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Monitoring and enhanced fatigue evaluation of a steel railway bridge

John Leander [a,*], Andreas Andersson [a,b], Raid Karoumi [a]

[a] *Division of Structural Design and Bridges, Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden*

[b] *Expert and Development Unit, Swedish Rail Administration (Banverket), 172 22 Sundbyberg, Sweden*

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ABSTRACT

During routine inspections of the Söderström Bridge in central Stockholm, one of Sweden's most important railway bridges, cracks were found in the web of the main steel beams. The finding initiated theoretical studies which showed that the cracks developed mainly due to poorly designed connections of the cross beams and out-of-plane bending of the web. The studies also showed an alarming result regarding the remaining fatigue life of the stringers and the cross beams. However, no cracks or other damage have been found on these components during the inspections. To explore the differences between the theoretical indications and the inspected reality, an extensive monitoring program has been performed. This article describes the monitoring program and the analysis methods used. Some results regarding the remaining fatigue life based on measured and theoretical values are presented.

1. Introduction

In recent decades, the traffic loads, volume and speeds on the Swedish railway network have greatly increased due to the demands of the continually growing economy and higher transport efficiency. As a consequence, many existing railway bridges are now subjected to loads and speeds higher than those for which they were designed. It is not possible for economic and environmental reasons to replace all these bridges in the foreseeable future. The assessment of existing bridges is thus a vital task, crucial for the development of rail transportation.

The Söderström Bridge in central Stockholm (Fig. 1), one of Sweden's most important railway bridges, has in theoretical studies [1] shown an alarming result regarding its remaining fatigue life. According to the methods of analysis, the stringers and cross beams have already exceeded their theoretical service life. During inspections, cracks in the web of the main steel beams have been discovered. However, no cracks or other damage have been found on the stringers or cross beams. An extensive monitoring program was designed to enable a thorough analysis of the bridge's true behaviour, as an attempt to clarify the discrepancy between the theoretical calculations and the inspected reality. This article describes the monitoring program and the analysis of the outcome. It also describes a methodology for performing a fatigue life analysis based on measured data.

Testing and monitoring of the actual condition of a structure and its true behaviour are a necessity for an enhanced assessment of a bridge. A monitoring program can be designed to reduce the uncertainties associated with bridge assessment, e.g., the static behaviour, cross section properties, material properties and load. There are many examples where monitoring has been used for bridge assessment. The three references [2–4] describe adequate approaches and results for the present case.

In [2], a procedure for evaluating the fatigue life of existing bridges through field strain measurements is proposed. It is stated that the most accurate way to determine the effect of the live load is to measure the strains in identified fatigue-critical members using strain gauges. Calculated stress ranges with simplified methods and regulated loads and distribution factors tend to result in insufficient remaining fatigue life. No assumptions need to be made regarding uncertainties in load distribution such as unintended composite action between structural components, the contribution of nonstructural members and the stiffness of various connections. A step-by-step procedure for evaluating the remaining fatigue life by strain measurement is outlined. The fatigue assessment is based on the American guidelines AASHTO [5,6].

In [3], an approach using monitored data for the reliability assessment of structural systems is presented. The proposed approach was used on a case study which, in contrast to the case in the present paper, was a bridge under construction during the mounting of the sensors. The possible errors in the measurement equipment and in the management of the same are paid substantial attention. It is stated that possible errors in the measurements must be taken into consideration in the interpretation of the results. A probabilistic assessment focused on the steel yielding and

* Corresponding author. Tel.: +46 8 7907955.
E-mail address: john.leander@byv.kth.se (J. Leander).

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Fig. 1. View of the Söderström bridge and Stockholm old town.

fatigue performance is shown. The fatigue assessment is based on the American guidelines AASHTO [7].

A case study of an existing steel railway bridge is presented in [4]. Monitoring data is used for fatigue life evaluation, for dynamic response analysis and the validation of reinforcement actions. It is shown that the secondary beams (the stringers) run a high risk of fatigue damage. The same scenario is apparent in the studies in the present paper.

The linear accumulation of fatigue damage according to Palmgren [8] and Miner [9] is the most widely used approach for remaining life predictions [10]. Despite its simplicity, the *S–N* curve (stress range versus number of cycles to failure) which is used as the input to these life predictions can include many of the complex factors influencing fatigue behaviour. The linear summation of damage ignores the load sequence and interaction, however, and this is often mentioned as its largest drawback [10–12].

An example of an alternative fatigue damage indicator is presented in [13], calculated with consideration to the loading history and sequence. The fatigue evaluations conducted within the scope of the present paper are done with the concepts of linear cumulation according to Miner [9]. The extensive volume of data is, however, a great asset for future detailed fatigue studies.

In [11], a survey of commonly used approaches for fatigue life prediction is presented. The approaches are divided into two groups based on the theories of cumulative fatigue damage (CFD) and fatigue crack propagation (FCP).

The *S–N* curve approach is assigned to the CFD theory together with, for example, the continuum damage mechanics approach. In [14], a fatigue life evaluation is presented based on monitored values and the continuum damage mechanics approach. The major deficiency of all CFD theories is, according to [11], the lack of a consistent definition of failure. The approaches are to varying extents based on geometrical simplifications and scattered data concerning material, stress state and environmental effects, all of which influence the fatigue life.

The properties of the studied object can more thoroughly be accounted for with the FCP theories, but they also require more input. For the present case, where the aim is to check a large number of sections with different properties, the *S–N* curve approach is considered to be the most appropriate. When the crucial sections are determined, an FCP theory might be used for more detailed fatigue studies.

2. The bridge

The Söderström Bridge in central Stockholm carries the main railway line between the northern and southern parts of Sweden. Its bearing capacity is crucial for freight transport as well as for passenger trains moving into and out of the city of Stockholm. About 520 trains pass over the bridge every day.

The bridge consists of a continuous steel grillage in six spans and has a total length of 190 m, as shown in Fig. 2. It has two tracks with wooden sleepers resting directly on the stringer beams Fig. 3. The supports and cross beams are oriented with a skew angle of 80° to the main beams. The substructure consists of columns on piled concrete slabs. The supports are numbered from 4 to 10 according to the original drawings. The horizontal alignment of the bridge is straight between support number 4 to 7 transcending to a constant radius of approximate 2500 m between support number 7 to 10.

The bridge was built around 1950 and was designed according to the contemporary codes.

About 60% of the traffic passing the bridge today are commuter trains, mostly of the Swedish X60 type (see Fig. 4). Only about 5% of the trains are freight transport with the possibility of high axle loads.

3. Previous theoretical studies

3.1. Fatigue assessment methods

As a consequence of the fatigue cracks encountered in the web of the main beams, theoretical fatigue assessments have been performed, based on the Swedish Regulations for Steel Structures [15] and the Swedish Regulations for capacity assessment of existing railway bridges [16]. Three levels of analysis were performed, hereafter referred to as methods 1 to 3.

Method 1 is the most simplified procedure and may at best serve as an indicator as to whether fatigue may be an issue. The method is frequently used both in the design stage of new bridges

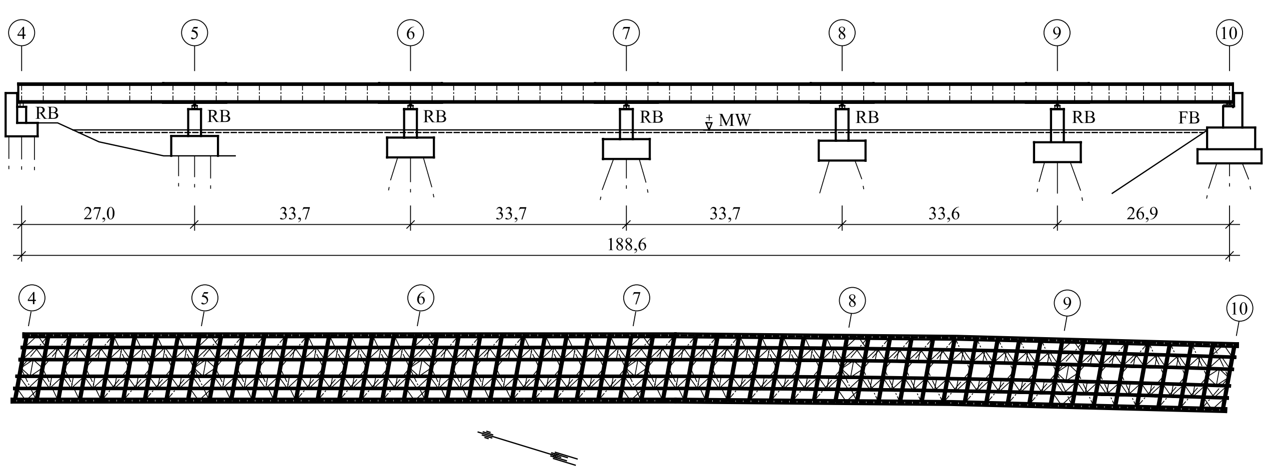

Fig. 2. Elevation and plan of the Söderström bridge. RB indicates roller bearings and FB indicates fixed bearings.