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A NOVEL FIBRE BRAGG GRATING CURVATURE SENSOR FOR STRUCTURE DEFORMATION MONITORING

Ming-Yao Liu[1,2], Shi-Guang Zhou[2], Han Song[1,2], Wei-Jian Zhou[2], Xiong Zhang[2]

1) *Wuhan University of Technology, School of Mechanical and Electrical Engineering, Wuhan 430070, Hubei, China* (*lmylyf@126.com*, ✉ *songhan@whut.edu.cn*, +86 027 181 0864 3852)
2) *Wuhan University of Technology, Hubei Digital Manufacturing Key Laboratory, Wuhan 430070, Hubei, China* (*274760169@qq.com*, *rodgeratzwj@163.com*, *181342229@qq.com*)

Abstract

Real-time monitoring of deformation of large structure parts is of great significance and the deformation of such structure parts is often accompanied with the change of curvature. The curvature can be obtained by measuring changes of strain, surface curve and modal displacement of the structure. However, many factors are faced with difficulty in measurement and low sensitivity at a small deformation level. In order to measure curvature in an effective way, a novel *fibre Bragg grating* (FBG) curvature sensor is proposed, which aims at removing the deficiencies of traditional methods in low precision and narrow adjusting. The sensor combines two FBGs with a specific structure of stainless steel elastomer. The elastomer can transfer the strain of the structure part to the FBG and then the FBG measures the strain to obtain the curvature. The performed simulation and experiment show that the sensor can effectively amplify the strain to the FBG through the unique structure of the elastomer, and the accuracy of the sensor used in the experiment is increased by 14% compared with that of the FBG used for direct measurement.

Keywords: fibre Bragg grating, curvature sensor, large structure parts, deformation monitoring.

1. Introduction

The deformation measurement of large-scale structural components is very important in the equipment engineering. As a support for the normal operation of the whole system, the stability of its structure parts – such as the base, main control, gantry and other structural components on heavy-duty machine tools – plays a vital role in the manufacturing industry [1]. The change of their parameters has a significant influence on the machining accuracy. The deformation of large-scale structure parts is often accompanied with the change of curvature, which is easily overlooked and difficult to be measured directly. Therefore, real-time monitoring of the curvature is of great significance in the field of modern mechanical precision machining.

Many scholars have studied the curvature measurement and achieved a lot of valuable results. Yili Fu *et al.* developed a light intensity modulation fibre-optic sensor for the curvature measurement. This sensor is suitable for measuring many kinds of structures, and it can be used to build a quasi-distributed fibre-optic sensor system that can simultaneously measure both curvature and

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torsion angle [2]. Arnaldo G. Leal *et al.* proposed a polymer optical fibre curvature sensor, and they explained how to overcome high hysteresis due to the polymer viscoelastic response [3]. Urszula Nawrot *et al.* designed a new mechanical transducer, which used a symmetric cantilever structure to magnify the strain of the fibre grating sensor and overcame the low sensitivity of natural frequencies and modal displacements to certain types of damage. The sensitivity to strain improved a lot [4]. Francesco Biral *et al.* also proposed a new type of composite sensor which compensated the positioning errors in large NC machines tools. The sensor can provide the real-time measurement of a deformed shape of the attached structure and it can also provide the deformed position of any given point of the structure by interpolation of the deformed position of sensor nodes [5].

Although the current research status is considerable, many sensors still face some problems in practical application: (1) the range of measurement is relatively limited and the sensors cannot adapt to a variety of cases, (2) the influence of environmental factors on the dynamic characteristic measurement cannot be avoided, (3) the characteristic parameters, such as natural frequency and damping ratio are less sensitive to certain strains. As new sensitive components, the sensors related to FBG have been widely researched and used in recent years [6–10]. Some sensors also use other materials for sensing and measuring [11–14]. Compared with them, FBG is a diffraction grating which is formed by the rotation of the refractive index of the fibre core with a specific method [15]. It has many advantages, such as small volume, light quality, high sensitivity and wide application scope [16–18]. The research on FBGs in sensing has attracted more and more attention.

In this paper, a new composite curvature sensor that combines FBG with an elastomer is proposed. The sensor can work on a side of large structure parts such as heavy-duty machine tools to monitor the change of curvature without affecting normal operation of the machine. The elastomer of the sensor has a specific structure, which can amplify the strain to the FBG to improve the sensitivity and avoid the deficiencies of direct measurement by a single FBG at the same time. The performed simulation and experiment have been directed particularly to analyse and test the sensor performance.

2. Principle of curvature sensor

In the mathematical theory, the first step to obtain the curvature is to construct a curve with a continuous derivative, and then take the limit of the ratio of chord length and inclination angle to calculate it. If the curvature is measured by means of the above method in the structural deformation, the preparation will become particularly complex. Another method used in the field of mechanical engineering is to obtain the curvature indirectly by measuring strain. The cross-section strain distribution of the bending deformation has the same magnitude and the opposite direction. If the strain of one position and the distance from it to the neutral layer are known, the curvature can be calculated. However, when it comes to practical application, many parameters are not easy to be obtained, and the accuracy of strain values also cannot be guaranteed when the degree of deformation is not large.

Since it is known that the strain can be measured to calculate the curvature, we consider designing a composite sensor using a novel approach to measure the curvature. The sensor uses an elastomer to amplify the strain and uses an FBG to measure it. The principle of the sensor is described below.

2.1. Principle of FBG sensing

As a passive filter, the FBG has many advantages over other structures. It is sensitive to changes of varying conditions such as temperature, strain and refractive index, which makes it very suitable for measurement in a complicated environment like a large structure component of a heavy-duty machine tool. In the process of sensing, the incident light is emitted by a broadband light source. When the incident light enters the optical fibre, the light matching the phase of the grating will be reflected and the light of other wavelengths will be transmitted. Then the strain can be calculated according to the wavelength of the reflected light. A schematic diagram is shown in Fig. 1.

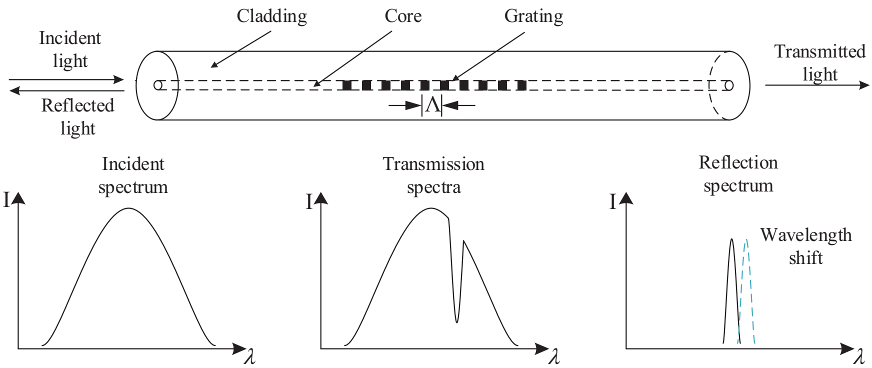

Fig. 1. A schematic diagram of FBG.

According to the coupled-mode theory of an optical fibre, the central wavelength λ_B of the FBG can be expressed as:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where n_{eff} is the effective refractive index and Λ is the grating period. The wavelength change $\Delta\lambda_B$ caused by the axial strain and temperature can be given by:

$$\Delta\lambda_B = (K_\varepsilon \Delta\varepsilon + K_T \Delta T)\lambda_B\,, \tag{2}$$

where $\Delta\varepsilon$ is the change of strain; ΔT is the change of temperature; and K_ε, K_T are the strain and temperature sensitivity coefficients, respectively. The optical elastic coefficient of a quartz fibre is 0.22 and K_ε is 0.78. When the wavelength change of the FBG is measured, the strain ε can be expressed as:

$$\varepsilon = \frac{\Delta\lambda_B - K_T \Delta T \lambda_B}{K_\varepsilon \lambda_B}\,. \tag{3}$$

2.2. Measurement principle of elastomer

In the application, the sensor is fixed on a side of the structure part and the two FBGs measure the strain at their heights respectively. As shown in Fig. 2, the distance between the two FBGs is d, and the strains of the FBGs are ε_1, ε_2, respectively. The following relation holds:

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{y+d}{y}\,. \tag{4}$$

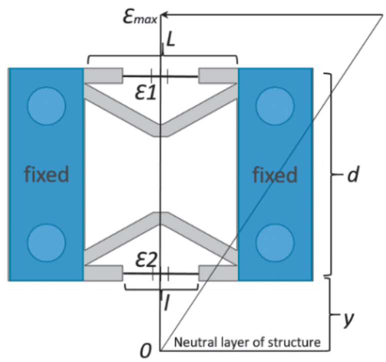

Fig. 2. A schematic diagram of the sensor.

And the distance from the second FBG to the neutral layer of the structure y can be obtained as follows:

$$y = \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} d. \tag{5}$$

The distance between the two fixed ends of the elastomer is L, and the fixed spacing of the FBG is l. The strain magnification coefficient of the sensor can be calculated as:

$$K = \frac{L}{l}, \tag{6}$$

ρ is the radius of curvature, and the relationship between it and the strain can be expressed as:

$$\varepsilon_1 = \frac{K(y+d)}{\rho} \varepsilon_2 = \frac{Ky}{\rho}. \tag{7}$$

With (5), (6) and (7), the radius of curvature can be expressed as:

$$\rho = \frac{Kd}{\varepsilon_1 - \varepsilon_2}. \tag{8}$$

According to (3) and (8), the effect of temperature on the strain of the two FBGs is compensated in the calculation and it can be used for long-term deformation monitoring of the structure parts. The curvature k of the structure part can be expressed as follows:

$$k = \frac{1}{\rho} = \frac{\varepsilon_1 - \varepsilon_2}{Kd} = \frac{\Delta\lambda_{B1}\lambda_{B2} - \Delta\lambda_{B2}\lambda_{B1}}{K_\varepsilon K d \lambda_{B1}\lambda_{B2}}. \tag{9}$$

The deformation of beam structures is usually a transverse bending, the plain assumption of a pure bending and no extrusion between the longitudinal fibres is not established. However, in practical application, the positive stress of a cross-section under the transverse force is calculated in a pure bending way since the error of the strain calculation formula of the pure bending is very small in the theoretical deduction and design, which is enough to meet the requirements of the engineering precision.

3. Structure design of curvature sensor

3.1. Design concept of curvature sensor

Functioning of the sensor is mainly based on a combination of an elastomer and two FBGs. The design of the elastomer should agree with the deformation rule of the structure part to be measured and should produce a reasonable strain field under an external force. Beyond that, the elastomer structure should be able to obtain the curvature with the existing parameters and the strain measured by FBG. Considering the above factors, a curvature sensor based on FBG is proposed, which can measure the curvature without knowing the position of the neutral layer of the structure component beforehand. A photo of the FBG curvature sensor is shown in Fig. 3. The whole sensor is composed of an elastomer and FBGs. It is fixed with four screws for reusing and replacing the FBGs. The elastomer structure is symmetrical and stiffness of both sides due to fixing is higher than that of the middle part for sensing the strain.

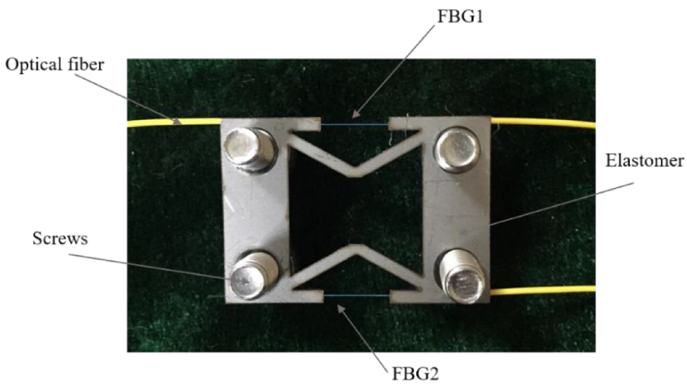

Fig. 3. A photo of the fabricated curvature sensor with marked locations of the FBGs.

Since the sensor works on a side of the structure part to measure the curvature, the structure design of the middle part of the elastomer adopts the V shape, which is more consistent with the actual situation of the bending deformation and avoids instability of the flexible hinge [19]. Two FBGs are horizontally fixed to specific locations of the elastomer with a pre-tightening force to measure the strain. A third FBG can also be mounted vertically in the middle shortest position of the elastomer in the same way if the tensile deformation needs to be measured. The unique structure design can transform the horizontal tensile strain into the strain of the FBG in the vertical direction. The ratio of height to base of the V-shape part is 1:4, which can effectively magnify the strain to improve the measurement sensitivity.

3.2. Structural analysis of composite curvature sensor

To analyse whether the sensor design meets the requirement under the constraints of other parts, we have built a three-dimensional (3D) model in SOLIDWORKS and used ANSYS to simulate it. The simulation model took the elastomer and the FBGs into account. The elastomer of the sensor was fabricated of stainless steel due to its good mechanical properties, stamping, tensile strength, corrosion resistance and many other advantages. The material parameters used in simulation are listed in Table 1.

Table 1. Material parameters used in simulation.

Component	Young modulus (GPa)	Poisson ratio
Elastomer	193	0.31
FBG	74	0.3
Base	110	0.28

The simulation diagram of the elastomer is shown in Fig. 4. When a force of 500 N was put vertically to the beam, the sensor fixed on its side was stretched or compressed in the horizontal direction. For a more accurate analysis, we magnified the simulation results by 10 times. It can be seen from the diagram that the strain is distributed centrally in the middle of the elastomer concentration, which can effectively transfer the strain to the FBGs.

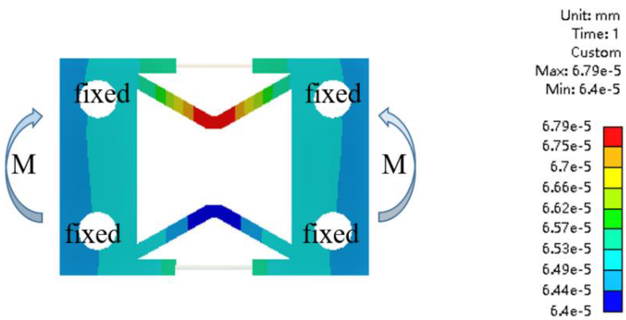

Fig. 4. The simulation diagram of the elastomer when a force of 500 N was put to the beam.

The sensor performance was considered for different deformation pressures applied to the structure: from 100 N to 700 N. The length, width and height of the structure were 1300 mm, 30 mm and 50 mm, respectively. For each experiment we calculated the curvature of the structure and compared it with the simulation result of the sensor without removing the strain magnification coefficient. Fig. 5 shows a linear relationship between curvature and pressure, and the two times amplification of curvature is expressed by the equations of fitting curves.

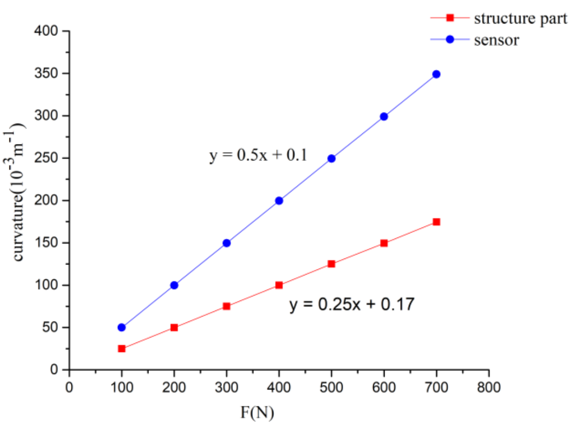

Fig. 5. A diagram of the curvature.

4. Performance test of curvature sensor

4.1. Experimental process

In order to test the sensor's working performance, it is necessary to verify the results by some experiments. Three curvature sensors were fixed on an aluminium alloy beam to evaluate their performance and the length, width and height of the beam were the same as in the simulation model. As shown in Fig. 6, the sensors in the experiment are fixed in different positions to avoid a contingency of measurement. Their horizontal distance is 150 mm and the vertical distance is 10 mm. The force is directed vertically down.

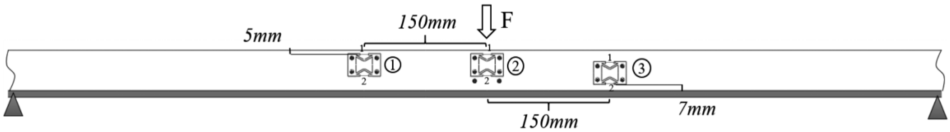

Fig. 6. A diagram of the sensors' locations.

In the experiment, the sensor was fixed with four screws on an aluminium alloy beam, then different values of pressure were applied to the beam and the curvature was measured. Similarly, three displacement sensors installed in the corresponding positions were used to construct the surface curve of the structure to obtain the actual curvature. Finally, the two results of the curvature were compared to analyse the sensor performance. A schematic diagram of the experiment setup is shown in Fig. 7.

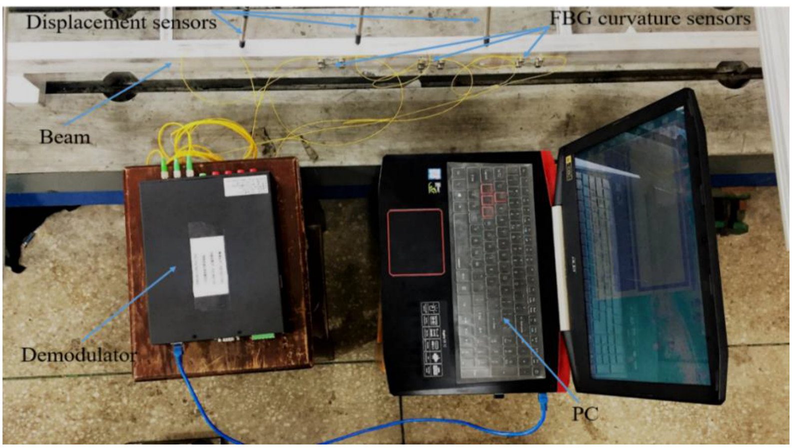

Fig. 7. The experiment setup.

The sensors used in the experiment were installed by wire cutting on a 1 mm stainless steel plate. The length and the width of the sensors were 40 mm and 28 mm, respectively. After cleaning the surface of the elastomer, two pre-strained FBGs were placed in the corresponding points using AB adhesive. The initial wavelengths of the FBG pairs located on the corresponding three sensors were 1546.951 nm and 1550.340 nm, 1547.012 nm and 1549.977 nm, 1546.899 nm and 1550.329 nm, respectively. The shift of the FBG wavelength was monitored by an SAI-112XAF demodulator with a frequency of 2 KHz.

After the whole test system was set up, the forces of 200 N, 300 N, 400 N and 500 N were put to the beam to test the performance of the three sensors, respectively. In addition, another long-term experiment has been carried out to evaluate the real-time measurement performance of the sensor at different environment temperatures.

4.2. Experimental results and discussion

The results of the experiment were finally evaluated by calculating the curvature. However, the curvature was calculated by the strain and the change of the strain was accompanied with the change of the FBG wavelength. We discuss the results of wavelength, strain, and curvature obtained for three parts, respectively.

As shown below, the wavelength shifts of the three sensors (see also Fig. 6) are presented when a force is applied to the beam. The bending is directed vertically down and the surface of the structure part is concave. The wavelength change of the FBG located above the neutral layer of the beam is opposite to that of the FBG located below the neutral layer and it has a linear relationship with the load. The farther the FBG is from the neutral layer, the greater the wavelength changes for the same degree of deformation. The other experiments using different sizes of sensors exhibit the same trend as shown in Fig. 8.

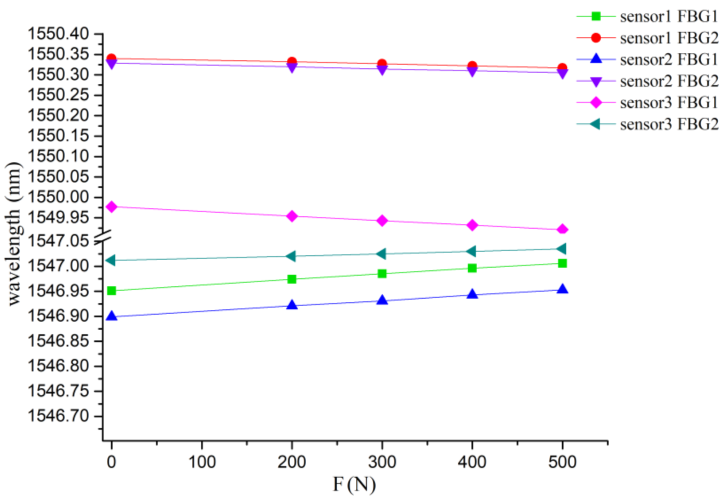

Fig. 8. The wavelength shifts of the sensors under a load.

Since sensor1 and sensor2 are fixed at the same height, the measured strains are only a little different. Fig. 9a and Fig. 9b show the strains. Sensor3 is fixed under the first two sensors and the strain measured is shown in Fig. 9c. Since the Young's modulus of the elastomer is 2.72 times greater than that of the beam and the strain measured by the sensor is about 0.735 times the strain of the beam, that explains that the sensor used in the experiment can magnify the strain by two times. The rate of accuracy is increased by 14% compared with that measured directly by FBG and the strain sensitivity is about 1 $\mu\varepsilon$/N. In the application, the strain magnification coefficient of the sensor can be adjusted by changing the l and L values if required.

During the tests, the actual curvature of the beam was monitored by three displacement sensors and the curvature measured by the sensor can be obtained by (9). The curvature of the beam measured by the sensors is shown in Table 2. Fig. 10 presents a graph of the actual curvature

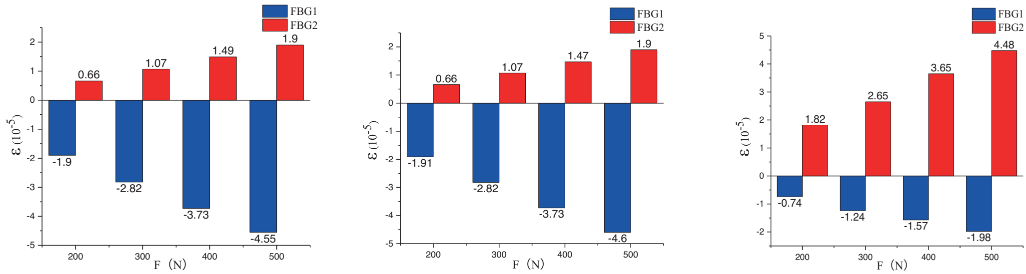

Fig. 9. The strain of the two FBGs on the sensors. The positive values in the graph represent tension, and the negative values represent compression.

and the curvature measured by the three sensors in the experiment. As expected, the curvature measured by the sensor under a large load is more accurate than that under a small load, but the relative error is contained within 3%. The curvature of the beam without load is caused by its own gravity and the error may be caused by adhesive or operational excitation.

Table 2. The curvature measured by the sensors.

F(N)	Sensor		
	Sensor1	Sensor2	Sensor3
200	98.46	98.85	98.46
300	149.62	149.62	149.62
400	200.77	200	200.76
500	248.08	250	248.46

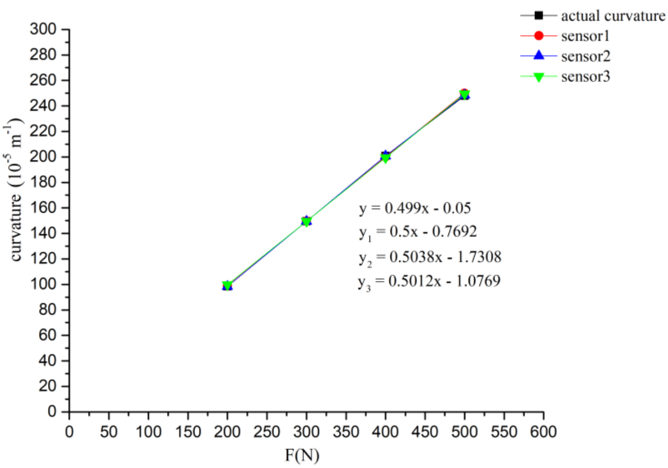

Fig. 10. A diagram of the curvature value obtained with the sensor and the actual one.

The ambient temperature recorded by the temperature sensor and the curvature curve of the beam monitored by the FBG curvature sensor and the displacement sensor within a 24 h period are shown in Fig. 11. Under a constant vertical downward force of 400 N, the curvature of the beam varies corresponding to the fluctuation of the ambient temperature ranging from 10.5°C to 19.7°C. Due to the difference algorithm, the temperature effect on the curvature measurement is compensated. The measurement error between the FBG curvature sensor and the displacement sensor is contained within 5%.

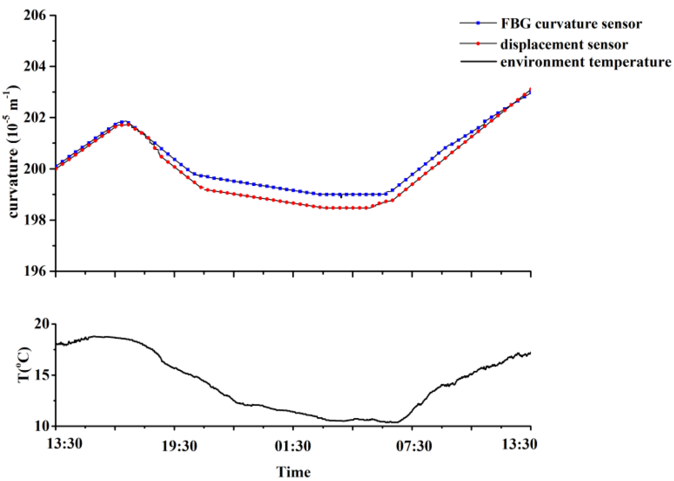

Fig. 11. A diagram of curvature and temperature values within a period of 24 hours.

5. Conclusions

Combining the elastomer with FBG, a novel curvature sensor is proposed in this paper. As long as the size of the sensor and some simple parameters of the structural part are known, the curvature of the structure part can be measured, which greatly simplifies its computation compared with the traditional measurement method. We have built a simulation model to analyse the strain transfer rule and the experiment results agree with the theoretical results perfectly. The unique structure design of the elastomer can not only satisfy the bending deformation rules of structural parts, but also amplify the strain and transfer it to FBG. The measurement accuracy is about 1.2 times higher than that of the traditionally measured directly by FBG, which effectively improves the curvature measurement sensitivity. The strain sensitivity is about 1 $\mu\varepsilon/\mathrm{N}$ and the curvature measurement error is less than 3%. The sensor presented in this paper can be seen as a significant means of monitoring the curvature of large-scale structures. It can also accommodate different situations by adjusting the relevant dimensions, which is a prospective solution.

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