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A STANDARD TEST METHOD FOR EVALUATING THE CRACK MONITORING PERFORMANCE OF DISTRIBUTED FIBER OPTIC SENSORS

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Abstract

In this paper, a standard test method of evaluating the measurement performance of Brillouin scattering based distributed fiber optic sensors (DFOSs) and other long gauge sensors for monitoring cracks is proposed. Performance evaluations of two types of Brillouin scattering-based DFOSs, named BOTDR (Brillouin Optical Time Domain Reflectometry) and PPP-BOTDA (Pulse Pre-Pump Brillouin Optical Time Domain Analysis), are then conducted based on the proposed test method. Experimental results illustrate that for Brillouin scattering-based distributed sensing techniques with 10cm-1m spatial resolution, the FOSs installed with the overall bonding (OB) method can hardly measure the crack width in a quantitative manner, while FOSs installed with the point fixation (PF) method can be used to measure the crack width with great performance. For the BOTDR sensing technique, with a limitation of spatial resolution on the order of 1m, loop installation of FOSs is the best way to accurately and stably monitor crack width. For the PPP-BOTDA sensing technique, despite possessing spatial resolution on the order of 0.1m, if the gauge length of the FOS is shorter than the critical effective sensing length (CESL), the measurement accuracy is significantly affected by the slippage between the core and the coating layer of the FOS.

INTRODUCTION

Strain and crack measurements are main concerns for the performance and condition assessments of different concrete structures. In the laboratory, the width of cracks can be well measured with crack gauges, displacement transducers, and so on. However, these crack width measurement methods are difficult to apply to practical large-scale infrastructures as distributed sensing and monitoring devices. Usually, crack detection for practical concrete structures is based on visual inspection, which is found to be a time-consuming, expensive, and unreliable procedure. Fortunately, the Brillouin scattering-based fiber optic sensing technique can provide a distributed way to measure physical parameters of structures over a long distance. The entire length of the fiber optic sensor (FOS) can be used for both data transmitting and sensing purposes, and thus a distributed sensor with a long and wide monitoring field can be realized.

For Brillouin scattering-based fiber optic sensing techniques, the corresponding spatial resolution is one of the most important issues that affect the measurement of results. When the uniform strain distribution of a FOS is longer than the spatial resolution, the strain value can be measured with high accuracy. However, when the strain distribution of the FOS is not uniform, or the uniform strain distribution is much shorter than the spatial resolution, the measured device will get different strain values in different conditions [5]. For a concrete structure, the cracks are typically local damage, and the crack width is much shorter than the spatial resolution of current versions of Brillouin scattering-based sensing devices which are limited to spatial resolution of 10cm-1m. It is critical to study the possibility and accuracy of using the Brillouin scattering-based sensing technique for monitoring cracks or other localized damage. Furthermore, recently, different kinds of novel sensors have been used for crack monitoring, such as long gauge FOSs and ETDR distributed strain sensors, among others. Thus, a standard test method for evaluating the crack monitoring performance of sensors is also desired and imperative. In this paper, a test method for evaluating the measurement performance of distributed or long gauge FOSs for monitoring cracks is proposed. Performance evaluation of BOTDR and PPP-BOTDA based DFOSs are then conducted based on the proposed method. Moreover, based on experimental results, the sensing features of the PPP-BOTDA and BOTDR are discussed.

BRILLOUIN SCATTERING-BASED FIBER OPTIC SENSING TECHNIQUE

Shift of Brillouin Scattering Frequency

The Brillouin frequency shift ν_B changes in proportion to a variety of strains or temperatures; the linear relationships between the Brillouin frequency shift and the strain or temperature can be expressed as follows:

$$\nu_B(T_0,\varepsilon) = C_\varepsilon(\varepsilon-\varepsilon_0)+\nu_{B0}(T_0,\varepsilon_0) \quad (1)$$

$$\nu_B(T,\varepsilon_0) = C_T(T-T_0)+\nu_{B0}(T_0,\varepsilon_0) \quad (2)$$

where C_ε and C_T are the strain and temperature coefficients, respectively, and ε_0 and T_0 are the strain and temperature that correspond to a reference Brillouin frequency ν_{B0}. Thus, continuous temperature and strain distributions along the fiber can be obtained.

Spatial Resolution

For Brillouin scattering–based distributed sensing techniques, the spatial resolution is an important issue. It determines the measurement ability of DFOSs to acquire the actual strain distribution along the fiber. The optimal spatial resolution of BOTDR is limited to about 1 m with the present measurement systems; for the PPP-BOTDA sensing technique, a spatial resolution on the order of about 10cm has been realized recently.

The Measurement Device

Recently, significant progress has been made in the development of distributed Brillouin scattering–based FOSs by improving spatial resolution and measurement accuracy and stability. Table 1 summarizes the specifications of the AQ8603-BOTDR system from Yokogawa Electric Co. Ltd. and the Neubrescope-BOTDA system from Neubrex Co. Ltd. in Japan.

Table 1: Specifications of current Brillouin back-scattering based systems.

Instruments	AQ8603(BOTDR)				Neubrescope(BOTDA)			
Readout Resolution	5cm				5cm			
Pulse Width (ns)	10	20	50	100	1	2	5	10
Spatial Resolution(m)	1	2	5	11	0.1	0.2	0.5	1
Max. Measurement distance(km)	10	25	45	55	1	5	10	20
Strain Measurement Accuracy(με)	±40	±40	±30	±30	±25	± 25	± 25	± 25

PROPOSED TEST METHODS FOR EVALUATING CRACK MONITORING PERFORMANCE OF DFOS

Proposed Test Method

In this study, a standard test method is proposed to calibrate the crack measurement performance of Brillouin scattering-based distributed optical fiber sensors and to evaluate the accuracy of measurements. A schematic illustration of a standard specimen is shown in Fig.1, in which two rectangular blocks are connected with two strips of FRP sheets and the small gap between the two blocks is utilized to simulate an ideal concrete crack. The specimen is axially loaded under a load or displacement control mode. Simultaneously, the width of the gap is measured by means of displacement transducers (DT) for comparison.

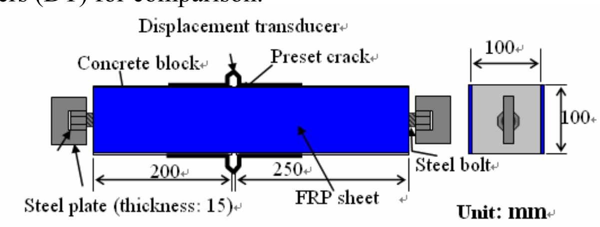
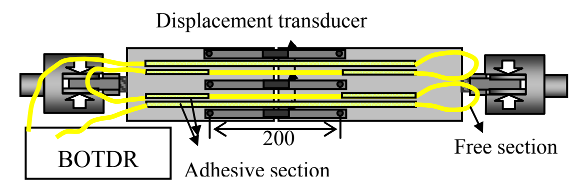


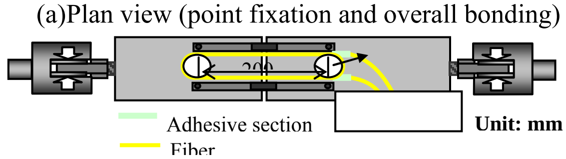
Figure 1. Specimen.

Placement of FOSs

Three methods were adopted for the installation of the BOTDR based DFOSs: overall bonding (OB), point fixation (PF) and loop installation, as shown in Fig.2. In this experiment, optical fiber of type 1 is used, and its cross section is illustrated in Fig. 3



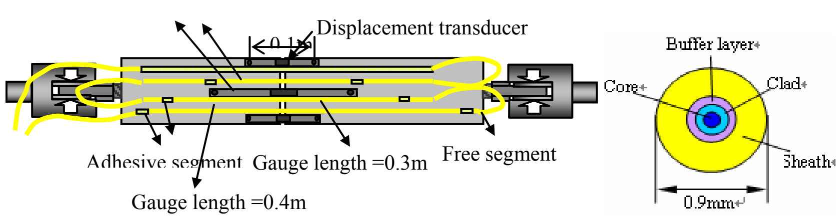
(a)Plan view (point fixation and overall bonding)



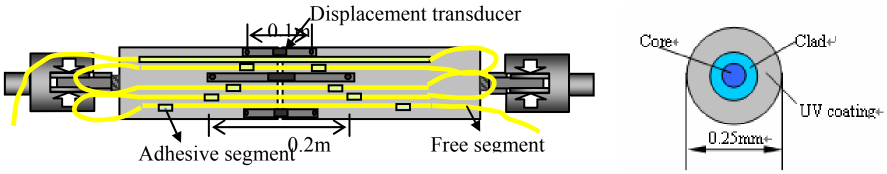
(b) Plan view (loop)

Figure 2. Placement of optical fiber.

Two methods were adopted for the installation of the PPP-BOTDA based DFOSs: PF and OB, as shown in Fig.3. Moreover, two types of optical fiber sensors with different coating manners are used in this experiment to compare the sensing behavior, as shown in Fig.3.



(a)Placement of optic fiber (Type 1)



(b) Placement of optic fiber (Type 2)

Figure 3. Installation of optical fiber.

PERFORMANCE ASSESSMENTS OF DFOS FOR CRACK MONITORING

Assessment of Point Fixation Method

BOTDR-Based Sensing Technique

In general, if the gauge length of the FOS installed by the PF method is longer than the spatial resolution (1m), then the correct result can be measured. However, the measured result over such a big sensing range could include several cracks. In order to get more localized information about the crack, in this experiment, the gauge length of the FOS installed by the PF method was chosen to be 0.2m. If the applied strain on the FOS is less than 1000 $\mu\varepsilon$, the real strain value of the sensing optical fiber can be calculated from the measured value of BOTDR by applying Eq. (3)[5].

$$\varepsilon_r = 5 \times \varepsilon_m . \tag{3}$$

Fig.4 shows the interrelation between the crack width measured by DT and BOTDR.

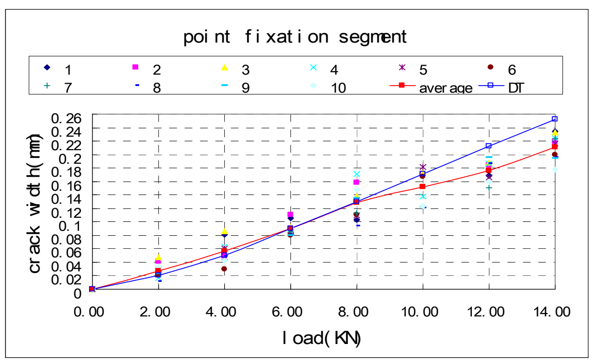


Figure 4. The measured crack width (PF).

In this experiment, the pretension strain of the sensing optical fiber is about 400 $\mu\varepsilon$. From Fig. 4, it is noted that when the crack has a width less than 0.12mm (corresponding to 600 $\mu\varepsilon$), the applied strain of the sensing optical fiber is less than 1000 $\mu\varepsilon$ (including pre-tensile strain), and the results measured with BOTDR agree with the value by DT well. On the other hand, when the crack width is larger than 0.12mm, which causes strain in the sensing optical fiber larger than 1000 $\mu\varepsilon$ (including pre-tensile strain), big differences can be found between the measurements from BOTDR and DT. Moreover, the maximum dispersion of the calculated strain from tests repeated 10 times is more than 300 $\mu\varepsilon$. One of the reasons for such a big dispersion can be explained by the fact that the error in the measured value is also enlarged by 5 times when the measured value is converted to the real strain value using Eq. (3).

PPP-BOTDA Based Sensing Technique

The results measured by FOS type1 are illustrated in Fig. 5.

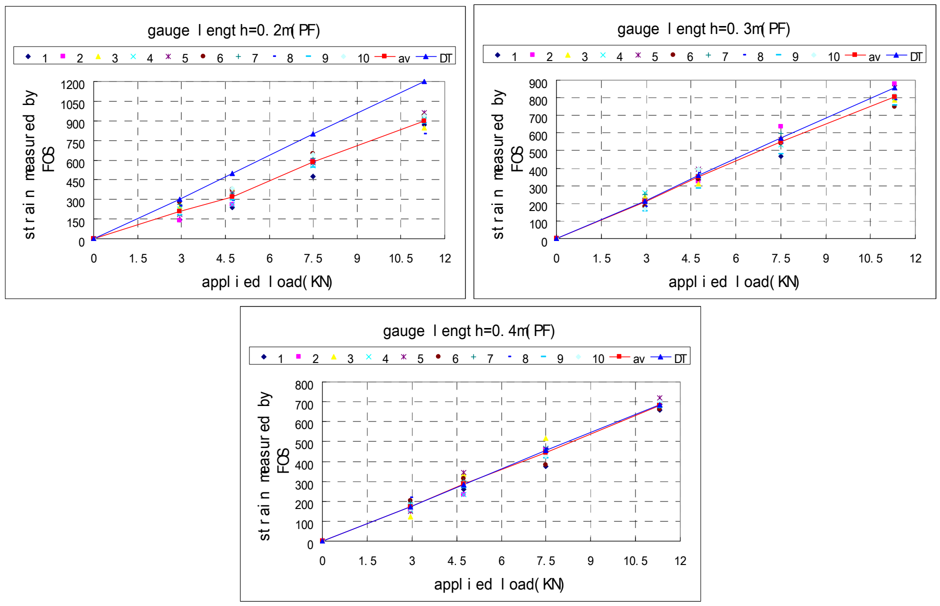


Figure 5. Test results of FOSs (type1).

According to Fig. 5, for the cases in which the gauge lengths of the FOS installed with the PF method were less than 0.4m, although the gauge is larger than the spatial resolution of PPP-BOTDA, the measured strain value is smaller than the converted strain from DT. The smaller the gauge length, the smaller the ratio between the measured strain from BOTDA and the converted strain from DT will be. Therefore, for this type of FOS, it can be concluded that a slippage between the bare fiber and the coating materials may occur. Subsequently, the strain in the optical fiber will redistribute as shown in Fig. 6, and this strain redistribution lowers the strain measured by BOTDA below the correct value.

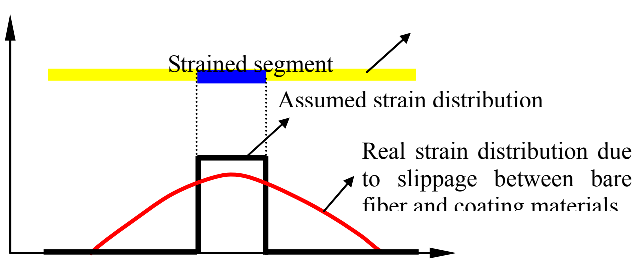


Figure 6. Strain redistribution in FOS.

To obtain a correct measured value with this type of FOS, the sensing length of the FOS should be longer than 0.4m, which can be considered the critical, effective, sensing length (CESL).
In order to confirm the slip features for different types of FOSs, another type of FOS is also tested. The measured results of the type 2 FOS are illustrated in Fig. 7.

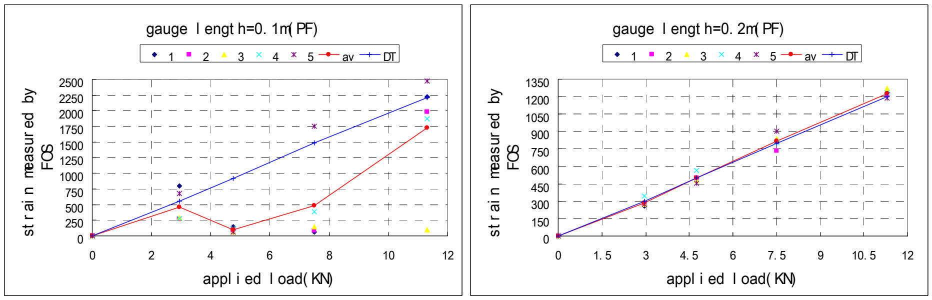


Figure 7. Test results of FOSs (type 2).

Based on Fig. 7, it can be found that when the sensing length of the type 2 FOSs is longer than 0.2m, the measurement from PPP-BOTDA agrees with that for DT closely. Therefore, the CESL of the optical fiber type 2 can be considered to be 0.2m, and the degree of slippage of the FOS type 2 is smaller than the FOS type 1.

Assessment of Overall Bonding Method
BOTDR-Based Sensing Technique

Fig. 8 shows the interrelation between the measured crack width for both DT and BOTDR.

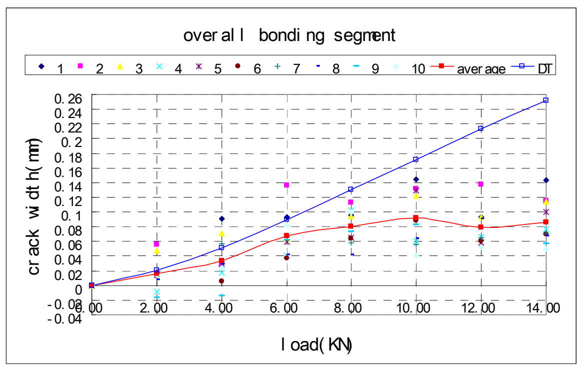
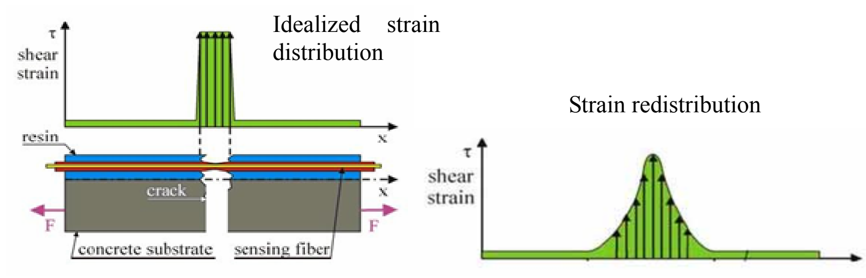


Figure 8. Measured crack width (overall bonding).

According to Fig. 8, for the preset crack width of 0.6cm (a value much less than the approximate 1m spatial resolution), it is obvious that the fiber optic installed by the OB method can hardly measure the crack width correctly, although the occurrence of a crack can be detected. The reason for this result is not far-fetched. Since the sensing region of the FOS is bonded completely to the specimen's surface with epoxy resin, the strain distribution generated in the concrete is thus directly transferred to the bonded FOS. For any occurrence and propagation of cracks in concrete structures, certain de-bonding between the epoxy resin and the cracked concrete surface must occur due to shear stress concentration around the cracks, as shown in Fig. 9 (a). In the case of perfect bonding, the fiber would never survive in such a localized strain concentration. Thanks to the slippage between the FOS and the epoxy resin, the FOS located at the cracked position is elongated. Moreover, this localized strain concentration also causes internal slippage of optical fiber, and the localized strain peak is distributed along the segment of optical fiber. Consequently, the strain distribution of the sensing fiber should be considered as in Fig. 9 (b).

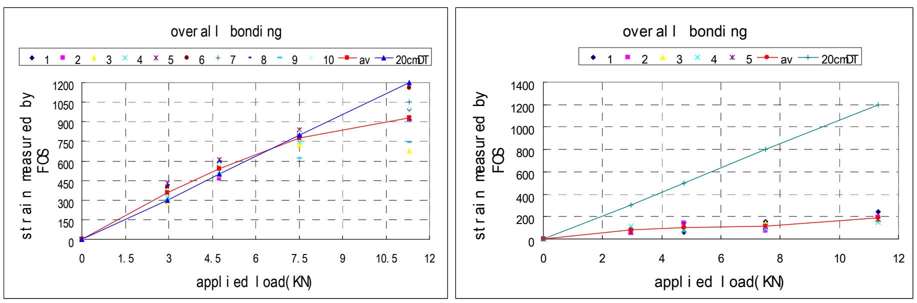


(a) (b)

Figure 9. Strain redistribution in optical fiber.

PPP-BOTDA Based Sensing Technique

The measured results from BOTDA with both types of FOS's are shown in Fig. 10.



Type 1 Type 2

Figure 10. Measurement results of FOS's.

According to Fig. 10, it is obvious that the FOS installed with the OB method cannot have the correct measurement same as BOTDR. For FOS type 2, because of better anti-slippage property, the measured result is much smaller than that of FOS type 1. Thus, for the OB method, the slippage of the FOS is favorable for monitoring cracks in concrete structures. If the slippage of the FOS can be thoroughly prevented, the OB method may lead to rupture of the optical fibers and should not be used to identify the existence of cracks or monitor local deformations.

However, the strain measurement performance close to cracks is still an unresolved problem and no stable relationship can be found between the measured strain of the FOS installed by the OB method and the converted strain from the DT. Thus, the OB method with PPP-BOTDA is still not feasible for monitoring crack width quantitatively.

Assessment of Loop Installation

For the BOTDR technique, loop installation is a good countermeasure for detecting localized damage [2], because the sensing length of the loop installed fiber can be prolonged by superposition of the optical fiber, as shown in Fig.11. In this experiment, the sensing length of the FOS is 1.47m (gauge length=0.2m), which is much longer than the spatial resolution.

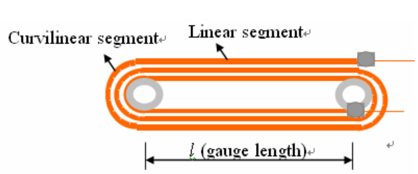


Figure 11. Different loop methods.

The crack widths versus the load relationships based on the measured strain distribution with the loop methods are illustrated in Fig. 12. The results measured with DT are also shown in the figure for comparison.

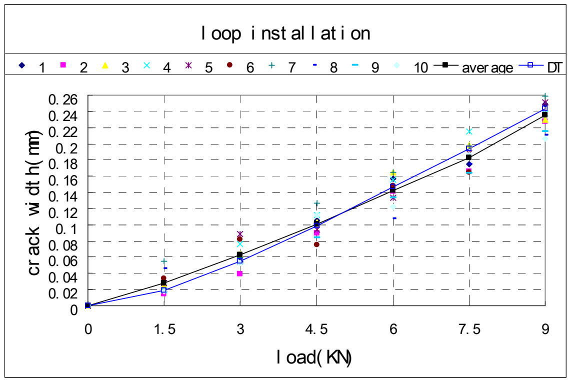


Figure 12. The measured result of loop method 2.

According to Fig.12, it is known that the tested values of optical fibers installed with the loop method agree with those from DT closely. It can be concluded that the loop installation of optical fibers can be used to accurately and stably monitor local deformation.

ACCURACY AND REPEATABILITY ASSESSMENT

● BOTDR

The measurement accuracy of BOTDR offered by the manufacturer is $\pm 40\,\mu\varepsilon$, which is the standard deviation (2σ) of 100 consecutive measured values of unstrained FOSs. In our experiment, when the FOS is installed with the loop method, according to measurement results from BOTDR, the maximum dispersion of the 10 repeated tests is about 120 $\mu\varepsilon$, and the maximum standard deviation (σ) of the measured strain is about 35 $\mu\varepsilon$. It is concluded that the maximum error level of a single measurement (2σ) is approximately $\pm 70\,\mu\varepsilon$. This error level is much bigger than the value offered by the manufacturer. One of the reasons for such big error can be explained by the fact that the fluctuating loads make the measurement stability and repeatability of strained fiber worse than unstrained fiber.

● BOTDA

According to Fig.5 and Fig.6, it is known that the maximum dispersion of the 10 repeated tests is as high as 130 $\mu\varepsilon$. The maximum standard deviation (σ) of the measured strain is about $\pm 40\,\mu\varepsilon$, and it is concluded that the maximum error level of a single measurement (2σ) is approximately $\pm 80\,\mu\varepsilon$.

CONCLUSIONS

1. The test method proposed in this paper can be used for evaluating the measurement performance of distributed or long gauge FOSs for monitoring cracks.
2. Even though the gauge length of the FOS installed by the PF method is less than spatial resolution, if the applied strain of the FOS is less than 1000 $\mu\varepsilon$ (including pre-tensile strain), the BOTDR sensing technique can be used to measure the crack width or the strain caused by localized deformation.
3. For the BOTDR technique, loop installation is the most effective way to test crack width or localized damage and deformation.
4. For the PPP-BOTDA technique, despite possessing an approximately 10cm spatial resolution, the gauge length of FOSs installed with the PF method should be longer than the CESL to obtain correct measured values because of the slippage between the bare fiber and coating layer of the FOS.. Different types of FOSs have different CESLs, and the worse the anti-slippage property, the longer the CESL.

5. Because of slippage between the bare fiber and the coating layer of the FOS, FOSs installed by the OB method can reflect the occurrence of cracks, but this installation method is still not feasible for monitoring crack widths quantitatively.

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