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Distributed fiber optic sensing of bridges with stress corrosion cracking

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ABSTRACT: Stress corrosion cracking (SCC) of prestressing steel represents a critical threat to the long-term safety and serviceability of aging bridge infrastructure. This phenomenon occurs within the cross-section and leads to the initiation and propagation of cracks, ultimately causing the rupture of the prestressing wires, which may ultimately result in sudden bridge failure. This underscores the need for reliable monitoring solutions. Traditional non-destructive testing techniques, while valuable, often lack high-resolution capabilities. In contrast, Distributed Fiber Optic Sensing (DFOS) has emerged as a transformative approach, offering high-resolution, continuous monitoring of strain distribution and crack development in concrete structures. This study demonstrates the practical application of DFOS technology for detecting and quantifying crack propagation in operational bridge structures affected by the risk of active SCC. By considering field investigations on four infrastructure projects the research evaluates DFOS performance for structures vulnerable to SCC. The paper demonstrates the technology's capability to monitor crack dynamics under operational conditions as anomalies in the crack pattern may indicate early symptoms of structural damage caused by SCC. By bridging knowledge gaps in the application of DFOS for infrastructure safety, the study advances the role of fiber optic sensing in addressing SCC challenges, ultimately contributing to the development of more resilient and sustainable bridge monitoring systems.

KEY WORDS: DFOS, distributed fiber optic sensing, stress corrosion cracking, bridge monitoring, SHM, structural health monitoring.

1 INTRODUCTION

1.1 Background and motivation

Stress corrosion cracking (SCC) is a critical degradation mechanism in prestressed concrete bridges. This phenomenon involves the initiation and gradual propagation of cracks in prestressing wires inside the cross-section, often remaining undetectable by conventional methods in early stages. As the process advances, stress concentrations may lead to surface cracking in prestressed elements. Progressive SCC results in sequential wire rupture, reducing structural capacity and potentially leading to sudden failure. This form of corrosion is particularly insidious due to its delayed manifestation and the absence of external indicators, making early detection extremely difficult. Numerous historical cases have shown that even well-constructed bridges can suffer unexpected failures due to SCC, emphasizing its relevance for long-term structural integrity [1]. As many existing bridges age and are subjected to increasing traffic loads, the risk posed by SCC continues to grow. Conventional inspection techniques often fail to capture early signs of SCC, prompting the need for advanced, reliable monitoring methods. Therefore, the development and implementation of modern evaluation and monitoring strategies are essential to ensure the safety and longevity of critical infrastructure.

1.2 Scope and objectives of the article

This paper focuses on the application of Distributed Fiber Optic Sensing (DFOS) in the monitoring of structures susceptible to SCC, with examples of identifying structural response to loading, crack detection, and evaluation of crack width changes. The article also outlines the advantages of DFOS over conventional inspection methods, emphasizing its ability to provide continuous, high-resolution, and little-invasive monitoring.

2 FUNDAMENTALS OF STRESS CORROSION CRACKING IN BRIDGES

2.1 Mechanisms of SCC in prestressing steel

The phenomenon of SCC refers to the chemical and/or electrochemical corrosion of a material under the simultaneous influence of static tensile stress. Two primary types of SCC in steel can be distinguished: anodic and cathodic corrosion [2]. Anodic corrosion involves the decomposition of material at the surface through an electrolytic reaction. Cracks form deep inside the crystal structure and are not visible from the outside. In contrast, cathodic corrosion occurs when free hydrogen atoms penetrate the metal's crystal structure. As hydrogen molecules form, they cause internal expansion, which leads to crack initiation along the grain boundaries.

Microscopic corrosion scars are usually the points of crack initiation. Scanning electron microscope (SEM) studies have shown that microcracks begin at weak points in the grain structure and grow into a honeycomb-like pattern [2]. The visible signs of stress corrosion manifest as numerous microcracks, perpendicular to the axis of the prestressing strand, starting at the surface and progressing inward —

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see Fig. 1. What makes SCC particularly dangerous is progression without visible deformation of the structure or expansive corrosion products, meaning failure often happens suddenly due to brittle fracture of the prestressing steel.

In Germany, high-strength steels with tensile strengths above 1700 N/mm², used primarily in the 1960s and 1970s, are considered particularly susceptible to SCC. This includes steel types such as Neptun St 145/160 (FRG), Sigma St 145/160 (FRG), and Hennigsdorf St 140/160 (GDR) [3].

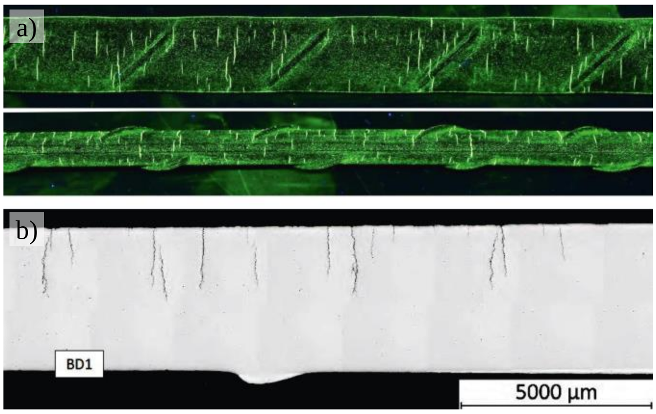

Figure 1. Inspection of the prestressing strand taken from the Carola Bridge (Dresden): a) microcracks visible by fluorescent magnetic particle method, b) longitudinal section [4]

2.2 *Impact of SCC on structural integrity and service life*

Several failures of well-designed and properly built structures have been linked to SCC. A prominent example is the partial collapse of a production hall in Mannheim in 1989, after 28 years of use. Investigations revealed that the primary cause was the loss of flexural capacity in the roof girders due to SCC. Despite proper grouting and maintained alkalinity, the prestressing wires showed numerous microcracks characteristic of SCC. Similar damage occurred in Mühlacker in 1992, where only rapid intervention prevented a collapse. Even with completely filled ducts, SCC-induced cracking was found in the prestressing steel. In some cases, such as the collapse of the Berlin Kongresshalle in 1980, SCC acted as an additional factor accelerating degradation, alongside moisture and chlorides.

Recent events underline the ongoing relevance of SCC: In September 2024, a 100-meter section of the Carola Bridge in Dresden collapsed due to severely corroded and fractured steel tendons [4]. The collapse caused major infrastructure and traffic disruptions in the city. Demolition of the remaining structure is currently planned. Similarly, in November 2024, the Elbe Bridge in Bad Schandau was immediately closed after inspections revealed longitudinal cracks in prestressed elements (particularly in the lower arch). The closure caused significant local transport disruptions, with temporary ferry services established. At the beginning of April 2025, load tests of the bridge were conducted. The collected results, including strain measurements using DFOS, were used to calibrate the computational model. Based on the performed analysis, authorities decided to temporarily reopen the bridge for use, with a restriction on the maximum allowed vehicle weight.

It is estimated that in Germany, there are at least 500 [5], [3] or even 1000 bridges [6] still in service that contain prestressing steel susceptible to SCC. Due to the considerable costs and potential socio-economic consequences, it is essential to take actions aimed at extending the service life of these structures while maintaining an appropriate level of safety and considering the economic and environmental impacts.

2.3 *Limitations of conventional monitoring technologies*

Conventional monitoring methods have notable limitations in detecting and observing SCC. Visual inspection, though widely used, is time-consuming, costly, and limited to surface-level damage. Moreover, the reproducibility is limited due to the high dependency of crack localization on the observer's perception, as well as on environmental conditions at the time of inspection, such as temperature and humidity. It cannot detect microcracks or subsurface flaws, which often form due to localized stress concentrations – such as those caused by ruptured prestressing tendons [7].

Non-destructive testing methods like ultrasonic or radiographic testing offer deeper insight but still struggle with early-stage SCC, particularly in inaccessible areas or complex geometries [8]. These methods require skilled operation, offer limited scanning depth, and are significantly affected by the density of reinforcement. Early-stage SCC, which typically begins as microscopic damage below the surface, can avoid being detected until it becomes critical. Conventional techniques lack sensitivity to local stress concentrations, which are critical indicators of potential SCC initiation [9].

3 DISTRIBUTED FIBER OPTIC SENSING (DFOS) FOR STRUCTURAL MONITORING

3.1 *Principles and advantages of DFOS*

DFOS systems utilize the Rayleigh, Brillouin, or Raman scattering mechanisms in optical fibers to measure strain, temperature, or vibration continuously along the fiber length [10], [11]. Optical fibers serve both as the sensing element and the transmission medium, making them ideal for long-range, distributed measurements without the need for discrete sensors. Depending on the chosen scattering principle and instrumentation (e.g., OFDR, BOTDA), high spatial resolution (down to the millimeter scale) and varying sensing ranges (from 100 m to over 80 km) can be achieved [12].

The DFOS technology offers the following advantages:

- Provides high-resolution structural monitoring over time and along the full length of the sensor [13].
- Enables early detection of the cracks in reinforced and prestressed concrete structures, with the sensitivity allowing to detect even microcracks with very small widths [14].
- DFOS can be integrated into digital twin models and automated data analysis pipelines, supporting predictive maintenance and real-time infrastructure assessment [15].

3.2 *Application of DFOS in crack detection and strain monitoring*

Distributed Fiber Optic Sensing (DFOS) enable continuous, high-resolution strain measurements that are particularly effective for detecting cracks and evaluating their width changes in reinforced and prestressed concrete structures. Cracks are identified by localized strain peaks in the profile, which are analyzed based on parameters such as prominence, height, and width. The key challenge lies in

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distinguishing these from peaks caused by noise or local deformation accumulations, which do not necessarily indicate cracks [16]. Crack detection is based on the algorithms employing a topographic approach, with peak height and prominence serving as key parameters. They quantify how distinctly a peak stands out from its surrounding strain environment. The careful selection of these parameters is critical: if set too high, adjacent cracks may be mistakenly interpreted as a single, broader crack, while if set too low, insignificant microcracks may be falsely detected, leading to overestimated number of cracks and underestimated widths of the real cracks at the same time. Additional parameters such as minimum peak width are employed to further filter out noise and ensure that only meaningful strain concentrations are considered.

The width of an identified crack is calculated as the integral of the strain distribution between local minima, which define the boundary of the strain peak – see Fig. 2. In reinforced concrete members, the tension stiffening effect reduces the apparent crack width, what is included by adjusting the area under the strain distribution curve according to the following equation

$$w_{cr,i} = \int_{x_{cr,i}-l_{t,i}^{-}}^{x_{cr,i}+l_{t,i}^{+}} \varepsilon\,(x) - \varepsilon^{\mathrm{TS}}(x)\mathrm{d}x \qquad (1)$$

where:

$x_{cr,i}$ – position of the crack,
$l_{t,i-}$ – distance to the preceding local minimum,
$l_{t,i+}$ – distance to the following local minimum,
$\varepsilon\,(x)$ – measured strain,
$\varepsilon^{\mathrm{TS}}(x)$ – strain resulting from tension stiffening effect.

Practically, the effect of tension stiffening is accounted for in crack width calculations by subtracting the shaded regions, representing the contribution of concrete, from the total area under the strain distribution curve. These regions are typically approximated as triangular zones with peak values located at midpoints between adjacent cracks.

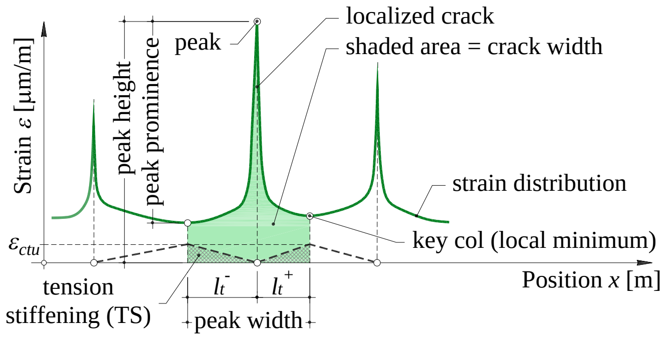

Figure 2. Parameters included in crack detection and estimation of crack width

The presented approach allows for accurate quantification of width changes as small as 0.02-0.05 mm [17]. Herbers et al. [18], [19] demonstrated that Rayleigh-based DFOS systems can reliably identify cracks across different fiber types and installation methods, achieving results comparable to those obtained using high-resolution digital image correlation (DIC) techniques.

In addition to crack monitoring, DFOS is also effective in identifying prestressing wire or tendon failures. Abrupt strain changes – such as localized jumps or sudden deviations in gradient – are key indicators of tendon breakage events and can be detected with high spatial resolution [20]. Such events can be detected using DFOS, which is particularly well-suited for periodic measurements. To enhance diagnostic capabilities, it might be advantageous to integrate DFOS with complementary, continuous monitoring techniques such as Acoustic Emission (AE). In this configuration, AE signals can serve as event-based triggers, initiating high-resolution DFOS measurements to enable accurate spatial localization of damage. As DFOS provides a thorough strain distribution along the length of the sensor, it allows also to determine the anchorage length of prestressing tendons based on strain measurements along the tendon axis after cutting [21]. Furthermore, DFOS facilitates the creation of digital crack maps and enables the tracking of strain development under load and temperature fluctuations. These features support automated condition assessment, early damage detection, and risk-informed maintenance strategies [22].

3.3 DFOS Performance in Detecting Crack Initiation and Propagation

The initiation of cracking in concrete is typically associated with a localized strain concentration, which DFOS detects as a sharp and narrow strain peak along the fiber path. These peaks emerge even before visible cracking occurs and serve as early indicators of damage accumulation. Once cracks are initiated, DFOS allows for real-time tracking of their propagation. Lemcherreq et al. [23] applied DFOS under monotonic and cyclic loading, demonstrating that cyclic strain accumulation is directly correlated with the development of microcracks and that bond shear stresses progressively redistribute toward the unloaded end with an increasing number of load cycles. Importantly, the repeated loading (1 000 000 load cycles) did not impair the quality or reliability of the DFOS measurements throughout the test.

Based on the study by Broth and Hoult [24], it can be concluded that after 3 600 load cycles, strain profiles still captured distinct peaks at crack locations, with strain gradients evolving due to stress redistribution. Crack breathing was clearly visible in the strain signals across load cycles. The sensors enabled the recording of a gradual increase in strain peaks during successive loading cycles, particularly in deep beams, which suggested the widening of previously formed cracks. Initially, the strain values at crack locations reached approximately 1400–1500 μm/m, increasing to nearly 2000 μm/m by the final cycle of the test.

The DFOS system described by Galkovski et al. [25] achieved a measurement resolution of up to 10 μm/m (0.001%), allowing for detection of early-stage microcracking. Strain peaks exceeding 12 000 μm/m (1.2 %) were measured at crack locations—well above the steel yield strain (~2 000 μm/m), indicating DFOS capability to track yielding and post-yield bond behavior.

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3.4 Limitations and Challenges

The application of DFOS in SHM of prestressed concrete structures susceptible to SCC offers comprehensive strain analysis. Conducting measurements that enable the acquisition of data essential for a reliable and unequivocal analysis necessitates careful consideration of the following aspect:

- interference from overlapping strains within the intensively cracked areas affected by superimposed long-term strains (from creep, shrinkage, or thermal gradients), complicating damage localization and potentially masking SCC-related events [26];
- proper choice of the sensor-adhesive combination and measurement settings are crucial for reliable measurement results and good quality data [19].
- quality of the installation – successful application of DFOS relies on the proper sensor installation. Adhesive selection, groove preparation, and embedding quality significantly influence data accuracy. Unsuitable adhesives or rough interfaces can introduce artificial strain peaks or suppress real ones [27];
- data interpretation – measurements, above all the 24/7 monitoring processes, produce large datasets requiring robust post-processing algorithms to distinguish true damage signs from noise, thermal effects, or adhesive degradation. Misinterpretation may lead to false alarms or overlooked damage [28], [29];
- sensor length affecting data quality – with longer sensors, optical device constraints lead to reduced spatial resolution and sampling rate [19]. This decline in performance is accompanied by increased measurement noise, which may obscure or distort strain events associated with SCC. In practical terms, a compromise must be made between coverage area and data fidelity, depending on the selected DFOS interrogation technology [11].

4 FIELD INVESTIGATIONS ON REAL INFRASTRUCTURE ASSETS

In the following section case studies demonstrating the application of DFOS for monitoring bridge structures susceptible to SCC are presented. The focus is on real-world infrastructure where DFOS enables early detection of microcracks, evaluation of changes in crack widths, and assessment of structural behavior under operational loading.

4.1 Considerations for DFOS Deployment at Bridge Structures

The installation of DFOS systems in existing bridge structures requires meticulous engineering, application-specific adaptation, and access to specialized equipment. Sensor routes must be defined with precision, targeting critical zones such as anchorage areas, webs, soffits, and coupling joints [30] – regions particularly vulnerable to hidden damage or prestressing wire fracture. For installations in existing structures reference measurements ("zero measurements"), ideally under constant loading conditions (no traffic), are used to initialize monitoring cycles and enable tracking of structural evolution over time.

The fiber optic sensors are typically bonded to prepared surfaces using adhesives. While exact details vary, the standard approach includes marking sensor paths, cutting grooves, and embedding the sensors with injection mortars, ensuring robust strain transfer from the measured substrate to the sensor core. These operations are carried out with specialized cutting and cleaning tools. Due to the location of sensors on the underside of structural elements, auxiliary access equipment, such as scaffoldings, under-bridge platforms, or telescopic lifts, is often necessary – see Fig. 3.

Figure 3. Examples of the special equipment for sensor installation: a) lifting platform, b) under-bridge inspection device

Furthermore, proper choice of the sensors used is crucial for meeting the demands of the monitoring purpose – for high-resolution crack assessment, monolithic fiber optic sensors provide the best results, while their consistent and rigid geometry ensures more direct strain transfer. This is essential for accurately capturing sharp strain gradients near cracks [19]. Environmental durability and system reliability are ensured not only by using robust sensors, but also by routing fiber leads in protective conduits and terminating them in sealed cabinets. Additionally, to distinguish mechanical strain from temperature-induced effects, several thermal compensation methods are employed in practice [31]. Temperature influence strain measurements through changes in the refractive index (which represents the dominant effect on the results) and the thermal expansion of the fiber. One approach involves interrogators based on Raman backscattering, which is sensitive to thermal effects only. Alternatively, two interrogators (e.g., Rayleigh and Brillouin) can be used on the same fiber, allowing for precise measurements but requiring laboratory calibration. Mechanically decoupled reference fibers, typically embedded in gel, may be affected by friction and are generally more suitable for shorter measurement sections. The simplest and most cost-effective, though less precise, solution involves pointwise temperature measurements using conventional resistance temperature sensors embedded in structural members – particularly suitable for applications with minimal temperature gradients. In such cases, compensation is performed by subtracting the strain resulting from the known temperature change.

In the following sections, four examples of monitoring bridges at risk of SCC using DFOS technology are presented. In all reported implementations, monolithic sensors EpsilonSensor Ø3 mm (manufacturer: Nerve-Sensors) were installed. These sensors featured single-mode (SM 9/125) optical fibers and an external braid that additionally enhanced adhesion. Measurements were carried out using Rayleigh backscattering technique, with a spatial resolution of either 1.3 mm or 2.6 mm, depending on the total sensor length. Thermal compensation was achieved based on discrete temperature measurements. These measurements accounted for the previously discussed effect of the temperature change and the associated thermally induced strain changes.

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4.2 Asset 1: Königsbrücker Str. Bridge in Dresden

The bridge at Königsbrücker Straße in Dresden, constructed in 1979, crosses railway infrastructure and consists of three structurally independent units: one for tram traffic and two for road traffic. Due to the use of Hennigsdorf's prestressing steel a dedicated structural health monitoring (SHM) system based on DFOS and AE combination was deployed to ensure continued structural safety and detect early signs of deterioration [32]. Fiber optic sensors were installed along the full length of each superstructure, embedded into grooves on the bottom surface and bonded with high-performance mortar, enabling high-resolution, distributed strain and crack monitoring – see Fig. 4. Measurements are being conducted since November 2023, including an initial zero measurement and further follow-up measurements under varying seasonal and operational conditions.

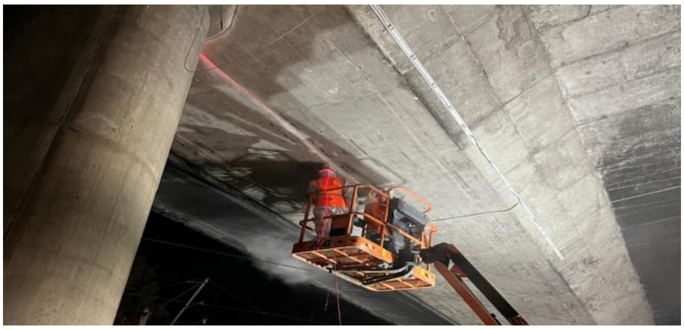

Figure 4. Installation of the optic sensor on the bottom surface of the girder

Across all monitored spans, the DFOS system consistently detected multiple microcracks, with crack width variations typically below 0.05–0.07 mm and strain peaks occasionally exceeding 1000–1600 µm/m – see Fig. 5.

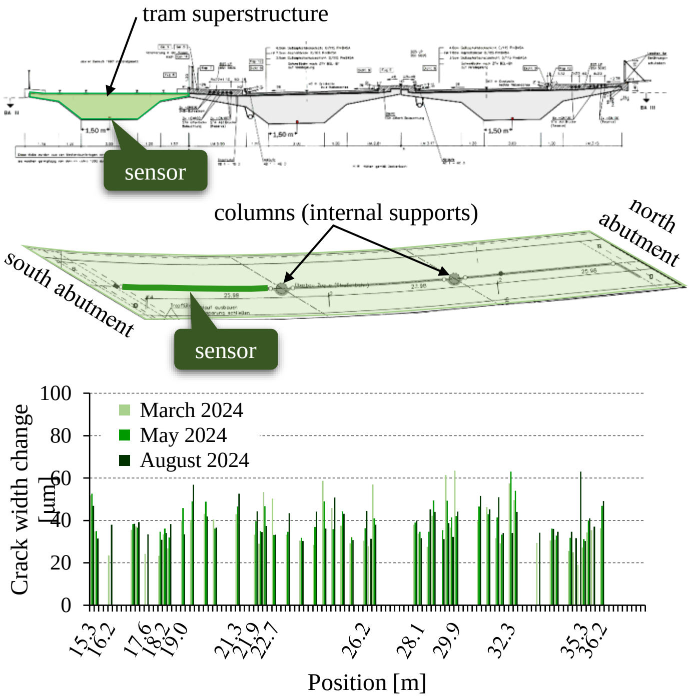

Figure 5. Comparison of the crack width change within the first span of the tram superstructure

In the latest, following measurement, only minimal crack width changes were noted compared to the previous measurements, suggesting no SCC-induced damage and confirming structural stability. The DFOS monitoring proved highly effective in characterizing microcrack evolution in SCC-susceptible girders and offers non-intrusive solution for long-term condition monitoring.

4.3 Asset 2: Road bridge in Waren (Müritz)

The bridge on federal road B192 over the railway line in Waren (Müritz) is a continuous three-span structure consisting of two separate overpasses. Due to the use of high-strength prestressing steel prone to hydrogen-induced SCC, continuous monitoring has been in place since 2014. Long-term inclinometer measurements indicated a successive reduction in structural stiffness, suggesting progressive structural degradation, due to SCC.

In preparation for an upcoming replacement of the bridge, the south span - temporarily carrying all traffic – was equipped with a DFOS system to monitor potential crack propagation. Two sensor lines (10.5 m and 11 m) were installed on the underside of the deck to detect strain changes and localize microcracks in the mid-span section. Initial load tests in April 2024 with a 50-ton truck showed only minor strain changes (0–50 µm/m) and microcrack width changes below 0.01 mm, with no macroscopic damage detected – see Fig. 6. A second load test in October 2024 confirmed these results, with strain peaks up to 80 µm/m and similar minimal crack width variations. The structural response remained consistent between both tests, and all observed strains were reversible after unloading.

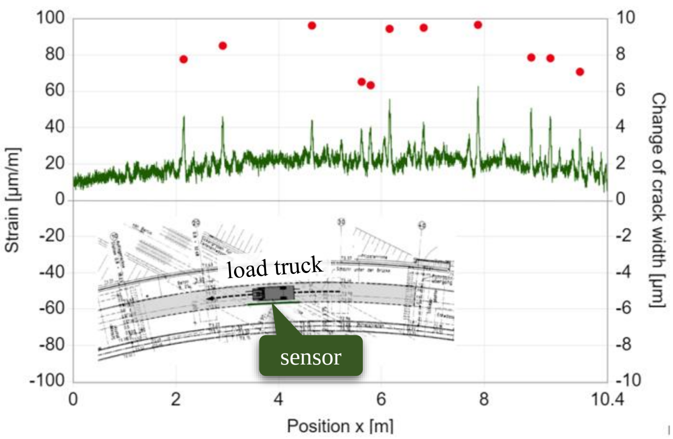

Figure 6. Strains (blue line) and change in microcrack (red points) resulting from truck load

Due to the results of long-term measurements, facing doubts about the condition and safety of the structure, it was decided to demolish and replace both spans, with the detonation of the north span scheduled for January 2025. Since the south span must carry all traffic during the construction period, DFOS measurements and load testing were carried out to assess whether the explosion on the north span had caused any damage to the south span and to ensure its safety for continued use. To this end, load testing was conducted using a 50-ton heavy-duty truck. Figure 7 presents the change in strains along the sensor segment at the mid-span, induced by the passage of

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the test vehicle. A gradual increase in strains is evident along the monitored length. Distinct strain peaks correspond to the locations of pre-existing cracks. Under loading, local strain peaks of up to 40 µm/m were recorded, while in the sections between the cracks, the strain values remained approximately constant at around 20 µm/m.

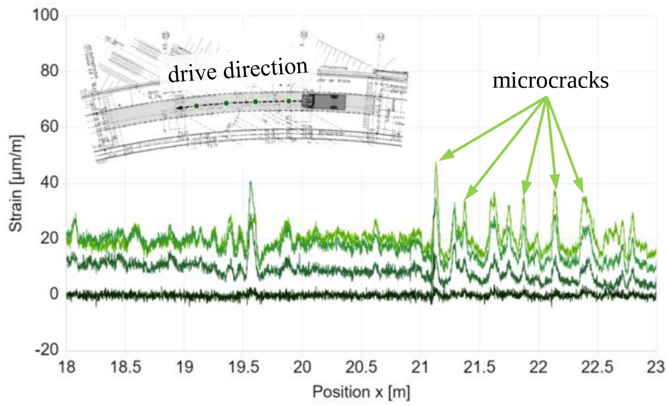

Figure 7. Strain change resulting from the passage of a test truck with distinct microcrack opening

DFOS measurements enabled the identification of crack locations at the very beginning of the loading test, even before the test vehicle reached the center of the monitored span. Strain development was most pronounced at the crack locations, with the progressive formation of peaks clearly visible. Due to the considerable stiffness of the structure, the variation in the microcracks, calculated according to the methodology described in Section 3.2, was minimal and did not exceed 0.01 mm.

The DFOS measurements, conducted before and after the controlled demolition confirmed no anomalies or damage to the monitored bridge segment. The consistent, low, and fully reversible strain values provide clear evidence that the structural integrity was not compromised by the blast or load tests.

4.4 Asset 3: Bridge BW55b in Döbeln

The B169 bridge near Döbeln (BW55b), built in 1966, is a prestressed concrete structure consisting of two hollow box girders connected by a concrete deck, spanning approximately 67 m with a total width of 16 m [33]. The bridge forms part of a vital route connecting the A4 and A14 motorways and remains structurally safe but is classified as highly susceptible to SCC due to the use of prestressing steel made from over 200 fine wires per tendon. Instead of replacing the bridge, the Saxon State Authority for Road Construction and Transport (LASuV) implemented an advanced SHM strategy to prolong its service life. This included the installation of DFOS on the undersides of the four longitudinal box girder webs, in total around 100 m of sensing length. The sensors were installed in grooves and bonded using high-performance injection mortar – see Fig.8.

The follow-up measurement performed under regular traffic revealed strain changes with peak values typically below 150 µm/m, and extremely small variations of crack widths – generally not exceeding 0.01 mm. Several local strain peaks were detected, suggesting the presence of microcracks, but no signs of active or progressive damage were observed. Temporary changes during vehicle crossings indicated reversible crack width variations between 5 and 20 µm, which immediately returned to previous state after the load passed, demonstrating the high stiffness and resilience of the structure. All measurements were temperature-compensated, and sensor performance remained stable. No anomalies indicating structural issues were identified. The purpose of the long-term DFOS monitoring supported by AE is the continuous assessment of the structure's condition, ensuring safe operation without the need for costly replacement.

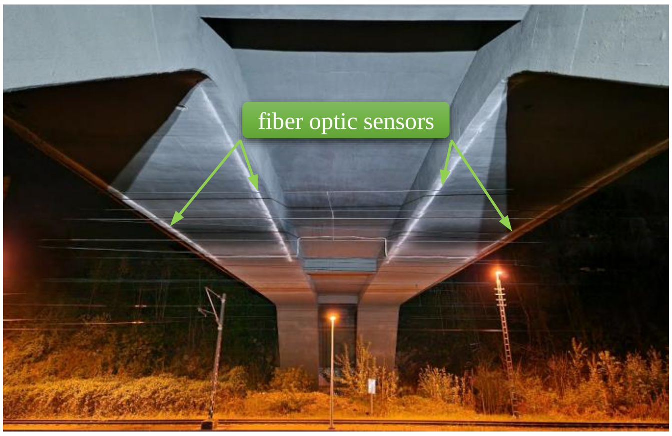

Figure 8. Layout of the sensors on the surface of hollow box

4.5 Asset 4: Budapester Str. Bridge in Dresden

The Budapester Straße Bridge in Dresden, built between 1963 and 1968, is a critical urban infrastructure linking the city center with the southern districts. The 850-meter-long structure spans the main rail yard of Dresden Central Station, tram lines, and the Ammonstraße, and is composed of multiple monolithically constructed prestressed concrete sections. Its overpasses were constructed with longitudinal post-tensioning using oil-tempered Henningsdorf's prestressing steel, a material highly susceptible to hydrogen-induced SCC. Cracks between 0.1 and 0.5 mm wide (Fig. 9a) and visible rust staining (Fig. 9b) have raised concerns about latent internal damage.

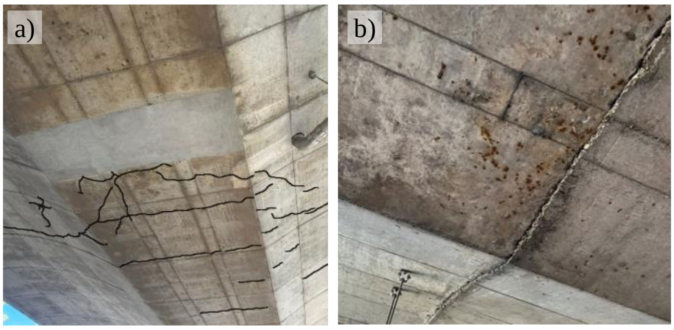

Figure 9. Visible damages: a) cracks with extensive widths, b) rust staining and displacement within coupling joint

To address the concerns and ensure long-term traffic safety without the necessity of a premature reconstruction, a comprehensive SHM system based on DFOS and acoustic emission is being installed – see Fig. 10. Around 880 meters of sensors are glued into the grooves along the underside of overpasses a and c. The system is designed to detect microcracks, localize strain peaks, and monitor changes over time under thermal and traffic-induced loading. Strain measurements are complemented by distributed temperature

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fiber optic sensors, using Raman backscattering, to ensure reliable thermal compensation for longer sections. The main goals include detecting potential wires breakage, tracking crack formation near coupling joints, and providing high-resolution insights into the bridge's response to operational and environmental loads.

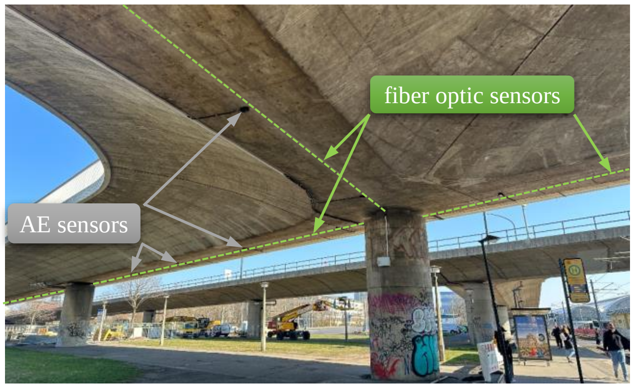

Figure 10. Localization of the sensors on the internal segment of the superstructure

The sensors are divided into 14 segments, each covering up to three spans, with data acquisition performed periodically using optical interrogators. This quasi-continuous monitoring allows localization of crack activity across the entire length of both overpasses. Although the installation in the existing structure obviously does not allow to monitor structural health from the "hour zero", DFOS enables ongoing evaluation of crack development and possible early signs of structural deterioration starting directly after the installation.

5 DISCUSSION

5.1 Comparison with Traditional Monitoring Methods

DFOS offers several advantages over conventional monitoring methods such as strain gauges, vibrating wire sensors, and visual inspections. Unlike these techniques, DFOS enables continuous, high-resolution strain measurements over long sensor paths.

In a study on the Black River Bridge in Ontario, DFOS successfully identified localized cracking and strain concentrations – insights that were missed by traditional gauges spaced every meter. It also detected unintended semi-rigid restraint conditions at supports, demonstrating its ability to capture unexpected behavior [34]. DFOS strain resolution (typically 1–5 µm/m) is comparable or superior to that of foil strain gauges (5–10 µm/m), while covering thousands of data points simultaneously. In the project described in [35], discrete sensors were replaced by more than 1500 m of fiber optic sensors, with each individual sensor providing approximately 38 400 measurement points.

Compared to visual inspection, DFOS provides objective, quantitative detection of crack formation and width changes. With strain change exceeding 50 µm/m, it can identify cracks smaller than 0.05 mm, well below the threshold of unaided visual assessment [20], [36]. Additionally, sensors can be embedded into structural components like tendons and rebar, enabling long-term monitoring of prestressing forces and internal damage progression – tasks that are difficult or impossible with surface-mounted sensors or manual inspection.

5.2 Interpretation of Long-Term Structural Behavior including thermal compensation

DFOS enables precise interpretation of long-term structural behavior by continuously capturing strain distributions and tracking crack evolution under both mechanical loading and environmental influences. Based on DFOS measurements carried out by the authors on actual bridges during in-service operation, over several years of continuous monitoring, following findings can be pointed out. At the Königsbrücker Straße bridge in Dresden, fiber optic sensors recorded mechanical strain responses caused by tram and road traffic, with peak strain values near supports and midspans. These strain concentrations corresponded to microcrack openings predominantly between 0.01–0.05 mm. Changes in crack width over time indicated stable structural behavior under service loads. In the bridge on the road B192 over the railway in Waren, strain peaks of 50–100 µm/m were recorded during staged loading under increasing traffic, allowing localization of microcracks with widths estimated around 0.02–0.05 mm. In both projects, thermal effects were observed as restrained strain patterns uniformly distributed along the spans, depending on exposure and structural response (imposed strains).

Thermal compensation is essential to distinguish thermal effects from mechanical responses. Rayleigh and Brillouin backscattering are sensitive to temperature-induced changes in the fiber, what needs to be considered in evaluation of mechanical strain readings [37]. Including the findings presented in [31], a temperature change of 1 K results in an additional strain of approximately 20 µm/m in monolithic sensors embedded in concrete structures. To address this, multiple solutions can be utilized for dedicated temperature measurements, allowing separation of thermal and mechanical effects and thus enabling accurate compensation and interpretation of structural behavior over time [38]. For real use cases the most practical approaches to thermal compensation include utilizing distributed temperature measurements with Raman backscattering or even local spot temperature sensors.

5.3 Enhancing Predictive Maintenance Strategies

The integration of DFOS into SHM systems offers multiple advantages. One effective strategy is the use of hybrid monitoring systems, where DFOS is combined with technologies such as acoustic emission sensors. An example of such implementations is Kreuzhof bridge in Munich, where real-time detection of wire breaks via AE was supplemented by spatially distributed strain monitoring via DFOS, significantly improving damage assessment reliability [39].

Beyond external installations, DFOS can also be integrated directly into structural elements such as prestressing tendons or reinforcement cages. This embedded approach enables continuous internal monitoring of strain and prestressing forces, providing detailed insights from the initial loading stages through the entire service life of the structure. A practical demonstration of this concept was presented in a study on a prestressed concrete bridge girder, where fiber optic sensor was installed during fabrication to successfully

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monitor strain development and crack formation under service and ultimate loads [40].

In addition, DFOS systems can be linked to digital twin platforms, enabling real-time data to support predictive maintenance, condition-based inspections, and system-wide risk assessments. This form of integration advances infrastructure monitoring from traditional inspection cycles toward proactive, data-driven management [15].

6 FUTURE RESEARCH DIRECTIONS

Despite significant progress in the deployment of DFOS for SHM, several open research questions remain, particularly addressed to:

- early-stage and automated SCC detection – future studies should explore enhanced DFOS signal interpretation methods, such as high-frequency dynamic strain analysis or modal-based decomposition, to identify signatures associated with early-stage wire degradation; the development of automated algorithms for the classification and localization of SCC-induced damage, based on DFOS strain gradients, could streamline monitoring and reduce the reliance on manual data interpretation; techniques such as anomaly detection, pattern recognition, and signal filtering are promising directions for algorithmic refinement.
- integration with predictive modelling – coupling DFOS data with finite element models and machine learning-based predictive tools would enable dynamic risk assessment by correlating measured strain patterns with probabilistic failure modes.

One of the most promising directions for the advancement of detecting tendon breakages is distributed acoustic sensing (DAS) technology. While distributed strain sensing excels in measuring quasi-static and low-frequency strain distributions with high spatial resolution, DAS extends the functionality of the same optical fiber network by enabling detection of dynamic, high-frequency acoustic signals along the entire fiber length. Mechanical disturbances, such as microcracking, prestress wire rupture, or acoustic emissions, alter the backscattering pattern, allowing the system to localize and characterize the source of dynamic events in real time. This makes DAS particularly suitable for detecting sudden or progressive failure mechanisms, including wire breakages or energy release events associated with SCC [41] However, the use of this technology still requires extensive research to determine the effective detection range around the optic sensor – i.e., the distance between the event and the sensor at which the event can be reliably detected. Further studies are needed to establish the optimal application pattern and to develop automated methods for data analysis.

Combining DSS and DAS in a hybrid sensing system can significantly enhance the sensitivity, reliability, and redundancy of SHM strategies. For instance, a wire rupture may first be identified as a sharp acoustic signal via DAS and subsequently confirmed and quantified by correlated local strain changes registered by DSS. This fusion of datasets might support cross-validation, improve false positive rejection, and enable automated alert systems for infrastructure operators.

7 CONCLUSIONS

The application of distributed fiber optic sensing in the structural health monitoring of bridges vulnerable to stress corrosion cracking demonstrates clear advantages over traditional inspection and sensing methods. DFOS provides continuous, high-resolution strain data capable of detecting early-stage microcracks, quantifying crack width changes, and localizing damage with high spatial precision. The case studies presented confirm the efficacy of DFOS in operational environments, with successful deployment across multiple bridge structures. Monitoring results revealed that even microcrack width changes (typically below 0.01 mm) could be captured, and strain peaks were localized precisely at pre-existing damage sites. Multiple real-world case studies have shown that DFOS systems can effectively monitor the evolution of cracks under operational conditions, offering valuable insights into the structural integrity and residual service life of aging infrastructure. The ability to detect reversible strain patterns and correlate them with loading events supports informed decision-making regarding the continued safe use of SCC-affected structures.

The integration of DFOS with other sensing technologies, such as acoustic emission, further enhances damage detection capabilities and supports predictive maintenance strategies. While there are still challenges, such as sensor installation complexities and the need for robust data processing algorithms, the DFOS technology can be perceived as a transformative tool in advancing resilient, data-driven infrastructure monitoring practices.

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