

A Review of International Guidelines for Railroad Bridges Focusing on Fatigue Assessment and Structural Health Monitoring

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ABSTRACT

Most steel bridges designed between the early 19th century and the mid-20th century were built of mild steel plates and profiles with riveted joints. The assessment of existing railroad bridges has become increasingly important in railroad infrastructure management. Many riveted bridge structures have exceeded their original design lifespan, requiring assessment to ensure structural safety and reliability requirements. The remaining fatigue resistance is often a dominant factor during assessment. Since historical construction methods, such as riveting instead of welding, differ from modern techniques, infrastructure operators seek tailored solutions for evaluating these structures. Structural Health Monitoring (SHM) is gaining prominence as a tool for enhancing assessment accuracy and supporting decision-making.

There are already various guidelines from railroad operators available. However, the integration of SHM in these guidelines is very different. Therefore, this study compares different assessing guidelines for existing railroad bridges, focusing on SHM integration and fatigue assessment for riveted steel bridges. The guidelines analyzed in-depth include “DB InfraGO AG. Handbuch 80500 – Tragsicherheit bestehender Eisenbahnbrücken“ (DB InfraGO AG. Manual 80500 – Structural safety of existing railroad bridges), “ÖNORM B 4008-2. Bewertung der Tragfähigkeit bestehender Tragwerke. Teil 2: Brückenbau“ (OENORM B 4008-2. Assessment of the load-bearing capacity of existing structures. Part 2: Bridge construction), and “Berliner Verkehrsbetriebe. Richtlinie zur Bewertung der Ingenieurbauwerke im Bereich der U-Bahnanlagen der Berliner Verkehrsbetriebe“ (Berlin transport company. Guideline for the assessment of engineering structures in the subway system of the Berlin transport company), additionally a US guideline will partly be considered. The comparison identifies differences, similarities, and gaps in current reassessment methodologies, particularly in fatigue assessment approaches and SHM applications. These results may form the basis for the development of harmonized recommendations for assessment of existing riveted railroad bridges.

INTRODUCTION

Many riveted steel bridges were constructed in the early 20th century and have now surpassed their originally intended design lifespans [1]. Nevertheless, considerations regarding sustainability, economic efficiency, and heritage preservation increasingly drive the need to extend the service life of these structures [2]. Achieving this goal requires reliable methods for assessing load-bearing capacity and remaining service life. The complexity is increased by material degradation and evolving safety standards.

Various guidelines developed by railroad operators provide frameworks for evaluating existing bridges. However, the extent to which Structural Health Monitoring (SHM) systems are integrated into these assessment processes varies widely, especially concerning fatigue evaluation in riveted steel bridges. In light of this, the present study compares different guidelines for the assessment of existing riveted railroad bridges, with a special focus on SHM integration and fatigue assessment. Guidelines analyzed in detail include Manual 80500 [3] of the German Federal Railways (DB), the Austrian standard OENORM B 4008-2 [4], a guideline from the Berlin transport company (BVG) [5] and the Manual for Railway Engineering [6] from the American Railway Engineering and Maintenance-of-Way Association (AREMA).

DB has established a comprehensive framework for the structural assessment of existing railroad bridges in Germany, applicable to bridges older than six years within the national railroad network. OENORM is an Austrian standard for the assessment of load capacity of existing bridges. BVG developed a guideline for the assessment of existing engineering structures with an age of at least six years within the public subway system of Berlin. The guidelines refer to the Eurocodes, which are European standards for design in the construction industry. AREMA is an American professional association that publishes recommended practices for railroad engineering infrastructure.

Since the remaining fatigue life is often a dominant factor during structural assessment [7], this paper focuses on the fatigue assessment of riveted steel bridges used in the different guidelines. Additionally, the integration of Structural Health Monitoring in the guidelines to support the fatigue assessment is investigated.

FATIGUE ASSESSMENT OF RIVETED STEEL BRIDGES

Fatigue Assessment in different Guidelines

All guidelines compared provide several different methods for fatigue assessment, see *Table I*. The complexity of the fatigue assessment methods increases from the top to the bottom of the table. The fatigue assessment methods can be divided into basic methods with little time required for calculation and advanced methods leading to improved results. Basic methods include no fatigue verification, fatigue strength verification and the estimation of remaining service life. The calculation of remaining service life and the determination of a service interval based on fracture mechanics are considered advanced methods.

No fatigue verification, according to DB, is required for steel railroad bridges with a service life of less than 60 years with sufficient structural safety in a good structural condition. BVG claims fatigue verification for existing steel bridges older than 30 years. Based on AREMA, for bridges with a traffic volume of less than 5 million tons per year

TABLE I. FATIGUE ASSESSMENT IN DIFFERENT GUIDELINES

	DB [3]	OENORM [4]	BVG [5]	AREMA [6]	Increasing complexity →
No fatigue verification	X	-	X	X	
Fatigue strength verification	X	-	X	-	
Estimation of remaining service life	X	-	-	-	
Calculation of remaining service life	X	X	X	X	
Determination of a service interval based on fracture mechanics	X	X	X	-	

of usual North American mixed traffic, a fatigue assessment is waived. A fatigue assessment is not necessary, referring to AREMA, if the construction detail meets certain design criteria.

A fatigue strength verification is allowed by DB and BVG. As stated by DB the fatigue strength is verified, if the stress ranges due to past and future loads, considering the dynamic coefficient, are below the value $\Delta\sigma_D = 50 \text{ N/mm}^2$. BVG requires 1.2 times the maximum stress range due to past and future operating loads, considering the dynamic coefficient, to be lower than the fatigue strength at five million cycles without additional safety factors for fatigue strength verification.

An estimation of the remaining service life of at least 30 years is permitted by DB, if the fatigue-relevant capacity value complies with a certain limit value.

A calculation of remaining service life based on the nominal stress range concept is included in all guidelines and is analyzed in detail in the following section.

The determination of a service interval based on fracture mechanics is covered by DB, OENORM and BVG. In compliance with DB and BVG the determination of a service interval is necessary, if the calculation of remaining service life returns a limited remaining service life of at most 15 years.

Calculation of remaining service life

Since a calculation of remaining service life based on the nominal stress range concept is covered by all guidelines, this concept is analyzed in detail.

As stated by AREMA, the combination of the design stress range and the total number of variable stress cycles has to be lower than the fatigue limit for the fatigue detail. The design stress range, according to AREMA, can be calculated by using a modified live load for fatigue design, which is increased by a fatigue design impact based on member type. Alternatively, the design stress range can be computed taking into account the past and future traffic loads.

DB, OENORM and BVG follow a similar concept for the calculation of remaining service life based on the Miner rule. To determine the remaining service life the remaining damage capacity for further operation based on the accumulated damage in the past D_{past} is divided by the annual accumulated damage in the future $D_{y,fit}$. From this value,

the difference between the year of calculation Y_{calc} and a reference year Y_{ref} is subtracted. The remaining service life R in years [a] can be expressed by [5]:

$$R = (1 - D_{past})/D_{y,fut} - (Y_{calc} - Y_{ref}) \quad [a] \quad (1)$$

In contrast to DB and BVG, OENORM differentiates between a simplified verification method based on the Eurocode collective coefficients and a verification method using collective coefficients of the past. Unlike the other guidelines, the DB employs a safety factor in the calculation of remaining service life. While DB and BVG limit the calculated remaining service life to 50 years, OENORM does not define a limit for the calculated remaining service life.

DETERMINATION OF THE ACCUMULATED DAMAGE IN THE PAST

The calculation of remaining service life includes the accumulated damage in the past. To emphasize the differences in the calculation, the equations used in the guidelines to determine the accumulated damage in the past are compared (*Table II*).

The term in parentheses is similar in all guidelines and comprises the dynamic coefficients φ and φ_2 , the maximum stress ranges $max\Delta\sigma_{LM71}$, $\Delta\sigma_{71}$ and $max\Delta\sigma_U$ as well as the fatigue strengths $\Delta\sigma_c$ and $\Delta\sigma_{Be,\kappa}$. As stated by DB and OENORM the dynamic coefficient and the maximum stress range for railroad loads from usual traffic on main lines according to Eurocode 1 are used. The BVG defines specific dynamic coefficients for the subway system of Berlin. According to BVG, the maximum stress range for a particular subway load model is applied. All guidelines indicate fatigue strengths at two million cycles.

For the calculation of the accumulated damage in the past in accordance with OENORM, partial safety factors according to Eurocode 3 are used, while DB and BVG do not consider partial safety factors.

In OENORM a damage equivalence factor λ_{old} , according to Eurocode 3, is employed, which considers span, traffic type and volume, service life and number of tracks. In contrast, a damage factor and various correction factors are used in the guidelines of DB and BVG. The damage factor depends on the traffic type, line type and the decisive length. DB additionally differentiates damage factors for single-span and continuous girders. The correction factors take into account the year of construction of the bridge, the annual traffic volume and the loading of multi-track superstructures. DB also takes into account a correction factor considering the local speed of the trains.

TABLE II. DETERMINATION OF THE ACCUMULATED DAMAGE IN THE PAST IN DIFFERENT GUIDELINES

DB [3]	
$D_{past} = \rho_1 \cdot \rho_2 \cdot \rho_3 \cdot \rho_4 \cdot \alpha \cdot [(\varphi \cdot max\Delta\sigma_{LM71})/\Delta\sigma_c]^5$	(2)
OENORM [4]	
$D_{past} = (\gamma_{FF} \cdot \gamma_{Mt})^5 \cdot [(\lambda_{old} \cdot \varphi_2 \cdot \Delta\sigma_{71})/\Delta\sigma_c]^5$	(3)
BVG [5]	
$D_{past} = \rho_1 \cdot \rho_2 \cdot \rho_3 \cdot \alpha \cdot [(\varphi \cdot max\Delta\sigma_U)/\Delta\sigma_{Be,\kappa}]^m$	(4)

DETAIL CATEGORIES AND FATIGUE STRENGTH

A factor influencing the accumulated damage is the fatigue strength of the component, which is described by the Detail Category for fatigue. All guidelines distinguish between different Detail Categories and provide an assignment of construction details to the Detail Categories. The fatigue strengths at two million cycles are specified in the guidelines and are compared below for a stress ratio of $\kappa = 0$. The stress ratio κ is calculated by dividing the minimum stress σ_{min} by the maximum stress σ_{max} from the permanent load and the most unfavorable live load including the dynamic coefficient [4].

DB and OENORM provide information on the fatigue strength of rivets in single or double shear joints that are subjected to shear stress. While OENORM defines a shear stress range of $\Delta\tau_c = 140 \text{ N/mm}^2$, the shear stress range of DB is between 77 N/mm^2 and 133 N/mm^2 , depending on the material. There is no information on shear stress range in the guidelines of BVG and AREMA.

DB and BVG specify fatigue strengths for base material and perforated components subjected to bending or longitudinal force. Both guidelines define the same fatigue strengths depending on the material. For steel St 52 (yield stress approx. 355 N/mm^2), DB specifies higher fatigue strengths than BVG. AREMA defines a fatigue strength of 165 N/mm^2 (24 ksi) for base material, which corresponds approximately to the fatigue strength of St 37 (yield stress approx. 235 N/mm^2) or mild steel produced after 1900 as a base material, given by DB and BVG. AREMA sets the fatigue strength of perforated components to 69 N/mm^2 (10 ksi). This value is below the fatigue strengths of perforated components identified by DB and BVG.

According to DB, the fatigue strength of bolted or riveted components subjected to bending or longitudinal force amounts to 58 N/mm^2 or 100 N/mm^2 , depending on the material. AREMA specifies a fatigue strength of connections with rivets of 69 N/mm^2 (10 ksi) or 90 N/mm^2 (13 ksi), depending on slip resistance, stress range and material.

OENORM and BVG provide specific information on the fatigue strengths for certain riveted construction details. The construction details comprise a symmetrical joint with splice plates, a bending beam with a continuous connection of the flange angles with the web and cover plates, the connection of a lateral bracing element to the tension flange of a girder and the onset of a cover plate. The connections of truss members are a construction detail for which only BVG specifies fatigue strengths. OENORM also contains fatigue strengths for latticed members under tension or compression loads and a one-shear joint with gusset plates. As stated by OENORM and BVG the fatigue strength of riveted components depends on the construction detail as well as the material and ranges from 58 N/mm^2 to 127 N/mm^2 .

FACTORS INFLUENCING THE FATIGUE STRENGTH

In addition to the Detail Category all guidelines take into account the material properties as a factor influencing the fatigue strength. DB differentiates between wrought iron and mild steel produced before 1900, St 37 and mild steel produced after 1900, St 48 (yield stress approx. 312 N/mm^2) as well as St 52. A similar classification can be found in the guideline of BVG, in which, in contrast to DB, the fatigue strength for St 48 and St 52 is identical. According to DB and BVG, the fatigue strength increases from steel produced before 1900 to steel produced after 1900 and from St 48 to St 52. OENORM defines a fatigue strength for wrought iron and mild steel produced before

1900 and specifies a combined fatigue strength for mild steel, St 37, St 48 and St 52. For a stress ratio of $\kappa = 0$, the fatigue strengths stated by OENORM are the same for all specified materials. AREMA gives specific information on the fatigue strength of wrought iron riveted connections. For different steels than wrought iron AREMA defines the same fatigue strength. The fatigue strength of different steels can be greater than that of wrought iron, which correlates with the specifications of DB and BVG.

DB, BVG and OENORM account for the influence of the mean stress on the fatigue strength by including the stress ratio κ . The fatigue strength declines in all guidelines with an increasing value of the stress ratio from $\kappa = -1.0$ to $\kappa = 1.0$. There are deviations between the fatigue strengths in the different guidelines when the stress ratio is taken into account. While DB specifies shear stress range as a function of the stress ratio, OENORM does not consider the influence of the stress ratio on the shear stress range.

For certain construction details, OENORM considers the influence of the type of load transfer mechanism in the connection on the fatigue strength. By analyzing the slip resistance, OENORM distinguishes between connections with a load transfer mechanism through shear stress and local stress concentration at the rivet hole as well as friction joints with slip resistance. If the shear stress per rivet is below the minimum value of slip resistance, the load is transmitted by clamping stresses in the rivet as a slip-resistant friction joint [4]. Therefore, the construction detail can be classified in a higher Detail Category. For a shear stress per rivet exceeding the minimum value of slip resistance, the load is transmitted through shear stress and local stress concentration at the rivet hole and the connection has a lower fatigue strength [4]. AREMA differentiates between normal and low slip resistance depending on the fabrication of the rivet holes (e.g. drilled or punched). For rivets with low slip resistance the fatigue strength is lower than for connections with a normal slip resistance. That concept corresponds to the influence of the type of load transfer mechanism in the connection on the fatigue strength described in OENORM.

When applying the Detail Categories for connections with rivets that have normal slip resistance, AREMA distinguishes between different stress ranges. For higher stress ranges AREMA determines a lower fatigue strength.

STRUCTURAL HEALTH MONITORING APPLICATIONS

Structural Health Monitoring (SHM) is gaining prominence as a tool for enhancing assessment accuracy and supporting decision-making. In general, it helps to determine the actual stress range in the component and it allows to estimate the loading in history and future. A permanent SHM allows the tracking of degradation over time of structures. Contrary SHM can provide an experimental assessment of the load-bearing capacity of a structure. *Table III* shows various applications of SHM in different guidelines.

DB and BVG make a distinction between static and dynamic measurements, contingent on the type of load. According to DB, static measurements are carried out in case of uncertainties regarding stress distribution and structural model under quasi-static traffic loads. Dynamic measurements are used to determine the dynamic loads as well as the dynamic behavior of the structure and are conducted with moving traffic loads [3].

Regarding the measurement period, BVG distinguishes between system identification and permanent measurements. For system identification short-term measurements under defined operating loads are conducted to improve the structural model [5]. As part

TABLE III. STRUCTURAL HEALTH MONITORING APPLICATIONS
IN DIFFERENT GUIDELINES

	DB [3]	OENORM [4]	BVG [5]	AREMA [6]
Experimental assessment of system behavior	X	X	X	X
Structural assessment based on measured values	X	X	X	X
Experimental assessment of load-bearing capacity	-	X	-	-
Permanent structural monitoring	-	X	X	-

of permanent measurements, the measured variables are recorded over a longer period of time. Permanent measurements are used to determine statistical data on actions and to monitor the load-bearing behavior, particularly with regard to structural changes [5].

An experimental assessment of the system behavior is included by all of the guidelines. This involves a comparison of the calculation results with the actual structure, whereby the calculation model of the structure is validated.

The structural assessment based on measured values is covered by all guidelines. For this purpose, the actual load-bearing behavior is recorded by measurement and the structural model is then calibrated using the measurement data.

An experimental assessment of the load-bearing capacity by means of load tests above the service load level, is permitted by OENORM, if sufficient load-bearing capacity cannot be verified by calculation. The permissible service loads result from the load level achieved in the load test and safety factors [4].

Permanent structural monitoring, in accordance with OENORM and BVG, can be carried out for structures with endangered safety. This includes an alarm trigger and an action plan if limit values are exceeded [4; 5].

DISCUSSION AND CONCLUSIONS

Fatigue assessment of riveted steel bridges in the different guidelines is based on common concepts. However, the fatigue assessment methods differ in detail leading to specific results for each guideline. While DB offers a great range of fatigue assessment methods, OENORM focuses on advanced fatigue assessment methods. BVG and AREMA provide basic methods like no fatigue verification and advanced methods as the calculation of remaining service life.

The calculation of remaining service life in all guidelines is based on the nominal stress range concept. AREMA takes into account the design stress range and the total number of variable stress cycles to verify the fatigue strength. DB, OENORM and BVG determine the remaining service life based on the accumulated fatigue damage using the Miner rule. To evaluate the calculated remaining service lives, the guidelines should be applied to representative bridge examples. The accuracy of the calculated remaining service lives can be assessed by comparing them with test results.

For the determination of the accumulated damage in the past DB and OENORM as national guidelines refer to Eurocode regarding the dynamic coefficients and the load

model. In contrast, BVG defines specific dynamic coefficients and a load model for the subway system of Berlin. Despite OENORM employs a damage equivalence factor, when DB and BVG use a damage factor and various correction factors, the factors consider similar parameters such as span, traffic type and volume, year of construction and the number of tracks.

Regarding Detail Categories and fatigue strength, DB and AREMA define fatigue strengths for riveted components in general, while OENORM and BVG deliver information on the fatigue strengths of specific riveted construction details. By defining fatigue strengths for certain riveted construction details, in contrast to DB and AREMA, an assignment of the examined riveted connection to a specific riveted construction detail is necessary. That leads to a greater range of fatigue strengths for riveted components in OENORM and the guideline of BVG.

As a factor influencing the fatigue strength OENORM and AREMA take into account the influence of the type of load transfer mechanism in the connection. Here the slip resistance, which depends on the clamping stress in the rivet, is an important factor. The clamping stress in rivets is strongly influenced by the manufacturing process. Due to the manual execution of the riveting process the clamping stress scatters. An effect of the clamping stress is the reduction of the local stress at the rivet hole, which leads to a higher fatigue strength [7]. Since the clamping stress can only be determined indirectly, it is challenging to estimate the clamping stress in the rivets and specify the actual fatigue strength.

Structural Health Monitoring applications, that are part of all guidelines, are the experimental assessment of system behavior and the structural assessment based on measured values. These applications provide the opportunity to enhance the assessment accuracy. With the experimental assessment of the load-bearing capacity and a permanent structural monitoring, OENORM provides a framework for structures with no sufficient calculated load-bearing capacity and endangered safety.

In general, the guidelines refer to Structural Health Monitoring as a method rather than providing a concept on how to use measured values in structural assessment. Therefore, it is necessary to incorporate concepts for fatigue assessment based on measured values into these guidelines.

REFERENCES

1. Kühn, B. et al. (2008) *Beurteilung bestehender Stahltragwerke: Empfehlungen zur Abschätzung der Restnutzungsdauer* in: *Stahlbau* 77(8):595–607, doi:10.1002/stab.200810072.
2. Kuhlmann, U. [Ed.] (2022) *Stahlbau Kalender – Türme und Maste, Brandschutz*. Berlin: Ernst & Sohn.
3. DB InfraGO AG (2024) *Handbuch 80500 - Tragsicherheit bestehender Eisenbahnbrücken*.
4. ÖNORM B 4008-2 – *Bewertung der Tragfähigkeit bestehender Tragwerke - Teil 2: Brückenbau*, Nov. 2019.
5. Berliner Verkehrsbetriebe (BVG) (2023) *Richtlinie zur Bewertung der Ingenieurbauwerke im Bereich der U-Bahnanlagen der Berliner Verkehrsbetriebe*.
6. American Railway Engineering and Maintenance-of-Way Association (AREMA) [Ed.] (2023) *Manual for Railway Engineering*.
7. Unterweger, H.; Derler, C. (2021) *Ermittlung von Inspektionsintervallen für Rissprüfungen an historischen genieteten Eisenbahnbrücken auf Basis der Bruchmechanik – Teil 1* in: *Stahlbau* 90(4):290–304, doi:10.1002/stab.202100004.