Strengthening the Caland Bridge Rotterdam for Increased Load

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Summary

The existing Caland Bridge in Rotterdam harbour will be improved for noise emission and this increases the dead load of the bridge. The bridge also will receive heavier train traffic since it will form part of the Betuweroute in the near future. Therefore, this truss bridge for combined rail and road traffic was recalculated. It was necessary to take connection stiffness into account. These calculations showed that the design of the bridge is critical. It was decided to limit the remaining design lifetime of the bridge to 15 years thus allowing adaptation of safety factors. Also, accurate calculations of the bridge buckling modes were made. Despite these efforts, it turned out to be still necessary to strengthen the bridge. The bridge strengthening was limited to the critical diagonals and connections. After strengthening the bridge, it is fit for service until the year 2020 when it is going to be replaced.

Keywords: steel, dead load, train load, railway bridge, truss, buckling, connection, strengthening.

1. Introduction

In The Netherlands a lot of building activity is going on in the field of railway bridges [1,2] and stations [2,4]. Two main railway projects are reaching completion: the high-speed passenger line towards Belgium and the cargo railway line from Rotterdam harbour to Germany, called Betuweroute.

The existing Caland Bridge in Rotterdam harbour forms part of the Betuweroute and is a combined road and double track railway truss bridge consisting of two approach bridges and a lift bridge. One approach bridge has continuous main truss girders on three supports spanning 79.10 m and 107.35 m. The other has simply supported truss main girders spanning 84.75 m. Between the approach bridges there is a movable vertical lift bridge spanning 67.80 m (Figs. 1 and 2).

For upgrading the Rotterdam harbour railway track as a part of the Betuweroute, it was necessary to take noise emission reduction measures for the Caland Bridge. These measures meant an increase of the dead load on the bridge. Besides this increase in dead load, also the train traffic on the bridge became more intense and the design load was increased.

It was therefore decided to recalculate the bridge. In the past these truss bridges were calculated as hinged trusses ignoring the secondary moments in static design. However, the design of the connections is such that they cannot be regarded as hinges and forces and bending moments should be calculated using frame theory. These new calculations showed that the design of the bridge is critical.

It was decided to try to keep the bridge in service until the year 2020 by:

- recalculation of the bridge with adapted safety factors aiming at a reliability index equal to $\beta = 3.6$ for the limited design lifetime of 15 years;

- taking train traffic measures to avoid two heavy trains on the bridge at the same time;
- using FEM calculations to accurately calculate buckling lengths of compression elements (diagonals and upper chords).

With these measures, the bridge structure was recalculated and just minimum strengthening of the structure (connections in the lower chord and six diagonals) turned out to be necessary to keep the bridge in service until the year 2020.

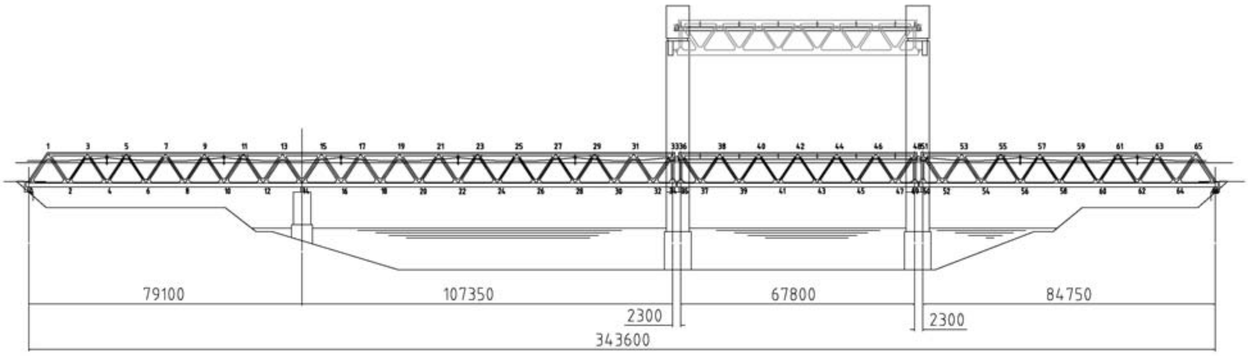

Fig. 1 *Caland Bridge, Rotterdam – side view*

Fig. 2 *Caland Bridge for rail and road, overview*

2. Heavier loads

2.1 Noise emission reduction measures

The Caland Bridge will receive more and heavier train traffic forming part of the Betuweroute. However, it was required that the bridge would produce less noise than in the old situation. For a new railway bridge, it is possible to design for minimum noise emission [5]. For existing bridges this is impossible, but several noise emission reduction measures are available. For the existing Caland Bridge, two measures were taken: adding mass and providing sandwich plates.

It was shown in earlier projects that it helps to increase the mass directly under the rail. This was done here by adding 100 kg steel mass blocks every 0,6 m under the deck plate between the two webs of the stringer carrying the rail (Fig. 3). In this figure the 50 kg steel mass blocks attached to each side of the cross girder are shown too.

A second measure to reduce noise emission is by attaching steel plates to the web of the stringer and to the deck plate (Figs. 3 and 4). This additional steel plate is connected by adhesive bonding thus forming a sandwich together with the load bearing steel plates of the deck and the webs of the stringer. The ratio of load bearing plate thickness to glue layer to additional plate thickness is 4:1:1. The additional plates are locked by bolts to enhance safety against loss of bonding strength.

Fig. 3 *Mass blocks under rail*

Fig. 4 *Sandwich plates added to deck plate and stringer*

The dead load increase due to noise emission measures is 4 kN/m per track which is about 4 % of the train traffic load.

2.2 Train traffic

The load configuration for heavy cargo trains is given in figure 5. The bridge was originally designed for load configurations indicated by the codes. These cover heavy cargo trains (90 kN/m per track) with axle loads P =225 kN (see Fig. 5). However, forming part of the Betuweroute, the bridge had to carry axle loads of P = 250 kN, corresponding to 100 kN/m per track. This meant an increase of 10% in train traffic loading.

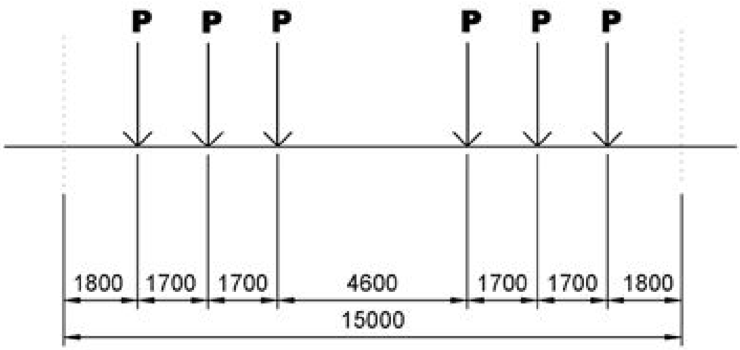

Fig. 5 *Load configuration*

2.3 Load increase

Because of the dead load increase due to noise emission measures (4% of train traffic load) and due to increased train traffic load (10%), the bridge had to be recalculated.

3. Recalculation of the bridge

3.1 Safety level

To show that the bridge was strong enough to cope with this load increase it had to be recalculated. In the past the bridge was calculated as hinged truss bridge ignoring the secondary moments in the connections in static design. However, the design of the connections is such (Fig. 6) that they cannot be regarded as hinges and forces and bending moments should be calculated using frame theory. These new calculations, using a train traffic load factor of 1.50, a dynamic factor of 1.30 and a model factor of 1.00, showed that the design of the bridge was critical. The combination of factors mentioned leads to a total factor of 1.95. It was decided to try to keep the bridge in service until the

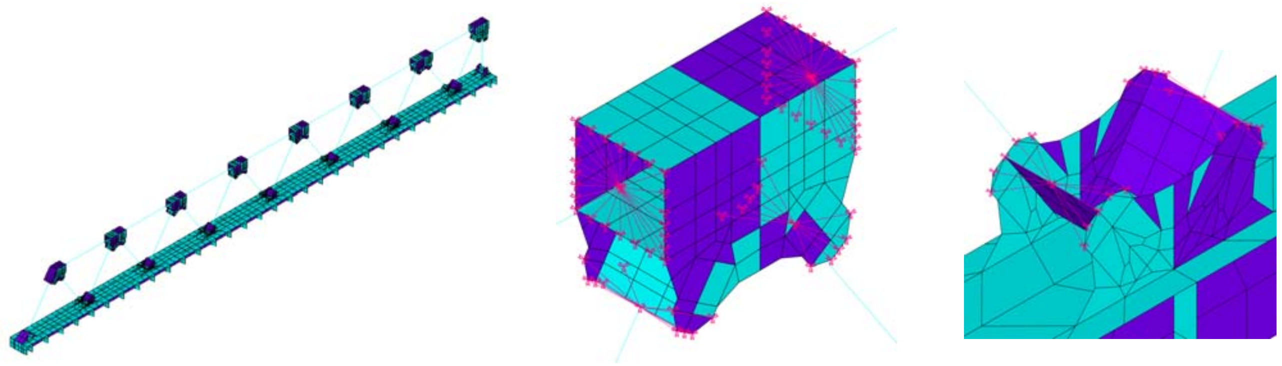

Fig. 6 *Three-dimensional calculation model (left to right: truss, upper and lower chord connection)*

year 2020 when it was planned to be replaced anyway. The limited design life of only 15 years allowed using reduced safety factors still achieving a reliability index equal to $\beta = 3.6$. Also, further studies [6] were carried out on the load, dynamic and model factors to be used resulting in the following set: 1.05, 1.14 and 1.20 respectively. The combination of these factors leads to a total factor of 1.44, considerably less than the previously used total factor of 1.95. In combination with adapting the load, dynamic and model factors, also traffic measures were taken avoiding two heavy trains on the bridge at the same time by a signalling system on both sides of the bridge.

3.2 Buckling lengths

Moreover, it was decided to accurately calculate buckling lengths of compression elements (truss diagonals and upper chords) by using the finite element method (FEM) for a 3-dimensional model where the nodes and lower chord are built up out of plate elements and the diagonals and upper chord consist of beam elements (Fig. 6).

Since the bridge does not have an upper wind bracing, the stability of the upper chord has to be provided through frame action by the diagonals and cross girders in the bridge deck. The Euler buckling mode calculated by FEM, corresponding to out of plane buckling, is shown in Fig. 7. On the basis of this Euler buckling mode and the corresponding lowest eigenvalue of $n = 12.6$ for the load case of factored dead load with traffic load, the buckling lengths for the upper chord and the diagonals can be calculated leading to $\ell_{buc} = 15.1$ m for the upper chord and $\ell_{buc} = 20.2$ m for the diagonal.

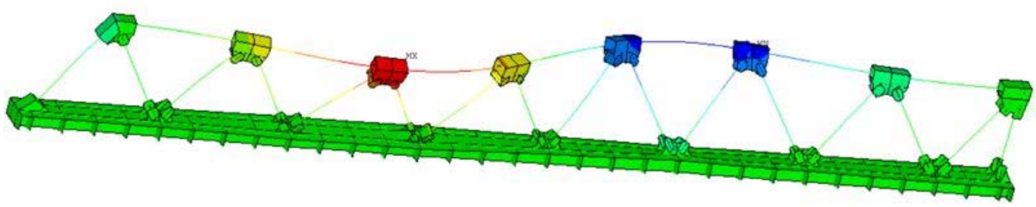

Fig. 7 *Buckling mode out-of-plane*

In [7] the elastic Euler buckling load is given for a bar with hinged ends on an elastic foundation under distributed axial loads (section 2.13 of [7]). For the Caland Bridge, the upper chord can be considered to be such a bar with the diagonals forming the elastic foundation. The modulus of the foundation for the Caland Bridge can be calculated as $\beta = 0.419$ N/mm^2. Using table 2-9 of [7] then yields $\ell_{buc} = 0.29\ell$ and with the upper chord total length being $\ell = 67.8$ m the buckling length of the upper chord becomes $\ell_{buc} = 19.7$ m. It can be seen that this is a more conservative buckling length than the one found in the finite element calculation $\ell_{buc} = 15.1$ m. The buckling lengths calculated by FEM were used for checking the individual members.

3.3 Checking the members

For all relevant load cases, the bending moments and the normal and shear forces were calculated by linear elastic analysis using the FEM model as shown in Fig. 6. Subsequently, member checks were carried out using the Dutch codes, which contain similar member checks as the Eurocodes. All members were checked for strength and stability by the appropriate interaction formulae. It could be shown that the unity checks for all upper and lower chords were satisfied. However, checking the diagonals did not result in satisfactory unity checks in all cases. For six diagonals, it could not be shown that they were sufficiently safe even when using the FEM buckling lengths and the reduced safety factors given above. Here, a typical example of such a unity check for a diagonal is given:

$$UC_1 = \frac{N_{Ed}}{N_{c,Rd}} + \frac{n_Y}{n_y - 1}\left(\frac{N_{Ed} \cdot e_y}{M_{c,y,Rd}} + \frac{M_{equ,y,Ed}}{\chi_{LT} M_{c,y,Rd}}\right) + \frac{n_z}{n_z - 1}\left(\frac{M_{equ,z,Ed}}{M_{c,z,Rd}}\right) \leq 1 \quad (1)$$

and

$$UC_2 = \frac{N_{Ed}}{N_{c,Rd}} + \frac{n_Y}{n_y - 1}\frac{M_{equ,y,Ed}}{M_{c,y,Rd}} + \frac{n_z}{n_z - 1}\left(\frac{N_{Ed} \cdot e_z + M_{equ,z,Ed}}{M_{c,z,Rd}}\right) \leq 1 \quad (2)$$

where:

UC unity check

N_{Ed} design value of the axial force, here e.g. $N_{Ed} = 9940$ kN;

$N_{c,Rd}$ design resistance of the cross-section for uniform compression, here e.g. $N_{c,Rd} = A_{eff} f_y$ =15702 kN;

n_y buckling factor with respect to out-of-plane buckling, here e.g. $n_y = 7.3$;

e_y imperfection, here e.g. $e_y = 45.2$ mm;

$M_{c,y,Rd}$ design resistance for bending out-of-plane, here e.g. $M_{c,y,Rd} = W_{eff,y} f_y = 7905$ kNm;

$M_{equ,y,Ed}$ equivalent design bending moment for out-of-plane bending, here e.g. $M_{equ,y,Ed}$ = 492 kNm;

χ_{LT} reduction factor for lateral-torsional buckling, here e.g. χ_{LT} = 0.79;

n_z buckling factor with respect to in-plane buckling, here e.g. $n_z = 13.2$

e_z imperfection, here e.g. $e_z = 5.7$ mm;

$M_{equ,z,Ed}$ equivalent design bending moment for in-plane bending, here e.g. $M_{equ,z,Ed}$ = 329 kNm;

$M_{c,z,Rd}$ design resistance for bending in-plane, here e.g. $M_{c,z,Rd} = W_{eff,z} f_y = 1251$ kNm;

A_{eff} effective area with respect to local buckling, here e.g. A_{eff} = 44231 mm^2;

W_{eff} effective section modulus with respect to local buckling, here e.g. $W_{eff,y} = 22268389$ mm^3 and $W_{eff,z} = 3523295$ mm^3;

f_y yield stress, here f_y =355 N/mm^2.

Using the values given above in equations (1) and (2) yields:

$UC_1 = 1.08 > 1$ and $UC_2 = 1.06 > 1$

This means that these checks are not satisfied.

The problem with the diagonals is that the cross-section has to be reduced for local plate buckling of web and flanges, which is expressed by A_{eff} and W_{eff}. It can be shown that for the situation where plate buckling is prevented and the gross cross-section can be used, the member check given above is fulfilled. It was therefore decided to strengthen the six diagonals by preventing local buckling.

3.4 Checking the connections

The connections were first checked by hand calculation indicating that high stress levels may be

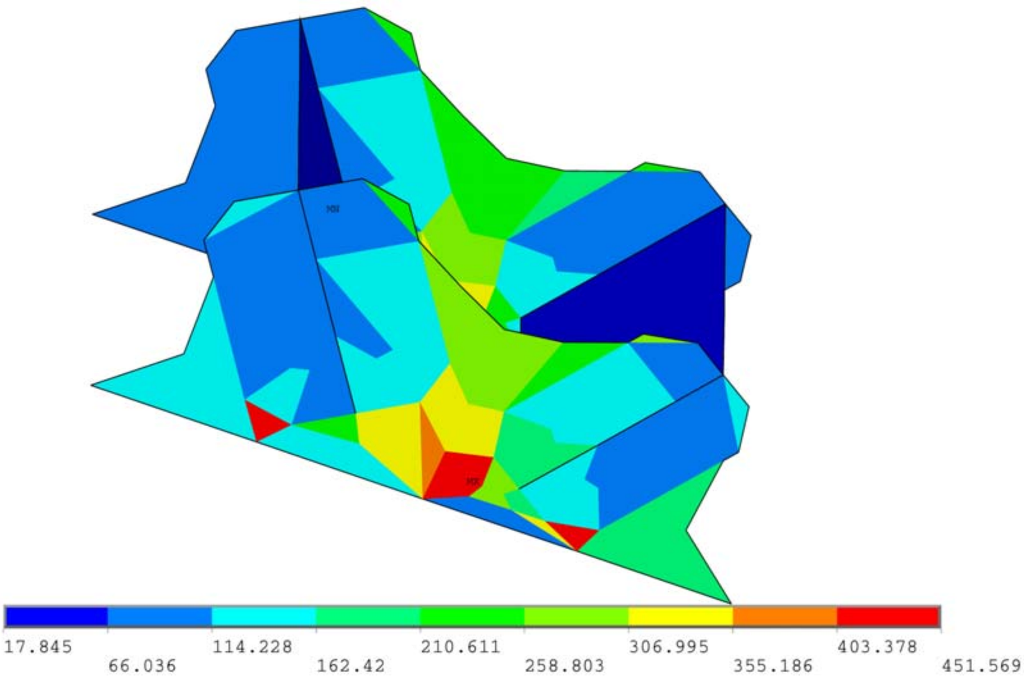

Fig. 8 *Peak stresses in the connection (mean Von Mises stresses per element)*

expected in the connections. Therefore, it was decided to model the connections in more detail in the finite element model as indicated in Fig. 6. Modelling the connections by plate elements allows studying the stress distribution in the connection. The stress levels in the connections of the upper chord were all sufficiently low. However, the stress levels in the connections of the lower chord were locally critically high. In figure 8, the mean Von Mises stresses per element are show. Though the element mesh is rather coarse and the element shapes are not optimal, Fig. 8 indicates stress levels well above the yield stress $f_y = 355$ N/mm^2 of steel grade S355 of the plate material used. These stresses are unacceptably high and can not be ignored. Therefore, it was decided to strengthen the connection by a reinforcing plate.

4. Strengthening measures

4.1 Strengthening the diagonals

The diagonals were strengthened in such a way that local buckling was prevented. Near the ends of the diagonal, where the compressive stresses are high enough to cause local buckling, the flange

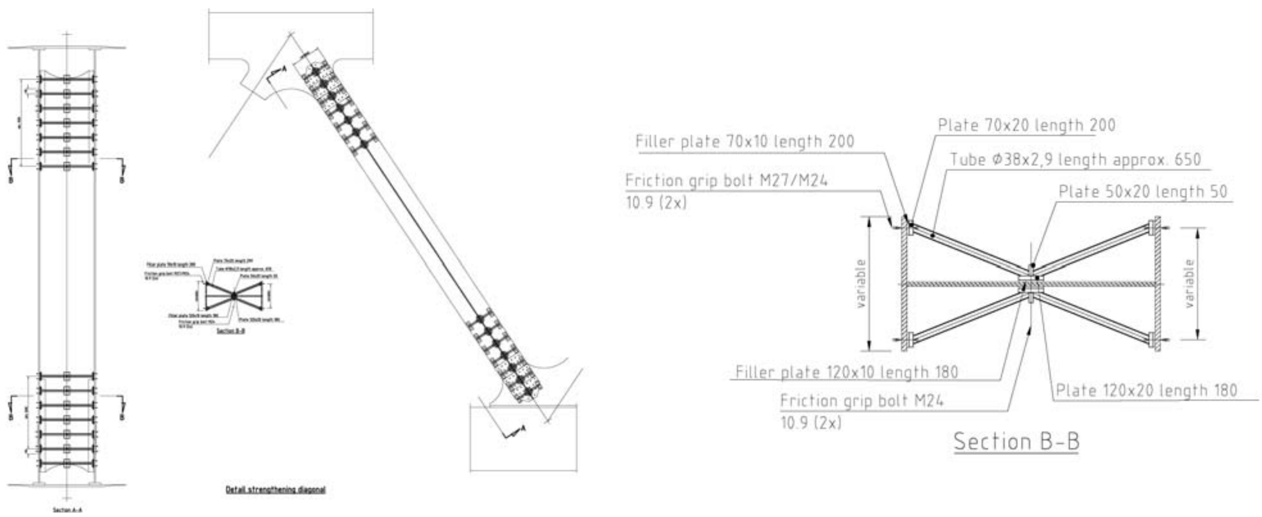

Fig. 9 *Strengthening of diagonals by preventing local buckling*

tips are supported by CHS 38 x 2.9 (Fig. 9). These supporting elements have header plates at their ends and are bolted to the flange tip and the web of the diagonal using high strength friction grip bolts M27 10.9 where these bolts replace rivets and M24 10.9 otherwise. This detail was developed in this way to get a good fatigue classification thus avoiding fatigue problems. At both ends of the diagonal, over a length of about 2 m, 7 supporting elements have been provided.

4.2 Strengthening the connections

Because of high stress levels it was decided to strengthen the connection in the lower chord by adding a reinforcing plate (thick 14 mm, 20 mm or 25 mm depending on the connection). To connect the reinforcing plate (Fig. 10), it was necessary to loosen the rivets in the connection below the splice plates of the flanges of the diagonals. Then, the reinforcing plate could be welded to these splice plates and to the flange plate attached to the top of the lower chord. At these locations, butt welds are used; elsewhere a fillet weld suffices. The rivets were then replaced by high strength friction grip bolts M27 10.9.

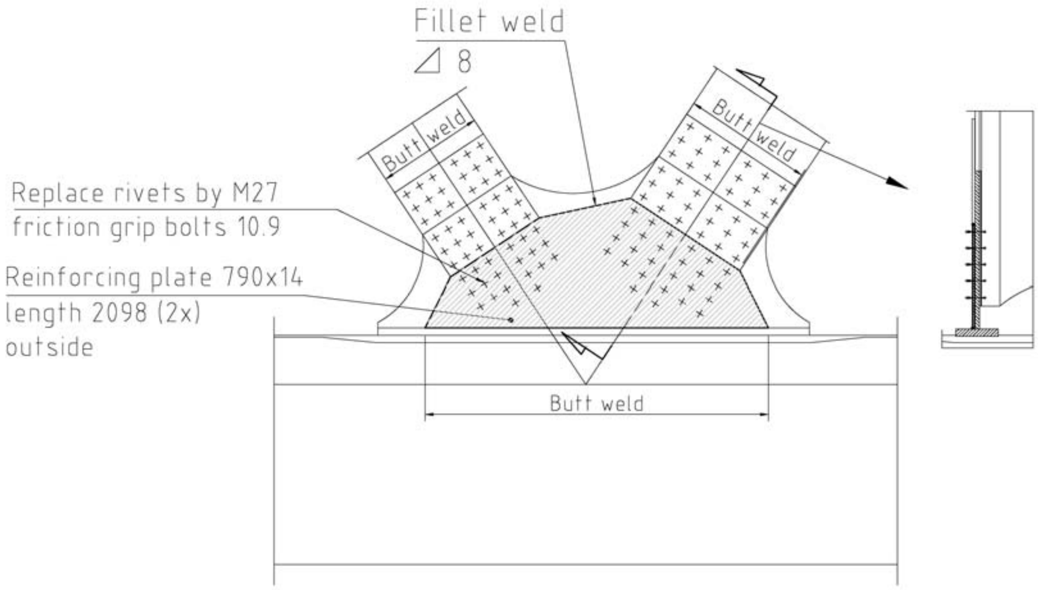

Fig. 10 *Strengthening the lower chord connection by a reinforcing plate*

5. Conclusions

The existing Caland Bridge, a combined road and double track railway truss bridge, now forms part of the Betuweroute, the cargo railway line from Rotterdam harbour to Germany, and therefore needs to be upgraded. Because the noise emission level had to be reduced, noise emission reduction measures were taken by adding mass closely to the rail and by adhesively bonded additional plates forming a sandwich structure with the load bearing plates. This however, meant additional dead load being added to the structure. Being part of the Betuweroute also means an increase of the train traffic loading due to heavy cargo trains. Because of dead load increase and train traffic load increase, the Caland Bridge was recalculated. It could be shown that the chords of the trusses and the connections in the upper chords were sufficiently safe. Despite the fact that the partial safety factors could be lowered thanks to a limited required remaining design lifetime of just 15 years, despite a signalling system on both sides of the bridge avoiding two heavy trains on the bridge at the same time and despite accurate calculation of elastic buckling lengths of the members, it could not be shown that all diagonals in the trusses and the connections in the lower chords were sufficiently safe. Therefore, these were strengthened. Six diagonals were strengthened by adding intermediate supporting elements between flange tips and web in highly stressed areas thus avoiding local buckling. The connections in the lower chords were strengthened by adding reinforcing plates at highly stressed locations. By these measures, the existing Caland Bridge (Fig. 11) is fit for service until the year 2020 when the bridge is to be replaced.

Fig. 11 *Caland Bridge fit for service until the year 2020*

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