Distributed Fiber-Optic Strain Sensing: Field Applications in Pile Foundations and Concrete Beams

Nils Nöther and Massimo Facchini

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Nils Nöther[1] and Massimo Facchini[1]

[1]fibrisTerre Systems GmbH, Berlin, Germany
nils.noether@fibristerre.de

Abstract. This paper gives an overview over industrial applications of distributed fiber-optic strain sensing in structural health monitoring, outlining both the benefits of the technology and its challenges regarding installation of the fiber-optic sensing cables and limitations of the measurement technology itself.

Keywords: Distributed fiber-optic sensing, Brillouin sensing, geotechnical monitoring, structural health monitoring, DTSS, DSTS

1 Distributed Fiber-Optic Strain Sensing Techniques

The family of fiber-optic sensing techniques has become wide during the past two decades, spreading into numerous applications not only in geotechnical and structural monitoring [1], but even into chemical industries, medical and health-care applications and many more. Means for categorizing the numerous members of this family include distinguishing by physical (or chemical quantity) such as strain, temperature, pressure, vibration frequency, refractive index or alike; by the specific optical effect being the provider of the desired information such as linear and nonlinear scattering, frequency-selective reflectivity of a grating, interferometry or other; or by the configuration of the physical or virtual sensing points along the fiber. This latter categorization is used here to set the focus on the group of distributed sensing techniques as opposed to discrete or point-wise sensors as well as quasi-distributed sensors, as shown in Fig. 1.

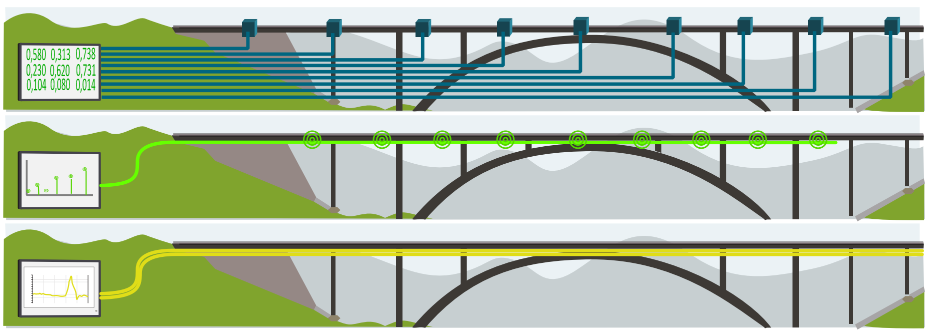

Fig. 1. Categories of fiber-optic sensing techniques – top: discrete sensor elements; center: quasi-distributed sensing elements along an optical fiber; bottom: truly distributed fiber-optic sensing

The advantageous nature of truly distributed measurements becomes apparent from the perspective of conventional measuring methods: Classic deformation monitoring (performed by strain gauges etc.) and temperature monitoring (Pt100 and alike) deliver data from fixed, single spots of a structure; quasi-distributed measurements (fiber Bragg gratings) provide a chain of discrete measurement points.
In contrast, an optical fiber connected to a device for distributed sensing will provide a continuous profile of the desired measurand – spatially resolved and over long lengths. The following table gives an overview over the most common distributed fiber-optic sensing techniques categorized with respect to the optical phenomenon on which they base their sensing capabilities.

Table 1. Overview of common distributed fiber-optic sensing techniques

Common name	Measurands	Optical effect	Fiber length	Spatial resolution
DTS	Temperature	Raman scattering	> 50 km	< 1 m
c-OFDR	Static and dynamic strain and temperature	Rayleigh scattering [2]	> 100 m	< 1 mm
BOTDA / BOFDA (DTSS)	Static strain and temperature	Brillouin scattering [3]	> 100 km	< 0.5 m
DAS / DVS	Vibrations; acoustic signals; dynamic strain; temperature gradients	Rayleigh scattering	> 50 km	< 1 m

In the context of structural health monitoring systems, these techniques can be considered as valuable sources of sensing data that can be not only used to stream strain and temperature data upon which threshold alarms can be triggered, but also to contribute to complex modelling and structural assessment methods. By merging distributed sensing data with other technologies like geodetic measurements, structural health monitoring systems can be created with comprehensive, high resolution deformation data beyond the accuracy of the single component technologies [2].

In the following, we will put the specific focus on distributed strain sensing techniques, based mainly on Distributed Brillouin Sensing, commonly referred to as DTSS (Distributed Temperature and Strain Sensing), or BOTDA/BOFDA (Brillouin Optical Time / Frequency Domain Analysis).

2 Brillouin Sensing and the Nature of Distributed Data

The common basic concept of all distributed fiber-optic sensing technologies is to measure the response of an optical fiber to the excitation by an injected optical pulse. The optical pulse travels along the fiber under test (e.g. the strain sensing fiber attached to the structure) and is subject to various 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 (Fig. 2).

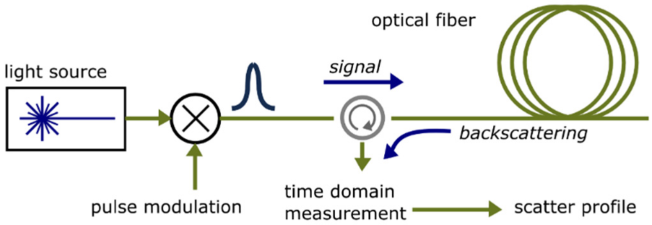

Fig. 2. Basic principle of distributed sensing techniques based on optical backscattering reflectometry

In the specific case of Distributed Brillouin Sensing, the backscattering carries the information of the fiber's local density, and thus on its strain and temperature condition at every position. This briefly outlines the principle of BOTDA measurements. An advancement of this concept, the BOFDA technology, substitutes the pulses with a series of harmonic signals, but remains equivalent regarding the result in terms of distributed strain and temperature data, retrieved from the optical fiber and resolved spatially along its length.

From this conceptual view, it is clear that the nature of sensing data from distributed measurements will differ substantially from that of conventional discrete sensors. Fig. 3 shows a typical example of a distributed strain measurement from a structural health monitoring installation (embedding in concrete).

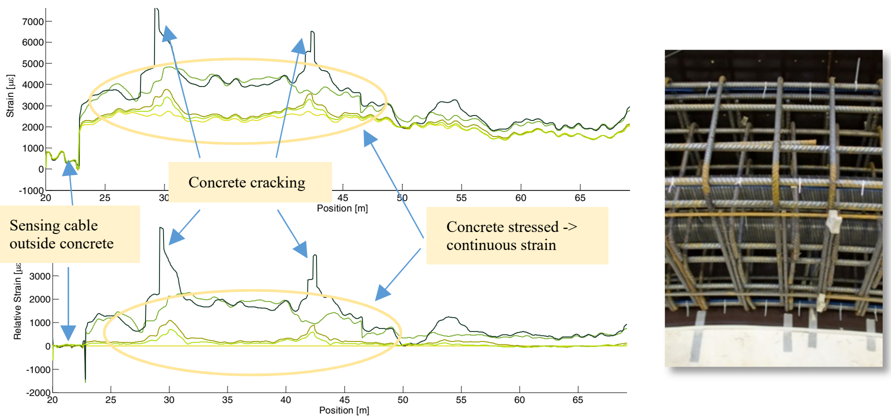

Fig. 3. Typical data set from distributed fiber-optic strain measurements using the BOFDA technology. Top: Direct strain reading, 5 data sets with increased load on structure. Bottom: Relative strain reading, first data set used as a baseline. Right: Installation with fiber-optic strain sensing cable (blue) fixed to the reinforcement before concrete pouring.

From this data example, it becomes clear that distributed sensing techniques are not to be considered a one-to-one replacement of discrete, point-wise sensors. In the above installation, discrete sensors such as extensometers or strain gauges would correspond to specific spatial sampling points of the distributed data curve. Whether point sensors would detect local mechanical events (cracks, localized deformation) depends on the selected positioning and the pre-defined gauge length, both parameters being subject to arbitrary decisions in the typical case of a priori unknown behavior of a structure during loading.

Table 2 summarizes the considerations of data handling for discrete and distributed sensors for the case of a fiber-optic sensing cable embedded into concrete, distinguishing between continuous and discrete strain events (as highlighted in Fig. 3).

Table 2. Comparison between discrete and distributed fiber-optic sensing techniques

	Continuous strain event: Stress, deformation	Discrete strain event: Cracking
Discrete sensor (strain gauge); also: Quasi-distributed (FBG)	Returns elongation of the structure over a previously defined gauge length (as a supporting point of the actual, continuous strain distribution)	Returns opening width of the crack Requires previous knowledge of the crack position; otherwise, no information is obtained
Distributed sensor (DTSS)	Returns full strain profile as a representation of the strain distribution in the structure	Returns crack detection as a localized event (with instrument spatial accuracy), but no quantified width of crack opening (no gauge length defined) Requires event width in range of instrument spatial resolution; otherwise, no information is obtained

When focusing on crack detection and monitoring in concrete installation, the shortcomings of the DTSS configuration in Table 2 can be addressed by discretizing the sensor configuration of the fiber-optic strain sensing cable, which is specifically feasible in surface application on concrete, as illustrated in Fig. 4.

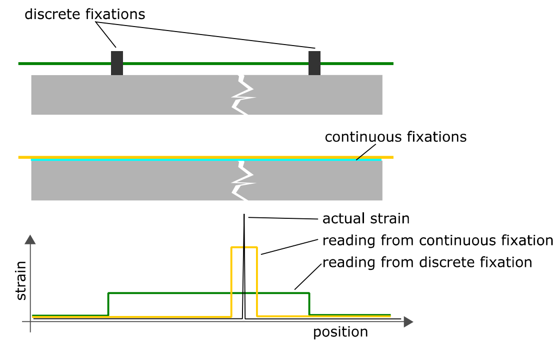

Fig. 4. Discrete and continuous fixations of sensing fibers to surfaces for crack measurements.

In effect, the discretization of distributed fiber-optic sensing configurations introduces a defined gauge length that even allows to quantify crack opening widths, while maintaining the advantage to provide information when no knowledge of the likely positions of crack appearance is available.

A comparison of both continuous and discretized surface application of optical sensing fibers has been performed on a concrete beam that was loaded after sensor installation applying defined load steps in order to induce stress resulting in cracking along the bending line. The discretization was achieved by fixing the sensing fiber at defined points with a distance of 0.25 m on the concrete surface. As a reference, a third sensing fiber was continuously applied in parallel and was interrogated using the c-OFDR technique at millimeter resolution [5]. The fixation is shown in the photographs in Fig. 5.

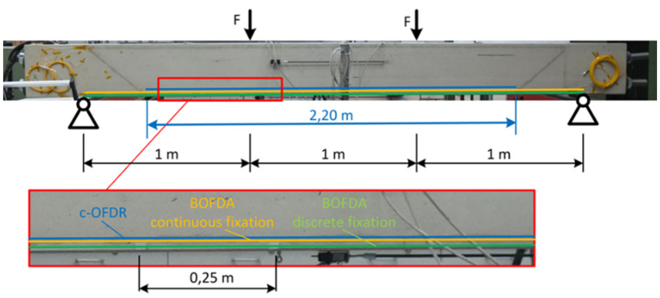

Fig. 5. Four-point-bending-test on a prestressed concrete beam and measurement setup.

The strain curve acquired with the c-OFDR measurement technique (Fig. 6, top) stands out due to several peak values in strain.

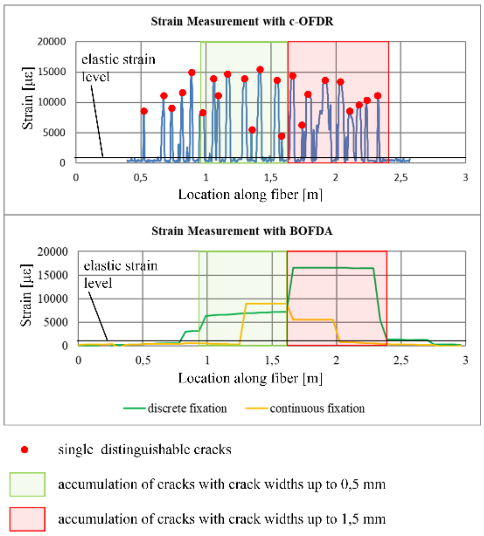

Fig. 6. Continuous strain measurement sample; (top) c-OFDR; (bottom) BOFDA.

Since these peak values 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. This digitally captured information about the cracks is in good agreement to the results which were determined by conventional, visual crack observations.

As expected, the BOFDA measurement using continuously fixed sensing fibers does not provide information on the crack opening, because every single crack is smaller in dimension than the instrument's spatial resolution of 20 cm.

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.

3 Field Experience Showing Distributed Sensing Data

An example of distributed strain measurements in loaded concrete structures, with a direct reference to discrete strain sensors, is given with the following installation in bored piles (Fig. 7).

Such measurements, using Brillouin DTSS systems for static load testing of concrete piles, have been reported for various sensing configurations [6].

The present application comprises a concrete-poured pile of 5 m depth; reinforced, steel-armored fiber-optic sensing cables were fixed to the reinforcement cage before entering the cage into the ground.

During the tests, an increasing vertical load from 150 kN to 900 kN was induced onto the pile, while subsequently extensometer data as point-wise references, temperature data at the extensometer positions and distributed Brillouin strain data were recorded.

With the exemption of the lowest extensometer, all the measurement points show good agreement between the classical data and the fiber-optic sensing data [7].

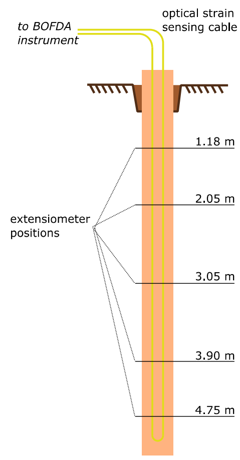

Fig. 7. Measurement set-up for static pile load testing

The following figures shows the evolution of strain for both the extensometers and the distributed Brillouin sensors (at the exact extensometer positions, compensated for the base line reading at 0 kN load) over time (Fig. 8) and spatial distribution (Fig. 9).

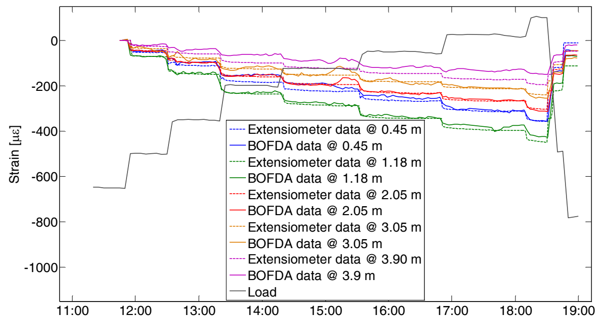

Fig. 8. Strain evolution: Extensometer and Brillouin DTSS data.

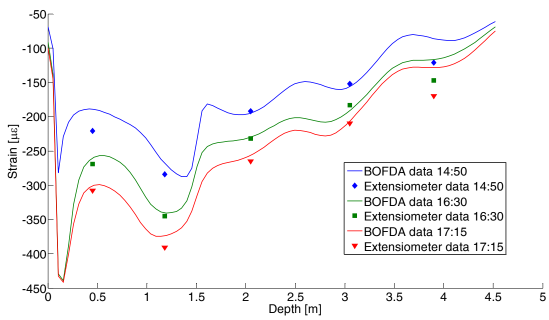

Fig. 9. Spatial strain in extensometer and Brillouin DTSS data

4 CONCLUSION

The distributed nature of fiber-optic strain measurements using the Brillouin sensing technology has been discussed and compared to the discrete configuration of conventional strain gauges. The advantages and limitations of distributed sensing techniques was shown with hands-on measurement examples.

From the presented examples, it becomes clear that distributed fiber-optic measurement techniques play their economic advantages specifically in large installations, where the cost of the sensing elements – which is considerably low for DFOS technologies using standard telecommunication fibers – is dominating the installation cost over the cost of the equipment. However, even in monitoring assignments of limited size, as in the examples described in here, the ability of distributed fiber-optic sensors to be daisy-chained, as well as installed in parallel and interrogated subsequently, introduces a strong cost advantage against classic single-point (discrete) sensors.

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