The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

RESEARCH AND DEVELOPMENT OF COEFFICIENT-ADJUSTABLE FBG STRAIN SENSORS

Zhi Zhou
Harbin Institute of Technology, China

Jun He
Harbin Institute of Technology, China

Shouwang Sun
Harbin Institute of Technology, China

Jinping Ou
Dalian University of Tech., China

Abstract
The aim of Structural Health Monitoring (SHM) is to detect damage and provide safety evaluation. In order to extend the measurement range of common FBG strain sensors, a novel design method of coefficient-adjustable FBG strain sensors has been created and two types of high qualified FBG strain sensors, the slice base and cylinder base, are also developed. Theoretical analysis and experiments have been conducted, and results show that the sensors based on this design method are suitable for practical applications.

INTRODUCTION

A Structural Health Monitoring (SHM) system, whose aim is to detect damage and provide safety evaluation for infrastructures, is useful in keeping structures in service. For a specified SHM system the selection of sensor is the first important matter determined by application, sensor sensitivity, power requirements, precision, range, reliability and so on[1]. The FBG sensor is one of the most promising sensors for SHM applications [2]. However, the maximum strain bare FBG is only about $5000\mu\varepsilon$ and the sensitivity of bare FBG is $1.2\,pm/\mu\varepsilon$, which can not be adopted to detect cracks (or strain large than 10,000 $\mu\varepsilon$), or high precision deformations. In order to overcome the sensitivity problems, many ideas have been proposed. A novel FBG strain sensor with springs inside was proposed to enhance the range to $10000\mu\varepsilon$ [3,4]. Besides this, other research such as using a fiber grating housed in a glass bubble[5, 6], using the enhancing-sensitivity coated jar[7], and packaging FBG with a polymer jacket[8], have been studied to enhance the sensitivity of FBG. But the above ideas are not useful for practical applications. In this paper, a novel method of coefficient-adjustable FBG strain sensors is proposed and two types of sensors, the slice mode and the cylinder mode, have been developed. Some theoretical analysis and experiments have been carried out to test them.

STRUCTURES AND PRINCIPLE

Principle of Coefficient-Adjustable FBG Strain Sensor with Slice Mode

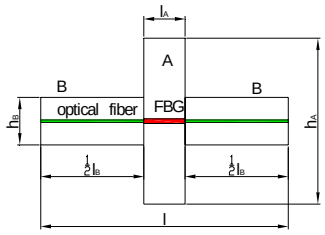


Figure 1. Sketch of coefficient-adjustable FBG strain sensor with slice mode.

When a package slice is divided into two parts with different areas but same thickness, shown as A and B, in Fig.1. When part B is under load, according to the material mechanics we can get

$$\frac{\varepsilon_A}{\varepsilon_B} = \frac{E_B S_B}{E_A S_A} \tag{1}$$

where E , S , ε is elastic modulus, area of the section and strain, respectively.

The total strain of the sensor can be expressed as

$$\varepsilon_{sensor} = \Delta l / l = (\Delta l_A + \Delta l_B)/(l_A + l_B) \tag{2}$$

Based on the geometry relationship, the practical strain of the FBG is

$$\varepsilon_{sensor} = \frac{1}{l_A + l_B}(l_A + \frac{E_A S_A}{E_B S_B} l_B)\varepsilon_A \tag{3}$$

So the adjustable coefficient can be defined as

$$K = \varepsilon_{sensor} / \varepsilon_A = (l_A / l_B + E_A S_A / E_B S_B)/(l_A / l_B + 1) \tag{4}$$

Let $K_l = l_A / l_B$, $K_E = E_A / E_B$, $K_S = S_A / S_B$, then

$$K = (K_l + K_E K_S)/(K_l + 1) \tag{5}$$

when $K > 1$, the sensitivity is decreased and vice versa. For practical projects the sensitivity decrease means we can get a large strain and a large range. On the other side, we can get high precision by the sensitivity enhancement method.

If A and B is the same material, $K_E = E_A / E_B = 1$, then

$$K = (K_l + K_S)/(K_l + 1) \tag{6}$$

If the thickness of the steel is uniform, $\delta_A = \delta_B$, then

$$K_S = S_A / S_B = h_A \delta_A /(h_B \delta_B) = h_A / h_B \tag{7}$$

And we can get:

$$K = (K_l + h_A / h_B)/(K_l + 1) \tag{8}$$

By making $K_h = h_A / h_B$, we can get

$$K = (K_l + h_A / h_B)/(K_l + 1) = (K_l + K_h)/(K_l + 1) \quad (9)$$

According to the above principle, two types of FBG sensors have been developed to meet the needs of the practical project. One is the adjustable coefficient $K > 1$ which is named the large strain sensor. The other is the adjustable coefficient $K < 1$ which is named the high-precision sensor. The details of design parameters are as follows.

Structure of the Large Strain FBG Strain Sensor with Slice Mode

In general, the biggest strain of a bare FBG works at 2000~3000 $\mu\varepsilon$, but as a large strain sensor, the biggest strain that the sensor can stand should be over $10,000\mu\varepsilon$, so we need $K = 3 \sim 4$. Based on the needs for application, we can can get $30 \le l_A + l_B \le 200$, $5 \le \max(h_a, h_b) \le 10$, $10 \le l_A \le 16$, $\min(h_a, h_b) \ge 1.5$. According to equation (9, the range of K of a large strain sensor is $1 < K \le 10.2$. Several structures and stress analysis have been designed to optimize the sensor, and the final one is shown in Fig.2. Based on these parameters, the theoretical value is $K_{st} = 3.38$. Fig.3 shows the picture of the large strain FBG strain sensor with slice mode.

Structure of the High-Precision FBG Strain Sensor with Slice Mode

The resolution of a bare FBG usually is about $1\mu\varepsilon$. But some high precision situations with small stain usually need the resolution up to $0.5\mu\varepsilon$ or smaller. According to the above theory, the adjustable coefficient K=0.5~0.625 will meet the needs. According to the application: $30 \le l_A + l_B \le 40$, $5 \le \max(h_a, h_b) \le 10$, $10 \le l_A \le 16$, $\min(h_a, h_b) \ge 1.5$, Then the range of K is $0.14 \le K < 1$.

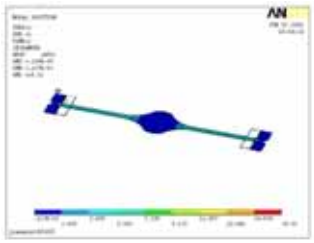


Figure 2. Finite element analysis for large strain sensor with slice mode.

Figure 3. FBG large strain strain sensor with slice mode.

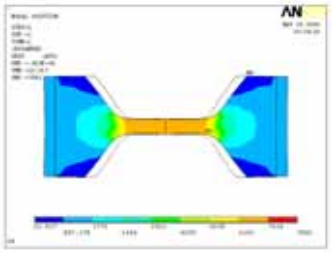


Figure 4. Finite element analysis for high-sensitivity sensor with slice mode.

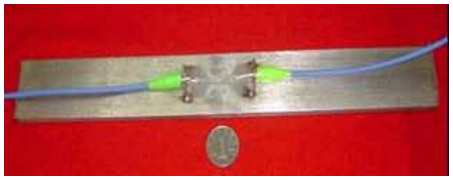


Figure 5. FBG-based high-sensitivity strain sensor with slice mode.

Principle of Coefficient-Adjustable FBG Strain Sensor with Cylinder Mode

Based on above method, the sensor with cylinder mode is developed as shown in Fig.6. Here, Fiber Reinforced Polymer(FRP) rebar with embedded FBG, named as FRP-OFBG bar, is regarded as the sensing component for this mode.

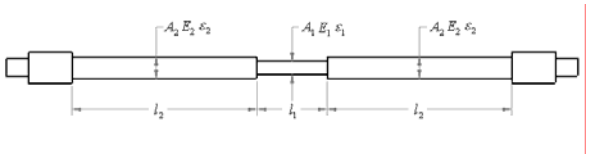


Figure 6. Sketch of coefficient-adjustable GFRP-OFBG bars.

Based on the above methods, the adjustable coefficient of the cylinder mode can be defined as:

$$K = \varepsilon_{sensor} / \varepsilon_{FBG} = (l_1 + 2l_2 A_1 / A_2) / (l_1 + 2l_2) \tag{10}$$

Let $\alpha = l_1 / l_2$, $\beta = A_1 / A_2 = d_1^2 / d_2^2$, where d_1 and d_2 are the diameters of the parts l_1, l_2 respectively, then we can get

$$K = 1 + 2(\beta - 1) / (\alpha + 2) \tag{11}$$

If $d_1 > d_2$, $K > 1$, it is named as large strain sensor. On the other, if $d_1 < d_2$, $K < 1$, it is named as high-precision sensor. According to the needs from SHM systems and manufacturing problems, some restrictions for the structure of the sensor are indicated as

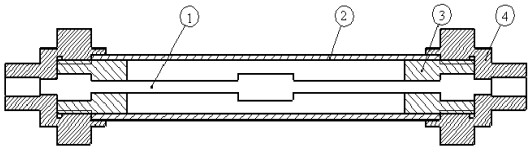
$l_{1\min} = 16\text{mm}$, $3\text{mm} \le d_1, d_2 \le 7\text{mm}$

Structure of the Long Strain FBG Strain Sensor with Cylinder Mode

From formula (11), when $K > 1$, the smaller α is, the larger β is, then the maximum K is

$$K_{\max} = (\alpha_{\min} + 2\beta_{\max}) / (\alpha_{\min} + 2) \tag{12}$$

So the range of the large strain FBG strain sensor with cylinder mode is $1 \le K \le 4.73$. According to the analysis and applications, the parameters are chosen to be $l = 114\text{mm}$, $l_1 = 30\text{mm}$, $l_2 = 42\text{mm}$, $d_1 = 5\text{mm}$, $d_2 = 3\text{mm}$. The theoretical adjustable coefficient of the large strain sensor with cylinder mode based on the upper parameters is $K_{cl} = 2.31$. The sketch of large strain strain sensor with cylinder mode is shown as Fig.7.



① GFRP-OFBG bar; ②Sleeve; ③ Anchor head inside; ④ Anchor head outside;

Figure 7. Sketch of large strain strain sensor with cylinder mode.

Structure of the High-Precision FBG Strain Sensor with Cylinder Mode

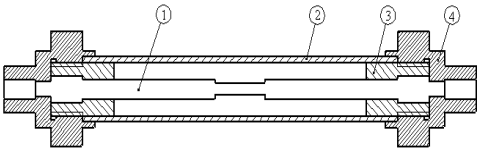
From equation (12), when $K < 1$ the smaller α is, the smaller β is, then the minimum K is

$$K_{\min} = (\alpha_{\min} + 2\beta_{\min}) / (\alpha_{\min} + 2) \tag{13}$$

So the range of the high-precision FBG strain sensor with cylinder mode is $0.31 \le K \le 1$. According to the practical

application, the parameters are chosen as $l = 100\text{mm}$, $l_1 = 16\text{mm}$, $l_2 = 42\text{mm}$, $d_1 = 3\text{mm}$, $d_2 = 5\text{mm}$.

Based on the parameters above the theoretical adjustable coefficient of the high-precision sensor with cylinder mode, we can get $K_{ch} = 0.462$. The sketch of high-precision strain sensor with cylinder mode is shown in Fig.8.



① GFRP-OFBG bar; ②Sleeve; ③ Anchor head inside; ④ Anchor head outside

Figure 8. Sketch of high-precision strain sensor with cylinder mode.

Fabrication of the Sensors with Cylinder Mode

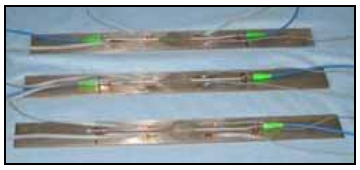
GFRP-OFBG bars are chosen as the sensing component for the coefficient-adjustable sensors with cylinder mode and its diameter is 7mm. The sensor picture is given in Fig.9.

Figure 10. Structure of coefficient-adjustable sensors with cylinder mode.

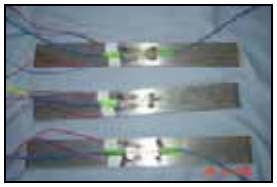
EXPERIMENT AND ANALYSIS

Experiments of Coefficient-Adjustable FBG Strain Sensor with Slice Mode

The experiments conducted on MTS are shown in Fig. 11. The reference strain is monitored using traditional strain gauge and SI425 provided by MOI is used to test the wavelength center of FBG. The strain and the wavelength center are recorded, and parts of data are shown in Fig.12.



a) Large strain sensor on the steel slice

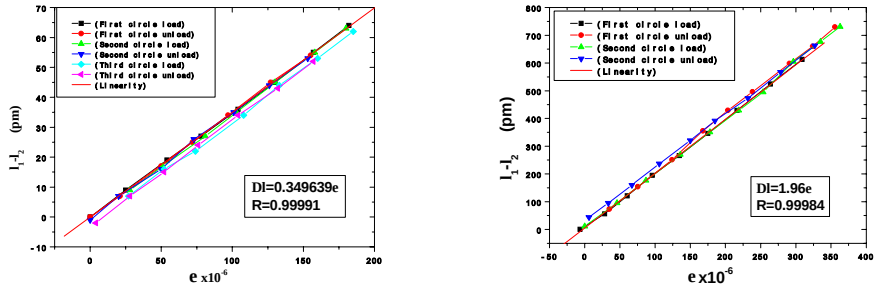


b) High-precision sensor on the steel slice

c) the experiment's photo from front

d) the experiment's photo from back

Figure 11. Sketch of preparation for trial.



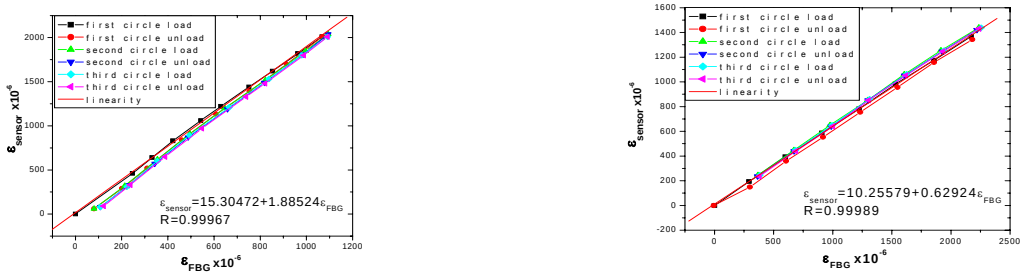
a) Large strain sensor on the steel slice b) High-precision sensor on the steel slice

Figure 12. Sensing properties of coefficient-adjustable based on slice mode.

Based on the parameters of sensor design, the coefficients of large strain sensor and high-precision sensor is 3.38 and 0.58, respectively. And the experimental coefficients of large strain and high-precision sensor is 3.43 and 0.61. From the above data, we can find the error is within 10% and it is good in linearity. The correlation coefficient is up to 0.999.

Experiments of Coefficient-Adjustable FBG Strain Sensor with Cylinder Mode

The experiment was done on MTS. The extensometer with the gauge length 50mm is used to monitor the strain of the transmutation while SI425 is used to test the center wavelength of FBG and the results of the experiments are shown in Fig.13.



a) Large strain sensor on the steel slice b) High-precision sensor on the steel slice

Figure 13. Sensing properties of coefficient-adjustable based on cylinder mode.

From the results of the experiments, the coefficient-adjustable FBG strain sensors with cylinder mode are good in linearity. The correlation coefficient is up to 0.999. The adjustable coefficient of the large strain sensor with cylinder mode from the experiments is $K_{cl}=1.89$ while one of the high-precision sensor is $K_{ch}=0.63$. And the error coefficients are $\eta_{cl}=22.2\%$ and $\eta_{ch}=26.6\%$, respectively.

Contrasts Among the Coefficient-Adjustable Sensors

According to the above data, the Comparison between theoretical and experimental results is shown in table.1.

Table 1: Comparison between theoretical and practical values

Type of sensor		Theoretical coefficient	Practical coefficient	Error (%)
slice mode	Large strain sensor	3.38	3.43	1.40%
	High-precision sensor	0.58	0.61	5.17%
cylinder mode	Large strain sensor	2.31	1.89	22.2%
	High-precision sensor	0.46	0.63	26.6%

CONCLUSIONS AND REMARKS

To meet the needs of monitoring cracks and some high-precision situations in Structure Health Monitoring (SHM), a novel method of coefficient-adjustable FBG strain sensor is proposed and two types of sensors, the slice mode and cylinder mode, have been developed. Some theoretical analysis and experiments have been conducted. The results indicate that the sensors have good linearity and resolution. The coefficient-adjustable FBG strain sensor can be used to solve the correlative problem for the civil engineering. Further research will focus on the optimization of the sensors' structure.

ACKNOWLEDGEMENTS

This paper is supported by NSFC (Granted no. 10672048, 50538020 and 50278029).

REFERENCES

1. P. Moyo et al. "Development of fiber Bragg grating sensors for monitoring civil infrastructure". Engineering Structure, 2005, 27: 1828-1834.
2. Li Hong-Nan, Li Dong-Sheng and Song Gang-Bing. "Recent applications of fiber optic sensors to health monitoring in civil engineering", Engineering Structures, 2004, 26(11): 1647-1657.
3. Zhi Zhou, Chunguang Lan, Jinping Ou, "New kind of FBG-based crack (large strain) sensor", Proceedings of SPIE , 2006,vol.6167,616714.
4. Zhi Zhou, Xuefeng zhao, et al, "Study on FBG sensor's steel capillary encapsulating technique and sensing properties", Chinese journal of lasers, 2002,vol.29, pp1089-1092.
5. Xu M G, Reekie L, Chow Y T et al. "Optical in fiber grating high pressure sensor". ElectronLett, 1993, 29(4):398~399.
6. Xu M G, Geiger H, Dakin J P. "Fiber grating pressure sensor with enhanced sensitivity using a glass bubble housing" [J]. Electronics Lett, 1996, 32(4):128~129.