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Autor: Akesson, Björn / Edlund, Bo

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Fatigue Life of Riveted Railway Bridges

Fatigue des ponts-rails rivetés

Dauerhaftigkeit genieteter Eisenbahnbrücken

Björn AKESSON
Research Associate
Chalmers Univ. of Technology
Göteborg, Sweden

Bjorn Akesson, born in 1959, graduated from Chalmers University of Technology and received his doctorate in 1994. His research interests are fatigue and the service life of railway bridges.

Bo EDLUND
Professor
Chalmers Univ. of Technology
Göteborg, Sweden

Born in 1936, Bo Edlund received his civil engineering degrees at Chalmers University. Since 1967, he has been teaching and conducting research in structural engineering. His special research interests are stability problems, steel structures, CAD/CAE and timber structures.

SUMMARY

Many old riveted railway bridges in Sweden from the turn of the century and the few decades thereafter are today still being kept in service, so their useful lifespan might be close to an end. However, as shown by several field investigations and extensive full-scale fatigue tests, for a well-maintained bridge the expected remaining fatigue life should be substantial.

RÉSUMÉ

Un grand nombre de vieux ponts-rails rivetés, construits en Suède à la fin du 19e siècle et au cours des décennies suivantes, sont toujours en service. Ces ouvrages devraient ainsi arriver au terme de leur durée de vie. Toutefois d'innombrables essais à la fatigue exécutés en plusieurs étapes, sur le site et en grandeur nature, montrent qu'il est possible de prolonger considérablement la durée de vie résiduelle des ponts correctement entretenus.

ZUSAMMENFASSUNG

Viele alte, genietete Eisenbahnbrücken aus der Jahrhundertwende und den folgenden Jahrzehnten sind in Schweden heute noch im Betrieb. Ihre Lebensdauer sollte bald abgelaufen sein. Wie jedoch in mehreren Felduntersuchungen und ausgiebigen Ermüdungsversuchen in Originalgrösse gezeigt wurde, kann die Restlebensdauer einer gut unterhaltenen Brücke beträchtlich sein.

1. BACKGROUND

Riveting was the dominating joining technique for the construction of railway bridges in Sweden from the last decades of the 19th century until the late 1930's. Many of the riveted railway bridges built during that period are today still being kept in service. Out of the 1100 railway bridges in steel that are being managed by the Swedish National Rail Administration around 600 are riveted structures. The average age of these riveted railway bridges is about 70 years and there are reasons to presume that their useful lifespan is close to its end.
However, some old riveted railway bridges are today replaced too soon due to general lack of knowledge about the expected lifespan. These particular bridges have often been judged to be unfit with reference to fatigue, although no analysis of the fatigue damage accumulation has been made. Further in those cases the assumed presence of fatigue cracks has not been confirmed. Additionally, no investigation has been made regarding the possibility to strengthen the structure in order to increase its load-carrying capacity and at the same time improve its resistance against fatigue.

Research concerning fatigue and lifespan expectancy of old existing riveted railway bridges in steel enables the railway authorities to plan and more accurately decide upon when and which of these bridges should be replaced or strengthened first. Over the last decades riveted railway bridges have sometimes been left without proper maintenance and only limited research has been made concerning these kind of structures. It may be stated that recent research has rather been focused on the development of new materials and structures than on further development and maintenance of existing structures. And, in these times of environmental awareness, more and more attention is also payed to the waste of our resources. Prolonging the useful lifespan of our old stock of riveted railway bridges by the help of this kind of research gives considerable economical savings not only to the railway authorities, but also to the society at large.

2. FIELD STUDIES

2.1 General

Several field investigations of riveted steel bridges have since 1989 been conducted at the Department of Structural Engineering, Chalmers University of Technology, In all, the field investigations have resulted in studies of 15 different riveted railway bridges built between 1903 and 1928.
The major concerns behind the decision to investigate the superstructure of these old bridges have been the following points:

- Static load-carrying capacity
- Magnitude of live load stresses
- Corrosion damages
- Hit damages or other defects
- Vertical and lateral deformations during train passages
- Dynamic amplification of the static response
- Fracture toughness of the steel
- Possibility that the steel is susceptible to ageing
- Expected lifespan according to a fatigue damage accumulation analysis
- Any visible fatigue cracks

2.2 Results

Among other findings, the major results from the field studies of the riveted railway bridges investigated by our department are:

- No major corrosion damages were found, despite neglected maintenance in some cases.
- No loose or faulty rivets were detected.
- No visible cracks were found.
- The maximum stress in the bridge superstructure was seldom exceeding 42 MPa, when the heaviest freight trains were passing.
- There is a good correspondence between theoretical strain values and the actual strain response.
- The dynamic amplification factor was found to be smaller that what can be assumed.
- Extensive ultrasonic crack controls have been performed, and not in a single case were fatigue cracks detected at or near the rivet holes.
- The fracture toughness of the steel has in general been inadequate with respect to present code requirements.
- The static load-carrying capacity has in many cases shown to be sufficient to carry modern “design traffic”.
- A fairly accurate estimate of the remaining fatigue life has been possible through a thorough study of the loading history. A remaining fatigue design life of 25 years or more has been the result for the bridges which have been analyzed.

2.3 Discussion

The fracture toughness of the steel was generally found to be too low compared with the generally accepted ductility requirements (the only “negative” finding presented above!). If so, why has there not been any brittle fractures? The different possible answers to this question are:

- Low stresses in general (i.e. low probability of a propagating fatigue crack).
- Despite the stress level, the major part of the fatigue life (say 90 - 95 %) is before the initiation of a fatigue crack, and therefore the probability of a brittle fracture during a normal service-life period is negligible.
- The strain rate is low (the fracture toughness increases with decreasing strain rate).

- The plate thicknesses are normally small (thin plates are more ductile than thick plates – and the fracture toughness requirements of today are based on thick plates). A thicker plate can be expected to fail in a more brittle manner due to:

  - a large probability for triaxial stress conditions,
  - large grain sizes,
  - an inhomogeneous and anisotropic material,
  - the size effect,
  - a high residual stress level.

- There is normally no other visible defect in the primary tension members than the rivet holes, and this stress raiser is by no means large enough to be the single cause for the initiation of a brittle fracture.

- The clamping force is introducing a triaxial compressive stress state at the rivet hole which prevents any fracture tendencies.

- A riveted built-up bridge member shows an inherent structural redundancy through "separate part composite action". A propagating crack will, without exception, be stopped when passing from a member part to another.

3. FULL-SCALE FATIGUE TESTS

3.1 Test results

When the old riveted railway bridge over the Vindelälven at Vännäsby (built in 1896) was replaced by the railway authorities in 1993 it was decided that one should take the opportunity to carry out an extensive full-scale fatigue testing programme comprising the stringers and floor-beams from the bridge. In the first series 10 stringers were tested in four-point bending. The stringers were 5,5 meters long (after being flame cut from the bridge) with a depth of 830 mm:

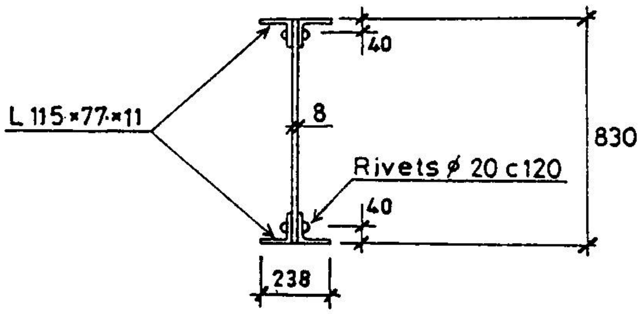

Fig.1 Dimensions of the built-up I-shaped stringers.

The results of the first series in the fatigue testing programme are presented in table 1:

Table 1 Results from the full-scale fatigue testing of the stringers.

Stress range σ_r 1)	Stress Ratio R	Stringer No	Number of cycles		
			Crack detection	Additional cycles	Failure
40 MPa	0.24	6B	-	-	(20 000 000) 2)
40 "	0.24	7A	-	-	(20 000 000) 2)
60 "	0.18	12A	-	-	(10 000 000) 2)
60 "	0.18	12B	-	-	(10 000 000) 2)
80 "	0.14	2A	5 893 350	102 520	5 995 870
80 "	0.14	3B	2 375 500	0	2 375 500
80 "	0.14	5B	6 370 440	114 900	6 485 340
100 "	0.28	4B	1 488 920	148 950	1 637 870
100 "	0.28	5A	2 038 660	146 240	2 184 900
100 "	0.28	10B	2 027 250	0	2 027 250

1) Based on net section area and the stresses are derived at the outermost edge of the beam (i.e. $\sigma_r = M_r/W_{net}$) instead of the actual critical rivet locations.

2) The test was discontinued after a prescribed high number of load cycles.

3.2 Summary

The main findings from the first full-scale fatigue test series of 10 riveted built-up stringers are:

- The fatigue lives of the nine stringers tested were *in accordance* with or *above* the fatigue design curve given in the structural steel codes for riveted details (C = 71 / category D), despite the suffering of almost 100 years of loading!

- The fatigue cracks always started and subsequently propagated in the *lower (tension) flange.*

- The fatigue crack initiations were, in five cases out of six, at a *flange rivet connection* outside the mid-span region. Only in one case was the fatigue crack emanating from a *"neck" rivet hole* in the mid-span region.

- A substantial amount of loading cycles were required to propagate the fatigue crack from one L-profile to the other (in average about 100 000 cycles!). The riveted built-up composite I-beams (i.e. the stringers) thus showed an *inherent structural redundancy.*

- The fatigue cracks were difficult to observe in the beginning of the propagation period. They were *almost invisible to the naked eye* when the stringers were temporarily unloaded.

- The fractured stringers were *capable of carrying a considerable static load* (greater than the maximum load of the fatigue test) after completed cyclic loading.
- A series of tension tests of the steel material showed that the mechanical properties were comparable to a *mild steel* with a yield point higher than many other riveted bridge steels tested.
- A *markedly ageing effect* was found for the steel after cold deformation and subsequent heat treatment.
- A transition temperature of approximately +12 °C was the result of the Charpy-V impact notch testing. This temperature is much above the lowest service temperature.
- A chemical analysis confirmed that we have an ordinary *carbon steel* with a low content of nitrogen.
- The clamping ratio (i.e. rivet clamping stress in relation to the yield stress of the rivet) was found to be 0.42 on an average.
- The fatigue damage accumulated in the stringers was approximately found to be *negligible*.

4. CONCLUSIONS

Both the full-scale fatigue tests and the different field investigations clearly show that there is a substantial remaining fatigue life of typical riveted railway bridges still in use today:

- The full-scale fatigue tests showed that the common fatigue design curve for riveted details is *underestimating* the fatigue lives. However, this curve can be used as a safe estimate of the *remaining* fatigue life of old riveted railway bridges still in service today.
- The different field investigations gave the conclusion that the maximum stress ranges *seldom, if ever, exceed the fatigue limit* for riveted details. The fatigue damage accumulated in the bridges can therefore be assumed to be negligible.

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