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THE COLLAPSE OF THE CAROLABRIDGE – A TRAGIC INDIVIDUAL CASE?

Summary: The majority of small and medium-span bridges in Germany are made of prestressed concrete. All bridges are inspected at regular intervals to identify damage or load-bearing deficiencies at an early stage. Nevertheless, on September 11, 2024, the prestressed Carola Bridge in Dresden partially collapsed without prior warning. This article first provides an overview of the bridge inventory in Germany and the normative regulations governing their monitoring. It then presents the special design of the Carola Bridge and its construction. The main part focusses on the search for the causes of the failure and an attempt to reconstruct the sequence of events leading to the collapse. The article concludes with an outlook on issues relating to the future handling of bridges containing prestressing steel that is susceptible to hydrogen induced stress corrosion cracking (SCC).

Keywords: stress corrosion cracking, prestressed concrete bridge, collapse

RUŠENJE KAROLA MOSTA – TRAGIČAN POJEDINAČNI SLUČAJ?

Rezime: Većina mostovskih konstrukcija malog i srednjeg raspona u Nemačkoj izvedena je od prethodno napregnutog betona. Vrši se redovan pregled mostova kako bi se u ranoj fazi identifikovala oštećenja ili nedostaci koji redukuju njihovu nosivost. Bez obzira na uobičajene postupke monitoringa, 11. septembra 2024. godine, bez prethodnih znakova upozorenja, desilo se delimično urušavanje prethodno napregnutog most Karola u Drezdenu. Ovaj rad najpre daje pregled podataka koji se odnose na inventar mostova u Nemačkoj i normativne propise koji regulišu njihov monitoring. Rad zatim opisuje projekat konstrukcije mosta Karola. Poseban fokus je na utvrđivanju uzroka kolapsa i rekonstrukciji niza događaja koji su do njega doveli. Na kraju, rad naglašava odrednice koje apostrofiraju upotrebu mostovskih konstrukcija sa prethodno napregnutim čeličnim komponenata koje su osetljive na dejstvo vodonične naponske korozije (SCC).

Ključne reči: prsline usled naponske korozije, most od prethodno napregnutog betona, kolaps

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1. INTRODUCTION

In 2024, there were 40.219 bridges in the stock of federal roads – these are national highway called "Bundesstraße" plus federal controlled-access highways named "Bundesautobahn" – in Germany with more than 31 million m² bridge deck area [1]. In addition, there are tens of thousands of bridges under the responsibility of the sixteen partly sovereign states, of rural and urban districts, local authorities, or e.g. the Deutsche Bahn. Since small and medium spans predominate in Germany, most of them are made of prestressed concrete. Germany's first prestressed concrete bridge was built by Dischinger in Aue in 1937 [2]. The construction method was quickly recognized as robust and efficient. The proportion of prestressed concrete within the range of used bridge building materials has risen steadily since the 1950s and now accounts for almost 70% of bridges on federal highways.

Damage cases involving corrosion-related prestressing steel breaks in prestressed structures or components are not new. International damage cases are compiled in [3]. Already between 1955 and 1965, there was an increase in reported damage cases in building construction and bridge construction. An overestimation of the load-bearing capacity of a finished structure was not the most common cause. Bulk of the damage occurred during construction or during or immediately after prestressing. The two main causes of damage were: (a) the use of prestressing steel that was susceptible to stress-corrosion cracking (SCC) and (b) deficiencies in the construction work, as moisture was often able to reach the prestressing steel unhindered.

The brisance of this issue was recognized very early. For example, strict regulations defining quality requirements for prestressing steel came into force in East Germany in the beginning of the 1950s [4]. Binding regulations were also established for protective packaging during shipping and for storage conditions prior to installation of the reinforcement. In the following decades, these regulations were continuously developed and adapted to new circumstances and knowledge. In the 1980s, a number of dramatic accidents occurred in Germany, concretely the partial collapse of the 'Schwangere Auster' (built with Sigma prestressing steel [5]) and a truss in a production hall in Mannheim in 1989 (built with Neptun prestressing steel [6]) brought the potential danger into focus.

As a result, a first guideline "*Empfehlungen zur Überprüfung und Beurteilung von Brückenbauwerken, die mit vergütetem Spannstahl St 145/160 Neptun N40 bis 1965 erstellt wurden*" (in English: Recommendations for the inspection and assessment of bridge structures built with oil-tempered prestressing steel St 145/160 Neptun N40 up to 1965) with recommendations for dealing with structures containing SCC-sensitive prestressing steel was published [7]. In [8], the group of SCC-sensitive prestressing steel was expanded to include Sigma prestressing steel and oil-tempered Hennigsdorf prestressing steel (until 1982).

2. DESIGN AND CONSTRUCTION OF THE BRIDGE

The Carola Bridge was designed in the 1960s as part of a design competition by the collective Thürmer, Spoelgen from a Dresden engineering office [11]. The approximately 400 m long structure with a single haunch at axis D and five individual spans between 44 and 120 m consisted of three individual superstructures a–c which were constructed as single-cell prestressed box girders [12], Figure 1. The bridge was 32 m wide in total. The superstructures a and b carried two-lane carriageways each (bridge class 60), while a double-track tram line was placed on superstructure c. The outer edges of superstructures a and c featured 3.2 m wide sidewalks for pedestrians and cyclist. Utility lines for district heating, gas, electricity, and water were integrated into the interior of the box girders.

The external shape of the bridge was defined within the frame of the design competition. Due to highly changing moments in a continuous solution, it would not have been possible to realize the spans as planned or to calculate the system at that time. Therefore, an unusual static system was chosen: each superstructure was subdivided by a total of three hinges (see sketch in the middle of Figure 1). This resulted in a two-span girder cantilevering 12 m towards the Elbe river in axes A–C on the Dresden old town bank. Supports D and E carry a single-span girder with two cantilevers – 44 m long towards the Elbe and 10 m long towards Dresden new town. Hinges I to III were arranged at the ends of the cantilever arms. A 64 m long suspension beam bridged the gap between the cantilever arms. An additional suspension beam was placed in the edge span on the new town side. The fixed point was located at the pier in axis D. Here, the superstructure had a maximum construction height of 5.2 m.

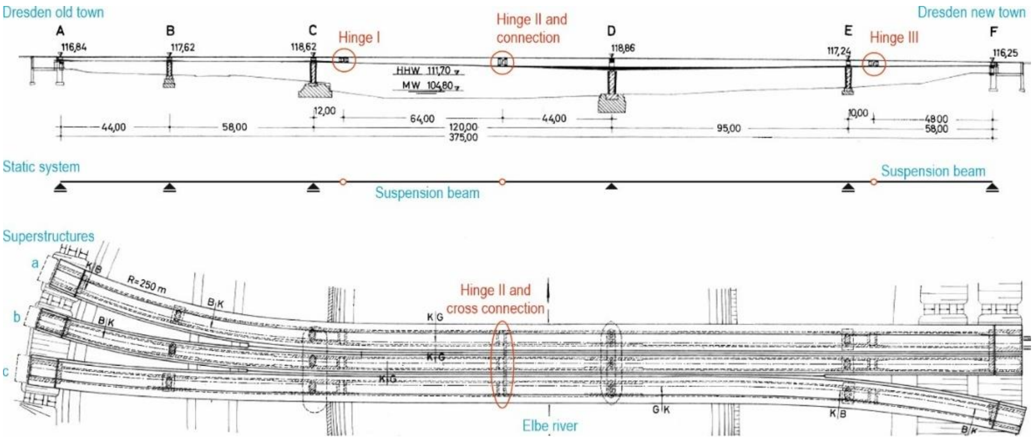

Figure 1: Longitudinal section, static system and ground plan of the Carola Bridge, left: Dresden old town, right: Dresden new town (technical drawings from [12], mod. by Silke Scheerer)

The superstructures were constructed in sections on falsework [14]. The cantilever beams on both sides of the river were erected first. Following, the suspension beam on the new town side and finally the beam over the river were concreted a bit higher than the final position, prestressed and then lowered down. The deck slab tendons were only fully prestressed and grouted after the suspension beams had been positioned. They therefore remained partially prestressed in the sheath tubes pipes for a long period of time and had to be protected against corrosion. Various measures were taken to ensure the best possible corrosion protection. In addition to temperature control and humidity monitoring in the tensioning shed, the BSG were intensively flushed with cold air through the grouting and venting openings daily between concreting and prestressing. This was primarily intended to remove any accumulated condensation. According to contemporary reports, the process was largely under control until the tendons were installed in the formwork, and no rust formation was detected. From then on, the corrosion protection measures are only sparsely documented.

The bridge was opened to traffic in June 1971. It was permanently monitored by different measuring technology, e.g. [30]. It underwent the prescribed structural inspections in accordance with DIN 1076 [10]. And it was recalculated twice. There were no signs of stress corrosion cracking. The renovation of superstructures a and b was completed in June 2024. The renovation of superstructure c was planned for 2025.

3. COLLAPSE ON SEPTEMBER 11, 2024

In the early hours of September 11, 2024, at approximately 2:58 a.m., the collapse of superstructure c of the Carola Bridge abruptly changed the cityscape of Dresden. A surveillance camera belonging to the Saxon Steamship Company, mounted on the bow of a ship, recorded the dramatic event (Figure 2). Looking upstream, it captured exactly the critical area between axes C and D. A frame-by-frame analysis showed the collapse process: first, the area of hinge II began to sink, while a crack opened up at the support cross-section of axis D. Shortly thereafter, the contact wire came into contact with the water. A flash of lightning illuminated the darkness, accompanied by a spraying fountain. Only about eight minutes before the failure, a tram had rolled over this very bridge and most likely initiated the kinematic chain. Fortunately, there were no pedestrians or cyclists on the structure at the time of the collapse.

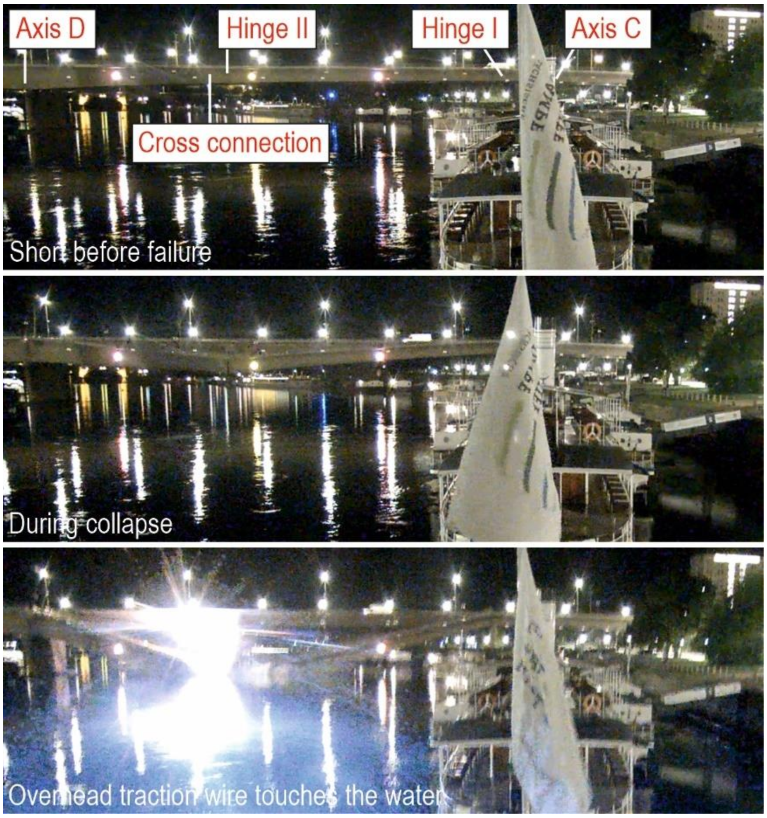

Figure 2: Recordings from a surveillance camera: initial state and moment of collapse (video from Saxon Steamship Company,[18])

At daylight, the extent of the damage became apparent (Figure 3). A state of emergency had already been declared, and the City of Dresden, the fire department, the Federal Agency for Technical Relief (THW), the police, and the German Armed Forces set up a crisis management team at the abutment on the old town side. The responsible road and civil engineering office convened a group of experts who first assessed the acute stability of the still standing superstructures a and b. A look at the torn-open cross-section in axis D of superstructure c immediately provided clues as to the cause of the damage. Just a few hours after the accident, technical documentation of the damage began – initially using drones, and later with photographs taken from the neighboring superstructure b.

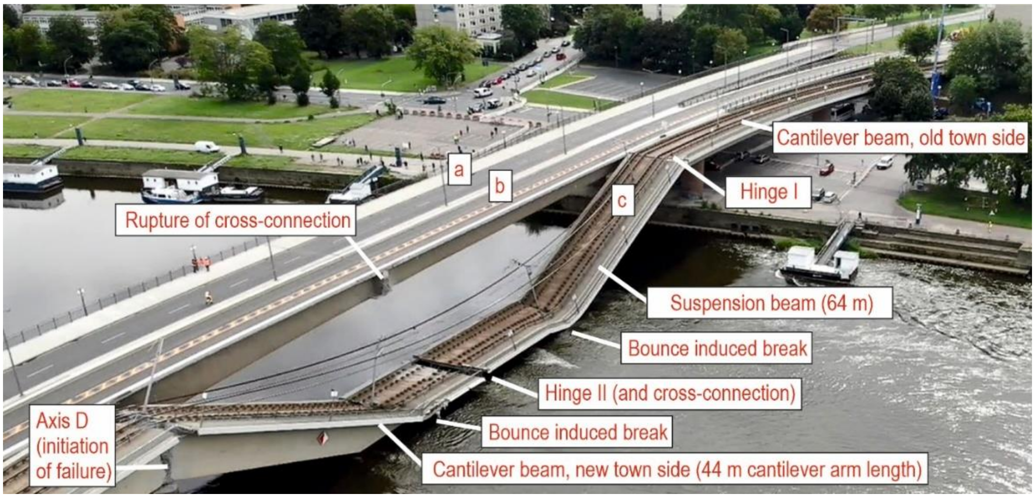

Figure 3: Carola Bridge immediately after the collapse of superstructure c (© MKP GmbH, [16][16, mod.)

4. INVESTIGATIONS AFTER THE COLLAPSE

4.1. GOAL AND EXTEND OF THE INVESTIGATION

The partial collapse of the Carola Bridge deeply shocked not only the city of Dresden but also the professional community in Germany and abroad. The sudden failure of an inner-city bridge structure of great infrastructural importance raised fundamental questions: How could such an event happen? What causes led to the failure? Where did the structural deficit occur? Why did no one detect any signs of an impending failure despite regularly bridge inspections, continuous measurements and successful recalculations? These questions concern not only the engineering assessment of the individual case, but also the derivation of possible consequences for other structures that may be at risk due to previously undetected load-bearing deficits. Last but not least, there is also the question of responsibility for this event.

In order to answer these questions, numerous investigations were carried out on samples from the Carola Bridge. The focus was on the short-term measures taken to assess the condition of the broken cross-section in axis D and to secure material samples in parallel with the dismantling of fields D–F (new town side). This had to be done quickly, as flooding was forecast immediately after the collapse. In addition, targeted investigations were initially carried out on the entire superstructure c. Later, superstructures a and b were also included in the investigations with the aim of obtaining information on their future viability and operational safety. The material-technical investigations were supplemented by an analysis of the inventory documents and interviews with contemporary witnesses, so that the course of the damage could be reconstructed and the cause of the damage clarified.

4.2. INVESTIGATION TO RECORD THE STATE OF DEGRADATION OF SUPERSTRUCTURE C

In the first few hours after the collapse, extensive photographic documentation of the general condition of the structure and, in particular, the broken cross-section at axis D was carried out. The aim was to prevent the condition assessment of the exposed reinforcement from being distorted by weather conditions and incipient corrosion. With the support of a drone squadron from the Arbeiter-Samariter-Bund (Workers' Samaritan Federation), almost all components were documented on the day of the collapse.

The condition of the prestressed wires was visually assessed and categorized. It was clearly visible that the deck slab tendons, which remained partially tensioned in the ducts during manufacturing of the suspension beams (see chapter 2), showed particularly severe pre-damage and dark corrosion on the fracture surfaces (top left photo in Figure 4). Obviously, these wires had been broken for quite some time. Fresh fracture surfaces (top right photo in Figure 4), mainly on web tendons, were metallically shiny with no signs of corrosion, but also without any ductile deformation in the form of necking in the fracture area. In some cases, tendons with visible necking were also found, indicating ductile failure.

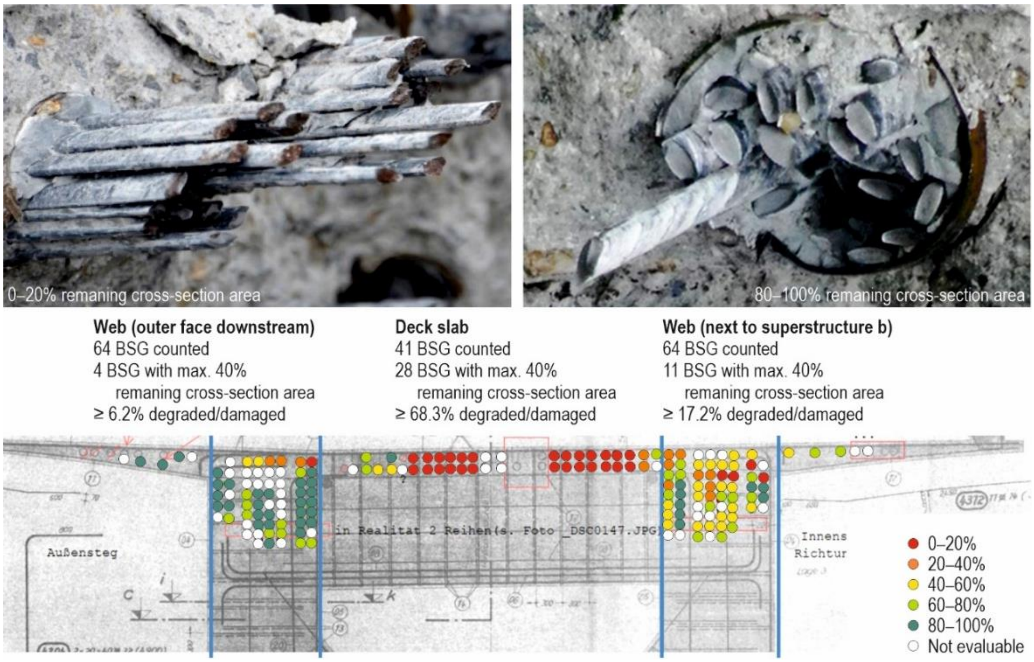

Figure 4: Results of photographic documentation of the condition of the prestressing wires, broken cross-section in axis D, superstructure c, view towards Dresden new town (© MKP GmbH,[16], [19])

In addition to the failed tendons, the broken cross-section of superstructure c was characterized by reinforcing steel that had been pulled out of the concrete in the upper reinforcement layers. This mainly 32 mm thick reinforcement showed no breaks, neckings, or cross-sectional losses, and only occasional, very minor signs of chloride-induced corrosion in the form of localized rusting of ribs. Chloride-induced pitting corrosion did not play a role in the fracture area. In the area of the deck slab, there was significant delamination in the concrete structure between the reinforcement layers. It is assumed that this damage was a direct consequence of the collapse due to the enormous deformations.

During demolition of the failed superstructure at new town side (axes D–F), as many tendon samples as possible were secured and stored for future investigations. Despite the critical timeline and lack of preparation time, individual samples and sampling conditions were documented as accurately as possible. However, with regard to the sampling location, it was often only possible to assign samples to specific spans.

Parallel to the ad hoc investigations, further diagnostic investigations were carried out on superstructure c, as the bridge parts on the old town side were to be demolished at short notice. There were only narrow time windows for further sampling in the dismantling schedule. Several approx. 1.5 m long tendon samples were taken from the remaining support areas in order to be able to compare them with the samples from axis D. Furthermore, tendons were taken in a targeted manner in the area of overhead traction wire masts. Here, penetration of chlorides or stray current corrosion could not yet be ruled out. In addition, tendon samples were taken in the field area from below as well as drill cores from the compression zone and from the roadway.

4.3. IDENTIFICATION OF FAILURE CAUSES

The search for possible causes of the collapse began immediately at September 11. The numerous clues and hypotheses collected from the public and from experts were meticulously investigated. The exclusion principle was applied to remain objective. Hypothesis after hypothesis was refuted systematically in order to ultimately identify a probable cause of the collapse based on a combination of hypotheses that could not be refuted.

Discussions were held with contemporary witnesses from the construction phase and with people responsible for the bridge at the city of Dresden and the Dresden transport company.

As-built documents, experts' opinions and reports were analyzed. This was sometimes difficult. Only some of the as-built documents had been preserved, and the preserved documents had been outsourced for digitization at the time of the collapse. Therefore, construction plans were only gradually available at first. Documents about investigations on the Carola Bridge, e.g. sampling, recalculations, repair works, long-term and short-term measurements (e.g. [17]), were also initially very incomplete. All these kinds of documents were successively completed, evaluated and included in the evaluation.

Many hypotheses could be classified into the categories "impact" and "material resistance". The first category included a possible collapse as a result of an earthquake, of thermal effects from the district heating pipe, which was placed in the hollow box girder, or of dynamic effects during operation. In the second category, particular consideration was given to chloride-induced, microbial or stray current corrosion of the reinforcement. In addition, the condition of the concrete was of interest and the bond behavior between reinforcement and concrete in cracked areas. Special design features such as the Gerber hinges or the cross-connection were also considered.

Thanks to the steady increase in knowledge, individual hypotheses could be ruled out over time. In parallel, the range of possible causes gradually narrowed.

4.4. MATERIAL ANALYSES

The samples obtained were first documented photographically in the laboratory and then subjected to further material tests. In some of the tendon sections taken from the area of the fracture, wire breaks were already detected when the tendon was opened (Figure 5, top). In some cases, cracks were even visible to the naked eye. Many fracture surfaces showed clear signs of corrosion (wires 17 and 18 in Figure 5). It should also be noted that prestressing wires with multiple fractures and a distance of less than 15 cm were found (see wire 17 in Figure 5). This indicates an immediate re-anchoring length of a few centimeters after a break.

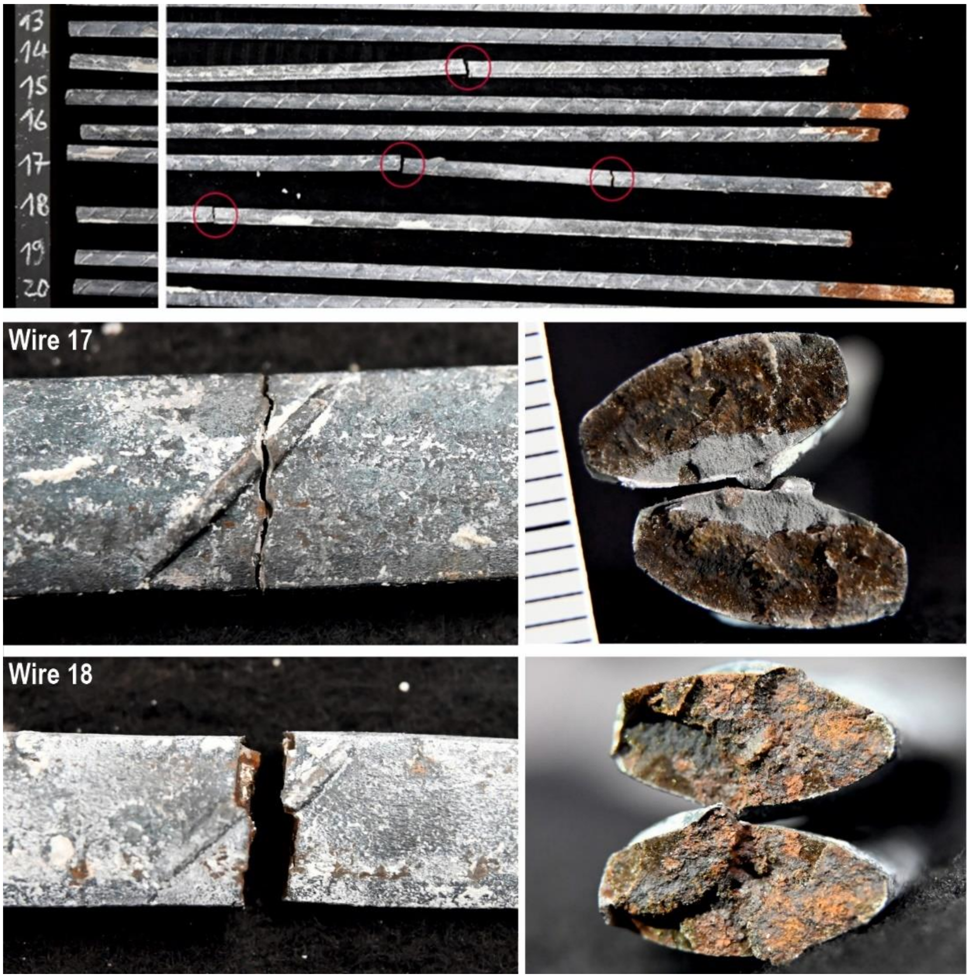

Figure 5: Breaks of wires from a tendon extracted from the failure area in axis D of superstructure c (top) and details of the breaks of the wire 17 and 18 (below) (photos: MKP GmbH,[18])

For further analysis, crack detection tests with magnetic powder, microscopic examinations of the fracture surfaces, microstructural examinations and examinations of the alloy composition carried out at the Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung – BAM), Berlin. Magnetic particle inspection (MPI) tests, cracks or material defects on the surface or close to it can be made visible under UV light using fluorescent magnetic powder particles. The top photo in Figure 6 shows a prestressing wire during MOI investigation with a large number of initial cracks, which can be clearly attributed to SCC. Figure 6 below shows a longitudinal section of a prestressing wire where the typical cracks are also clearly visible.

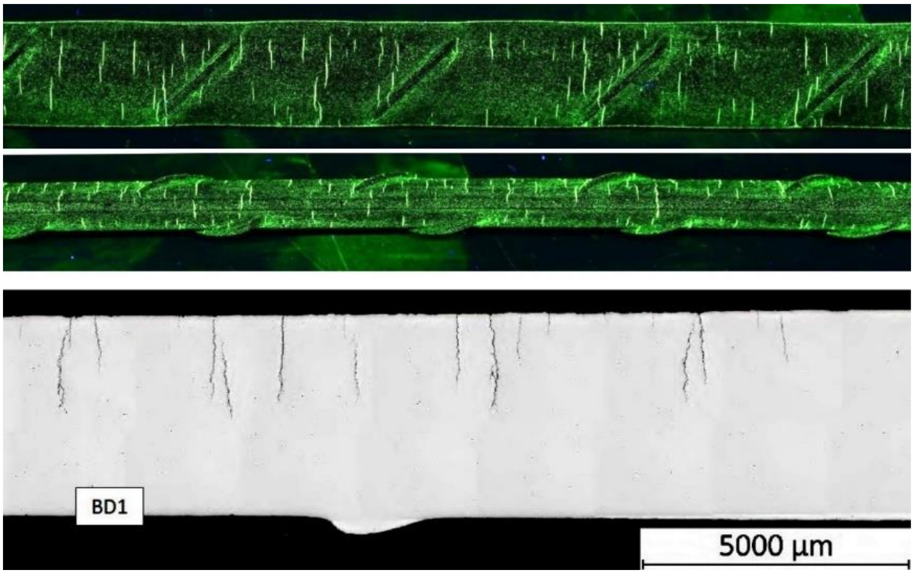

Figure 6: Initial crack detection using fluorescent magnetic powder (top) and longitudinal sectioning (bottom) of two prestressing wires taken from the Carola Bridge (photos: BAM Berlin, [16])

On the post-tensioned tendons in the deck slab in axis D, superstructure c, almost black fracture surfaces were detected on many of the prestressing wires (top left photo in **Error! Reference source not found.** 4). This type of corrosion had already been detected at a bridge that had been constructed using the tension block method [20]. It was therefore known that such oxide layers develop on fracture surfaces that were still exposed to a sufficiently high humidity but not to a high oxygen content. For the time being, however, it remained unclear why only a defined group of prestressing wires exhibited this damage pattern. No significant corrosion damage and in particular no perforation corrosion could be detected locally in the associated ducts. Interaction with penetrating media during operation of the bridge could therefore be ruled out, and also stray current corrosion for the same reason. The most likely assumption is that the prestressing wire fractures most probably occurred during construction or shortly afterwards, but, in any case, a long time ago. During later microscopic examinations of broken wires, mortar adhesions were found on some of the failure surfaces (**Error! Reference source not found.**ure 7), which are a clear indication that these breaks must have occurred before or during grouting.

Figure 7: Wire break with mortar at the fracture surface (photo: BAM Berlin, [19])

It has not yet been conclusively confirmed how the electrolyte that triggered the SpRK came into contact with the prestressing steel. In [21], a significantly increased SO_2 content in the air is suspected. The cause could be the widespread use of lignite for energy production without flue gas desulfurization at the end of the 1960s. Research had revealed daily peak values of up to 1.05 g/m³ SO_2 for the winter months at that time. This is almost 1000 times higher than the values measured today. Attempts are still underway to recreate an electrolyte and use it to treat steels from that period, including prestressed steels with a tempered structure and strength classes St125/140 and St135/150.

The alloy composition of extracted prestressing wire was also determined at BAM using spark emission spectroscopy (FES) in order to rule out any deviation of the chemical composition from the standard values and a resulting batch-by-batch increase in the susceptibility of the prestressing material. A total of eleven batches of different prestressing wire compositions were identified, most of which complied with the specifications of [13]. A higher than general susceptibility of the Hennigsdorf prestressing steel to SCC could not be deduced. The metallographic investigations showed a classic quenched and tempered microstructure with the usual edge decarburization effects in some areas. In static tensile tests at the Otto Mohr Laboratory (OML) of TU Dresden and at BAM, tensile strengths slightly above the nominal values of TGL 101-036 [13] were determined. The plastic deformation capacity was clearly reduced compared to [13]. MPI tests had not been carried out in advance. Further investigations into the tensile and fatigue behavior of prestressing wires taken from the Carola Bridge are currently being planned.

5. RECONSTRUCTION OF THE DAMAGE SEQUENCE

5.1. PHENOMENOLOGICAL INTERPRETATION

The available results indicate that stress corrosion cracking initiated during the construction phase, combined with subsequent progressive damage to the prestressing wires as a result of fatigue loading, was the main cause of the failure. Consequently, in terms of the service life of the bridge, the failure occurred randomly, although external influences contributed to or ultimately caused the failure event.

The main external influence in the hours before the collapse was a drop in ambient temperature, which, however, did not exceed the magnitude that the structure had already endured during its lifetime. When the environment cools down, there is a constant temperature change in the superstructure and also linearly varying temperature differences between the upper and lower edges of the cross-section. The latter result in vertical deformations of the superstructure from a global perspective. A cooling of the ambient temperature causes, for example, a lifting of hinge II. The coupling of the individual superstructures by the cross-connection unwanted generated a static indeterminacy indeterminate in the transverse direction, accompanied by undefinable constrained internal forces. If it is now assumed that superstructure c has already been supported for some time via the cross-connection beam by the superstructures b and a and that there was already a loss of stiffness in superstructure c due to prestressing steel failure in axis D, two scenarios for the damage sequence are conceivable.

In scenario 1, it is assumed that there was already a very large loss of stiffness in axis D of superstructure c. If superstructure c had been a separate, independent system, it would have lifted to a lesser extent than superstructures a and b at hinge II when the environment cooled down. However, due to the existing cross-connection to superstructure b, superstructure c would have been lifted or increasingly supported by it until the cross-connection beam itself failed. In the course of this failure, a redistribution of the transmitted shear force would have taken place, which would then have led to overstressing of the cross-section axis D of superstructure c due to bending.

In scenario 2, it was assumed that the loss of stiffness in axis D of superstructure c had only a minor effect on the deformations of an independent superstructure c system. In this case, superstructure c at hinge II would have risen more than superstructures a and b, as it exhibited a deviating, linearly variable temperature change over the cross-section height due to the missing road surface. As a result, the cross-connection was relieved and the bending stress in axis D increased. This in turn caused overloading there and thus further damage until superstructure c was again sufficiently deposited on the cross-connection as a result of the decreasing cross-sectional stiffness. A state of equilibrium was briefly restored. As the ambient temperature continued to decrease, this process may have been repeated several times, leading to progressive damage in axis D of superstructure c. Similarly, the traffic may have generated fatigue-relevant stresses, e.g. due to the locally concentrated load introduction via the rail support point humps. Ultimately, the stiffness of superstructure c at axis D was reduced to such an extent that scenario 1 was forced to occur and the cross-connection beam and subsequently superstructure c in axis D failed completely.

In addition to the global influence that the change in ambient temperature had on the system, non-linear temperature differences resulted in residual stress states in individual components, which acted as additional stresses on the respective cross-sections. This could have led to additional tensile stresses in the tendons close to the surface and further accelerated the progression of damage in the prestressing wires, particularly in the area of the cross girder inside the box-girder at axis D (deck slab height approx. 1.40 m).

The hinge gap measurements at hinge II [15] showed that the last tram crossing approx. 8 min before the complete failure had initiated a reversal process in the superstructure deformation at this point and that, contrary to the expected superstructure deformation, hinge II did not rise any further as a result of the ambient temperature change. During the streetcar crossing, there was also a partial force redistribution from superstructure c to superstructures b and a, which were not under traffic load at that time. This additional load was absorbed by the cross-connection beam and it can be assumed that no overloading of the connection had occurred up to that point. Accordingly, progressive prestressing wire damage must have occurred in axis D in a short period of time before the collapse event. Analogous to the above description of the process for the ambient temperature change, the interaction between weakening in axis D and increased stress on the cross-connection led to its failure. The streetcar crossing therefore also contributed to the progression of damage in axis D.

5.2. SPECIAL FEATURES OF THE CONSTRUCTION

Mathematical investigations have shown that the impacts that occurred at the time of failure or shortly before did not cause any particularly large or unusual stresses. On the contrary, the cross-section of axis D of superstructure c had already been in a critical condition for some time. Even if the structure had almost only had to support itself, even a small number of further wire breaks would have led to overstressing. This was facilitated by the fact that, particularly in the case of superstructure c, the variable actions that actually occur cause only a small proportion of the bending stress in axis D (cf. [15]). An externally visible announcement of the poor condition of the cross-section at axis D of superstructure c was prevented by the support of the cross-connection at hinge II.

The structural analyses of the Carola Bridge have confirmed that the structure was designed, structurally developed and built with a very high cross-sectional utilization, see [12, 18]. This special feature stood in the way of a pronounced crack formation indicating failure. The expected crack widths remained clearly below the normative limit values for prestressed concrete components, so that the announcement of a critical condition for load bearing capacity would in fact not have taken place at all or only much too late. A reliable prediction, e.g., according to the crack-before-fracture criterion [7], [9], would therefore not have been possible with the permissible and usual methods.

6. CONCLUSION AND OUTLOOK

In summary, it can be stated that the bridge was inspected and monitored in accordance with established engineering standards. Nevertheless, there was no advance warning of an impending failure, and, based on current knowledge, it would not have been possible to detect one. Other damage cases in Germany, such as the bridge over the national highway B 2 near Leipzig, the Damaschke Bridge in Magdeburg, the A 100 ring road bridge at the motorway interchange ‘Funkturm‘ in Berlin, and the bridge on the B 101 near Großenhain, were only detected because there was a reason for a targeted inspection. Consequently, there is a need to critically examine the current national regulations and to adapt them.

The Federal Ministry of Transport (Bundesministerium für Verkehr – BMV) has initiated the research project “Investigation and verification of the causes of the failure of the Carola Bridge with a view to reviewing and possibly revising regulations for concrete bridges” (funding code 15.0729/2024/HRB), in which the effects of the findings from the collapse of the Carola Bridge on other structures are being investigated. As part of the project, the results of the investigations on the Carola Bridge and findings from other privious and current damage cases are being compiled and evaluated. The aim is to identify generally applicable correlations in order to achieve a targeted adaptation of the current guidelines and instruction for action.

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