Study of structure health monitoring using distributed optical fiber sensing for concrete beam structures—Taking bridge deflection measuring as an example

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ABSTRACT

The deflection change of concrete beams will cause concrete cracking and reinforcement corrosion, which will affect the use function of the concrete beam structures such as bridges and tunnels etc. Distributed optical fiber sensing (DOFS) was introduced to measure the deflection distribution of the concrete bridge structures in case avoiding the weakness of traditional monitoring methods in this paper. Above all, based on the analysis of the principle of DOFS Brillouin Optical Frequency Domain Analysis (BOFDA) measurement, the layout and deployment of optical fibres on the bottom of the concrete beam in a bridge for deflection measurement is proposed. Then, according to the fiber optic strain distribution, the qualitative characterization of the concrete bridges' deflection was studied. Later, the mathematical expression of the optical fiber strain quantifying the bridge deflection was deducted theoretically through the analysis of the geometric principle of the optical fiber deformation when the concrete bridge deflection occurred. Finally, the indoor model experiment simulating the concrete bridge deflection has been carried out based on BOFDA. The results show that the concrete bridges' deflection measured by BOFDA was the same as that measured by the dial indicators. BOFDA cannot only characterize the degree of concrete bridges' deflection, but also accurately denote the deformation range and deflection distribution. It shows that BOFDA technology is effective and feasible for deflection measurement of concrete beam bridges.

Keywords: Distributed optical fiber sensing, Brillouin optical frequency domain analysis, concrete bridge structures, structure health monitoring

1. INTRODUCTION

Nowadays most of the civil engineering construction structures, such as bridges and tunnels etc., are made of concrete beams. Under the action of long-term load, and the influence of creep and other factors, the deflection change of concrete bridges will cause concrete crack[1]. For examples, the bridge deflection will aggravate the corrosion of reinforcement and weaken the bonding performance between reinforcement. Finally, it will affect the long-term use performance of the reinforced concrete bridge; make it lose the safety and durability of the structure when it is far from reaching the design service life of the structure[2]. Therefore, the bridge deflection is not only an important parameter to determine the overall stiffness and bearing capacity of the bridge[3], but also the basis to determine the damage degree of the bridge. It can reflect the health status of the bridge structure as a whole, and has the overall characteristics[4]. Therefore, it is necessary to conduct real-time deflection monitoring on the bridge performance, timely find its structural damage, predict its performance changes and make maintenance decisions[5]. Through the bridge deflection deformation monitoring, the weak and unsafe positions will be found, the hidden dangers of the bridge structure will be discovered in time, the health status will be evaluated, and the correct decision can be made, which is of great significance for the normal and safe use of the bridge.

Common methods for bridge deflection monitoring[6] mainly include deflection meter, dial indicator, connecting pipe method, GPS observation method, measurement robot method, etc. The traditional monitoring method not only makes the sensor vulnerable to electromagnetic interference, but also affects its survival rate, stability and durability; moreover, the sensors are usually arranged according to "certain distance interval" which will form monitoring missing points and monitoring blind areas. If the bridge deformation happens in the monitoring blind area, it will cause monitoring failure.

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Third International Conference on Computer Science and Communication Technology (ICCSCT 2022)
edited by Yingfa Lu, Changbo Cheng, Proc. of SPIE Vol. 12506, 125064X
 · doi: 10.1117/12.2661757

Therefore, in recent years, the Distributed Optical Fiber Sensing (DOFS) technology has been widely welcomed by the bridge structure health monitoring industry[7] at home and abroad due to its corrosion resistance, flame retardancy, moisture resistance, electromagnetic interference resistance, etc. In 2017, Bennett et al.[8] applied DOFS to monitor a three span pre-stressed concrete beam slab bridge in Cambridge of England, and studied the strain changes of concrete structure induced by creep and shrinkage. In 2018, Barrias et al.[9] conducted DOFS monitoring on the stress generated in the concrete box girder of Barcelona bridge in Spain. Siwowskia et al.[10] conducted DOFS monitoring on the first fiber reinforced polymer FRP composite bridge in Poland in 2021, and verified the effectiveness of DOFS through load test and finite element analysis (FEA). In 2018, Jiang et al.[11] monitored the Jianghan super major bridge, which showed that DOFS can accurately identify and locate the location of strain abnormal points in the beam, and can more sensitively reflect tis strain variation. Many other scholars, such as Wosniok[12] and Liu[13] have also verified the effectiveness of DOFS in bridge strain monitoring through the field monitoring, and confirmed the feasibility of DOFS in bridge structure health monitoring. However, at present, there is fewer scholars directly measure bridge deflection through DOFS, especially the relevant reports on the application of BOFDA sensing technology in bridge deformation monitoring. Therefore, this paper attempts to propose a distributed bridge deflection monitoring method based on BOFDA, which is expected to contribute to the popularization of DOFS in bridge monitoring.

2. BRILLOUIN OPTICAL FREQUENCY DOMAIN ANALYSIS (BOFDA)

DOFS uses optical fiber as both sensor and optical transmission medium to sense the spatial distribution and time-varying information of measurands (such as stress, crack, etc.) along the axial distribution of optical fiber [7]. Although BOFDA was invented later than Brillouin Optical Time Domain Reflection (BOTDR) and Brillouin Optical Time Domain Analysis (BOTDA) among DOFS, it has attracted much attention due to its advantages of high signal-to-noise ratio, low cost, high testing accuracy, high spatial resolution and large dynamic range, and has been widely used in the field of structural health monitoring. Therefore, this paper intends to study the effectiveness and feasibility of BOFDA bridge deflection deformation monitoring through theory analysis and indoor model test.

BOFDA is based on the measurement of Complex Baseband Transfer Function, which links the amplitude of pump light with the geometric length L of the fiber while the probe light wave propagating along the fiber. The basic configuration of BOFDA is shown in Figure 1.

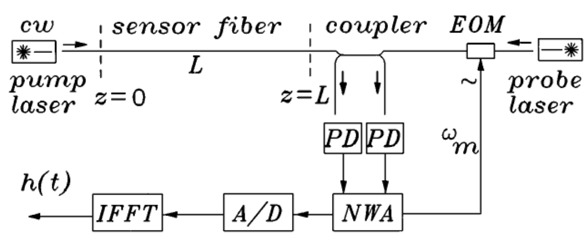

Figure 1. Basic configuration of BOFDA. NWA: network analyzer, EOM: Electro-Optic Modulator, PD: photodiode, A/D: Analog-to-Digital converter.

The Continuous Wave (CW) of the narrow linewidth pump light is coupled to one end of the single-mode fiber, and the CW of the narrow linewidth probe laser is coupled to the other end. Its frequency is lower than that of the pump light by an amount equivalent to the characteristic Brillouin frequency of the fiber. In this configuration, the probe light is amplitude modulated by an Electro-Optic Modulator (EOM) with variable angle modulation frequency ω_M. For each value of ω_M, the alternating part of the modulated probe light intensity and the modulated pump light intensity is recorded at the end of the sensor fiber. At this time, the Brillouin loss of the pump light induced by the probe light is used to measure. In this configuration, the output signal of the photodetector (PD) is fed to the Network Analyzer (NWA), which determines the baseband transfer function of the test fiber. The output of NWA passes through Analog-to-Digital converter (A/D), and it is digitized and fed to the signal processor, which calculates the Invers Fast Fourier Transform (IFFT). The IFFT can better show the impulse response of the test fiber, and is similar to the temperature and strain distribution along the fiber. The spatial impulse response indicates that Brillouin frequency shift f_B is related to temperature T and strain ε, they have a good linear relationship, just showed as followed.

$$f_\beta(\varepsilon) = f_\beta(0) + \frac{df_\beta(\varepsilon)}{d\varepsilon}\cdot\varepsilon \tag{1}$$

$$f_\beta(T) = f_\beta(0) + \frac{df_\beta(T)}{dT}\cdot T \tag{2}$$

where, ε is strain variation and T is temperature variation; $f_B(0)$ is the initial Brillouin frequency; $f_B(\varepsilon)$, $f_B(T)$ is the Brillouin center frequency after changed. $df_B(\varepsilon)/d\varepsilon$, $df_B(T)/dT$ are strain and temperature variation coefficients respectively.

3. ANALYSIS ON DEFLECTION MEASUREMENT OF CONCRETE BRIDGE BY BOFDA

3.1 Optical fiber layout for strain characterization of bridge deflection

Through reasonable optical fiber layout, the optical fiber strain can be used for geometric measurement of optical fiber deformation, and then combined with the characteristics of a bridge's vertical displacement; the bridge deflection deformation can be calculated.

The commonly used optical fiber deployment techniques are internal implantation method and surface adhesion method. For concrete bridges, the internal implantation not only cannot ensure the survival rate of optical fiber, but also cannot ensure long-term real-time maintenance of optical fibers in the monitoring process due to the concrete pouring. Moreover, there not only be a large workload for the concrete surface grooving and embedding method, but also be difficult and dangerous in the field construction. Therefore, the surface bonding method is usually used for optical fiber layout of concrete bridges. Therefore, this paper attempts to do the research by laying optical fibers along the span direction on the bottom of the bridge and measuring the deflection of the bottom of the bridge.

3.2 Analysis on quantitative characterization of bridge deflection by optical fiber strain

We assumed the following conditions for the study:

- The pre stretched optical fiber AC is horizontally arranged at the bottom of the bridge. The linear section AC of the optical fiber is deformed into A'C' section with the deflection of the bridge and the strain changes, as shown in Figure 2.
- It is assumed that the part outside the AC straight section of the optical fiber has no stress effect and no strain change, point A and point C maintain the initial state, and the strain change is zero.
- The AC section of the optical fiber is affected by the deflection deformation of the bridge, resulting in axial tension. The strain of the AC section of the optical fiber is positive, and the AC section of the optical fiber is a positive strain curve distribution.
- It is assumed that there is only one maximum settlement displacement point in the fiber AC section, that is, the point M between the filers AC is the location of the maximum deflection of the bridge beam structure.

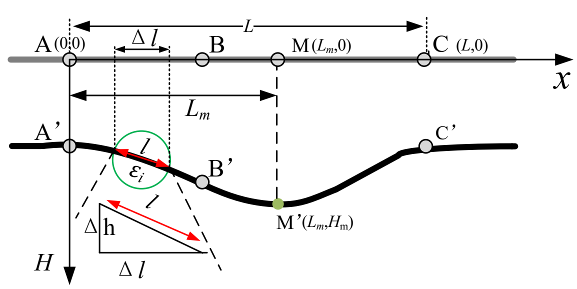

Figure 2. Schematic diagram of optical fiber layout and optical fiber deformation in concrete bridge beam settlement monitoring.

When the sampling resolution of BOFDA is the fiber length Δl, the deformed length and fiber optic strain of i-th sampling interval fiber segment is l *and* ε_i respectively, $l = \Delta l \cdot (1+\varepsilon_i)$, and the vertical deformation of the sampling interval Δh_i is:

$$\Delta h_i = \Delta l \cdot \sqrt{\varepsilon_i^2 + 2\varepsilon_i} \approx \Delta l \cdot \sqrt{2\varepsilon_i} \tag{3}$$

Obviously, when point M is the maximum settlement displacement point of the optical fiber, the vertical displacement of any point from A to M and from C to M can be obtained as follows:

$$H_{\overline{AM}} == \Delta l \cdot \sum_{i=1}^{m} \sqrt{2\varepsilon_i + \varepsilon_i^2}, (m = \frac{Lm}{\Delta l}) \text{, or } H_{\overline{CM}} = \Delta l \cdot \sum_{i=n}^{m} \sqrt{2\varepsilon_{\text{i}} + \varepsilon_i^2}, (n = \frac{L}{\Delta l}, m = \frac{L_m}{\Delta l}) \tag{4}$$

Therefore, the deflection change of the corresponding bridge's settlement deformation section can be obtained by solving the settlement displacement of any point in the fiber deformation section.

4. INDOOR MODEL TEST OF BOFDA MEASURING CONCRETE BRIDGE DEFLECTION

In this paper, we carried out an indoor model tests in order to verify BOFDA's theory of measuring bridge deflection. An equal-density wooden plate model supported at both ends simulating the bridge structure. The model was deflected and deformed when a graded concentrated load was applied in the middle of the model. Because we only consider the strain and deformation of the density plate, the influence of the mechanical and physical properties of the density plate on the deformation of the beam model can be ignored. In this paper, pre stretched sensing optical fiber is directly pasted on the lower surface of the model plate to measure the deflection. The fixing method of optical fiber in the model test is slightly different from the actual engineering application, but the principle is the same.

4.1 Layout of BOFDA model test system

The model test materials mainly include BOFDA fTB 2505 analyzer, 0.9 mm polyurethane tight sleeve optical fiber, dial indicators and equal density plate simulating bridge structure. The BOFDA test used a sampling resolution of 0.05 m. During the test, the refractive index is set to 1.468, the starting frequency and ending frequency of the instrument are set to 10.5~11.0 GHz, the center frequency is 10.8390 GHz, and the frequency interval is 5 MHz

The model test layout of bridge deflection measurement is shown in Figure 3. The model test is set according to the following steps: (1) Place both ends of the 2300 mm long equal density plate on the fixed support to form a model structure simulating the bridge. (2) Use epoxy resin to paste the optical fiber on the bottom midline line of the density board. (3) Install a dial indicator at the L/2 length of the gauge panel on the density board and the L/4 position at both ends. (4) BOFDA connects both ends of the test optical fiber through optical fiber jumpers to form a complete loop system of strain measurement, as shown in Figure 3.

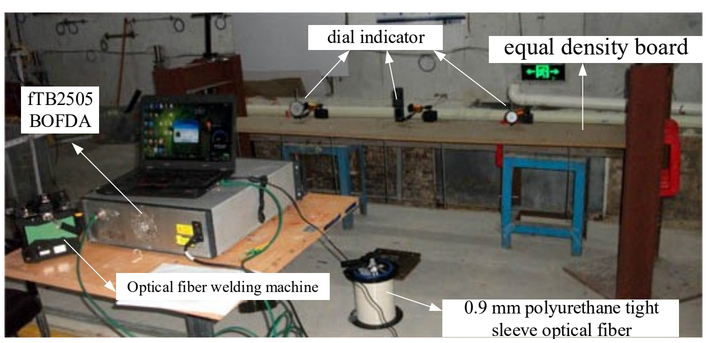

Figure 3. Layout of model test for BOFDA optical fiber strain measuring bridge deflection.

4.2 Test process

Since BOFDA can measure the strain and temperature changes of the optical fiber at the same time, temperature compensation is required for structural health strain monitoring to offset the impact of temperature on strain. If the temperature change does not exceed 5°C, the influence of temperature can be ignored due to experiments and applications[13-15]. During the test, the indoor temperature change did not exceed 3 °C after actual test. Therefore, the impact of temperature can be ignored. Before the load is applied to the bridge model, the initial strain value of the optical fiber is tested, and the initial values of the three dial indicators of the test displacement are read at the same time. During the test, the concentrated load is applied at the middle position L/2 of the length direction of the bridge model by stages. The initial load is 20 N, and gradually applied to 30N, 40N, 50 N, 60 N, 70 N, and 80 N. When the bridge model bends and sinks stably under the action of the overlying load, the strain test shall be carried out with BOFDA first, and then the dial indicator value shall be recorded in every stage that the load is increased. After that, the load shall be loaded for the next measurement test stage. In this paper, the tensile strain of optical fiber is defined as positive strain, and the compressive strain of optical fiber is defined as negative strain.

4.3 Test results

BOFDA monitoring shows that the strain of optical fiber in the deformation section of the density plate presents a positive strain distribution, and the strain of optical fiber increases with the load grading, and the deflection of the bridge model increases step by step, as shown in Figure 4.

In the figure, as the load is applied, the strain distribution of the optical fiber shows an obvious strain variation section, and the strain curve of the optical fiber under all levels of load shows a gradual lifting and increasing phenomenon. This shows that the strain of the fiber bonded to the bottom of the bridge model not only increases with the application of the graded load, but also has a positive proportional linear relationship with the deflection of the bridge model.

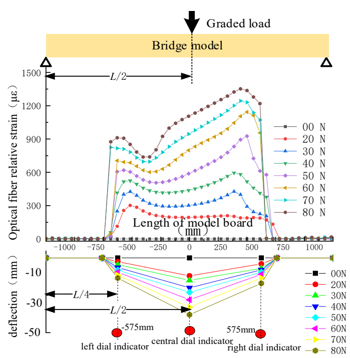

Figure 4. Optical fiber differential strain curve and measured deflection of dial indicator.

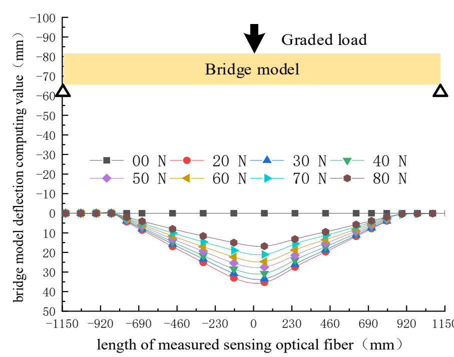

Figure 5. Deflection curve of optical fiber strain characterization beam in model test.

4.4 Analysis and discussion of optical fiber strain of bridge deflection change

The deflection of the bridge model is calculated by formula (4). There is an obvious strain change in the optical fiber between -675.62 and 675.62 mm from the midpoint of the bridge model as shown in Figure 5. With the load of the bridge model applied, the deflection characterized by optical fiber strain increases gradually. Compare the vertical displacement measured by the dial indicators with the characterized deflection at these three positions, as shown in Figure 6.

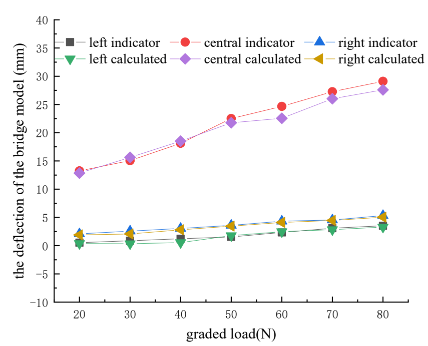

Figure 6. Compared deflection of strain characterized and measurement of dial indicators.

It is found that the maximum error between the dial gauge measurement and the optical fiber strain calculation is less than 0.5 mm at L\4 on both sides. The measured value is slightly larger than the calculated value, and the maximum error is 1.53 mm at the middle, which is still within the allowable error range. It can be seen that the measured deflection is consistent with the model deflection quantitatively characterized by the optical fiber strain.

The test results show that the BOFDA optical fiber strain distribution cannot only determine the position range and deformation degree of the deflection deformation section of the bridge model, but also quantitatively characterize the deflection change of the beam.

5. CONCLUSION

Through theoretical analysis of BOFDA bridge deflection measurement and indoor bridge model test based on BOFDA measurement, the following results are obtained:

- BOFDA optical fiber strain distribution curve not only reflect the range of deflection, but also increases step by step with the increasing deflection of the bridge model while the optical fiber is layout on the bottom of the bridge model along the span direction, indicating that the optical fiber strain changes in a positive proportion to the bridge deflection.
- The bottom deflection of the bridge model calculated using BOFDA optical fiber strain is consistent with the measured deflection of the dial indicators in the test, which shows that the distributed measurement of bridge deflection is effective and feasible based on BOFDA.

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