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Theoretical and experimental study on strain transfer of distributed optical fiber sensor

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ABSTRACT

Distributed optical fiber sensor(DOFS) is widely used because of its high resolution and high precision. However, due to strain transfer, the strain measured by the sensor is different from the actual strain. Therefore, strain transfer was analyzed on terms of theory in this paper. Then, sensors with different bonding methods were used for test to verify the reliability of the theoretical analysis. The results demonstrate that with the increase of adhesive thickness, the average strain transfer rate decreases. And the strain transfer rate increases with increasing shear modulus of adhesive. The test results are almost consistent with the theoretical analysis.

Keywords: DOFS; strain transfer; adhesive

1. INTRODUCTION

With the development of building technology, a number of projects vital to social economy have been completed and put into operation. The failure of key structures in these buildings will cause significant loss of life and property. Structural health monitoring has already become an important conception in the discipline of civil engineering currently for its ability of locating structural damage and evaluating the safety of structure (Xie 2001). Health monitoring refers to the use of in-situ, nondestructive sensing and analysis of structural characteristics, including the structural response, for the purpose of detecting changes that may indicate damage or degradation (Housner 1997). Structural health monitoring is a real-time online monitoring technology, including sensor system, data acquisition and transmission system, damage identification and safety evaluation system, data processing system (Hui 2006). Identifying the health condition of constructions must be based on the measurement of sensors which were adhered to or embedded in the host structure. Therefore, what kind of sensors to choose is crucial to structural health monitoring.

In compared with other kinds of sensors, fiber optic sensors, with advantages of immunity to electromagnetic inference, high accuracy, reliability, long-distance

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transmission (Ren 2007) and immunity to corrosion (Nanni 1991), are particularly attractive for using in hostile conditions. Now, optic-sensor technology is widely used in structural health monitoring of bridges, offshore platforms (Ren 2008) and other constructions. Because of the incertitude of the construction site, optical fibers are easily to be destroyed. So optical fiber used in applications must be protected by various configurations, such as adhering to structure (Li 2004), embedding in structure (Sun 2005), packaging by steel tube (Yang 2004). No matter what kind of fiber optic sensors, there is strain transfer loss between host structure and them. In order to measure the true strain of the structure accurately, the strain transfer mechanism should be taken into consideration.

The shear-lag theory developed by Cox (1952) provides theoretic foundation for research of optical fiber strain transfer. Nanni (1991) firstly proposed the existence of strain transfer rate between fiber optic sensors and concrete structure by experiment. Pak (1999) studied the strain transfer to, and the strain and stress concentrations caused by, an optical fiber embedded in a homogeneous matrix that is subjected to a far-field longitudinal shear load. Ansari (1998) analyzed strain transfer model of optical fiber sensors, developed the equation which provide a quantitative calculation for engineering application. Li (2005) summarized research results and established a complete theoretical system of optical fiber strain transfer. Li (2009) proposed strain transmission equation takes the influences caused by the stiffness of substrate and FBG as well as the bonding layer characteristics, i.e. the length, thickness and shear lag parameter into consideration and validated respectively by numerical simulations using finite element method and experiments. Guo (2011) developed a model to study the strain transfer coefficient to gain the rate of strain transfer and analyzed influential factors.

At present, the objective of fiber strain transfer theory researches are mostly devoted on the optic fiber Bragg grating sensor, whereas the material of distributed fiber is the same as the bare optic fiber Bragg grating sensor, so the theory of fiber grating strain transfer is also applicable to distributed fiber. On the basis of strain transfer theoretical derivation of surface-adhered FBG deduced by Guo (2011). This paper deduces the equation of the average strain transfer rate, proposes a new method with distributed optic fiber based on OFDR technique to test the impact caused by the thickness and the shear modulus of the adhesive layer, the bonded length of the optic fiber.

2 STRAIN TRANSFER RATE EQUATION ANALISIS OF OPTICAL FIBER SENSORS

Generally bare optical fiber consists of glass core and cladding, both of which are composed of silicon dioxide. The diameter of glass core is from 5 to 50 μm and cladding's diameter is 125 μm. The glass core and cladding can be seen as a concentric cylinder. When the optical fiber is pasted on the surface of the structure, there is an adhesive layer between optical fiber and the host structure. The strain of the host material is transferred to bare fiber through the adhesive layer. The strain transfer mechanism of pasted optic fiber sensor is shown in Fig.1

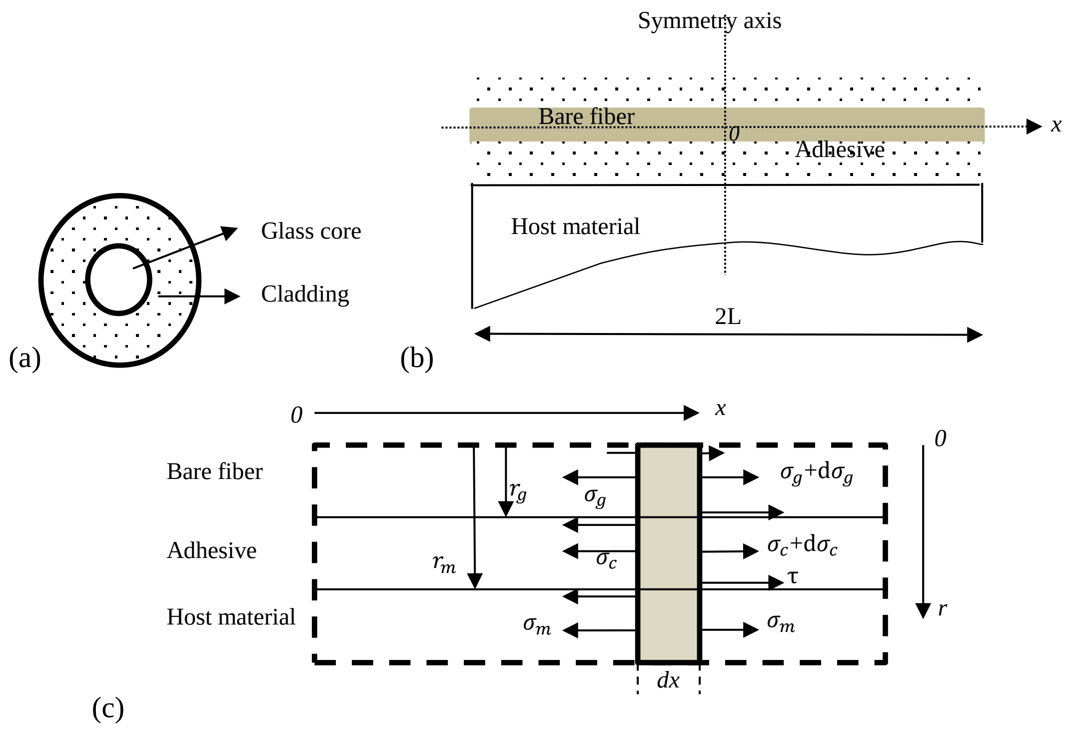


Fig.1 Coordinate system and free body diagram of longitudinal section of optical fiber; (a) Cross section of optical fiber; (b) Optical fiber attached on the host material; (c) Stress distribution of fiber and adhesive layer.

where σ is the normal stress of the study object, τ is the shear stress between two layers. Subscript g, c, m represents optical fiber, adhesive and host material respectively. r is the radius.

The optical fiber sensor is adhered to the surface of the structure by adhesive. There is strain loss in the transferring course from the host material to the bare fiber. The average strain transfer rate is defined as the ratio of the measured strain to the actual strain of the host material. In order to improve the measurement accuracy, the strain transfer rate should be taken into consideration.

Guo (2011) proposed a strain transfer model of a pasted optical fiber sensor under the following assumption:

1. All the materials are linear elasticity. The host material is only subjected to uniform tension along the axis of the fiber, transfer strain to the optical fiber through the adhesive. The optical fiber is only subjected to the stress along its pasting direction.
2. Optical fiber includes the fiber core and cladding. It is considered that the mechanical properties of them are approximately equal.
3. The bare fiber and the adhesive, the adhesive and the host material are bonded well. There is no de-bonding between them.
4. Pasting optical fiber sensor has no influence on the host material.

The strain transfer rate along the pasted optical fiber is:

$$\alpha(x)=\frac{\varepsilon_g(x)}{\varepsilon_m}=1-\frac{\cosh(kx)}{\cosh(kL)} \quad , \tag{1}$$

And the average strain transfer rate of the pasted optical fiber in this paper is:

$$\bar{\alpha}=\frac{\overline{\varepsilon_g(x)}}{\varepsilon_m}=\frac{2\int_0^L \varepsilon_g(x)dx}{2L\varepsilon_m}=1-\frac{\sinh(kL)}{(kL)\cosh(kL)} \quad , \tag{2}$$

where L is the half length of the optical fiber pasted on the host material ; ε is strain; k is a coefficient that determined by the mechanical properties of the adhesive layer and optical fiber given by the equation:

$$k^2=\frac{DG_C}{\pi r_g^2 E_g(r_m-r_g)} \quad , \tag{3}$$

where D is the width of adhesive layer; G_c is the shear modulus of the adhesive; r_g is the external radius of the fiber; E_g is the Young's modulus of the optic fiber; r_m is the external radius of the adhesive layer.

According to the equation (2) and (3), the parameters which influence the strain transfer are the bonded optical fiber length L, the adhesive layer is width D, the adhesive is shear modulus G_c, and the thickness of the adhesive layer $(r_m - r_g)$.

3 THE EXPERIMENTAL ANALISIS OF INFLUENCING FACTORS

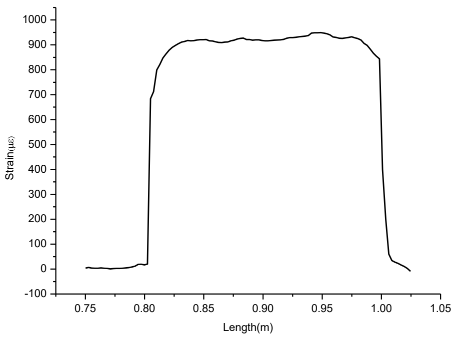
From the equation (2) and (3), it can be inferred that strain transfer rate is negatively correlated with thickness and positively correlated with the increase of the shear modulus of the adhesive, the width of the adhesive layer and the length of pasted optic fiber. Based on the results given in reference (Zhang 2013), the average strain transfer rate does not change significantly with the width of adhesive layer from 0.2cm to 1.2cm which agrees with the actual engineering situation. Thus only the left two influence parameters will be discussed in this paper.

3.1. The influence of the thickness of adhesive layer

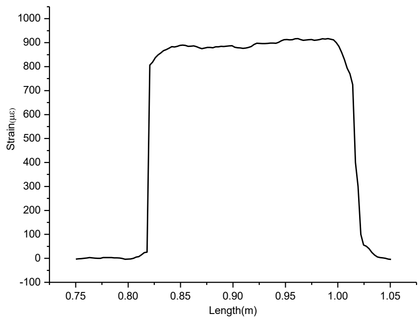
In application, epoxide resin is used as the adhesive material. In the following tests, the ratio of E-44 epoxy resin to polyamide resin was 1:1. As shown in Fig.5, the length of the test segment is 20cm. Making sure that the steel plate was polished by sandpaper and cleaned up before bonding the optic fiber sensor. At first, masking tape was attached on the surface of the steel plate to form a rectangular area (20cm × 1cm). Then the optical fiber sensor was placed in the center of this area. In the end, adhesive layer was filled in with different thickness of 0.5mm, 1.5mm, 2.5mm and 3.0mm respectively.

Fig.5 Steel plate used in the tests of thickness

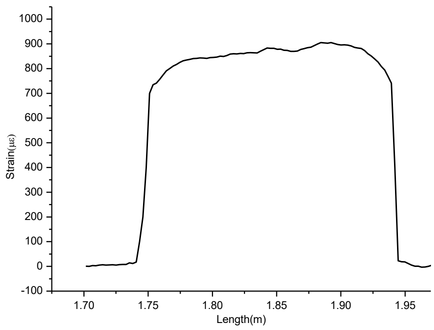
Comparing the results shown in the figure above, it can be seen that the average strain decreases as the thickness of adhesive layer increases which agrees with the theoretical strain transfer rules, and the comparison of the experimental value and the theoretical value of the average strain transfer rate is shown in the Table 2 and Fig. 7. The unevenness of adhesive layer causes the unsmooth performance of the curve in Fig.6.



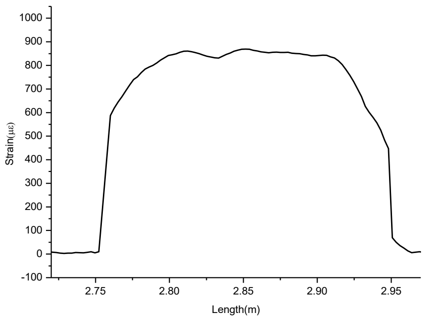
(a) Strain distribution with 0.5mm adhesive layer thickness



(b) Strain distribution with 1.5mm adhesive layer thickness



(c) Strain distribution with 2.5mm adhesive layer thickness



(d) Strain distribution with 3mm adhesive layer thickness

Fig.6 Strain distribution of different adhesive layer thickness

Table 2 Comparison of the theoretical and the experimental transfer

$r_m - r_g$ (mm)	Theoretical strain transfer rate	Experimental strain transfer rate
0.5	0.977462095	0.954506908
1.5	0.96096401	0.928338879

2.5	0.947474287	0.896863472
3.0	0.942457863	0.831102592

3.2. The influence of the shear modulus of adhesive

The ingredient change of the epoxide resin will alter the properties of the adhesive, such as shear modulus. As shown in Fig.7, two segments of one fiber, with sensing length of 20cm each, were bonded to the surface of the steel plate along the axis direction. Segment 1 was bonded by the adhesive material with ratio of E-44 epoxide resin to polyamide resin being 1:1. The ratio of adhesive material used to bond segment 2 was 2:1 and shear modulus is larger than the former one. Tensile test of this steel plate was also carried out on a universal testing machine according to the proposed load programs.

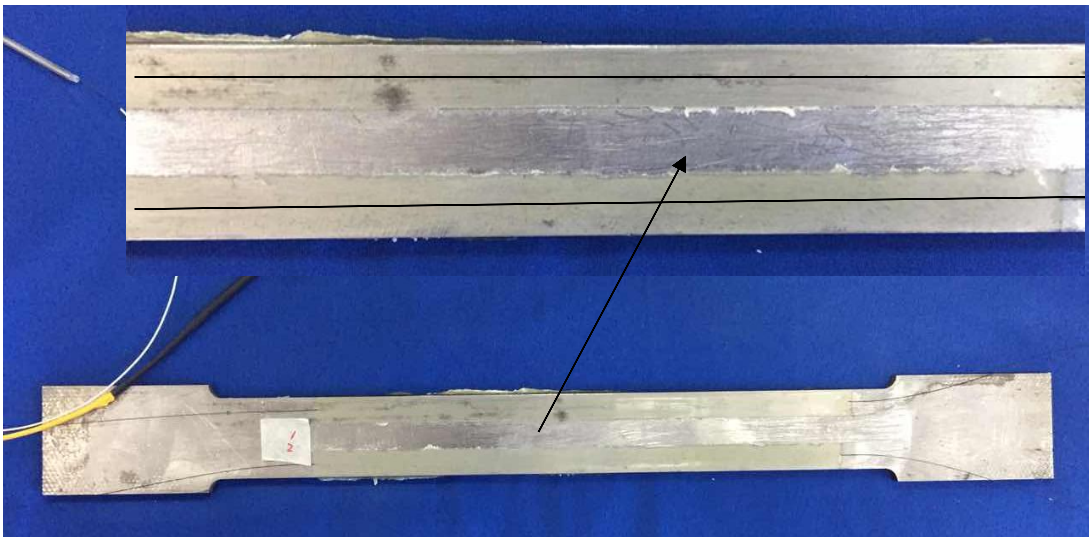


Fig.7 Steel plate used for the test of different shear modulus of adhesive

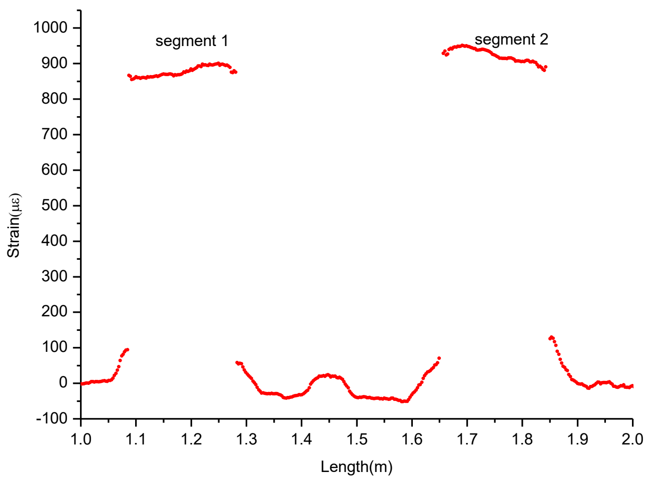


Fig. 8 Strain distribution of different shear modulus of adhesive

Considering that it is difficult to determine the shear modulus of adhesive material accurately, the shear modulus is the only variable in this test. It is illustrated in Figure 8 that with the increase of the shear modulus of the adhesive material the average strain transfer rate increases. Different ratio will affect the colloidal solidification time, viscosity, strength, durability and other properties of the adhesive itself. In practical applications, increase the proportion of epoxy resin as possible.

4 CONCLUSIONS

Application of Optical Fiber Sensor in monitoring is more and more widely spread. It is necessary to study the effect of strain transfer rate, based on which the packaging method of optic fiber sensors could be further improved The OFDR-based distributed strain measurement provided a superior way for the experimental research. Theoretical and experimental results are analyzed. The results show that the thickness of the adhesive layer has a great influence on transmission rate, with the increase of adhesive thickness, the average strain transfer rate decreases. The strain loss becomes less if the sensing part of the fiber is lengthened. The strain transfer rate rises with the increase of shear modulus of adhesive. The results of the tests are almost consistent with the values deduced by the equations. In the actual installation of sensors, the adhesive layer thickness should be minimized to make the measured strain more accurate. It is recommended that the sensing length of the surface-attached fiber-sensors should be more than 7cm. Also the increase of the adhesive shear modulus would lead to better measurement results.

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