TELKOMNIKA, Vol.12, No.3, September 2014, pp. 589~596
ISSN: 1693-6930, accredited A by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v12i3.107

Strain Transfer and Test Research of Stick-up Fiber Bragg Grating Sensors

Wang Bing*[1], Wang Xiaoli[2]
Huaihai Institute Of Technology, Lianyungang, China
Mechanical Engineering School
*Corresponding author, e-mail: hrbwb2001@163.com, wangxiaoli-dream@163.com

Abstract

Because of the flaws of fiber Bragg grating, needs to set up protective layer between the structure and fiber layer to protect the fiber grating. Firstly the strain transferring rules of the FBG sensors is analyzed, carefully analyze the main factors influencing the fiber Bragg grating strain sensor transfer, and analyze concretely effect of each factor, the fiber Bragg grating sensors embedded angle deviation is analyzed and influence on the measured results. Finally, by a series of repeated, coherent, dynamic and fatigue characteristic test, it is proved that the FBG sensor has applied value.

Keywords: *fiber Bragg grating sensors, strain transfer, angle deviation*

1. Introduction

To optical fiber Bragg grating optical fiber grating sensor, its advantage is that: the measuring signals from the optical fiber bending loss, loss of connection, the influence of light source fluctuation and detector aging factors, to avoid the phase measuring interferometer fuzzy problems of fiber optic sensor; In more than series on a single fiber Bragg grating, the fiber optic embedded stick (or to) structure to be tested, can be obtained at the same time, several measuring target's information, and can realize quasi distributed measurement, for example through real-time measurement of stress, temperature, vibration and other sensor information [1].

Interface transmission characteristics of optical fiber sensor haves attracted attention, and some useful results are obtained. Sensor with optical fiber coating layer is presented [5], the matrix structure, the matrix structure to the stress of the fiber optic sensor transitive relation. Analysis of the elastic modulus and thickness of coating layer's influence on the stress transfer and stress (concentration). Explores the cladding [6], the characteristics of optical fiber sensors embedded concrete and its importance, and in view of the outside load parallel to the fiber direction applied to concrete members, the cladding of fiber optic sensor material properties and thickness of concrete internal stress concentration characteristics of some research are made. Fiber optic sensor test strain and concrete strain relationships was roughly got [7],also gives the corresponding optical fiber sensing mechanics model was given [8], but not considering the influence of the paste layer thickness, packaging materials, not easy to analyze issues of optical fiber sensor encapsulation, setting process. The optical fiber sensing model considered the influence of paste layer, but did not consider longer fiber affect the geometric properties of substrate material [9]. It did not discuss based on the practical application of grating, also can't solve effects such as protective layer, encapsulation, adhesives, etc. Under the condition of material and middle layers in the elastic stage [10], give improvement of the transmission formula of strain [11], get more accurate optical fiber strain sensor transfer formula.

2. Strain transfer analysis

2.1 Strain transfer analysis of fiber Bragg grating sensors

The basic assumptions are studied: 1) all materials (including the fiber core, the structure of the coating layer and substrate) are linear elastic material, interface combined with perfect no relative slip. 2) Ignoring the differences between the material properties of the optical fiber core and fiber core cover, the fiber core can be seen as a kind of glass fiber which is

Received March 5, 2014; Revised May 26, 2014; Accepted June 15, 2014

composed of a single material. 3) Coating layer composed of a polymer only endure shear stress. 4) Matrix structure endure axial normal stress, parallel to the optical fiber coating layer and the optical fiber is not direct force. 5) In the midpoint of optical fiber sensor, suppose optical fiber, coating layer and substrate structure at the same strain [12].

The optical fibers first used by fiber Bragg grating sensor and ordinary communication optical fiber basic same, all are composed by the fiber core, the cladding and coating layers form the right total internal reflection condition limit light in the fiber core, the waveguide optical fiber for light transfer its decisive role [13].

$$\frac{d\sigma_g}{dx} = -\frac{2\tau(x, r_g)}{r_g} \quad (1)$$

On the middle tier take out the period and analyze:

$$\tau(x,r) = \frac{r_g}{r}\tau_g(x, r_g) - \frac{r^2 - r_g^2}{2r}\frac{d\sigma_c}{dx} \quad (2)$$

Put equation (2) into (1),

$$\tau(x,r) = -\frac{r_g^2}{2r}\frac{d\sigma_g}{dx} - \frac{r^2 - r_g^2}{2r}\frac{d\sigma_p}{dx} \quad (3)$$

Because fiber radial deformation is small, the Poisson effect can be ignored (assuming sum of the circumferential and radial stress is zero), then

$$\tau(x,r) = -\frac{r_g^2}{2r}E_g\frac{d\varepsilon_g}{dx} - \frac{r^2 - r_g^2}{2r}E_c\frac{d\varepsilon_c}{dx} = -\frac{E_g r_g^2}{2r}\left(\frac{d\varepsilon_g}{dx} - \frac{r^2 - r_g^2}{r_g^2}\frac{E_c}{E_g}\frac{d\varepsilon_c}{dx}\right) \quad (4)$$

Due to the optical fiber and the middle tier deform together, the strain changing rate is similar [14]

$$\frac{d\varepsilon_g}{dx} \cong \frac{d\varepsilon_c}{dx} \quad (5)$$

And due to elastic modulus of the optical and middle layer is large difference (about more than ten times), so

$$k^2 = \frac{2G_c}{r_g^2 E_g \ln(\frac{r_m}{r_g})} = \frac{1}{(1+\mu)\frac{E_g}{E_c}r_g^2\ln(\frac{r_m}{r_g})} \quad (6)$$

while $G_c = E_c/[2(1+\mu)]$, is shear modulus of middle layer

$$k_m^2 = \frac{2}{r_g^2 E_g\{\sum_{i=2}^{n}\frac{1}{G_i}\ln(\frac{r_i}{r_{i-1}}) + \frac{1}{G_c}\ln(\frac{r_1}{r_g})\}} \quad (7)$$

while, k_m is parameter which is decided by thickness of adhesive layer and shear modulus.

2.2 Analysis of influence parameters

Factor affecting the fiber grating sensors average strain transfer rate mainly include the length of the fiber grating sensors *L*, the thickness of the interlayer ($r = r_m - r_g$), elastic modulus of interlayer and Poisson's ratio of interlayer.

Table1. Mechanical properties of the optical fiber

Material parameter	Symbol	Number range	Unit
Elastic modulus of optical fiber	E_g	7.2*10^{10}	Pa
Elastic modulus of middle tier	E_c	3-5*10^9	Pa
poisson's ratio the middle tie	μ	0.25-0.35	--
Outer diameter of middle tier	r_m	400	μm
Outer diameter of optical fiber	r_g	62.5	μm
Sensor length	L	20-50	*mm*

2.2.1 Effect of elastic modulus of interlayer

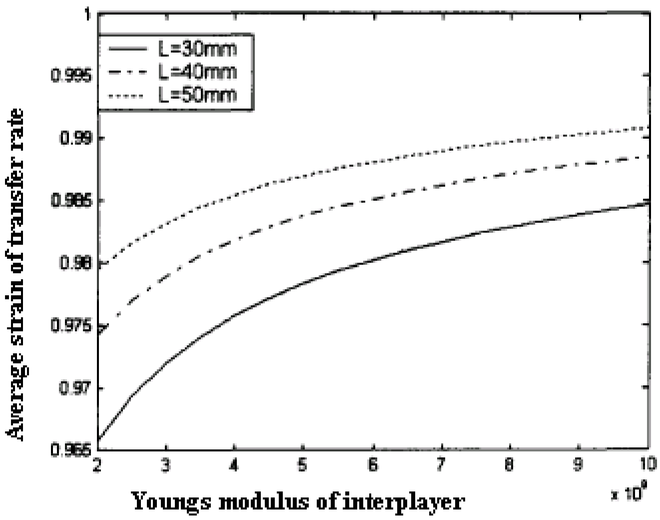

Figure 1. The average strain transfer rate distribution along Young's modulus of interlayer

Figure1 shows when the middle thickness is 0.2 mm and Poisson's ratio of the interlayer is 0.31, elastic modulus of the middle layer influence on the average strain transfer rate, L refers to the length of the sensor. The greater the middle tier of the modulus of elasticity, the greater the average strain transfer rate, the stronger section combine, the more abundant the stress transfer. In the range of modulus of elasticity on middle tier, elasticity modulus of the average strain transfer rate has a great influence. In practical engineering applications, can appropriate adjust the proportion of epoxy resin components; make the elastic modulus of middle tier as large as possible. The longer the sensor, the smaller of the average strain transfer rate on middle tier to elastic modulus, the average strain transfer rate variation amplitude is reduced. At the same time, the average strain transfer rate increases with the increase of elastic modulus with the middle tier. Envisioned when the modulus of elasticity middle layer reaches low-carbon steel modulus of elasticity, even if the layer thickness is 6 mm when the average strain transfer rate can reach 0.99718, the strain is less than 0.3% loss, which indicates that strain steel encapsulated FBG sensor measurement error less than 3%, the accuracy of measurement in the experimental research is able to meet the requirements.

2.2.2 Effect of interlayer thickness

To paste the light grating sensor firmly and structure to be tested, need to have a certain thickness of the paste layer. If the paste layer is too thin, when structure deform, it is easy to fall off the sensor, deformation of the fiber Bragg grating sensor and matrix structure is inconsistent to make the sensor failure; On the contrary, if the middle paste layer is too thick, make the strain transfer coefficient is too small, especially in dynamic measurement also might cause strain lag, make produce very big error measurement results. And cross section stress concentration near the embedded sensor depends largely on the package layer thickness and material properties, the smaller the cladding diameter, the smaller the stress and strain concentration.

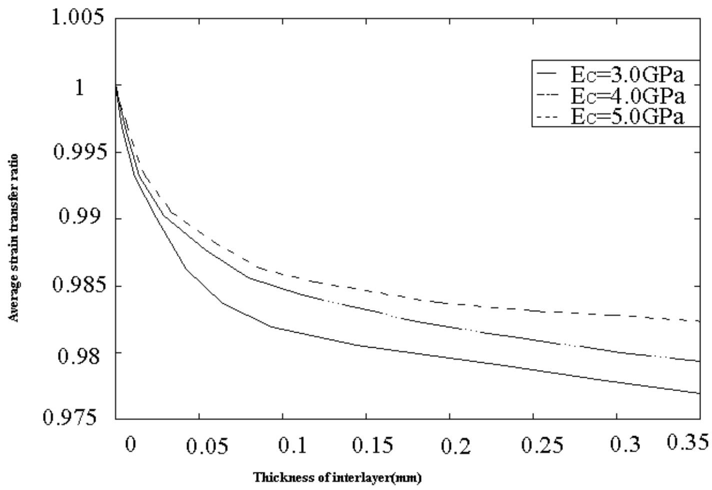

Figure 2. The average strain transfer rate distributions along the thickness of interlayer

Figure 2 shows when the length is 0.2 mm and Poisson's ratio of the interlayer is 0.31, the average strain transfer rate changes along with the change of thickness of interlayer. E_c is elastic modulus of interlayer, In general the average strain transfer rate decreases with the increase of thickness of interlayer, and its changing rate gradually decreases, the effect of strain transfer coefficient is more and more small by the thickness of inter layer; At the same time, with the elastic modulus of interlayer increases, the average strain transfer rate increases, the changing amplitude of average strain transfer rate decreases. The smaller the thickness of interlayer, the smaller effect of elastic modulus of interlayer on the average strain transfer rate.

2.2.3 Effect of interlayer Poisson

Structure mainly passed strain to fiber Bragg grating sensor through the interlayer shear deformation. Middle layer shear modulus can reflect through the Poisson's ratios of interlayer.

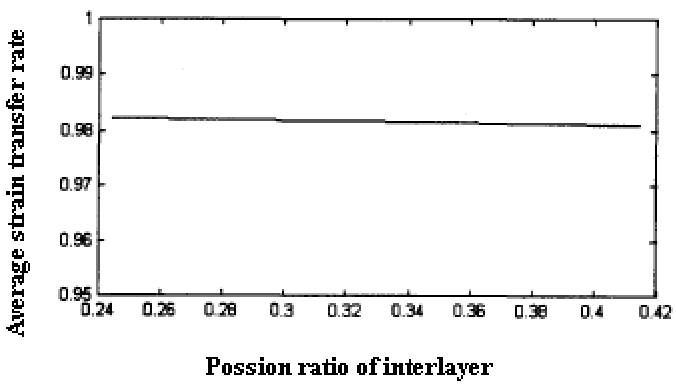

Figure 3. The average strain transfer rate distribution along the Poisson ratio of interlayer

Adopting interlayer thickness r=0.2mm, Elastic modulus of interlayer $E_c = 4GPa$, length of fiber Bragg grating sensor is 40mm, Figure 3 shows the average strain sensing rate decreases with Poisson's ratio of interlayer increase, which becomes a linear change. But from the average strain transfer rate value, the influence of Poisson's ratio of the interlayer on the average strain transfer rate is very small. Due to the Poisson's ratio of interlayer materials range is not big, so can be ignored.

Considering the parameters influencing the average strain transfer rate, the thickness of interlayer dominate, the smaller the thickness of interlayer, the greater the average strain transfer rate, the influence of other parameters on the average strain transfer rate also correspondingly reduced, the influence of the elasticity modulus of interlayer is small, the average strain transfer rate increases with the interlayer elastic modulus increasing, when the elastic modulus of interlayer reaches elastic modulus of low-carbon iron, strain transfer ratio is close to 1, it is feasible by steel pipe directly encapsulated FBG sensor; The Poisson's ratio on the average strain transfer rate is not obvious.

3. The strain transfer analysis of fiber Bragg grating sensor under non-axial force

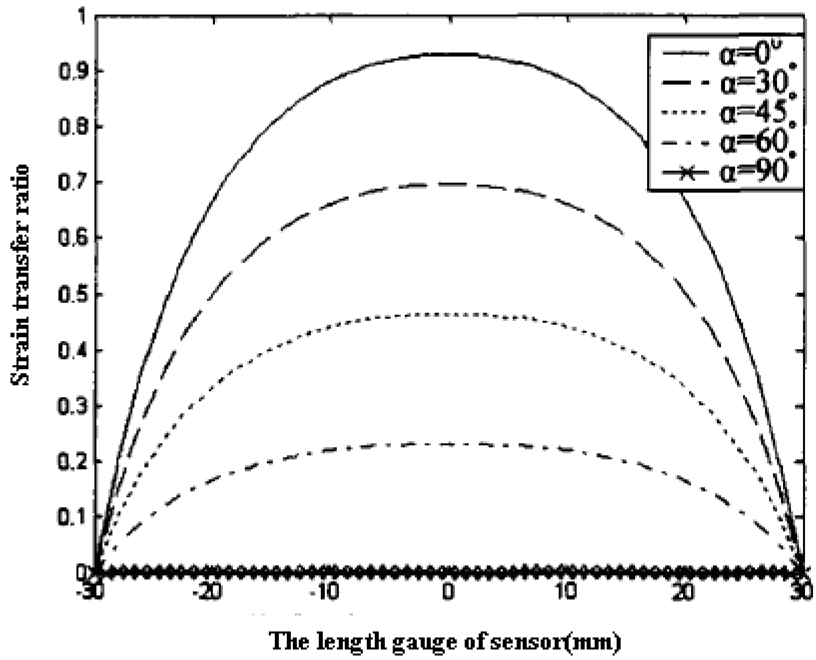

Figure 4. Distribution of normal strain transfer rate in fiber along the length with different angle

As can be seen from Figure 4, under the angle of each sensor, strain transfer ratio is biggest in the center of the sensor on both sides to reduce gradually, and the more close to the end, the greater the rate of strain transfer rate. α refers to the degree between the basic structure of the principal stress and the fiber grating sensors (unit, degree).

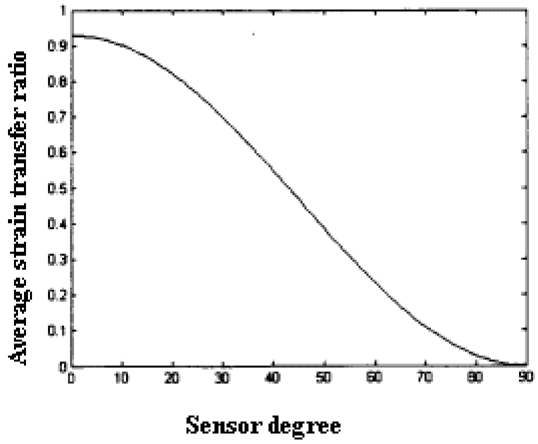

Figure 5. The average strain transfer rate distribution along the angle of fiber Bragg sensor

As can be seen from Figure 5, fiber grating sensors, the smaller of the angle between the principal stress axis and matrix, the greater the average strain transfer rate. With the angle increases, the average strain transfer rate decreases, the rate of change of the average strain transfer rate increased gradually. When optical fiber sensor is vertical with the matrix principal stress, the average strain transfer rate is zero, the fiber Bragg grating strain sensor can't detect structure strain.

4. Characteristic test of FBG sensor

In order to eliminate the influence of temperature, the temperature compensation of fiber grating sensor is adopted which is a hollow cylindrical structure. Temperature compensation sensor is actually a paste type strain sensor, the measured structural material paste it in the same material support, its specific structure guarantee the temperature sensor is not subject to stress, when used with the strain sensors at the same temperature field. When the temperature changes, the same wavelengths of two kinds of sensor caused by temperature change, so temperature compensation can be used.

4.1 Fatigue Test

In order to investigation of the fiber Bragg grating strain sensor and anti-fatigue properties of installation process, adopted a method of accelerated fatigue experiment research of sensor. Use figure fatigue test with temperature compensation of FBG sensor. Strain sensor position paste in the middle of the steel rule, and in the steel rule and on the corresponding FBG sensor position is high precision resistance strain gages. Steel rule fixed in the loading device, through stepping motor driven load device add, unloading. Steps by controlling the motor to control the size of the steel rule form variable, the maximum stroke is 10000 steps, each 500 steps record a wavelength data. In a test, loading and unloading cycles, a total of 10000 times, three drawn at random during the test (one month early, middle and late) data. Fatigue data displays wavelength maximum drift is 4.95 nm. Through 10000 times fatigue test, the sensor is in good condition; In different periods under the same load, the maximum load wavelength deviation is 88 PM, the largest uninstall wavelength deviation is 125 PM. Maximum wavelength deviation is respectively of 1.7% and 2.5% of full scale. Uninstall error is bigger which may be associated with the precision of the step motor drive. Illustrate that the sensors for strain measurement can meet the requirements of fatigue for a long time, and with very good repeatability.

4.2 Consistency and calibration

Adopting a standard equal strength beam as experiment device, carry through consistency testing and calibration. Bunch four different center wavelength strain sensors together, paste on the equal strength beam axis of each point, at the same time, paste a high precision resistance strain gages and adapt the resistance strain gauge measured strain values as a standard, through weight loading during the test, the wavelength demodulation with Fiber Bragg Grating demodulation instrument FBGIS (Fiber Bragg Grating Interrogation System). The wavelength of the device resolution is 1 PM, scanning range is 1285 nm - 1285 nm, sweep frequency is 50 Hz. With general optical fiber sensors adopt FC/APC jump stitches. Wavelength-strain relation curve is shown in Figure 6.

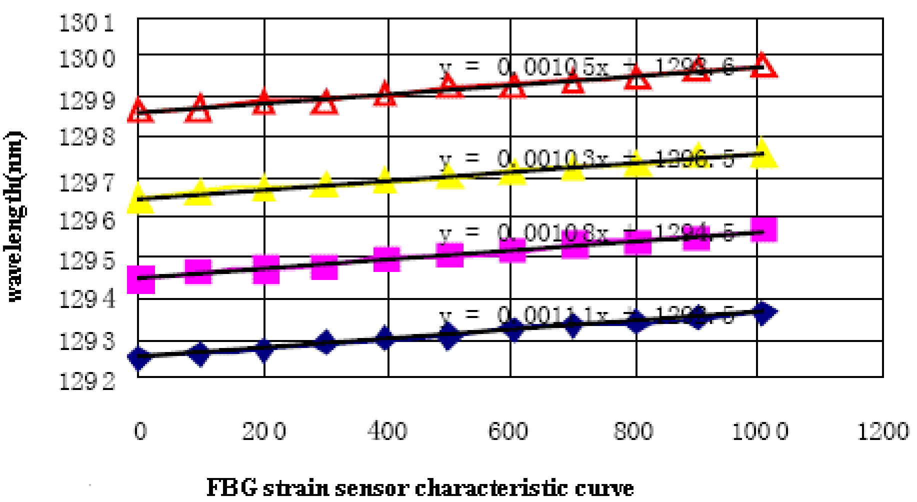

Figure 6. Fiber bragg grating strain sensor characteristic curve

According to Figure 6, the result is shown

(1) Good linearity: linear relationship by a fiber Bragg grating sensor and resistance strain gauge measurement experiment data is the fitting equation, the linear fitting is reaching more than 0.99;
(2) High sensitivity: the slope of the fitting line. respectively 1.05 PM/mu epsilon, 1.03 PM/mu epsilon, 1.08 PM/mu epsilon, 1.11 PM/mu epsilon zero, with a mean of 1.068 PM/mu epsilon, maximum error is 7.5%, basic consistent, explain four grating strain sensor consistency is good, shows that reasonable design and packaging.

5. Conclusion

Based on the common shear lag method's basic principle, adopts a series of realistic assumptions, or direct buried pipe encapsulation is established when the axial force under the action of fiber Bragg grating sensor in each point of the relationship between the strain and matrix structure of the actual strain, thus the sensor length is obtained at various points within the scope of the strain transfer ratio and overall length is within the scope of the average strain transfer rate, fiber grating sensors are also discussed and the matrix structure is the angle between the principal stress to the effects of the average strain transfer rate. And axial force under the action of strain transfer model were compared and transferred correspondingly.

Finally discussed the embedded fiber Bragg grating angular deviation for the average strain transfer rate and the impact of the measurement results, the research results show that:

(1) No matter what angle sensor in the strain transfer ratio from the sensor end to the center point increases gradually, reached the maximum in the center, make the greatest stress transfer.
(2) The bigger of the angle in the fiber Bragg grating sensor and the matrix maximum principal stress, the smaller the average strain transfer rate. With the decrease of the angle, the

average strain transfer rate increases gradually, the change of the average strain transfer rate decreases. Therefore, under the premise of the actual situation should try to reduce the fiber Bragg grating sensor in the axial and the angle between the principal stress matrix structures.

(3) When there is deviation the embedding angle sensor, strain measurement error as the embedding angle increases, the rate also increased, which under the same deviation angle, the greater the embedding angle of measurement error.

Reference

[1] Zhang Bo-ming, Leng Jin-song, Du Shan-yi. Compatibility study of optic fiber and matrix in smart composite material. *Journal of Functional Materials*. 1998; 29: 240-245.
[2] Pak YE. Longitudinal shear transfer in fiber optic sensors. *Smart materials and structures*. 1992; 1: 57-62.
[3] Betz DC., Thursby G, Culshaw B. Advnaces layout of a fiber bragg grating strain gauge rosette. *Journal of lightwave technology*. 2006; 24:1019-1026.
[4] Nanni A, Yang CC, Pan K. Fiber-optic sensor for concrete strain/stress measurement. *ACI Materials journal.* 1992; 88: 257-264.
[5] Ansari F, Yuan LB. Mechanics of bond and interface shear transfer in optical fiber sensors. *Journal of engineering mechanics.* 1998; 4: 385-394.
[6] Li QB, Li G, Wang G. Elasto-plastic bonding of embedded optical fiber sensors in concrete. *Journal of engineering mechanics*. 2002a; 128: 471-478.
[7] Li DS, Li HN. Strain transferring analysis of fiber Bragg grating sensors. *Optical engineering.* 2006b; 45:27-34.
[8] Yuan LB, Zhou L. Sensitivity coefficient evaluation of an embedded fiber-optical sensors. *Journal of engineering mechanics.* 1998; 128: 471-478.
[9] Ren L, Li HN, Zhou J. Applications of tube-packaged FBG strain sensor in vibration experiment of submarine pipeline model. *China ocean engineering.* 2006; 20:155-164.
[10] Prabhugoud M, Gill A and Peters K. *Modified transfer matrix model for Bragg grating strain sensors*. Smart structures and materials: Smart sensor technology and measurement systems, Proceedings of SPIE, SanDiego. 2004: 5384-24.
[11] Ling HY, lau KT, Cheng L. Embedded fibre Bragg grating sensors for non-uniform strain sensing in composite structures. *Measurement science and technology.* 2005; 16: 2415-2424.