DOI: 10.3217/978-3-99161-057-1-096

Detection of steel fractures in existing prestressed bridges with DFOS

Harald Burger[1], Nicholas Schramm[2], Oliver Fischer[1,2]
[1]Chair of Concrete and Masonry Structures, TUM School of Engineering and Design, Technical University of Munich, Theresienstraße 90, Building N6, 80333 München, Germany
[2]Büchting + Streit AG, Gunzenlehstraße 22 - 24, 80689 München, Germany
email: harald.burger@tum.de, nicholas.schramm@buechting-streit.de, oliver.fischer@tum.de

ABSTRACT: Prestressed concrete bridges are designed to limit cracking. Aging can lead to prestressing steel fractures with strain changes without visible cracks. To detect and locate fractures, long-term monitoring with distributed fiber optic sensors in combination with acoustic emission sensing is useful. This study focuses on fiber optic sensing based on Rayleigh backscattering. A long-term monitoring system was installed to ensure the service of two prestressed concrete bridges in Munich. Their prestressing steel is at risk of stress corrosion cracking. For reliable operation of the fiber optical measurements, tests were carried out both in the lab and in the field to investigate the measurement signal in conditions that are as isolated as possible. On the bridges data is collected at three-month intervals starting in 2021. Furthermore, strain changes caused by temperature fluctuations and traffic loads were captured. Moreover, valuable insights are being gained in a long-term operation. The investigations show that long-term fiber optical strain measurements are useful to assess the structural behaviour of existing prestressed bridges over several years and can ensure safety of structures.

KEY WORDS: SHMII-13; prestressed bridges, DFOS, stress corrosion cracking.

1 INTRODUCTION

The first standards and regulations for prestressing steel in Germany were developed after 1945 [1]. The first decades of the use of prestressing steel were the source of many structural problems in prestressed bridges. Due to the lack of knowledge at that time, some deficiencies can still be found in existing bridges today. One such material defect is the susceptibility of prestressing steel to stress corrosion cracking. This can lead to brittle failure of the steel without plastic deformation and subsequent collapse of the component without warning. Recently stress corrosion cracking led to the component failure of the Carola Bridge in Germany [2]. In this case, cracks were observed years before failure, but the existing crack widths were below the standard limits [3]. Acoustic emission (AE) monitoring is proposed for the remaining bridge components [4].

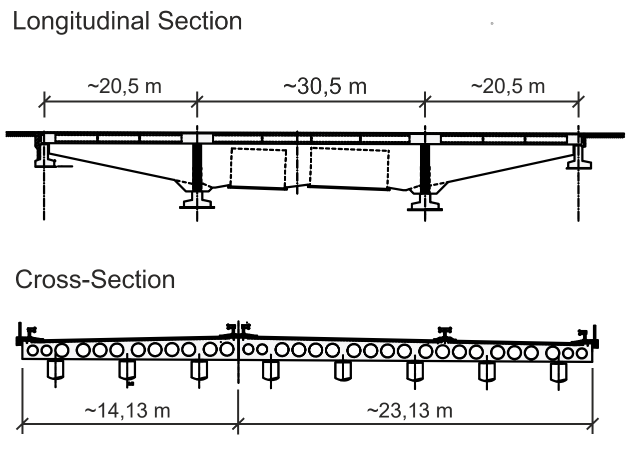

Figure 1. longitudinal and cross-section of the bridge „Kreuzhof“ BW40/45

In Munich, a monitoring system with AE has been in operation since 2021 on two bridges with prestressing steel sensitive to stress corrosion cracking. Additionally, distributed fiber optical sensors (DFOS) are in usage for crack detection. On these bridges, DFOS can also be used to monitor structural behaviour. This application of DFOS for structural behaviour monitoring has been carried out in many cases. [5], [6], [7] and [8] are just a few examples. This case study provides some insights into the laboratory and field tests and shows selected results from the past years.

2 MONITORING KREUZHOF BRIDGES

German bridges with stress corrosion cracking sensitive steel must be reassessed according to the guideline HA SpRK [9]. This guideline recommends the numerical verification of sufficient warning behaviour as crack-before-failure. For both "Kreuzhof" bridges, the crack-before-failure criterion could not be verified in every section. But even in areas with sufficient warning behaviour, an object-related inspection instruction must be defined.

The bridges were built in 1967 and span a four-lane road. They are three-span slab bridges with longitudinal tubular voids and span lengths of about 20.5 m – 29.0 m – 20.5 m. The concrete slabs are prestressed by the bonded post-tensioning system according to the approval of the company “Polensky und Zöllner”. There is a minimum of two and a maximum of six post-tensioning tendons in each web between these hollow bodies. Figure 1 shows the longitudinal and the cross-sectional profiles of bridge “BW40/45”.

Acoustic emission sensors have been installed for direct detection of steel fractures. They are measuring continuously since 2021. The local and global structural response to fractures is measured as strain changes along the length of the bridge.

DOI: 10.3217/978-3-99161-057-1-096

Data is collected three to four times a year using BRUSens V9 distributed fiber optical sensors. Rayleigh backscattering technology is used with the ODiSI instrument manufactured by Luna Innovations Incorporated. The DFOS are applied in a groove milled into the structure and are located in every second web on the bottom of the slabs. In addition, 1.5 years of data acquisition was carried out using different sensor technologies for object-specific traffic load determination (B-WIM system). More details can be found in [10] and [11].

3 VERIFICATION OF STRAIN MEASUREMENTS

For verification of the measurements tests were performed in the laboratory using the same type of sensor. The BRUSens V9 is a layered sensor with an outer PA sheath, a stainless steel tube and a multilayer buffer to the optical fiber. In order to simulate the strain transfer from the host material to the sensor core in an equivalent way, the sensor was applied to a concrete specimen using the same method. The aim of these tests was to investigate conditions that were as isolated as possible. This was achieved by applying pure compressive, tensile or temperature loads, generating a specific crack width and performing a long-term test under constant conditions. In addition, different sensors with the same and different measurement principles were used for each test to validate the reliability of the strain signal.

Test loads were also applied to the bridges by trucks at the beginning of the monitoring and repeated after six months. The tests were carried out to assess structural behaviour and to analyse environmental effects on the measured data. For in-field verification, it was possible to compare the DFOS results with those from the B-WIM strain gauges.

4 RESULTS AND DISCUSSION

Laboratory tests show reliable results for compressive and tensile strains in the uncracked concrete. When cracks appear, due to the sensors layers a slippage can occur. In this case the crack width can no longer be determined exactly. Various studies have also analysed the measurement signal at crack opening with different sensors, i.e. [5], [12], [13], [14]. The appearance of a crack manifests itself always as a strain peak, even in the case of slippage. In prestressed structures already new formed small cracks are first signs of a deterioration.

If a test specimen is subjected to a constant temperature load, the DFOS BRUSens V9 will record the thermal expansion of the inner stainless steel jacket layer. In addition, the strain profile scatters over the sensor length with increasing temperature difference. In the tests, a value between 15 und 19 × 10^{-6}/K was determined for the thermal expansion coefficient of the sensor, whereby the average value is 16 × 10^{-6}/K according to the manufacturer Solifos AG [15].

Strain measurements on the bridges show that only very small strain changes of less than 30 µm/m (0.03 ‰) occur when two trucks with a maximum vehicle weight of 42 tonnes are loaded. This means that the measurement signal from light vehicles such as cars is masked by the DFOS measurement noise. On both bridges no cracks have been detected since the start of monitoring.

In contrast, strain changes due to temperature variations are particularly pronounced. Figure 2 presents selected results from the mid-span of the 'Kreuzhof' bridges. The raw data taken on twelve different days since November 2021 are shown. When these results are compared with the theoretical strain change at the given temperature, the same influence of thermal expansion on the data as in the laboratory results is observed. Furthermore, strain peaks in Figure 2 have a dominance of approx. 200 µm/m (0.20 ‰). In laboratory tests, such peaks are an indication of the presence of a crack. A visual inspection of the bridge revealed an offset in the concrete surface in the location of the peak. This concrete offset results in a longitudinal offset of the sensor, which means that linear strain transmission between the concrete and the glass fibre core is not possible. When comparing all measurements over several years, the strain peaks appear in the same location. Provided a single measurement signal is referenced to a measurement taken at a similar temperature, no more pronounced strain peaks are visible. The conclusion is that no new strain change has occurred at these locations. In a theoretical case of a possible prestressing steel fracture, a local peak would appear that could be distinguished from the temperature.

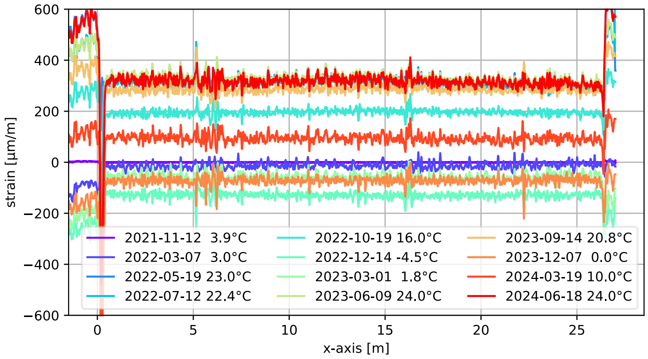

Figure 2. Raw data of the results and the corresponding temperature in the mid-span of bridge BW40/45 from November 2021 to June 2024

5 CONCLUSION

The long-term monitoring on the “Kreuzhof” bridges in Munich, employing acoustic emission sensors and distributed fiber optic sensors (DFOS), does guarantee a safe operation of the bridge service. Laboratory tests have been crucial in understanding the limitations and reliability of the DFOS measurements, particularly in the presence of cracking and temperature variations. While with in field tests object specific limitations are discovered.

The City of Munich decided to replace the bridges due to the risk of stress corrosion cracking in the prestressing steel and a future tram line which will pass under these bridges. In January 2025 destructive structural tests were carried out shortly before the partial dismantling to validate the monitoring system. The first results will be generated in the middle of the year 2025.

ACKNOWLEDGMENTS

The authors would like to thank the Department of Civil Structures of the City of Munich for the project assignment and the pleasant cooperation.

DOI: 10.3217/978-3-99161-057-1-096

REFERENCES

[1] S. Geßner, R. Niedermeier, M. A. Ahrens, J. Hegger, O. Fischer und P. Mark, "Spannbetonbau – Entwicklung, Bemessung und Konstruktion," in Beton-Kalender 2017: Spannbeton, Spezialbetone. 2017

[2] Marx Krontal und Partner GmbH. Carolabrücke - Schadensursache und Hergang des Teileinsturzes. Retrieved March, 2025, from https://ratsinfo.dresden.de/si0056.asp?__ksinr=14555

[3] Landeshauptstadt Dresden. Carolabrücke. Retrieved March, 2025, from https://www.dresden.de/de/rathaus/aktuelles/pressemitteilungen/2024/12/pm_024.php

[4] Marx Krontal und Partner GmbH. Vorläufige Erkenntnisse zur Ursache und Hergang des Teileinsturzes der Carolabrücke. Retrieved March, 2025, from https://www.dresden.de/media/pdf/presseamt/2024_12_11_Carolabruecke_Zusammenfassung-Ergebnisse.pdf

[5] Monsberger, C.M.; Lienhart,W. Distributed Fiber Optic Shape Sensing of Concrete Structures. Sensors, 21, 6098. 2021 https://doi.org/10.3390/s21186098

[6] Bednarski L.; Sienko R.; Howiacki T.; Zuziak K.; The Smart Nervous System for Cracked Concrete Structures: Theory, Design, Research, and Field Proof of Monolithic DFOS-Based Sensors. Sensors 22, 8713. 2022 https://doi.org/10.3390/s22228713

[7] Novák, B.; Stein, F.; Reinhard, J.; Dudonu, A.: Einsatz kontinuierlicher faseroptischer Sensoren zum Monitoring von Bestandsbrücken. In: Beton- und Stahlbetonbau Volume 116, Issue 10, S.s 718-726. 2021 https://doi.org/10.1002/best.202100070

[8] Herbers, M; Richter, B.; Bartels, J.; Al-Zuriqat, T.; Smarsly, K.; Marx, S.: openLAB – A large-scale demonstrator for advancing digital twin developments of bridges. Ed.: Richard S. Henry, Alessandro Palermo: fib. The International Federation for Structural Concrete- ReConStruct: Resilient Concrete Structures. 2024

[9] Bundesministerium für Verkehr, Bau und Stadtentwicklung: Regelungen und Richtlinien für die Berechnung und Bemessung von Ingenieurbauwerken (BEM-ING) –Handlungsanweisung Spannungsrisskorrosion - Handlungsanweisung zur Überprüfung und Beurteilung von älteren Brückenbauwerken, die mit vergütetem, spannungsrisskorrosionsgefährdetem Spannstahl erstellt wurden. Bonn, 2011.

[10] Burger, H; Tepho, T.; Fischer, O.; Schramm, S.: Performance assessment of existing prestressed concrete bridges utilizing distributed optical fiber sensors. Biondini, F.; et al. [edit.] Life-Cycle of Structures and Infrastructure Systems. London: CRC Press. 2023

[11] Burger, H; Tepho, T.; Fischer, O.; Schramm, S. Load testing on existing prestressed concrete bridges to determine long-term effects on strain measurement. Jensen, J. S. et al. [edit.] Bridge Maintenance, Safety, Management, Digitalization and Sustainability. London: CRC Press. 2024

[12] Fischer, O., Thoma, S. & Crepaz, S.: Distributed fiber optic sensing for crack detection in concrete structures. In Civil Engineering Design, 1 (2019): 97-105. https://doi.org/10.1002/cend.20190000

[13] Herbers M.; Richter B.; Gebauer D.; Classen M.; Marx S.: Crack monitoring on concrete structures: Comparison of various distributed fiber optic sensors with digital image correlation method. Structural Concrete Volume 24, Issue 5. 2023 https://doi.org/10.1002/suco.202300062

[14] Bassil, A., Chapeleau, X., Leduc, D. & Abraham, O.: Concrete Crack Monitoring Using a Novel Strain Transfer Model for Distributed Fiber Optics Sensors. Sensors, 20, 2220. Basel, Switzerland. 2020 https://doi.org/10.3390/s20082220

[15] Breuer, S. (Solifos): personal communication, June 16, 2022