Design and Implementation of FBG Three-dimensional Stress Sensor for Complicated Stress Test in Rock Strata

Shiming Wei1,2, Zesheng Zhang1* and Liqing Zhang1
1 School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China
2 Collaborative Innovation Center of Coal Safety Production of Henan, Jiaozuo 454000, China
Email: sming2002cn@163.com; Corresponding Author Email: zhang_zesheng@qq.com

Abstract. A fiber Bragg grating (FBG) sensor was presented and designed which was used to monitor the three-dimensional stress independently in rock strata. The sensing elements with FBGs in x, y, and z directions were combined in one intact material, and the stress/strain would be obtained without interference from other directions because each element could deform independently. By numerical modeling, the stress was applied respectively in different directions on the surface of the sensor, and the result revealed that the stress distributed in the direction applied was far more than other directions, which indicated that every element of the sensor was only sensitive to the stress in one direction. To get the relationship between applied stress and wavelength drifts of the FBG sensor, the calibration experiments were carried out, and the sensitivities in x, y, and z direction were obtained. It is of great significance for obtaining complicated stress state in rock strata and achieving intrinsically safe mining in coalmine.

1. Introduction
In underground coal mining, the structural elements are coal and rock strata surrounding it, while the pressure is the in-situ stress existing in the earth’s crust. Both quantities must be measured and known for dealing with coal mining ground control problems [1]. The conventional methods for in-situ stress measurement are to use electrical sensors, such as the electrical resistance strain gauge which has been widely used in many areas, but is not suited in underground mining environment due to the influence of dust, dirt, water, moisture, shock, or vibration.

In recent years, fiber Bragg grating (FBG) sensors have been studied and used widely for measurement of strain, pressure, vibration, or temperature[2-5]. Such sensors offer significant advantages such as resistance to electromagnetic interference, water resistance, small size, and so on. They have also been reported of the application of FBG sensors for measurement of temperature and strain in electrical power cables[6], oil/gas territory[7], and for structural health monitoring of large industrial and civil works such as dams[8], bridges[9], large subway areas[10] and tunnels[11].

However, in practical engineering systems, if the angle of the principal stress is unknown, or the structure of the measured object is complex, it is often required to measure combined stress such as triaxial stress rather than unidirectional stress. FBG rosette seems to be a good solution to this problem as reported, and several FBG rosette sensing systems have been used for the measurement of structure combined strain[12-18]. In these schemes, one rosette usually consists of three FBG sensors which are paved as 0°–45°–90° rectangular pattern, or 0°–60°–120° triangular pattern, and so on. For most FBG
rosette sensors, the sensing FBGs were often laid in the material altogether rather than independently, which may cause the test course of FBG be interfered with each other, and the stress/strain in each direction may not be measured exactly\cite{19-22}. But in some complicated environments, it is necessary to measure the stress/strain in x, y and z axes respectively to obtain more accurate results. Therefore, it is of importance to design a kind of FBG sensor which can test the three-dimensional stress/strain independently.

In this paper, a FBG three-dimensional stress sensor was presented and designed, and each fiber grating was laid independently in one direction. By calibration experiments, numerical modeling experiment, the in-situ stress of rock was measured, and the three-dimensional stress state was obtained.

2. Principle of FBG Sensing
The incident light in the fiber will be divided transmission and reflection light when it passes gratings. The center wavelength of the reflected light can be expressed as following \cite{23}:

$$\lambda_B = 2n_{\text{eff}} \Lambda$$

(1)

Where $\lambda_B$ is the FBG reflected center wavelength, $n_{\text{eff}}$ and $\Lambda$ are the effective refractive index and grating period of the fiber core, respectively. Interference from external environmental factors, such as strain and temperature, will cause the center wavelength of the reflection light shift. The effect of the change in strain and temperature on FBG can be expressed by\cite{24}:

$$\frac{\Delta \lambda_B}{\lambda_B} = (1 - P_e) \Delta \varepsilon + (\alpha + \zeta) \Delta T$$

(2)

Where $\Delta \lambda_B$ is the wavelength drift, $\Delta \varepsilon$ is the strain change, $\Delta T$ is the temperature change, $P_e$ is the effective photo-elastic coefficient (theoretical value 0.22) of the FBG, $\alpha$ and $\zeta$ are the thermal expansion coefficient and thermo-optical coefficient, respectively.

3. Design of FBG Three-dimensional Stress Sensor
Presently, many FBG three-dimensional stress sensors were generally designed that FBGs are laid in different directions in an intact material. By sensing the deformation of the material with FBG and calculating with generalized Hook's law, the stress monitoring process can be achieved. This method is applicable when the amount of stress change in each direction is small. But if the stress in one or two directions is much higher than stress in other directions, it will play a leading role and have a great influence on the process of stress monitoring. In view of this, a sensor that is sensitive only to x, y and z direction was presented in this paper, which was used to measure three-dimensional stress without interference from other directions.

The sensor was composed of three rubber cylinders in x, y and z directions. The shape and structure were shown in Fig.1. Each FBG was pasted along the ring surface of each cylinder, forming sensing element in every direction. The shell was installed outside the radial surface of the cylinder to shield it from radial stress. Therefore, each cylinder was able to only sense the stress in the axial direction and the test process would be achieved independently. There was a gap between the protective shell and the cylinder so that it had a certain radial deformation space.

The sensor's substrate was shock-reducing rubber (the mechanical parameters were shown in the table1), and the vertical and horizontal shell were plastic with high strength. Each cylinder was 25mm in length and 30mm in diameter with grooves on the surface to protect fiber. The epoxy resin adhesive was used as the glue, and the flexible coat was installed on the leading part of the fiber to prevent it from breaking during connection.
Figure 1. Structure of the FBG sensor.

Table 1. The mechanical parameters of substrate material.

| Material              | Elasticity modulus | Poisson's ratio |
|-----------------------|--------------------|-----------------|
| Shock-reducing rubber | 10MPa              | 0.445           |

4. Stress Analysis for the FBG Three-Dimensional Stress Sensor with Numerical Modeling

By numerical computer modeling, the stress distribution of the FBG sensor can be exhibited. The process was achieved by Solidworks, and the stress was applied to substrate material and protective shell respectively to obtain the stress distribution and strain variation.

4.1. Stress Distribution of the Substrate Material

4.1.1. Vertical stress applied

The vertical stress of 2MPa was applied on the upper surface of the model, and the base surface of the substrate material model was fixed to limit the vertical movement. The stress measuring points were arranged in the model to obtain the simulated values of internal stress. The results were shown in Fig.2.

Three measuring points were arranged in the sensor detection area. It can be obtained that the maximum stress in the vertical stress detection area of the sensor is about 2MPa, but in the horizontal area, the values were about 600Pa and 980Pa, which were smaller than the points in vertical direction. This indicated that stress in one direction had less influence on other directions.
4.1.2. **Vertical stress applied**

The stress of 2MPa was applied to the horizontal outer surface of the sensor, and the fixed constraints were applied to the inner surface of the vertical stress detection area. The stress results were shown in Fig.3.

![Stress distribution](image1)

(a) Stress distribution

![Strain variation](image2)

(b) Strain variation

**Figure 3.** Stress and strain analysis when applied to horizontal stress.

Three measuring points were arranged in the sensor detection area. It can be obtained that the maximum stress in the horizontal stress detection area of the sensor was about 2MPa, but in the vertical stress detection area, the values at the measuring points were 500Pa, which were smaller than those at the horizontal stress detection points.

4.1.3. **Vertical stress applied**

The stress of 2MPa was applied in vertical and horizontal direction simultaneously, and the stress results were shown in Fig.4.

![Stress distribution](image3)

(a) Stress distribution

![Strain variation](image4)

(b) Strain variation

**Figure 4.** Stress and strain analysis when applied to three-dimensional stress.

Three measuring points were arranged in each testing area of the substrate material. In the substrate material, the stress value in the vertical stress area and the horizontal stress area was all about 2MPa, and the stress of all parts in the substrate material was uniform. From this, it can be inferred that, although three-dimensional stress was applied to the sensor, the stress in one direction can be tested without interference from other directions, and the independent test of the stress by one sensor can be achieved.

4.2. **Shell Strength Analysis**

For the installed vertical shell, to simulate the force characteristics of it, the specific simulation conditions were set as follows:

The bottom edge of the shell was fixed to simulate the force state after installing the shell. The vertical shell was applied to 2MPa, and the stress/strain results were shown in Fig.5.
For the installed horizontal shell, the specific simulation conditions were set as follows: The bottom surface of one end of the shell was fixed to simulate the working state after installing the shell. The vertical shell was subjected to 2MPa stress at the end face and radial direction, and the results were shown in Fig.6.

According to the test results in Fig.5 and Fig.6, the deformation of the shell was so smaller than that of the substrate, which meant that the shell had enough strength to shield the stress in radial direction of the cylinder. The measurement points were randomly set in the sensor, and the deformation of the measurement points was about 0.4μm.

5. Calibration Experiments of the FBG Sensor
To get the relationship between applied stress and wavelength drifts of the FBG sensor, the calibration experiments were carried out. The method is to apply load on the sensor in three directions respectively with the range of 5.66kPa~39.62kPa. The sensor was loaded 6 times in every direction, and the wavelength drifts of FBG were averaged. The results were shown in Fig.7~9. It can be inferred that the sensitivity in x, y, and z direction is about 8 pm/kPa, 5 pm/kPa, 9 pm/kPa respectively.
6. Conclusion
Based on sensing theory of FBG, a kind of FBG sensor was presented and designed which was used to monitor three-dimensional stress independently in rock. By numerical modeling, it reveals that the sensor had good sensing property of testing stress in x, y, and z direction. To get the relationship between applied stress and wavelength drifts of the FBG sensor, the calibration experiments were carried out, and the sensitivities in x, y, and z direction were 8 pm/kPa, 5 pm/kPa, 9 pm/kPa respectively. This provides a new method for three-direction stress detection in surrounding rock, which is of great significance for surrounding rock support design.

7. Acknowledgments
This research was funded by National Natural Science Foundation of China (51674099).

8. References
[1] S S. Peng. Coal mine ground control. 3rd ed., Morgantown, WV: S S. Peng: 2008. P. 30.
[2] Ching-Yu Hsu, Chia-Chin Chiang, Tso-Sheng Hsieh, et al. A study of strain measurement in cylindrical shells subjected to underwater shock loading using FBG sensors, Optik 217 (2020), 1–11.
[3] Zhang Jiana, Li Wei. The study on the novel distributed vibration sensing system based on the adjacent FBGs reflected lights interference, Optik 169 (2018), 85-89.
[4] Jussi Salo, Ilkka Korhonen. Calculated estimate of FBG sensor’s suitability for beam vibration and strain measuring, Measurement, 47(No. 1), 2014, 178-183.
[5] Junlei Chen, Jihui Wang, Xiaoyang Li, et al. Monitoring of temperature and cure-induced strain gradient in laminated composite plate with FBG sensors, Composite Structures, 242 (2020), 1-9.
[6] F.M. Araujo, M. Teixeira, L.A.A. Ferreira, I.M. Dias, A. Quintela, J.L. Castro, Surveillance of fiber optic and electric power cables using fiber Bragg grating sensors, *Proc. SPIE* 3541 (1999) 279-290.

[7] X. Qiao, M. Fiddy. Distributed optical fiber Bragg grating sensor for simultaneous measurement of pressure and temperature in the oil and gas downhole active and passive optical components for WDM communications, *Proc. SPIE* 4870 (2002) 554–558.

[8] L. Ren, H.N. Li, X. Li, J. Zhou, L. Xiang, Application of FBG sensors in rolled concrete dam model, *Proc. SPIE* 6174 (2006) 617436.

[9] Casas J R, Cruz P J S. Fiber Optic Sensors for Bridge Monitoring. *Journal of Bridge Engineering*, 2003, 8(6):362-373.

[10] Y. Zhou, Y.-F. Wang, B. Han, Z. Zhi, Health monitoring for subway station structure by fiber Bragg grating sensors, *Proc. SPIE* 6933 (2008) 693316.

[11] P.M. Nellen, A. Frank, R. Bronnimann, U. Sennhauser, Optical fiber Bragg gratings for tunnel surveillance, *SPIE* 3986 (2000) 263–270.

[12] W. Shen, R. J. Yan, L. Xu, et al. Application study on FBG sensor applied to hull structural health monitoring, *Optik* 126 (2015), 1499-1504.

[13] H. Li, L.Q. Zhu, G.K. Sun, Deflection monitoring of thin-walled wing spar subjected to bending load using multi-element FBG sensors, *Optik*, 164(No. 7) 2018, 691-700.

[14] Y. Li, H.P. Wang, W.B. Cai, et al. Stability monitoring of surrounding rock mass on a forked tunnel using both strain gauges and FBG sensors, *Measurement* 153 (2020), 1-10.

[15] S. Opoka, R. Soman, M. Mieloszyk, et al. Damage detection and localization method based on a frequency spectrum change in a scaled tripod model with strain rosettes, *Marine Structures* 49 (2016), 163-179.

[16] Rohan Soman, Magdalena Mieloszyk, Wiesław Ostachowicz. A two-step damage assessment method based on frequency spectrum change in a scaled wind turbine tripod with strain rosettes, *Marine Structures* 61 (2018), 419-433.

[17] Ramos C A, De Oliveira R, Marques A T, et al. Design and experimental evaluation of a composite strain rosette using fibre Bragg grating. *Microwave and Optical Technology Letters*, 2011, 53 (8):1853-1857.

[18] Zhao P, Pisani D S, Lynch C. Piezoelectric strain sensor/actuator rosettes. *Smart Materials and Structures*, 2011, 20 (10):102002.

[19] H C Xu, S Wang, X G Miao. Research of three-dimensional force sensor based on multiplexed fiber Bragg grating strain sensors. *Optical Engineering*. 2017, 56(4): 047103.

[20] L Xiong, G Jiang, Y Guo, et al. A three-dimensional fiber Bragg grating force sensor for robot. *IEEE Sensors Journal*, 2018:3632-3639.

[21] C Sonnenfeld, G Luyckx, S Sulejmani, et al. Microstructured optical fiber Bragg grating as an internal three-dimensional strain sensor for composite laminates. *Smart Materials & Structures*, 2015, 24(5):55003-55015.

[22] K M Feng, C Y Wu, J H Yan, et al. Fiber Bragg grating-based three-dimensional multipoint ring-mesh sensing system with robust self-healing function. *IEEE Journal of Selected Topics in Quantum Electronics*, 2012, 18(5):1613-1620.

[23] R. Yun-Jiang, In-fiber Bragg grating sensors, *Meas. Sci. Technol.* 8 (1997)355–375.

[24] M Mousumi, T K Gangopadhyay, A K Chakraborty, et al. Fiber Bragg gratings in structural health monitoring-Present status and applications. *Sensors and Actuators A: Physical*, 2008, 147(1):150-164.