Surface-applied distributed fiber-optic monitoring for crack detection in concrete structures: Technology overview and application challenges

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ABSTRACT: Truly distributed fiber-optic strain measurements provide the possibility to detect and quantify cracks in prestressed concrete structures without previous knowledge of the location where cracks are likely to appear.

With the Distributed Brillouin Optical Frequency Domain Analysis (BOFDA) and the coherent Optical Frequency Domain Reflectometry (c-OFDR), two complementary technologies have been applied to crack measurements on prestressed concrete beams within the scope of this work. This article highlights the strengths and challenges of both technologies, with special focus on the differences in how the fiber-optic sensors are applied to achieve optimum results. Comparisons of different fiber and cable types are made as well as different bonding techniques like continuous and point-wise gluing and anchoring.

The implications for analyzing the data from both technologies are shown and verified by experimental data from true-scale laboratory tests and on-site applications.

1 INTRODUCTION

The inspection and test of civil engineering structures, particularly infrastructure buildings, play a significant role to ensure public safety. Therefore, intervals and scope of these inspections are prescribed in several building codes, i.e. DIN 1076 (1999). According to many authors, such as Fischer et al (2019), the assessment of reinforced concrete structures is mainly based on crack detection, which result from damage to the concrete or to the embedded reinforcement steel.

Using conventional sensors at local measuring points, such as strain gauges, only known cracks can be observed, since their location is unknown before the onset of cracking. With continuous fiber-optic strain measurements, on the other hand, the overall strain curve along the fiber path is measured. Cracks forming along the fiber result in peak values of the measurement curve. Thus, cracks are detected at a very early stage, and their change in crack width can be monitored during the service life of the engineering structure. Due to these properties, continuous fiber-optic strain measurements are ideally suited to detect critical states of aging structures on time, as well as to recognize or to determine their remaining load capacities.

In recent years, fiber-optic sensors have increasingly been deployed for strain measurements both inside the concrete body (installed by fixing to the rebars before pouring the concrete), and on the surface (installed by gluing to the cured surface).

Integrating fiber-optic sensors into the concrete provides a reliable strain transfer from within the geometry of the structure, simultaneously protecting the fiber-optic sensing cable from mechanical damage. However, in the specific case of existing structures, where embedding sensors into the concrete is not possible, surface application of fiber-optic sensing cables is a feasible way for retrofitted structural health monitoring.

2 DISTRIBUTED FIBER-OPTIC STRAIN MEASUREMENT TECHNIQUES

Fiber-optic sensors for strain measurements provide significant advantages over conventional electric strain gauges: They are inert to the chemical ambience in the concrete, they are immune to electric fields and lightning puncture, and they provide intrinsically electrical safety.
Among the various types of fiber-optic sensors, there are point-wise strain measurement techniques such as Fabry-Perot-Interferometers (FPI), and quasi-distributed sensors such as Fiber-Bragg-Grating sensors (FBG). Both of these types are able to measure strain at pre-defined locations over a defined gauge length (Glisic et al (2008)).

In contrast to these point-wise and quasi-distributed methods, truly distributed fiber-optic sensing techniques provide continuous strain readings over the entire length of the optical fiber that is the sensor. Each measurement point of these readings represents the local strain state at the specific location.

In the scope of this paper, two different fiber-optic sensing technologies that provide distributed strain measurements have been investigated: The coherent analysis of Rayleigh scattering, specifically the c-OFDR (Coherent Optical Frequency Domain Reflectometry), and distributed Brillouin sensing, specifically the BOFDA (Brillouin Optical Frequency Domain Analysis).

Both technologies employ an optical reflectometry, which measures the response of an optical fiber to the excitation of an injected optical signal. The specific frequency-domain techniques of the technologies under investigation can be derived from the classical time-domain reflectometry scheme as outlined in Figure 1.

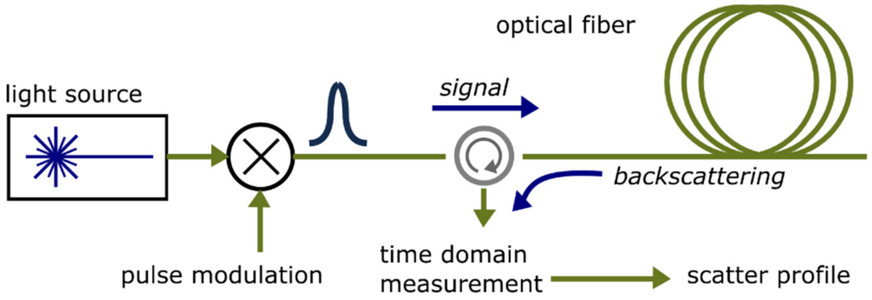


Figure 1: Basic principle of distributed sensing techniques based on optical backscattering reflectometry

The injected optical signal travels along the fiber under test (e.g., the strain sensing fiber attached to the structure) and is subject to number of backscattering effects along the way. From every location the signal passes by, portions of light are being thrown back and travel to the injection end, where they are recorded over time. From the time of flight, the origin of the received backscattering at every instance in time can be reallocated. Thus, a distributed profile of optical backscattering can be recorded for the entire length of the fiber under test.

Despite this common ground, the two investigated technologies differ in the specific optical backscattering effect they work with, which will be discussed in the following. For practical implications, the main differences of the two technologies lie in their overall performance parameters: The c-OFDR technology provides millimeter-range spatial resolution over some tens of meters of range, whereas the BOFDA technology offers a spatial resolution down to 20 cm, but enables measurement lengths of several tens of kilometers. Therefore, they are often considered to be complementary rather than to be competing technologies.

2.1 *Strain measurements with the c-OFDR technology*

The c-OFDR technology measures the distributed profile of the intensity of Rayleigh backscattering, as described in Speck (2019), Lanticq et al (2009) and Palmieri et al (2013). This backscattering profile can be considered as a unique fingerprint of the microscopic structure of the optical fiber, and is assumed to be stable over time – with limitations due to ageing, water intrusion, radioactive impact etc. For sensing purposes, the fiber's local displacement can be seen as a local shift of the backscattering profile when directly compared to the known backscattering profile from previous measurements.

By correlating one reading to a reference measurement, the local fiber strain can be derived (Froggatt et al (1998), Liehr et al (2010)). It shall be highlighted that the raw measurement data represents the local displacement of the backscattering profile, and the strain reading is gained indirectly as the derivative of displacement (which is a geometrical information) with respect to the fiber position. This is outlined in Figure 2.

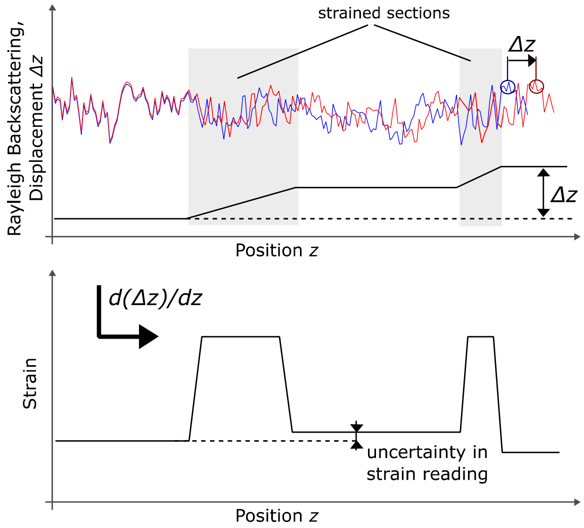


Figure 2: Strain and displacement measurements derived from distributed readings of Rayleigh backscattering.

2.2 Strain measurements with the BOFDA technology

In distributed Brillouin sensing, two optical signals with a defined frequency offset are injected from the opposite ends of the fiber under test. They excite a nonlinear effect known as Stimulated Brillouin Scattering, the intensity of which is measured over time as in Figure 1, while the frequency offset of the two optical signal is varied. For each location along the fiber, a characteristic frequency offset with maximum Brillouin scattering is found. This frequency corresponds to the local strain and temperature of the fiber, as it is dependent on the medium's acoustic velocity at every position of the fiber, see Nikles et al (1996).
In contrast to the c-OFDR technology, the raw measurement data represents the local strain of the fiber. If, within the sensing tasks when applying the technology to structural monitoring, the displacement of a specific position along the fiber is required (so as to determine the cumulated opening of cracks), this needs to be gained indirectly as the integral of strain (which physical (density, or acoustic velocity) information) over the fiber position, as outlined in Figure 3.

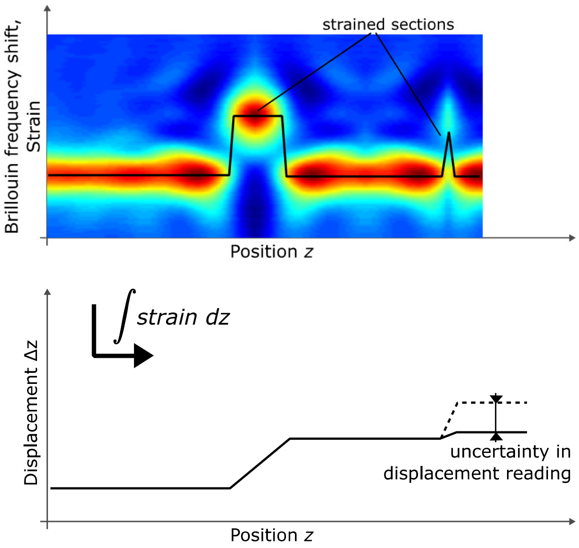


Figure 3: Strain and displacement measurements derived from distributed readings of Brillouin backscattering. The above (colored) graph depicts the Brillouin scattering intensity over the frequency offset of the optical signals. For each position, the fiber's local strain is derived from the frequency value with highest scattering intensity.

From this comparison of the physics and sensing techniques behind the two technologies, it can be said that both are well suitable to provide accurate strain readings when applying them to health monitoring of concrete structures. However, from the different approach to strain and displacement, it becomes clear that in both technologies, limitations and uncertainties have to be accounted for:

Displacement readings from distributed coherent Rayleigh measurements are inherently accurate to the specifications of the sensing system. Strain measurements rely on the long-term stability of the fiber's backscattering profile; every local change or measurement error will induce an error in all subsequent strain readings.

Strain readings from distributed Brillouin sensing are inherently accurate to the specifications of the sensing system. Displacement measurements will bear the integrated measurement error of the strain measurements, especially when local strain events are smaller than the system's spatial resolution, as shown in Figure 3.

3 DISTRIBUTED FIBER-OPTIC STRAIN SENSORS ON CONCRETE SURFACES

When applying fiber-optic sensors, whether embedded into specific strain sensing cable designs, or as bare fibers with primary coating only, several considerations need to be accounted for:

- An accurate, continuous strain transfer from the structure to the fiber is required to ensure correct strain measurements at each fiber position and to provide exact localization of the strain events (cracks etc.).
- The fiber needs to be protected from excessive strain that would lead to fiber break (in practice, 2% strain should not be exceeded; fiber and cable manufacturers often specify 1% to account for aging and plastic deformation effects).
- In order to avoid strain events that are smaller than the spatial resolution of the sensing system (especially for distributed Brillouin sensing, as discussed above), the strain should be discretized to a gauge length larger than the spatial resolution.

The apparent contradictions in the above considerations require a trade-off between the desired continuous fixation and protection of the fiber. The two possibilities to achieve this are depicted in Figure 4:

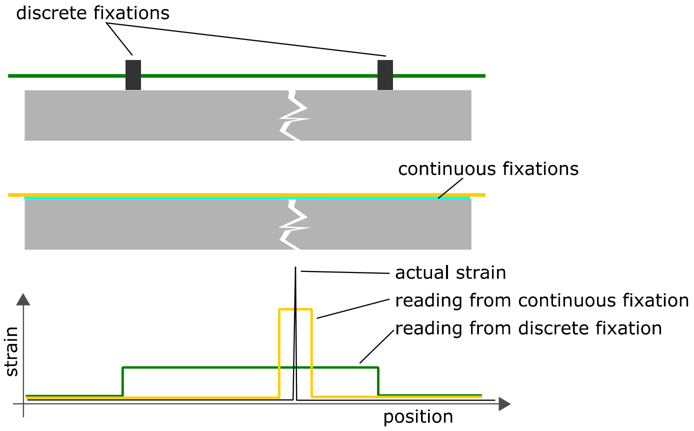


Figure 4: Discrete and continuous fixations of optical fibers to concrete surfaces for crack measurements.

- Continuous fixation by gluing the fiber. The elasticity of the gluing layer allows for a slight distribution of local strain, avoiding excessive strain that endangers the fiber.
- Discrete fixations allow for accurate readings of integral strain over a defined gauge length.

Both fixation techniques have been deployed in the test campaign as discussed in the following.

4 APPLICATION TO A LABORATORY TEST

The aforementioned fiber-optic measurement techniques were used to monitor a laboratory four-point-bending test on a prestressed concrete beam as shown in Figure 5. For the shown load pattern, cracks are to be expected near the bottom surface of the beam. There, two BOFDA sensors were attached to the surface, one with continuous fixation along the whole sensor length, the other with discrete, point-wise fixation every 0.25 m. A single c-OFDR sensor was attached continuously parallel to the BOFDA sensors.

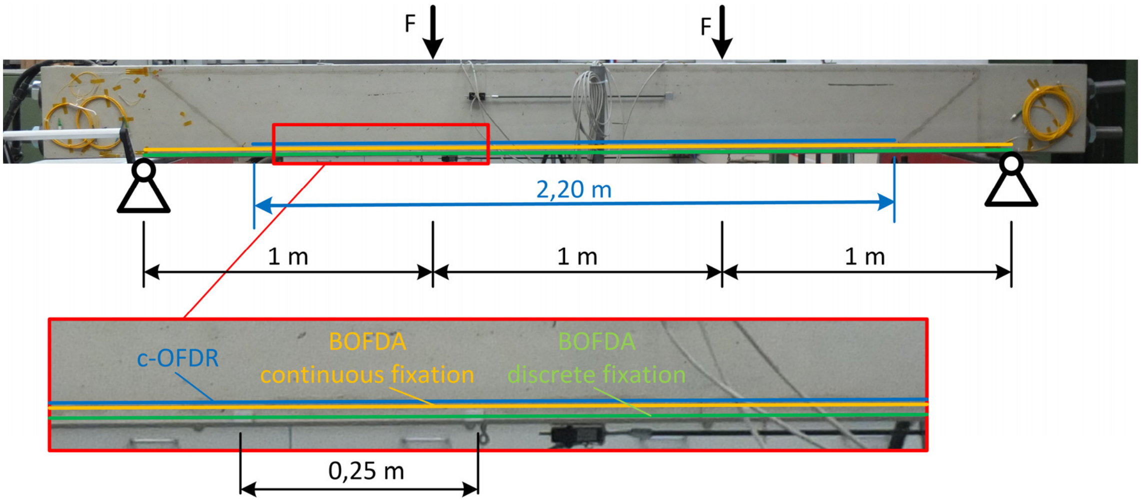


Figure 5: Four-point-bending-test on a prestressed concrete beam and measurement setup.

The load F was applied in six load steps, 10% through 60% of the theoretically predicted beam's load capacity. Figure 6 shows the strain measurements along the three fiber-optic strain sensors during the 60%-load-step.

The strain curve acquired with the c-OFDR measurement technique (Figure 6, top) stands out due to several peak values in strain. Since these clearly exceed the elastic strain level of concrete, they correspond to crack openings. Because of the high spatial resolution of c-OFDR it is possible to distinguish single cracks from each other, to determine their corresponding crack width, and to locate the position of the cracks along the fiber. These digitally captured information about the cracks are in good agreement to the results, which were determined by conventional, visual crack observations.

The measurement curves resulting from the BOFDA measurement technique are shown in the bottom graph of Figure 6. Except for a small portion of the sensor fiber, the strain in the continuously fixed sensor appears to be below the elastic strain level showing no indication of cracks. This is inconsistent with the visual inspection of the cracks on the beam's surfsace, as well as with the c-OFDR measurement. Apperently, the BOFDA method in combination with the continuous fixation misses to detect the cracks, because the local strain events caused by cracks are too small compared to the spatial resolution of the BOFDA measurement technique.

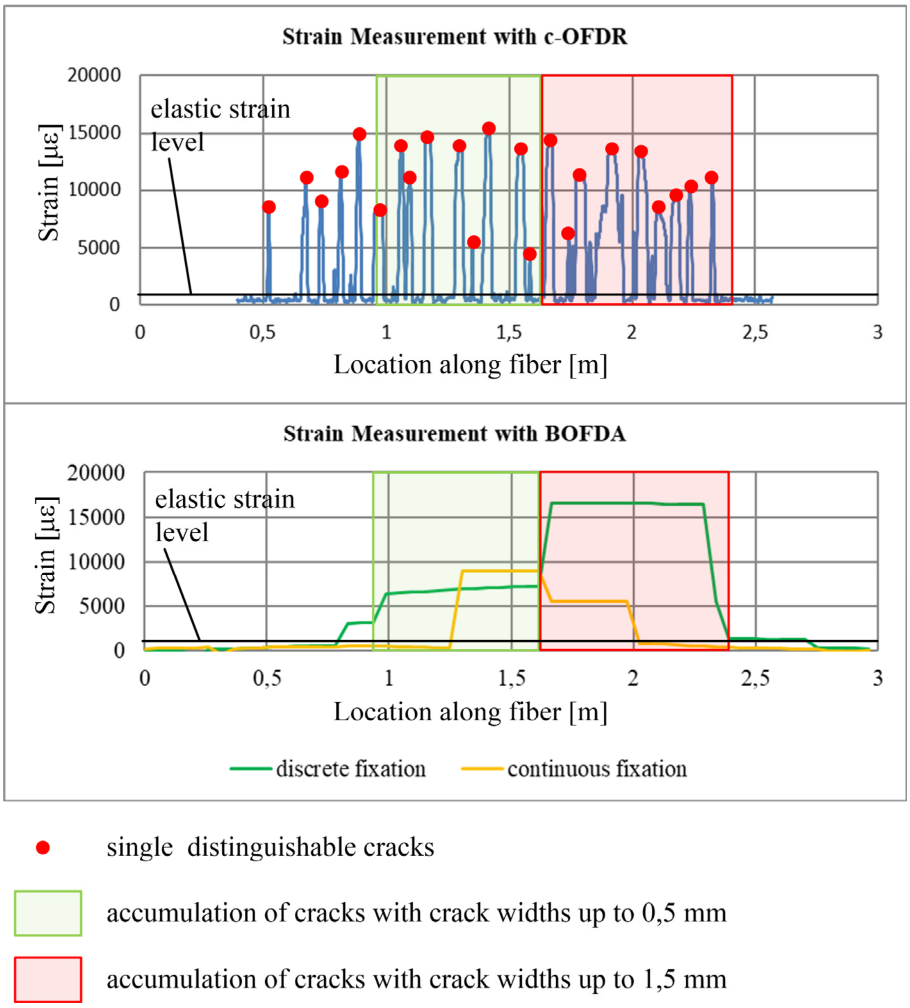
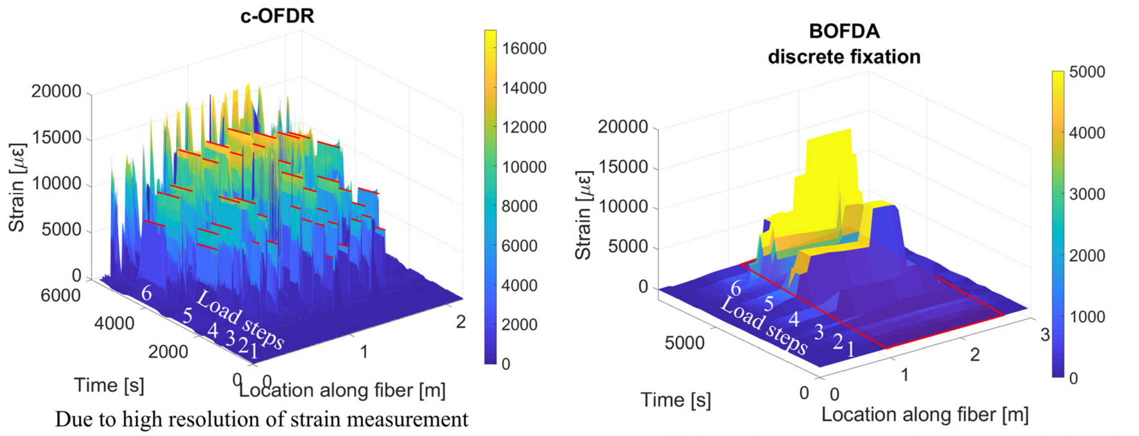


Figure 6: Continuous strain measurement sample; (top) c-OFDR; (bottom) BOFDA.

The strain curve of the BOFDA measurement in combination with the discrete fixation, on the other hand, exceeds the elastic strain limit in a larger portion of the sensor-fiber. Due to the discrete fixation, the local strain event caused by a single crack is distributed along the fixation distance of 0.25 m. Since this length is larger than the spatial resolution of the BOFDA method, the distributed strain enhancement due to the crack can be recognized. The resulting strain curve is in good agreement to the c-OFDR measurement and to the visual inspection. Although, single cracks and their width are not determinable, an accumulation of cracks can clearly be identified.

Figure 7 shows the overall measurements of both measurement techniques during the whole period of the experimental test. The onset of cracking is visible using both techniques in load step 3 (30 %), by visual inspection cracks were not detected before load step 4 (40 %). The growth in crack width and the accumulation of cracks with increasing load can be comprehended in both data sets.



— Due to high resolution of strain measurement individual cracks distinguishable from loadstep 3 through 6.

▭ High strain measurements due to accumulation of cracks from loadstep 3 through 6

Figure 7: Strain measurement along the whole fiber path during all the load steps of the four-point-bending-test; (left) c-OFDR; (right) BOFDA

5 CONCLUSION

Both the c-OFDR and the BOFDA strain measurement techniques are ideally suited for the inspection and test of concrete structures. Hereby, the observation of cracks plays a very important part, to ensure the serviceability of the structure under inspection. It was shown, that the onset of cracking is recognized at a very early stage using both techniques. The advantage of the c-OFDR is, that the cracks location, as well as their width can be precisely determined. The strength of the BOFDA technique is the large measurement range of several tens of kilometers. Considering a suitable fixation of the sensor to the structure, the accumulation of cracks can be well recognized.

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