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Identification and quantification of concrete cracks using various distributed fiber optic sensing techniques

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ABSTRACT: Distributed fiber optic sensors (DFOS) are extensively used for concrete crack monitoring in recent years, especially in scientific-related applications and laboratory testing. These mainly focus on Rayleigh scattering due to its high spatial resolution and strain resolution, but with significant limitations in the sensing range. This contribution introduces an enhanced laboratory test series, in which five individual test specimens were equipped with multiple installation setups and tested under well-known conditions. The sensing network was interrogated using four different sensing units based on high-resolution Rayleigh as well as Brillouin scattering. The resulting strain sensing profiles do not only allow an identification of the crack location itself, but also a quantification of the crack width. It can be demonstrated that Brillouin sensors are definitely capable of capturing reliable crack widths over long distances, despite their limitation in the spatial resolution. The outcomes are significantly important in practice as civil infrastructures often require monitoring over several kilometers.

KEY WORDS: Distributed fiber optic sensing, crack sensing, concrete structures, structural integrity monitoring, laboratory testing

1 MONITORING OBJECTIVES & TEST SETUP

In recent years, the capabilities of distributed fiber optic sensors (DFOS) for monitoring concrete cracks are demonstrated in various scientific-related projects and laboratory testing, which commonly utilize Rayleigh scattering (e.g. [1] or [2]). This sensing technique can provide measurements with high spatial and strain resolution, but with significant restrictions in the sensing range. Brillouin sensing is capable of monitoring large-scale civil infrastructure as they can provide measurements over numerous kilometers, which however results in spatial limitations and therefore impedes the capabilities for strain-based crack monitoring.

This contribution analyzes the suitability of Brillouin interrogators for identifying and quantifying evolving cracks inside concrete. An enhanced laboratory test series including five individual test concrete specimens equipped with multiple installation setups was realized at Graz University of Technology (TU Graz, Laboratory for Structural Engineering). For applying the loading force during testing, one central reinforcement bar (diameter: 18 mm) was embedded in each concrete specimen (total length: 3000mm). Thin steel plates were attached to the formwork and cast into the concrete to weaken the cross-section at defined locations, which ensures a controlled cracking of the structure during loading. The five specimens vary depending on the number of crack locations, ranging from one to five defined cracks.

The testing specimens were equipped with twelve different layers of fiber optic sensing cables per specimen, including tight-buffered optical fibers [3] as well as prefabricated sensing cables from numerous manufacturers [4–6]. The sensors were either glued to the reinforcement, directly embedded inside the specimens in different arrangements or glued to the outer surface using different adhesive after concreting. Each specimen was tested separately under controlled axial loading, where the rebar was fixed at the bottom and pulled apart at the top side (Figure 1) to initialize the crack opening along the specimen at the predefined locations.

Figure 1. Practical realization of laboratory test setup with one defined crack location.

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Loading for all specimens was performed in two steps with 15 kN each up to the initial cracking, which was determined to be around 30 kN. Afterwards, the load was further increased in 10 kN steps up until the ultimate failure of the specimen at around 100 kN and beyond. By applying the mechanical crack initiation steel plates, it could be ensured that primary cracks only open at well defined locations.

The DFOS sensing network was interrogated by Brillouin interrogators from three different manufacturers utilizing the Brillouin Optical Time Domain Analysis (BOTDA) as well as the Brillouin Optical Frequency Domain Analysis (BOFDA) with a spatial resolution of 0.5 m at each load step. To verify the recorded Brillouin strain distributions, reference measurements were acquired using a high-resolution OBR from Luna Innovations Inc. (USA) based on the OFDR (Optical Frequency Domain Reflectometry). The load was kept constant for each load step to ensure identical loading conditions for all interrogators. Multiple distance transducers (DD-1) from HBM GmbH (Germany) were placed at the specimens' surface to measure the true crack width.

2 CRACK ANALYSIS & TESTING RESULTS

The aim of the five sample test series is to analyze crack patterns with different spacing and crack widths. The analysis presented in this extended abstract focus on the crack localization and width derivation, which is why only one specimen with one defined crack location is discussed. The resulting strain sensing profiles along a concrete-embedded sensing cable [4] for all different interrogators are depicted in 2. It must be noted that the data represents the raw measurement signal with a physical spatial resolution of 0.5 m, but with different spatial sampling and is not further processed or filtered. The high-resolution OFDR measurements (left) confirm the initial crack opening at the loading step of 30 kN, with a significant peak arising in the middle of the specimen (position: 1.5 m) over an area of approx. 200 mm. The Brillouin sensing techniques are not capable to visualize the initial cracking with such high resolution due to their spatial limitations, although interrogator B-02 also indicates cracking already at 30 kN. The peak width and magnitude is continuously increasing with each subsequent load step up to the maximum load of 130 kN applied for the actual specimen. Even if the strain peak appears over a larger area, Brillouin interrogators B-02 and B-03 can represent the OFDR technique well for loads higher than 30 kN. The B-01 signal, however, only represents major strain events for the last three load steps.

The strain distribution for Brillouin sensors is usually derived by determining the mean Brillouin frequency for each position along the optical fiber using curve fitting methods (e.g. Lorentzian fitting). In order to optimize the strain sensing results for B-01, comprehensive data reprocessing has been performed by low-pass filtering of the full Brillouin spectrum before curve fitting. The resulting strain profiles depicted in Figure 3 demonstrate that the data can be significantly optimized to reproduce the strain peak due to the developing crack similar to other Brillouin interrogators.

The crack width derivation itself may be performed by numerical integration of the measured strain sensing values over the area of interest, i.e. the strain peak area. The integration length, or rather the start and end point of the crack induced area along the signal, can be practically determined by analyzing the strain gradient at each side of the peak. These points are identified as the locations, at which the strain variation does not exceed a certain threshold within a defined number of subsequent data points. For further information and details on the determination principle reference is given to [7].

The crack widths derived for all DFOS technologies and the reference distance transducer are listed in Table 1. The results of the Brillouin interrogators are in good agreement with those of the high-resolution OFDR, with maximum deviations lower

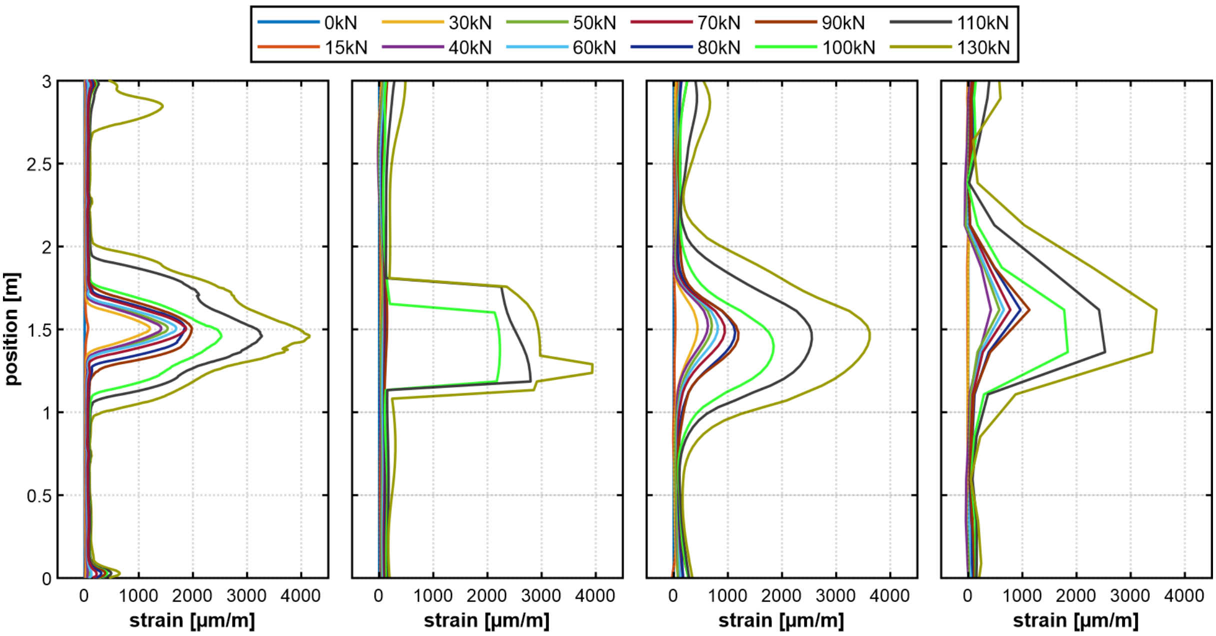

Figure 2. Strain profiles recorded by various DFOS interrogators during load test: Rayleigh OFDR and Brillouin B-01/B-02/B-03 (left to right).

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than 0.1 mm at loads of up to 90 kN or rather a width of approx. 0.6 mm. Cracks in reinforced concrete structures are usually controlled under service in a range of 0.2 to 0.4 mm [8], which can be obviously determined for all sensors. The distance transducers mounted on the surface also confirm the absolute accuracy for load steps up to 90 kN. Higher loads indicate minimal local slippage between the sensing cable and the concrete or even the different sensing cable layers at the crack location, which is why the width derivation using numerical strain integration seems to be no longer applicable.

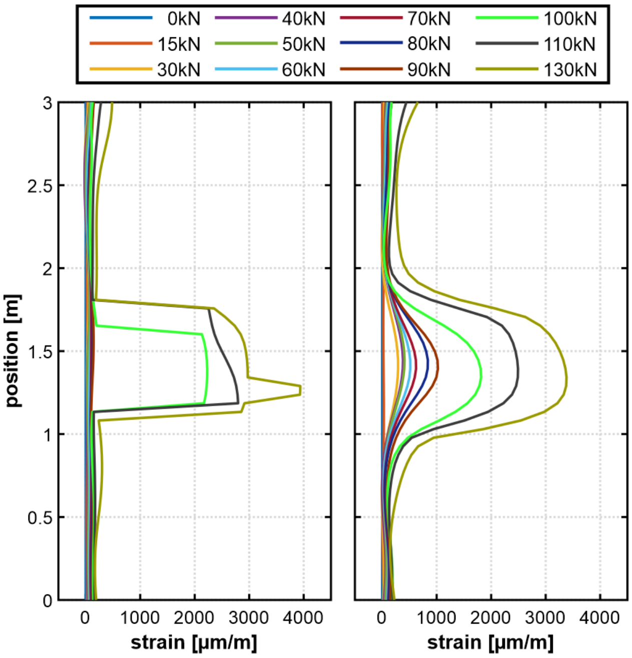

Figure 3. Strain sensing profiles of Brillouin interrogator B-01 before (left) and after spectrum filtering (right).

It must be noted that the quality of the crack width derivation is strongly related to the parameter settings for the integration length. These vary depending on not only the sensing technique but also the installation technique of the optical sensing cable. The dedicated test series is capable of providing an essential lookup table to appropriately perform the integration length determination for different configurations for future monitoring applications.

Table 1. Crack widths derived from various DFOS interrogators and measured by conventional distance transducers at different load levels.

load [kN]	crack width [mm]				
	DD-01	OFDR	B-01	B-02	B-03
15	0.00	0.00	0.05	0.00	0.00
30	0.28	0.22	0.20	0.18	0.00
40	0.38	0.30	0.27	0.25	0.26
50	0.39	0.35	0.30	0.30	0.32
60	0.40	0.41	0.36	0.34	0.37
70	0.46	0.48	0.43	0.40	0.46
80	0.53	0.57	0.55	0.52	0.52
90	0.61	0.66	0.67	0.56	0.60
100	0.72	1.10	1.21	1.08	1.11
110	1.24	1.81	1.88	1.77	1.77
130	1.57	2.68	2.85	2.79	2.87

3 CONCLUSIONS & OUTLOOK

This extended abstract discussed the suitability of numerous Brillouin interrogators for localizing concrete cracks and quantifying their corresponding width. An enhanced test series with five individual specimens equipped with multiple DFOS installation setups was realized to investigate crack opening under well-known laboratory conditions. The crack location along the resulting strain profiles could be well captured by all interrogation units and enabled the derivation of crack widths for different load levels using numerical integration. The derived values correspond well with reference measurements from the distance transducer mounted at the surface for all tested Brillouin interrogators, with maximum deviations of approx. 0.1 mm within the usual service range for reinforced concrete structures.

It could also be demonstrated that the original data processing might fade out local deficiencies like cracks in the strain sensing profiles. This limitation may be overcome in this specific case by applying appropriate filtering to the raw Brillouin spectrum data.

The presented research focused on the traditional strain-based data analysis. In addition, initial tests for crack width determination using a feature extractor based on a CNN (Convolutional Neural Network) autoencoder, which was applied to the raw Brillouin spectrum along the sensing network [9]. This artificial intelligence (AI) approach will be further investigated and optimized to provide more comprehensive methods for analyzing concrete cracks along civil infrastructure.

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