Distributed cracks detection by BOTDA and its application in corrosion cracking monitoring

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ABSTRACT: Cracking monitoring is an important means to evaluate structural health state. Distributed optical fiber sensor based on Brillouin scattering can measure and monitor strain and temperature along an optical fiber. It can effectively avoid undetected phenomenon existed in a point-wise test method. It also owns characteristics of electrical insulation and magnetic interference; therefore, it is suitable for corrosion-induced cracking monitoring. In this paper, the theoretical model of cracking monitoring based on Brillouin Optical Time Domain Analysis (BOTDA) is introduced, and the numerical equation between fiber strain and cracking width is established by a calibration test. The optical fiber sensors are bonded around cylindrical RC specimen to monitor the time-dependent corrosion process which is simulated by an accelerated corrosion test. The time of initial cracking is judged and also cracking width during the whole experiment is estimated. The feasibility of reinforcement corrosion monitoring based on BOTDA has been proved.

1 INTRODUCTION

Reinforcement corrosion has been considered as one of the major deteriorations of RC structures (Tuutti (1982)). The corrosion of steel bar would lead to obvious volume expansion. The expansive force acts on concrete could result in cracking, spalling and delamination. (Alonso et al (1998)). Cracking monitoring could play an important and effective role for evaluating structural health state. A wide variety of corrosion measurement techniques have been developed to analyze corrosion process, and also to identify locations of corroded parts (Agarwala et al (2000)). As a novel technique, optical fiber sensors exhibit many advantages. Comparing to traditional sensors, they are flexible, embeddable, electrical magnetic interference immutable. Many optical fiber sensors for corrosion monitoring have been reported. Optical fiber sensor with special polymer cladding is invented (Ghandehari (2001)), it detects the change of cladding’s properties caused by chloride corroding. The PH sensor used to monitor alkaline value of concrete is another kind of optical fiber sensor (Melhorn et al(2007)). The optical fiber sensor by measuring light power reduction is introduced (Leung et al (2008)); the decrease of iron film at the end of fiber reduces light reflectivity from fiber’s end. However, the parameters measured by aforementioned sensors are correlated to corrosion products or environment; meanwhile the principles are rather complicated.

Monitoring of strain caused by corrosion would be the most straightforward and intelligible way to investigate corrosion. Pre-strained fiber Bragg grating (FBG) coated by metal tube is developed (Lo (1998)), but corrosion of metal tube itself would lead to misunderstand on results. The improved FBG sensor is fabricated (Lee (2010)); it is installed on a sacrificial plate which is made of the same material as structure. Although FBG sensors can get the corrosion strain, positions of reinforcement corrosion and concrete cracking are quite uncertain. It is
impossible to consider all potential corrosion regions to install point-wise sensors like FBG sensor. The ability of distributed monitoring of Brillouin Optical Time Domain Analysis (BOTDA) can overcome above problems. In this paper, the theoretical model of cracking monitoring based on BOTDA is established. The optical fiber sensors are bonded around cylindrical RC specimen to monitor the time-dependent corrosion process. By analyzing the test results, the moment of initial cracking is judged and cracking width is estimated.

2 PRINCIPLE OF CRACKS DETECTION BASED ON BOTDA

2.1 Principle of BOTDA

The frequency shift has a linear relationship with strain and temperature respectively. The relationship between strain variation (Δε), temperature change (ΔT) and Brillouin frequency shift (Δνp(ε,T)) is shown as equation 1 (Kwon (2003)):

$$\Delta ν_p(ε,T) = \frac{dν_p(T)}{dT}ΔT + \frac{dν_p(ε)}{dε}Δε$$

(1)

There is no coupling between temperature and strain; therefore temperature compensation fiber without strain can eliminate the influence of temperature on strain monitoring.

2.2 Model of cracking detection

The cracking optical fiber sensors are laid crossing cracks, and then increase of cracking width generates tensile strain which can be detected by BOTDA. The model of cracking detection is shown as figure 1, there is an angle (θ) between fiber sensor and crack.

![Figure 1. Model of cracking detection based on BOTDA.](image)

The relationship between fiber strain (ε) and cracking width (w) is expressed as:

$$ε = \frac{L - L'}{L} = \sqrt{1 + 2\sinθ(w/L) + (w/L)^2} - 1$$

(2)

It can be learned that cracking width (w) and angle (θ) could be calculated once the bonding length (L) and the fiber strain (ε) have been knew. In generally, direction of corroded cracking is along the steel bar, it is reasonable to set angle (θ) to 90° by laying fiber sensor perpendicular to cracks. Hence equation 2 can be simplified as following:

$$ε = \frac{w}{L}$$

(3)

The bonding length (L) sets to 300mm in following theoretical analyses and experimental research. In consequently, theoretical proportional coefficient between fiber strain and cracking width is 3333. As a kind of distributed testing technique, limitation of spatial resolution (minimum 0.5m) is the main disadvantage. The strain of each sample point is gained by averaging all strains within spatial resolution. Free sections of fiber without any strain would decrease the strain of sample points located in uniform section (as illustrated as figure 1). There is no theoretical method to achieve the accurate strain while the uniform section is shorter than
spatial resolution. In this case, calibration test would be the most effective way to establish the correction coefficient between test results and theoretical values.

2.3 Calibration test

The layout of cracking simulation is illustrated as figure 2. The opening width between two steel plates is controlled by threaded nails fixed on each plate. The width is recorded by dial indicator with 0.01mm measuring precision.

![Figure 2](image)

Figure 2. Layout of calibration test.

Optical fiber with 250μm diameter is used as tensile strain fiber sensor. The sensors are bonded on the surface of steel plate by glue. The distance between two bonding points determines bonding length \(L\); in this case it sets to 300mm. The fiber strain is recorded by BOTDA (DITEST STA-R), the spacing of sample points in this experiment is 0.1m, and 0.5m spatial resolution is adopted. Cracking process is described as following: crack opening increased from 0.0mm to 0.6mm, 0.05mm for each step. The experimental results are plotted in figure 3.

![Figure 3](image)

Figure 3. Curves between measured strain and cracking width.

The linear relationship between cracking width and fiber strain can be obviously observed, and three different fiber sensors agree well with each other. The relationship is fitted as equation 4:

\[
\varepsilon = 503w = 0.15\varepsilon'
\] (4)

Here \(\varepsilon\) is measured strain and \(\varepsilon'\) is theoretical strain calculated from equation 3. Due to the spatial resolution, measured strain is much smaller than theoretical strain; however a good relationship between them can be established by experiment. This calibration test shows that the mentioned model of cracking detection can be used to monitor cracking process. Although the insuperably limitation on spatial resolution makes it impossible to detect cracking width directly, a correction coefficient gained from a calibration test can be used to calculate cracking width.
3 CORROSION CRACKING DETECTION

Reinforcement corrosion is a time-dependent process. Firstly, volume expansion of rust products create pressure on boundary between concrete and steel bars, tensile strain around concrete is formed. Secondly, corrosion cracks are created on the surface of concrete once tensile strain has exceeded the ultimate tensile strain. Finally, cracking width increases as time going. In this section, an accelerated corrosion test was applied to a cylinder specimen with 95mm diameter to simulate reinforcement corrosion; meanwhile optical fiber sensors were used to measure cracking width.

3.1 Experiment design

The steel bar with 16mm diameter was connected to positive pole of direct current, while stainless steel net was tied on negative pole. In order to accelerate corrosion processing, current density was kept at high level (0.5mA/cm²) during the whole experiment. The specimen including connect fibers were immersed in 5% NaCl saltwater. On one hand, it provided an environment for chloride corrosion. On the other hand, the temperature could keep constant at about 20°C, so the temperature affect could be ignored. All optical fiber sensors used the same material as calibration test, but two different kinds of bonding methods were used. As illustrated in figure 4, one group of fiber sensors (P-1, P-2, P-3 and P-4) were bonded by point, therefore the sensor length is 298mm (close to 300mm); the other group of fiber sensors (D-1, D-2, D-3 and D-4) were adhered round the whole circle.

Figure 4. Layout of corrosion test.

All fibers were connected to strain measuring equipment BOTDA (DITEST STA-R Series), the 0.5m spatial resolution and 0.1m sample distance were set up. The corrosion experiment lasted for three days, all strain data were recorded by BOTDA automatically.

3.2 Results and discussion

Although the top of the specimen was airproofed by epoxy resin, tiny bug between epoxy and concrete surface provided direct path for chloride migrating. As the experiment going, corrosion cracks appeared at the top of specimen firstly, then spread along axial direction of the specimen. Figure 5 shows the final distribution of cracks, thicker dot dash lines present wider cracks.
Cracks were observed at five different sensing sections (P-1, D-1, P-2, D-2 and P-3). BOTDA can monitor and store fiber strain automatically, the entire expanding and cracking process were easily recorded, as shown as figure 6. Fiber strains were plotted every twelve hours, five obvious sections with high tensile strain were observed.

![Figure 5. Final distribution of cracks.](image)

![Figure 6. Fiber strain of the whole experiment.](image)

It can be learned that strain of each section at the same time were different. Taking P-1 and P-3 for example, the maximum strain of P-1 increased from 2000με to 6000με at the third day (from 48 hours to 72 hours), however strain of P-3 were only 700με at 72 hours. By comparing strain values, it can estimate that cracking width in P-3 section could be ten times smaller than section P-1, it had been proved by visual inspection. In other words, the time-dependent characteristic of corrosion cracking can be achieved by comparing each sensing sections along axial direction of the specimen. However, estimation of initial cracking moment and cracking width are difficult to carry out by analyzing figure 6. The curves between time and strain of one sample point at four sections were plotted in figure 7.

![Figure 7. Time-dependent curve of fiber strain.](image)
The strain of concrete expansion (caused by volume expansion of rust) was also included in figure 7, which did not exist in the calibration test. Zero point of cracking width was set at 150με which is close to the ultimate tensile strain of concrete. The initial cracking moment of section P-1 and D-1 is around 15 hours, and nearly 30 hours for section P-2 and D-2. The visual measurement of cracking moment and cracking width during experiment cannot be carried out, because it could easily damage the fragile optical fiber. In the end, the width of cracks were measured after removing all optical fiber sensors. The total width at section P-2 (at 72 hours) was closed to 2.0mm which is smaller than the estimated cracking width (2.4mm), because some tiny cracks distributed around specimen could be ignored when inspecting by manual (shown as figure 5). Although cracking moment and width calculated from fiber strain had not been approved by other methods during experiment, the achievement of time-depended strain curve would be useful for monitoring and evaluating the reinforcement corrosion.

4 CONCLUSIONS

In this paper, the theoretical model of cracking monitor by distributed optical fiber sensor is investigated. Meanwhile, the numerical equation between fiber strain and cracking width is established by both theoretical analyzing and the calibration test. The accelerated corrosion test was applied to the cylindrical specimen which had been installed with fiber sensor, the strain of the specimen were recorded on-line by BOTDA. The moment of initial cracking was judged and also cracking width was estimated. This novel method was proved as a feasible and effective means to monitor reinforcement corrosion. However, further systematic research should be carried out to improve the stability, precision and applicability of this method. The optical fiber which possesses the sufficient strength for visual inspection should be selected or fabricated. The relationship between fiber strain and cracking width also needs to be refined by more systemic experimental researches.

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