

Riveted Railroad Bridge under Dynamic Load

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Abstract:

Bridges are a fundamental component of a nation's critical infrastructure. In Germany, a considerable number of railway bridges are in poor to very poor condition. Due to the advanced age of many structures, specific characteristics such as aged steel materials and riveted connections are common, particularly in historic railway bridges. These features necessitate detailed structural assessment.

As part of the research project RISK.twin – Intelligent Critical Technical Infrastructure [1], experimental investigations are being carried out at the Institute of Structural Engineering at the University of the Bundeswehr Munich (UniBw M) on a dismantled railway underpass. This paper presents the experimental setup and provides insights into failure mechanisms and damage development. In addition, the test structure is compared with data from operational railway bridges to place the experimental findings in a broader context.

Keywords: Railway bridge, Fatigue, Damage progress, Brittle failure

1 Introduction

The stock of bridges of Deutsche Bahn still includes a considerable number of historic railway bridges that remain in service. An analysis of existing documentation indicates that approximately 45% of these structures (as of 2019) were constructed before 1940. The average service life of steel bridges currently stands at 81 years [2]. Most of these bridges were built using cast iron, wrought iron, or mild steel. Prior to the widespread use of welding techniques in the 1950s, riveting was the dominant method for joining iron members in railway bridge construction.

Due to increasing traffic volumes and higher axle loads, these bridges have been subjected to significantly greater demands than originally anticipated, accelerating their aging processes. While some older steel structures are considered brittle and potentially prone to failure, no bridge collapses have been reported to date.

Nevertheless, many of these bridges no longer fully meet the requirements imposed by modern standards like [3], particularly with respect to fatigue strength and expected service life. Despite these challenges, a significant number of historic bridges have remained in excellent condition over the decades. Efforts to keep them in service are driven not only by economic considerations but also by ecological factors, provided that their structural integrity and safety can be ensured. Furthermore, some of these historic bridges are of high technical value and should be preserved as important engineering monuments.

To improve the understanding of failure mechanisms and to assess the remaining service life of a historic railway bridge, a dedicated test facility was established at the University of the Bundeswehr Munich. This facility allows full-scale testing of historic bridges without structural limitations, providing valuable insights into their structural behavior and long-term durability.



(a) View from above



(b) View from below

Figure 1: Bridge Gau-Algesheim before dismantling

2 The test facility for full scale bridge testing at UniBw M

2.1 The riveted bridge Gau-Algesheim

The historic bridge from Gau-Algesheim station, used for the experimental investigation, was constructed in 1903 and remained in service for over a century before being dismantled in 2020. Gau-Algesheim is located on the railway line between Mainz and Cologne, one of the busiest railway corridors in Germany. The underpass served as an access for passengers to reach the various platforms (Figure 1).

Over the decades, the bridge carried both heavy freight trains and high-speed passenger trains. The structure is a half-through construction made of casted iron. It consists entirely of angle sections and flat plates, some of which are riveted together in multiple layers. The bridge spans 4.8 meters and has a width of 3.0 meters. The curved steel plates are also riveted to the transverse connection beams. In its operational state, ballast, sleepers, and rails were placed directly on top of the curved steel plates [4].

2.2 The test facility

The test facility shown in Figure 2, located at the University of the Bundeswehr Munich, enables both static and dynamic investigations on full-scale bridge structures under controlled laboratory conditions.

For static testing, vertical loads can be applied precisely at mid-span, allowing for accurate measurement of bridge deflection and subsequent determination of global stiffness.

Dynamic testing is performed using a combination of static ballast and a centrally positioned unbalanced vibration exciter, simulating the dynamic effects of passing trains. To match the structural response to realistic conditions, steel plates are added (Figure 2), reducing the natural frequency of the bridge from approximately 40 Hz to 12 Hz. This adjustment is essential, as the vibration exciter operates at a maximum rotational speed of 1000 rpm [5]. The excitation frequency can be continuously adjusted to match the bridge's natural frequency. When resonance is achieved, the vibration amplitude reaches its maximum [6]. The excitation force can be controlled by varying the unbalanced mass of the exciter. At resonance, vibration amplitudes equivalent to those induced by real train crossings can be generated with minimal energy input. The setup offers an optimal configuration, providing excellent accessibility, flexible load application, and well-defined support conditions, ensuring reproducible and representative test results.



Figure 2: Test setup of riveted bridge

The secured environment on the campus of the University of the Bundeswehr Munich offers advantages for experimental investigations on full-scale bridge structures. In contrast to tests on in-service bridges, the facility enables comprehensive testing without operational constraints. Entire original bridges can be examined up to their ultimate failure without compromising passenger safety or interfering with railway operations. This setting allows for controlled progression of damage and facilitates detailed observation of failure mechanisms under realistic boundary conditions. Furthermore, the test setup enables accurate determination of the remaining service life and provides valuable insights into structural behavior beyond standard design limits. Since the experiments can be continued up to the point of complete collapse, they offer a rare opportunity to study the full failure process of historic bridge structures under defined load conditions [4].

Another significant advantage of the test bridge lies in the unrestricted instrumentation possibilities. Sensors can be installed at any desired location, including areas that require removal of protective coatings—something typically not feasible on operational bridges. The test specimen is equipped with a comprehensive sensor system. Strain gauges are positioned at the midspan of each main girder to monitor local elongations under load. A displacement sensor is mounted at the center of the bridge span to measure vertical deflections and determine vibration amplitudes. In addition, numerous accelerometers are distributed across the structure to capture dynamic responses during excitation. The collected data allow for precise monitoring of the loads acting on the bridge and provide a basis for assessing structural behavior under both static and dynamic conditions.

3 Result of experimental investigations

3.1 Fatigue test in original condition

The simulation of train crossings was achieved by combining static ballast and an unbalanced vibration exciter. The ballast served a dual purpose: it established a mean stress state in the structure and lowered the natural frequency of the bridge to match the operational range of the exciter. Under resonance conditions, the resulting vibration amplitudes were equivalent to those induced by actual train passages.

A total of five million load cycles were applied, corresponding to the fatigue strength threshold as defined in [8]. During the test, a vertical deflection amplitude of 3.1 mm was measured at mid-span. The experimentally induced strain levels were recorded using strain gauges and confirmed by analytical calculations. As shown in Figure 3 and determined from equations (1.1) and (1.2), the stress amplitude at the central cross girder reached 51.0 MPa. At the longitudinal main girder, which runs along the length of the bridge, a stress amplitude of 25.2 MPa was observed, as illustrated in Figure 3 and derived from equations (2.1) and (2.2). These results demonstrate that the test conditions effectively replicate realistic dynamic loading scenarios and enable the evaluation of the fatigue behavior of historic riveted bridge structures.

In addition to the laboratory investigations, in-situ measurements were carried out on a similar riveted railway bridge located within the active rail network. The bridge features comparable structural design, age, and span length to the test specimen used in the experimental setup. During the monitoring campaign, various train types were recorded, including freight trains, high-speed ICE trains, and regional passenger trains. The stress levels induced by heavy freight traffic reached values comparable to those observed in the laboratory tests, with maximum stress amplitudes of up to 50 MPa at the central cross girder. In contrast, passenger trains—both regional and high-speed—generated significantly lower stress levels within the structure [10]. These field measurements confirm the relevance of the experimental loading scenarios and support the transferability of the laboratory findings to actual operating conditions of historic riveted railway bridges.

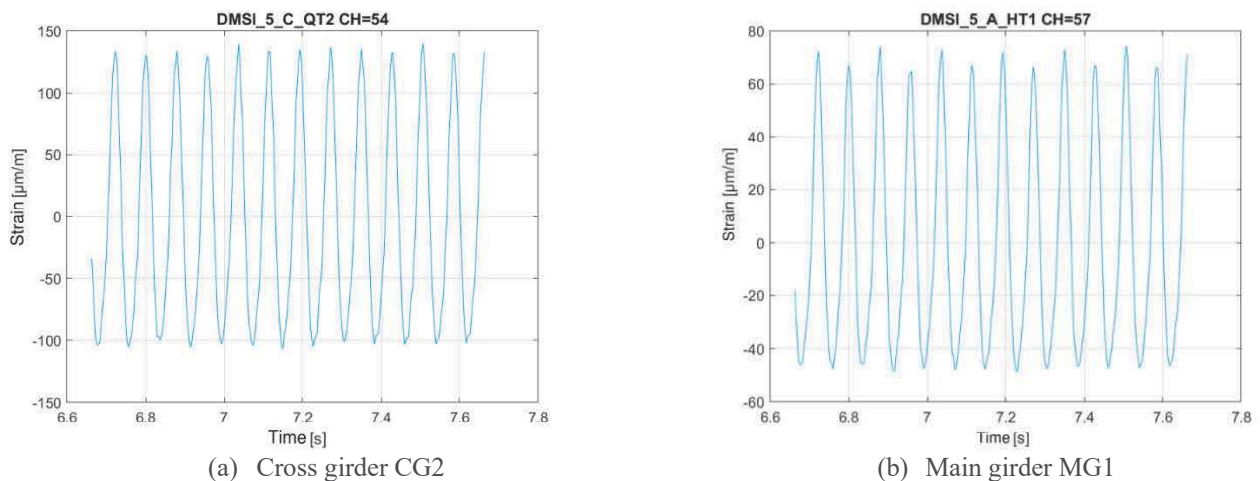


Figure 3: Strain measurement during dynamic test

Cross girder 2 (CG2)

$$\Delta\varepsilon_{CG2} = 140 \mu\text{m/m} - (-103 \mu\text{m/m}) = 243 \mu\text{m/m} \quad (1.1)$$

$$\Delta\sigma_{CG2} = \Delta\varepsilon_{CG2} \cdot E = 243 \mu\text{m/m} \cdot 210.000 \text{ MPa} = 51 \text{ MPa} \quad (1.2)$$

Main girder 1 (MG1)

$$\Delta\varepsilon_{MG1} = 73 \mu\text{m/m} - (-47 \mu\text{m/m}) = 120 \mu\text{m/m} \quad (2.1)$$

$$\Delta\sigma_{MG1} = \Delta\varepsilon_{MG1} \cdot E = 120 \mu\text{m/m} \cdot 210.000 \text{ MPa} = 25,2 \text{ MPa} \quad (2.2)$$

Throughout the course of the five million load cycles, no damage was detected on the tested riveted bridge structure. Neither crack initiation nor loose rivets or other structural deficiencies were observed during or after the test. In contrast, the test rig itself experienced multiple mechanical failures and had to be repaired repeatedly over the duration of the experiment, indicating the high mechanical demands imposed by the long-term dynamic loading.

The results provide strong evidence that riveted bridges constructed from historic materials are not inherently prone to fatigue cracking or brittle failure, even when subjected to a high number of load cycles under realistic service conditions. These findings underscore the potential for continued safe use of historic riveted bridge structures, provided that their structural integrity is verified and maintained through appropriate assessment and monitoring strategies.

3.2 Fatigue test with artificially introduced damage

Following the successful completion of five million load cycles without the occurrence of visible damage, targeted modifications were made to the test setup to further investigate the fatigue behavior under altered boundary conditions. To reduce system damping, the original concrete ballast blocks were replaced with welded steel plates. The concrete elements had introduced significant damping due to friction and movement at the joints. Additionally, the blocks had sustained damage during earlier test phases. The welded steel plates significantly lowered the system's damping, resulting in more stable vibration amplitudes over longer periods under constant excitation power.

As naturally occurring imperfections from over 100 years of in-service use showed no influence on the fatigue strength, artificial pre-damaging measures were introduced in the subsequent test phases. These were carried out in several steps, beginning with partial cross-section weakening.

In the first phase, two rivets were removed at critical locations. One of the resulting rivet holes was closed using a preloaded bolt to simulate thermal prestress, which is relevant to fatigue behavior [7]. Furthermore, semicircular notches with diameters of 0.9 mm and 2.3 mm were milled into the bottom plate of the central cross girder, which is composed of angles and profile sections (see Figure 4).

In the second phase, controlled damage was introduced in the form of welds: one longitudinal weld limited to the central region, and one transverse weld extending across the full width of the girder. Given that the material under investigation was wrought iron—a historical material with a high carbon content—its poor weldability posed a challenge. The heat input during welding presented a risk of embrittlement in the heat-affected zone.

To monitor damage evolution, all artificially introduced flaws were examined every 100,000 load cycles using magnetic particle testing (MT). This non-destructive method allows for the early detection of surface-breaking cracks in metallic components [9].

After subjecting each of the pre-damaged states to one million load cycles, no crack formation could be detected, even as the severity of the flaws increased—from drilled holes to full transverse welds.

In the third phase, a more severe level of artificial damage was introduced. Due to the segmented construction of the girders—consisting of individual angles and plates—earlier damage scenarios had affected only portions of the cross-section. In this phase, both the lower flange plate and the associated angle (forming the lower chord) of the central cross girder were removed. Additionally, a sharp notch was cut into the web plate to create a pronounced stress concentration (see Figure 4).

Following these interventions, crack initiation was observed for the first time. The crack exhibited slow and continuous growth without any abrupt failure, indicating ductile fracture behavior. The progression of the crack was documented at intervals of 10,000 load cycles, marked by red arrows in Figure 4. The increasing distance between consecutive arrows indicated an accelerating crack growth rate. The crack propagated toward a rivet hole but did not lead to brittle failure. These experiments provide valuable insights into the fatigue behavior and failure mechanisms of historic riveted bridge structures. Even under artificially induced damage, the tested components did not exhibit sudden or brittle failure. The historic wrought iron material showed a ductile response under realistic load conditions, suggesting that riveted structures of this type are not inherently prone to critical failure.



Figure 4: Crack caused by dynamic load

4 Conclusion

A full-scale fatigue test was conducted on a riveted railway bridge originating from Gau-Algesheim. The structure, built in 1903, had been in service for over 100 years before being decommissioned. The test was performed under realistic boundary conditions and loading amplitudes, simulating over five million load cycles. Remarkably, no fatigue damage was observed during this phase. Subsequently, minor artificial defects were introduced into the structure; however, these did not initiate crack formation. Only after severe damage was applied—specifically, cutting through the bottom chord and notching the web plate—did crack initiation and propagation occur. Even under these extreme conditions, no brittle fracture was observed. These results provide valuable insights into the fatigue resistance and failure mechanisms of historic riveted bridge structures. The findings suggest that such constructions, despite their age, can exhibit significant robustness under repeated loading and may retain substantial residual capacity if properly maintained and monitored.

5 Outlook

A new test rig has already been installed at the University of the Bundeswehr Munich, incorporating several improvements over the previous setup. Notably, enhancements have been made to the pre-tensioning system of the ballast blocks to ensure more stable boundary conditions during dynamic excitation. Additionally, automated amplitude control has been implemented, enabling compensation for minor variations caused by temperature changes, precipitation, or other environmental influences.

A more powerful vibration exciter has been integrated into the system, allowing for higher excitation amplitudes and testing of stiffer bridge structures. A riveted railway bridge from Andernach, featuring a span of 6.8 m, has already been mounted in the new setup (Figure 5). The structural condition of this bridge is significantly more deteriorated compared to the Gau-Algesheim bridge; loose rivets, weld seams, and visible cracks are present. Another bridge from Andernach with a 3.6 m span is planned for subsequent testing. The experimental objectives remain consistent: to investigate fatigue behavior and failure mechanisms of historic riveted bridge structures under realistic conditions.



Figure 5: Test setup for bridge Andernach

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6 References

- [1] Universität der Bundeswehr, RISK.twin [online]. <https://dtecbw.de/home/forschung/unibw-m/projekt-risk-twin>, [accessed on: 12.06.2025]
- [2] Naraniecki H., Zustandsentwicklung und -prognose von Eisenbahnbrücken (2019), <https://doi.org/10.15488/5532>
- [3] Ril 805, 2012: DB Netz AG: Richtlinie 805 – Tragsicherheit bestehender Eisenbahnbrücken
- [4] Seitz F., Spannaus M., Experimentelle Untersuchungen an Bahnbrücke – Digitaler Zwilling (2022)
- [5] Schenck Process Group, Richterreger DF Servicehandbuch BV-H2041
- [6] Petersen, C.: Dynamik der Baukonstruktionen, Friedrich Vieweg & Sohn Verlagsgesellschaft mbH Braunschweig / Wiesbaden, ISBN 3-528-08123-6, (1996).
- [7] Riedel, T.; Sieber, L.; Flederger, H.. Influence of rivet clamping stress on fatigue crack growth behaviour, Accepted in: Ernst & Sohn e-journal ce/papers (Eurosteel 2021, Sheffield).
- [8] Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau
- [9] Weißbach W.; Dahms M.; Jaroschek C.: Werkstoffkunde: Strukturen, Eigenschaften, Prüfung (2015)
- [10] DB Netze AG, Messwertgestützter Tragsicherheits- und Ermüdungsnachweis für die EÜ Bahnsteigtunnel Bahnhof Biblis in km 28,140 der Strecke 4010: Mannheim-Frankfurt (Main)-Stadion (2018)