13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure

DOI: 10.3217/978-3-99161-057-1-118

# The Collapse of the Carola Bridge – Forensic Engineering and Palliative Monitoring

Max Fiedler[1, 0000-0003-1375-826X], Gregor Schacht[1], Robert Ritter[1], Steffen Marx[2], Silke Scheerer[2], Luise Clages[1], Gino Ebell[3], David Czeschka[1], Chris Voigt[1]

[1]MKP GmbH, Altenzeller Straße 19, 01069 Dresden, Germany

[2]Institute of Concrete Structures, Technical University of Dresden, August-Bebel-Straße 30/30A, 01219 Dresden, Germany

[3]Federal Institute for Materials Research and Testing, Department 7.6 Corrosion and Corrosion Protection, Unter den Eichen 87, 12205 Berlin, Germany

email: Max.Fiedler@marxkrontal.com

ABSTRACT: The events of September 11, 2024, will remain etched in the collective memory of Germany’s bridge engineering community. The sudden and unannounced partial collapse of a prestressed concrete bridge rightfully reverberated across society at large. The structure in question was the Carola Bridge in Dresden. This architecturally refined and exceptionally slender bridge is, with good reason, regarded by professionals as an icon of its time's structural engineering. Even by today’s standards, its design and construction would pose a considerable challenge. This paper presents the main findings from investigations undertaken to determine the cause of the collapse and attempts to reconstruct the failure process. Additionally, the acoustic monitoring system implemented to safeguard the remaining superstructures is also presented.

KEY WORDS: Carola Bridge; Bridge Collapse; Prestressed Concrete; Stress Corrosion Cracking; Bridge Monitoring; Acoustic Emission Analysis; Forensic Engineering.

## 1 INTRODUCTION

The partial collapse of the Carola Bridge on September 11, 2024, sent shockwaves not only through the city of Dresden but also across the engineering community. The abrupt failure of an urban structure of such infrastructural importance raised fundamental questions: How could such an incident occur? What mechanisms led to the structural failure? At which location did the critical deficit manifest? And why did early indications of the developing failure remain undetected for so long despite routine structural monitoring?

These questions extend far beyond the technical assessment of a singular event. They also pertain to the derivation of potential implications for other structures that may be subject to previously undetected load-bearing deficiencies. Moreover, they address the issue of accountability for this structural failure, although a definitive attribution of responsibility may prove elusive.

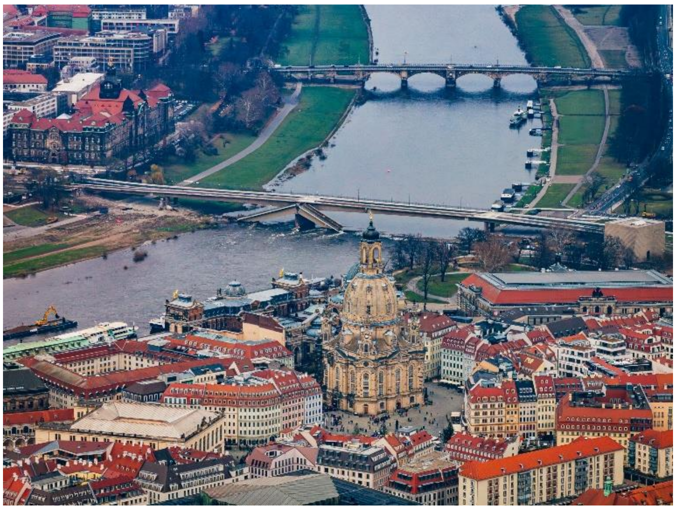

Figure 1. The Carola Bridge in the heart of Dresden’s historic city centre, photographed on December 12, 2024, from a south-westerly perspective, with the Frauenkirche prominently in the foreground and the Albert Bridge visible in the background (Photo: Alex Burzik).

To investigate the incident, a comprehensive examination of both the collapsed section and the remaining superstructures was initiated. This paper presents the main findings of those investigations and elaborates on the subsequent failure analysis, with particular attention to the ad-hoc measures taken to assess the condition in the region of the fracture cross-section at axis D. In addition to material testing, an in-depth review and interpretation of the original construction documentation supplemented the analysis. This integrative approach enabled a reconstruction of the sequence of events leading to the collapse. Furthermore, the report outlines the monitoring that was enacted to ensure the continued operational safety of the remaining superstructures during their residual service life.

## 2 THE STRUCTURE

### 2.1 Overview

Based on the winning competition design, the new bridge over the river Elbe was designed by the state-owned VEB Design and Engineering Office for Road Construction (EIBS, Dresden division), under the leadership of Eckhardt Thürmer.

The Dr.-Rudolfs-Friedrich Bridge, inaugurated for traffic on 3 July 1971, was the longest-span prestressed concrete bridge in the German Democratic Republic (GDR) at the time [1], and has since become a defining feature of Dresden’s cityscape (Figure 1). In 1992, it was renamed the Carola Bridge.

The approximately 400 m long structure, with five individual spans ranging from 44 to 120 m, has an overall width of 32 m and comprises three separate superstructures, each designed as a single-cell prestressed box girder (Figure 3). The fixed point is located at the pier in axis D, where the superstructure reaches its maximum structural height of 5.2 m. Towards the

DOI: 10.3217/978-3-99161-057-1-118

abutments, the cross-section tapers to 1.6 m and 1.8 m, respectively.

Due to pronounced moment variations under continuous beam conditions, the superstructure was subdivided by three hinges. This resulted in a two-span girder between axes A and C with a 12 m long cantilever towards the Elbe (hinge I). A single-span girder with two cantilever arms—44 m towards the Elbe (hinge II) and 10 m towards the Neustadt side (hinge III)—rests on piers D and E. A 64 m long suspended main-span beam bridges the gap between the cantilever arms. An additional suspended beam was placed in the edge span on the Neustadt side.

Superstructures a and b carried two-lane roadways in opposing directions (bridge class 60), while superstructure c accommodated a double-track tramway. The outer edges of superstructures a and c featured 3.2 m wide sidewalks for pedestrians and cyclists [3]. Utility lines for district heating, gas, electricity, and water were integrated into the interior of the box girders.

One of the design-specific challenges was developing an appropriate tendon layout. In the construction stage—before the installation of the suspended beams—positive bending moments prevailed in approximately 70% of the span between supports D and E. In contrast, the final state was characterised predominantly by negative bending moments. In addition, significant creep and shrinkage deformations were anticipated during the construction period. The chosen solution involved the use of three different types of tendons: permanent tendons to carry the dead load, construction-stage tendons for temporary stabilisation during erection, and post-tensioned tendons that were activated in the final state. From today's perspective, this tendon strategy represents a key construction-related contributing factor to the collapse, as some of the tendons were exposed to extended idle periods in ungrouted sheaths.

Another noteworthy structural feature was the transverse connection at the location of hinge II, where the three individual superstructures were interconnected via a cross-beam (Figure 2). During construction, vertical stressing jacks were used at this location to compensate for height differences between the successively erected superstructures. In the final state, the transverse connection equalised differential deflections between the three very slender and separate box girders, which resulted from shrinkage, creep, thermal effects, and traffic loading. Furthermore, it enabled the redistribution of transverse loads, effectively enforcing load-sharing between adjacent superstructures.

## 3 MAINTENANCE AND REHABILITATION

### *3.1 Monitoring of Structural Deformations*

A prerequisite for the structural integrity of the bridge was sufficient prestressing of the coupling bolts between the steel hinges and the web tendons. Of the total 504 bolts installed across all joints, 121 were designed as measuring bolts. The existing bolt forces were inferred from the difference in elongation between the zero reading and the measurement under load, recorded using high-precision mechanical dial gauges. Data on bolt forces is available from the time of construction and subsequently from the years 1974, 1979, 1982, and the early 1990s.

Significant deflection at hinge II had been known since the 1980s. A measurement campaign conducted in the early 1990s aimed to determine the causes and assess the impact on the usability of the structure. Within the box girder of superstructure c, inclinations, displacements, vibrations, and temperatures were recorded using various measuring instruments at different locations, partly over a period exceeding one year. The absolute values of the coupling bolt

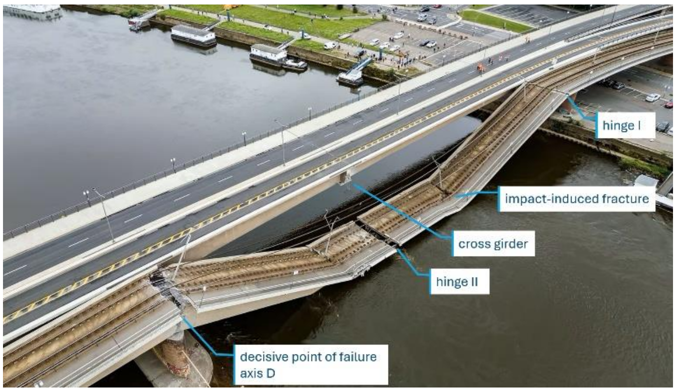


Figure 2. Building immediately after the collapse.

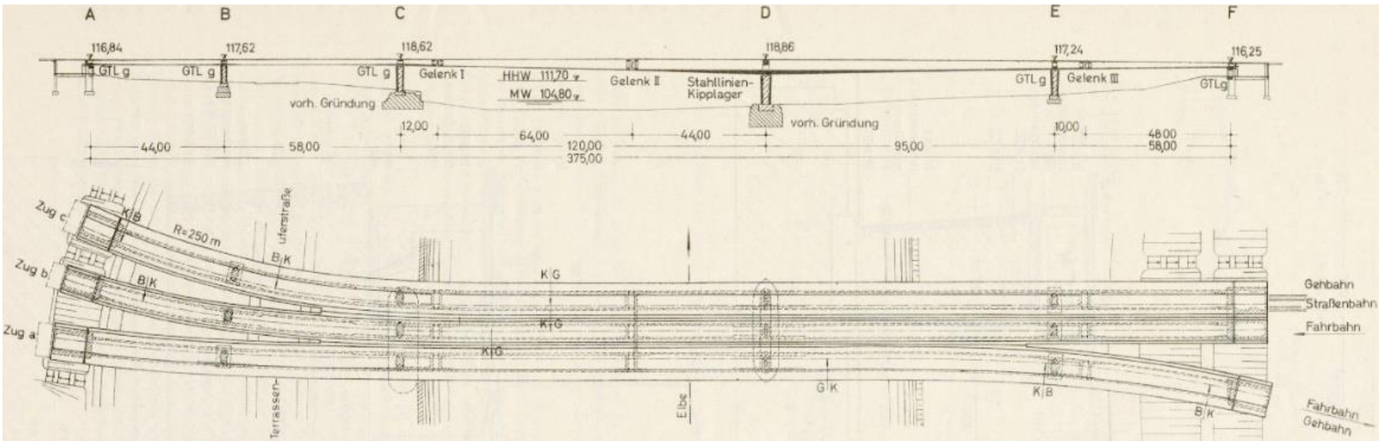


Figure 3. Longitudinal section and ground plan of the Carola Bridge, from [2].

DOI: 10.3217/978-3-99161-057-1-118

forces exhibited large scatter and decreased continuously since the initial prestressing, though at a progressively slower rate. These force reductions were attributed to creep and shrinkage deformations and were thus considered explainable. At the time, damage to the prestressing tendons was not considered a possible cause. Nor was the structural safety called into question.

The passage of a tram caused vertical displacements at hinge II in superstructure c of approximately +12 mm (downward) and –3 mm (upward). Deformations due to temperature variations were significantly larger, reaching up to 65 mm within 1.5 days. Relative to the zero position, deflections ranged from –20 mm to +80 mm. Based on measured data and theoretical evaluations, it was estimated that by early 1993, hinge II had experienced an average downward deflection of approximately 30 cm, equivalent to roughly 80% of the total deformation expected over the entire 80-year design life.

In addition to long-term monitoring, short-term measurements were performed in 2004 as part of static and dynamic load testing on superstructure a, to assess the actual structural behaviour and the effective interaction with adjacent superstructures b and c. The tests did not reveal any plastic deformations. Movements of transverse cracks in the underside of the roadway slab remained minimal. Load redistribution through the transverse connection at hinge II was quantified at a maximum of 39–34–27% (superstructures a–b–c, respectively) under traffic loading applied to a. Neither the long-term nor short-term investigations indicated any critical implications for the global structural integrity.

### *3.2 Issue of Prestressing Steel*

The issue of stress corrosion cracking (SCC) in prestressing steel was already known in connection with the Carola Bridge. Structural inspections were conducted regularly, following DIN 1076 [4], and initially revealed no abnormalities. A first recalculation was carried out in 1996, following [5], which successfully demonstrated the structure’s failure annunciation behaviour.

Transverse cracks have been definitively documented since the year 2000. Two leading causes were considered: excessive creep deformations or failure of the prestressing reinforcement, e.g. as a result of SCC. Since high creep deformation was known, it was plausibly assumed to be the primary cause of the cracking. Potential tendon failures were not taken into account. The cracks showed only minor widths, within the permissible limits for prestressed concrete structures. As the failure annunciation behaviour had been analytically verified, larger crack widths would have been expected in the event of an actual pre-failure condition.

The limited rotational capacity of the cross-sections, caused by the high reinforcement ratio and high utilisation levels, was not sufficiently considered. Additionally, the transverse load distribution via the cross beam at hinge II was underestimated. The mutual support between superstructures resulted in minimal changes in crack width, even in the presence of critical damage in one of the superstructures.

From 2004 onwards, deformation monitoring was performed by measuring crack widths and joint openings at hinge II. From today’s perspective, these measurements were not suitable for identifying early indicators of failure.

### *3.3 Chloride Exposure*

Sections of the three superstructures—especially between axes D and E—were affected by chloride-induced corrosion. The failure of a drainage line was the cause of this. The resulting damage was repaired. Following a non-destructive electrochemical chloride extraction, the interior surfaces of the box girders were sealed with a crack-bridging protective coating.

During the structural investigation in autumn 2024, corroded prestressing steel and passive reinforcement were identified. However, these were not determined to be the cause of the collapse.

### *3.4 Other Aspects*

Throughout the bridge’s service life, numerous investigations were carried out. All irregularities were followed up, and the condition of the structure was continuously assessed. No serious deficiencies have been identified in the repair works.
As a result, a rehabilitation programme was initiated, beginning with the superstructure a in 2020/21. Due to chloride contamination, this superstructure was considered particularly critical. Rehabilitation of superstructure c was scheduled to start in early 2025. Measures to enhance the durability of this structure were also planned.

## 4 COLLAPSE

In the early hours of September 11, 2024, at approximately 02:58 a.m., the collapse of superstructure c of the Carola Bridge abruptly altered the Dresden cityscape. A camera operated by Sächsische Dampfschifffahrt, mounted on the bow of a ship,

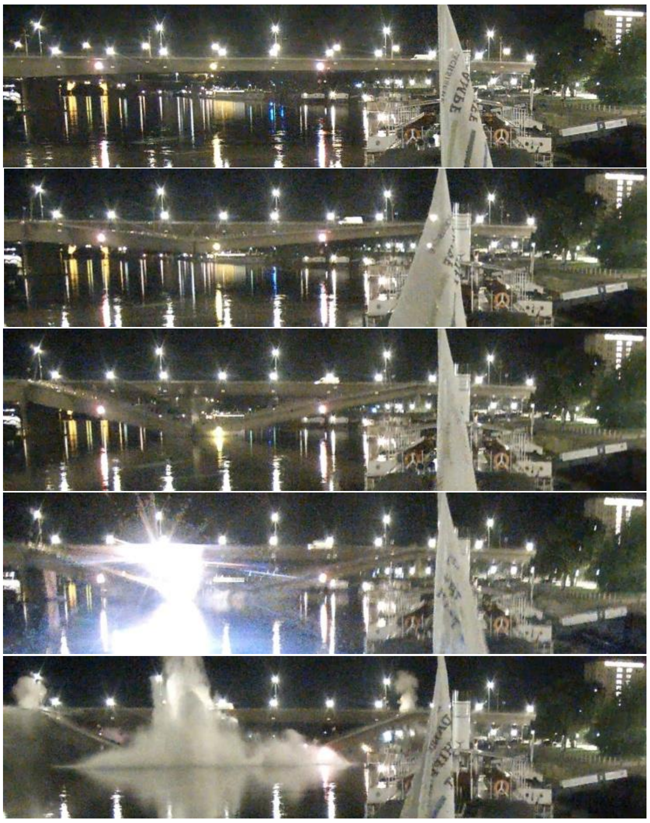

Figure 4. Recordings from a surveillance camera: initial state and moment of collapse.

DOI: 10.3217/978-3-99161-057-1-118

captured the incident as it unfolded (Figure 4). Facing upstream, the camera recorded precisely the critical area—the river span between axes C and D.

A frame-by-frame analysis of the footage reveals the sequence of events: initially, the region around hinge II began to subside, while a crack opened at the support cross-section in axis D. Moments later, the overhead tram catenary came into contact with the river. A flash of light illuminated the night sky, accompanied by a column of spray erupting from the water's surface.

Just eight minutes before the failure, a tram had crossed this very span, likely initiating the kinematic chain leading to collapse. Fortunately, no pedestrians or cyclists were present on the structure at the time of failure. Only a delivery van travelling on superstructure a was crossing the river span as superstructure c gave way.

## 5 MATERIAL INVESTIGATIONS

### *5.1 Ad-hoc Measures for Assessing the Damage Condition of Superstructure c*

In the very first hours following the collapse, an extensive photographic documentation of the general structural condition—and particularly of the fracture cross-section—was carried out. The aim was to ensure that the assessment of the exposed tendons and reinforcement would not be compromised by environmental influences or incipient corrosion. With the support of numerous contributors, nearly all components were documented on the day of the collapse itself.

The condition of the prestressing tendons was evaluated visually and classified into damage categories. It became evident that the post-tensioned tendons in the roadway slab area, in particular, showed advanced pre-existing damage and had failed long before the collapse. These post-tensioned tendons had only been stressed after a time delay, following the installation of the suspended main-span beam; see also [2]. This conclusion was drawn from the almost black fracture surfaces of many tendons (top right in Figure 6), indicating an oxygen-deficient environment within the still-intact sheathing. As such, these wire fractures occurred either during construction or shortly thereafter, but in any case, a considerable amount of time ago.

Later microscopic investigations of fractured wires, conducted by the Federal Institute for Materials Research and Testing (BAM), Berlin, revealed mortar residues on some fracture surfaces—clear evidence that these fractures had occurred before or during the grouting process. Fresh fracture surfaces appeared metallic and glossy, without signs of corrosion, and also showed no ductile necking in the failure zone (bottom right in Figure 6). Even the prestressing steels without pronounced crack initiation lenses showed signs of embrittlement.

A characteristic feature of the fracture cross-section—beyond the failed prestressing tendons—was the presence of reinforcement bars that had been pulled out from the concrete section in the upper reinforcement layers (Figure 5). In several cases, the reinforcing bars exhibited no signs of fracture, necking, or cross-sectional loss. Only isolated and minimal indications of chloride-induced corrosion were visible externally (e.g. slight pitting corrosion at the ribs).

Subsequent analyses of concrete samples taken from the fracture zone confirmed that chloride-induced pitting corrosion did not play a relevant role in this area. The tightly spaced arrangement of tendons and reinforcement bars likely impaired the bond performance, which may have contributed to the complete pull-out of some reinforcing bars from the roadway slab.

Figure 5. Failed cross-section in axis D with pulled-out steel reinforcement.

.

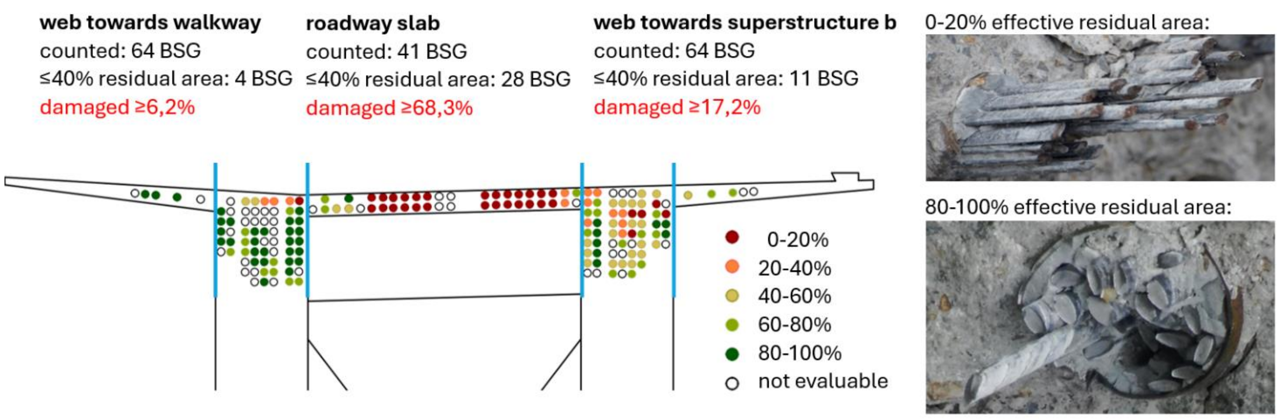


Figure 6. Results of photographic documentation of the condition of the broken prestressing wires at axis D of superstructure c, view direction Dresden-Neustadt (mid of December 2024).

DOI: 10.3217/978-3-99161-057-1-118

## 6 ACOUSTIC MONITORING FOR THE SUPERSTRUCTURES A AND B

As the Elbe River and the southern (Altstadt-side) riverbank were gradually cleared of the remnants of superstructure c in December 2024, increasing attention was directed toward reopening the waterway and ensuring the safe underpassage beneath the remaining superstructures a and b. However, a general opening of the adjacent banks and associated roads, footpaths, and cycleways was not pursued, as these areas would soon have to be closed again for the dismantling of the remaining bridge sections. In contrast, due to its role as an international waterway critical to freight transport for the Czech Republic, the navigability of the Elbe was given priority.

An evaluation of the structural safety could not be guaranteed solely through static analysis under the prevailing conditions. Therefore, a prerequisite for reopening the Elbe to ship traffic was the implementation of acoustic emission monitoring to detect new wire break events [6], [7]. Shortly after the partial collapse, a small number of sensors were installed in the roadway slab above pier D in superstructures a and b to ensure safety during on-site diagnostic investigations. In January 2025, this system was expanded to cover the entire main river span and the support regions at axis C (Figure 7 and Figure 8).

As of February 3, 2025, controlled ship passages were permitted based on real-time monitoring data, solely for operationally critical transit (Figure 9). Initially, a ship-specific clearance protocol was applied. From 18 February onward, clearance was planned to be issued daily, allowing navigation within predefined time windows. However, on the morning of 18 February at 04:50 a.m., the first wire break events were recorded. Several additional events followed within hours, concentrated on the axes and adjacent roadway slabs. At axis D, up to six spatially correlated events were detected within 24 hours. This sudden development was most likely triggered by pronounced temperature differentials compared to previous days.

In preparation for the monitoring program, quantitative threshold values were determined through static analysis for the monitoring region. Engineering assumptions were made to estimate the loading condition that, with high confidence, had still been acting on the superstructure shortly before the partial collapse. Based on this load model, the equivalent number of prestressing wires available as structural reserve was determined. For axis D, a calculated reserve of 14 locally correlated wire breaks was established. Approximately 40% of this reserve was consumed within a very short period.

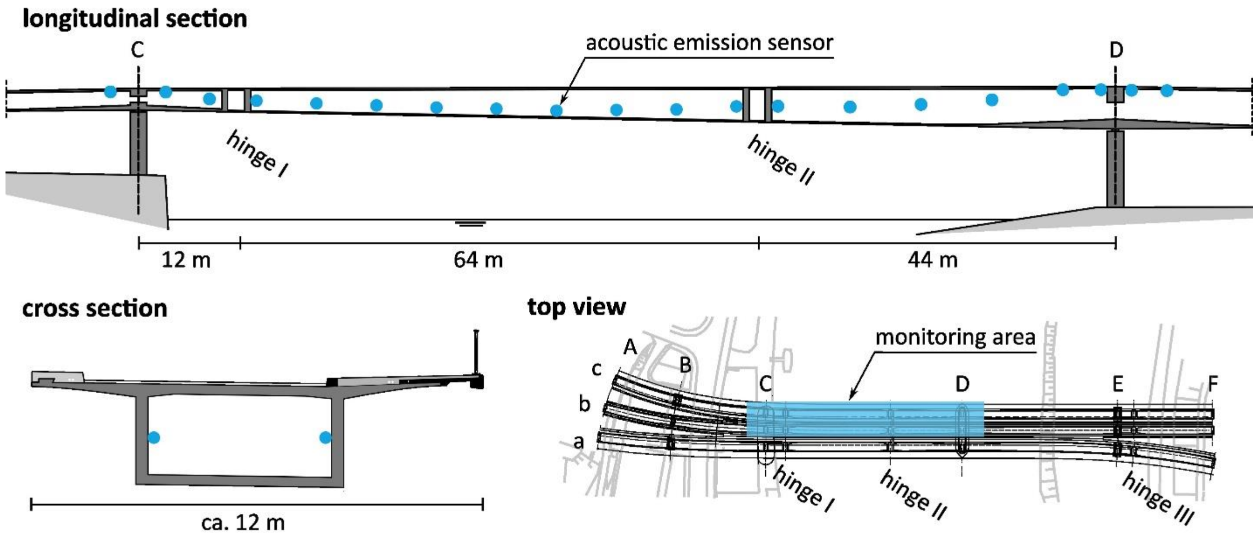


Figure 7. Overview of the monitoring area and the sensor layout for the acoustic emission monitoring system.

Figure 8. Acoustic emission sensor in superstructure b.

Figure 9. First ship passage after the collapse of the bridge and the installation of the monitoring system.

DOI: 10.3217/978-3-99161-057-1-118

It was assumed that further significant temperature fluctuations would occur in the following weeks, which could again lead to an abrupt reduction in the remaining structural reserve. As an immediate response, a wire-break-free monitoring period of 72 hours was mandated before any further ship passages could even be considered. Subsequently, a day-by-day clearance protocol was reintroduced. Ship passages were permitted only under direct real-time monitoring using the installed measurement systems.

Ultimately, these events highlighted the vulnerable and undefined structural condition of the remaining bridge components, forming the basis for the decision to proceed with prompt deconstruction.

## 7 CONCLUSION

With knowledge of the brittle failure risk associated with the prestressing reinforcement, re-commissioning of superstructures A and B was deemed unacceptable. This decision was thoroughly examined and carefully weighed, as the Carola Bridge had represented an essential component of Dresden's road infrastructure. Among the options considered was a controlled load test. However, such a test would have only provided a snapshot of the current load-bearing capacity. Its predictive value for future performance would have remained uncertain, as the damage mechanism—stress corrosion cracking—may temporarily cease under the alkaline conditions of the grouting mortar. Still, the progression of fatigue-related damage could not have been reliably assessed at the observed level of deterioration, even if a load test had returned positive results, a residual risk would have persisted, one that could not be ethically or technically justified.

It must be acknowledged that the bridge had been inspected and monitored in accordance with established engineering standards. This highlights the need for a critical review and update of these standards. Current regulations prescribe recalculations, diagnostic investigations, and visual assessments from the exterior. However, it remains challenging to make definitive statements about the internal condition of structural components. Insights gained from the Carola Bridge investigations are now being systematically compiled and evaluated within the research initiative "Investigation and Verification of the Causes of the Carola Bridge Failure concerning the Review and Potential Revision of Concrete Bridge Design Codes" (Project No. FE-15.0729/2024/HRB). The objective is to assess the broader implications for similar structures and to initiate corresponding changes to design and inspection standards.

Measurement-based monitoring techniques—such as acoustic emission monitoring for detecting wire breaks in prestressed tendons—are playing an increasingly important role in this context and must be formally incorporated into regulatory frameworks. Ultimately, this method remains the only available approach capable of directly detecting and localising wire breaks at the moment of occurrence, thereby enabling meaningful insights into the progression of damage. Within the broader context of the tragedy resulting from the partial collapse, the successful application of this technique stands out: it was only through this method that navigation on the river Elbe could be safely resumed at minimal residual risk.

## REFERENCES

[1] Schlimper, H.: Festansprache. In: Bau der Nord-Süd-Verbindung in Dresden : Erinnerungsschrift, Dresden, 1971, S. 1–3.

[2] Berger, R.; Franke, M.; Thürmer, E.: Projektierung der Dr.-Rudolfs-Friedrich-Brücke. DIE STRASSE 11 (1971) 6, S. 266–277.

[3] Kriesche, K.: Entwurfs- und Bauvorgaben für die Dr.-Rudolfs-Friedrich-Brücke. DIE STRASSE 11 (1971) 6, S. 264–277.

[4] DIN 1076:1999-11: Ingenieurbauwerke im Zuge von Straßen und Wegen – Überwachung und Prüfung.

[5] Bundesministerium für Verkehr (BMV, Hrsg.): Empfehlungen zur Überprüfung und Beurteilung von Brückenbauwerken, die mit vergütetem Spannstahl St 145/160 Neptun N40 bis 1965 erstellt wurden. 07/1993.

[6] Fiedler, M.; Pirskawetz, S.; Kaplan, F.; Holst, R.; Saloga, K.; Schmidt, S.; Sodeikat, C.: Detektion von Spanndrahtbrüchen mit Schallemissionsanalyse – Die neue Richtlinie SE 05 der DGZfP. Beton- und Stahlbetonbau, online first: 18.12.2024 – DOI: 10.1002/best.202400098

[7] Käding, M.; Marx, S.; Schacht, G.: Schallemissionsmonitoring zur Spanndrahtbruchdetektion. In: Bergmeister, K.; Fingerloos, F.; Wörner, J.-D. (Hrsg.): 2023 BetonKalender, Berlin: Ernst & Sohn, 2023, S. 745–777 – DOI: 10.1002/9783433611180.ch15, 2022.