DOI: 10.3217/978-3-99161-057-1-018

Advancements in Distributed Fiber-Optic Sensing: Comparing Brillouin and Rayleigh Technologies for Geotechnical and Structural Monitoring

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ABSTRACT: We report on recent developments in distributed fiber-optic strain and temperature sensing (DTSS) technologies. In recent years, both Brillouin- and Rayleigh-based fiber-optic sensing systems have found an increasing number of applications measuring static and dynamic displacement and deformation events in geotechnical and structural health monitoring. The focus of this contribution is on Brillouin-based DTSS systems, for which we present recent advancements in spatial resolution and signal-to-noise ratio under harsh real-world conditions. The state-of-the-art Brillouin DTSS technology is considered also in relation to Rayleigh-based technologies like c-OFDR and DAS systems that also play an increasing role in geotechnical and structural monitoring, in order to illuminate the technology-specific strengths and challenges within the DFOS family. Recent insights from industrial projects and research activities in embankment monitoring are presented.

KEY WORDS: Distributed Fiber Optic Sensing, Structural Health Monitoring, geotechnical monitoring, Brillouin DTSS, BOFDA, embankment monitoring, crack detection

1 INTRODUCTION

Fiber-optic sensing is applied in many different domains of structural and geotechnical surveillance. Among the various technologies available, Brillouin-based Distributed Temperature and Strain Sensing (DTSS) offers particular advantages in that it addresses the analysis of physical parameters with measurement performance that meets engineering requirements particularly well. These performances, in particular the spatial resolution, accuracy and measurement range, integration time, long-term reliability continue to evolve thanks to a continuous development effort from the scientific and industrial community. The type of optical sensing fibers and deployed sensors in general, as well as the installation procedures and the management techniques for sophisticated measurement data sets must also be continuously adapted to the demanding needs of continuously more complex projects and the new technological possibilities that become available.
In this study, an overview of the most widely used distributed fibre-optic sensing technologies is presented, with a comparison of these technologies according to their key advantages.

In particular, we demonstrate the latest developments achieved by the Brillouin Optical Frequency Domain Analysis (BOFDA) technology, in terms of enhanced spatial resolution and deployability on various types of sensing fibers.

These performances make it possible to achieve measurement results with previously unattained quality and flexibility. This is demonstrated by the application of crack detection on dike covers presented in this article.

2 DISTRIBUTED FIBER OPTIC SENSING TECHNIQUES FOR STRUCTURAL AND GEOTECHNICAL MONITORING

Monitoring of buildings, transport infrastructure and the geotechnical and hydrogeological natural environment using distributed fiber optic sensors is becoming widespread.
The availability of a range of complementary measurement techniques on the market to suit the specific requirements of diverse applications and environments has enabled DFOS to be used on a large scale and for a variety of different Structural Health Monitoring (SHM) and geotechnical monitoring projects [1]. Even more importantly, a new generation of interdisciplinary engineers is arising and tackling large-scale and complex DFOS-based projects mastering dedicated instrument and sensors integration procedures as well as data management models complying with the spatially distributed nature of the DFOS, also deploying artificial intelligence and digital twins [2].
Complementary DFOS measurement techniques can be applied alternatively or jointly in structural monitoring campaigns [3, 4]. Different sensing technologies have advantages and disadvantages in terms of sensitivity to specific physical quantities, spatial distribution, temporal response, stability, field applicability, and financial cost.
The most relevant DFOS technique of interest for structural and geotechnical monitoring are shortly presented here after.

2.1 High-spatial resolution coherent Optical Frequency Domain Reflectometry (c-OFDR)

In the case of structures of limited dimensions (typically smaller than 100 m), monitoring with coherent Optical Frequency Domain Reflectometry (c-OFDR) [5, 6] is often the preferred choice.

DOI: 10.3217/978-3-99161-057-1-018

The c-OFDR technology measures the distributed profile of the intensity of Rayleigh backscattering. This backscattering profile constitutes a unique fingerprint of the microscopic distribution of the scattering centers along the optical fiber, and is assumed to be stable over time – with limitations due to ageing, water intrusion, radioactive impact, etc. With its sub-centimeter spatial resolution and microstrain accuracy over tens of meters, c-OFDR is well suited for precise monitoring in SHM applications, achieving high acquisition rates (up to few hundreds of Hz for small objects under test), allowing for dynamic measurements. Commercial instruments are, on the other hand, limited in monitoring large structures and for long-term measurement campaigns. Even if rectification of the decorrelation of measurements in the long-term have been demonstrated in post-processing of acquired data [7, 8], the technique is mostly deployed in laboratory environments or for short, discrete measurement campaigns.

For the structural and geotechnical monitoring of larger objects, long spatial range DFOS techniques such as Distributed Temperature and Strain Sensing (DTSS) based on Brillouin analysis, and Distributed Acoustic Sensing (DAS) based on the dynamic analysis of Rayleigh scattering are widely preferred.

2.2 Dynamic measurements by Distributed Acoustic Sensing (DAS)

Distributed acoustic sensing (DAS), also referred to as phase sensitive optical time-domain reflectometry (Φ-OTDR), is a fiber optic sensing technology also relying on Rayleigh backscattering and is sensitive to strain and temperature perturbations in the fiber [9, 10]. By injecting pulses of coherent laser light into an optical fiber, an optical phase change is recorded, resulting from the backscattered light between two sections of fiber. DAS broadband capability at frequencies of several kHz and its high sensitivity in the picostrain range makes it ideally to be deployed in application fields such as geophysics (seismology, oil and gas, geothermal energy), electricity distribution, and perimeter monitoring. On the other hand, its inadequate performance to detect strain changes at low frequencies implies that its deployment is rare in long-term quasi-static geotechnical applications, where changes occur in time scales ranging from seconds (e.g. by pile loading tests) to years (e.g. for monitoring tunnel convergence, subsidence in transport infrastructure, landslides). One of the rare deployment examples of low-frequency DAS to characterize the movement of slow-moving shallow landslides is recurrently cited in literature [11].

On the other hand, DAS finds possible deployment opportunities in SHM, for example for monitoring the dynamic response of built structures such as bridges [4]. Namely the combination of DAS with long-term stable DFOS techniques, such as Distributed Temperature and Strain Sensing (DTSS) based on Brillouin Optical Time/Frequency Domain Analysis (BOTDA / BOFDA), comes with several advantages. Both the Brillouin and Rayleigh backscatter are sensitive to strain and temperature changes, but complementary spectral information can be gained. DAS is mainly sensitive to strain changes caused by acoustic signals or vibration along the fiber with acquisition rates up to several kHz. This allows insights on the vibration behavior of the bridge. Brillouin sensing, in contrast, offers highly stable and reliable measuring of long-term evolutions of strain and temperature.

2.3 Long-term stable DTSS by Brillouin Optical Time/Frequency Domain Analysis (BOTDA / BOFDA)

Brillouin scattering allows for measurement of the absolute material density state of an optical fiber, thereby providing strain and temperature profiles over more than 50 km, with a spatial resolution down to 50 cm. These performance figures make distributed Brillouin sensing highly suitable for monitoring large structures [12, 13, 14].

The basic principle of all distributed sensing principles based on Brillouin scattering is to spatially resolve the nonlinear Brillouin interaction along an optical fiber in order to retrieve the locally characteristic Brillouin frequency shift, which in turn is (over most of the strain and temperature ranges that are relevant for geotechnical monitoring) linearly connected with the fiber's density. The Brillouin frequency shift can be retrieved from the Brillouin backscattering in a reflectometric set-up, which requires access to only one end of the sensing fiber; such configurations are denoted by the letter "R" in the common acronyms (BOTDR/BOFDR). The signal quality of distributed Brillouin sensing can be highly improved by analyzing the resonance frequency between two counterpropagating optical signals injected from both ends of the sensing fiber. Such configurations bear the letter "A" at the end of the specifying acronyms (BOTDA/BOFDA). Whether the spatially resolved profile of the Brillouin frequency shift is recorded in the time domain or the frequency domain, is denoted by the letters "T" and "F" (BOTDA/R, BOFDA/R).

Due to its primarily measured material parameter being the intrinsic density of the optical fiber, the BOTDA/BOFDA technology is specifically long-term stable and free from the requirement of on-site sensor calibration both at the initial baseline measurements and during long-term operation. With the calibration parameters known for the fiber-optic sensing cables in use (to be acquired from one-time laboratory tests), the Brillouin frequency shift from each measurement iteration can be converted into absolute values for temperature and strain, with no drift being caused by aging, fatigue, or changes in the optical properties of the cables and connectors. Therefore, the technique is especially suitable for geotechnical and structural monitoring over a time horizon even of many years.

For reliable and stable measurements, the behavior of the bonding between the fiber-optic strain sensing cable and the surrounding structure under test must be considered. This is a key point when defining the integration procedures of the sensors in the host structure. On concrete structure the sensor can be embedded with high during the construction process, e.g. close to reinforcement elements (re-bars, pre-stained tendons), or applied on surface by retrofitting (by continuous gluing or using discrete fixation anchors). In the case of geotechnical monitoring this can be optimized, for example by burring the sensing cables in compacted soil or more efficiently in combination of smart geocomposites [15].

Often it is necessary to compensate the effect of temperature on the strain measurement (since Brillouin, as well as Rayleigh sensing show strain-temperature cross-sensitiveness). In order

DOI: 10.3217/978-3-99161-057-1-018

to separate strain and temperature, the use of dedicated (loose-tube) fiber-optic temperature sensing cables, in which the fiber is mechanically decoupled, in parallel to a tight-buffered strain sensing cable is often the preferred monitoring configuration.

2.4 Cracks, voids, debonding detection by Distributed Temperature Sensing (DTS)

Distributed Temperature Sensing (DTS) using Raman (and also Brillouin and Rayleigh) scattering is widely used in geotechnical and structural monitoring. It ensures accurate deformation measurements by compensating for thermal effects, tracks exothermic reactions in concrete curing, and detects fluid seepage in dams, pipelines, and tailings storage [16]. It has also been shown how DTS can be effectively applied to detect the presence of subsurface defects (voids) in concrete-filled structures [17]. The DTS methodology combined with heat conduction modeling, and inverse analysis has been applied to measure the geometry of foundation piles and to calculate their bearing capacity [18].
Recent studies demonstrate how Brillouin-based DTS can be used for non-intrusive detection of desiccation cracks in dikes. This application is discussed in a later section of this work.

2.5 Key takeaways

- DTS & Brillouin-based DTSS offer the best long-term stability, making them ideal for infrastructure monitoring over decades.
- DAS is highly reliable for dynamic applications, such as seismic, traffic monitoring, vibrational mode analysis.
- c-OFDR provides high precision, but is more sensitive to environmental factors over time.

3 PERFORMANCE PARAMETERS AND PRACTICAL IMPLICATIONS OF BOFDA MEASUREMENTS

Specifically for the Brillouin Optical Frequency Domain Analysis (BOFDA), the technology on which the focus of this work lies, we would like to go into deeper detail on two performance aspects for practical distributed measurements in optical fibers.

3.1 Performing DFOS measurements in multi-mode optical fibers using Brillouin sensing system:

It is commonly accepted that for each of the different DFOS technologies, the respective optimum fiber type shall be used in order to gain optimum performance. In Raman DTS systems, these will be multi-mode optical fibers due to their ability to handle high optical power levels (even though dedicated single-mode Raman DTS systems exist, minimizing modal dispersion to achieve higher distance ranges). In contrast, for Brillouin DTSS, literature clearly states that the use of single-mode optical fibers is mandatory. The reason here is that, in multi-mode optical fibers, the excitation of the Brillouin interaction needs to be achieved for each optical mode separately, which makes the backscattering intensity (or the Brillouin gain) highly sensitive to the arbitrary modal distribution of the involved optical signals [19]. While earlier works had shown that a strict limitation to exciting the fundamental mode only when injecting the optical signals into the fiber under test [20], such an approach has not found its way into practice, with the consequence of a clear directive to practical users of Brillouin DTSS to exclusively use single-mode optical fibers as sensors.

However, in many real-world application scenarios, the user might not have the choice of the fiber type – be it due to previously installed fiber-optic cables that comprise multi-mode fibers for whatever reason, or due to imperfect project design or any other cause. Therefore, Brillouin DTSS measurements in multi-mode fibers have been frequently reported, and the results show that they are indeed suitable for quantitatively meaningful strain and temperature sensing. One of such application scenarios is reported in a later section of this work.

In general, the design variety of multi-mode optical fibers contains specifications on the core diameter (typically 50 µm and 62.5 µm), and the refractive index profile between core and cladding being a gradient or a step-function profile.

On order to give a generic orientation for Brillouin DTSS performance in a common-type multi-mode optical fiber, we present laboratory measurements from a step-index 50/125 µm (core/cladding diameters) step-indexed optical fiber of 445 m length. The measurements are performed using a BOFDA system on an optical fiber loop with the multi-mode optical fiber under test connected in series with a standard single-mode optical fiber (ITU-T G.652) of 120 m length for reference.

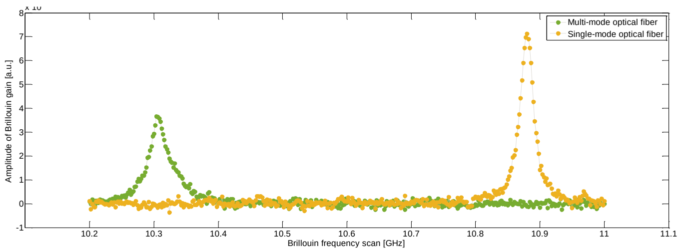

Figure 1. Brillouin gain spectra from one BOFDA measurement on a multi-mode and a single-mode optical fiber

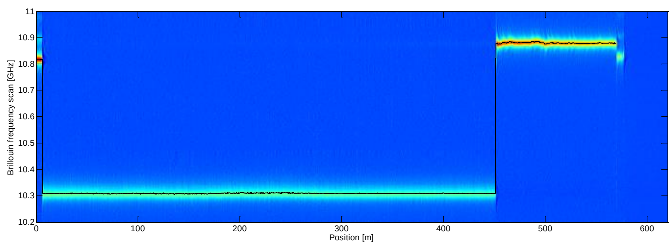

Figure 2. Full BOFDA measurement result: Intensity of Brillouin interaction (color map); local Brillouin frequency shift (black trace)

The measurement results (figures 1, 2) show that the characteristics of Brillouin sensing for a specific fiber type, specifically the characteristic parameters of the Brillouin gain spectrum, indeed differ between the multi-mode optical fiber under test and the reference single-mode fiber:

1. Brillouin frequency shift: While single-mode fibers have a characteristic Brillouin frequency shift (at room temperature and under strain-free conditions) at values between 10.6 GHz and 10.9 GHz, the multi-mode fiber shows a considerably

DOI: 10.3217/978-3-99161-057-1-018

lower Brillouin frequency shift at 10.31 GHz. This is a quantitative difference, but does not at all compromise the performance of Brillouin sensing, because the observed frequency lies well within the scan range of commercial interrogator units.

2. Brillouin linewidth: The full width at half its maximum of the Lorentzian-shaped Brillouin gain spectrum is observed as 36 MHz for the multi-mode fiber and 25 MHz for the single-mode fiber. Again, this is merely a quantitative characterization and does not imply a significant degradation of the measurement quality.

3. Brillouin gain: The amplitude of the Brillouin gain spectrum of the multi-mode fiber is observed to be 3 dB (half intensity) below the reference single-mode fiber. The direct consequence of this discrepancy is a loss of 3 dB in signal-to-noise ratio between the two fiber types, confirming that single-mode optical fibers are better suited for distributed Brillouin sensing. However, considering the very clear implication of single-mode fibers being the obligatory choice, this 3 dB difference is considerably small. All in all it can be stated that multi-mode optical fibers can in fact be used for distributed Brillouin sensing.

3.2 The spatial resolution of BOTDA and BOFDA systems

The spatial resolution is one of the central performance figures of any DFOS system. In general, the following definition has been widely accepted throughout the industry [21]:

The spatial resolution is specified for a fiber by the minimum distance between two step transitions of the fiber's strain / temperature condition. It is directly related to the pulse length of the measuring instrument.

For general time-domain DFOS systems, the relation between the pulse length Δt_p and the spatial resolution δz is

$$\delta z = \frac{1}{2}\frac{c_0}{n}\Delta t_p$$

with c_0 being the vacuum light speed and n the group refractive index of the optical fiber. A rectangular pulse of 10 ns length thus allows a spatial resolution of 1 m.

When considering incoherent frequency-domain systems, such as BOFDA, the pulse length is not directly determinable because no physical pulses are used. In BOFDA, a series of sinusoidally modulated signals is injected into the optical fiber as the pump light; the received signal (the Stokes wave, upon which the sinusoidal modulation is transferred) is analyzed by gain and phase, which – over the full series of different modulation frequencies – results in the complex transfer function, that, eventually, can be converted into the pulse response (and thereby the equivalent time-domain signal of a BOTDA system) by means of an inverse Fourier transform.

Whereas in a time-domain system, the spatial resolution is directly related to the pulse width, in a frequency-domain system it is related to the width of the virtual pulse after the inverse Fourier transform, and therefore, in its origin, determined by the bandwidth (or range of the frequency scan) of the sinusoidal intensity modulation.

The equivalent relation found in literature implies that a bandwidth of 100 MHz results in a spatial resolution of 1 m. We hereby state that this appears to be not consistent with the theory behind nor with experimental results. The key to this discrepancy between commonly accepted literature and everyday observation is that these literature sources neglect the complex nature of the retrieved transfer function. The true assumption there is that the number of scanned frequencies of the transfer function within the given bandwidth equals the number of points along the equivalent time axis for the relation 100 MHz bandwidth ⇔ 1 m spatial resolution.

However, every frequency point of the complex transfer function comprises two values in the complex domain (gain and phase, or real and imaginary part, respectively). Conservation of information energy results in the fact that this doubles the number of points along the time axis (and thus the equivalent spatial axis), and results in a spatial resolution twice as narrow as the above cited literature implies. The relation for incoherent frequency-domain systems, specifically BOFDA, becomes

$$\delta z = \frac{1}{4}\frac{c_0}{n}\frac{1}{\Delta f_m}$$

in which Δf_m is the bandwidth of the sinusoidal intensity modulation.

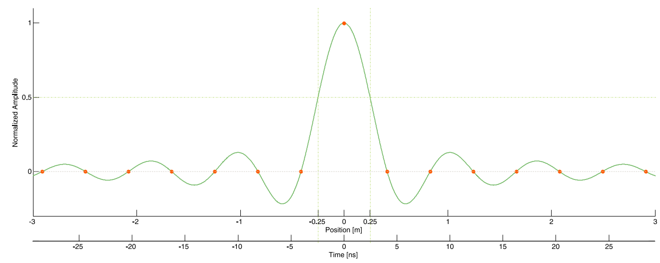

Figure 3. Virtual pulse in the time / spatial domain from a BOFDA acquisition scan

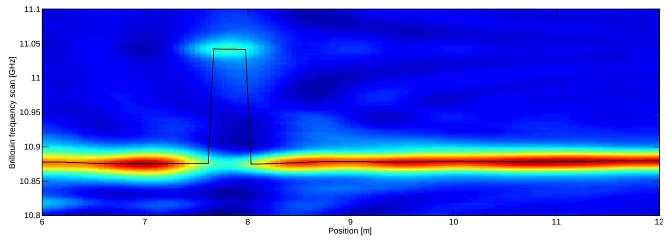

Figure 4. Discrete strain event of 0.5 m along an optical fiber, measurement result from BOFDA ($\Delta f_m = 101.76$ MHz)

For future developments, this means that a native spatial resolution (virtual pulse width) of 0.25 m is achievable by increasing the bandwidth of the intensity modulation to 200 MHz, which is subject to current research by the authors.

DOI: 10.3217/978-3-99161-057-1-018

4 APPLICATION CASE: UNINTRUSIVE CRACK DETECTION ON DIKE COVERS BASED ON DTS

In the Netherlands, levees also referred to as 'dikes' are built from locally obtained materials like sand, clay, and peat, with peat and clay as the most common and abundant materials. They are used as they are the least permeable and most cohesive, thus most mechanically stable and erosion resistant. The outer portions of dikes tend to be made of grass covered hard clay, while the inner portions may be made of sand or peat for easier drainage and flexibility. Nonetheless, these materials respond differently to prolonged drought conditions. Under prolonged periods of dry weather, clay and peat dominated soils tend to develop desiccation cracks in the outer parts and thus the evaporating of moisture tends to increase their dimensions in time. Peat for example, is also a very organic and porous soil which shrinks massively during drought periods which also causes mechanical fracturing of the outer covers of dikes. These processes can seriously compromise the dike's ability during a sudden storm as faster infiltration will saturate the dike core faster which in combination with a high-water level may result in a slope stability failure and consequently an eventual dike breach.

Currently, the detection of desiccation cracks over dikes involves is done mostly by visual inspection and only prior and during drought periods which normally occur during the spring and summer [22]. These inspections, often result in subjective conclusions and their spatial density and frequency are significantly low with respect to their natural occurrence [22]. Some attempts have been made to increase efficiency in their detection by developing artificial intelligence methods which combine visual inspection and satellite data in machine learning algorithms to analyze dike sections susceptible to cracking and predict them based on exogenous variables [23]. Such methods are useful, but they still depend on extensive human-supplied datasets, which can be inaccurate and relatively small.

For the present study, the main hypothesis is that a DTS fiber-optic (FO) cable-based sensor can be used to differentiate 'healthy' dike cover area from a similar area with desiccation cracks, without requiring the sensing cable to be buried in the ground. It is expected that the thermal response along the FO cable must differ significantly among the two types of surfaces given that the thermal emission and absorption will be highly influenced by the difference in thermal capacity and thermal conductivity. FO cables have been already widely used in geohydrological research [7] such as temperature monitoring for abnormal seepage water flow detection and soil moisture content measurement [26, 27]. It is important to note that by making the system as less intrusive as possible, the collected thermal signal is highly influenced by a larger number of external environmental heat sources such as solar radiation (absorption and reflection) wind thermal advection, convection and dispersion, grass moisture content, evapotranspiration, ground heat flux cycle and cable material emissivity among the most important. All these processes and their influence in the thermal response recorded by the sensor have been studied in detail via finite element model and can be found in [24].

To test the main hypothesis, setup under real scale and representative environmental condictiones was built at 'Flood Proof Holland'; a Dutch real scale dike and flood defense testing facility operated by Delft University of Technology among other local governmental and private partners.

The setup consisted in the installation of a multi sensor thermal monitoring system over a pre-existing desiccation peat-based crack found on one of the lab dikes. The cracked area thermal emission was monitored during a period of 20 days and 20 nights with a frequency of 15 minutes. The crack was monitored simultaneously with a Thermal Forward-looking infrared Remote sensor Camara (TRC), a conventional pc webcam and a DTS based FO sensor (See Figure 5).

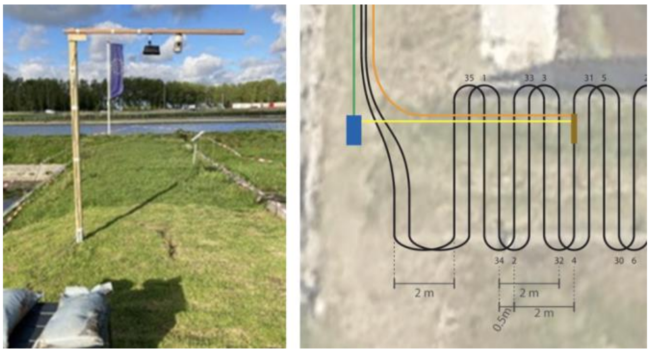

Figure 5. Dike Crack Monitoring setup at FPH, The Netherlands.

The TRC recorded 16-bit (uint16) thermal images of the crack throughout the measurement period (See figure 6). Each image had a thermal a resolution of 256 × 320 thermal pixels and an intensity range spanning from 0 to 2^{16}-1. Its calibration was performed using the recorded air temperature in the climatological Rotterdam Airport from the KNMI (Royal Dutch Metrological Institute), located approximately 5 km from FPH.

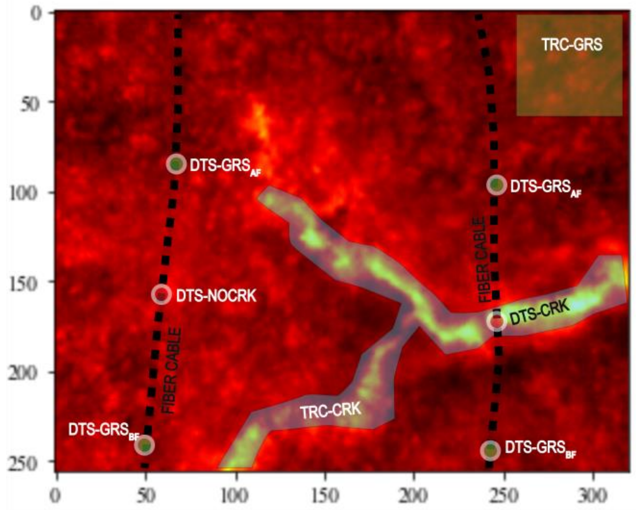

Figure 6. Thermal image of crack with chosen TRC areas for pixel averaging and point DTS fiber cable measurement locations for time series retrieval.

The TRC was mounted just on top of the crack at an elevation of 2.6 m. This made possible to cover an approximate area of 2 m by 1.80 m wide. Over the same surface, the FO multimode

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cable was laid and anchored to the ground in linear transects orthogonally directed with respect to the main axis of the crack. The DTS system consisted on a BOFDA interrogator manufactured by fibrisTerre Systems GmbH type fTB 2505 [28] and a fiber-optic cable of 3 mm of external diameter (including Kevlar isolation, armoring and polystyrene jacket) with a multi-mode optical fiber as the sensing elements.

Each transect was approximately 4.5 m in length spaced every 0.5 m as shown in Figure 1. The first part of the study consisted in analyzing and post-processing time series extracted only from the TRC images by choosing representative areas inside them and averaging their temperature values per area from the thermal pixels. The time series are presented in Figure 7. Each area represented different elements (see Figure 2) to be analyzed such as a bare grass covered area (TRC-GRS), a cracked area (TRC-CRK) and the environmental air temperature (KNMI).

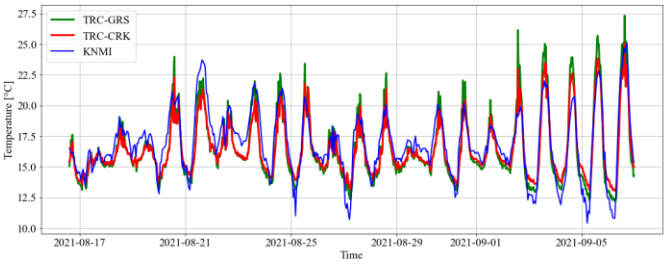

Figure 7. Time series generated from averaging thermal pixel on each image at different locations.

From Figure 7, it can already be observed that there is almost no delay among the three different time series given the chosen recording frequency (15 minutes). However, in terms of amplitude of the signal it can be observed that the TRC-GRS is greater most of the time with respect to the TRC-CRK which implies that the cracked areas have less capacity of storing the heat and may also release the stored one in a faster way, especially for the hotter days at the end of the monitored period. In addition, it can also be observed that both type of dike surfaces is always warmer when comparing them to the nocturnal environmental temperature during the last days which also can be explained by the stored heat during the day.

So, from this preliminary analysis, it was concluded that the best way to characterize the thermal response of each of the surfaces while reflecting both emission and storage of heat, was by estimating the maximum daily amplitude on each of the surfaces. To validate this, the time series analysis of specific points over the grass before and after the crack (See figure 6) and the temperature in the segment of FO exactly over the crack were analyzed as well.

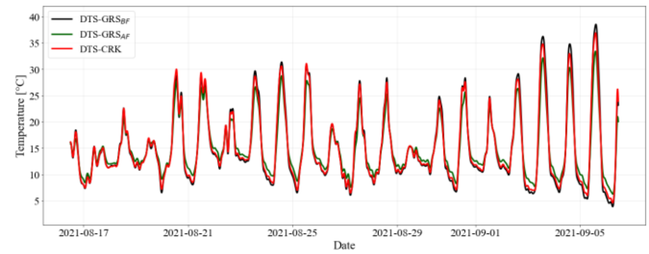

Figure 8. Thermal image of cracks with chosen areas for pixel averaging and DTS fiber cable approximate locations for time series retrieval.

It is important to note that the cable's exposure to the environment affects its temperature readings. The estimated temperature from the TRC-GRS will differ from the DTS-GRS due to the thermal properties and emissivity of the cable jacket material, which absorbs and releases heat at a different rate compared to the grass surface. This is why in the Figure 4, it can be observed that the amplitude values is greater for the cable in cracked zones which contradicts what was observed with the TRC in Figure 7. This is due to the effect of the very different thermal properties of the cable with respect to the grass and crack cover when directly exposed to the solar radiation and environment moisture. Nonetheless while inverse, the relation holds trough out the whole-time span of the experiment which means that it can still be used for crack detection despite of presenting the opposite thermal behavior of the actual soil medium.

Now based on these conclusions, a way of reflecting the difference in thermal properties at each location (cracked and healthy), is proposed based on the estimation of the maximum daily amplitude value (A_{max}) from each thermal signal withdrawn from the DTS. To do that, we propose to plot the cracked and non-cracked A_{max} ratio between DTS and KNMI versus the same A_{max} from KNMI as shown in Figure 9.

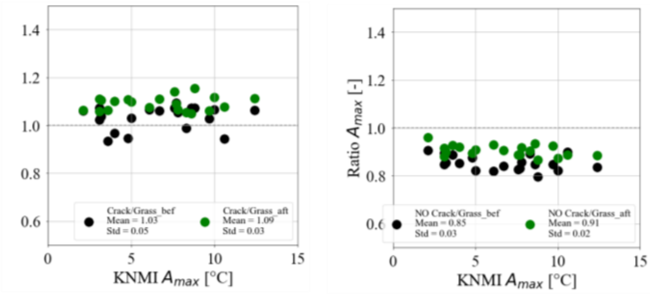

Figure 9. Amplitude ratios of DTS over KNMI plotted against maximum daily amplitude from KNMI. Left plot corresponds from cable over crack. Right plot comes from cable where no crack is present (see Figure 6).

From this last figure, the results indicate that indeed, in locations where a crack is present, the ratio of heat amplitude at a point with a crack compared to a point without one is typically greater than 1 due to the influence of the thermal properties of the cable. In contrast, at locations where no crack exists at the midpoint, this ratio is consistently less than 1. This suggests that areas with cracks tend to release heat more quickly and cool to lower temperatures at night compared to areas where the grass remains unfractured. We have also confirmed these findings through a finite element model study. Based on all the observations reported earlier, this study concludes that a DTS FO based sensor can be used to effectively detect cracks using daily cycle measurements taken at three points along a cable sensor. This conclusion relies on the physical principle that the recorded internal temperature of the cable tends to be higher in cracked surfaces during daytime and colder during nighttime with respect to the cable reading over grass. This behavior is inverse to the one observed by monitoring the temperature with TRC which reflect the actual thermal emission from the grassed surface without any interference.

DOI: 10.3217/978-3-99161-057-1-018

5 CONCLUSIONS

This study highlights the effectiveness and evolving capabilities of distributed fiber-optic sensing technologies for structural and geotechnical monitoring. Among these, Brillouin-based systems, particularly BOFDA, demonstrate specifically long-term measurement stability, making them well-suited for complex infrastructure applications. The successful use of DTS for non-intrusive crack detection on dike covers further underlines the potential of fiber-optic sensors in surface-level diagnostics without the need for invasive installation. By leveraging the thermal response differences across varied surface conditions, DTS proves to be a powerful tool for environmental and structural assessments. The findings presented herein lend further support to the ongoing integration of DFOS in contemporary monitoring strategies, a process that is set to be further accelerated by the ongoing advancement of sensing technologies (instrumental performance, sensors quality), integration procedures, and complex data interpretation methodologies.

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