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Fatigue safety examination of a 150-year old riveted railway bridge

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ABSTRACT: Built in 1859, the railway bridge over the Rhine between Koblenz (Switzerland) and Waldshut (Germany) consists of a three span continuous riveted steel truss girder and an approach viaduct in natural stone masonry. Due to ever increasing traffic demands the fatigue safety and service life of the bridge needed to be examined. Examination methods as defined in the new Swiss Codes on Existing Structures using updated load models and structural resistance are applied to investigate this structure that is for more than 150 years in service. Due to this rational approach, it could be shown that the bridge can remain in service for a long future service life. This paper describes the chosen approach and reports on the most significant results. In particular, the main principles and assumptions followed in this project are outlined. Also, scenarios for future maintenance and rehabilitation interventions are developed and compared on the basis of life cycle costing. The approach allows for more realistic examination of the fatigue life of the riveted steel structure and also includes an comprehensive approach including cultural and economic valuations.

1 INTRODUCTION

Riveted bridges were built over a period of more than 100 years up to the 1950s. There are thousands of riveted bridges around the world in service. Some of them are considered historical and should be preserved as architectural heritage. Often, an important remaining service life may be identified such that economically, it is not justified to replace a bridge because of some arbitrary age criterion.

Bridges are built to serve several generations of users. As part of the transportation infrastructure, bridges add value to the public economy. Therefore, there is a high interest in their efficient economic performance while providing the intended utilisation without any restriction (e.g. limits on traffic load). Also, the safety of the individual and society need to be considered in a well-balanced manner for the bridge and its significance within a given transportation system.

This paper deals with the examination of the oldest existing wrought-iron railway bridge still in service in continental Europe. This bridge is part of a railway line belonging to the Zurich suburban railway system. The main objective of the present examination was to verify the structural and fatigue safety for a long term future utilisation of the bridge and to show the consequences in terms of rehabilitation interventions while preserving the cultural values of the bridge.

Both owners, the Deutsche Bahn AG and the Swiss Federal Railroads SBB, want to exploit the railway line in a long term perspective. For the bridge, the question arises regarding the necessary interventions to reach this objective in view of an increase in Line class to C3 as a minimum requirement, i.e., maximum allowable axle and line loads of 200kN and 72kN/m' respectively, for a maximum train speed of 60km/h and an additional service life of at least 80 years. Also, the study should reveal the necessary interventions for the scenario of higher line classes (e.g., D4 or E5).

This paper has the objective to explain the methodology applied in the examination of this more than 150 years old riveted railway bridge. Emphasis is given on the verification of the structural and fatigue safety for a long term future use of the bridge. The concept for rehabilitation interventions is outlined and economic as well as life-cycle aspects are presented.

2 STRUCTURAL ENGINEERING IN THE DOMAIN OF EXISTING STRUCTURES

The contemporary approach to existing structures is based on an inherent methodology that essentially includes collecting detailed in-situ information from the structure. The controlling parameters are determined as precisely as needed. The structural safety is proven using so-called updated values for actions (loads) and resistance. In this way, it can often be shown that an existing bridge structure may be subjected to higher traffic loads while meeting the safety requirements, and hence interventions may be avoided.

This methodology inherent to existing structures has evolved and already been successfully applied over the last 20 years. However, it has not yet been really adopted by many structural engineers. This is explained by the fact that there are no codes on existing structures available an engineer can rely on. As current codes do not address major issues of existing structures, applying them is fundamentally wrong and often leads to unnecessary interventions.

A change of paradigm is needed aiming the structural engineering community to clearly distinguish between codes for new and for existing structures. For this reason, the Swiss Society of Engineers and Architects (SIA) recently released a series of standards for existing structures (Brühwiler et al., 2012).

3 DESCRIPTION OF THE BRIDGE

3.1 *Bridge structure*

The investigated bridge (Fig. 1) crosses the Rhine river in northern Switzerland to carry a one lane railway line between Koblenz (Switzerland) and Waldshut (Germany). It was built in 1859 and comprises riveted wrought iron members. The straight lattice-truss structure is one of the last examples of a construction type that was typical for the railroad construction boom in Europe during the third quarter of the 19th Century.

Figure 1. Railway bridge over the Rhine between Koblenz (Switzerland) and Waldshut (Germany).

The wrought iron structure was designed as a continuous girder over three spans of 37.5m, 55m and 37.5m with a total length of 130m supported by abutments and piers in natural stone masonry. The bridge girder carries a single track by an open deck carriageway, i.e. the timber sleepers are directly fixed to the stringers. The bridge was initially designed to carry two tracks; however, it ever only carried one track.

3.2 *Cultural values*

This bridge is generally accepted as being an engineering monument of high value. In 1994, it was given a Brunel Award which is the most important award for railway architecture. The cultural values of this bridge are evaluated as follows:

Historic value: The multiple lattice girder structure is one of the last representatives of a type of construction which is typical for the pioneer's time of the railway construction in the 3rd quarter of the 19th century. The structure which is still in its original condition is an important reference in the work of Robert Gerwig (1820-1885), who was the builder of the north ramp of the Gotthard railway and other important railways in Central Europe. Robert Gerwig is considered as one of the most important engineers of railway construction in the 19th Century.

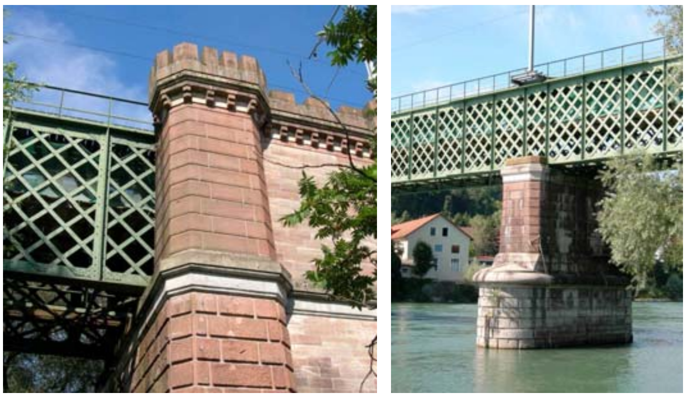


Figure 2. Details showing the interrelation between the wrought iron lattice girder and natural stone pier and abutment.

Aesthetics: the bridge convinces aesthetically, first of all, by the transparency of the lattice girder structure and its interrelation with the massive river piers and abutments in natural stone masonry (Fig. 2). The wrought iron structure is characterized by the riveted construction. It looks filigree and bold despite of the strong appearance as a continuous beam of constant height. The massive river piers and abutments contribute significantly to the impression of stability.

The bridge’s slenderness and the transparency of the lattice girder visualize technical efficiency. The symmetry and repetition of identical structural elements contribute to uniformity and order. This functional structure embedded in natural surroundings was simply and properly designed. Any decorative elements were omitted. The bluish colour of the corrosion protection painting is correct as it is one of the possible colours of iron.

Relation to the surroundings: The bridge stands as a Rhine crossing at a well visible place. The sober continuous girder bridge with its severe lines stands in contrast to the river landscape. The piers and abutments and the subsequent approaching masonry viaduct located on the Swiss side create a harmonious transition of the riveted structure characterizing a technical object, to the natural surroundings.

Appreciation: This bridge stands for highest engineering efficiency in all matters: short time of construction, low material use, minimized cost of construction as well as a sober and clear appearance. Its cultural values are to be assessed as being very high. This bridge belongs undoubtedly to the most important existing riveted bridges in Europe. It is a monument of the art of structural engineering.

3.3 *Condition of the bridge*

During its service life the bridge was well maintained. Based on information from the inspection reports and a site visit, the condition of bridge is assessed as "satisfactory to good".

The open deck carriageway (Fig. 3) has resisted since its construction in 1912 to the railway traffic solicitation without considerable damage. However, with the introduction of the suburban passenger trains since 1999 the solicitation of the carriageway significantly increased in terms of axle loads and number of trains. Cracks and loose rivets were detected during inspections. This damage was due to unfavourable local bearing conditions and unplanned distortions of single elements of the carriageway and could not be anticipated by structural analysis. The appearance of this damage was nevertheless not surprising, as this kind of damage is known from other open deck carriageways. The origin of this damage was also clarified by means of deformation measurements in 2005. Repair works were conducted in the meantime.

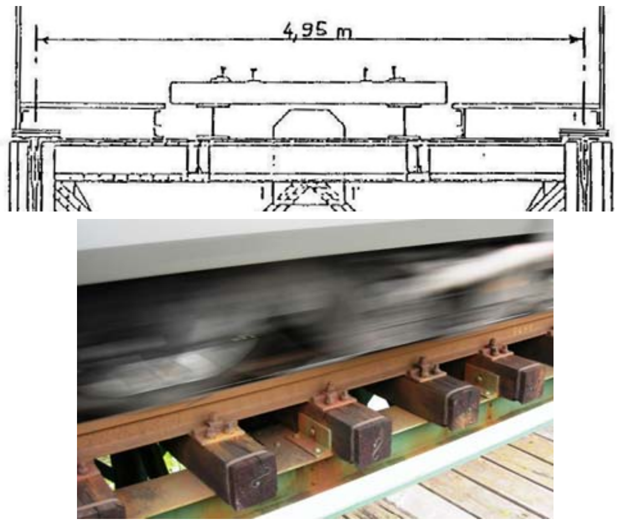


Figure 3. Open deck carriageway mounted on the wrought iron girder.

The corrosion protection coating has proved itself of value, and since the last renewal in 1991 only some isolated spots show some peeling of the surface layer (Fig. 4).

Figure 4. Condition of the corrosion protection coating.

The bearings of the girder are composed of a series of iron rollers extended along a rather long support (Fig. 5). The condition of the rollers is deficient as they do no longer function properly. The bridge girder seems to slide on them.

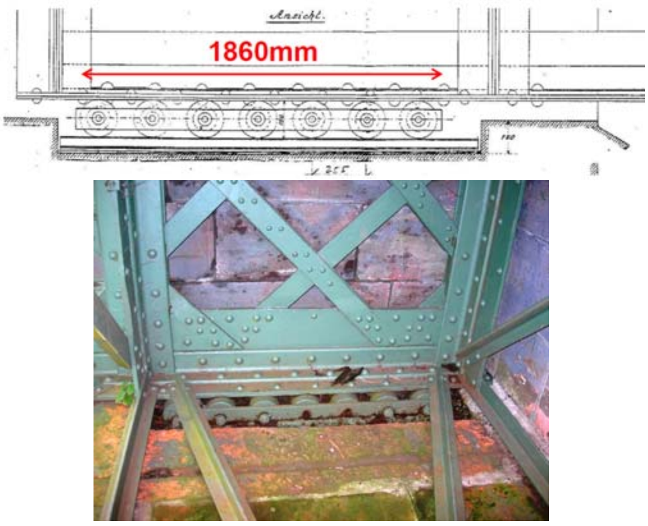


Figure 5. Series of rollers forming the bearing at the abutment.

The natural stone masonry of the embankments and river piers show usual signs of deterioration, however, limited in extent.

Considering the whole service life, the cumulated expenditures for maintenance and rehabilitation were very low. With the exception of the corrosion protection paintings, the renewal of the carriageway in 1912 and recent repair works of the carriageway no interventions were performed during the whole more than 150-year long hitherto service life.

4 STRUCTURAL AND FATIGUE SAFETY

4.1 *Background*

In the following, topical issues of structural and fatigue safety verification of riveted bridges are outlined, and the results obtained for the present bridge structure are described. The investigations are performed applying the Swiss standards SIA 269 (SIA 269, 2011), SIA 269/1 (SIA 269/1, 2011) and SIA 269/3 (SIA 269/3, 2011) as well as results of the European research project “Sustainable Bridges” concluded in 2007 (Sustainable bridges, 2007) regarding existing railway bridges in view of higher future traffic load and frequency demands on the European railway network.

4.2 *Principles of verifications*

The notion of degree of compliance n is introduced in the Swiss Standard SIA 269 for the deterministic verification of the structural safety and fatigue safety:

$$n = \frac{R_{d,updated}}{E_{d,updated}} \tag{1}$$

where $R_{d,updated}$ and $E_{d,updated}$ are the so-called examination values of (ultimate or fatigue) resistance and action effect, respectively.

The degree of compliance is a numerical statement showing the extent to which an existing structure fulfils the structural safety requirements. This formulation not only gives the information whether the structural safety is fulfilled, i.e., it also indicates by how much the verification is fulfilled (or not). The latter is necessary for the evaluation of results and in view of the planning of interventions.

In accordance with the standard SIA 269 the fatigue safety verification is performed in several steps:

First, verification with respect to the fatigue limit is performed using updated fatigue load model. If this verification is not fulfilled, fatigue safety is checked in a second step with respect to the fatigue strength by calculating the equivalent stress range as well as considering the fatigue effect due to past railway traffic. Thereby, fatigue solicitation from railway traffic which has taken place before 1940, is often negligible.

In a third step, and if the stress spectrum for a determinant structural detail is known (or has been obtained through measurements), the fatigue safety verification is performed by fatigue damage accumulation calculation applying the Palmgren-Miner rule with respect to a damage limit value of 1.0.

4.3 *Railway traffic action*

The available information on past railway traffic over the bridge revealed a rather modest traffic.

The estimated total number of 1.20 million trains during the past service life of more than 150 years is rather low, compared to bridges on main lines (totalling typically 5 to 7 million trains for the same service life). Actually, with the introduction of the suburban traffic in 1999, the train frequency increased significantly with currently 74 trains per day (Fig. 6).

Figure 6. Top: passenger train in 1961, bottom: today's passenger trains crossing the bridge.

The bridge structure was subjected from 1859 to 1991 to mixed freight and passenger trains. The heavy axle loads were due to locomotives and heavy freight wagons. It can be deduced from existing information that maximum axle and line loads were 180kN and 50kN/m' respectively which corresponds to Line Class B1 according to European Railway Line classification (UIC Code 700, 2004).

The standard SIA 269/1 defines the load models representing railway traffic of the various Line classes (Fig. 7). A reference carriage is defined as a static live load that is placed on the structure in arbitrary number and in the most unfavourable position. Railway authorities define the Line class and thus the corresponding valid load model that may be considered as updated live load acting on the bridge structure.

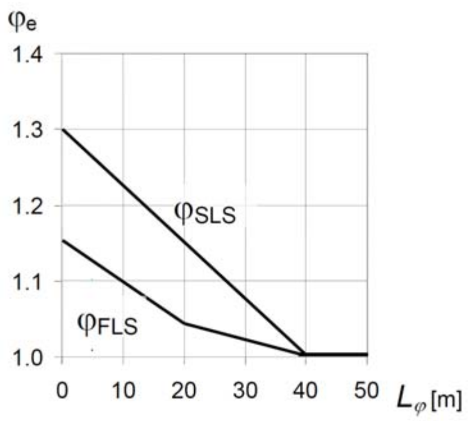
Line class	Nominal axle load $Q_{k,updated}$ [kN]	Spacing of axle loads in [m] for 1 reference carriage $2 \times Q_{k,updated}$	$2 \times Q_{k,updated}$
C3	200	1,5 1,8 4,50 11,10	1,8 1,5
D4	225	1,5 1,8 4,65 11,25	1,8 1,5
E5	250	1,5 1,8 4,75 11,35	1,8 1,5

Figure 7. Reference carriages for line classes C3, D4 and E5, taken from (SIA 269/1, 2011).

The static axle loads of the load model are multiplied by a dynamic amplification factor accounting for dynamic effects due to dynamic train – structure interaction. Several dynamic amplification factors are defined according to ultimate, fatigue and serviceability limit states (Brühwiler & Lebet, 2010, Ludescher & Brühwiler, 2009).

Under service conditions, the structure behaves elastically. The corresponding dynamic amplification factors φ_{FLS} for fatigue limit state and φ_{SLS} for serviceability limit state are fixed according to acceptable probability of occurrence as rare or frequent values respectively (Fig. 8a).

a)



b)

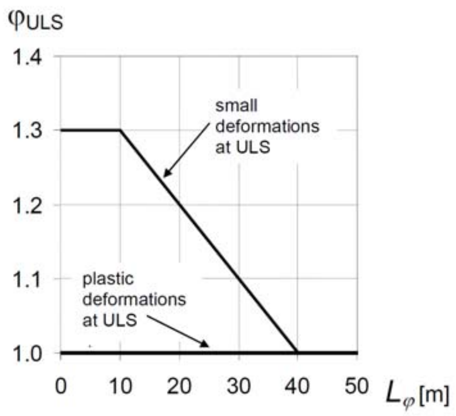


Figure 8. Dynamic amplification factors : a) at SLS and FLS for elastic structural behaviour, and b) at ULS depending on the structural failure behaviour; L_φ: determinant element length.

The dynamic amplification factor to be considered for the structural safety verification depends on the deformation capacity of the structure at ultimate limit state. At ULS, structural elements provide significant plastic deformation due to yielding of the steel. In this case, deformation induced by dynamic forces may also be dissipated by the structural element. (Ludescher, 2004) and (Herwig, 2008) showed by means of dynamic structural models how the external work due to dynamic action effects (i.e. impact-like events, excitation by surface irregularities) is dissipated in common structural elements without fracture of the element. A dynamic amplification factor of $\varphi_{ULS} = 1.0$ is considered in case of ductile failure behaviour and the conditions for application of plasticity methods are fulfilled. In case of failure behaviour with small deformation capacity a dynamic amplification factor decreasing with increasing live load (or determinant length of the structural element) is considered according to Fig. 8b.

In the present case, the action effect $E_{d,updated}$ due to railway traffic was determined following:

$$E_{updated} = E(\varphi_i \cdot Q_{k,updated}) \tag{2}$$

and using the aforementioned updated static loads $Q_{k,updated}$ for the considered line class models and the dynamic amplification factor φ_i depending on the considered ultimate limit state.

4.4 *Mechanical properties of wrought iron*

Ultimate resistance: The standard SIA 263/3 (SIA 269/3, 2011) defines the characteristic values of the material used for the construction of riveted bridges, i.e. including wrought iron (fabricated from 1850 to 1890), early mild steel (1890-1925) and steel (1925-1955) similar to contemporary material. Moreover, the standard defines the characteristic values of ultimate resistance of riveted connections. The coefficient of resistance is fixed in dependence of the basic material and its production year.

In the present case, an updated value of ultimate resistance of wrought iron of 220MPa was assumed together with a coefficient of resistance of 1.15 for the verification of the structural safety of the wrought iron structure.

Fatigue strength: Research activities over the last 25 years resulted in reliable knowledge about the fatigue behaviour and fatigue strength of riveted joints and structural elements (Brühwiler et al., 1991). The most recent comprehensive analysis and interpretation of available test results from riveted joints and structural elements (that implicitly include local stress concentrations in joints and due to eccentricities of truss bars) are given in (Taras & Greiner, 2010).

The Standard SIA 269/3 adopts the results of this study and defines fatigue strength categories of different riveted details. These detail categories correspond to straight fatigue strength lines in the S-N (Wöhler) diagram with a slope of m = 5. The updated coefficient of fatigue resistance is determined in dependence of the accessibility for inspection of the structural detail and the consequences in case of failure.

In the present case, a detail category of 71MPa was applied together with a coefficient of fatigue resistance factor of 1.15.

4.5 *Accurate determination of stresses*

Accurate determination of realistic stresses in the structure due to fatigue loading is of utmost importance. For riveted structures a detailed structural model is often justified to identify locations of higher solicitation. Also, strain measurements provide valuable information about the real structural behaviour.

In the present case, the structural behaviour of the wrought iron structure was measured by load testing performed in 1999 (Quoos, 1999). Maximum stresses in the range of 25 to 35MPa were measured in the wrought iron structure due to locomotives simulating maximum loading due to Line class B1.

The measurements indicated notable transverse out of plane bending of the cross girders which is due to the global deformation of the girder structure.

4.6 *Likelihood of sudden failure*

Wrought iron and early mild steel show relatively low fracture toughness values when compared to contemporary steels. Therefore, it is often speculated that riveted railway bridges inherently may show a danger of sudden (brittle) failure, particularly because there might be fatigue cracks or other small defects in the plates.

Knowledge of the fracture toughness alone is not sufficient for determination of critical crack lengths (Brühwiler et al., 1990). To investigate the scenario of sudden failure, two cases shown in Fig. 9 were investigated using linear elastic fracture mechanics. Case 1 is an edge crack and Case 2 is a crack on both sides of a rivet hole in an infinitely wide plate subjected to a uniform tensile stress. The objective of the analysis was to determine the tensile stress leading to sudden fracture of the plate weakened by a crack of a critical length.

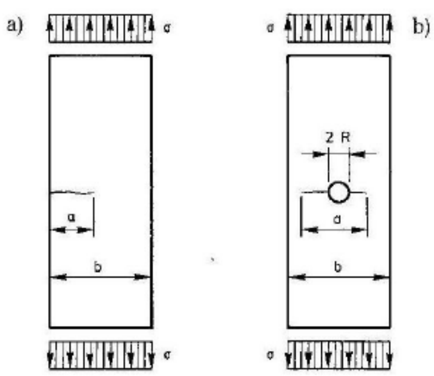


Figure 9. Cases of cracks in wrought iron plates.

The calculations revealed that Case 1 is more sensitive to sudden fracture than Case 2. However, Case 1 fatigue crack is less likely to occur due to the higher fatigue strength of the plain plate detail.

In Case 1, the tensile stress leading to sudden failure is 150MPa assuming a fracture toughness of $1500 N/mm^{3/2}$ for wrought iron (Brühwiler et al., 1990). And for Case 2, the tensile stress for sudden fracture was calculated to be 200MPa which is close to the yield stress of 220MPa.

These stress values are significantly higher than actual maximum tensile stresses of 60MPa occurring as action effect from railway traffic loading for Line class E5. This can be explained by the rather low stress level in the riveted structure. In addition, the composed riveted sections of structural elements offer significant potential of local stress redistribution.

As a consequence, the likelihood of sudden failure of structural elements in the bridge structure is rather small and thus acceptable, even for higher future traffic loads.

4.7 *Piers and abutments*

Calculated examination values for action effect in the natural stone masonry were about 0.7 to 1.1MPa (Fig. 10). Considering an examination value of ultimate resistance of the given natural stone masonry of 10MPa (SIA 269/6, 2011), the degrees of conformity are larger than 9. Similar results were obtained for the foundation consisting of wooden piles; the value for uniformly distributed stress is about 0.5MPa which is well resisted.

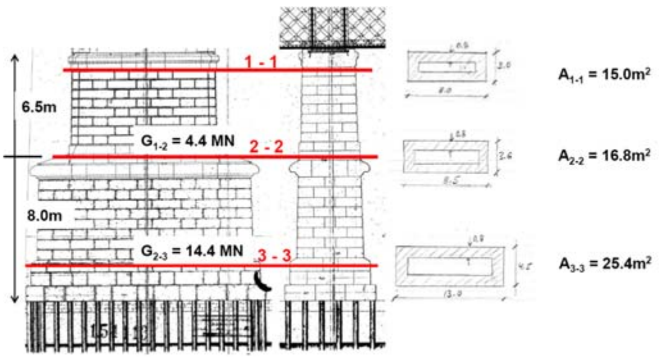


Figure 10. Solicitation of the river pier.

4.8 *Summary of results*

The verifications of the *structural safety* of the wrought iron riveted bridge structure revealed significant reserves in the load bearing capacity. In fact, degrees of conformity in the range of 1.25 to 1.75 were obtained for the relevant cross sections and zones over the piers and at the mid-spans of the lattice girder as well as for the cross girder and bracings even for higher future train loads. Also, the natural stone masonry piers and abutments as well as the foundations show enough load-carrying capacity.

The *fatigue safety* could be verified for the carriageway and the wrought iron bridge girder considering higher future traffic loads corresponding to Line classes C3, D4 and E5. At the first verification level with respect to the fatigue limit, a lowest degree of conformity equal to 1.02 was obtained for the tensile flange of the side spans of the lattice girder due to Line class C3 fatigue loading. For the higher fatigue loading due to Line classes D4 and E5, the fatigue safety verification is fulfilled based on the check with respect to the fatigue strength.

Under these fatigue loads and the assumption of higher train frequencies in the future, the remaining fatigue life was calculated to be longer than 80 years. Also, the fatigue damage due to past railway traffic (according to Line class B1) turned out to be small enough to be negligible.

Consequently, considerably higher traffic loads could be allowed and no limitation of train velocity needs to be imposed. This result is largely explained by the fact that the structure was originally designed for two lanes but it was and will be used for one lane of railway traffic only.

5 MAINTENANCE INTERVENTIONS

5.1 *Principles and objectives*

The fundamental idea of the designed maintenance interventions in view of a long future service life of 80 years, consists in protecting the bridge, and particularly the wrought iron riveted structure, against effects of the railway traffic by distributing and damping train loads, against environmental influences by reducing direct contact of the riveted structure with rain water, and limiting the visual impact of interventions on bridge appearance.

Although the verifications by calculations are also fulfilled for higher traffic loads, possible increase in traffic loading should be conducted with the necessary prudence. In fact, the wrought iron structure is a complex assembly of plate and angle irons, and secondary load bearing effects leading to distortion may not be excluded.

The objective of interventions finally is to restore construction details and elements such as to allow for unambiguous structural behaviour.

5.2 *Types of interventions*

Implementation of this concept led to four kinds of maintenance interventions which are all well compatible with the requirements of modern railway traffic and protection of monuments. The construction costs for these interventions were estimated in collaboration with specialized companies:

1 Carriageway: The most important intervention consists in replacing the existing carriageway by a new open deck carriageway that is placed on damping bearing pads. Three variants were designed: (1) an improved construction similar to the existing one, (2) a new construction consisting of prefabricated reinforced concrete slab elements for fixed track (Fig. 11), and (3) a steel trough with ballast.

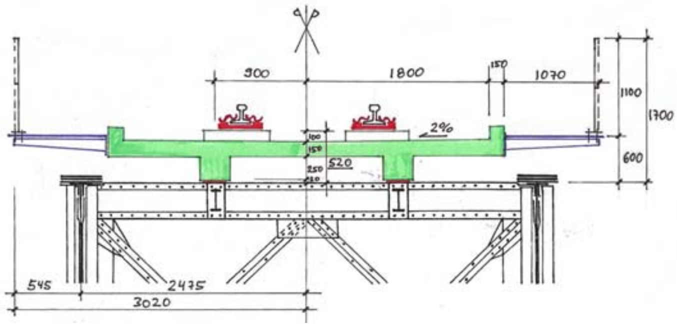


Figure 11. New carriageway: Variant 2.

Comparison of the three variants showed that the steel trough with ballast had the by far highest cost and would significantly increase permanent loads leading to important additional solicitation of the riveted structure; this variant was discarded. The first two variants have similar estimated costs and technical advantages and will be studied in more detail.

2 Corrosion protection coating: Two options were investigated. The first option consists in repairing the relatively few zones with active corrosion of the existing corrosion protection coating and to apply an additional surface layer. This soft intervention is obviously only feasible because the corrosion protection is still in fair condition (Fig. 4). The second option consists in a full replacement of the existing corrosion protection coating. Both options differ regarding the duration of the effectiveness of the corrosion protection as well as the costs.

3 Bearings: The replacement of the roller bearings by modern bearings is necessary to create clear support conditions of the bridge girder. The investigations showed that the installation of tailored long sliding bearings (Fig. 12) is feasible while keeping the original bearing concept of the structure.

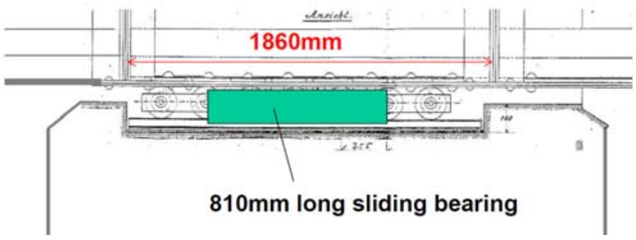


Figure 12. Concept of new bearings.

4 Piers and abutments in natural stone masonry: conventional remedial measures will be needed consisting in repairs of joints (in particular restoring the finishing joints close to the surface) and of single stones. Cavities inside the piers do not need to be injected. Remedial measures can be subdivided into works above and below the water level. The protection against scour of the pier foundation (consisting of timber piles) needs eventually to be improved by placing additional rock blocks.

5.3 *Economic and life-cycle aspects*

In addition to the construction cost for the four types of interventions, the expenses for the monitoring and maintenance over the future service life of 80 years were estimated. Using these basic cost elements, two variants were examined with regard to economic effectiveness:

Variant 1: The bridge structure is fully rehabilitated by executing all four maintenance interventions in the year 2015. In this way, the expenditure for monitoring and maintenance can be kept low over the future service life of 80 years.

Variant 2: Elements of the bridge are rehabilitated only when required by the condition. No improvements are carried out in 2015 to reduce future expenditure.

A plan for the expenditures for expected maintenance interventions from 2015 to 2095 was then established for the two variants, and the economic effectiveness was estimated by determining the present discounted value for each variant. As commonly applied by the two railway companies, a rate of 5% was used for discounting while no inflation rate (price rise) was considered.

The results revealed the following: The total sum of the investments over 80 years of Variant 2 is about 20% higher than for Variant 1.

On the other hand, Variant 2 is economically more effective as the present discounted value of all interventions turned out to be about 30% lower than for Variant 1.

These simplistic (commonly applied) calculations for life-cycle considerations obviously also showed that assuming a higher discount rate leads to postponing maintenance interventions if the requirement of economic efficiency is respected.

Although Variant 2 is theoretically more economical, it was recommended to perform Variant 1 for the purpose of investing into a long term view as well as to keep significant future interventions to a minimum knowing that significant interventions often produce collateral expenditures.

Overall, this study of economic aspects clearly revealed that preservation for the next 80 years of the more than 150 year old bridge will be significantly more economic than bridge replacement. The construction cost of a new bridge was estimated to be about 4 to 5 times higher than the maintenance interventions in 2015 following Variant 1.

6 CONCLUSIONS

The examination of the performance of the railway bridge over the Rhine river between Koblenz (Switzerland) and Waldshut (Germany), revealed that no extraordinary interventions need to be performed to keep the bridge in service for the next 80 years.

The study showed that preservation and further use of the more than 150 year old bridge is much more economical both in terms of costs for maintenance interventions, compared to bridge replacement (an option that was often and still is commonly chosen in similar situations).

This important monument of structural engineering will remain in service for modern railway traffic despite its relatively high age. There are no “old” bridges; there are only bridges that provide adequate performance (or not). This approach is clearly in agreement with the principles of sustainable development. Extending the service life finally means giving value to bridges as well as appreciating the art of structural engineering and the identity of structural engineers.

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