Assessment of the Safety Against Fatigue Failure of Riveted Railway Bridges Based on Fracture Mechanics

Determining the Operating Period of the Elbe Bridge Meissen

Thomas Riedel [1] ✉, *Lars Sieber* [2], *Holger Flederer* [3], *Martin Mensinger* [4], *Ralf Steinhausen* [5]
✉ e-mail: thomas.riedel@deutschebahn.com
[1] DB InfraGO AG
[2] Hochschule für Technik und Wirtschaft Dresden - University of Applied Sciences, Civil Engineering, Laboratory for Structural Engineering, Dresden, Germany
[3] Hochschule für Technik und Wirtschaft Dresden - University of Applied Sciences, Civil Engineering, Chair for Bridge Engineering, Dresden, Germany
[4] Technische Universität München, TUM School of Engineering and Design, Chair for Metal Structures, Munich, Germany
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Abstract The fracture mechanics concept is becoming increasingly important in the assessment of the fatigue safety of historic railway bridges. Compared to the stress-life-concept, the main advantage is that only the current and future traffic loads must be considered. The crack model, fracture-mechanical material parameters and the size of suspected or actual fatigue cracks are other significant factors influencing the fracture-mechanical crack growth calculations. This paper focuses on the characterization of these input variables.

Hot-driven rivets generate a clamping force due to shrinkage during cooling after manufacture. This has the effect of compression stress on the connected parts and has a positive influence on the fatigue behavior of the component. This article presents a crack model for determining the stress intensity factor of riveted components. The model can consider not only the component stress acting orthogonally to the crack plane but also the rivet clamping force acting orthogonally to the sheet metal plane.

The material properties of steels from the first half of the 20th century differ significantly from those of modern structural steels. The results of the Paris-Parameters for crack growth on structural steel St 48 from 1925 are presented.

The fracture mechanics assessment of cyclically loaded structures includes inspections as well as crack growth calculations. In riveted structures, fatigue cracks occur at the point of greatest notch stress, at the edge of the rivet hole. An inspection method has been developed for this area, hidden by the rivet head, which can be used to detect fatigue cracks at a very early stage.

The influence of the three parameters mentioned – crack model, Paris-Parameter, and initial crack

length – on the result of fracture mechanics crack growth calculations is presented using the example of the Elbe-Bridge in Meissen.

1 Introduction

Many railway bridges built in Europe at the beginning of the 20th century are still in operation. As cyclically loaded structures, railway bridges are subject to fatigue loading. Infrastructure operators are required to always ensure the safe operation of the railway infrastructure. In this context, there is an economic need to optimise the timing of bridge replacements and to carry out maintenance in a targeted and efficient manner. The application of appropriate methods for assessing the condition of railway infrastructure is an important basis for this. In addition to the nominal stress concept, the concept of fracture mechanics has become established for assessing the fatigue safety of historic railway bridges. Fracture mechanics can be used to describe the crack growth process and the failure behaviour of cracked components. In this paper, the proof of fatigue safety of an almost one hundred-year-old riveted railway bridge is presented using the fracture mechanics method.

2 The bridge over the Elbe in Meissen

The double-track railway bridge over the Elbe was built in 1925. It consists of two single-track, separate superstructures on solid piers and abutments. The three main spans over the river, each 56.20 metres wide, are built with continuous truss superstructures. The trusses of the main girders have a rhombus shape. The cross girders and stringers are positioned approximately in the centre of the main girder height. Figure 1 shows a sketch of the structure in longitudinal section and Figure 2 a cross-section.

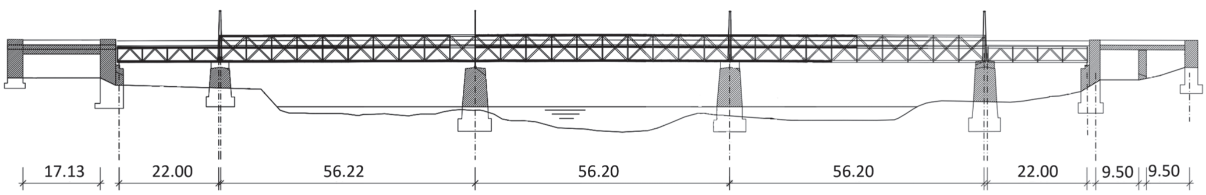


Figure 1: Elbe Bridge Meissen

In 2011, the entire structure was refurbished. The anticorrosive coating of the steel structure was renewed, the steel structure was repaired, and individual highly stressed areas were reinforced.
The cross section of the cross girder as well as the stringer are composed of four flange angles, and a web plate as shown in Figure 2. The bottom chords of the stringers are made from double angles L 90x90x13 mm. They are separated at the cross-member connections. The continuous effect of the stringers is achieved using cover plates. At each crossing point, the cover plates are connected to the bottom chords of the cross girder with four rivets each.

The bending stressed bottom chords of the cross beams in the area of the stringer connections were identified as fatigue-critical details of the structure in an earlier expert assessment [1], [2]. Starting from 2011, a remaining service period of 20 years was determined based on the stress-life-concept. This paper presents the methodology and results of an investigation based on fracture mechanics.

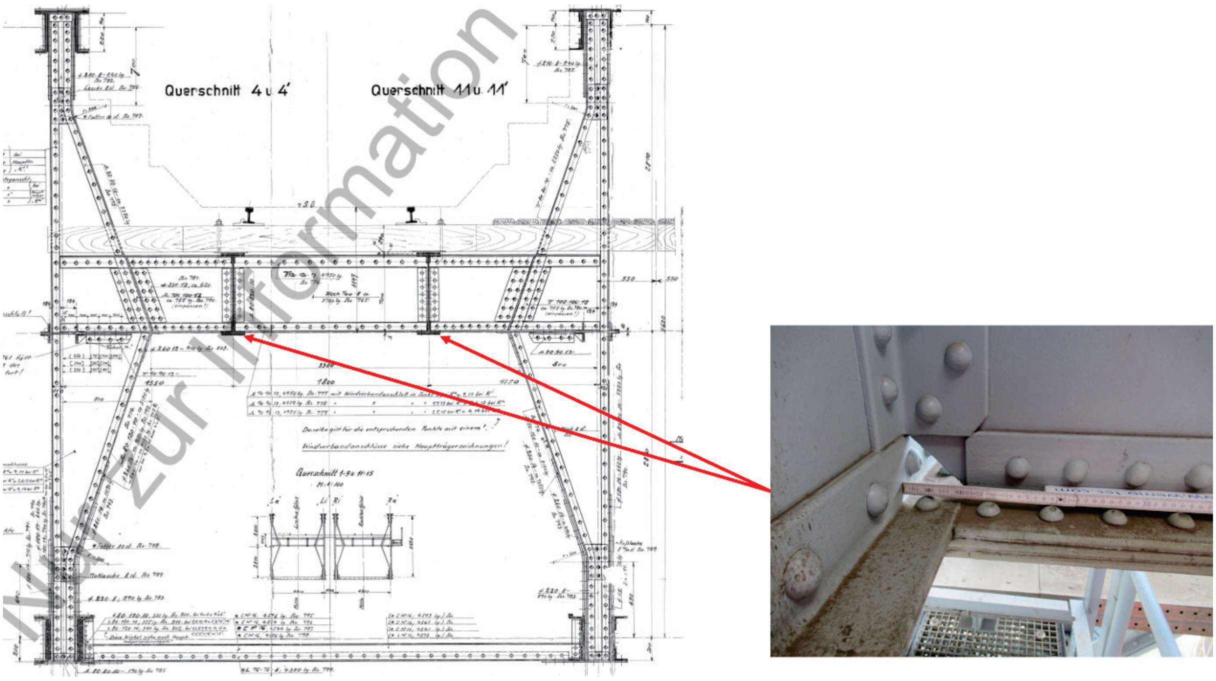


Figure 2: Cross-section of a bridge superstructure

3 Fracture mechanical crack growth calculations

Crack growth in structures under cyclic loading is described by the crack growth law according to Paris / Erdogan [3].

$$\frac{da}{dN} = C_{Pa} \cdot \Delta K^{m_{Pa}} \tag{1}$$

The left side of the equation describes the change in crack depth a over the number of load cycles N and thus corresponds to the crack growth rate. For $N \rightarrow 1$, the change in crack depth is Δa for one load cycle ΔN. The right side contains the cyclic stress intensity factor ΔK as well as the material-specific parameters m_{Pa} and C_{Pa}. It corresponds to the difference in stress intensity for one load cycle.

$$\Delta K = K_{max} - K_{min} \tag{2}$$

The stress intensity factor K is the essential parameter for describing the status of the cracked component when using Linear Elastic Fracture Mechanics (LEFM).

$$K = \sigma_{brut} \cdot \sqrt{\pi \cdot a} \cdot Y \tag{3}$$

The Stress Intensity Factor (SIF) depends on the nominal component stress σ_{brut}, a and the correction function Y. This is used to describe the influence of the component and crack geometry and to take additional influences on the crack tip stress into account.
For many component geometries, the correction function can be taken from the literature [4], [5]. Y is in most cases dependant on the crack depth a. The correction function for determining the rivet clamping effect is explained in more detail as follows.
The influence of the rivet clamping stress on crack growth was investigated both numerically and experimentally in [6]. Figure 3 shows the numerical model of a riveted joint with schematic details of the external stress and the residual stress state due to the rivet clamping effect.

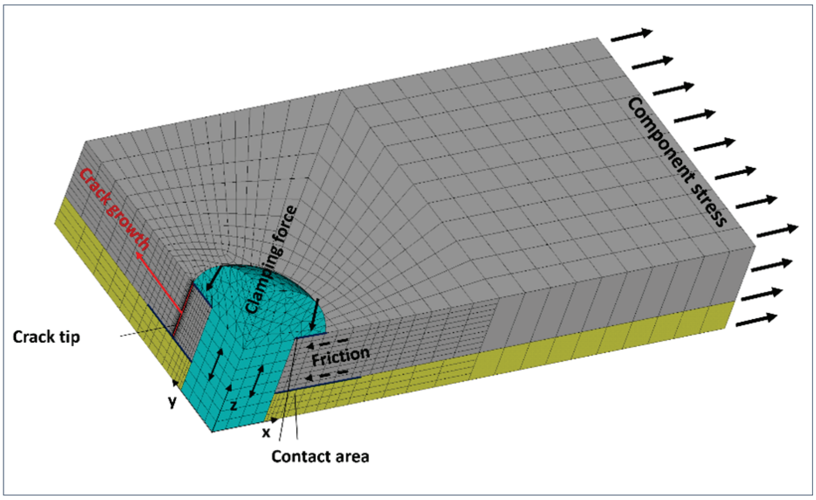


Figure 3: Numerical model of a riveted joint

The compressive stress generated by the rivet clamping in the sheet thickness direction results in additional compressive stress in the sheet plane due to the restricted strain. This is overlaid with the component stress responsible for the crack opening and is directed in the opposite direction. If the crack tip is located within this stress field, the crack tip stress is reduced. The part of the SIF resulting from this effect is referred to below as K_{press}.
The movement of the crack faces during crack opening as a result of cyclic loading causes a tangential stress in the opposite direction on the sheet metal surfaces. The rivet clamping stress and friction have a significant influence on the tangential stress. The restricted crack opening also reduces the stress intensity at the crack tip. The part of the SIF that can be accounted for by this is referred to below as K_{fric}.
The stress at the crack tip according to equation (3) is thus made up of three stress components. K_{geo} results from the holed component geometry (holed sheet metal), K_{press} results from the compressive stress and K_{fric} from the friction between the elements of the cross-section.

$$K = K_{geo} + K_{press} + K_{fric} \tag{4}$$

When using linear elastic fracture mechanics, all three stress components can be determined using the numerical model (Figure 3). The stress component K_{geo} can be determined independently of the above using formulised solutions from the relevant literature [5]. For the case of holed plates, the solution from Führing [7] was used in all calculations.
For typical rivet and component dimensions of riveted joints, the influencing factors Y_{fric} were determined in a parameter study in [6]. Figure 4 contains the calculated data for the sheet thickness t_{plate}=12 mm and hole diameter d_{shank}=20 mm. Y_{fric} is shown as a function of ω and the ratio $(r+a)/W$. The parameter r is the radius of the rivet hole and W is half the model width of the crack model. The parameter ω indicates the ratio of the total tangential force applied to the tangential force that can be transmitted by friction.

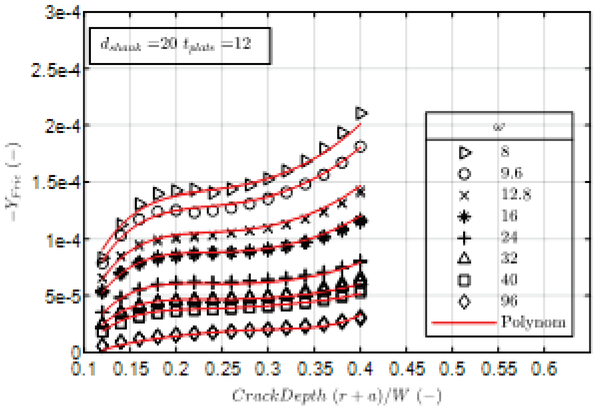


Figure 4: Correction function Y_{fric} for t_{blech}=12 mm and d_{schaft}=20 mm

The presented corrective function for the consideration of rivet clamping is considered in the calculation of crack growth by evaluating equation (1).

3.1 Material characteristics

St 48 was used for the bridge in accordance with the historical documents. As no detailed material properties are documented, extensive material analyses were carried out. The focus of the tests was on the determination of the fracture mechanical material parameters C_{Pa}, the Paris constant and m_{Pa}, the Paris exponent according to equation (1).
The chemical composition was determined using Spark-Optical Emission Spectrometry (OES) to classify the steels and to categorise the material quality. Yield strengths and tensile strengths were also determined.
The tests were carried out on samples from six locations distributed across both bridge superstructures. Table 1 shows the results of the chemical analysis for two representative sampling points.

Given the results of the chemical analyses, it can be assumed that contrary to the information on the as-built plans, the higher-strength structural steel St 48 was not used for all components, but that normal-strength steel St 37 was also used.

Table 1: Results of the chemical analyses

Sample	Chemical composition							
	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Al (%)	Cu (%)	N (%)
DD1 b	0.13	0.007	0.42	0.038	0.063	0.0002	0.22	0.0074
R2 a	0.27	0.250	0.57	0.025	0.032	0.0002	0.24	0.0055

Figure 5 shows the sample distribution of the values for the Paris exponent m_{Pa} determined using crack growth tests according to [8]. The results are based on 18 individual tests. An influence of the material type on the crack propagation behaviour cannot be determined based on the test results.

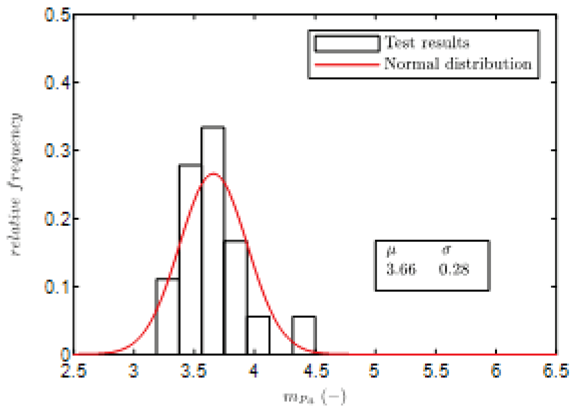


Figure 5: Distribution of the Paris exponent m_{Pa}

In [8] and [6] it was shown that for old steels there is a strong correlation between the Paris parameters C_{Pa} and m_{Pa} of equation (1). The regression relationship is generally described by the following relationship:

$$C_{Pa} = A \cdot \Delta K_0^{-m_{Pa}} \tag{5}$$

A and ΔK_0 are material-specific correlation parameters. They were determined as A=2.13e-5 and ΔK_0= 15.63 for the steel of the Elbe Bridge in Meissen. The correlated values for the sample of the Elbe bridge Meissen are shown in Figure 6.

3.2 Determination of the initial crack depth a_0

The crack growth is usually described for an interval between an initial crack depth a_0 and a final crack depth. Since the latter determines the failure of the cracked component, it is referred to as the critical crack depth a_c.

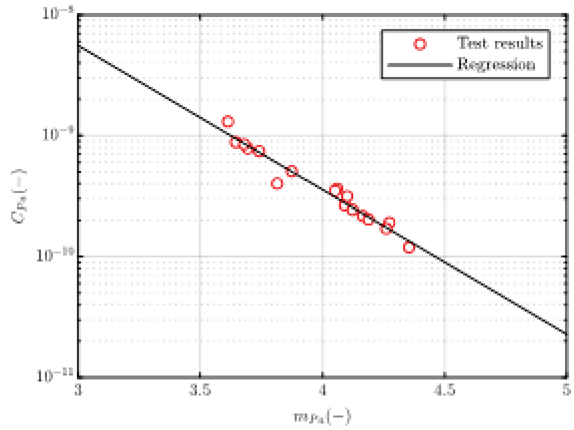
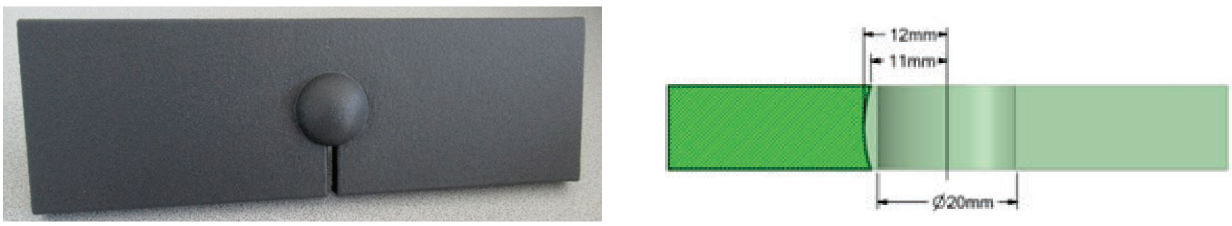


Figure 6: Correlation relationship between the Paris parameters

In the case of the assessment of a structure for which no cracks are known, which occurs predominantly in practice, the initial crack a_0 to be assumed must be selected as being as large as a crack that could have been overlooked during the inspection.
The determination of the initial crack depth is therefore largely dependent on the inspection method used for the bridge assessment.
The time between crack initiation at the edge of the hole until a crack length of detectable size is present is a significant part of the actual remaining service life of the structure. For this reason, the detection of cracks on riveted bridges using phased array ultrasonic was tested and further developed for the application.
As part of the Non Destructive Testing (NDT) investigations, it was first necessary to clarify, which crack size can be detected with certainty at the edge of the hole, considering the specific structural conditions (geometry of the construction detail, coating, accessibility). Following this, all locations of the structure with the fatigue-critical detail had to be checked.
To develop the test concept and validate the test method, six test specimens were prepared as shown in Figure 7, each consisting of a sheet with a hole and a screw with a semi-circular head in it. Cracks with different geometries (corner crack, through thickness crack) were applied under the rivet head.



a) Coated test specimen

b) Cross-section with artificial 'crack'

Figure 7: Test specimens for the process validation of crack detection using phased array ultrasonic

During testing in the structure, no cracks with a crack depth > 1 mm were detected at any of the points characterised as fatigue relevant.

3.3 Rivet clamping forces

Rivet clamping forces cannot be determined non-destructively on the structure. To be able to take rivet clamping forces into account in the crack growth calculation, the statistical evaluation of a large number of experimentally determined rivet clamping forces from various structures is used. Earlier experimentally determined rivet clamping forces are known from the literature by Graf [9], Valtinat [10] and Zhou [11]. Leonetti [12] presented a detailed test programme for determining rivet clamping stresses on components of the Botlek Bridge.
Figure 8 shows the density distribution of the rivet clamping stresses of a joined statistical evaluation with rivet clamping stresses determined experimentally at the University of applied sciences Dresden on components from five different structures. The mean value for the rivet clamping tension is 108 MPa and the standard deviation is 42.5 MPa. A total of 152 individual data points were available.

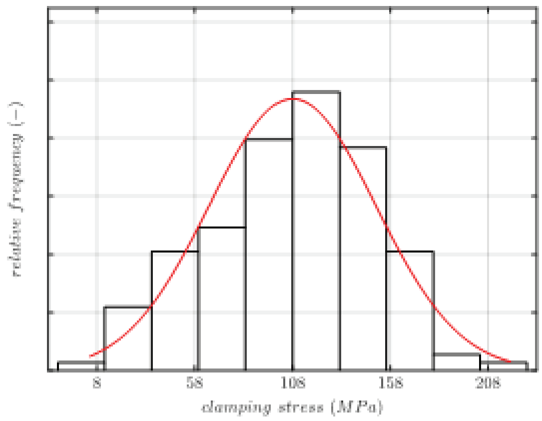


Figure 8: Distribution of the rivet clamping stress

According to the rules of DIN EN 1990 [13], the characteristic value of the rivet clamping stress for rivets with a shank diameter of d_{shank}=20 mm and a shank length of l_{shank}=24 mm was determined to be 66 MPa.

This value applies to hot-driven rivets made of St 34. According to Taras [14], friction forces in riveted joints made of higher-strength materials (St 44, St 48, St 52) should be reduced by a third. As this is the case with the Elbe bridge in Meissen, the reduced rivet clamping force approach is used.

3.4 Results

Using the crack growth law of Paris / Erdogan [3], crack growth intervals are determined for the relevant points in the structure of the Elbe bridge Meissen with the described boundary conditions. Figure 9 shows the calculated crack growth curves.

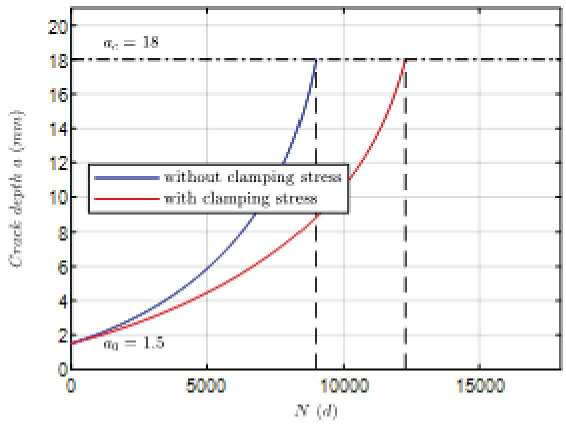


Figure 9: Crack growth curves

Under the current operational load, the period for stable crack growth without reaching the critical crack size is 9002 days (approx. 25 years). Considering the rivet clamping, the crack growth period is 12290 days (approx. 34 years). As there are no signs on the structure that indicate loose rivets, as for example gap corrosion, the author believes that consideration of the rivet clamping force is appropriate.

4 Summary / Conclusions

Riveted bridges still represent a large part of the railway infrastructure in operation. The question of safety against fatigue failure becomes increasingly important as the age of the structures in question increases. The fracture mechanics concept is an effective method of accurately describing the fatigue condition of these structures. This will enable infrastructure operators to make economic decisions about continued operation, replacement, or reinforcement. The consideration of the rivet clamping force in the crack propagation calculation makes it possible to realistically describe the capacity of these structures.

The detectable initial crack size has a significant influence on the result of fracture mechanics calculations. Using the phased array ultrasonic method, it is possible to ensure a detection precision of approx. 1,0 mm for cracks that occur under the rivet head at the edge of the rivet hole.

The example of the Elbe bridge in Meissen has shown that the safe continued use of historic bridge structures is possible with the aid of precise crack detection methods and fracture mechanics assessment.

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