-Technical Paper-

PERFORMANCE EVALUATION OF BOTDA BASED DISTRIBUTED OPTIC FIBER SENSORS FOR CRACK MONITORING

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ABASTRACT

In this paper a standard method is proposed to evaluate the measurement performance of the distributed and long-gauge FOSs for crack monitoring. The performance evaluation of the pulse-prepump Brillouin Optical Time Domain Analysis (PPP-BOTDA) based distributed FOSs is then performed based on the proposed method. Experimental results show that point fixation installation methods can effectively and correctly detect crack width when the gauge length of FOSs longer than the critical effective sensing length (CESL), and the overall bonding method still not feasible for monitoring crack width quantitatively.

Keywords: crack monitoring, PPP-BOTDA, distributed optical fiber sensors, performance evaluation

1. INTRODUCTION

Strain and crack width measurement is main concern for performance and condition assessment of concrete structures. In laboratory, the width of cracks can be well measured with crack gauges, displacement transducers. However, these crack width measurement methods are difficult to be applied to practical large-scale infrastructures. Usually the crack detection for practical concrete structures is based on visual inspection, which is found to be time consuming, expensive and unreliable procedure. Recently, some investigations on the application of BOTDR techniques for crack monitoring have been carried out [1-5]. However, the spatial resolution of BOTDR technique is 1m with a strain measuring accuracy of ±50με. Consequently, BOTDR cannot meet the requirements for local and global monitoring of civil structures. In our previous investigation, loop installation of FOSs is a good countermeasure for BOTDR, but this method is still not convenient.

The newly developed PPP-BOTDA sensing technique improves largely the spatial resolution (10cm) and strain measurement accuracy. In our previous investigations, application of BOTDA techniques for crack monitoring shows that it is a powerful tool. Based on this technique, we try to develop a novel, ease and effective distributed crack monitoring and measuring method for practical infrastructures. This kind of BOTDA based crack monitoring method may provide practical large-scale structures with a distributed crack detection and measurement in a real time manner.

In this paper, a standard method is proposed to evaluate the measurement performance of the distributed and long-gauge FOSs for crack monitoring. The performance evaluation of the BOTDA based distributed FOSs are then performed based on the proposed method. Experimental results show that point fixation installation methods can effectively and correctly detect crack width when the sensing length of FOSs longer than critical effective sensing length (CESL), and the overall bonding method is not feasible for monitoring crack width quantitatively.

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2. PPP-BOTDA BASED DISTRIBUTED SENSING TECHNIQUE

2.1 Measurement Principle of BOTDA[6-9]

The BOTDA technique is based on the stimulated Brillouin back scattering, and two laser sources are needed. One is pulse laser (pump laser) source and the other is continuous laser source, which are introduced into the optic fiber from different ends of the fiber. When the frequency difference between the two lasers is equal to the Brillouin frequency shift, the back Brillouin scattering will be stimulated, and energy transfer will be generated between the two lasers as well. As shown in Fig.1.

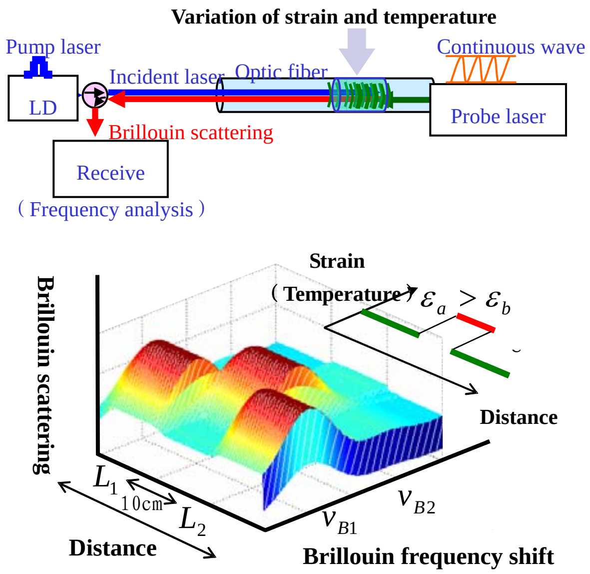


Fig.1 Principle of BOTDA

The Brillouin frequency shift is linear with strain and temperature. The Brillouin frequency shift ν_B changes in proportion to that variety of strain or temperature, the linear relationships between the Brillouin frequency shift and strain or temperature are as follows:

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

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

where C_ε and C_T are the strain and temperature coefficients, respectively, and T_0 and ε_0 are the strain and temperature that correspond to a reference Brillouin frequency ν_{B0}.

2.2. Spatial Resolution

The key to improve the spatial resolution of Brillouin scattering sensing is to shorten the pulse width of the laser pulses. However, for normal BOTDA sensing technique, if the laser pulse width is shorter than 28ns, the phonons cannot be fully stimulated, and the stimulated Brillouin gain is also decreased. As a result, the measuring accuracy is deteriorates abruptly. To overcome this difficulty, pre-pump technique has been developed, where two laser sources are introduced into the optic fiber as shown in Fig. 1. The main difference is in the pump laser source, which factually includes two types of pulse. One is pre-pump laser (PL) that is applied to fully stimulate phonons, and the other is detection pump (PD) used as detecting laser. Due to the existence of PL, the phonons can be fully stimulated before the arrival of PD. As a result, the pulse width of PD can be decreased to 1ns without influence on the stimulation of Brillouin scattering and stimulated Brillouin gain. Accordingly, a spatial resolution of ≈10cm order is realized recently.

2.3 The Measurement Device

Recently, significant progresses have been made in the development of distributed Brillouin scattering–based optic fiber sensors for improving spatial resolution and measurement accuracy and stability. A strain/loss analyzer (Neubrexcope, Neubrex Co. Ltd. in Japan.) based on the BOTDA technique is used for continuous strain distribution measurement with an optic fiber sensor. Table 1 summarizes the specifications of Neubrexcope-BOTDA system

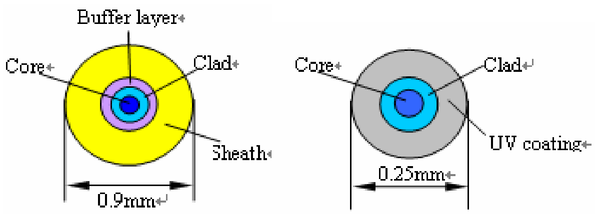
Table1: Specifications of current BOTDA systems (Neubrexcope)

Sampling resolution	5cm			
Average count	2^5-2^{23} times			
Pulse width(ns)	1	2	5	10
Spatial Resolution(m)	0.1	0.2	0.5	1.0
Dynamic range(DB)	1	2	3	5
Max. Measurement distance(km)	1	5	10	20
Strain Measurement Accuracy($\mu\varepsilon$)	±25	±25	±25	±25
repeatability($\mu\varepsilon$)	±50	±50	±50	±50
Temperature test accuracy(℃)	±1	±1	±1	±1

3. Different type of optical fiber and installation method

3.1 different type of FOSs

In order to compare the measurement behavior of different types of optical fiber, 2 types of fiber were used in our experiment, the cross section of optical fiber are shown in Fig.2.



(a)PM fiber (type 1) (b) UV fiber (type 2)

Fig2. Two types of optic fiber

3.2 different installation methods

For different measurement purposes, two kinds of method for installation of optic fibers sensor to the surface of the specimen are proposed and studied. One is termed overall bonding (OB) method with which the necessary measured length of fiber optic is bonded completely on the surface of specimen with resin. The OB is suitable for monitoring strain distribution over a large area. Another is termed point fixation (PF) bonding method with which the two ends of the part of the fiber optic sensor are bonded to the specimen in order to form a uniform strain distribution within two bonding points. The measured value of this uniform strain distribution area can be regarded as an average strain value of the measured length. Consequently, the PF installation can be used effectively to monitor and measure crack width of civil engineering structures since local initiation and propagation of concrete cracks may lead to rupture of optic fibers with an OB installation or other types of crack measurement means such as a long gauge foil strain gauge. Fig. 3 schematically demonstrates the OB and PF installation.

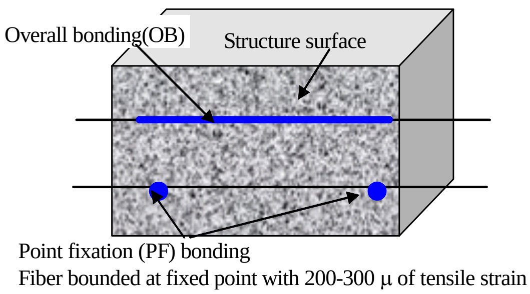


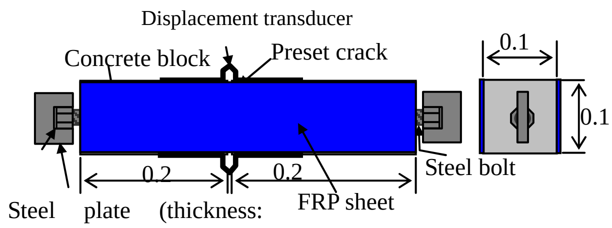
Fig3. OB and PF installation of FOS

4. STANDARD METHODS FOR MONITORING CRACK WIDTH BY DISTRIBUTED OR LONG GAUGE FOSs

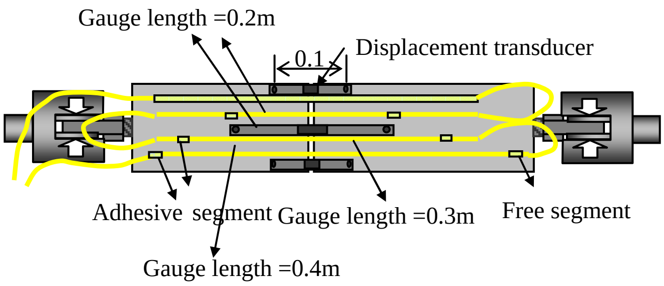
4.1Development of Standard Method

In this study, standard experiments are proposed to calibrate the crack measurement performance of the BOTDA based distributed optical fiber sensors and evaluate the accuracy of measurement.

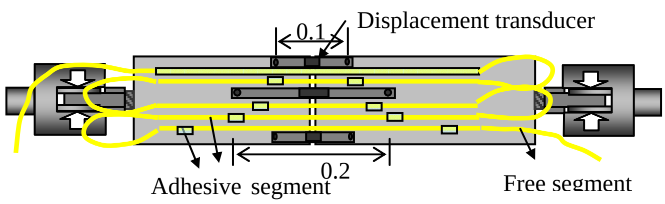
The schematic illustration of applied standard specimen is shown in Fig.4. Where two rectangular concrete blocks are connected with two strips of FRP sheets and the small gap between the two blocks is utilized to simulate an ideal concrete crack. The specimen is axially loaded under a load control mode. Upon loading, the gap becomes wide, and its width is measured by BOTDA based distributed optic fiber sensors. Simultaneously, the width of gap is measured by means of displacement transducers (DT) for comparison. In addition, two type of FOSs shown in Fig2 are use in this experiment, the installation method of FOSs adopt point fixation and overall bonding. For FOS type 1, the gauge lengths of point fixation adopt 0.2m, 0.3m and 0.4m respectively, and for FOS type 2, the gauge lengths of point fixation adopt 0.1m, 0.15m, 0.2m and 0.3m respectively.



(a) Side view



(b) Layout of optic fiber (Type 1)



(c) Layout of optic fiber (Type 2)

Fig.4 Experiment specimens

4.2 Performance Assessment of BOTDA for Crack Monitoring

In this experiment, the measured data of DT is used as baseline to check accuracy of BOTDA.

The tested results of DT in different gauge length and different load level are shown in Fig. 5.

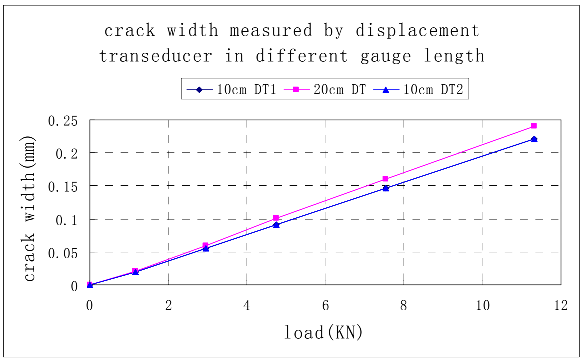


Fig5. Measurement result of DT

According to Fig.5, two DT whose gauge length equals 10cm get almost same measured value, and the measured values of DT whose gauge length equals 20cm are bigger than that of the DT whose gauge length equals 10cm, therefore, the deformation of specimen can be simplified as Fig.6, this kind of deformation can be used to simulate an ideal concrete crack, in addition, the elastic deformation of concrete block can't be neglected.

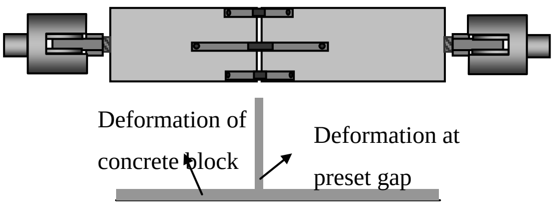


Fig.6 Longitudinal deformation of specimen

According to Fig.6, the deformations over the gauge length of 0.1m 0.15m, 0.2m and 0.3m can be calculated. Moreover, these deformations over different gauge length can be converted to corresponding strain value and used to check the test accuracy of BOTDA. The measured results of FOS type1 are shown in Fig7-10.

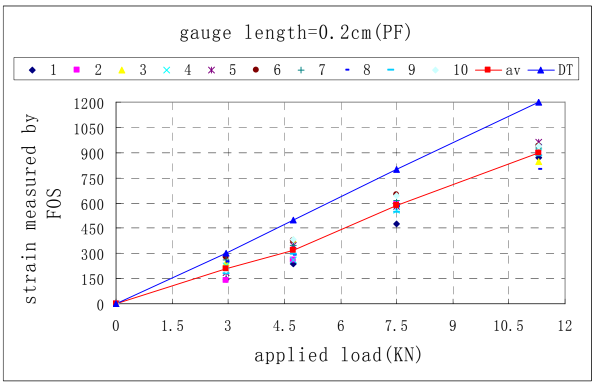


Fig7. Measurement result of FOSs (Type 1)

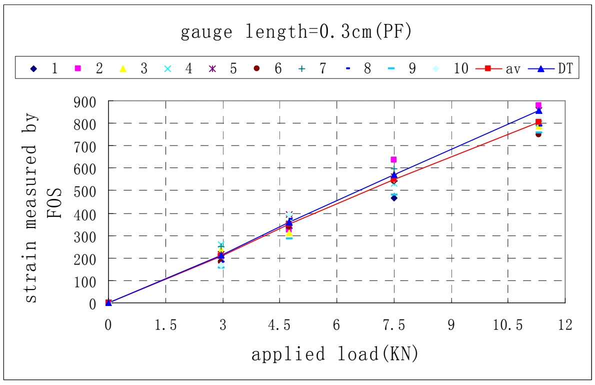


Fig8. Measurement result of FOSs (Type 1)

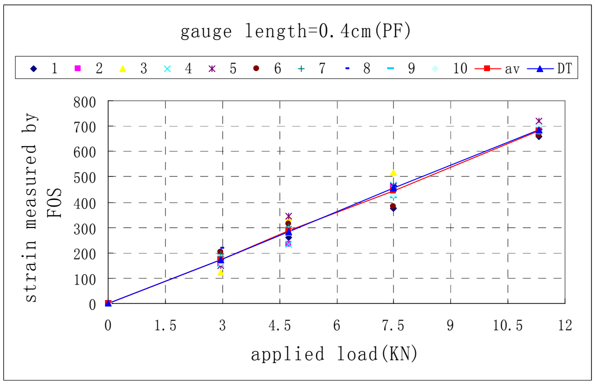


Fig9. Measurement result of FOSs (Type 1)

According to Fig.7-9, for FOSs type 1, one important issue should be noticed, in despite that the nominal spatial resolution of BOTDA is 10cm, if gauge length of FOSs less than 0.4m, the measured strain value of BOTDA is smaller than the converted strain of DT, and the smaller the gauge length, the smaller the ratio between measured strain of BOTDA and the converted strain. Actually, before this experiment, some preliminary experiment have been finished, and the 10cm-order spatial resolution have been verified, and strain coefficient of different type of fiber have been calibrated. Therefore, it can be concluded that in the interior of FOSs, there must be slipped between the core and sheath of FOSs. In this paper, we defined the length of 0.4m as critical effective sensing length (CESL), if gauge length of FOSs bigger than CESL, BOTDA can monitor crack width correctly.

Fig. 10 show the measurement results of overall bonding installed FOS.

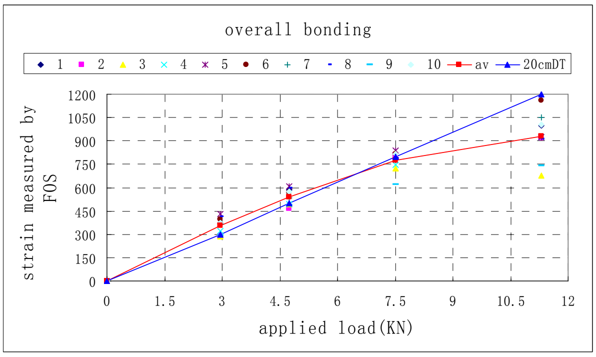


Fig10. Measurement result of FOSs (Type 1)

According to Fig.10, the measured result of FOSs type1 installed in overall bonding method can reflect the existence of crack too, but we can’t get a stable relationship between the measured strain of overall bonding and the converted strain of DT, therefore, the overall bonding method still not feasible for monitoring crack width quantitatively.

The measured results of FOS type 2 are shown in Fig11-15.

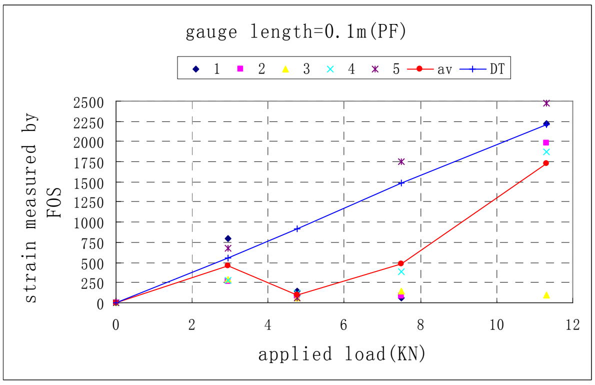


Fig11. Measurement result of FOSs (Type 2)

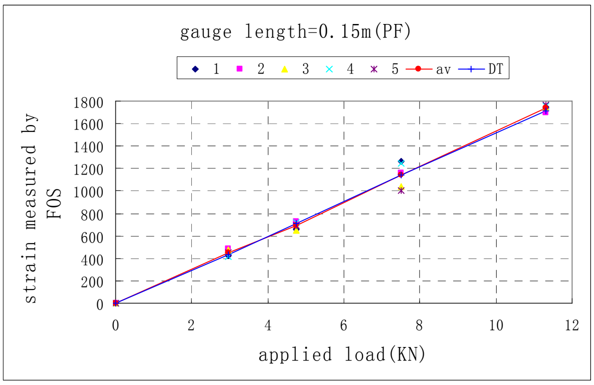


Fig12. Measurement result of of FOSs (Type 2)

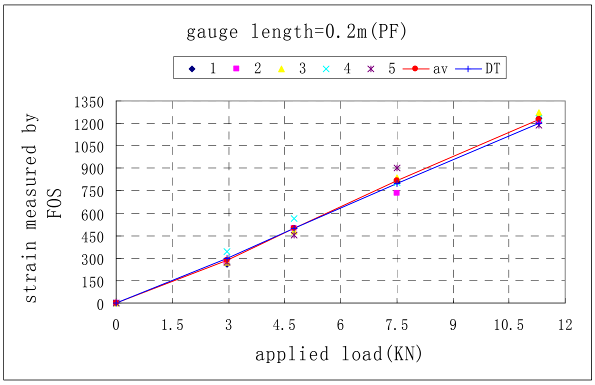


Fig13. Measurement result of FOSs (Type 2)

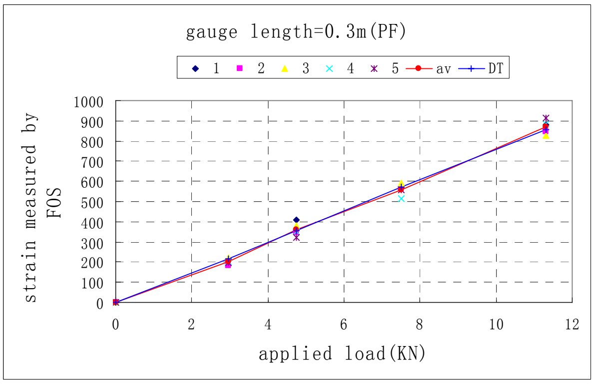


Fig14. Measurement result of FOSs (Type 2)

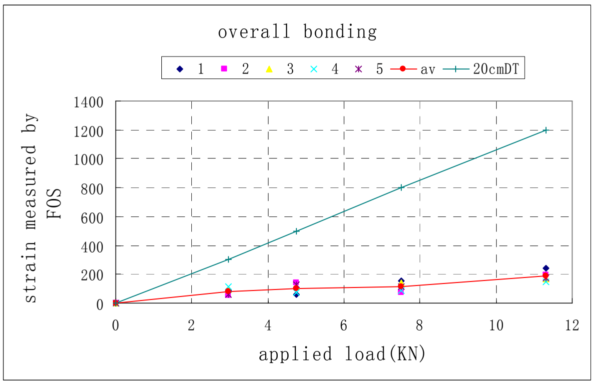


Fig15. Measurement result of FOSs (Type 2)

Based on Fig.11-14, if sensing length of FOSs type 2 longer than 0.15cm, the measurement of BOTDA is agrees with DT very well. Therefore, the CESL of optical fiber type 2 is 0.15m. It can be known that different type FOS has different CESL, the longer the CESL, the worse the anti-slipped property.

According to Fig.15, for optic fiber type 2, because of well anti-slipped property, the measured result of optic fiber installed in overall bonding method is much smaller than that of FOS type 1. Therefore if the slippage can be prevented thoroughly, the overall bonding method may lead to rupture of optic fibers and can’t be used to reflect the existence of crack or monitor local deformation.

4.3Accuracy and repeatability assessment

According to Fig.6-13, it can be known that the maximum dispersion of the 10 times repeated tests are as high as 120 $\mu\varepsilon$, then the error level of single measurement should be very big. The maximum error of the average value of 10 times repeated tests is about 30 $\mu\varepsilon$, Therefore it is an effective way to reduce the error level of BOTDR by adapting average values of several times measurements.

The measured dispersion keeps constant in different applied load level and different sensing length, therefore, the tested data of BOTDA is very stable. The maximum standard deviation (σ) of 10 times measured strain is about 40 $\mu\varepsilon$, and the repeatability of BOTDA (2$\times\sigma$) equals about 80 $\mu\varepsilon$, It is can be concluded that influenced by fluctuant load, the measurement accuracy and repeatability of BOTDA in our experiment is worse than the nominal value.

5 CONCLUSIONS

1. For PPP-BOTDA technique, point fixation of FOS is an effective method to monitor crack width correctly.

2. Because of the slippage in optic fiber, in despite of possessing 10cm order spatial resolution, if sensing length of FOS less than CESL, the measurement result of BOTDA is still not correct.

3. Different type FOS has different CESL, the longer the CESL, the worse the anti-slipped property.

4. For the existence of slippage in optic fiber, overall bonding method can reflect the existence of crack, but still not feasible for monitoring crack width quantitatively.

5. It is an effective way to reduce the error level of BOTDA by adapting average values of several times measurements.

6. In this paper, there is only one crack in the specimen, in fact, for PF bonding method, if there are several crack within the CESL, the total crack width still can be measurement correctly, for OB bonding method, if the distance between two crack is small than spatial resolution, because of the overlapped effect of slippage, the measurement result will be very complicate, therefore, it is necessary to develop an new type of optic fiber with no slippage.

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