Moisture Measurement in Masonry Materials Using Active Distributed Optical Fiber Sensors

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Abstract. A Brillouin Optical time-domain analysis (BOTDA) sensor has been used to perform distributed temperature measurements along a fiber optic cable with an electrically conductive armoring heated via electrical resistance. The thermal response of a fibre-optic probe put in contact with yellow tuff samples at different moisture content is measured by the BOTDA sensor, paving the way to distributed measurements of moisture content in masonry materials.

Keywords: Distributed optical fiber sensors · Active thermometry · Moisture measurements

1 Moisture Measurement by Active Thermometry

Yellow tuff is a very common building material in Campania (Southern Italy), and tuff masonry often presents damages due to water uptake phenomenon [1, 2]. Capillary rise can have potentially devastating consequences for buildings (biological corrosion, worsening of indoor comfort parameters, worsening of thermal resistance, etc.). Therefore, measuring moisture in building structures is still a current research issue.

Among the methods for non-destructive and continuous measurement of moisture content, the heat-pulse method determines the thermal properties of a material by monitoring the temperature transient resulting from the application of electrical heating. As the moisture content affects the thermal conductivity of the material, the heat-pulse method can be used to determine the moisture after proper calibration. Heat-pulse techniques based on fiber-optic distributed temperature sensors (DTS) has several advantages compared to other technologies, including the capability to monitor the temperature at several locations simultaneously [3–8]. In addition, by using an armored cable, the same cable can be used to perform the measurement of the temperature through the embedded fiber, as well as to apply the heat pulse by injecting electrical current in its conductive armoring. Finally, it is worth to mention that the cable can be simply put in contact with the material, with minimum invasiveness compared to other methods such as the hot-ball probe [9].

B. Andò et al. (eds.), *Sensors*, Lecture Notes in Electrical Engineering 431,
DOI 10.1007/978-3-319-55077-0_20

2 Experimental Results

Distributed temperature sensors (DTS) based on stimulated Brillouin scattering (SBS) retrieve the temperature profile along an optical fiber with high spatial resolution and accuracy [10]. In the Brillouin Optical Time-Domain Analysis (BOTDA), a continuous wave probe signal and a frequency-shifted, pulsed pump signal are injected at the two opposite ends of an optical fiber. Provided that the frequency offset between the two waves is close to the Brillouin Frequency Shift (BFS) of the fiber, the two optical waves interact via stimulated Brillouin scattering (SBS), so that the pump field is backscattered reinforcing the probe field. The gain of the emerging probe beam is measured as a function of the time, for an interval of pump-probe frequency shifts. At each section along the fiber, the local BFS is determined by fitting a spectral shape to the measured Brillouin gain spectrum (BGS). Sensing is based on the (linear) dependence of the BFS from the temperature (about 1 MHz/°C).

The experimental set-up schematically shown in Fig. 1.

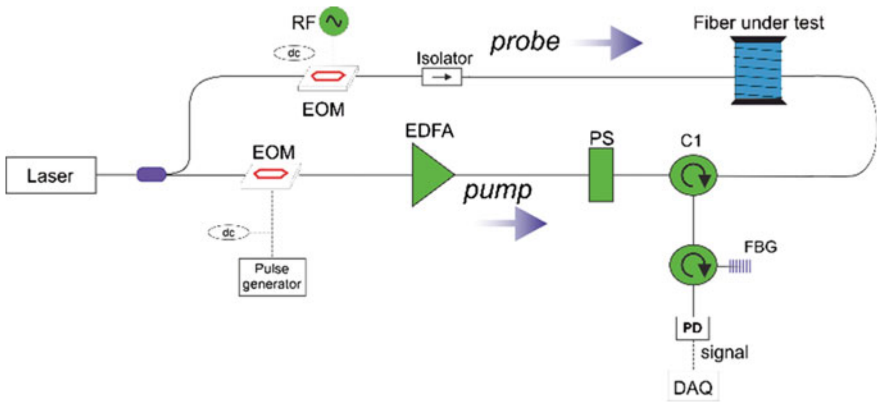

Fig. 1. Experimental set-up for distributed measurement of temperature in optical fibers. *EOM* electro-optic modulator, *PS* polarization scrambler, *EDFA* erbium-doped fiber amplifier, *PD* photodetector, *FBG* fiber Bragg grating

Light from a 1.55 μm distributed feedback (DFB) laser diode is split in two arms to generate the pump and the probe fields. A spectral shift between the two fields is achieved by double sideband, carrier-suppressed modulation in the upper branch: at the modulator output, the sideband with lower frequency acts as the probe beam, while the upper sideband is filtered out through a fiber Bragg grating (FBG) placed before the detector. The latter is a 125 MHz photoreceiver, connected to a data acquisition card (DAQ) with a sampling rate of 250 MS/s. Spatial resolution is dictated by the pump pulse duration, with a 10-ns pulse width giving rise to a 1-m spatial resolution. The set-up allowed us to measure the temperature with a spatial resolution of 1 m, a digital sampling step of 40 cm, an accuracy of 0.1 °C and a temporal resolution of a few seconds.

For the experimental test, a fiber-optic heatable cable with a diameter of 4.0 mm was employed. The cable comprises a central loose tube with two single-mode fibers and two multimode fibers, a copper conductor with an overall cross-section of 0.83 mm^2 for active sensing, stainless steel strength members and double layer polyamide (PA) outer sheath. The amplitude of the electrical current is a trade-off between sensitivity and the requirement of keeping temperature disturbance at minimum, in order to have minimal redistribution of moisture. As an example, we show in Fig. 2 the BFS profile retrieved along the fiber at 1-m spatial resolution and 1-min temporal resolution, after application of a 30-A electrical pulse and with the heatable cable exposed to air.

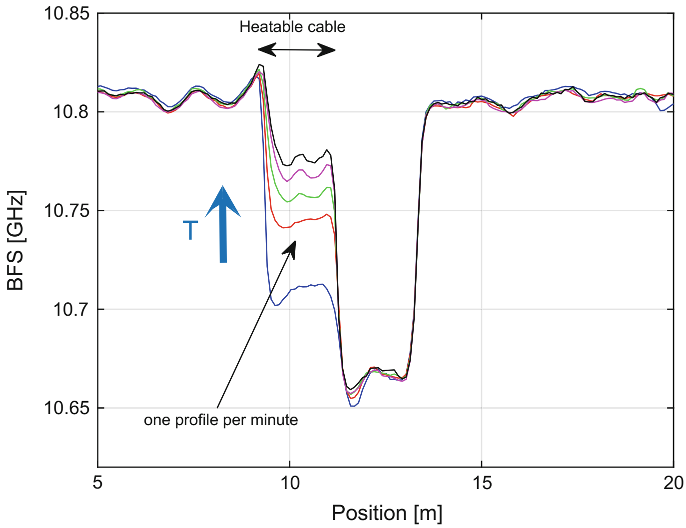

Fig. 2. BFS profile along the sensing fiber, as retrieved by the distributed sensor

In Fig. 3, we show the thermal response acquired by the DTS in a point of the heatable cable, upon the application of a 10-A electrical pulse. Note that the response was acquired at a reading frequency of 0.14 Hz and with the cable exposed to air.

In order to calibrate our sensor for moisture content measurements in the tuff, a relationship must be found between the moisture content and the acquired thermal response. For soil moisture monitoring, two main approaches are being followed. The former derives the thermal conductivity from the slope and intercept of a line fit to the temperature response following an extended heat pulse [4, 5]. Rise time or fall time (or both) can be used to infer the moisture content. The second approach makes use of the cumulative temperature increase over a certain period of time [6, 7], i.e.:

$$T_{cum} = \int_0^{t_0} \Delta T(dt) \tag{1}$$

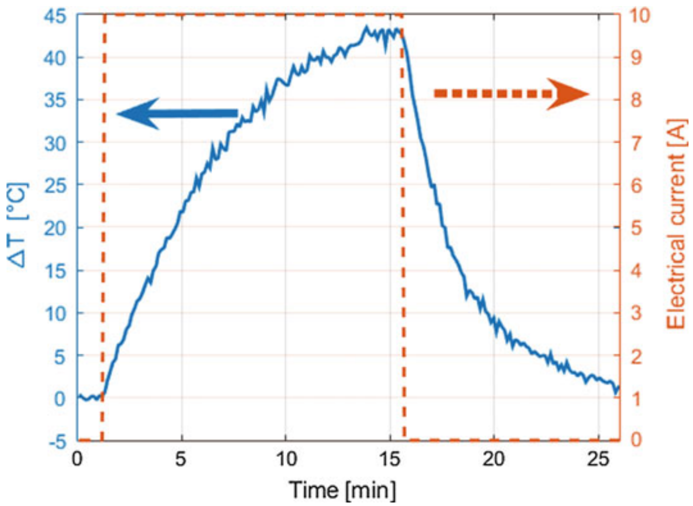

Fig. 3. Example of thermal response acquired upon injection of a 10-A electrical pulse in the active optical cable in air

where T_{cum} is the cumulative temperature increase (°C · s) during the time of integration t_0, and ΔT is the DTS reported temperature change from the prepulse temperature, as in Fig. 3. The integral approach leverages the sensitivity to moisture content of the overall magnitude of the temperature change. Furthermore, there is an intrinsic improvement in sensitivity found in integral methods compared to derivative (slope) approaches. On the other hand, the integral approach has the drawback of being sensitive to the amount of injected energy. In particular, any change in the injected electrical current will result in a change of the cumulative temperature, which may be erroneously ascribed to moisture content changes. Due to this reason, we have opted for the former (derivative) approach.

Measurements were carried out over a Neapolitan yellow tuff sample with size 37 cm × 25 cm × 3 cm, porosity about 50% and an oven-dried weight of 1610 g. The tuff stone was firstly immersed into water for 24 h, in order to reach the saturated state. The weight of the saturated tuff was 2315 g. The thermal response of the tuff was acquired in successive tests, in order to follow the variations of thermal conductivity with the moisture content. The moisture content was calculated in each test by weighting the tuff stone with an electronic scale having a resolution of 5 g. Thus, we measured the gravimetric water content (moisture) by taking the ratio between the mass of water and the mass of the oven-dried material, while the thermal response was acquired by the DTS and post-processed in order to determine the fall time of the thermal response. Each measurement was carried out by applying an electrical pulse having the same characteristics (10 A amplitude, 15 min duration) and by putting a 1-m piece of the cable in contact with the tuff sample.

We report in Fig. 4 the inverse of the fall time of the thermal response as a function of the moisture, together with the fitting (third-order polynomial) curve. As expected, the fall time of the thermal response is inversely related to the moisture content.

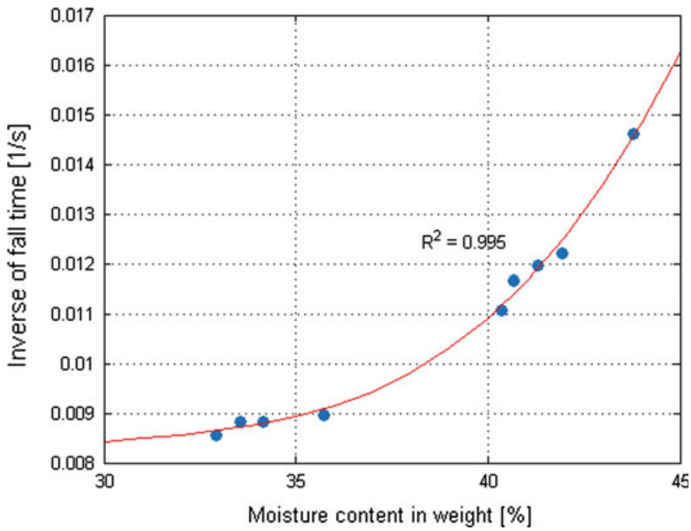

Fig. 4. Slope of the thermal response as a function of the moisture content: experimental (*dots*) and fitted data (*solid curve*)

3 Conclusions

The BOTDA technique has been used for acquiring the thermal response of an optical fiber cable put in contact with a tuff sample at varying moisture contents. A heat-pulse is applied to the sensor by injecting electrical current in the armoring of the optical cable. The relationship between the thermal conductibility measured by the BOTDA sensor, and the volumetric water content measured gravimetrically, has been experimentally determined over samples of yellow tuff. The obtained results show that thermal conductivity is sensitive to moisture variations, suggesting that the DTS technology is a promising tool for moisture measurement in building materials. The obtained results confirm that the BOTDA sensor provides reliable readings of temperature, which can be correlated to the water content in the tuff rock. However, further investigation is needed in order to get more insight about the thickness of tuff rock actually affecting the observed thermal response at the surface. Future work will be also devoted to the design of a custom probe capable of ensuring a good and stable thermal contact between the fiber cable and the sample.

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