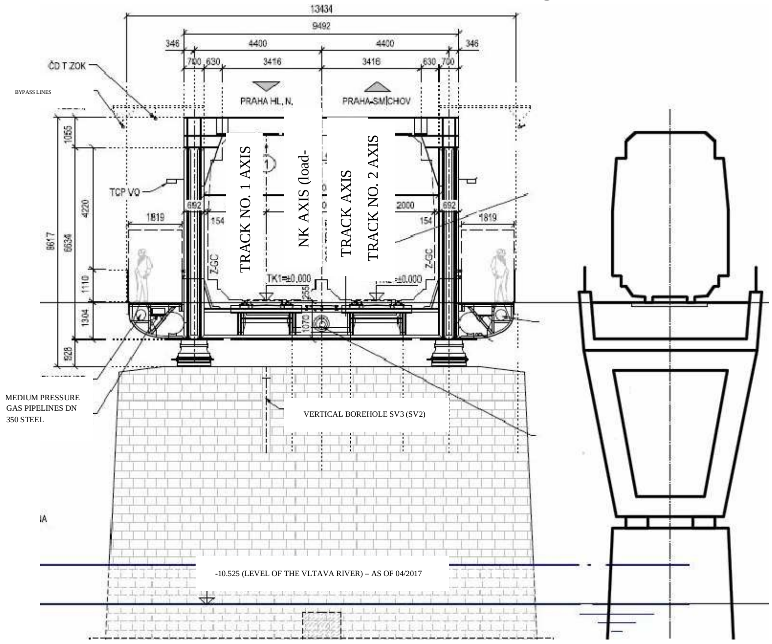

Fig. 30: Cross section through the joint bridges, two tracks on the original reconstructed bridge, third track on a parallel separate single-track bridge.

Fig. 31: Pictures showing an example of a implemented single-track steel bridge Zweite Hinterrheinbrücke in Switzerland near Chur (Load-bearing structure of 2 steel beams 1.7 m high, 0.5 m above the rail grade line, trough for railway bed, diagonal braces, span of bays approx. 46.5 – 40.1 – 63.0 – 45.9 m)

7 CONCLUSIONS AND RECOMMENDATIONS

The opinion of prof. Brühwiler basically confirmed the correctness of the previous conclusions [1–3], i.e. that due to the **current state of the bridge, the situation had to be addressed very urgently.** In comparison to the existing view of the repair presented by the SUDOP documentation, the professor comes up with innovative but, from the Czech viewpoint, experimental and untested approaches that are not codified in the legal environment.

According to the professor, the repair only makes sense if the damaged elements of the main beams do not have to be replaced with new ones, i.e. if it can be implemented without dismantling the structure, with minimal closures and at a cost (immediate + related + long-term) lower than a new construction, so that the long-term service life of at least 80 years, which is close to the value considered for a new bridge, i.e. 100 years, is guaranteed in his opinion.

The professor proposed a structural modification of the rail-track to a fixed track and outlined possible ways of repairing the main beams. The application of fixed track has not been tested anywhere in the Czech Republic on bridge structures yet. This would therefore be the first application and would mean, among other things, to address the approval procedures and possible modifications of the SZCZ regulatory base.

In view of the proposed repair approach, corrosion product cleaning tests were subsequently carried out to verify the possibility of repairing the main beams and to specify the complexity of such repair. Based on the cleaning tests, it can be concluded that the cleaning of corrosion products including the application of CPC and the repair of damaged elements would be a time-consuming operation that would probably require the exclusion of operation on the entire bridge for a minimum of two years, with the need to create a catchment system for the return collection of water with lead-containing blasting waste products.

The experience of professional companies in the Czech Republic, the designer SUDOP and also SZCZ representatives states that reconstruction without the replacement of damaged elements would represent a high risk of faulty execution of details, which could result in reduced durability, reduced static reliability and the need for further interventions in the near future.

Information from the Client of this report has shown that the so-called three-track option is being seriously considered. Prof. Brühwiler suggested in his document that in the event that the request to transfer the three tracks over the Vltava River is implemented, the construction of a new final parallel single-track bridge could be a solution. This solution would help the eventual reconstruction of the original bridge. This solution would reduce the associated costs (no temporary bridge, no moving off the track axis) and maintain at least single-track temporary operation without a complete closure. This means, however, that the new bridge would have to be built very quickly (the service life of the existing rail-track according to SUDOP calculations is until 2024). There are certainly several three-track options. To evaluate and decide which option to choose, it is recommended to prepare so-called Technical Status Certificates for each option.

Currently, a large number of assessments and expertise have been carried out in an effort to preserve the existing bridge. **Considering the current structural condition of the bridge, which needs to be addressed very urgently, the current high traffic intensity and even higher planned, the possibilities of repair and risks during the implementation of the repair and future operation and other aspects, the most feasible option seems to be the implementation of a new bridge.**

It is up to the discretion and decision of the Client and the investor of the construction as to what weight and importance to assign to the individual criteria, or whether not to choose other new ones. It is one of a few possible ways how to arrive at a rational and defensible decision from a technical and cultural and social point of view.

8 LIST OF ANNEXES

ANNEX 1 – Railway Bridge "Pod Vyšehradem" in Prague – Preservation of the existing bridge: Assessment and feasibility study for the restoration, prof. Brühwiler

ANNEX 2 – Experimental verification of blasting and corrosion removal methods on the Pod Vyšehradem Bridge, team led by doc. Ryjáček

ANNEX 3 – MEMORANDUM – Evaluation of the Report: Experimental verification of blasting and corrosion removal methods on the Vyšehrad Bridge, prof. Brühwiler

ANNEX 4 – Evaluation of the condition of the crevices the steel structure of the bridge SO 201 at km 59.126; Volary – Černý Kříž (Dobrá na Šumavě) after one year since the CPC implementation, Ing. Kudláček, Ph.D. and team.

The conclusions presented in this report have been formulated on the basis of the documentation provided and the results of our own diagnostic work carried out in certain areas, i.e. the findings of visual inspections and laboratory analyses. The author reserves the right to make corrections and additions to the conclusions if additional material facts are discovered which are beyond the scope of the diagnostics performed or are subsequently discovered outside the scope of the work performed and commissioned, or were unknown to the author at the time the report was prepared, or were falsely communicated to the author or withheld from the author.