# Cracking and Fatigue of Heavy Loaded Prestressed Concrete Bridge in Sweden

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## Abstract

A prestressed concrete bridge was built in 1963 with BBRV cables. It has three spans and a total length of 134.8 m. Due to mining activities the bridge was loaded with trucks with a total weight of 90 ton during 2012-2014 and from 2019. Crack development has been monitored manually and from 2020 with strain gauges and LVDTs. Cracks normally vary between 0.1 to 0.3 mm in width and grow in length with time. In November 2020 some of the strain gauges on the concrete showed alarming growth and the bridge was closed for traffic. Additional strain gauges were installed on vertical reinforcement bars and an assessment was carried out of the fatigue capacity of the bridge. It was found that the new strain gauges did not indicate any growth in strain and that the fatigue capacity was sufficient. The bridge could be opened again for traffic after being closed for five weeks. Monitoring drift in the strain gauges and fatigue are discussed.

**Keywords:** Prestressed concrete bridge, cracking, fatigue**,** monitoring, assessment, heavy loading,

## 1 Introduction

Many prestressed concrete bridges in the world have an age of more than 50 years and questions are being raised about their condition and load-carrying capacity [1]-[3]. In this paper a case study is presented of a bridge built in 1963 over Torne River at Autio in northern Sweden, not far from the border to Finland, see Figure 1, [4].

## 2 Design and Construction

The bridge has a total length 138.8 m and has three spans: 36.4 + 62.0 + 36.4 m. The width is 7.48 m. The prestressing was applied with BBRV cables of 32 $\phi$ 6 mm wire. The bridge was built in the following order with formwork supported by trusses:

(1) Abutments and intermediate supports.
(2) Main beams for side spans + consoles for main span (16 m) + cross beams.
(3) Prestress stage I (side spans).
(4) Concrete deck for side spans and consoles.
(5) Prestress stage II (side spans).
(6) Remaining mid span (30 m).
(7) Prestress stage III (mid span);
(8) Bitumen and railings.

The concrete for the beams and deck were originally set to K400 and K300 respectively. However, the quality in the beams had to be raised to K450 with a nominal compression strength of 45 MPa. The allowable stress for K400 for shear **or**

*Figure 1. Prestressed Concrete Bridge over Torne River at Autio built in 1963 with three spans and a total length of 134.8 m. View towards SE*.

torsion was at that time 0.85 MPa and for torsion **and** shear together 1.25 · 0.85 = 1.1 MPa. If any of these stresses were exceeded, the principal stresses were to be checked, and they should be smaller than 0.34 MPa. The allowable stresses for concrete in shear are nowadays about half of what they were at the time.

Drilled out cores tested in 2021 showed a compressive strength of 66.1 MPa and a tensile splitting strength of 3.9 MPa.

The reinforcement in the beams was Ks40 with a nominal yield strength of 400 MPa. In the deck slab, the quality was Ks60 with a nominal yield strength of 600 MPa. A cross section is shown in Figure 2. The vertical shear reinforcement is only $\phi$ 10 s 250 mm.

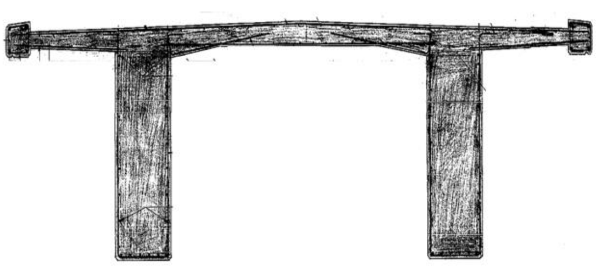


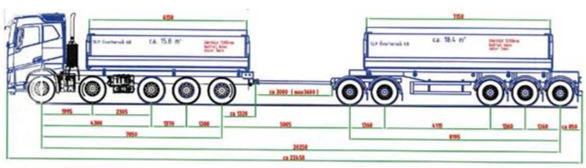
*Figure 2. Cross section. The beams have generally a width of 0.7 m which is widened to 1.0 m over the midspan supports. The height varies between 2.27 and 3.15 m*

The rest of the shear is supposed to be taken by prestressing reinforcement and the concrete. The BBR prestressing strands had a diameter of 6 mm, a nominal yield 0.2 stress of 1500 MPa and an ultimate stress of 1700 MPa. A cable with 32 strands has an area of $32*\pi*3^2$ = 904.78 $mm^2$ and could be stressed up to 0.65 of its ultimate stress which gives $P$ = 0.65*1700 * 0,000904 MN = 0.999 MN (≈ 100 ton)

# 3 Assessment

## 3.1 Heavy traffic

The original traffic loads included an axle load of 140 kN with a dynamic increment of 40 %. The distributed load was 24 kN/m. In 2011 an assessment was made that showed that the bridge could carry trucks with a total load of 900 kN driving in the middle of the bridge, see Figure 3.



***Fiure 3.*** *Mining lorry with 10 axles with 90 kN giving a total load of 900 kN . Axle distances 1,995 + 2,305 + 1,370 + 1,380 + 5,005 + 1,360 + 4,115 + 1,360 + 1,360 = 20,250 m, [4], [5]*

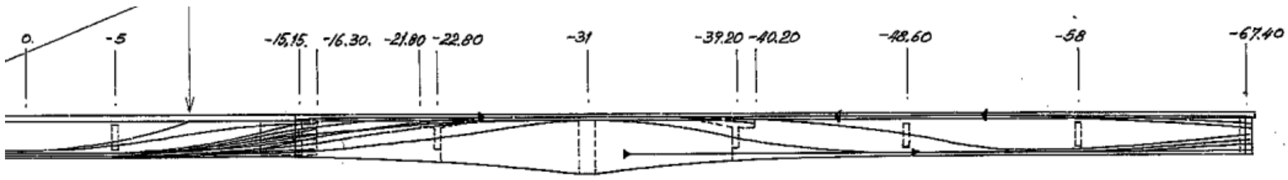



*Figure 4. Prestressing reinforcement for one symmetrical half of the bridge (with the midpoint to the left). There is a joint for the reinforcement at the distance 15.50 to 16.30 m from the midpoint, [4], [5].*

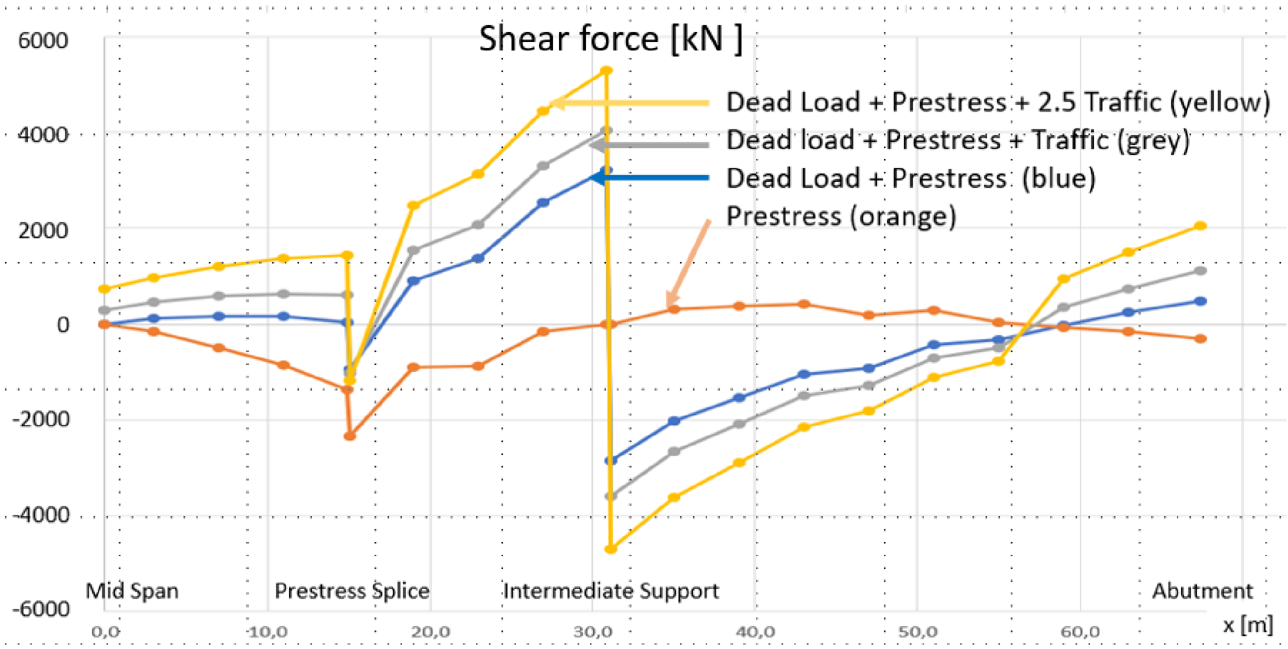



*Figure 5.. Shear forces according to the original design. From Andersson & Leidzén [5].*

In the following year mining was started in the neighbourhood and heavy mining trucks started to travel over the bridge. However, the mine went bankrupt in 2014 due to a drop in ore prices.

A new assessment was done in 2019 and a new mine started right after that with new heavy trucks travelling on the bridge, [4], [5].

### 3.2 Moment capacity

There are no problems with the bending moment capacity. The models to be used are clear and simple to apply. There are many prestressing cables, see Figure 4, and their lever arms are enough to carry the applied moments.

### 3.3 Shear capacity

The shear capacity is more problematic. The original design is illustrated in Figure 5. If the traffic load is multiplied with 2.5, a maximum shear force of ca 5.5 MN is obtained. If we consider the positive influence of the intermediate support, the needed capacity for the beams can be reduced to ca 5 MN. These loads give a shear stress $\tau$ = 1.2 MPa close to the midspan and a maximum principal stress $\sigma_1$ = 0.36 MPa. Due to so small principle concrete stresses, only a minimum shear reinforcement of $\phi$ 10 c 250 was needed.

The shear capacity is hard to model correctly with code models, as has been shown in several full-scale tests to failure, see e. g. Bagge et al [6] - [9], Nilimaa et al. [10], [11], Bien et al. [12], Elfgren et al. [13], [14] and Häggström et al. [15].

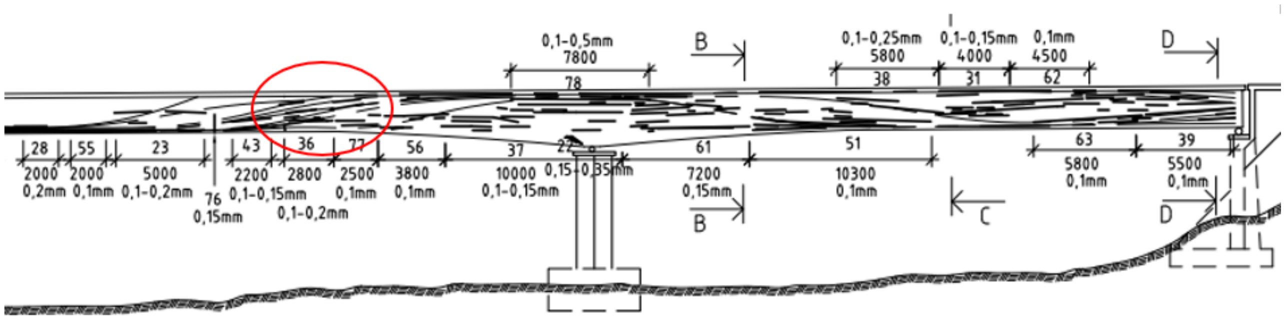



*Figure 6. Cracks on the outside of the West Beam of the Autio Bridge, September 15, 2020. Ca 15 m to the left of the mid-span support there is a section where mid-span and support cables are anchored.*

As mentionend, according to the original design there were only very small principle stresses and they could be carried by the concrete. Probably the prestressing forces over the years have been reduced due to shrinkage, creep and relaxation [8]. This may have increased the principle tensile stresses to become higher than the concrete tensile strength and to be the cause of the extensive cracking which has been observed, see Figure 6 and below.

Furthermore, there is, as mentioned, only $\phi$10 c 250 Ks 40 as vertical reinforcement in the beams. Their capacity can be estimated assuming 45°-cracks over a height of 2 m. This will for one crack give $2\sqrt{2}/0{,}25$ = 11.3 stirrups per beam side. With four beam sides and a stirrup area of $\pi \cdot 5^2$ = 78.54 mm$^2$ we obtain

$\boldsymbol{V_s} = A_s \cdot f_y \approx$ 4 · 11,3 · 78.54 · 400 N = 2554 · 400 N = 1,42 MN

If we assume a flatter crack angle more loads can be taken by the stirrups. But still there is a substantial load that must be carried by the prestressed concrete.

## 4 Cracking

Thin horizontal cracks were observed in the main beams in 2014. Some 20 cracks were measured, usually with a width of 0.1 – 0.2 mm with a length of a few m When the mine started again in 2019, regular crack inspections were carried out about four times a year. Most of the cracks are parallel to the prestressing cables. At one inspection in September 2020, see Figures 6 and 7, some 60 cracks were measured with widths from 0.1 – 0.35 mm, most of them with a width of 0.2 mm and with lengths from 1 – 22 m.

The cracks seem to be a natural consequence of the fact that there are principal concrete stresses in tension in parts of the bridge. This, in combination with thermal stresses, are probably the cause of the cracks. No corrosion can be seen around the cracks and the deformations are too small to indicate any yielding of the stirrups so far. The strains in some stirrups are now being monitored to check if there are any fatigue problems.


*Figure 7. Crack pattern at section 77 in Figure 6 (the 1/4-point) where joints of the prestressing reinforcement are situated. There are five cracks of width 0.1 mm, but they are hard to see for the naked eye.*

## 5 Monitoring

To reduce the need of frequent visits to the bridge, some cracks were instrumented in the spring of 2020. Some concrete strain gauges were also glued to the concrete surface. In November 2020 some of the strain gauges on the concrete showed alarming growth and the bridge was closed for traffic. One reason for the growth of the strains may be concrete cracking, another one could be drifting of the strain gauges.

The gauges were inspected, and the temperature compensation was investigated. However, nothing wrong could be found.

Additional strain gauges were then spot-welded to a reinforcement bar in the bottom of the midspan and to another one in the top of a midspan support. Strain gauges were also installed on some vertical reinforcement bars 6 and 10 m from the midspan support. It was found that the new strain gauges did not indicate any growth in strain. The measured stress ranges were also so small that there was no risk for a fatigue failure. So, it was concluded that something must have happened to the original strain gauges. We have learnt that drifting of strain gauges, glued to concrete, does occur now and then. All things being considered, the bridge was deemed to be fit to be opened again for traffic after being closed for five weeks.

Almost a year later, in October 2021, the crack measurements indicated no further growth of the crack widths. Maximum recorded values of increase were only of the order of 0.001 mm.

At the same time maximum strain ranges of 300 μm/m were observed for a 900 kN mining truck crossing the bridge. This gives a longitudinal steel stress range $\Delta\sigma = E \cdot \Delta\varepsilon = 200 \cdot 10^9 \cdot 300\ 10^{-6}$ Pa = 60 MPa. In the stirrups the strain range was 150 μm/m, see Figure 8. This corresponds to a stress range in the stirrups of $\Delta\sigma = 30$ MPa.

The midspan deflection for traffic loads was calculated to 46 mm < L/500 = 124 mm in the original design.

Measurements with a Noptel gave as of October 2021 a maximum midspan deflection of 60 mm for a passing of a mining truck of 90 ton.

## 6 Fatigue

For fatigue, according to the *fib* Model Code 2010 [16], prestressing curved tendons in steel ducts with a stress range $\Delta\sigma_s$ < 120 MPa will last more than $10^6$ load cycles. Splice devices with $\Delta\sigma_s$ < 80 MPa will also last more than $10^6$ load cycles. For ordinary reinforcement the corresponding allowed stress ranges are higher [17].

The present production sends about 30,000 trucks over the bridge every year. Allowing $10^6$ load cycles with $\Delta\sigma_s$ < 80 MPa, gives that it is possible to carry on more than 30 years before there would be any fatigue problems in the prestressing strands

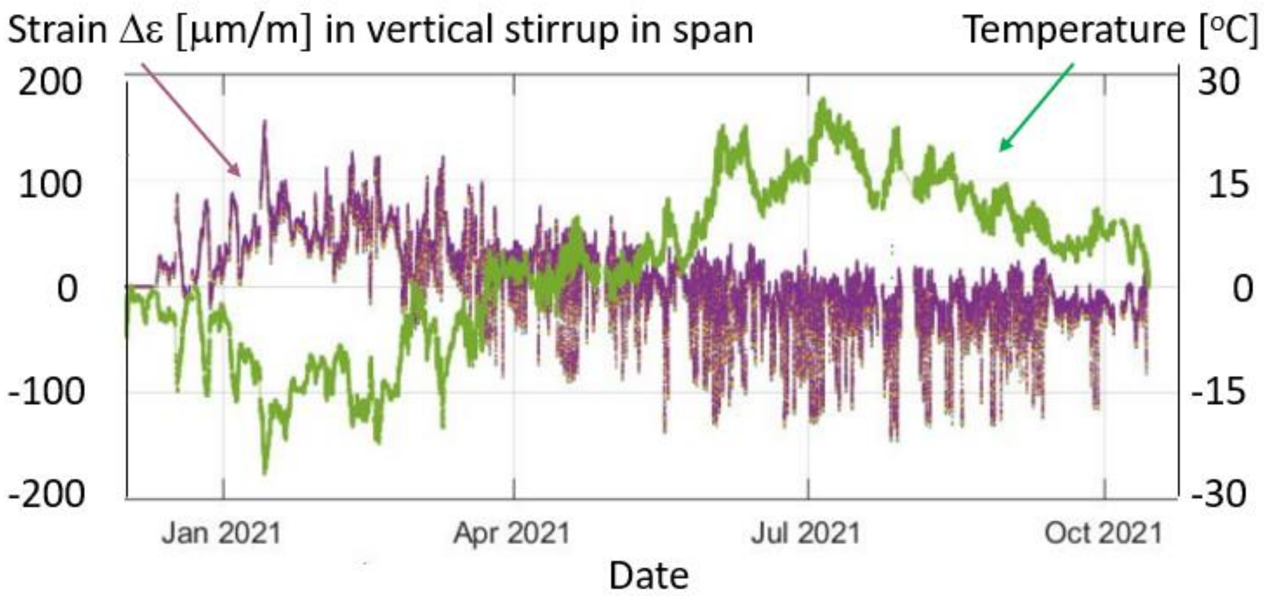



*Figure 8. Strain (violet) in a vertical stirrup in midspan and Temperature (green) from Dec 2020 to October 2021. Max strain range $\Delta\varepsilon \approx 150$ μm/m. Temperature range -25 to +25 °C, [4].*

However, fatigue is a tricky question especially if it may be **combined with corrosion** as was shown in the collapse of the Polcevera-Morandi bridge in Genoa on August 14, 2018, see e.g., Morgese et al. [18], [19].

No signs have been seen so far of any corrosion on the Autio bridge and the climate is favourable with dry summers and winters. Another bridge in a similar climate was tested to failure In Kiruna in 2014, [7] – [11] and no trace was found on corrosion on the prestressed bars. It would be valuable to see if modern non-destructive testing methods, NDT, can be used to secure this also for the Autio bridge. It would also be of interest to determine the remaining prestresses forces [8], [20] and to create a non-linear finite element model, NLFEM, of the bridge.

A more detailed fatigue analysis can also be made with the Rain-Flow method and with Palmgren-Miner hypothesis [21], [22] according to the same method as has been used by Häggström [15], [23, 24] in the analysis of two twin railway metal truss bridges.

## 7 Discussion

This paper presents experiences from a 58-year-old prestressed concrete bridge in Sweden. The bridge, as other bridges that have been tested, seems to have a considerably higher capacity than the original design calculations indicated. Tests to failure for bridges have shown differences, e.g., in material properties, load distribution support conditions and code models, which have resulted in considerable extra "hidden" capacities as presented in [6] – [15].

Society may learn and save money from the experiences from "full-scale" failure tests. They can act as a complement to the experiences from unwanted and unexpected failures due to increased loads, scour, corrosion, fatigue, and other forms of deterioration. It is therefore recommended that additional tests are to be carried out to further improve the understanding of existing bridges. The tests should as far as possible be based on realistic load cases, to optimize the outcome. As the tests are costly it is important that planning, preparations, and analysis are done in a careful way [6], [11].

Different bridge types can be tested to check their real capacity to give a base for establishing and calibrating numerical models to be used for reliable assessment of existing bridges to improve quality control, a cost-efficient bridge management and a sustainable usage of the existing bridge stock.

## 8 Conclusions

(1) There seems to be no problem with the bending resistance or the deflections of the studied bridge. This is also an experience from other tested bridges [8], [13].

(2) Also, there seems to be no problems with the shear and torsion capacity, which was feared, due the extensive cracking. Also, design philosophy has changed over the years. The concrete shear and tensile design capacities were earlier about twice as high as today. Thus, there is only very small vertical reinforcement ($\phi$ 10 c 250) in the beams and the shear forces are supposed to be balanced by the prestressing forces. The prestress forces may in their turn have been reduced due to creep, shrinkage, and relaxation (to be studied). Combined with thermal stresses this is probably the main cause to the extensive concrete cracking.

However, the stirrups struggle faithfully with the shear forces and no signs of fatigue can be seen. Monitoring of some of them indicate that they may safely function for many decades to come. This may be garanteed by continouous monitoring.

(3) We recommend non-destructive testing (NDT) to remove uncertainties regarding remaining prestressing force, possible corrosion, and settlements.

(4) The overall conclusion is that the bridge is safe and can stay put for a long time, as is the case with many other bridges, which are maintained carefully.

## 9 Acknowledgements

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