Development of No-slip Optic Fibers as Brillouin Scattering Based Distributed Sensors

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Abstract In this paper, the sensing behavior of the pulse-prepump Brillouin Optical Time Domain Analysis (PPP-BOTDA) based distributed sensing technique with a 0. 1 m-order spatial resolution is experimentally studied, and the sensing features of different types of fiber optic sensors (FOSs) are compared. Based on experimental results, we found that slippage occurred between bare fibers and coating materials, and that a different FOS type has a different degree of slippage. Despite possessing 10 cm-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. In order to enhance the sensing performance of FOS, a packaging design for the practical adaptation of no-slip FOS for structural health monitoring applications is proposed. Finally, the performances of packaged optic fibers are experimentally verified.

Keywords FOS; PPP-BOTDA; Slippage; Package method; No-slip FOS

1 Introduction

Recently, research and application of structural health monitoring (SHM) for large-scale structures have attracted extensive attention. With the developments of advanced sensing technologies, SHM plays an important role in damage detection, reliability and performance evaluation of existing infrastructures. Basically, a SHM system includes sensing, data acquisition and processing, communication, and decision-making units. With a novel sensing system and an advanced structural analysis technique, health monitoring and damage assessment of civil engineering structures have become more practical. Therefore, the sensing techniques including sensors and their system are crucially important for different SHM systems. Nowadays, different kinds of fiber optic based sensing techniques have been widely developed and applied for the SHM of large-scale structures due to their advantages of distributed sensing, rapid data transmission, small dimension, ease installation and immunity from electromagnetic influence and so on.

One of the most applicable approaches for the distributed optical fiber sensing technology method is the Brillouin Optical Time Domain Reflectometry (BOTDR) based technique as demonstrated by Horiguchi *et al.* and Bao *et al.* [1-3]. Some investigations on the application of BOTDR techniques for SHM have been carried out and significant progress has been made. However, the spatial resolution of the BOTDR technique is 1 m with a strain measuring accuracy of ± 50 $\mu\varepsilon$. Consequently, BOTDR cannot meet the requirements for local and global monitoring of civil structures. In our previous investigation, loop installation of optical fibre is a good countermeasure, but this method is still not convenient for monitoring practical structure. Recently, the newly developed PPP-BOTDA sensing technique improves largely the spatial resolution (10 cm), and some applications of PPP-BOTDA based DFOSs for structural health monitoring have been carried out.

The improvement of spatial resolution significantly increases the sensing performance of DFOSs for structural health monitoring. In this paper, firstly, in order to make good use of this powerful tool, the basic sensing behaviors of PPP-BOTDA based DFOSs with a 0. 1 m order spatial resolution are experimentally studied. Secondly, the sensing features of different types of optical fiber are investigated and compared. Based on the experimental result, in despite of possessing a 10 cm-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 occurring between bare fibers and coating materials. The bare fiber is verified that it can be used directly to bond with the host structure with no-slip way and measure strain with satisfied accuracy and stability. However, due to the fragility of bare fiber whose coat has been removed from commercial optical fiber, the appropriate methods for package and bonding with host structures should be carefully considered to protect the brittle fiber from harsh environments. Therefore, it is critical to develop a type of no slip FOSs for practical application. In this paper, a packaging design for the practical adaptation of no-slip FOS in civil structural health monitoring is proposed, and the packaged fiber is experimentally verified such that it can be used as one type of no-slip FOS.

2 PPP-BOTDA Based Distributed Sensing Technique

2.1 *Measurement Principle of BOTDA*

The BOTDA technique is based on the stimulated Brillouin back scattering, and two laser sources. One is a pulse laser (pump laser) source and the other is a 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. This is as shown in Fig. 1.

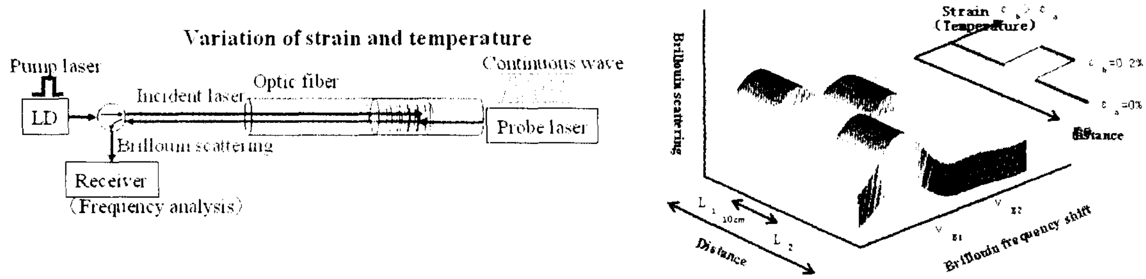


Fig. 1 Principle of BOTDA

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

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

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

where C_ε and C_T are the strain and temperature coefficients, respectively, and 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*

The key to improving the spatial resolution of Brillouin scattering sensing is to shorten the pulse width of the laser pulses. However, for the normal BOTDA sensing technique where the laser pulse width is shorter than 28 ns, the phonons cannot be fully stimulated, and the stimulated Brillouin gain is also decreased. As a result, the measuring accuracy deteriorates abruptly. To overcome this difficulty, a 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 actually includes two types of pulse. One is a pre-pump laser (PL) that is applied to fully stimulate phonons, and the other is a detection pump (DP) used as detecting laser. Due to the existence of PL, the phonons can be fully stimulated before the arrival of DP. As a result, the pulse width of DP can be decreased to 1 ns without influence on the stimulation of Brillouin scattering and stimulated Brillouin gain. Accordingly, a spatial resolution of approximately 10 cm order has been realized recently.

2.3 *The Measurement Device*

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

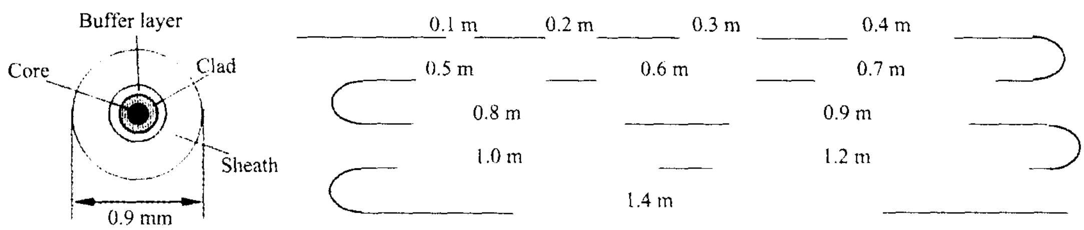
Table 1 Specifications of current BOTDA systems

Sampling resolution	5 cm			
Average count	$2^5 \sim 2^{23}$ 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 Measurement Behavior of Different Types of FOS

3.1 *Experimental Investigation on Basic Measurement Behavior of BOTDA-based DFOSs*

Strain measurement behavior of optic fibers is examined through basic tests. In the experiment conducted here, one piece of optical fiber (type 1, its cross section as shown in Fig. 2(a)) was adhered with a uniform tensile steel specimen by an overall bonding method and 13 different sensing lengths (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2 and 1.4 m) are set in series. In addition, different sensing fibers are separated from each other by an interval of 2 m of free fiber as shown in Fig. 2. The applied strain level of steel specimen is controlled by strain gauge.



(a) Cross section of optical fiber (b) Placement of fiber optic sensors

Fig. 2. Experimental investigation

3.2 *Sensing Result of FOS*

Under loading levels of 300,800 and 1 500 $\mu\varepsilon$, the 10 times measurement strain values of optical fiber in different sensing lengths are shown in Fig. 3 ~ Fig. 5.

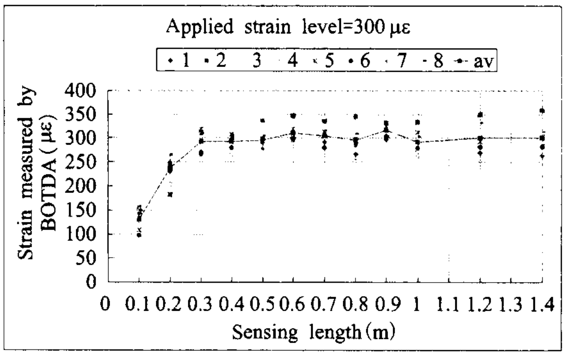


Fig. 3 Testing value of optical fiber in different sensing length

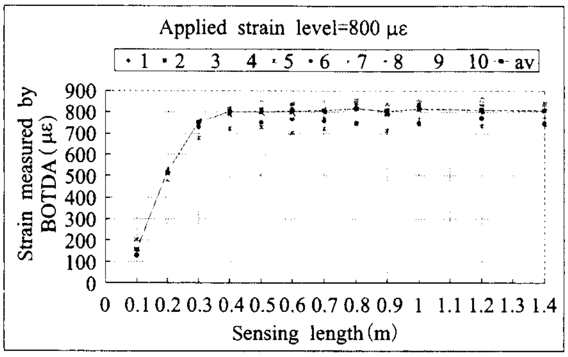


Fig. 4 Testing value of optical fiber in different sensing length

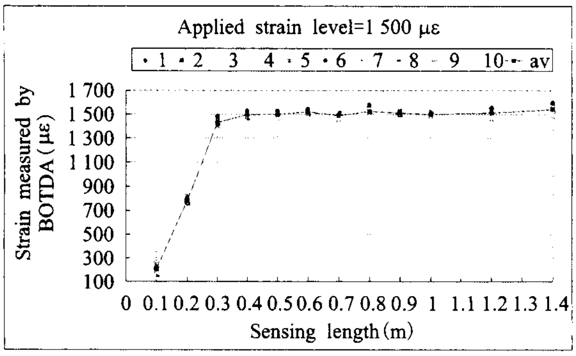


Fig. 5 Measurement value of optical fiber in different sensing length

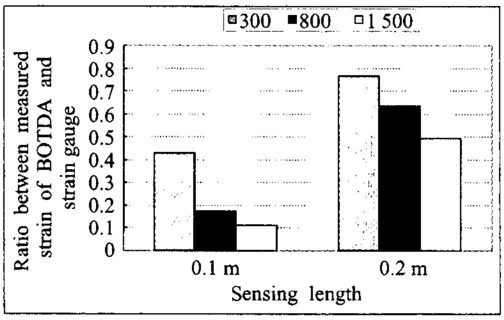


Fig. 6 Sensing behavior of optical fiber

Based on Figs. 3 ~ 5, one important phenomenon is distinct. Despite the 10 cm order spatial resolution, if the sensing length of the optical fiber is shorter than 0. 4 m, the measured strain value of BOTDA is still less than the strain gauge. In order to explain this phenomenon, the ratio between measured strain value of BOTDA and strain gauge in different load levels are analyzed, as shown in Fig. 6.

According to Fig. 6, the larger the applied strain is, the smaller the ratio of measured strain value of BOTDA and strain gauge becomes. Therefore, for this type of FOS, it can be realized that a slippage between the bare fiber and coating materials may occur. Consequently, the strain in optical fiber will redistribute as shown in Fig. 7 and this strain redistribution lowers the measured strain of BOTDA which is less than the correct value.

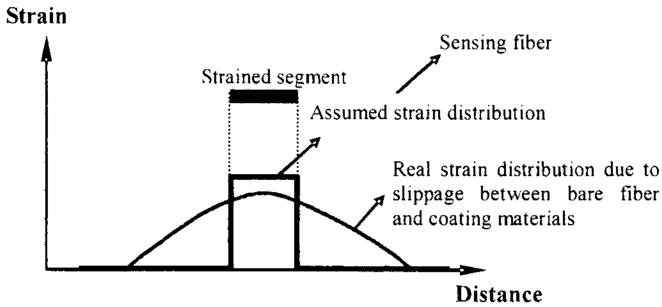


Fig. 7 Strain redistribution in FOS

At present, the detailed strain distribution of FOS still remains an unresolved problem. Nevertheless, based on the aforementioned analysis, it can be known that to obtain a correct measured value with this type of FOS, the sensing length of FOS should be longer than 0. 4 m which can be considered the critical effective sensing length (CESL).

3.3 *Measurement Behavior of Other Optical Fiber Types*

In order to verify the slippage of different types of FOS and check the spatial resolution of BOTDA, several other types of optical fiber were adhered with the same tensile steel specimen and under the same experimental procedure. The experimental results are discussed as follows.

3.3.1 *FOS Type* 2

The cross section of FOS type 2 is illustrated as Fig. 8. Four different sensing lengths (0.1, 0.15, 0.2 and 0.3 m) are set in series. Under the loading level of 800 $\mu\varepsilon$, the 10 times measurement strain values of optical fiber in different sensing length are shown in Fig. 9

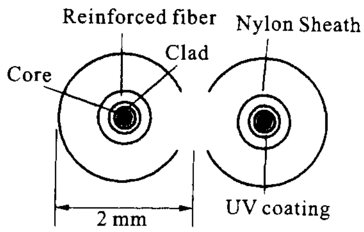


Fig. 8 FOS type 2

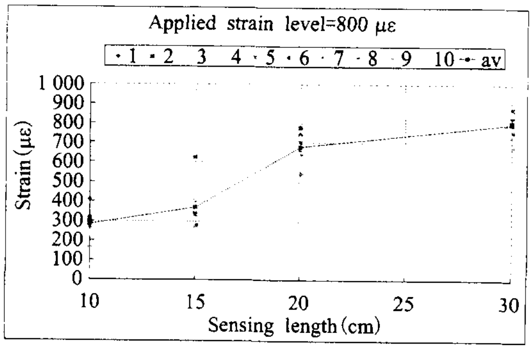


Fig. 9 Sensing behavior of optical fiber (type 2)

According to Fig. 9, if the sensing length of optical fiber type 2 is longer than 0.3 m, the measurement of BOTDA is correct. Thus, the CESL of optical fiber type 2 can be considered as 0.3 m.

3.3.2 *FOS Type* 3

The cross section of FOS type 3 is illustrated as Fig. 10. The experimental results of FOS type 3 in the same experiment are shown in Fig. 11

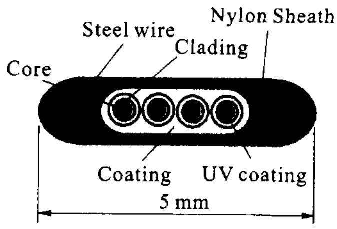


Fig. 10 FOS type 3

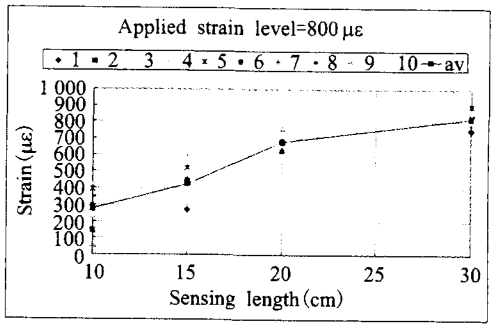


Fig. 11 Sensing behavior of optical fiber (type 3)

According to Fig. 11, if sensing length of optical fiber type 3 is longer than 0.3 m, the measurement of BOTDA is correct. Thus, the CESL of optical fiber type 2 is also equal to 0.3 m.

3.3.3 *FOS Type* 4

The cross section of FOS type 3 is illustrated as Fig. 12. The experimental results of FOS type 3 in the same experiment are shown in Fig. 13.

According to Fig. 13, if the sensing length of optical fiber type 4 is longer than 0.2 m, the measurement of BOTDA is correct. Thus, the CESL of optical fiber type 4 can be considered as 0.2 m

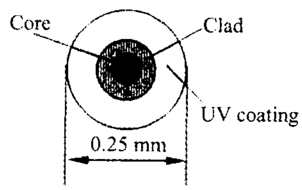


Fig. 12 FOS type 4

Based on the aforementioned discussion, it can be safely concluded that different types of FOS have different CESLs. The longer the CESL is, the worse the degree of anti-slippage of FOS becomes.

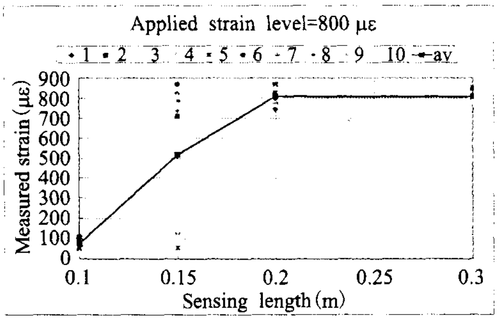


Fig. 13 Sensing behavior of optical fiber (type 4)

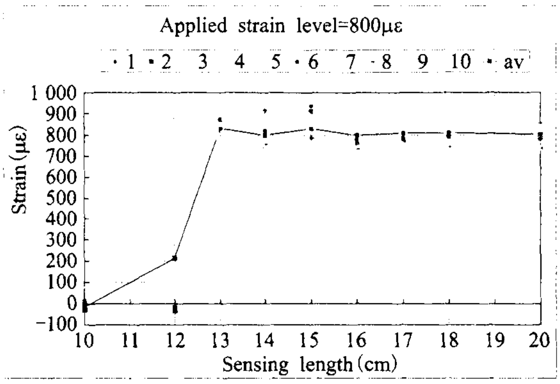


Fig. 14 Sensing behavior of bare fiber

3.4 *Measurement Behavior of Bare Optical Fiber*

To completely prevent slippage of FOS, the UV coating of FOS type 4 is peeled and bare optic fiber is used directly to carry out the same experiment. The experimental results are illustrated in Fig. 14.

From the experimental results as depicted graphically in Fig. 14, it can be concluded that if the sensing length of bare FOS is longer than 0.13 m, BOTDA can give the correct measurement. Thus, the CESL of bare optical fiber can be considered as 0.13 m. The reason why the measurement is exceptionally undervalued when the sensing length is just 0.1 m can be explained. During measurement, the minimum sampling interval is 0.05 m; thus, there is a gap between the sampling point and the starting point of sensing fiber, the length of gap is considered to be from 0 to 5 cm. Because of the existence of this gap, the 0.1 m uniform strain distribution is hardly considered within a certain sampling point measurement by the PPP-BOTDA with a 0.1 m spatial resolution. Thus, in this experiment, only if the sensing length of bare FOSs is longer than 0.13 m can the measured value of PPP-BOTDA be equal to the value of strain gauge.

4 Development of No-slip FOS

Based on the aforementioned discussion, it can be noted that the slippage between the bare fiber and coating materials of FOS can cause large measurement errors in the measured value, and especially for distributed measurements, the occurrence of slippage in the interior of FOS result in the strain distribution of FOSs different with the real strain distribution of host structure. Although the bare fiber is verified such that it can be used directly to bond with the host structure with no-slip way. However, due to the fragility of bare fiber whose coat has been removed from commercial optical fiber, the brittle bare fiber should be protected from damage from harsh environments. Therefore, it is critical to develop one type of packaged no-slip FOSs. A packaging design for the practical adaptation of no-slip FOSs in civil structural health monitoring is illustrated in Fig. 15.

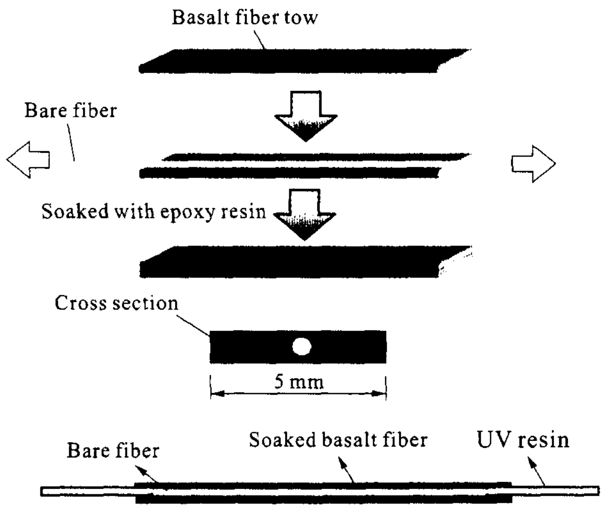


Fig. 15 The packaged method

The developed FOS was adhered with the same tensile steel specimen and underwent the same experimental procedure. Nine different sensing lengths (0.11 ~ 0.18 m and 0.2 m) were set in series. Under a loading level of 800 $\mu\varepsilon$, the 10 times measurement strain values of packaged FOS in different sensing length are shown in Fig. 16.

From the experimental results as illustrated graphically in Fig. 16, it can be concluded that if the sensing length of newly developed FOS is longer than 0.14 m, BOTDA can give the correct measurement. The CESL of optical fiber type 4 can be considered as 0.14 m.

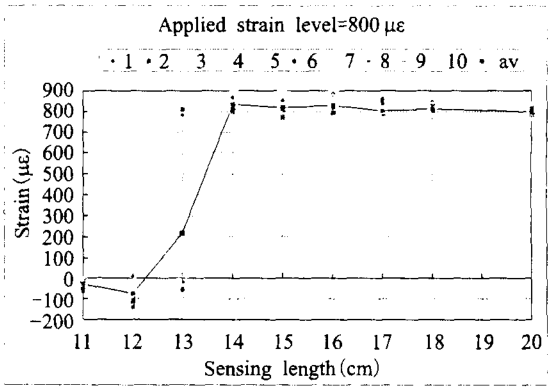


Fig. 16 Sensing behavior of developed FOS

Obviously, the CESL of newly developed FOS is longer than CESL of bare fiber (13 cm). When the sensing length of newly developed FOS adopts 13 cm, in 10 experiments, there are three correct measurements. The reason for this result is not far-fetched. After packaging, the bare fiber is protected and reinforced with basalt fiber. In case of bonding with the structure, the strain distribution of newly developed FOSs should be similar as Fig. 17.

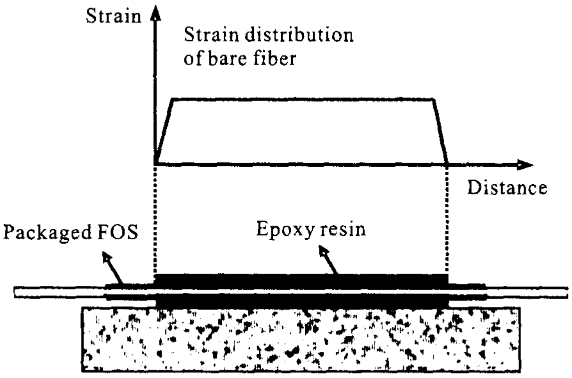


Fig. 17 Strain distribution of packaged FOS

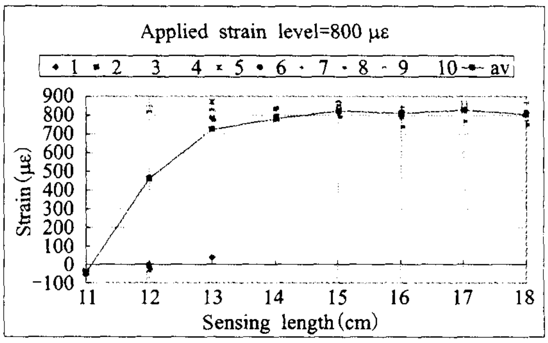


Fig. 18 Sensing result of thinner developed FOS

The strain of host structure is firstly transferred to the reinforced basalt fiber, and the strain distribution of bare fiber comes from the basalt fiber. Therefore, a specific length is necessary to ensure that the strain of host structure can be transferred to the bare fiber completely, and this specific length can be considered as strain transferred length (STL), which results in the increase of CESL. In order to prove this assumption, we adopt another thinner basalt fiber tow whose width is about 1/3 of the former to package the bare fiber in the same method. The measured results of the thinner packaged FOS are illustrated in Fig. 18.

When the sensing length of the thinner packaged FOS adopts 13 cm, in 10 experiments, there are nine correct measurements. According to Fig. 16 and Fig. 18, it seems that the STL is necessary for transferring strain completely; in addition, the bigger stiffness of packaged material may cause the increase in STL.

From what has been discussed above, the developed FOS is preliminarily verified such that it can be used as a type of no-slip FOS, and the packaged method proposed in this paper is simple and effective. However, there is still something to be desired, such that in future investigations, the packaged method will be improved and verified ulteriorly.

5 Conclusions

(1) Based on the experimental result of bare fiber, the PPP-BOTDA sensing technique has the ability of 10 cm-order spatial resolution.

(2) Despite possessing the 10 cm order spatial resolution, because of the slippage between bare fiber and coating materials of optic fiber. If the gauge length of FOS is less than CESL, the measurement result of BOTDA may still not be correct.

(3) Different types of FOS have different CESL; the longer the CESL, the worse the anti-slippage property.

(4) The newly developed FOS can be used as a type of no-slip FOS.

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