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

Zhishen Wu, Hao Zhang
Ibaraki University, Japan

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

1. INTRODUCTION

Strain and crack measurements are main concern for the performance and condition assessment of different concrete structures. In 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 be applied to practical large-scale infrastructures as distributed sensing and monitoring devices. Usually the crack detection for practical concrete structures is based on visual inspection, which is found to be time consuming, expensive and unreliable procedure. Fortunately, the Brillouin scattering based fiber optic sensing technique can provide a distributed measurement way of physical parameters of structures over a long distance. The entire length of the FOS can be used for both data transmitting and sensing purposes, and thus a distributed sensing with long and wide monitoring field can be realized.

To Brillouin scattering based fiber optic sensing techniques,, the corresponding spatial resolution is one of the most important issues that affect the measurement results. When an uniform strain distribution of FOS is longer than spatial resolution, the strain value can be measured in a high accuracy. However, when the strain distribution of FOS is not uniform, or uniform strain distribution is greatly shorter than the spatial resolution, the measured device will give different strain value in different condition[]. For a concrete structure, the cracks are typical local damage and the crack width is much shorter than the spatial resolution of current version of Brillouin scattering based sensing device with a limited spatial resolution of 10cm-1m. It is critical to study the possibility and accuracy of Brillouin scattering based sensing technique for crack or other localized damage monitoring. Furthermore, recently, different kinds of novel sensors has been used for crack monitoring, such as long gauge FOS, ETDR distributed strain sensor et. al. Thus, a standard test method for evaluating 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 crack is first proposed. The performance evaluation of BOTDR and PPP-BOTDA based DFOSs are then performed based on the proposed method. Moreover, based on experimental result, the sensing features of the PPP-BOTDA and BOTDR are discussed.

2. BRILLOUIN SCATTERING-BASED FIBER OPTIC SENSING TECHNIQUE

2.1 Shift of Brillouin scattering frequency

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 can be expressed as follows:

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

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

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}. Thus continuous temperature and strain distributions along the fiber can be obtained.

2.2. 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 at the present measurement system, For PPP-BOTDA sensing technique, a spatial resolution of about 10cm order is realized recently.

2.3 The Measurement Device

Recently, significant progresses have been made in the development of distributed Brillouin scattering–based FOSs for improving spatial resolution and measurement accuracy and stability. Table 1 summarizes the specifications of AQ8603-BOTDR system from Yokogawa Electric Co. Ltd. and 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
Dynamic Range(db)	4	8	12	15	1	2	3	5
Max. Measurement distance(km)	10	25	45	55	1	5	10	20
Strain Measurement Accuracy(με)	±40	±40	±30	±30	±25	± 25	± 25	± 25

3 PROPOSED TEST METHODS FOR EVALUATING CRACK MONITORING PERFORMANCE OF DFOS

3.1 Proposed test method

In this study, a standard test method is proposed to calibrate the crack measurement performance of the Brillouin scattering based distributed optical fiber sensors and evaluate the accuracy of measurement. The schematic illustration of applied standard specimen is shown in Fig.1, where 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 gap is measured by means of displacement transducers (DT) for comparison.

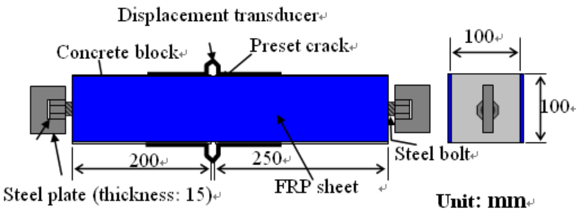
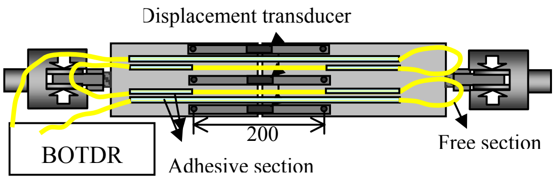


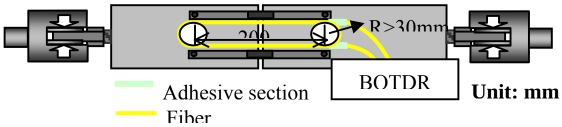
Fig.1 Specimen

3.2 Placement of FOSs

The installation method of BOTDR based DFOSs adopt three methods: OB, PF and loop installation, as shown in Fig.2. In this experiment, optical fiber type 1 is used, and its cross section is illustrated in Fig. 3



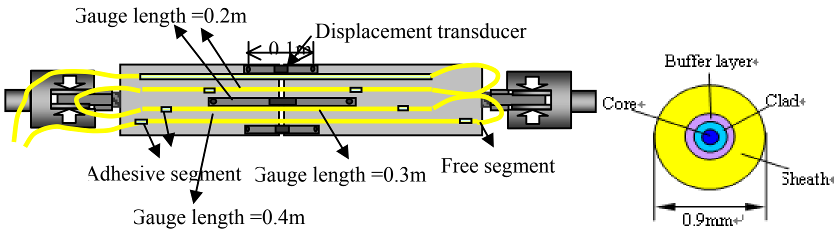
(a)Plan view (point fixation and overall bonding)



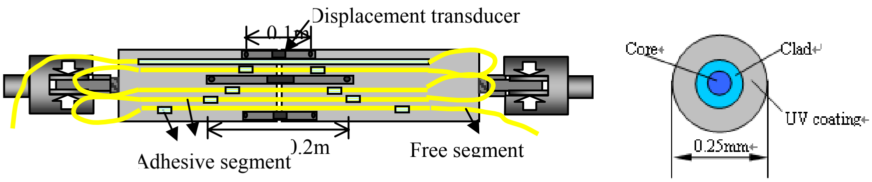
(b) Plan view (loop)

Fig.2 Placement of optical fiber

The installation method of PPP-BOTDA based DFOSs adopt two methods: PF and OB, as shown in Fig.3. Moreover, two types of optical fiber sensors with different coating mannersare 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)

Fig.3 Installation of optical fiber

4 PERFORMANCE ASSESSMENTS OF DFOS FOR CRACK MONITORING

4.1 Assessment of point fixation method

4.1.1 BOTDR-based sensing technique

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

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

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

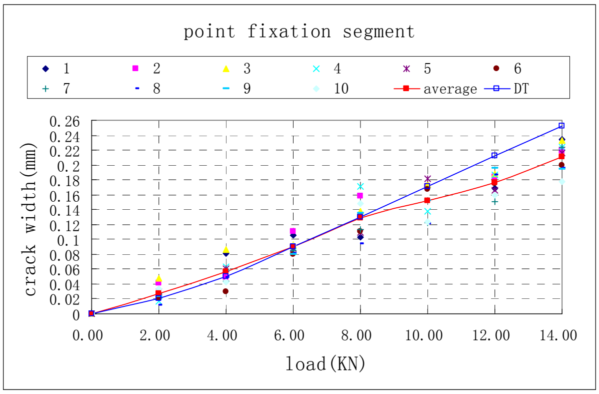
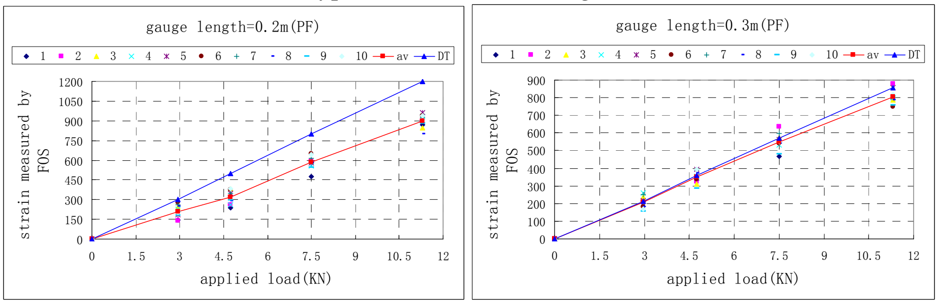


Fig.4 The measured crack width (PF)

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

4.1.2 PPP-BOTDA based sensing technique

The measured results of FOS type1 are illustrated in Fig5.



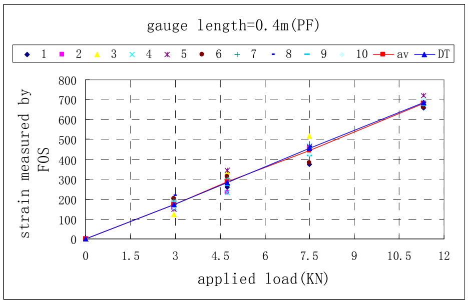


Fig.5 test result of FOSs (type1)

According to Fig.5, For the case that gauge lengths of FOS installed with PF method less than 0.4m, although the gauge length is large than the spatial resolution of PPP-BOTDA, the measured strain value 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 of DT. Therefore, for this type of FOS, it can be realized that a slippage between the bare fiber and coating materials may occurs. To obtain correct measured value with this type of FOS, the sensing length of FOS should longer than 0.4m which can be considered being the critical effective sensing length (CESL) . 加图

In order to confirm the slip features for different types of FOSs, another type FOS is also tested. The measured results of the FOS type2 are illustrated in Fig6.

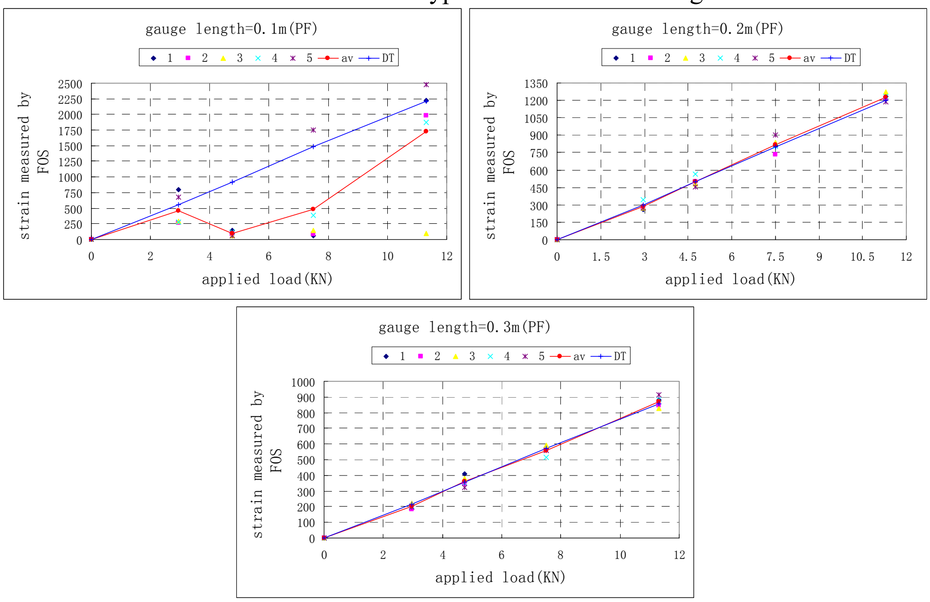


Fig.6 test result of FOSs (type 2)

Based on Fig.6, it can be found that if sensing length of FOSs type 2 is longer than 0.2cm, the measurement of PPP-BOTDA agrees with DT closely. Therefore, the CESL of the optical fiber type 2 can be considered as 0.2m, and the degree of slippage of the

FOS type 2 is smaller than the FOS type 1

4.2. Assessment of overall bonding method

4.2.1 BOTDR-based sensing technique

Fig.7 shows the interrelation between the measured crack width with both DT and BOTDR.

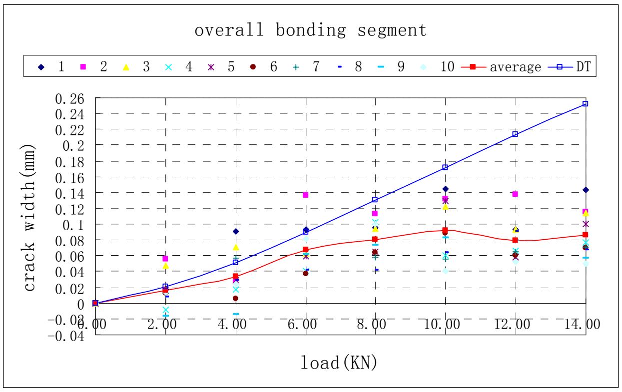
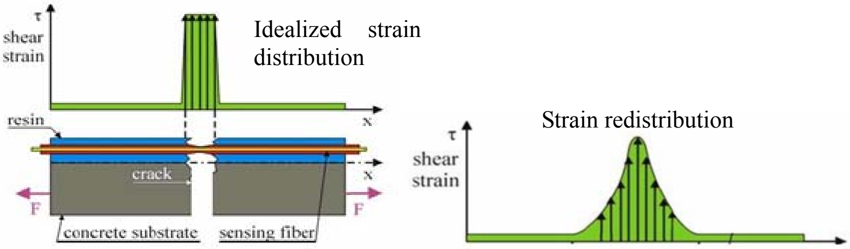


Fig.7 Measured crack width (overall bonding)

According to Fig.7, for the preset crack width of 0.6cm (a value much less than 1m-order spatial resolution), it is obvious that the fiber optic installed by OB method can hardly measure the crack width correctly, although the occurrence of 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, there must be occur certain de-bonding between epoxy resin and cracked concrete surface due to shear stress concentration around the cracks, as shown in Fig. 8-(a). In case of perfect bonding, the fiber would never survive in such a localized strain concentration. Thanks to the slippage between FOS and epoxy resin, the FOS located at cracked position is elongated. Moreover, this localized strain concentration also causes internal slippage of optical fiber, and the localized strain peak can distributed near the segment of optical fiber. Consequently, the strain distribution of sensing fiber should may be consideded as Fig. 8-(b).

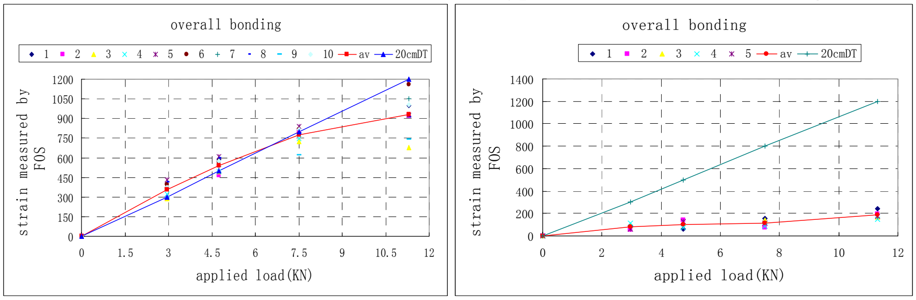


(a) (b)

Fig.8 strain redistribution in optical fiber

4.2.2 PPP-BOTDA based sensing technique

The measured results of BOTDA with both types of FOS are shown in Fig.9.



Type 1 Type 2

Fig9. Measurement result of FOSs

According to Fig.9, it is obvious that the FOS installed in OB method can't have correct measurement same as BOTDR. For FOS type 2, because of well anti-slipped property, the measured result is much smaller than FOS type 1. Thus, for OB method, the slippage of FOS is favorable to monitor crack of concrete structure, if the slippage of FOS can be prevented thoroughly, the OB method may lead to rupture of optic fibers and can't be used to identify the existence of crack or monitor local deformation.

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

4.3 Assessment of loop installation

For BOTDR technique, loop installation is a good countermeasure for detecting the localized damage, because the sensing length of loop installed fiber optic can be prolong by superposition of optical fiber, as shown in Fig.10. In this experiment, the sensing length of FOS is 1.47m (gauge length=0.2m), and which is much longer than the spatial resolution.

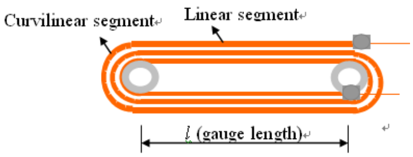


Fig.10 Different loop method

The crack widths versus load relationships based on the measured strain distribution with loop methods are illustrated in Fig. 11. The measured results withy DT are also shown in the figures for comparison.

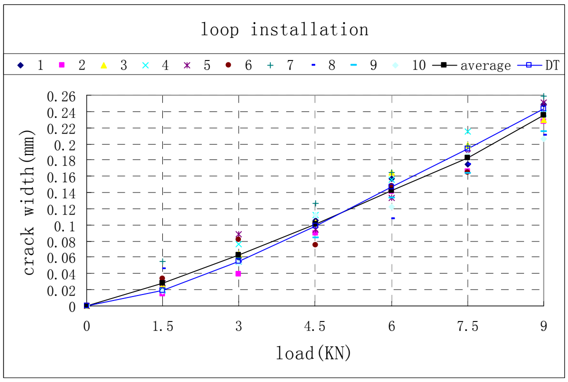


Fig.11 The measured result of loop method 2

According to Fig.11, it can be known that the tested values of fiber optics which installed with loop method agree with that of DT closely. It can be concluded that the loop installation of fiber optics can be used to accurately and stably monitor local deformation.

5 Accuracy and repeatability assessment of crack monitoring

● BOTDR

When FOS is installedwith loop method, according to measurement result of BOTDR, the maximum dispersion of the 10 repeated tests is about 120 $\mu\varepsilon$, and this dispersion remains constant in different applied load level and different gauge lengths. Therefore, the repeatability of BOTDR is considered very stable. Because the maximum standard deviation (σ) of the measured strain is about 35 $\mu\varepsilon$, it can be concluded that the maximum error level of a single measurement (2σ) is about $\pm$70 $\mu\varepsilon$. Thus, for just single test, the total crack width detection accuracy can be determined as $\pm$7×GL (gauge length)×10^{-5}m.

● BOTDA

According to Fig.5 and Fig.6, it can be known that the maximum dispersion of the 10 times repeated tests are as high as 130 $\mu\varepsilon$. 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 $\pm$40 $\mu\varepsilon$, and the repeatability of BOTDA (2×σ) equals about $\pm$80 $\mu\varepsilon$. Thus, for just single test, the total crack width detection accuracy can be determined as $\pm$8×CESL×10^{-5}m. For different type of FOS, the smaller the CESL, the higher accuracy the measured crack width.

6. CONCLUSIONS

1. The standard method proposed in this paper can be used for evaluating the measurement performance of distributed or long gauge FOSs for monitoring crack.
2. For BOTDR sensing technique, despite that the gauge length of FOS installed by PF

method is less than spatial resolution, if applied strain of FOS is less than 1000 $\mu\varepsilon$ (including pretension strain), it still can be used to measure the crack width or the strain caused by localized deformation.
3. Loop installation of fiber optics can be used to accurately and stably monitor local deformation. Therefore, for BOTDR technique, loop installation is the most effective way to test the localized damage and deformation or the overall deformation due to the localized damage.
4. For PPP-BOTDA technique, FOS installed by PF method can monitor crack width correctly. Because of the slippage between the core and coating layer of FOS, in despite of possessing 10cm order spatial resolution, if gauge length of FOS in stalled in PF method less than CESL, the measurement result of BOTDA is not correct.
5. Different type FOS has different CESL, the longer the CESL, the worse the anti-slipped property.
6. Because of slippage between the core and coating layer of FOS, The FOS installed by OB method can reflect the existence of crack, but still not feasible for monitoring crack width quantitatively.

REFERENCE

1.Wu, Z.S., Takahashi, T. and Sudou, K. An experimental investigation on continuous strain and crack monitoring with fiber optic sensors, Concrete Research and Technology, 13(2), 139-148. 2002.
2. Zhishen Wu, Bin Xu. Infrastructural health monitoring with BOTDR fibre optic sensing technique, *Proceeding of first international workshop on structural health monitoring of innovative civil engineering structures*, ISIS Canada Research network, pp.217-226. 2002.
3. F. Katsuki. The experimental research on the crack monitoring of the concerete structures using optical fiber sensor, *Proceeding of structural health monitoring and intelligent infrastructure*, pp.277-281. 2003.
4. Zhishen Wu, Bin Xu. Fiber optic sensing of PC girder strengthened with prestressed PBO fiber sheets, In *Proceeding of structural health monitoring and intelligent infrastructure*, pp.1191-1199. 2003.
5. H. Zhang, and Z.S Wu. Performance evaluation of BOTDR based distributed optic fiber sensors for crack monitoring, Structural Health Monitoring. (In press) 2007
6. Zhishen Wu , Kentaro Iwashita, Songtao Xue and Hao Zhang: Experimental Study on Crack Monitoring of PC Structures with Pulse-prepump BOTDA-based Distributed Fiber Optic Sensors, Concrete research and technology. vol.18, No.2, PP49-58