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TECHNICAL ASSESSMENT OF 120-YEAR-OLD RAILWAY RIVETED TRUSS BRIDGE

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Abstract. A 120-year-old railway truss bridge over the Bóbr River, Poland, is investigated in this paper from the mechanical and chemical properties of the materials by testing of old steel samples in a lab – through geodetic measurements, bathymetric measurements of the riverbed and dynamic measurements of bridge spans under service load – to the analysis of structural behaviour by finite-element modelling. The mechanical and chemical properties of the structural old steel are investigated by testing steel elements extracted from the old bridge. Structural analysis shows that the bridge is eligible for renovation or replacement for a new one due to unfulfilled today's load requirements in terms of bearing capacity. The paper begins with a survey of chosen literature carried out on the investigation of the old steel railway bridge's subject matter. This paper can provide scientists, engineers, and designers with an experimental and structural basis in the field of old steel riveted railway truss bridges.

Keywords: bridge engineering, mechanical properties, steel bridge, structural analysis, truss bridge.

Introduction

Nowadays, and all over time, transportation has played an important role in various aspects of human life and has influenced the country's development.

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New trade routes resulted in civil and engineering infrastructure development. Building new bridges and viaducts has improved the mobility of goods transport. Since ancient times, bridges have been the most visible testimony of the engineer's craft and often are the country's heritage. Bridges are among the most expensive investment assets of any country's civil infrastructure. Development in material science and the application of steel to bridges provided possibilities to develop and erect new bridge types (Siwowski et al., 2020). The joint steel elements were begun by riveted. In the 1930s (Alencar et al., 2019; Hołowaty, 2018), welding was introduced to bridge structures and the riveted steel joints were replaced by welding as well as bolt joints. Old, like new bridges require regular inspections for timely upgrades. Due to the requirements of continuous stable operation of bridges like other structures need to be maintained properly. Reconstruction and renovation of old bridge structures and adaptation to new traffic loads are complex issues often requiring not only the experience of civil engineers but also that of the scientific community. The protection of old bridges coincides with the preservation of their cultural heritage (Kalman, 2017).

The steel riveted bridges are widely tested, and investigated by engineers, researchers, and scientists (see (Ambroziak & Malinowski, 2023) where references to over 100 publications are given). A new investigation on old steel bridges has been published since 2023. Simoncelli et al. (2023) proposed a practical chart to directly connect visual inspection and safety checks based on statistical fragility estimation of the steel bridges. Al-Ghalib (2023) performed damage identification of the 53-year-old simply supported steel truss ADA bridge using discriminant analysis of factor analysis loadings. Azhar et al. (2024) gave a literature review on present vibration-based structural health monitoring on steel bridges. Chmielewski & Muzolf (2023) discussed the impact of corrosion damage and fatigue on the distribution of stresses in the 91-year-old bridge structure. Mash et al. (2023) investigated the repair of corroded steel bridge girder end regions by conventional bolted steel repair, encasement in conventional reinforced concrete, encasement in ultra-high performance concrete, and reinforcement with externally bonded fibre-reinforced polymer plates and sections. Vůjtěch et al. (2023) analysed traditional strengthening methods and proposed new approaches for strengthening historical steel bridges with the use of modern materials such as shape memory alloys, ultra-high performance concrete and carbon-fibre-reinforced polymers. Anastasopoulos & Reynders (2023) performed benchmark modal strain monitoring of a 110-year-old Nieuwebrugstraat riveted railway bridge with fiber-Bragg gratings. Zhang et al. (2023) tested the application of a directed energy deposition laser to repair corrosion-damaged sections of low-carbon steel taken from a corroded steel bridge in Massachusetts, USA. Ambroziak & Malinowski (2023) performed the structural analysis of an old steel riveted railway truss bridge located over the Maruska River on the Działdowo – Olsztyn, Poland railway. Matos et al. (2023) discussed bridge condition rating systems in Italy, Slovakia, and Portugal and the conclusions indicated that the unification of bridge management systems was necessary. The authors show that the methodologies should include the prioritization of bridge assessment based on the importance and current structural state of the bridge. The laboratory test results (tensile tests, impact tests through the Charpy pendulum impact V-notch, and an optical emission spectrometer) of the old steel were also given. Parodi-Figueroa et al. (2024) described a novel fatigue damage assessment considering principal tensile stresses, a detailed and realistic loading spectrum based on real train data and frequency, and all structural changes of the 127-year-old Chilean riveted Howe bridge. Šplíchal et al. (2024) applied the hybrid identification method, which combined a metaheuristic optimisation technique aimed at multilevel sampling with an artificial neural network-based surrogate model for damage detection of riveted truss bridge. Teixeira et al. (2024) presented a case study of hierarchical fatigue analysis of critical riveted railway bridges based on a three-scale concept applied to riveted connections. Milone et al. (2024) developed refined multi-scale modelling and performed fatigue assessment of a riveted railway bridge located in Italy. Ivorra et al. (2024) performed dynamic identification, with application of operational modal analysis, of a historic steel railway bridge after its restoration process. Ambroziak et al. (2024) gave interesting and untypical foldable prefabricated steel Bailey-type bridge redevelopment with a bascule span. Nguyen et al. (2024) described data processing algorithms based on artificial neural networks and adaptive neuro-fuzzy inference systems and predicted the dynamic behaviour of railway steel arch bridge during the passage of trains. Brighenti et al. (2024) provided a review (including 224 references) of bridge management systems and demonstrated its significant developments. The four main maintenance strategies (corrective, preventive, condition-based maintenance, and predictive maintenance) have undergone significant changes toward digitalisation automation, and innovative technologies. Rajchel & Siwowski (2024) carried out a fatigue assessment of the double-track railway bridge built in 1928 with a four-span truss steel structure. Authors concluded that, in the case of old riveted steel bridges, even despite their sufficient actual load-carrying capacity, fatigue assessment should always determine the possibility and economic sense of bridge rehabilitation.

The present study is aimed at a 120-year-old railway truss bridge over the Bóbr River, Poland, from the mechanical and chemical properties of the materials by testing of old steel samples and brick support samples in a lab – through geodetic measurements, bathymetric measurements of the riverbed and dynamic measurements of bridge spans under service load – to the analysis of structural behaviour by finite-element modelling. The mechanical and chemical properties of the structural steel are investigated by testing steel elements extracted from the old bridge. Structural analysis shows that the bridge is eligible for renovation or replacement for a new one due to unfulfilled today's load requirements in terms of bearing capacity. The paper begins with a survey of chosen literature carried out on the investigation of the old steel railway bridge's subject matter. This paper can provide scientists, engineers, and designers with an experimental and structural basis in the field of old steel riveted railway truss bridges.

1. Bridge description

The railway riveted truss bridge (see Figure 1), which is the subject of this study, is located over the Bóbr River, Poland. The year of construction of the bridge was 1904 (see Figure 2), while in 1957 the bridge was completely renovated. The renovation covered cleaning of corrosion and applying protective paint coatings, as well as replacing the deck sheathing. After nearly 50 years of service, it is necessary to verify that the bridge meets today's load requirements in terms of bearing capacity, and serviceability state and make decisions on a range of reconstruction and repairs.

Figure 1. View on railway truss bridge

Figure 2. Photo from the building time of the bridge

The load-bearing structure of the bridge consists of 5 simply supported truss spans with theoretical spans L_{t1} = 17.0 m, L_{t2} = 61.8 m, and $L_{t3,4,5}$ = 3×32.67 m (see Figure 3). Each span is a riveted double-girder system with trusses with parallel chords, N-type lacing, an overhead driveway, with an open carriageway (railway rails laid on bridge girders resting on the belts of upper stringers). Span no. 1 and spans 3–5 are structures with trusses open at the top (without top bracing); the structure of the water span no. 2 consists of a system of truss girders closed at the top (see Figure 4). The platform in each span forms a grid of mutually perpendicular stringers and crossbars. The crossbars are connected to the truss girders in the lower nodes of the main girders. Bottom bracing – the lower wind girder in span 1 has a K-type grating, and in spans 2–5 – with has an X-type grating. Top bracing – the upper wind girder in span No. 2 has an X-type grating. The bodies of the abutments and pillars are of brick construction with stone cladding.

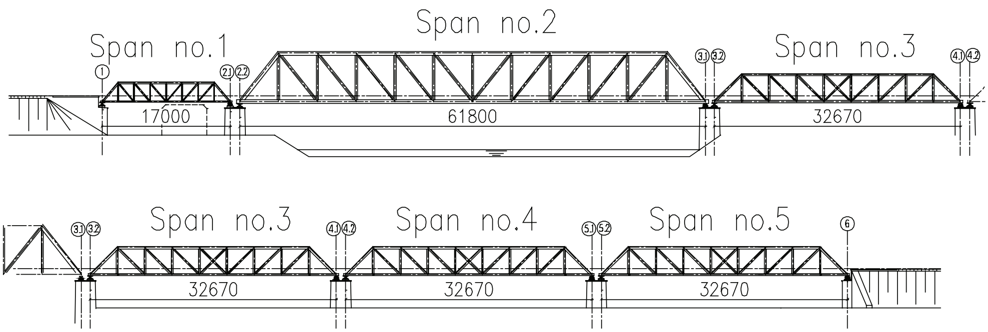
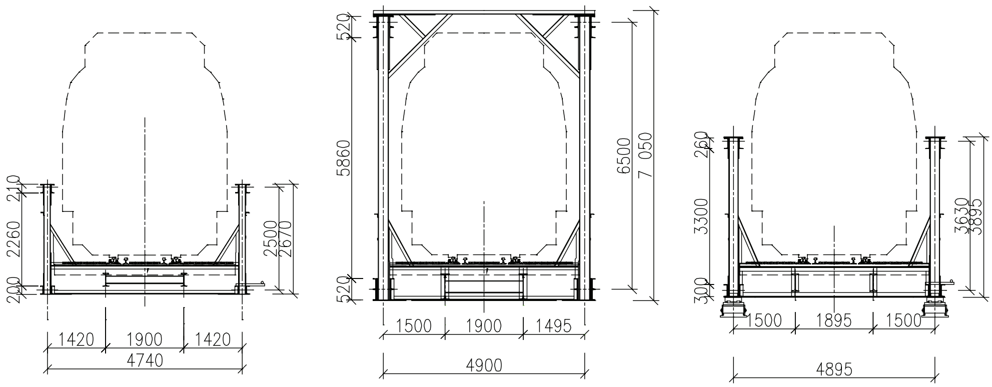


Figure 3. Scheme of the bridge spans



(a) **(b)** **(c)**

Figure 4. Cross-sections of bridge span structures: (a) Span 1; (b) Span 2; (c) Span 3-5

The uniaxial tensile test of old steel was carried out according to ISO 6892-1 (ISO, 2019) standard. To proceed with this, the strength-testing machine of the Zwick/Roell 250 type was employed in the laboratory tensile tests. The assessment of impact toughness in the range of 0 °C and −20 °C was performed by the Zwick/Roell RPK 450 hammer. The Zwick/Roell RPK 450 hammer executed an impact test through the Charpy pendulum impact V-notch according to standard ISO 148-1 (ISO, 2016). The optical emission spectroscopy technique (Devia et al., 2015; Nasiłowska et al., 2023; Sanekata et al., 2021) was used to perform an old steel sample analysis. The Q8 MAGELLAN high-end spark-OES spectrometer for identification of the old steel chemical composition was used.

2. Bridge inspection

Bridge technical inspection on the bridge site is the first necessary part of an expert opinion, and it is an important phase in the proper evaluation of bridge-bearing capacity. Detailed visual inspections of all structural elements with their joints are carried out. The next step covers geodetic measurements and bathymetric measurements of the riverbed. The rapid growth of new techniques, like laser scanning, photogrammetry techniques, and ground penetrating radar, have been observed in terms of monitoring, inventory control and structural inspection of bridges (Abdallah et al., 2022; Binczyk et al., 2020; Lõhmus et al., 2018; Lubowiecka et al., 2009; Luo et al., 2023; Marchewka et al., 2020; Riveiro et al., 2013; Valença et al., 2017). Periodically inspections should indicate necessary repair works to ensure adequate safety and performance of the bridge throughout its service life.

The technical condition of the bearing-capacity structure of the bridge (see Figure 5), after the bridge technical inspection, is assessed as inadequate. The condition of the span structure bridge deck, supports, slopes and embankments are considered sufficient. The railway superstructure condition on the facility is insufficient due to a lack of anti-derailment plates, fire protection plates, and compensating devices, and the profile of the rolling rails was inconsistent with ID-2 (PKP, 2005). Expansion joints are faulty operation because expansion joints jammed – blocking the span structure for the horizontal shift on supports No. 3 and 6. The condition of the railway superstructure on the access roads, the load-bearing structure of the spans – lattice girders (degree of corrosion, local deformations, cracks, losses), bearings (degree of corrosion, contamination, excessive displacement of movable bearings on pillars No. 3, 4, 6), service sidewalks (surface defects) is considered insufficient. The bridge site inspections indicated that the bridge was eligible for repair due to high corrosion, local deformations and cracks of structural elements, which was an issue for the bridge superstructure.

Figure 5. Bridge technical inspection – view on chosen defected elements of the railway truss bridge

3. Laboratory test results of old steel and discussion

The steel samples for laboratory tests were taken from the structural elements of supports (Silarski et al., 2019). Based on performed tensile tests according to ISO 6892-1 (ISO, 2019) standard, the following mechanical parameters are specified: the mean yield strength R_e = 334.8 MPa, the mean ultimate tensile strength R_m = 396.7 MPa with mean elongation at fracture A = 35.3%, and the mean necking at fracture is equal to 74.7%, see Table 1. Based on the statistical analysis, the final characteristic value of the yield strength of old steel is estimated at f_y = 299 MPa (334.8–1.645 · 21.6), and tensile strength f_u = 374 MPa (396.7–1.645 · 13.5).

Table 1. Mechanical properties of old steel samples (Silarski et al., 2019)

Sample No.	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation at fracture, %	Necking at fracture, %
1	343	399	34.7	74
2	354	413	35.0	74
3	336	407	35.7	75
4	358	400	37.3	75
5	312	380	35.3	74
6	306	381	34.0	76
mean	334.8 ± 21.6	396.7 ± 13.5	35.3 ± 1.1	74.7 ± 0.8

Based on the performed impact test according to standard ISO 148-1 (ISO, 2016), the old steel samples showed very low resistance to brittle cracking at low temperatures with the kV^2 mean values equal to 4.7 and 7.1 (see Table 2) for the impact toughness at temperatures −20 °C and 0 °C, respectively.

Table 2. Impact resistance properties of old steel samples (Silarski et al., 2019)

Sample No.	Impact toughness, temp. −20 °C, kV^2/J	Impact toughness, temp. 0 °C, kV^2/J
1	4.8	7.8
2	4.6	7.6
3	5.0	7.4
4	4.5	6.3
5	4.6	6.7
6	5.4	6.0
7	4.5	7.4
8	4.5	7.0
9	4.6	7.5
mean	4.7 ± 0.3	7.1 ± 0.6

Based on the optical emission spectroscopy analysis, the base chemical element compositions of the old steel are specified in Table 3. The results of basic elements composition can be compared with the data available in the literature (see Table 4). Large data on the chemical compositions of old steel from a road bridge from 1857 and 29 railway bridges from 1873 to 1995 can be found in the publication (Hołowaty & Wichtowski, 2016). The investigated 120-year-old railway riveted truss bridge was made of cast steel, and the chemical composition showed low carbon content.

Table 3. Base chemical composition of the old steel specimens – element content in % (Silarski et al., 2019)

Chemical elements	Specimen 1	Specimen 2	Specimen 3	Mean values
Al	< 0.002	0.005	0.008	0.005
C	0.035	0.031	0.035	0.034
Cr	0.012	0.010	0.009	0.010
Cu	0.17	0.18	0.17	0.173
Mn	0.44	0.29	0.39	0.373
Ni	0.022	0.019	0.018	0.020
P	0.12	0.051	0.044	0.072

Table 4. Base chemical composition of the old steel specimens – element content in %

Chemical elements	Wrought steel (Wichtowski & Hołowaty, 2011)	Wrought steel (Hołowaty & Wichtowski, 2015)	Wrought steel (Lesiuk et al., 2011)	Cast steel (Wichtowski & Hołowaty, 2011)	Cast steel (Hołowaty, 2017)	Cast steel (Lesiuk et al., 2011)
Al	-	-	-	0.01–0.02	0.01–0.02	-
C	0.018 –0.30	0.04 –0.30	0.03 –0.35	0.03–0.35	0.03–0.35	0.018–0.3
Cr	-	-	-	0.007–0.014	-	-
Cu	-	-	-	0.11–0.14	0.11–0.14	-
Mn	traces –0.33	traces –0.33	0.04–0.75	0.04–0.75	0.04–0.75	traces –0.33
Ni	-	-	-	0.03–0.04	0.03–0.04	-
P	0.02–0.46	0.02–0.46	0.004–0.16	0.004–0.16	0.004–0.16	0.02–0.46
Si	0.10–0.33	0.10–0.33	traces–0.18	traces –0.18	traces –0.18	0.1–0.33
S	0.01–0.06	0.01–0.06	0.004–0.16	0.004–0.115	0.004–0.115	0.01–0.06

The metallurgical and mechanical weldability of old steel is evaluated (Adamiec & Dziubiński, 1995; Wichtowski, 2014) according to the calculated values of the carbon equivalent C_e, the carbon equivalent for cold cracking C_e', the heat-affected zone (HAZ) hardness HV_{max}, and the hot cracking sensitivity HCS, as follows.

$$C_e = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} = 0.11\% < 0.34\%, \tag{1}$$

$$C'_e = C + \frac{Mn}{6} + \frac{P}{2} + \frac{Mo}{4} + \frac{Ni}{15} + \frac{Cr + V}{5} + 0.0024 \cdot t = 0.2\% < 0.4\%, \tag{2}$$

$$\begin{aligned} HV_{max} &= 1200 \cdot C'_e - 200 = 40HV < 350HV \\ HV_{max} &= 90 + 1050 \cdot C + 47 \cdot Si + 75 \cdot Mn + 30 \cdot Ni + 31 \cdot Cr = 155HV < 350HV, \end{aligned} \tag{3}$$

$$HCS = \frac{C\left(S + P + \frac{Si}{25} + \frac{Ni}{100}\right)}{3Mn + Cr + Mo + V} \cdot 1000 = 3\% < 4.0\% \cdot \tag{4}$$

The determined parameters are below the indicated limits; therefore, the tested old steel may be recognised as weldable. The hot cracking susceptibility (HCS) parameter 2 < HCS < 4 indicated that the hot cracking might occur. Due to this, precautions should be taken to control the arc energy or low preheating in the welding process of the old steel. Nevertheless, due to the very low carbon content (about 0.034%), the welding process of old steel is not recommended before additional laboratory tests on welded old steel samples are performed. Additionally, the low carbon content in the old steel increases the ageing rate of steel over the years, steel becomes stronger as it ages, i.e., its tensile strength, yield strength, and hardness increase, while parameters such as elongation, narrowing, and impact strength decrease, which may reduce the structure's resistance to brittle cracks.

4. Results of in situ tests – Measuring works

4.1. Geodetic measurements

Geodetic measurements (height of supports, level of spans, deflection of the support) were made at measurement points adopted and established 3 years earlier before present geodetic measurements were made. Measurements were made using a total station: Leica MS60 and Leica TS12 and a precision levelling Leica DNA03. Based on the analysis of the geodetic measurement results, it can be concluded that the bridge supports did not experience any settlement compared to the previous measurement. The obtained values of the ordinates of the support settlement measurement points are slightly higher than the values obtained in the previous measurements. This may be due to the displacement of the comparative benchmarks.

For spans no. 1, 2, and 5, practically no increase in the deflection of the span structure was observed. For spans 3 and 4, a slight negative increase in the deflection of the structure was observed, which might be the result of the location of measurement points (points on structural elements marked with paint – no benchmarks). Summing up, it can be concluded that no increase in deflections of the span structure was observed in the unused state, which proved the proper operation of the spans and the lack of significant damage (e.g., loosening of rivets, significant corrosion losses, exceeding the fatigue strength of steel, etc.).

Based on the analysis of the results, it can be concluded that the maximal average angle of rotation of supports is $\alpha = 87.3°$ and has slightly increased compared to early measurements, on average by $\Delta\alpha = 0.2°$.

Figure 6. The banks of the Bóbr River near the bridge site

4.2. Bathymetric measurements of the riverbed

The riverbed shape may be monitored with the use of classical surveying methods or various remote sensing methods: 3D laser scanning and synthetic-aperture radar, light detection and ranging or satellite and aerial imagery (Dysarz et al., 2023; Rusnák et al., 2024; Szombara et al., 2020). Frizzle et al. (2024) assessed LiDaR topo-bathymetry for riverbed elevation. Farina et al. (2025) described method for the enhancement of river bathymetry in LiDaR-derived digital elevation model.

Bathymetric measurements of the riverbed within and in the vicinity of the bridge are performed (see Figure 6). The measurement of the bottom elevation was made with a single-beam HydroBox echo sounder with a 200 kHz transducer. The echo sounder was positioned using the RTK GPS - Leica System1200 satellite positioning system, which used the correction of the position transmitted from the LEICA SMARTNET system. The digital model of the riverbed is created by the grasshopper method, which involves targeted measurements at specific points. Based on measurement points, isobaths and cross-sections are generated. The riverbed digital model is made in a hydrographic program.

The results of the bathymetric measurements are shown in Figures 7 and 8. A map of ordinates (Figure 7) and cross-sections of the river bottom with ordinates (Figure 8) give the accurate river bottom shape. The water level during measurements was about 73.83 m over sea level. The bottom of the river bed under the spans of the structure – even and hard, about 2 m deep. On the right bank – in the vicinity of pillar no. 2 – the bottom is inclined at an angle of about 15°, there is a riprap at the bottom, no washout and no losses of the riprap. At the left bank – in the vicinity of pillar no. 3 – at a distance of about 1 m from the support face – the bottom gradually rises, and the depth of the bottom is about 1.5 m. In the vicinity of the body and foundation of pillar no. 3, deposits of silt with a thickness of about 1 m and the lack (washing out) of the riprap were found. Based on the tactile condition assessment (complete lack of visibility due to silting of the bottom), no mechanical damage and no losses of the pillar body were below the water table.

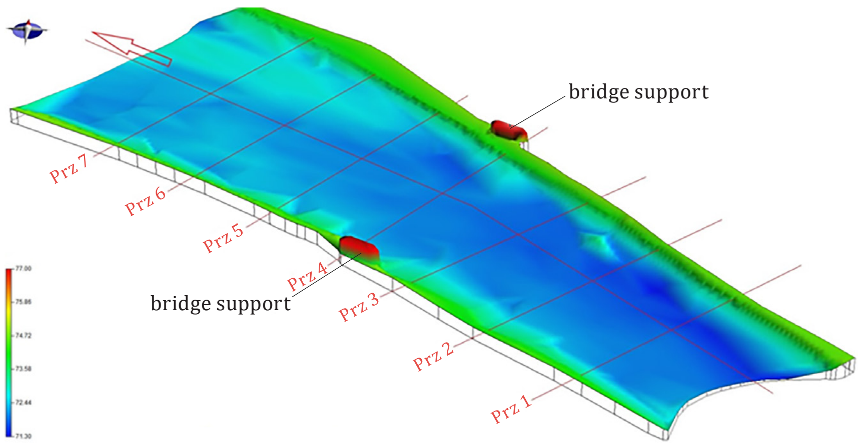


Figure 7. River bottom with local river axis and cross-sectional diagram

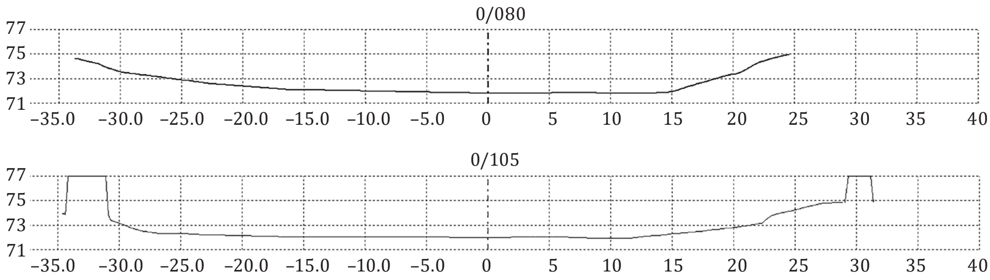


Figure 8. Cross sections 3 and 4 of the river bottom

4.3. Dynamic measurements of bridge spans under service load

Dynamic measurements of bridge spans under actual service load (passage of trains) were performed. The dynamic analysis of bridges under moving loads requires the determination of the dynamic parameters of bridge spans and moving vehicles (Kilikevičius et al., 2018; Paeglitis & Paeglitis, 2014; Siwowski et al., 2021; Szafrański, 2021; Zoltowski et al., 2022; Zwolski & Bien, 2011). The dynamic tests cover the following: measurements of the vertical and horizontal components of transverse accelerations of span structures; measurements of vertical displacements – deflections of span structures; and measurements of strains and normal stresses in the bottom chords of truss girders (see Figures 9 and 10).

Dynamic tests under service load aimed to determine the actual response of the structure to present railway loads and to identify the modal parameters of the bridge structure, as follows: forms and values of natural vibration frequencies, damping coefficient values, and dynamic coefficient values. The obtained results allowed for the validation of the numerical FE computational model of the bridge developed and used to determine the current load-bearing capacity and fatigue life of the bridge structure.

(a) (b)

(c) (d)

Figure 9. View on chosen measurement points: (a) – Strain measurement point; (b) – Vertical displacement measurement point; (c), (d) – Acceleration measurement points

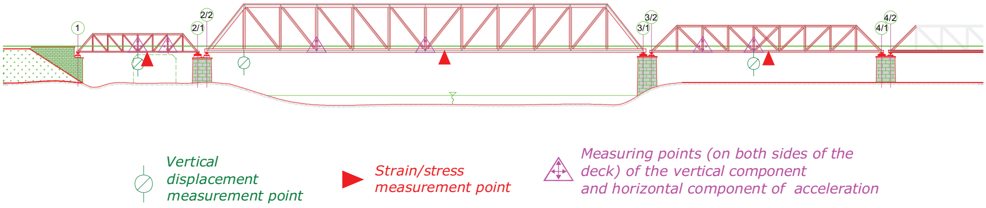


Figure 10. Visualisation of the measurement point layout

Based on the carried out dynamic tests and obtained results (see Table 6), the following conclusions are made:

- Passages of real rolling stock do not cause excessive vibrations in the bridge structure;
- The identified modal parameters do not differ significantly from the theoretical values;
- Damping properties are typical of this type of bridge construction;
- Construction of the bridge spans does not tend to rumble;
- Dynamic coefficients estimated based on the analysis of the dynamic test results are lower than the theoretical values according to PN-EN 1991-2 (PKN, 2007a);
- Obtained results of the dynamic tests confirmed the theoretical assumptions and validated the FEM model.

Table 6. Results of dynamic measurements of bridge spans under service load

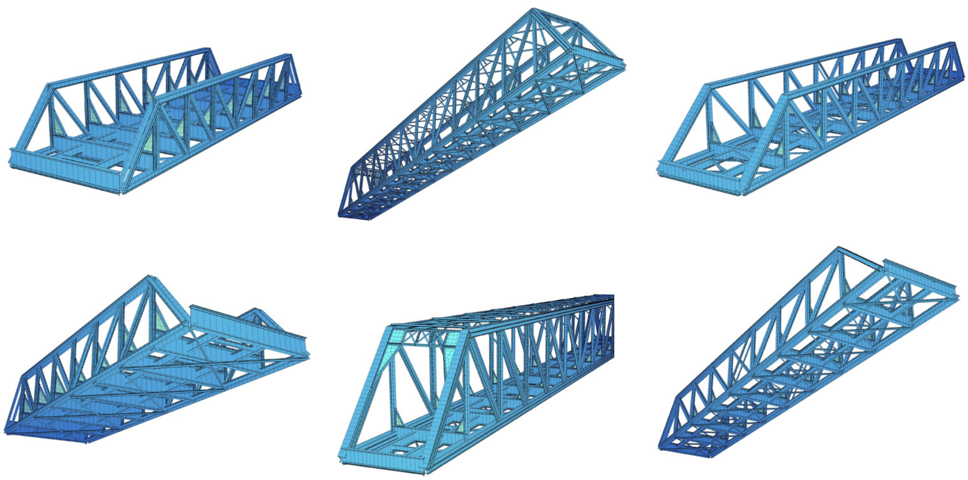
Parameters measured or theoretical	Span no. 1	Span no. 2	Span no. 3
The measured lowest natural frequency value	8.6 Hz	2.3 Hz	4.3 Hz
The theoretical lowest value of the natural frequency	8.82 Hz	2.29 Hz	4.31 Hz
The measured lowest vertical eigenfrequency value	3.5 Hz	10.9 Hz	6.0 Hz
The theoretical lowest value of the vertical eigenfrequency	3.35 Hz	10.94 Hz	6.1 Hz
The determined value of the logarithmic damping decrement	0.033	0.043	0.037
The estimated value of the dynamic coefficient φ	1.03	1.07	1.07
Tendency to rumble the bridge span structure	no tendency	no tendency	no tendency

5. Structural analysis

5.1. Description of FEM model

Numerical analyses of the load-bearing bridge structure were made using the SOFiSTiK system applying the finite element method (FEM) (see, e.g., Banas & Jankowski, 2020; Malinowski et al., 2018; Zoltowski et al., 2022). The authors exploited his own experiences in the design and monitoring of bridge structures to the construction of the FEM model (Malinowski et al., 2017, 2018). The three-dimensional finite element model of the railway truss bridge was built followed by numerical calculations and structural analysis. Due to the freely supported girders static scheme (see Figure 3) separate modelling of individual spans can be carried out (see Figure 11). The shell (SH3D) and 3D beam (B3 D) finite elements (FE) are applied in the FEM model. The finite elements are 4-node isoparametric shell finite elements of DKMQ type and 2-node 3D beam elements of the Timoszenko type, C0 class with linear shape functions.

The following structural conditions were taken into account in the numerical FEM model: mutual position of individual structural elements – eccentricities; non-flexible truss girder nodes; geometric and material parameters adopted based on own inventory measurements and laboratory test results.



(a) (b) (c)

Figure 11. Visualisation of the FEM computational model: (a) Span 1; (b) Span 2; (c) Span 3

The following loads were taken into account during the generation of load combinations:

- Permanent loads: self-weight of the load-bearing structure and equipment elements; the values of permanent loads were adopted based on on-site measurements of the bridge;
- Standard railway class load LM71 according to PN-EN 1991-2 (PKN, 2007a), taking into account appropriate dynamic coefficients;
- Standard railway service load with model wagons of all line categories according to PN-EN 15528 (PKN, 2022) with dynamic coefficient values appropriate for the given speed according to PN-EN 1991-2 (PKN, 2007a);
- Real rolling stock load by the SA108 and SA133 railbuses;
- Load from traction and braking forces on the bridge according to PN-EN 1991-2 (PKN, 2007a);
- Load from nosing forces according to PN-EN 1991-2 (PKN, 2007a);
- Wind load for unloaded structure and loaded with rolling stock according to PN-EN 1991-1-4 (PKN, 2018);
- Thermal load according to PN-EN 1991-1-5 (PKN, 2005).

5.2. Results of structural analysis

The numerical structural analysis of girders, under combinations of loads described in the previous section, is carried out. In the static-strength calculations, the load-bearing capacity of the elements is checked in the following cases: tension, compression, bending in the vertical plane, bending in the horizontal plane, two-way bending, compression with buckling, stability of bending and compression elements with a constant cross-section. Based on the performed numerical and structural analysis, the following is stated:

- The construction of all truss girders spans meets the strength conditions according to PN-EN 1991-2 (PKN, 2007a) for the basic standard load LM71 with the coefficient $\alpha = 1.10$;
- The structure of all span platforms (stringers, crossbars) does not meet the strength conditions according to PN-EN 1991-2 (PKN, 2007a) for the basic standard load LM71 with the coefficient $\alpha = 1.10$;
- The load-bearing conditions for the platform elements are maintained for the basic standard load LM71 with the coefficient: $\alpha = 0.91$ for span no. 1; $\alpha = 0.75$ with careful track maintenance, and for standard track maintenance the load-bearing conditions are not met for any value of coefficient α for span no. 2; $\alpha = 1.00$ with careful track maintenance, and for standard track maintenance, the load-bearing conditions are met for $\alpha = 0.75$, for spans no. 3–5;
- Load-bearing conditions according to PN-EN 1991-2 (PKN, 2007a) are fulfilled for truss girders and platform elements, for all considered

categories of model wagons A–D4 according to PN-EN 15528 (PKN, 2022) and for SA108 and SA133 railbuses, at the rolling stock speed V = 80 km/h (spans no. 1 and 2) and V = 30 km/h (spans no. 3–5), for careful track maintenance, and standard track maintenance.

6. Assessment of fatigue performance of the span structure

Reliable structural integrity and remaining bridge life assessment are key factors for the assessment of fatigue performance (Kużawa et al., 2018; Pipinato, 2010; Rakoczy, 2021; Siwowski, 2015; Wysokowski, 2020). During the bridge site inspection, no fatigue cracks, loose rivets or defects were found. The places potentially exposed to exhaustion of fatigue life are deck elements (stringers, crossbars), especially in tension zones; connection of stringers with crossbars; nodes and cross-sections of truss girder bars; most stressed zones in load-bearing connections; elements showing damage. The assessment of fatigue resistance of bridge members, connections and joints is performed according to the PN-EN 1993-1-9 (PKN, 2007b) standard. Exceeding the condition of fatigue resistance of the structure was obtained in span no. 1: in the lower chord of the truss girder in the middle bays, in the chords of the lower stringers in the end and middle fields of the span, in the middle of the span between the cross-beams; in the span – truss no. 2: in the diagonal in the middle fields of the truss girder, in the chords of the lower stringers in the end and middle fields of the span, in the middle of the span between the cross-beams, in the upper chords of the stringers in the end field of the span, in the middle of the span between the cross-bars, in the lower chord of the third cross member at the connection point with the stringer; in the span no. 3: in the strips of the lower crossbars; the extreme one – in the middle of the span and the third counting from the support – in the middle of the span and at the connection with the stringer, in the chords of the lower stringers in the end and middle fields of the span, in the middle of the span between the cross-beams, in the upper chords of the stringers, in the extreme field of the span and the middle, in the middle of the span between the cross-bars.

It should be noted that the method guidelines by PN-EN 1993-1-9 (PKN, 2007b) standard are recommended for the design of new structures and do not necessarily prove that the load-bearing structure has exceeded the fatigue strength. The method used is characterised by high safety margins due to its assumptions.

Accurate analysis of the fatigue life of the span supporting structure is impossible due to the lack of such data as characteristics of the rolling stock (weight, number and axle loads) moving around the facility throughout its previous operation; and railway traffic intensity in individual years of its operation. Therefore, it is not possible to unambiguously determine the spectrum and the range of stress variability in structural elements of the system due to the actual loads on the rolling stock. It is recommended to periodically observe places and elements that are particularly exposed to exhaustion of fatigue life.

Conclusions

A 120year-old railway riveted truss bridge located over the Bóbr River, Poland, has been examined in this paper, from the properties of the materials by testing samples in a lab – to the structural behaviour by finite-element modelling, with the following results:

- The technical condition of the railway truss bridge is insufficient. The technical condition is the result of many years of operation of the bridge.
- The load-bearing capacity of the bridge structure and its usability are determined mainly by the structure of the platform.
- The steel structure of the span was made of cast steel. At low temperatures, old steel shows a significant reduction in impact strength, which may reduce the structure's resistance to brittle cracks; currently, the properties of the old steel may differ quite significantly from the original properties because, as a result of the material ageing process, parameters such as strength limit, yield point or hardness increase over time, while elongation, narrowing and impact strength decrease.
- Internal forces for this type of bridge structures, during their design period (beginning of the 20th century), were calculated based on influence lines for simple, statically determinate static systems (straight beams, trusses with hinges in nodes); at that time, the spatial cooperation of all elements in the system was not taken into account, which is now possible through the use of spatial computational models.
- The load-bearing structure of the spans does not meet the strength conditions according to PN-EN 1991-2 (PKN, 2007a) for the basic standard load LM71 with the coefficient $\alpha = 1.10$ (the load-bearing conditions according to PN-EN of the platform elements (stringers, crossbars) are not fulfilled practically for any value of the standard coefficient α).
- Load-bearing capacity was met for all considered categories of model wagons A–D4 according to PN-EN 15528 (PKN, 2022) and for real trains in the form of SA108 and SA133 railbuses, at the speed of the rolling stock V = 30 km/h, both in the case of careful and standard track maintenance.
- To increase the temporary load capacity of the span bridge structure, it is technically possible to strengthen the platform elements: stringers and crossbars.

- Due to the identified incorrect displacements of the movable bearings, it is recommended to monitor the displacements of the bearings with the frequency of measurements every 3 months, with the simultaneous measurement of the temperature of the span structure. Displacements of movable bearings should be measured as the relative displacement of the centres of the upper and lower bearing plates. It is recommended to permanently mark the centres of the upper and lower plates of the movable bearings to make the above-mentioned measurements. Measuring the temperature of the structure is necessary to unambiguously assess the cause of the displacement of the moving bearings.
- Due to the blocking of expansion joints on supports no. 3 and 6, it is recommended to immediately unblock the expansion joints by undercutting the steel elements of the platform structure, so that the span structures can move freely on movable bearings.
- Monitoring of the height ordinates of all supports and load-bearing structures of the spans and the inclination of pillar no. 3 should be continued under the monitoring plan.
- Taking into account the age of the object, its technical condition and the current carrying capacity, a more justified decision from the economic and technical point of view is the decision to replace the object with a new one. This variant is more expensive than the renovation of the facility, but ultimately, a facility with parameters that meet the currently applicable standards and technical requirements is obtained.
- Necessary renovation works can be divided into variants depending on the necessary date of their implementation and the goal that will be achieved after their completion: works necessary to be performed immediately to ensure the safety of use; works to ensure the safety of use and protection of the facility against further degradation; works to ensure the safety of use and restore the functionality and proper load capacity of the facility.
- Generally, the bridge is eligible for renovation or replacement for a new one.

Lots of existed historic and old bridge structures require restoration and reconstruction, which require not only a proper financial plan but also an appropriate assessment of structural safety and load-bearing capacity (Ambroziak & Malinowski, 2021). Technical assessment of each bridge construction is an individual case. Complex cases often require not only the experience of civil engineers but also that of the scientific community. Assessment procedures and rehabilitation criteria for bridges should be unified between European countries. Nevertheless, development in assessment techniques of bridges is still observed, and standard procedures should be updated. The paper provides scientists, engineers, and designers with technical assessment example of the 120-year-old railway riveted truss bridge. This investigation may be treated as an impulse to new investigations on riveted truss bridges.

Disclosure statement

The authors declare no conflict of interest.

REFERENCES

Abdallah, A. M., Atadero, R. A., & Ozbek, M. E. (2022). A state-of-the-art review of bridge inspection planning: Current situation and future needs. *Journal of Bridge Engineering*, *27*(2). https://doi.org/10.1061/(ASCE)BE.1943-5592.0001812

Adamiec, P., & Dziubiński, J. (1995). *Pękanie i trwałość napawanych części maszyn*. Wydawnictwo Politechniki Śląskiej.

Al-Ghalib, A. A. (2023). Damage identification of old ADA steel bridge using discriminant analysis of factor analysis loadings. *Journal of Civil Structural Health Monitoring*, *13*(6–7), 1207–1219. https://doi.org/10.1007/s13349-023-00707-3

Alencar, G., de Jesus, A., da Silva, J. G. S., & Calçada, R. (2019). Fatigue cracking of welded railway bridges: A review. *Engineering Failure Analysis*, *104*, 154–176. https://doi.org/10.1016/j.engfailanal.2019.05.037

Ambroziak, A., & Malinowski, M. (2021). A 95-year-old concrete arch bridge: From materials characterization to structural analysis. *Materials*, *14*(7), Article 1744. https://doi.org/10.3390/ma14071744

Ambroziak, A., & Malinowski, M. (2023). Case study of old steel riveted railway truss bridge: From material characterization to structural analysis. *The Baltic Journal of Road and Bridge Engineering*, *18*(3), 188–216. https://doi.org/10.7250/bjrbe.2023-18.614

Ambroziak, A., Malinowski, M., & Wałęga, M. (2024). Rebuilding bailey bridge to bridge with bascule span- case study. *The Baltic Journal of Road and Bridge Engineering*, *19*(1), 136–161. https://doi.org/10.7250/bjrbe.2024-19.631

Anastasopoulos, D., & Reynders, E. P. B. (2023). Modal strain monitoring of the old Nieuwebrugstraat Bridge: Local damage versus temperature effects. *Engineering Structures*, *296*, Article 116854. https://doi.org/10.1016/j.engstruct.2023.116854

Azhar, A. S., Kudus, S. A., Jamadin, A., Mustaffa, N. K., & Sugiura, K. (2024). Recent vibration-based structural health monitoring on steel bridges: Systematic literature review. *Ain Shams Engineering Journal*, *15*(3), Article 102501. https://doi.org/10.1016/j.asej.2023.102501

Banas, A., & Jankowski, R. (2020). Experimental and numerical study on dynamics of two footbridges with different shapes of girders. *Applied Sciences*, *10*(13), Article 4505. https://doi.org/10.3390/app10134505

Binczyk, M., Kalitowski, P., Szulwic, J., & Tysiac, P. (2020). Nondestructive testing of the miter gates using various measurement methods. *Sensors*, *20*(6), Article 1749. https://doi.org/10.3390/s20061749

Brighenti, F., Caspani, V. F., Costa, G., Giordano, P. F., Limongelli, M. P., & Zonta, D. (2024). Bridge management systems: A review on current practice in a digitizing world. *Engineering Structures*, *321*, Article 118971. https://doi.org/10.1016/j.engstruct.2024.118971

Chmielewski, R., & Muzolf, P. (2023). Analysis of degradation process of a railway steel bridge in the final period of its operation. *Structure and Infrastructure Engineering*, *19*(4), 537–553. https://doi.org/10.1080/15732479.2021.1956550

Devia, D. M., Rodriguez-Restrepo, L. V, & Restrepo-Parra, E. (2015). Methods employed in optical emission spectroscopy analysis: A review. *Ingeniería y Ciencia*, *11*(21), 239–267. https://doi.org/10.17230/ingciencia.11.21.12

Dysarz, T., Kałuża, T., Mickevičius, K., Veigneris, J., Zawadzki, P., Kujawiak, S., Zaborowski, S., Wicher-Dysarz, J., Walczak, N., Nieć, J., & Baublys, R. (2023). Application of physical and numerical modeling for determination of waterway safety under the bridge in Kaunas city, Lithuania. *Water*, *15*(4), Article 731. https://doi.org/10.3390/w15040731

Farina, G., Pilotti, M., Milanesi, L., & Valerio, G. (2025). A simple method for the enhancement of river bathymetry in LiDAR DEM. *Environmental Modelling & Software*, *186*, Article 106354. https://doi.org/10.1016/j.envsoft.2025.106354

Frizzle, C., Trudel, M., Daniel, S., Pruneau, A., & Noman, J. (2024). LiDAR topo-bathymetry for riverbed elevation assessment: A review of approaches and performance for hydrodynamic modelling of flood plains. *Earth Surface Processes and Landforms*, *49*(9), 2585–2600. https://doi.org/10.1002/esp.5808

Hołowaty, J. (2017). Toughness tests on steels from old railway bridges. *Procedia Structural Integrity*, *5*, 1043–1050. https://doi.org/10.1016/j.prostr.2017.07.067

Hołowaty, J. (2018). Properties of high tensile steels in historical railway bridges. *Construction Materials*, *171*(6), 234–245. https://doi.org/10.1680/jcoma.17.00012

Hołowaty, J., & Wichtowski, B. (2015). Properties of steel in railway bridge constructed in 1887. *Roads and Bridges - Drogi i Mosty*, *14*(4), 271–283. https://doi.org/10.7409/rabdim.015.018

Hołowaty, J., & Wichtowski, B. (2016). Ocena wytrzymałościowa stali mostów historycznych w świetle badań nieniszczących. *Przegląd Spawalnictwa*, *88*(10), 51–56. https://doi.org/10.26628/ps.v88i10.686

ISO. (2016). *ISO 148-1 Metallic materials - Charpy pendulum impact test - Part 1: Test method*. International Organization for Standardization.

ISO. (2019). *ISO 6892-1 Metallic materials - Tensile testing - Part 1: Method of test at room temperature*. International Organization for Standardization.

Ivorra, S., Torres, B., Bru, D., & Camassa, D. (2024). Dynamic identification of a historic railway riveted bridge. *Proceedings of the 10th International Operational Modal Analysis Conference* (pp. 68–77). https://doi.org/10.1007/978-3-031-61421-7_7

Kalman, H. (2017). Destruction, mitigation, and reconciliation of cultural heritage. *International Journal of Heritage Studies*, *23*(6), 538–555. https://doi.org/10.1080/13527258.2017.1289475

Kilikevičius, A., Bačinskas, D., Jurevičius, M., Kilikevičienė, K., Fursenko, A., Jakaitis, J., & Toločka, E. (2018). Field testing and dynamic analysis of old continuous truss steel bridge. *The Baltic Journal of Road and Bridge Engineering*, *13*(1), 54–66. https://doi.org/10.3846/bjrbe.2018.394

Kużawa, M., Kamiński, T., & Bień, J. (2018). Fatigue assessment procedure for old riveted road bridges. *Archives of Civil and Mechanical Engineering*, *18*(4), 1259–1274. https://doi.org/10.1016/j.acme.2018.03.005

Lesiuk, G., Rabiega, J., & Szata, M. (2011). Problem kruchości stali zgrzewnych w warunkach strukturalnej degradacji – badania statyczne, cykliczne i dynamiczne. *Zeszyty Naukowe / Wyższa Szkoła Oficerska Wojsk Lądowych Im. Gen. T. Kościuszki*, *4*(4), 254–269.

Lõhmus, H., Ellmann, A., Märdla, S., & Idnurm, S. (2018). Terrestrial laser scanning for the monitoring of bridge load tests – two case studies. *Survey Review*, *50*(360), 270–284. https://doi.org/10.1080/00396265.2016.1266117

Lubowiecka, I., Armesto, J., Arias, P., & Lorenzo, H. (2009). Historic bridge modelling using laser scanning, ground penetrating radar and finite element methods in the context of structural dynamics. *Engineering Structures*, *31*(11), 2667–2676. https://doi.org/10.1016/j.engstruct.2009.06.018

Luo, K., Kong, X., Zhang, J., Hu, J., Li, J., & Tang, H. (2023). Computer vision-based bridge inspection and monitoring: A review. *Sensors*, *23*(18), Article 7863. https://doi.org/10.3390/s23187863

Malinowski, M., Banas, A., Cywiński, Z., Jeszka, M., & Sitarski, A. (2017). Zur Wiedergeburt einer historischen Gitterbrücke. *Stahlbau*, *86*(9), 789–796. https://doi.org/10.1002/stab.201710523

Malinowski, M., Banas, A., Jeszka, M., & Sitarski, A. (2018). Imaginative footbridge in Mikolajki, Poland. *Stahlbau*, *87*(3), 248–255. https://doi.org/10.1002/stab.201810582

Marchewka, A., Ziółkowski, P., & Aguilar-Vidal, V. (2020). Framework for structural health monitoring of steel bridges by computer vision. *Sensors (Switzerland)*, *20*(3), Article 700. https://doi.org/10.3390/s20030700

Mash, J. A., Harries, K. A., & Rogers, C. (2023). Repair of corroded steel bridge girder end regions using steel, concrete, UHPC and GFRP repair systems. *Journal of Constructional Steel Research*, *207*, Article 107975. https://doi.org/10.1016/j.jcsr.2023.107975

Matos, J. C., Nicoletti, V., Kralovanec, J., Sousa, H. S., Gara, F., Moravcik, M., & Morais, M. J. (2023). Comparison of condition rating systems for bridges in three European countries. *Applied Sciences*, *13*(22), Article 12343. https://doi.org/10.3390/app132212343

Milone, A., D'Aniello, M., & Landolfo, R. (2024). Advanced fatigue assessment of riveted railway bridges on existing masonry abutments: An Italian case study. *Buildings*, *14*(8), Article 2271. https://doi.org/10.3390/buildings14082271

Nasiłowska, B., Skrzeczanowski, W., Bombalska, A., & Bogdanowicz, Z. (2023). Laser emission spectroscopy of graphene oxide deposited on 316 steel and Ti6Al4V titanium alloy suitable for orthopedics. *Materials*, *16*(7), Article 2574. https://doi.org/10.3390/ma16072574

Nguyen, D. C., Salamak, M., Katunin, A., Poprawa, G., Przystałka, P., & Hypki, M. (2024). Vibration-based SHM of Dębica railway steel bridge with optimized ANN and ANFIS. *Journal of Constructional Steel Research*, *215*, Article 108505. https://doi.org/10.1016/j.jcsr.2024.108505

Paeglitis, A., & Paeglitis, A. (2014). Traffic load models for Latvian road bridges with span length up to 30 meters. *The Baltic Journal of Road and Bridge Engineering*, *9*(2), 139–145. https://doi.org/10.3846/bjrbe.2014.18

Parodi-Figueroa, C., D'Ayala, D., & Sebastian, W. (2024). Fatigue assessment of historic retrofitted through-truss riveted railway bridge. *Engineering Structures*, *307*, Article 117812. https://doi.org/10.1016/j.engstruct.2024.117812

Pipinato, A. (2010). Step level procedure for remaining fatigue life evaluation of one railway bridge. *Baltic Journal of Road and Bridge Engineering*, *5*(1), 28–37. https://doi.org/10.3846/bjrbe.2010.04

PKN. (2005). *PN-EN 1991-1-5 Eurocode 1: Actions on structures – Part 1-5: General actions – Thermalactions*. Polish Committee for Standardization.

PKN. (2007a). *PN-EN 1991-2 Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges*. Polish Committee for Standardization.

PKN. (2007b). *PN-EN 1993-1-9 Eurocode 3: Design of steel structures – Part 1-9: Fatigue*. PKN (Polish Committee for Standardization).

PKN. (2018). *PN-EN 1991-1-4 Eurokod 1: Actions on structures – Part 1-4: General actions – Wind actions*. Polski Komitet Normalizacyjny.

PKN. (2022). *PN-EN 15528 Railway applications – Line categories for managing the interface between load limits of vehicles and infrastructure*. Polish Committee for Standardization.

PKP. (2005). *Id-2 Technical conditions for railway engineering structures (Warunki techniczne dla kolejowych obiektów inżynieryjnych).* PKP Polskie Linie Kolejowe S.A.

Rajchel, M., & Siwowski, T. (2024). Fatigue assessment of a 100-year-old riveted truss railway bridge. *Journal of Constructional Steel Research*, *217*, Article 108662. https://doi.org/10.1016/j.jcsr.2024.108662

Rakoczy, A. M. (2021). Fatigue safety verification of riveted steel railway bridges using probabilistic method and standard S-N curves. *Archives of Civil Engineering*, *67*(4), 625–642. https://doi.org/10.24425/ace.2021.138522

Riveiro, B., González-Jorge, H., Varela, M., & Jauregui, D. V. (2013). Validation of terrestrial laser scanning and photogrammetry techniques for the measurement of vertical underclearance and beam geometry in structural inspection of bridges. *Measurement*, *46*(1), 784–794. https://doi.org/10.1016/j.measurement.2012.09.018

Rusnák, M., Kaňuk, J., Kidová, A., Lehotský, M., Piégay, H., Sládek, J., & Michaleje, L. (2024). Inferring channel incision in gravel-bed rivers: Integrating LiDAR data, historical aerial photographs and drone-based SfM topo-bathymetry. *Earth Surface Processes and Landforms*, *49*(8), 2475–2497. https://doi.org/10.1002/esp.5840

Sanekata, M., Nishida, H., Nakagomi, Y., Hirai, Y., Nishimiya, N., Tona, M., Hirata, N., Yamamoto, H., Tsukamoto, K., Ohshimo, K., Misaizu, F., & Fuke, K. (2021). Dependence of optical emission spectra on argon gas pressure during modulated pulsed power magnetron sputtering (MPPMS). *Plasma*, *4*(2), 269–280. https://doi.org/10.3390/plasma4020018

Silarski, A., Praszelik, Ł., Chrapek, S., Mikuszewski, B., & Plewnia, Ł. (2019). *Linia kolejowa nr 370 Zielona Góra – Żary: RAPORT Z PRZEGLĄDU SPECJALNEGO Most w km 28,268*.

Simoncelli, M., Aloisio, A., Zucca, M., Venturi, G., & Alaggio, R. (2023). Intensity and location of corrosion on the reliability of a steel bridge. *Journal of Constructional Steel Research*, *206*, Article 107937. https://doi.org/10.1016/j.jcsr.2023.107937

Siwowski, T. (2015). Fatigue assessment of existing riveted truss bridges: Case study. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *63*(1), 125–133. https://doi.org/10.1515/bpasts-2015-0014

Siwowski, T., Rajchel, M., & Wlasak, L. (2021). Experimental study on static and dynamic performance of a novel GFRP bridge girder. *Composite Structures*, *259*, Article 113464. https://doi.org/10.1016/j.compstruct.2020.113464

Siwowski, T., Zobel, H., Al-Khafaji, T., & Karwowski, W. (2020). The recently built polish large arch bridges – a review of construction technology. *Archives of Civil Engineering*, *66*(4), 7–43. https://doi.org/10.24425/ace.2020.135207

Šplíchal, B., Lehký, D., & Lamperová, K. (2024). Damage detection of riveted truss bridge using ANN-aided AMS optimization method. In *Bridge Maintenance, Safety, Management, Digitalization and Sustainability* (1st ed., pp. 2279–2286). CRC Press. https://doi.org/10.1201/9781003483755-270

Szafrański, M. (2021). A dynamic vehicle-bridge model based on the modal identification results of an existing EN57 train and bridge spans with non-ballasted tracks. *Mechanical Systems and Signal Processing*, *146*, Article 107039. https://doi.org/10.1016/j.ymssp.2020.107039

Szombara, S., Lewińska, P., Żądło, A., Róg, M., & Maciuk, K. (2020). Analyses of the Prądnik riverbed shape based on archival and contemporary data Sets – Old maps, LiDAR, DTMs, orthophotomaps and cross-sectional profile measurements. *Remote Sensing*, *12*(14), Article 2208. https://doi.org/10.3390/rs12142208

Teixeira, R., Horas, C. S., De Jesus, A. M. P., Calçada, R., & Bittencourt, T. N. (2024). Innovative hierarchical fatigue analysis of critical riveted railway bridges: A case study. *Engineering Structures*, *317*, Article 118629. https://doi.org/10.1016/j.engstruct.2024.118629

Valença, J., Puente, I., Júlio, E., González-Jorge, H., & Arias-Sánchez, P. (2017). Assessment of cracks on concrete bridges using image processing supported by laser scanning survey. *Construction and Building Materials*, *146*, 668–678. https://doi.org/10.1016/j.conbuildmat.2017.04.096

Vůjtěch, J., Ryjáček, P., & Matos, J. C. (2023). Dealing with defects and strengthening historical steel bridges. *Structural Engineering International*, *33*(1), 195–205. https://doi.org/10.1080/10168664.2022.2080150

Wichtowski, B. (2014). Load-carrying capacity of steel railway bridges of the second half of XIX century – discussion. *Roads and Bridges – Drogi i Mosty*, *13*(3), 261–269. https://doi.org/10.7409/rabdim.014.017

Wichtowski, B., & Hołowaty, J. (2011). Structural steels in old railway bridges analized by hardness and chemical content (Analiza stali starych mostów kolejowych według badań twardości i składu chemicznego). *XXV Konferencja Naukowo-Techniczna - Awarie Budowalne*, 1259–1266.

Wysokowski, A. (2020). Impact of traffic load randomness on fatigue of steel bridges. *The Baltic Journal of Road and Bridge Engineering*, *15*(5), 21–44. https://doi.org/10.7250/bjrbe.2020-15.505

Zhang, S., Hou, P., Kang, J., Li, T., Mooraj, S., Ren, Y., Chen, C. H., Hart, A. J., Gerasimidis, S., & Chen, W. (2023). Laser additive manufacturing for infrastructure repair: A case study of a deteriorated steel bridge beam. *Journal of Materials Science & Technology*, *154*, 149–158. https://doi.org/10.1016/j.jmst.2023.01.018

Zoltowski, K., Banas, A., Binczyk, M., & Kalitowski, P. (2022). Control of the bridge span vibration with high coefficient passive damper. Theoretical consideration and application. *Engineering Structures*, *254*, Article 113781. https://doi.org/10.1016/j.engstruct.2021.113781

Zwolski, J., & Bien, J. (2011). Modal analysis of bridge structures by means of forced vibration tests. *Journal of Civil Engineering and Management*, *17*(4), 590–599. https://doi.org/10.3846/13923730.2011.632489