The Rendsburg High Bridge across the Kiel Canal

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Abstract

The Rendsburg High Bridge – a railway viaduct across the Kiel canal – is a more than 100 year old technical monument. Nevertheless, it is used under full traffic load – as a bottleneck for the traffic to Scandinavia. The bridge, a riveted steel construction, is currently being extensively retrofitted. The measures comprise, beside the renewal of the corrosion protection and the repair of defects, a strengthening for today's railway traffic loads. Thus, the bridge can be preserved for the long run – also an important contribution to the building culture.

Keywords: railway bridge, riveted structure, historical monument, retrofitting.

1 Overview of the structure

The Rendsburg High Bridge is one of the most important technical monuments in Germany and the landmark of the town Rendsburg. The more than 100 year old bridge leads the railway line Hamburg–Flensburg (–Denmark) across the Kiel Canal. This railway line is the main line to Scandinavia, which lies under a very heavy railway traffic. The viaduct was built between 1911 and 1913 and facilitates a clear passage height for the shipping of 42 m.

Due to the great importance of the bridge for the national and international railway traffic, the bridge is being extensively retrofitted by its owner, the Federal Water and Shipping Administration (WSV), as well as by the German railway company Deutsche Bahn (DB).

The structure is built as a riveted steel construction with an entire length of nearly 2.5 km.

Figure 1. Rendsburg High Bridge

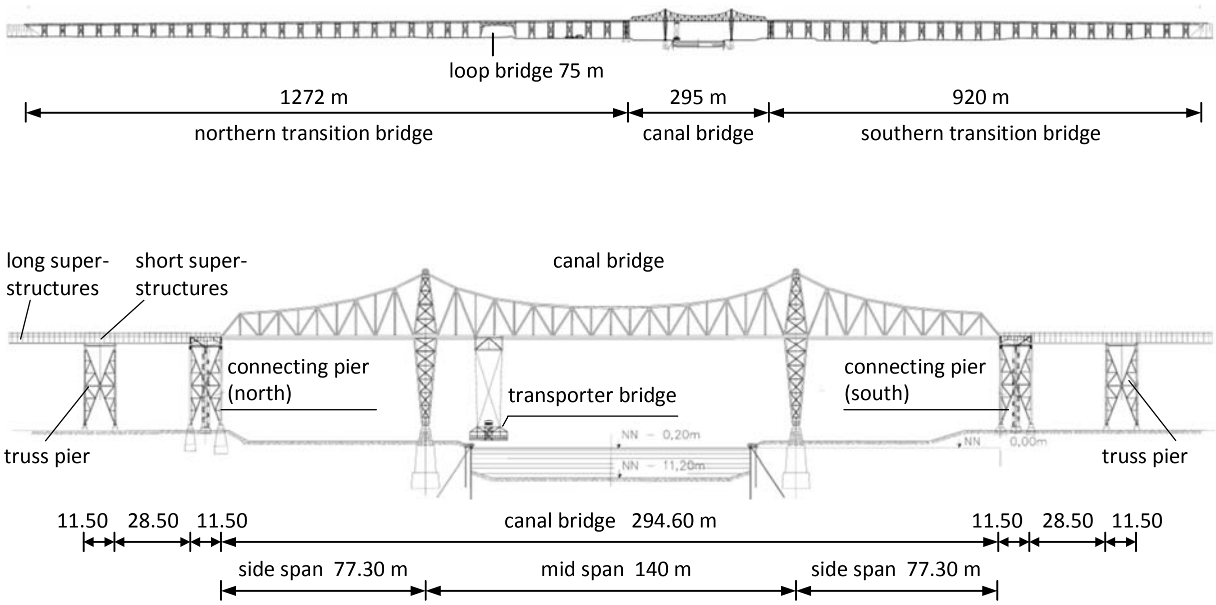

Figure 2. General view of the Rendsburg High Bridge and detail of the canal bridge

The main bridge ("*canal bridge*", Figure 1) is situated in the middle of the structure. It has a length of 294.6 m and a free span of 140 m above the canal. The main structure of the *canal bridge* is built as a framework, while both longitudinal and transverse girders are built as solid-web-girders.

The *canal bridge* is linked by the *connecting piers* to the northern and southern transition bridges (Figure 2). The transition bridges consist of a chain of piers and superstructures – 51 piers and 105 superstructures. The superstructures, which are constructed as single-span solid-web girders are single-tracked. Thus, each two side-by-side superstructures yield the double-tracked railway line. The substructures are built as *truss piers*. On each *truss pier* two short superstructures (L = 11.50 m) are situated side-by-side. Between the *truss piers* two long superstructures (L = 28.50 m) are situated side-by-side.

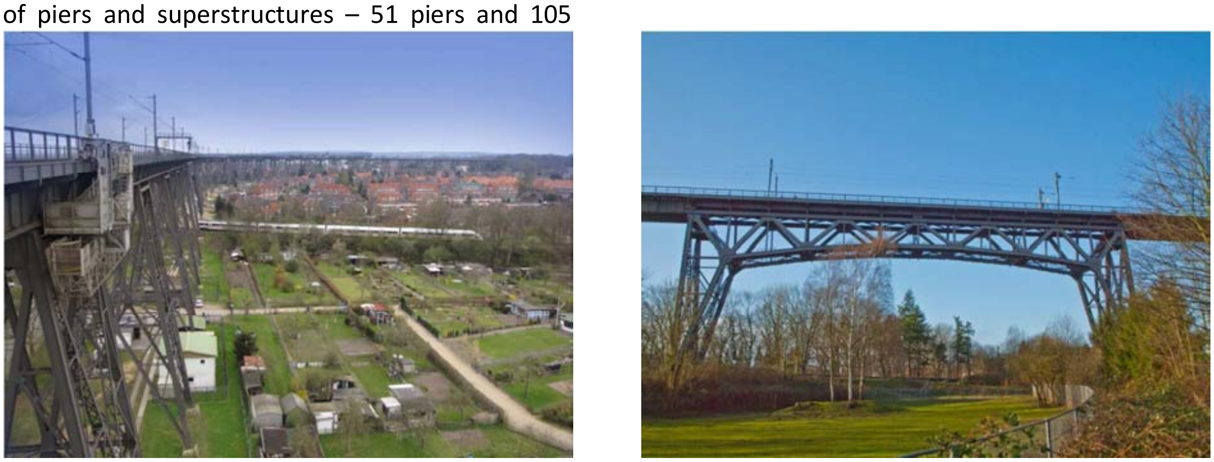

Figure 3. Northern transition bridge at the loop (right), loop bridge (left)

The northern transition part contains additionally another bridge with a length of 75 m, the so called "*loop bridge*". Since the railway line needs to reach the Rendsburg train station at the north of the viaduct, but still has to overcome a height difference of about 30 m, the line is routed in a wide loop. The line crosses itself at the so called loop point. There the *loop bridge* is situated, a trussed frame structure.

A special feature is the additional transporter bridge at the *canal bridge*. It consists of a segment of roadway (a gondola) that is carried by cables, which are fixed to an upper carriage. The upper carriage, which is driven electrically, runs on special rails between the pylons of the *canal bridge*. Up to 4 cars but primarily pedestrians and cyclists can be transported by the transporter bridge.

Figure 4. Transporter bridge

The construction material of the viaduct is a SIEMENS-MARTIN-steel from the beginning of the 20th century ("Flusseisen nach 1900" according to the German standard). Its strength characteristics are similar to the today's steel S235 but with a larger scatter. The remaining service life of the bridge is estimated to be more than 50 years according to the standardised assessment method of the DB guideline "Richtlinie 805" (Ril 805 – Structural safety of existing railway bridges) [3]. That estimated period is typical for a double-tracked bridge constructed after 1900 and having a good transverse load distribution.

The bridge has been retrofitted during the last years. The measures comprise, beside the renewal of the corrosion protection and the repair of defects, a strengthening for today's railway traffic loads. The following paper focuses on the strengthening measures.

2 Development of traffic loads

The bridge was originally designed for the so called "Preußischer Lastenzug A" (LZ A – Prussian load arrangement A). Additionally, a reserve of 20% referred to LZ A was regarded with farsightedness for later load increases at the design of the *canal bridge*, the *loop bridge* and the piers. The load arrangement LZ A consists of two locomotives (axle load 17 t, distributed load 71 kN/m), two tenders (13 t, 65 kN/m) and single-sided waggons (13 t, 43 kN/m).

In the future the bridge will be used by the following load arrangements:

- double-tracked traffic with a freight train of load class D2 (axle load 22.5 t, distributed load 64 kN/m) on one track and a lightweight passenger train on the other track or
- single-tracked traffic with a freight train of load class D4 (22,5 t, 80 kN/m)

The load effect of various passenger trains is represented by the load arrangement "defined passenger train" (DRZ – "definierter Reisezug"). That load arrangement DRZ was created especially for the Rendsburg High Bridge. It consists of a locomotive (axle load 20 t, distributed load 60 kN/m over a length of 30 m and single-sided waggons (20 kN/m over a maximum length of 390 m).

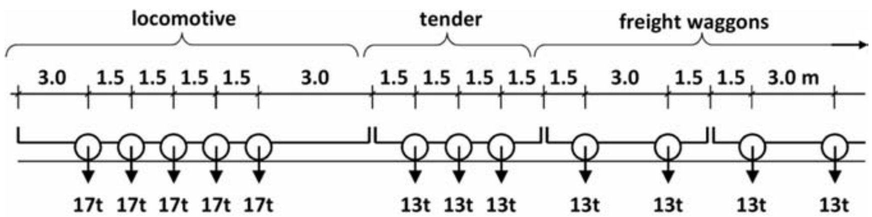

Figure 5. Load model LZ A from 1911 2 locomotives, 2 tenders, single-sided waggons

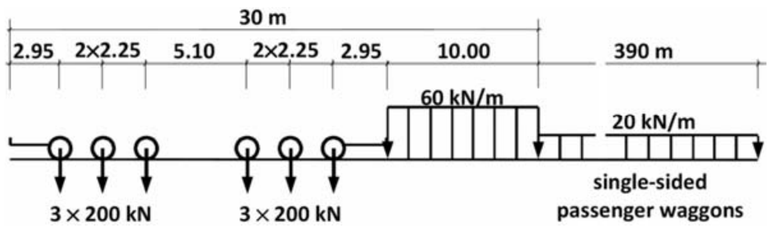

Figure 6. Load model DRZ (defined passenger train) locomotive, single-sided passenger waggons

The lengths of the trains are up to 835 m. These overlong trains have been run at the transit line between Denmark and Hamburg/Germany since 2012 and pass the Rendsburg High Bridge.

In terms of distributed loads, the vertical forces of the former load arrangement LZ A and those of the today's loads D2/DRZ (double-tracked) and D4 (single-tracked) are almost of the same amount. Only the axle loads are higher today. However, a considerable increase concerns the horizontal (longitudinal) forces caused by braking and acceleration. Whereas in the past the braking forces were determined by 1/7 of the vertical loads, today they are determined by 1/4 of the vertical loads – that is nearly a doubling of the braking forces. In Addition, an acceleration force of 1000 kN (transferred on a length of 30 m) is to be considered on the second track. These high horizontal forces lead to a great load increase for the high and slender bridge. This applies especially to the acceleration force, whose load length of 30 m nearly matches the structural length of a *truss pier* with its associated (longitudinally fixed) long superstructure.

3 Horizontal load transfer and rail stresses

In longitudinal direction the viaduct is divided into single structures. These longitudinal decoupled single structures are the *canal bridge*, every *truss pier* with its associated superstructures and the *loop bridge*. The horizontal (longitudinal) forces may only be transmitted between these single structures by the rails and the friction bearings of the superstructures. The friction bearings are plates steel on steel with a friction coefficient μ = 0,2-0,4. Under the effect of vertical loads horizontal loads may also be transmitted. That horizontal load transfer by the rails and the friction bearings along the bridge enables a load distribution of concentrated horizontal loads, primarily of the acceleration forces.

A direct application of the high acceleration forces and braking forces to the analysis model would cause a numerical overloading of the single structures, mainly the *truss piers*. Thus, a realistic load transfer / load distribution needs to be considered. Referring to the DB-guideline Ril 804 [2], where load distribution factors ξ are considered for short bridges, new load distribution factors $\xi^*_{acceleration}$ and $\xi^*_{braking}$ are to be determined for the Rendsburg High Bridge. The longitudinal load transfer was determined by a non-linear analysis model of the whole bridge including the rails. The analysis model (program SOFISTIK) takes into account load-dependent non-linear force-displacement-functions between the rails and the railroad-sleepers and the girders as well as at the friction bearings. The non-deterministic parameters of the force-displacement-functions were varied by numerous calculations. The results of the analysis are the realistic horizontal forces undertaken by the single structures – represented by reduction ratios (Table 1). The definition of the design load values were made according to the upper boundary of the computation results including additional safety factors.

Table 1. Reduction ratios for acceleration and braking rorces

Structure	**influence length**	$\xi^*_{accel.}$	$\xi^*_{braking}$
canal bridge	294.60 m	0.4	0.9
connecting pier at the canal building	11.50 m	0.4	4.5
truss piers near the canal building	40.00 m	0.4	1.7
truss piers at the abutment	68.50 m	0.4	1.0
truss piers (other)	ca. 40 m	0.4	1.3
loop bridge	129.50 m	0.4	1.0

Table 1 shows, that the high, local induced acceleration force of 1000 kN may generally be reduced to 400 kN per single structure ($\xi^*_{accel.}$ = 0.4). The remaining load is distributed to the nearby single structures. The distribution of the braking forces is more sophisticated. The *canal bridge* passes loads to the piers, while the abutment with the dam absorbs load from the piers.

An integral part of the load distribution calculation is the analysis of the rail stresses. The rails at the Rendsburg High Bridge (type S54) are laid without gaps. Additional safety rails are existing along the whole bridge with gaps every 30 m. The maximum rail stresses arise at the dilatation joints between the *canal bridge* and the *connecting piers* as well as at the abutment and amount up to 88 N/mm². That exceeds the limit value for the permitted additional rail stress which is defined as 82 N/mm² for the rails type S54 (compare the stress limit value of 92 N/mm² for rails UIC60 according to the Eurocode 1-2 [1], 6.5.4.5.1). Due to the exceeding of the rail stress limit, local sections of the rails will be replaced by full-web rails (rectangular cross section instead of Vignol rails).

The computation was verified by in situ measurements (Figure 7).

Figure 7. In situ measurements of braking loads at the bridge

4 Structural analysis

For each single structure (*canal bridge*, *loop bridge*, superstructures, all types of piers) 3D-analysis models were generated. The analysis models contain, in addition to the main structures of the frameworks, all deck elements (longitudinal and transverse girders), all bracing members (wind bracing, bracing for braking thrust, deck bracing) as well as other elements. The truss nodes are usually generated as rigid joints, so that secondary stresses can be determined.

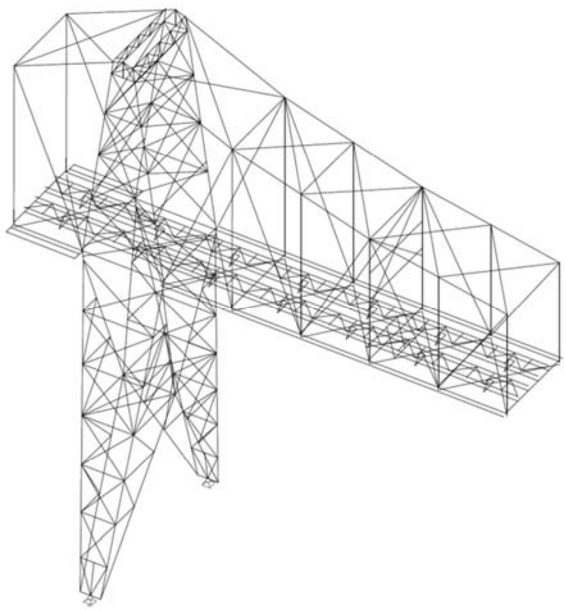

Figure 8. Computation model of the canal bridge (detail pylon and deck)

The bridge is in good condition. Local corrosion defects cause usually less than 5% loss of cross section. According to the Ril 805 [3] the corrosion defects are taken into account at the analysis by an additional partial safety factor γ_B = 1.05. Corrosion defects > 5% needs to be repaired. The partial safety factor γ_B is considered on the material side:

$$f_{y,d} = \frac{f_{y,k}}{\gamma_M \cdot \gamma_B} = \frac{235\,N/mm^2}{1.15 \cdot 1.05} = 194.6\,\frac{N}{mm^2} \quad (1)$$

(Strength and partial safety factors according to Ril 805 [3])

5 Strengthening concept

The structural analysis yielded some typical cases of overstress at the bridge under the today's traffic loads:

- members that are directly affected by the higher acceleration and braking forces, e.g. the main diagonal bars of the *truss piers* and the foundations of the *truss piers* (overturning of the piers)
- members that are affected by the higher axle loads of the trains, e.g. the longitudinal and transverse girders of the deck
- members that participate unintentionally at the primary load-carrying system, e.g. wind bracing and deck elements

The overstressed members need to be strengthened. Typical strengthening measures at the riveted construction are:

- strengthening plates on the truss members; the strengthening plates need to be integrated into the truss joints
- latticing of open cross sections in order to increase the torsional stiffness (lateral torsional buckling)
- replacement of rivets against fitted bolts if the shear capacity is exceeded
- replacement of whole truss members; generally only for secondary members possible, e.g. the wind bracing

The (well tried) static system of the bridge construction should not be changed.

Figure 9. Technically challenging measures

The execution of the strengthening measures at the riveted framework construction with manifold graded cross sections is technically very challenging. Often additional connecting and filler plates are necessary (Figure 9). Welding at the old material is not intended.

Most of the strengthening measures are carried out under railway traffic. Until 2014 the bridge had been under single track traffic (Figure 10), since the beginning of 2015 the bridge has been under double-track-traffic.

Figure 10. Working under traffic load

As the Rendsburg High Bridge is a listed historical cultural monument the appearance of the bridge must not be affected by the strengthening measures.

6 Examples of strengthening

6.1 Diagonal bars at the piers

One of the most frequently applied strengthening measures is to add plates on the truss members. The main diagonal bars of the *truss piers* are an example for that measure (Figure 11). The strengthening plates are fastened on the bars by fitting bolts. The integration of the strengthening plates into the truss joints is done by additional connection plates. The connection plates are split into two side-by-side-parts which are mounted successively, so that during the assembly not all rivets/bolts of the joint have to be opened at the same time.

Figure 11. Strengthening of the main diagonal bars at the truss piers

6.2 Wind bracing at the canal bridge

One of the strengthening measures at the *canal bridge* is to replace the wind bracing (Figure 12). The wind bracing participates unintentionally at the primary load-carrying system, for what it was not designed originally. In order to strengthen it, the bars are replaced with new bars of the same cross section but of a higher steel quality (S355). Thus, the strength of the bar is raised but not the stiffness. If the cross section were increased, the bracing would, due to the higher stiffness, participate more at the primary load-carrying system, which would reduce the effectiveness of the strengthening.

Figure 12. Replacement of the wind bracing

6.3 Foundation of the piers

The *truss piers* as well as the *connection piers* get overturning loads by the horizontal forces from braking and acceleration, but also from wind and centrifugal forces. That results in force couples at each of the four foundations of every pier. The foundations need to be strengthened for uplifting loads while they have sufficient bearing capacity for downward directed loads.

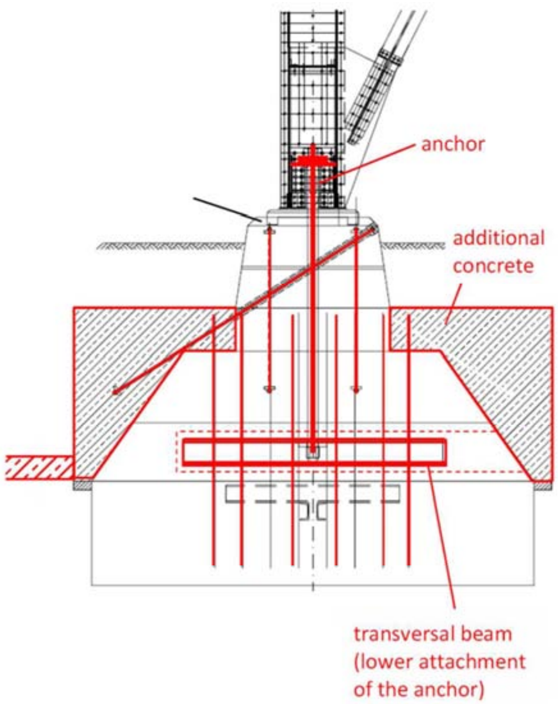

Figure 13. Elements of foundation strengthening

The main components of the strengthening are the replacement of the anchors (new anchors Ø115-125 mm) and a concrete topping (Figure 13, Figure 14).

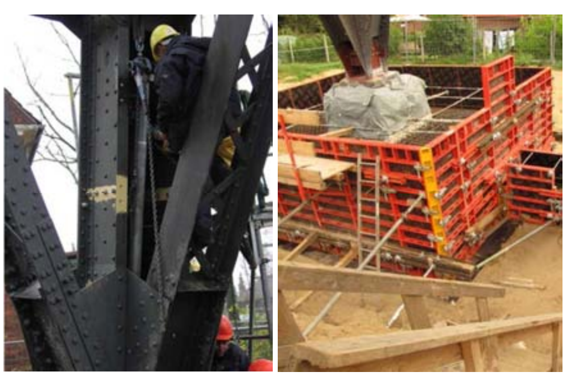

Figure 14. Foundation strengthening

The anchor connects the steel construction of the pier tightly to the concrete foundation. The lower end of the anchor is attached (screwed) to a transverse beam, which is inserted into the foundation through a horizontal bore hole. The top concrete raises the dead load of the foundation.

7 Conclusions

With extensive repair and strengthening measures the over 100 hundred year old Rendsburg High Bridge is being retrofitted for many years to come. The today's railway traffic loads and thereby, especially the acceleration and braking forces, are significantly higher than the original design loads. Sophisticated computations and dynamic measurements make it possible to identify and to verify remaining load capacity. Only by that the bridge can be retrofitted in a technically and economically feasible way. The measures are usually carried out under railway traffic, which makes high demands on their design, planning and execution.

The Rendsburg High Bridge is a masterpiece of civil engineering. Preserving it is an important contribution to the building culture.

8 References

[1] Eurocode 1-2 *Acts on structures – Traffic loads on bridges*. 2010

[2] Richtlinie 804 *Eisenbahnbrücken planen, bauen und instand halten*. DB Netz AG, 2013

[3] Richtlinie 805 *Tragsicherheit bestehender Eisenbahnbrücken*. DB Netz AG, 2000