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Monitoring the Fatigue-Induced Strain Evolution of Concrete Bridges using Fiber Optic Sensors

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Abstract

Concrete bridges with low shear reinforcement ratios erected in the mid-20th century are subjected to rapidly increasing traffic loads in the last decades. In the absence of precise methods for assessing the remaining service life, the detection of the slightest damage (e.g., cracks and corrosion) immediately leads to a partial or complete restriction of traffic. Major parts of the ultimate fatigue capacity are therefore not yet utilized. Addressing the aspects of sustainability and capacity of traffic infrastructure, it is crucial to extend the service life of existing bridges by optimized assessment concepts that cover the development of the actual damage state of the critical structural components. Therefore, this paper presents a novel monitoring concept for the strain development of pre-damaged concrete structures. First experimental studies demonstrate that Fiber Optic Sensors (FOS) are ideally suited to capture the strain development of concrete structures under fatigue loading. Therefore, the developed measurement concept is based on this technology and can contribute to extend the service life of concrete bridges through comprehensive monitoring strategies.

Keywords

Concrete bridges, Fatigue, Monitoring, Fiber Optic Sensors (FOS), Digital Image Correlation (DIC), Service life.

1 Introduction

Fatigue of reinforced concrete (RC) is a major factor that prevents civil engineering structures, particularly bridges, from reaching their expected lifespan. A fundamental understanding of the degradation processes that lead to fatigue failures in RC is therefore a substantial requirement. In recent years, experimental research has been conducted in various areas of concrete fatigue – under a huge variety of loading types –, showing that the overall strain development provides a very promising indication of the underlying damage condition (e.g., [1–4]).

For a reliable service life prediction of concrete structures under high-cycle fatigue loading, in-depth knowledge of the damage development is therefore essential. Even though computational models are becoming increasingly capable of performing numerical analyses on the fatigue behavior of concrete (e.g., [5–8]), complete, interconnected structural systems are still highly challenging and require immeasurable computational effort. In addition, a realistic prediction of the damage evolution is impossible without considering the true loading history. Thus, in the absence of viable alternatives, the remaining service life is usually evaluated by visual inspection of the concrete surface alone.

To improve this laborious process, it is essential to incorporate information on the damage state of the existing structure obtained continuously by comprehensive strain measurements. In combination with selected mechanics-based service life prediction models, this will lead to an enhanced assessment of the structural safety, as necessary maintenance measures can be conducted prior to the occurrence of irreparable damage and bridge operation is not unnecessarily inhibited at a premature damage state. Achieving this overall goal first requires a concept for large-scale strain monitoring that is applicable to existing structures and durable over decades.

A key challenge in developing this concept is the inhomogeneity of RC; linear elastic strains as well as local microcracks due to fatigue damage are not uniformly distributed over the entire structure. Since strain gauges detect only local phenomena – resulting in a deceptive or incomplete picture of the global strain state – continuous, large-scale measurement is essential for a reliable evaluation of the complete strain profile [9]. Digital image correlation (DIC) and fiber optic sensors (FOS) are ideally suited for this purpose.

Within this paper, first experimental studies are presented, conducted to investigate the suitability of these

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two measurement techniques on fatigue-loaded concrete members. Furthermore, a general concept is proposed, which processes the raw measuring data, feeds it into a system of multiple service life prediction models, and ultimately enables an assessment of damage condition and remaining service life.

2 Experimental investigation

As part of a research campaign on the propagation of compressive fatigue in externally prestressed concrete beams [9], several experiments were conducted that provided the opportunity to test various measurement techniques for their ability to accurately measure the strain evolution on the concrete surface over a long period of time. In the following, selected results will be presented and discussed.

2.1 Specimen geometry, test setup, and material

The experimental campaign was conducted using 1.4-meter-long inverted T-beams, tested in four-point bending (Figure 1). The beam design aims to impose the highest compressive stress at the top and allow it to propagate downward through the cross-section. Therefore, it is subject to a bending moment (imposed via two single loads shown in the center) and pre-stressed by an external, eccentric normal force. This normal force, along with the bottom chord, increases the cracking moment at the bottom of the beam and prevents cracking until failure. A more detailed explanation of the design process and the newly developed test setup can be found in [9].

Various concrete mixtures were tested in the course of the campaign. The test, which is presented in the following, was mixed with a cement type CEM I 32,5 R, had a maximum grain size of 8 mm (quartz), and a water–cement ratio of 0.56. To evaluate the concrete properties, various material samples were prepared and tested after 26 days. Compressive strength, modulus of elasticity, and splitting tensile strength were determined on 300 mm high and 150 mm wide cylinders as 23.4 MPa, 26,220 MPa, and 2.2 MPa, respectively. The material samples were cast in non-metallic forms, cured in the formwork together with the T-beams for one day, and subsequently stored under controlled conditions until further preparation.

2.2 Applied measurement techniques

Along with conventional linear-variable displacement transducers (LVDT) – for the measurement of mid-deflection and bottom strain – three separate measurement techniques (namely DIC, FOS, and strain gauges (SG)) were employed to capture the continuous degradation process throughout the fatigue life, monitoring the strain evolution with field data, line data, and point data (Figure 1). Each of these measurement techniques has its advantages and disadvantages, which will be evaluated and discussed in the following.

2.2.1 SG

Figure 1 shows that five 2 cm long SG – depicted in light green – were placed evenly spaced over the height of the beam and attached directly to the concrete surface with a dry-curing methyl methacrylate-based adhesive.

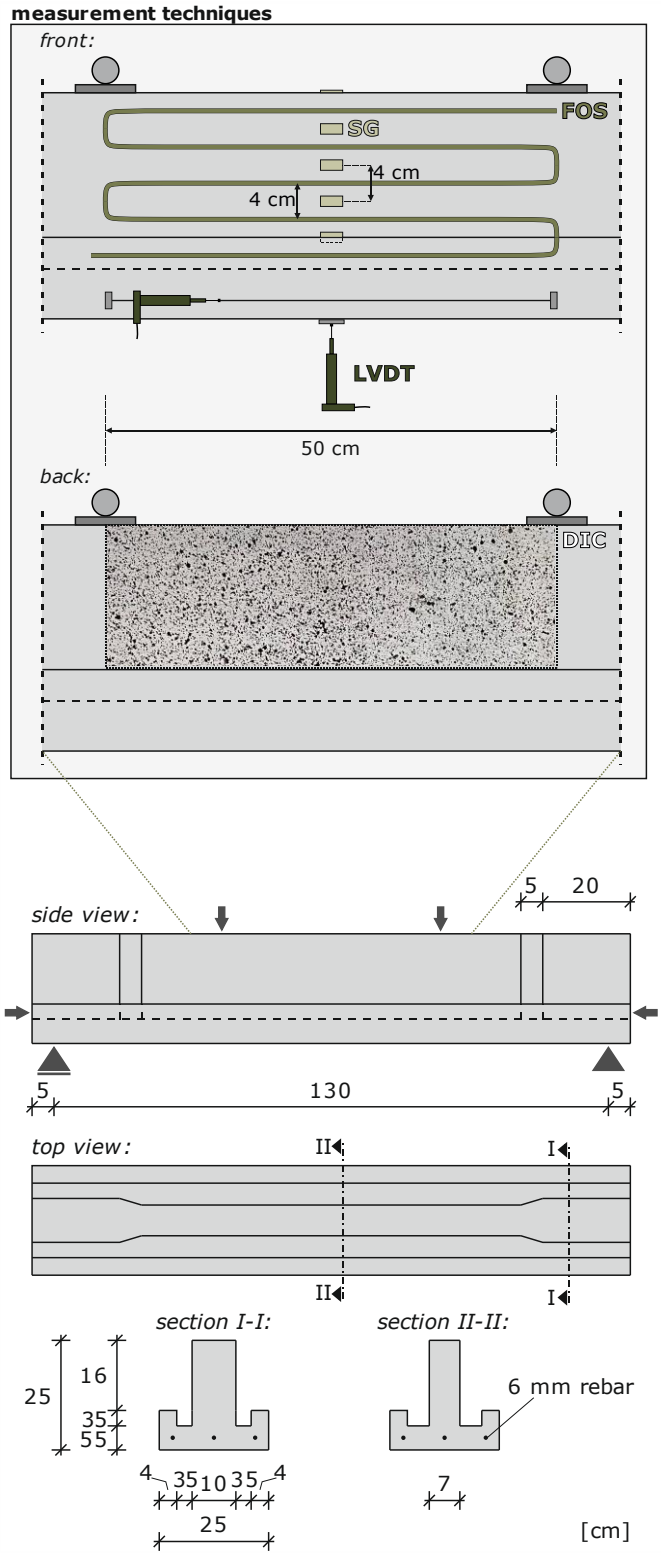


Figure 1 Specimen geometry and employed measurement techniques.

The SG were applied with a 4 cm spacing to determine height-dependent strain variations and the uppermost SG was positioned in the center of the upper side of the beam. Since the amount of data generated by SG is relatively small compared to other measurement techniques, the sampling frequency was chosen to be 50 Hz, which is equivalent to 20 times the loading frequency (2.5 Hz).

2.2.2 FOS

To improve the limited punctual information provided by

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SG, FOS was installed on each beam. One of the key benefits of FOS is its ability to provide quasi-continuous strain measurement over a long measuring length. To this end, the measuring fiber was continuously bonded to the concrete surface using the same dry-curing methyl methacrylate-based adhesive as was used for SG. The measurement system utilized was the *ODiSI 6108* system from *Luna Innovations Incorporated* with a minimum measurement point distance of 0.65 mm.

Over the past years, a wide variety of fiber types have been established on the market. The main distinguishing feature is the coating, which has a significant influence on the measurable strain i.e., the local resolution. To determine the most fitting fiber coating for the study outlined in this article, preliminary tests were carried out on two widely used fiber types (Figure 2 and Table 1). It should be noted that all compressive strains are represented as positive values since the focus of this study was solely on compressive behavior. For the best possible comparison of the measurement results, both fibers were bonded directly next to each other on the concrete surface. While the mean strain of both fibers is approximately the same, the scattering differs significantly (Table 1). Figure 2 clearly shows that an acrylate-coated fiber leads to significantly smoother and more stable recording results compared to a polyimide-coated fiber. In addition, the acrylate-coated fiber appears to provide consistent measurements across various load levels, while the polyimide-coated fiber is subject to greater scatter as the load increases. These observations are supported by the calculated standard and maximum deviation (Table 1). Conclusively, acrylate-coated glass fiber was used in all conducted tests.

To measure the strain at various heights and additionally determine the strain profile along the longitudinal beam axis, only one single measuring fiber was applied, which was arranged in a meandering pattern with a spacing of 4 cm over the height of the specimen (Figure 1). This approach reduces costs and simplifies production, handling, and evaluation compared to using multiple fibers. Since FOS with such a low measurement point distance generates a lot of data during high cycle fatigue testing, a special measurement routine was programmed. Every 40 seconds, 17 measurements were taken at a frequency of 20 Hz, which corresponds to slightly more than 2 cycles per 100 cycles given a cyclic load frequency of 2.5 Hz. This results in high-resolution data throughout the entire fatigue life while significantly reducing the amount of data.

Table 1 Acrylate-coated fiber vs. polyimide-coated fiber at various load levels.

Coating	Value [µm/m]	Load Step [kN]		
		100	200	300
Polyimide	Mean	75	165	254
	Standard deviation	31	74	114
	Maximum deviation	294	741	996
Acrylate	Mean	76	171	258
	Standard deviation	5	7	5
	Maximum deviation	36	46	27

2.2.3 DIC

DIC allows for the measurement of three-dimensional displacement within a designated measurement field, offering greater versatility for strain evaluation compared to the unidirectional measurement capability of FOS, yet also producing significantly more data in the process. In the scope of the presented study, a 3D DIC system with a 4096 x 3000 pixel resolution was utilized, which has been successfully applied in previous fatigue tests at the authors' institute for crack and strain analysis [10]. To achieve precise measurements, one side of the beam was painted white and a stochastic point pattern – a *speckle pattern* – was applied (Figure 1). The software *GOM Correlate Professional* was utilized to calculate the strain distribution on the concrete surface based on the captured images using homologous position tracking.

Since measurements with DIC generate substantially more data than measurements with SG or even FOS, a predefined measurement routine is essential to reduce the dataset and facilitate the subsequent evaluation. Hence, in general, 20 pictures were taken every 40 s with a sampling frequency of 24 Hz. As with the FOS measurement, this correspondence to slightly more than 2 measured cycles every 100 cycles.

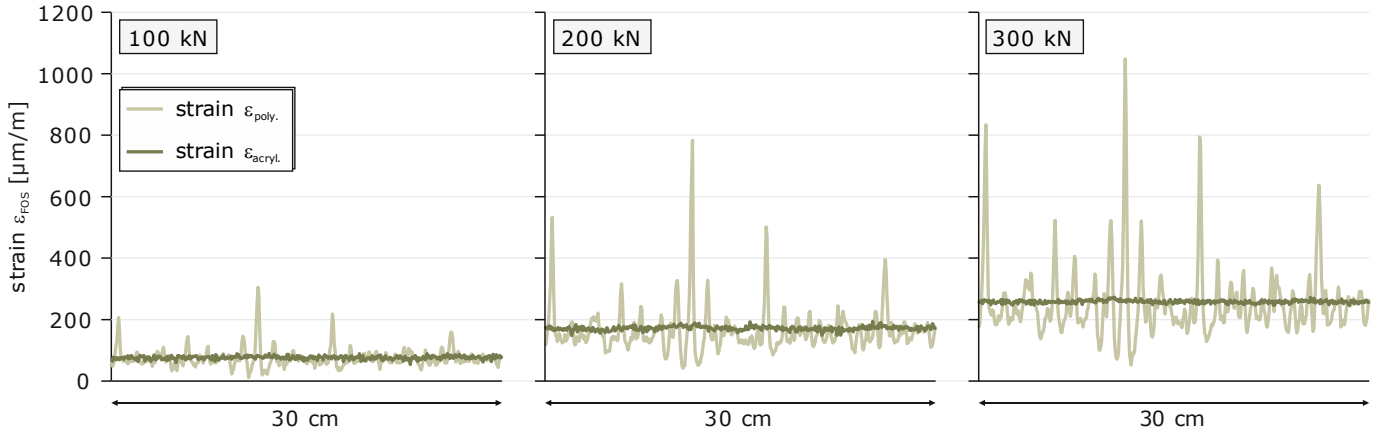


Figure 2 Comparison between an acrylate-coated fiber and a polyimide-coated fiber at various load levels.

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2.3 Results and discussion

The underlying objective of the presented study was to capture the progressive degradation – and accompanying propagation – of concrete under fatigue loading. As previously described, three main measurement techniques were utilized for this endeavor. To estimate the applicability of these techniques in terms of durability, accuracy, and evaluability, tests under monotonic and fatigue loading were conducted and are evaluated in the following section.

2.3.1 *Monotonic loading*

For the assessment of the measurement performance under monotonic loading, the beam was subjected to four distinct load levels while continuously measured with all measurement techniques. The strains measured along the cross-section height at various load levels – including preloading, lower loading, mean loading, and upper loading – are shown in Figure 3. Light green and dark green dots represent the results of SG and FOS, respectively. To illustrate the strain progression over the cross-section height, the individual results were linearly connected, while the dashed lines indicate a possible further progression of the FOS strain outside of the measured range.

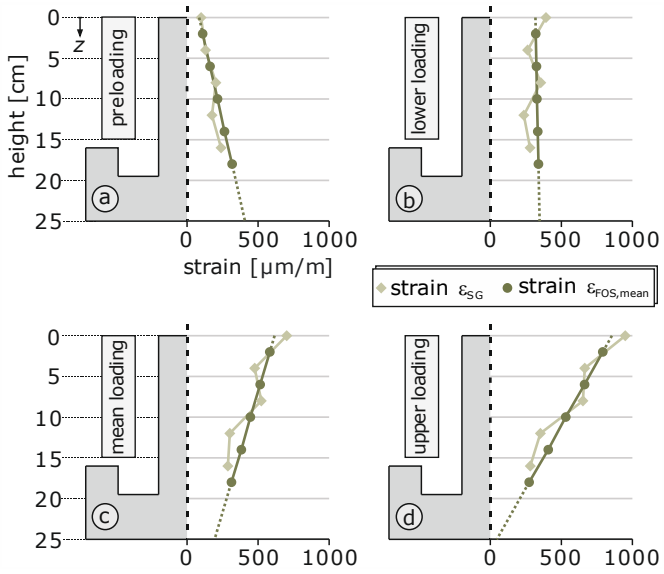


Figure 3 Strain measured with SG and FOS at a) preloading, b) lower loading, c) mean loading, and d) upper loading.

Across all load levels, the FOS results show the expected linear strain progression, while the SG result can only approximate this linearity (Figure 3). These fluctuations within the SG strain profile, however, are not due to measurement errors but result from local strain variations in the inhomogeneous concrete. Due to the high accuracy of the FOS results, it is convenient to check whether the targeted strain levels have been achieved. Looking at the strain profile at upper loading (Figure 3), it can be seen that – as intended – the top edge of the beam is under significant compression while no tension occurs at the bottom edge.

Figure 4 presents the FOS measurement results along the cross-sectional length for three separate load levels: preloading, lower loading, and upper loading. The five longitudinal strain profiles in each graph correspond to the individual fiber sections at the displayed heights. Each measuring section contains 461 measurement points (0.65 mm apart), which add up to about 30 cm in length. The individual strain values for each fiber height in Figure 3 are composed of an arithmetic mean of these measurement sections. Figure 4c clearly illustrates the aforementioned local strain variations, such as the strain in the uppermost measuring section (z = 2 mm) which varies by up to 200 µm/m. Since the measurement does not show any outliers, there is no need for further data processing and the raw data can be used immediately for deeper interpretation. No filter has corrected or smeared the displayed results.

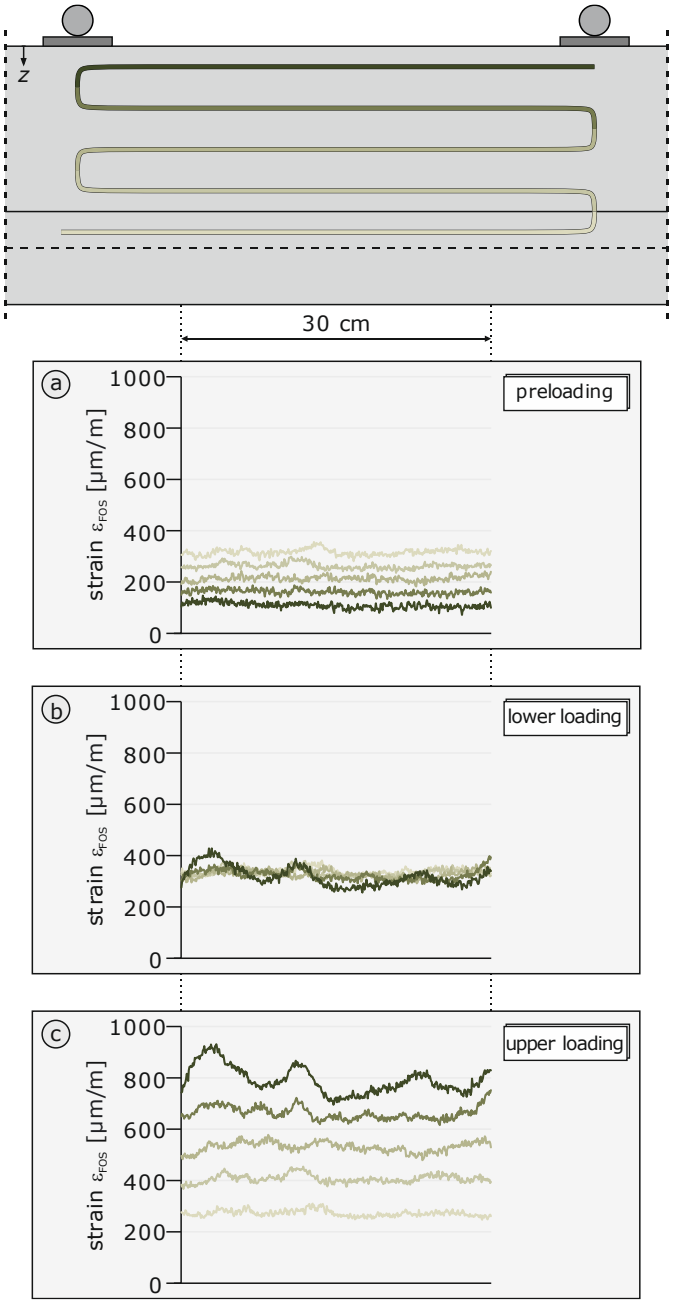


Figure 4 Strain distribution of FOS measurement along the beam length over various heights at a) preloading, b) lower loading, and c) upper loading.

FOS and SG were applied to the same side of the specimen, while DIC was measured from the opposite side (Figure 1). Although the inhomogeneity of the concrete prevents direct compression of the measured strain pro-

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files, a general agreement should be apparent. The compressive strains in the longitudinal direction of the beam (measured with DIC) are depicted in Figure 5. Areas with red and blue represent low and high compressive strains, respectively.

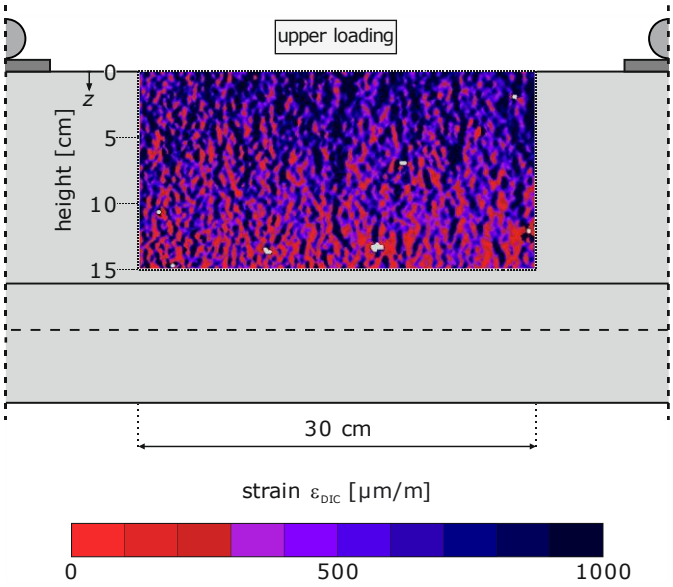


Figure 5 Compressive strain profile in longitudinal direction measured with DIC.

The general magnitude as well as the profile of the measured strain are in agreement with the FOS results. However, the two-dimensional strain profile does not offer any real added value compared to the one-dimensional strain profiles shown in Figure 4. Although the general inhomogeneity of the concrete is evident, specific numerical values are difficult to identify and critical strain peaks could go unnoticed. Only a transformation of the two-dimensional field data into line data would allow intuitive processing. On the upside, this transformation would have the additional advantage that the elevated heights are freely selectable, yet it would require a processing step that is not necessary for FOS evaluation. While clustering would certainly be much more recognizable by DIC for larger strain differences (e.g., [9]), this benefit is not present for small strain variations.

2.3.2 Fatigue loading

The studies presented so far show that DIC and FOS perform reliably and accurately under monotonic loading conditions. FOS in particular stand out positively due to the smaller amount of data, more intuitive readability, and a lower evaluation effort. However, whether this result is also consistent under repeated subcritical loading, could be evaluated in a fatigue test where the beam was subjected to more than 1 million cycles.

The FOS measurement results presented in Figure 6a illustrate the strain evolution along the cross-section height, with different color gradations indicating varying numbers of cycles. As outlined in Section 2.3.1, the depicted mean values were obtained directly from 461 raw FOS measuring points. Despite undergoing approximately 1.6 million cycles, the test still shows a nearly linear strain profile along the cross-section height. Noteworthy, the strain increases not only in the uppermost measuring section (z = 2 mm) but also in the lowest section (z = 18 mm), suggesting that the minimum strain (z = 25 mm) is consistently at approximately 0 µm/m.

Figure 6b-d depict the strain results that make up the mean values of position z = 2, 6, and 10 cm in Figure 6a. The failure of several measuring points at roughly 1.6 million cycles can be recognized in Figure 6b. The displayed strain profile was reconstructed based on previous measurements and the available 18 data points. Consequently, averaging is heavily influenced by the position of these remaining intact data points and no longer accurately reflects the actual mean concrete strain, which is why in Figure 6a, the last linear connection (N = 1,550,000 between z = 2 mm and z = 6 mm) is depicted as dashed. However, as can be noted in Figure 6c and d, this issue does not affect the lower fiber sections, indicating two conclusions: first, only a high strain amplitude over several hundred thousand cycles has a negative impact on the quality of the FOS measurement results; second, other fiber sections are not negatively affected by this data point loss.

The strain profiles shown in Figure 6b-d highlight that the heterogeneity of the concrete increases even further during the fatigue process. At approximately 1.6 million cycles, the strains in the uppermost measuring section vary by nearly 2000 µm/m.

3 Development of a lifetime prediction method

Based on the previously illustrated findings, which confirm that FOS is an adequate technology for consistently monitoring the strain state of concrete structures, a monitoring concept for existing and new concrete structures is going to be developed in a research subproject (Project number: 501771082) within the scope of the Priority Program

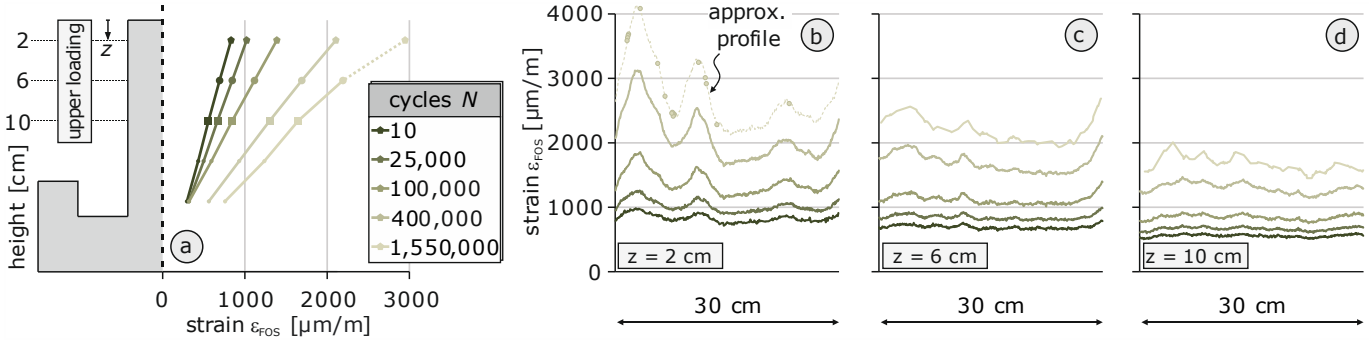


Figure 6 FOS strain measurements at upper loading and various cycles a) over the beam height and b, c, d) along the beam length.

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SPP 2388 "100 plus". The overall goal of this subproject is the lifetime prediction of concrete bridges under traffic load by means of continuously gained information on the structure's deformations, including linear-elastic strains and micro/macrocracking.

As a central tool for the evaluation of the FOS-captured strain data, a digital twin of a real bridge structure is developed. This 3D geometry model collects and transforms the measured strain data, and it includes several computational models which derive the actual damage state from the strain information. Thus, the real twin can be observed continuously without requiring on-site inspections.

3.1 FOS application concept

To determine the fatigue-relevant strain of an RC structure as well as the resulting micro- and macrocrack widths, critical areas of the structure are equipped with a fiber optic measuring network. The basic suitability of such systems has been confirmed in our own preparatory work on strain monitoring of concrete surfaces [9] and crack width calculation via FOS [11]. So far, fiber optic measurement methods have mainly been used for one-dimensional strain measurements. However, the use of measuring networks installed on concrete surfaces for the high-resolution determination of strain fields, as schematically depicted in Figure 7, has so far remained largely unexplored. Such network-like FOS applications on concrete structures promise a more comprehensive capture of the strain evolution and crack development, in comparison to linear FOS applications. Compared to DIC, which also provides two-dimensional strain state information, an FOS network causes a reduced evaluation effort, produces significantly fewer data, and is easier to apply on large-scale bridge structures.

Based on the presented preliminary studies, various fiber coatings, grid concepts and spacings, application methods as well as sampling frequencies will be investigated in uniaxial-tensile and four-point-bending tests under static and cyclic loading in the further course of the project for their suitability to determine the two-dimensional strain state before and after cracking. In particular, the fine balance between high-resolution strain measurement in the uncracked state and robust/reliable strain measurement after cracking will be of decisive importance. To evaluate the respective measurement quality, the strain results obtained through FOS are checked via DIC and SG measurements.

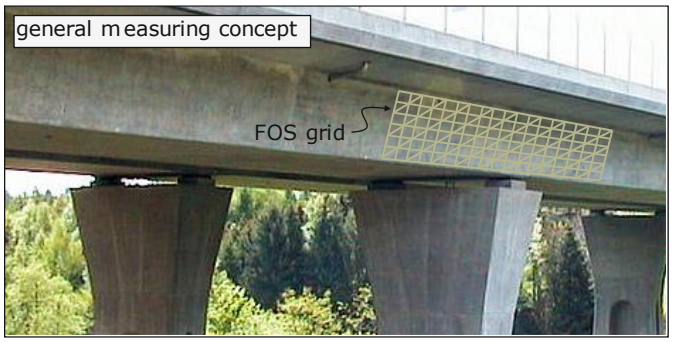


Figure 7 Exemplary FOS grid application on a bridge structure [12].

3.2 Evaluation methodology on the digital twin

The installed FOS grid provides one-dimensional raw strain data of the real twin (Figure 8a). Since this data includes not only fatigue-relevant strain from load and constraint but also temperature, an additional measuring fiber – decoupled from the structure – is installed within the measuring network. This reference measurement can be used to isolate temperature-related deformations. Furthermore, the spatial deviation from the real fiber position to the nominal fiber position has to be corrected (Figure 8b). Finally, the corrected strain data is filtered to reduce the total data amount, eliminate anomalies, and smooth the strain profile (Figure 8c). Spatial and temporal postprocessing of this strain data results in local strain information condensed to selected nodes that allow accurate conversion of the one-dimensional measurement data into the x-, z-, and ξ-directions of a two-dimensional strain field. Using suitable approaches for strain interpolation between adjacent nodes, smoothed strain as well as relative deformation fields can be visualized.

As long as the concrete is uncracked, the principal strains can be determined from the node strains ε_z, ε_x, and ε_ξ via principal axis transformation (Figure 8d). In addition,

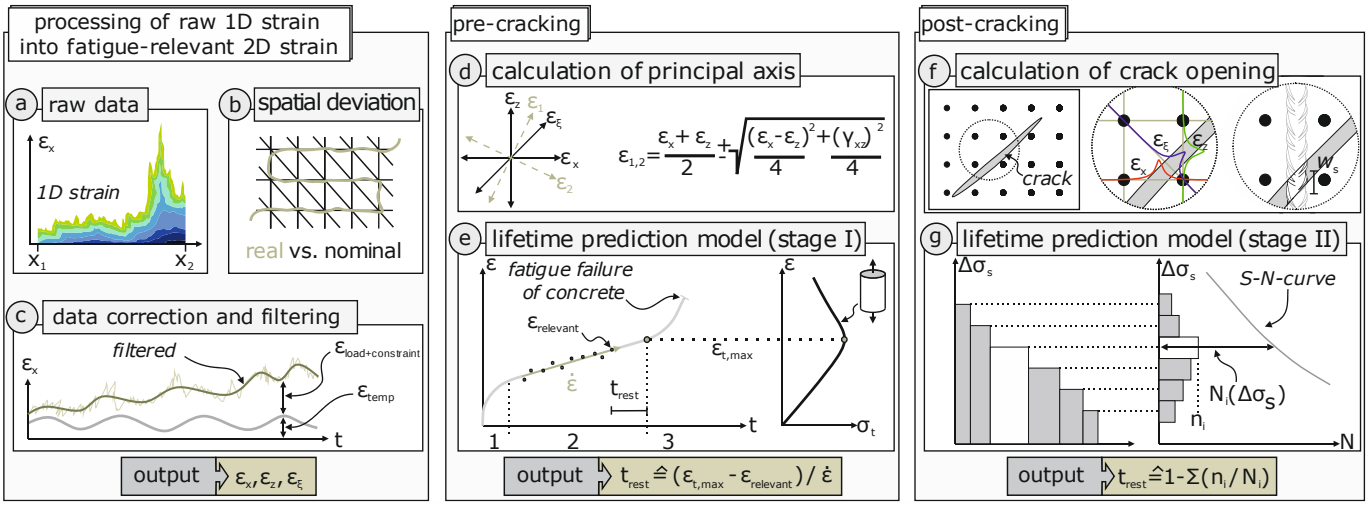


Figure 8 Schematic illustration of the approaches used to determine a-c) the filtered and corrected fatigue-relevant 2D strain, d-e) the remaining service life in stage I, and f-g) the remaining service life in stage II.

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based on our preliminary work [9; 11], a routine is being developed that automatically detects and localizes cracks when they form within the structure and re-calculates crack propagation angle and crack width (Figure 8f) [13]. Noteworthy, all aggregated strain and crack information is integrated into the digital twin as central database for the structure.

3.3 Data aggregation and implementation in a lifetime prediction model

To derive a prediction about the remaining service life from the strain and deformation data collected, three main states are to be identified and characterized in a comprehensive lifetime prediction model: a) the fatigue behavior before macrocrack formation (stage I), b) the transition from stage I to stage II, and c) the fatigue behavior of the shear reinforcement after macrocrack formation (stage II).

Using the principal strain data provided by the digital twin, the fatigue criterion proposed by Thun [14] – and confirmed in our own preliminary work [4; 15] – is utilized to predict the remaining service life until the onset of unstable microcracking (Figure 8e). A change in the principal compressive stress angle by about 10-12°, observed in our preliminary work [16], serves as an indicator for the localization of a crack band to a critical macro shear crack. Thus, in combination with the local strain data of each measuring node, the onset of macrocracking can be determined fairly accurately.

Once the critical macro crack has fully developed, fatigue of the shear reinforcement begins. The linear damage accumulation hypothesis by Palmgren/Miner described in [17] is used to predict the remaining service life of the shear reinforcement in stage II (Figure 8g). For each shear reinforcement crossing a shear crack, the remaining load cycles can be estimated by comparison with a material-specific S-N-curve. If the successive fatigue failure is tracked metrologically and computationally, a comparison with the residual structural capacity leads to a prediction of the global remaining service life.

4 Conclusions and outlook

RC fatigue plays a critical role in preventing bridge structures from reaching their expected lifespan, since – in the absence of precise methods for assessing the remaining service life – the detection of the slightest damage can lead to a partial or complete restriction of traffic, even if the structure could still be operated for decades. To provide a solution to this dilemma, a service life prediction model based on concrete strain measurement via FOS is being developed within the scope of the SPP 2388. First studies comparing FOS, SG, and DIC on concrete surfaces have shown that traditionally utilized SG can lead to a deceptive evaluation for measuring strain development during fatigue life in inhomogeneous materials such as concrete since the strain profile is strongly influenced by local phenomena. FOS and DIC offer a more comprehensive understanding of the strain evolution, capturing both the global strain profile and specific local effects. FOS in particular provide a highly efficient evaluation process and intuitive readability while allowing for key parameters to be determined with a minimal amount of data. Furthermore, acrylic-coated measuring fibers are very well suited for strain measurements on concrete surfaces, providing accurate results even after more than 1 million cycles.

The presented findings indicate that the measurement with FOS offers numerous advantages, which are essential for the use in a lifetime prediction model. In the following months, the ideal application method of the proposed FOS grid will be investigated, the transformation of 1D line data to 2D field data will be assessed, and the lifetime prediction quality in stages I and II will be quantified.

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