APPLICATION OF FBG SENSORS TO MONITOR THE CABLE FORCES IN A SMALL-SCALE CABLE-STAYED BRIDGE MODEL

X. Feng
State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

Z. Fan
State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

J. Hu
State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

L. Ren
State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

J. Zhou
State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

For a small-scale model of cable-stayed bridge, the cross-sectional dimensions of tension cables are very tiny, which leads to the difficulty for the currently-existed techniques to measure the cable forces in the model test. In this paper, we designed a gripper-based FBG sensor with enhanced strain sensitivity to monitor the cable forces in the scale model tests for cable-stayed bridge. Firstly, the gripper-based FBG sensors were fabricated and attached on the model cables. And then the gripper FBG sensors were experimentally calibrated by the standard extension test of the instrumented tension cables. Secondly, the static tests of the model bridge were performed and the cable forces were measured by the gripper-based FBG sensors. Finally, the measured cable forces were compared with the results of numerical simulations. It is indicated that the gripper-based FBG sensors are suitable to monitor the cable forces for the small-scale model of cable-stayed bridge, which has the advantages of small size, high precision, and multiplexibility.

Corresponding author's email: fengxin@dlut.edu.cn

APPLICATION OF FBG SENSORS TO MONITOR THE CABLE FORCES IN A SMALL-SCALE CABLE-STAYED BRIDGE MODEL

Xin Feng, Zhe Fan, Jian Hu, Liang Ren, and Jing Zhou

State Key Lab of Coastal & Offshore Engineering, Dalian University of Technology, Dalian, China

ABSTRACT: For a small-scale model of cable-stayed bridge, the cross-sectional dimensions of tension cables are very tiny, which leads to the difficulty for the currently-existed techniques to measure the cable forces in the model test. In this paper, we designed a gripper-based FBG sensor with enhanced strain sensitivity to monitor the cable forces in the scale model tests for cable-stayed bridge. Firstly, the gripper-based FBG sensors were fabricated and attached on the model cables. And then the gripper FBG sensors were experimentally calibrated by the standard extension test of the instrumented tension cables. Secondly, the static tests of the model bridge were performed and the cable forces were measured by the gripper-based FBG sensors. Finally, the measured cable forces were compared with the results of numerical simulations. It is indicated that the gripper-based FBG sensors are suitable to monitor the cable forces for the small-scale model of cable-stayed bridge, which has the advantages of small size, high precision, and multiplexibility.

1 INTRODUCTION

Nowadays, cable-stayed bridge plays an important role in the transportation of modern society and has become a major bridge style to meet the requirement of long span capacity. Though it has many advantages, it still faces to some problems that may threaten the safety of the bridge. Based on the survey by Federal Highway Administration (2005), the effective durability and lifespan of bridge is continuously decreasing as a result of the destructive effects of defect, deterioration, and damage. To validate the design and to evaluate the performance of the cable-stayed bridge, the numerical simulation is the commonly used approach in the field of bridge engineering. In spite of the large number of theoretical studies performed, relative few experimental investigations have been reported (Belillo et al., 2004). The scaled model tests can be utilized to investigate the stress pattern of the main girder and the pylon near the bottom of the pylon and to evaluate the capacity of overloading, the modes of failure, and capacity of the safety reserve of the bridge. Since cable forces play an important role for the cable-stayed bridge, the measurements of cable forces become very crucial in the model tests (Shao et al., 2005). In our experiments, to meet the similitude requirements,

the model cables were simulated as steel string with the diameters that are less than 1 mm. As a result, it is very difficult to measure the tension forces of the model cables. Due to the excellent performance of immunity to electromagnetic perturbation, small weight penalty, non-invasiveness, durability, and multiplexing or distributed sensing, optical fiber sensor has drawn more and more attentions in civil structures (Todd et al., 2007; Ko & Ni, 2005). The small dimension as well as easy installation of optical fiber sensor make it to be an ideal candidates for measuring cable force. However, to the best knowledge of the arthors, rare literatures report the ulization of optical fiber sensor to monitor the cable force in the small-scaled model bridge. In this study, the gripper-based fiber Bragg grating (FBG) sensor was proposed to monitor the cable force change of a small-scale cable-stayed bridge in the laboratory. A finite element (FE) model was also established to compare with the physical model. The change of the experimental cable forces were compared with the numerical results, and the performance of the gripper-based FBG sensors were investigated for the small-scale cable stayed bridge.

2 FBG SENSOR FOR MONITORING CABLE FORCE

2.1 Basic principle of FBG

FBG is a section of fiber with periodic changes of the refractive index. The center wavelength of Bragg grating is given by:

$$\lambda_B = 2n\Lambda \tag{1}$$

Where Λ is the period of the grating; n is the effective refractive ratio. The light wave whose center wavelength is λ_B will be reflected by FBG. λ_B varies with n and Λ, thus 'wavelength drift' occurs. The 'drift' property makes it possible for FBG to measure various parameters. The strain and temperature are the two physical quantities that lead to the 'drift' phenomenon directly.

The relationship between the shift of center wavelength $\Delta\lambda$ and the axial strain $\Delta\varepsilon$ can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\Delta\varepsilon \tag{2}$$

$$P_e = -\frac{1}{n}\frac{dn}{n\varepsilon} \tag{3}$$

Where P_e is elasto-optic coefficient of optical fiber. It is assumed that temperature change is ΔT, and then the corresponding variation in center wavelength $\Delta\lambda$ can be given by:

$$\frac{\Delta\lambda}{\lambda_B} = \left(\alpha_f + \xi\right)\Delta T \tag{4}$$

$$\alpha_f = \frac{1}{\Lambda}\frac{d\Lambda}{dT} \tag{5}$$

$$\xi = \frac{1}{n}\frac{dn}{dT} \tag{6}$$

Where α_f and ξ are elasto-optic coefficient and thermal-optic coefficient of optical fiber, respectively. Then the total wavelength drift can be expressed as:

$$\Delta\lambda = \lambda_B(1-P_B)\Delta\varepsilon + \lambda_B(\alpha+\xi)\Delta T \quad (7)$$

When FBG is used to measure strain, the strain sensitivity coefficient K_ε and temperature sensitivity coefficient K_T can be obtained by the calibration test. By omitting the strain caused by the temperature, the structural strain $\Delta\lambda_B$ is expressed as:

$$\Delta\lambda_B = K_\varepsilon\Delta\varepsilon \quad (8)$$

Before the measurement, the strain sensitivity coefficient should be calibrated by the experiment.

2.2 Gripper-based FBG sensor for monitoring cable force

The damage is prone to occur for bare FBG sensor in hostile environments, and the multi-peak will happen in the case of the bare FBG directly glued on the structural surface. Thus it is very important to package the FBG sensor for civil structure application. The steel tube is the most popular way for packaging FBG sensor. According to Biswas et al. (2009), the steel tube should have the anchorage points at the both ends of the FBG sensor. For real structure, it is easy to mount the packaged sensor on or embed inside the structure by the anchorage points. For small-scaled bridge model, it is difficult to mount the tube-packaged FBG on the model cable with tiny diameter (i.e. the diameter of model cable is less than 1 mm). In this study, a gripper-based method was proposed to monitor the cable force of small-scaled bridge model. The main idea of the proposed method is that the both ends of FBG sensor encapsulated by steel tube are installed with gripper, and the inner part of the FBG is filled with adhesive. The strain of the component is transferred to the FBG through the gripper, which makes FBG deform with the deformation of cable accordingly. The mounted method between gripper-based FBG sensor and model cable was schematically illustrated in Figure 1.

2.3 Sensor calibration

In order to calibrate the sensitivity coefficient of cable force, a standard tension test was carried out. Firstly, the gripper-based FBG sensor was installed on each model cables. Then one end of the tested cable was fixed while the other end was loaded by the dead weights. With the increase of the dead weight, the corresponding wavelengths were measured by a commercial FBG interrogation system. By using of the recorded data of dead weights as well as corresponding wavelengths, the sensitivity coefficient of cable force and the central wavelength of FBG sensor were determined by the linear regression for each model cable. The calibration results of all the FBG sensors are listed in Table 1. The calibrated coefficient was utilized to measure the cable force change in the model tests in Section 3

Table 1. The calibration results of FBG sensors.

Sensor number	Sensitivity coefficient	Center wavelength(nm)	Sensor number	Sensitivity coefficient	Center wavelength(nm)

1	0.492	1549.4	16	0.66	1561
2	0.464	1533.7	17	0.498	1540.7
3	0.435	1536.2	18	0.643	1578.8
4	0.531	1556.2	19	0.46	1520.9
5	0.529	1530.9	20	0.536	1580.1
8	0.602	1522.3	21	0.693	1557.2
9	0.534	1528	22	0.584	1576.1
10	0.52	1513.3	23	0.569	1554.2
11	0.466	1536.2	24	0.476	1582.8
12	0.602	1568.1	25	0.623	1564.5
13	0.507	1515.5	26	0.726	1538.3
14	0.611	1570.8	27	0.528	1573.5
15	0.513	1585	28	0.515	1543.4

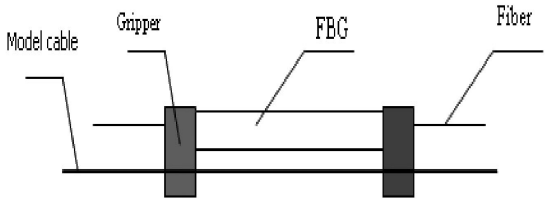

Figure 1. The shematic diagram of gripper-based FBG sensor

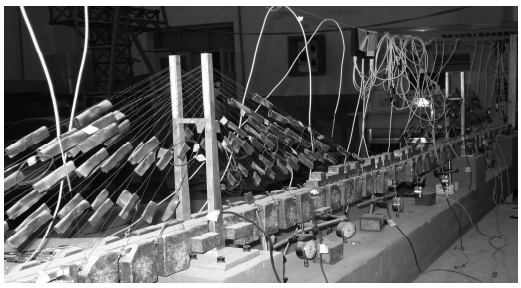

Figure 2. Cable-stayed bridge model.

3 EXPERIMENTAL VERIFICATION

3.1 Experimental Results

A small-scale cable-stayed bridge, with scale ratio 1:150, was built in the laboratory based on the similitude theory. The bridge pylon and deck were made of aluminum alloy, and steel strings were used to simulate the stay cable. To model the gravity similitude, the additional masses with lead blocks were placed on the cables, main girders, and pylons. The FBG sensors were mounted on the cable by glued the grippers at the both ends. The cables were numbered 1 to 11 at each side span of the bridge from the pylon. The model bridge was shown in Figure 2.

The mass blocks were used to model the vehicle loads. There were 2 types of the mass blocks: type A with weight of 0.6kg each, and type B with weight of 0.6kg each. To simulate the vehicle group, there are 8 A mass blocks as well as 4 B mass blocks. Thus a total of 8.8kg mass blocks were placed in sequence on the middle span of the bridge.

To simulate the damage or deterioration case of the cables, some of the cables were loosed in the experiments. For instance, case B5(1) represents the cable which were numbered 5 (near the north pylon)in the bank span were loosed, while case R9(4) represents the 4 cables which were numbered 9 in the river span were all loosed. And then the cable force change was measured by the gripper-based FBG sensors. The experimental results were illustrated for different damage cases in Figure 3 to Figure 6.

3.2 Comparison with numerical simulations

The theoretical analysis was also carried out based on the FE model, which is shown in Figure 7 by using ANSYS software. The variations in cable forces due to damages computed by FE model were compared with the experimental results to verify the effectiveness of the proposed method. It can be seen from Figure 3 to Figure 6, most of the experimental results are in close agreement with those from FE analysis. For example, in Figure 4, 4 peak values of experimental data are almost similar with the theoretical results from FE analysis. The results also show that the loosing of the cable usually has more significant effects on the cable that are next to the loosed cables. That is, the variations in the cable forces of the neighbor cables are larger than those far away from the loosed cables. It demonstrates that the proposed gripper FBG sensor has high precision for measuring the cable forces in the model test, which overcome the difficult of the thin cross-section of the model cable due to the small-scale modeling.

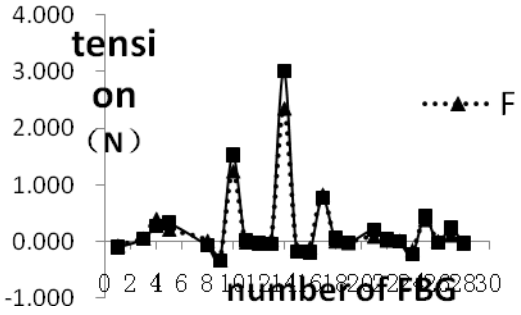

Figure 3. Cable force change of case B5(1).

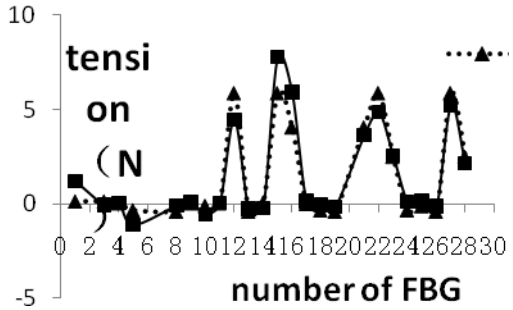

Figure 4. Cable force change of case R9(4).

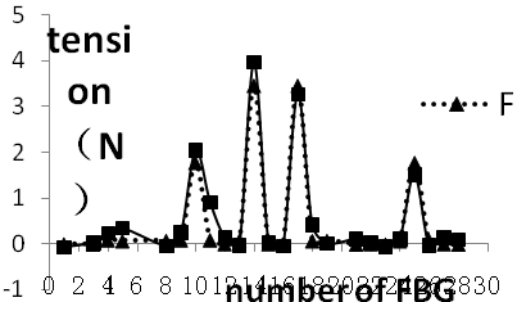

Figure 5. Cable force change of case B5(4).

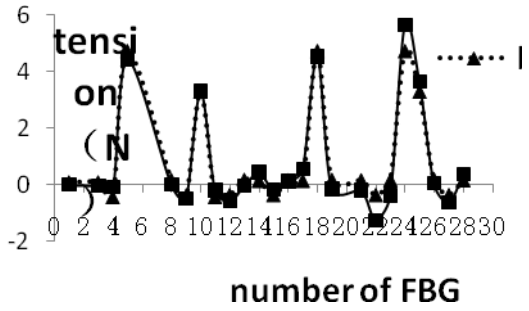

Figure 6. Cable force change of case B9(4).

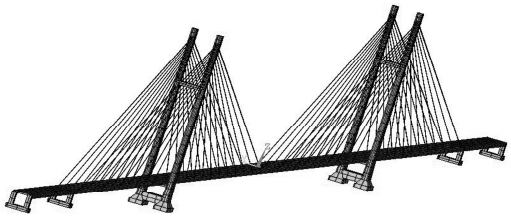

Figure 7. FE model of the cable-stayed bridge.

4 CONCLUSIONS

A novel method based on gripper FBG sensors is proposed to monitor the cable forces for a small-scale cable stayed bridge model in this paper. The gripper-based FBG sensors were fabricated and calibrated before the model bridge tests. In the experiments, the cables were loosed to simulate the damage or deterioration, and the changes in the cable forces were measured by the gripper-based FBG sensors under the static loads. To investigate the effectiveness of the gripper-based FBG sensors, the numerical simulations were carried out and the theoretical results were compared with the experimental data, which shows the good agreements between them. It indicates that the proposed method is a promising approach to monitor the cable forces for the small-scale cable-stayed bridge model.

References

Belillo, C, Bergmam, LA, and Kuchma, D. 2004. Experimental investigation of a small-scale bridge model under a moving force. *Journal of Structural Engineering, ASCE*, 130(5): 799-804

Biswas, P, Bandyopadhyaya, S, Kesavanb, S, Parivallal, S, Sundaramb, SA, Ravisankarb, K, and Dasguptaa, K. 2010. Investigation on packages of fiber Bragg grating for use as embeddable strain sensor in concrete structure. *Sensors and Actuators A*: *Physical*, 157: 77-83

Federal Highway Administration (FHWA).2005. National bridge inventory. *http://www .fhwa.dot.gov/bridge/nbi.htm*

Ko, JM, and Ni, YQ. 2005. Technology developments in structural health monitoring of large-scale bridges. *Engineering Structures*, 27: 1715-1725

Shao, X, Zhao, H, Li, L, Peng, W, Liu, G, and Yan, B. 2005. Design and experimental study of a harp-shaped single span cable-stayed bridge. *Journal of Bridge Engineering, ASCE*, 10(6): 658-665

Todd, MD, Nichols, JM, Trichey, ST, Seaver, M, Nichols, CJ, and Virgin, LN. 2007. Bragg grating-based fibre optic sensors in structural health monitoring. *Phil. Trans. R. Soc. A*, 365: 317-343