Temperature Control Measurement of Bridge Foundation Concrete based on the Optical Fiber Sensing Technology

Chunfeng Li, Wenyong He, Yong Luo and Yuanjiang Zou
Guizhou Transportation Planning Survey & Design Academe Co. LTD, Guiyang, 550001, P. R. China
Correspondence should be addressed to Y. Luo, luoyong2019@163.com

Abstract: Temperature monitoring is an important component of structural health monitoring of mass concrete after pouring. This study investigates temperature measurements of mass concrete based on Brillouin optical time-domain analysis (BOTDA). First, the fundamental principle of using BOTDA-based distributed optical fiber sensing (DOFS) technology to measure temperatures is provided. Then, a temperature-measuring system is introduced. Finally, a case study on an engineering structure was conducted to explore issues relating to the practical application of BOTDA-based DOFS technology, including optical fiber cable laying and protection, measurement and results analysis. In addition, point temperature sensors and precision thermometers were used to measure the temperatures at several points along the optical fiber cable and the ambient temperature, respectively. The measurement results were compared with those measured by the optical fiber cable. Our study shows that BOTDA-based DOFS technology can be used to take accurate distributed temperature measurements of mass concrete structures. This temperature-measuring method provides an effective means for measuring the temperature of mass concrete structures.

1. Introduction
Brillouin optical time-domain analysis (BOTDA), a new optoelectronic measurement technology developed based on Brillouin optical time-domain reflection (BOTDR), is capable of taking distributed ambient temperature measurements along the sensing optical fiber by comprehensive use of Brillouin scattering spectroscopy and optical time-domain measurement technologies. BOTDA has multiple advantages, including distributed temperature measurements, high measurement accuracy, absolute measurements of the state parameters of a structure, a simplified measurement signal transmission and acquisition system, sensing and transmission functions, long-range detection and transmission, high resistance to electromagnetic interference, corrosion resistance, long service life and low maintenance costs during the service life. However, BOTDA signal demodulation equipment is currently relatively costly. Conventional point sensors are only able to measure temperatures at monitoring points, require a large number of measurement lead wires, and are challenging to bury during installation. At present, BOTDA has achieved fruitful results outside China, and its measurement accuracy has been continuously improving[1-5]. Neuberx (Japan), Smartece and Omnisens (Switzerland), Micron Optics, Inc. (USA) and OZ Optics (Canada) have successively launched commercial BOTDA-based measurement systems. In the past decade, research institutions in China have conducted extensive theoretical and experimental research on BOTDA and BOTDR and used them to measure the temperature of key engineering structures and have obtained many notable achievements[6-9]. The application and research and development of BOTDA are of great significance to safety monitoring, health diagnosis and theoretical studies of key engineering structures in China. A novel and simple mathematical model to obtain a more accurate expression of
zero sensor output, which makes the sensor output more robust at high temperature was proposed by Yang et al.\[10\].

After a mass concrete structure is poured, cracks will form if the surface tensile stress during the heating process and the surface shrinkage stress during the cooling process exceed the ultimate tensile strength of the concrete structure, potentially leading to structural failure. Therefore, temperature monitoring and measurements are an important component of structural health monitoring of a mass concrete structure, based on which proper measures can be implemented during construction to control the temperature inside the concrete structure to prevent the formation of harmful cracks. Researchers in China and elsewhere have conducted extensive and continuous research on temperature measurements of mass concrete structures \[11-14\]. However, the use of BOTDA-based distributed optical fiber sensing (DOFS) technology to measure the temperature of mass concrete structures has been less frequently studied.

In this study, temperature monitoring of a mass concrete structure using an optical fiber cable purposely designed for temperature measurements based on BOTDA-based DOFS technology was investigated through experimentation. First, the fundamental principle of using BOTDA-based DOFS technology to measure temperatures is provided. Then, a temperature-measuring system is introduced. Finally, issues relating to the use of BOTDA-based DOFS technology to measure the temperature of a selected engineering structure, including optical fiber laying and protection, temperature measurement and results analysis, are discussed. In addition, point temperature sensors were used to measure the temperature of the selected engineering structure. The results are compared with those obtained using the optical fiber cable. BOTDA DOFS technology can be used to take accurate distributed temperature measurements of mass concrete structures and is of demonstration and reference value to distributed temperature measurements of structures similar to mass concrete structures.

2. Brief Introductions of BOTDA-based DOFS Technology

Light scattering is a phenomenon in which a light wave deviates from the original propagation direction when propagating in an optical fiber and disperses in other arbitrary directions. Light scattering includes scattering in non-pure media and pure media. There are mainly three types of light scattering in pure media, namely, Rayleigh scattering, Raman scattering and Brillouin scattering. Brillouin scattering is nonlinear, and its associated frequency shift is mainly determined by the acoustic, elastic mechanical and thermoelastic properties of the optical fiber medium. Strain and temperature changes in the environment where a sensing optical fiber is located produce changes in the properties of the optical fiber medium, thereby resulting in a frequency shift. The fundamental principle of BOTDA-based DOFS technology is as follows. Two beams of light are injected into a sensing optical fiber from its two ends as the pump and probe light. The frequency difference between the two beams of light is adjusted to maximize the Brillouin scattering gain. Distributed strain and temperature measurements are obtained by measuring the frequency shift of excited Brillouin scattered light and applying the relationships between the frequency shift and the strain and temperature in the environment where the sensing optical fiber is located. Fig. 1 shows a block diagram of the principle of a BOTDA-based DOFS system.

There is a linear relationship between the Brillouin frequency shift of a sensing optical fiber and the strain and temperature variables of its environment. The relationship between the changes in the axial strain on an optical fiber, the temperature of its environment and its Brillouin frequency shift is as follows:

$$\nu_b(\varepsilon, \theta) - \frac{d\nu_b(\theta)}{d\theta} (\theta - \theta_0) = \nu_b(0) + \frac{d\nu_b(\varepsilon)}{d\varepsilon} \varepsilon$$

where $\nu_b(0)$ is the Brillouin central frequency under the initial strain and at the initial temperature, $\nu_b(\varepsilon, \theta)$ is the Brillouin central frequency under strain $\varepsilon$ and at temperature $\theta$, $d\nu_b(\theta)/d\theta$ is the temperature proportionality coefficient, $d\nu_b(\varepsilon)/d\varepsilon$ is the strain proportionality coefficient, $\theta - \theta_0$ is the change in the temperature of the optical fiber, and $\varepsilon$ is the change in the strain of the optical fiber.
3. Temperature-measuring System
The BOTDA-based distributed temperature-measuring system consists mainly of a distributed optical fiber strain and temperature sensor and a temperature-sensing optical fiber. In addition, other external control systems can be used as supplements based on the actual situation and needs.

3.1. Distributed Strain and Temperature Sensors
The distributed strain and temperature sensor is a BOTDA signal demodulation device, which includes (1) a pumping and detection laser, (2) a backscattered light receiver, (3) a data acquisition system, (4) a microprocessing system that converts light signals to temperature and location signals, (5) a communication module that contains an external control interface, (6) a storage device and (7) an operating system and software.

The temperature measurement range of the sensor is -270 to 800 °C (depending on the sensing optical fiber material), a minimum sampling distance resolution of 5 cm, a spatial resolution of 0.2 m, a temperature resolution of 0.005 °C and a temperature measurement accuracy of 0.5 °C.

3.2. Temperature Sensor
The temperature sensor is an optical fiber cable specially designed and customized for measuring temperatures. This optical fiber cable has a circular cross section, and its central parallel structural units include a loosely shielded optical fiber cable, a stainless-steel shield and an external sheath. The temperature-measuring optical fiber cable can eliminate external stresses and prevent the strain from affecting the acquired Brillouin frequency shift signals. Thus, the change in the strain of the optical fiber cable, \( \varepsilon \), is 0. Based on the results of an indoor calibration experiment, the temperature proportionality coefficient, \( \frac{d\nu_B(\theta)}{d\theta} \), is 0.998 MHz/°C. The initial temperature measured when the optical fiber cable is being laid and the initial central frequency that is affected only by the ambient temperature are designated \( \theta_0 \) and \( \nu_B(0) \), respectively. Based on the aforementioned conditions, the ambient temperature, \( \theta \), can be measured by measuring the Brillouin central frequency, \( \nu_B(\varepsilon, \theta) \).

4. Experimental Study on the Engineering Application of BOTDA-based DOFS Technology

4.1. General Information on the Selected Engineering Structure
The Hezhang Super-long-span Bridge is a full-width bridge with a total length of 1,072.8 m. Its upper structure consists of a 9-40 m prestressed concrete simply supported-continuous T-beam bridge, a 96+2-180+96 m prestressed concrete continuous rigid-frame bridge and a 5-30 m prestressed concrete simply supported-continuous T-beam bridge. The No. 11 main pier of the Hezhang Super-long-span Bridge is a 195 m tall twin-legged thin-walled pier with a pile-group foundation, and its bearing platform has a volume of 23×27×6 = 3,726 m³. All the piers of the bridge approach are two-column piers with a pile foundation except for the No. 8 pier, which is a thin-walled pier with a pile-group foundation. The bridge has a gravity U-shaped abutment with a spread foundation and is rated for a Highway Class I design load.

4.2. Laying of an Optical Fiber Cable
This study aims to investigate the feasibility and reliability of using BOTDA-based DOFS technology to measure the temperature of a mass concrete structure as an alternative to multiple individual
temperature measurements. Therefore, an optical fiber cable was laid within a typical cross-section of the bearing platform of the No. 11 main pier of the Hezhang Super-long-span Bridge, as shown in Fig. 2(a). Fig. 2(b) shows the location and meter marks of the optical fiber cable within the cross section. The temperature-measuring optical fiber cable had a total length of 58 m, and its sections from 0 to 1.0 m and from 57.4 to 59 m lay outside of the bearing platform. During the laying process, the optical fiber cable was bound along the rebar using cable ties and laid in areas resistant to damage. This laying method can help locate the optical fiber cable and satisfactorily protect it from damage caused by construction.

After pouring the bearing platform, each end of the optical fiber cable was connected with a fixed connection/angled physical contact jumper and placed in a splice closure for protection. In addition, an enclosure was constructed to protect the optical fiber cable from damage caused by construction.

4.3. Measurement Analysis and Discussion

4.3.1. Measurements obtained using the optical fiber cable. The mass concrete structure constituting the bearing platform of the No. 11 main pier of the Hezhang Super-long-span Bridge was poured for three consecutive days from February 14 to 17, 2011. Based on the objective of this study, changes in the temperature of the mass concrete structure after pouring and field measurement conditions, the temperature of the mass concrete was measured for four consecutive days from February 18 to 21, 2011. Fig. 3 shows the temperature measurements. In Fig. 3, the x-axis represents the location of each measuring point (adjacent measuring points were 5 cm apart, and the temperature at each measuring point was measured) along the optical fiber cable (based on Fig. 2, the location of each measuring point in the bearing platform can be determined), and the y-axis represents the temperature measurement corresponding to each measuring point. To examine long-term changes in the temperature inside the mass concrete structure, temperature measurements were taken when field conditions permitted (temperature measurements were in fact taken on July 19, November 15 and December 27, 2015). Fig. 3 shows the temperature measurements.

4.3.2. Analysis of temperature measurements obtained using the optical fiber cable. Fig. 3 shows the measuring location–temperature relationship for each measurement operation. The x-axis represents the location of each measuring point (adjacent measuring points were 5 cm apart, and the temperature at each measuring point was measured) along the optical fiber cable, and the y-axis represents the temperature measurement corresponding to each measuring point. The following can be derived from a comparative analysis of temperature measurements obtained during each operation and the way the optical fiber cable was laid.

(1) The sections of the optical fiber cable in the bearing platform from 1.0 to 6.8 m and from 57.4 to 51.6 m were laid at the same location; its sections from 34.6 to 40.7 m and from 46.8 to 40.7 m
were symmetrical around its cross-section at 40.7 m, and its cross sections at 22.1 and 48.4 m were at the same location. The temperature measurements at each measuring point obtained during different operations were in satisfactory agreement despite a difference at some measuring points (maximum difference: 0.2 °C). This finding suggests that it is stable and reliable to use an optical fiber cable to measure the temperature of a concrete structure.

(2) Each measuring point along the sections of the optical fiber cable from 0 to 1.0 m and from 57.4 to 58.0 m outside of the bearing platform was configured to measure the ambient temperature of the environment where the optical fiber cable was located outside of the bearing platform. The temperature measurements at the measuring points along these two sections obtained during each operation were in complete agreement and are reflected by horizontal straight lines in Fig. 3. Table 1 summarizes the comparison of ambient temperatures measured by the sensing optical fiber and thermometers.

From February 18 to 21, 2011, the top of the bearing platform was impounded with water. Because the optical fiber cable was laid inside the bearing platform, the ambient temperature refers to the temperature of the environment surrounding the temperature-measuring optical fiber cable instead of air temperature. As demonstrated in Table 1, the ambient temperatures measured by the thermometers were essentially in agreement with those measured by the optical fiber cable during the same operation (maximum difference: 0.08 °C). This agreement validates the temperature measurement accuracy of the optical fiber cable.

![Figure 3. Relationship curve of each test between position and temperature](image)

| Time       | Temperatures from optical fiber (°C) | Temperatures from thermometer (°C) |
|------------|-------------------------------------|-----------------------------------|
| 2011-02-18 | 25.44                               | 25.50                             |
| 2011-02-19 | 45.65                               | 45.62                             |
| 2011-02-20 | 43.86                               | 43.79                             |
| 2011-02-21 | 36.83                               | 36.81                             |
| 2011-07-19 | 39.00                               | 38.98                             |
| 2011-11-15 | 20.00                               | 20.07                             |
| 2011-12-27 | 5.00                                | 5.08                              |

4.3.3. Comparison with temperatures measured by point temperature sensors. To further examine the accuracy and reliability of using BOTDA-based DOFS technology to measure the temperature of a mass concrete structure, a point temperature sensor (JMT-36B voltage semiconductor temperature sensor) was buried adjacent to the temperature-measuring optical fiber cable at 12.8, 16.0, 27.4, 29.0, 40.7 and 57.4 m, as shown in Fig. 4 (the six temperature sensors are labeled CD1, CD2, CD3, CD4, CD5 and
After placing the sensors at the design locations, a reading device was used to take measurements, and the temperature at each measuring point under each condition was calculated. Table 2 summarizes the comparison of temperatures at each measuring point measured by the optical fiber cable and sensors during each operational step. As demonstrated in Table 2, the temperatures measured by each temperature sensor and the sensing optical fiber at the corresponding measuring point during different operations were in satisfactory agreement (maximum difference: 0.23 °C), which further validates the temperature-measuring accuracy of the optical fiber cable. A point temperature sensor can measure the temperature only at the site where it is placed. By contrast, a distributed optical fiber can measure the temperature at each point along its length and can thus provide comprehensive information on the temperature inside a mass concrete structure.

![Figure 4. The schematic of cable layout in pile cap](image)

**Table 2.** Comparison of cap concrete temperature measured by optical fiber and temperature sensor (°C)

| Time     | 2011-2-18 | 2011-2-19 | 2011-2-20 | 2011-2-21 | 2011-7-19 | 2011-11-15 | 2011-12-27 |
|----------|-----------|-----------|-----------|-----------|-----------|------------|------------|
| 12.8m    | Optical fiber | 36.89  | 30.51    | 27.99     | 26.99     | 14.22      | 13.45      | 10.65      |
|          | Sensor CD1  | 36.83    | 30.66    | 27.92     | 27.04     | 14.15      | 13.3       | 10.45      |
| 16.0m    | Optical fiber | 23.1    | 20.65    | 19.85     | 18.11     | 9.13       | 7.81       | 7.38       |
|          | Sensor CD2  | 23.2     | 20.51    | 20.18     | 18.02     | 9.22       | 7.7        | 7.4        |
| 27.4m    | Optical fiber | 47.53   | 40.9     | 38.96     | 36.87     | 17.78      | 14.31      | 10.88      |
|          | Sensor CD3  | 47.3     | 40.8     | 39.13     | 37.02     | 17.96      | 14.4       | 11.02      |
| 29.0m    | Optical fiber | 43.33   | 38.62    | 36.03     | 33.46     | 15.14      | 13.62      | 10.83      |
|          | Sensor CD4  | 43.19    | 38.6     | 36.36     | 33.42     | 15.16      | 13.71      | 10.8       |
| 40.7m    | Optical fiber | 33.39   | 30.54    | 28.34     | 26.11     | 11.96      | 8.8        | 7.87       |
|          | Sensor CD5  | 33.43    | 30.6     | 28.33     | 26.17     | 12.08      | 8.91       | 7.87       |
| 57.4m    | Optical fiber | 25.43   | 45.64    | 43.82     | 36.82     | 38.99      | 19.95      | 5.01       |
|          | Sensor CD6  | 25.4     | 45.71    | 43.88     | 36.81     | 39.03      | 19.9       | 5          |

5. Conclusions

Through a case study on measuring the temperature inside the mass concrete structure constituting the bearing platform of the No. 11 main pier of the Hezhang Super-long-span Bridge along the Bijie–Weining Highway in Guizhou Province, China, the accuracy and reliability of using BOTDA-based DOFS technology to measure the temperature of a mass concrete structure were examined. The main conclusions derived from this study are summarized as follows:

1) The temperatures at each measuring point measured using BOTDA-based DOFS technology during different operations were in satisfactory agreement, although there was a difference at some measuring points (maximum difference: 0.2 °C). The ambient temperatures measured using
BOTDA-based DOFS technology and conventional thermometers were in satisfactory agreement (maximum difference: 0.08 °C).

2) The concrete temperatures measured using BOTDA-based DOFS technology and conventional temperature sensors were in satisfactory agreement (maximum difference: 0.23 °C only).

3) BOTDA-based DOFS technology can be sufficiently used to take accurate distributed temperature measurements of mass concrete structures with a measurement accuracy of 0.3 °C, which meets the field measurement and equipment performance requirements, and produce reliable and accurate results. BOTDA-based DOFS technology is an advanced and reliable temperature-measuring technology that can provide comprehensive information on the temperature and temperature changes inside a mass concrete structure, facilitate establishment of a three-dimensional temperature field, and thereby help control the temperature difference between the inside and outside of a mass concrete structure to prevent the formation of cracks and structural damage. This technology provides an effective means for measuring the temperature of mass concrete structures.

6. Acknowledgments
This study was supported by Mountain Geohazard Prevention R&D Center of Guizhou Province, P. R. China.

7. References
[1] K. Hotate, “Recent progress in Brillouin based fiber sensor technology correlation based continuous wave technique,” J OFS, vol. 15, no. 1, pp. 297-300, 2002.
[2] K. Hotate and S. Ong, “Distributed dynamic strain measurement using correlation based Brillouin sensing system,” IEEE Photon Technol Lett, vol. 15, no. 2, pp. 272-274, 2003.
[3] R. Fabien, X. Bao, and Y. Li, “Signal processing technique for distributed Brillouin sensing at centimeter spatial resolution,” J Lightwave Technol, vol. 25, no. 11, pp. 3610-3618, 2007.
[4] S. Jeffrey, Y. Li, and R. Fabien, “Stabilization of electro-optic modulator bias voltage drift using a lock-in amplifier and a proportional integral derivative controller in a distributed Brillouin sensor system,” Appl Opt, vol. 46, no. 9, pp. 1482-1485, 2007.
[5] Z. Zhang, C. Liang, and X. Bao, “Partial bit delay correlative modulation used to improve the dispersion tolerance of an optical duobinary system”, Opt Express, vol. 16, no. 15, pp. 1344-1353, 2008.
[6] B. Shi, H. Xu, and D. Zhang, “Feasibility study on application of BOTDR to health monitoring for large infrastructure engineering,” Chinese Journal of Rock Mechanics and Engineering, vol. 23, no. 3, pp. 493-499, 2004.
[7] H. Sui, B. Shi, and D. Zhang, “Study on distributed optical fiber sensor-based monitoring for slope engineering,” Chinese Journal of Rock Mechanics and Engineering, vol. 27, no. s2, pp. 3725-3731, 2008.
[8] Y. Ding, P. Wand, and N. He, “New method to measure deformation of SMW piles based on BOTDA,” Chinese Journal of Geotechnical Engineering, vol. 33, no. 5, pp. 719-724, 2011.
[9] H. Hu, “Experimental research on layout technics of BOTDA distributed optical fiber strain sensor,” Nanjing: Southeast University, 2007.
[10] W. Yang, B. Fang, Y. Tang, and X. Qin, “A Temperature Compensation Model for Low Cost Quartz Accelerometers and Its Application in Tilt Sensing,” Mathematical Problems in Engineering, vol. 2016, Article ID 2950376, 2016.
[11] K. Huo and F Shi, “Temperature control of mass concrete in the base slab of Badong Yangter River Bridge,” Rock and Soil Mechanics, vol. 23, no. s, pp. 238-240, 2002.
[12] B. Zhu, “Temperature stress and temperature control of mass concrete,” Beijing: China Power Press, 1999.

[13] D. Cai, X. He, and S. Cai, “Optical Monitoring Technology for Three-Dimensional Temperature Field of Big-sized Concrete Structure,” *Journal of China Three Gorges University (Natural Science)*, vol. 27, no. 2, pp. 97-100, 2005.

[14] W. Xu, J. Hou, and D. Li, “Application research on temperature monitoring in concrete of Jinghong hydropower station by distributed optical fiber temperature measurement system,” *Journal of Hydroelectric Engineering*, vol. 26, no. 1, pp. 97-101, 2007.