Development and implementation of FBG sensors for bridge health monitoring

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ABSTRACT: The fiber Bragg grating (FBG) technique was firstly reported approximately two decades ago and since then the applications of FBG in building and civil infrastructures have been a research interest. For the further application, the promised attractive performances of FBG strain sensor over the conventional sensor on electromagnetic immunity and repeatability, zero drift, should be verified and quantified. In the paper, the FBG strain sensors were tested first in lab to compare with the common sensors for its workability and durability. Several kinds of sensors based on FBG were then used for the measurement of a concrete column and structural health monitoring (SHM) of a large span steel arch bridge. The performance of the FBG sensor was evaluated for both short term measurement and long term measurement. Moreover, the paper also reported the development of an accelerometer based on the FBG technology.

1 INTRODUCTION

The FBG technique was firstly reported approximately two decades ago, and since then the applications of FBG have been increased (Hill et al. 1978). The FBG technologies offer a viable alternative sensing approach with some advantages over traditional technologies. These advantages are electromagnetic immunity, light weight, small size, multiplexing capabilities and corrosion resistance (Joan et al. 2003). So the applications of the FBG in civil engineering have been a research interest, especially in the area of SHM. Davis et al. (1996) discussed how to use the FBG sensors for the measurement of static loads as well as modal response of a bridge section. Austin et al. (1999) discussed how to use the FBG sensors to monitor the fatigue crack growth and delamination within hybrid laminates. Conventionally, the FBG sensing technology has been employed for the measurement of strain and temperature. At the same time, the FBG sensing technology has been used as sensors that offer a capability to monitor a wide range of physical parameters like degree of inclination, acceleration, corrosion. Accelerometers play a key role in the SHM system. In the early stage of its development, the optical accelerometers have been typically configured within an interferometric architecture. Recently, several accelerometers based on FBG have been proposed. Berkoff et al. (1996) proposed an FBG accelerometer. They embedded a Bragg grating element into a commercially available elastomer that is attached to a mass. The natural frequency of the sensor was set at about 2 KHz or higher to detect the high frequency components. This sensor, however, suffers from the cross-axis sensitivity and birefringence splitting of the Bragg reflection peak. Todd et al. (1998) improved the performance of an FBG accelerometer by using beam-plates. They were able to minimize the cross-axis sensitivity to less than 1% of the primary axis sensitivity. Although their system has many desirable features, the resolution in the low frequency range is not enough for civil and building application. Moreover the distribution of strain along the beam-plate to which a Bragg grating element is glued is not uniform so that the Bragg reflection peak may be broadened to result in reduced resolution. Akira Mita et al. (2001) presented a type of FBG accelerometer. The system consists of a cantilevered beam and a mass. In the system, a Bragg grating element is not directly glued to a cantilever to avoid possible non-uniform strain in the element. However the system need other compensating-temperature measures. Because no damping element was added, the working range was seriously limited, and the life-span of the accelerometer was reduced accordingly.

For the further realization, the performances of the FBG strain sensors like electromagnetic immunity and repeatability, zero drift, show be contentment compared with the common sensor. In the paper, the FBG strain sensors were firstly tested in lab to compare with common sensor for its workability and durability. Several kinds of sensors based on the FBG technique were then used for the measurement of a concrete column and SHM of a large span steel arch bridge. Their performances were accordingly evaluated for both short term measurement and long term measurement. Moreover, the paper also reported the development of an accelerometer using the FBG sensing technologies.

2 EXPERIMENTAL EVALUATION OF THE FBG STRAIN SENSORS COMPARED WITH THE CONVENTIONAL SENSORS

Experiments were carried out to evaluate the performance of the FBG strain sensors on electromagnetic immunity, repeatability, zero drift and other performances over the conventional resistance strain chip.

2.1 *Electromagnetic immunity*

In the experiment, an interphone was used to test the electromagnetic-immunity of two kinds of sensors in a three-meter-radius area. The electromagnetic immunity curve of the resistance strain chip shows obvious fluctuates (see Figure 1). However, Figure 2 shows that the FBG sensors have good performance on the electromagnetic immunity.

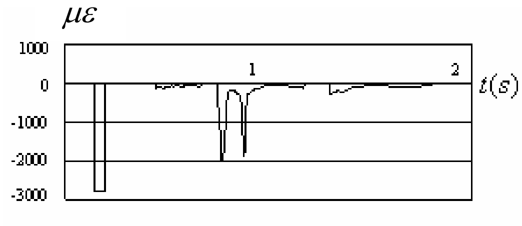

Figure 1.The electromagnetic immunity curve of the resistance strain chip

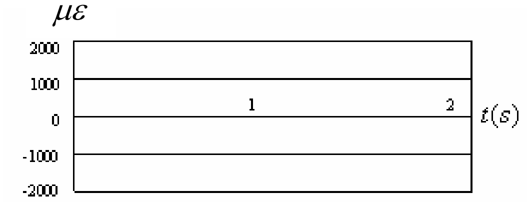

Figure 2.The electromagnetic immunity curve of FBG sensors

2.2 *Precision and repeatability*

Two FBG strain sensors were respectively installed on the upper and lower surfaces of a beam with constant strength. So there is no need compensating the temperature influences. The measurement of the FBG strain sensors are shown in table 1. Compared with the theoretical results shown in the last column of the table, the measured strain values match the theoretical values very well. The largest deviation between the measurement value and the theoretical value is about 0.7%. It shows that the FBG strain sensors have excellent precision. Four levels of static loads, form $525g$ to $3025g$, are subjected to the beam. The tests of each loading states are repeated three times. The results are also listed in three times. The results are also listed in table 1. The

Table 1. Strain of FBG sensors

Weight (including ray)	Measurement (x_i)													Theoretical data (x_t)
	1				2				3					
g	upper		lower		upper		lower		upper		lower			$\mu\varepsilon$
1	2	3*	4	5*	6	7*	8	9*	10	11*	12	13*	14**	15
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
525	209.8	-0.1	-210.1	0.0	209.2	-0.4	-209.5	0.2	208.6	***-0.7***	-209.4	0.3	***0.3***	210
1525	609.3	-0.1	-609.6	0.1	610.2	0.0	-610.7	-0.1	611.4	0.2	-611.2	-0.2	0.2	610
2025	811.3	0.2	-810.2	0.0	810.6	0.1	-810.8	-0.1	809.6	0.0	-809.8	0.0	0.1	810
3025	1210.8	0.1	-1209.3	0.1	1211.6	0.1	-1210.5	0.0	1209.5	0.0	-1211.8	-0.1	0.1	1210

*These columns list the relative deviations (%) between the measurement value and the theoretical value. The formula is $\frac{x_i - x_t}{x_t} \times 100\%$.

** The column lists the repeatability (%) of the FBG strain sensors. The formulas are $\frac{x_{\max} - \overline{x}_i}{\overline{x}_i} \times 100\%$ and $\overline{x}_i = \frac{1}{n}\sum_{i=1}^{n} x_i$.

measurement data verified the good repeatability of the FBG strain sensors as the relative variations between those tests are all below
0.3%.

2.3 *Zero drift (within an hour)*

To evaluate the performance of the sensors on the zero drift, a series of tests were performed on the above constant-strength beam under zero loading state, and the strain curves have been recorded for an hour. Figure 3 shows that the strain curve of the resistance strain chip has 1.5-microstrain fluctuate. The FBG sensors have no zero drift (see Figure 4).

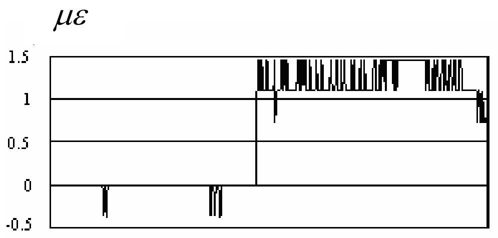

Figure 3. Zero drift of the resistance strain chip (within an hour)

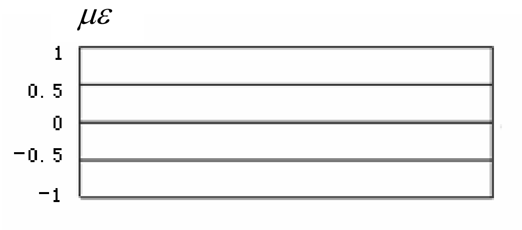

Figure 4. Zero drift of the FBG sensors (within an hour)

2.4 *Other performances*

The proportional limiting strain for the FBG materials was measured by increasing the strain gradually. The extreme value is more than 3000 $\mu\varepsilon$. Simultaneously, the sensing capabilities of stain shows high stabilization.

One of the advantages of the FBG sensors is its multiplexing capabilities. To verify this, an experiment was conducted. During the experiment, a demodulation device (PI03-4) was used to measure the wavelength shift to test how many FBG strain sensors could be linked along a single fiber. The result shows that up to 25 sensors can be linked along one single fiber within the measurement range of $1000\mu\varepsilon$ for the general applications.

However, the line-joining technique of FBG sensors is more complex than that of the resistance strain chips. In the field, the environment facters, which include wind, dust, vibration and so on, have negative influence on the fusion splicer that is used to connect fibers. These negative influences are likely to increase the loss of the optical power at the joints along the fiber. Furthermore, only the well-trained technician can operate the fusion splicer. This is one of the bottleneck for the application of the FBG sensors.

3 APPLICATIONS

To verify the feasibility and applicability of the above presented technology, an experiment study on a small-scale concrete column and a real test on the LuPu bridge were conducted.

3.1 *Small-scale physical models of structure*

To verify the accuracy of the FBG sensors for the measurement of the strain and displacement, a quasi-static experimental study was conducted on a small-scale concrete column. Besides the embedded and surfaced FBG strain sensors (see Figure 5), the FBG-based steel bar strain sensors (FBGG-01、FBGG-02) and the FBG-based displacement sensor (FBGGD120-01) were installed, which correspond to the conventional sensors. The FBG-based steel bar strain sensors and the FBG-based displacement sensor were placed (see Figure 6 and Figure 7). During the test, two actuators were employed to apply the push and pull force along the horizontal direction on the top left and right sides (as shown in Figure 7).

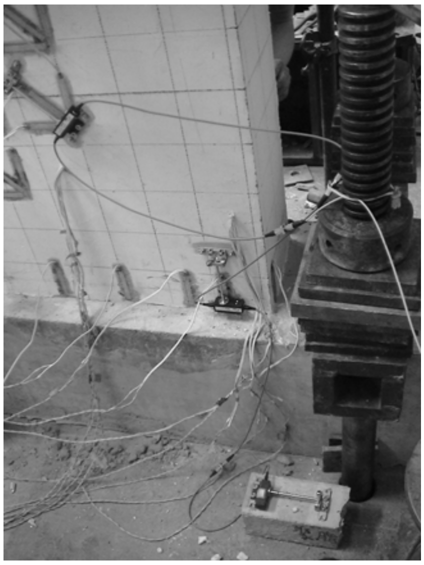

Figure 5. Surfaced FBG strain sensors

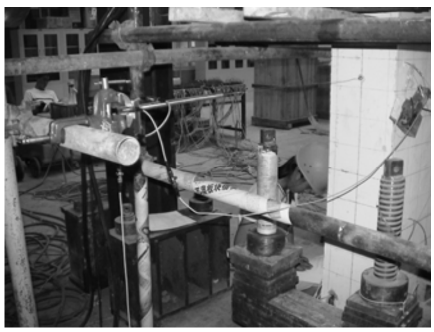

Figure 6. FBG displacement sensors

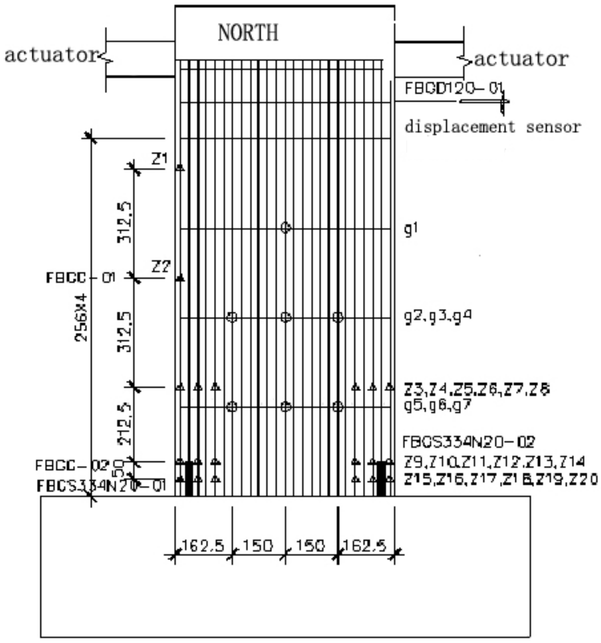

Figure 7. Locations of of steel bar strain sensors and displacement sensors

Figure 8-10 show the output from the FBG-based steel bar strain sensors and the FBG-based displacement sensor along with the conventional sensors corresponding to them. The results show that the measurements form the FBG sensors match quite well with the conventional stain and displacement sensors.

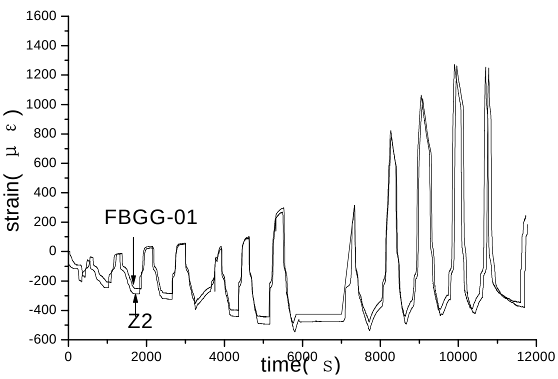

Figure 8. Outpt of FBGG-01 and Z2

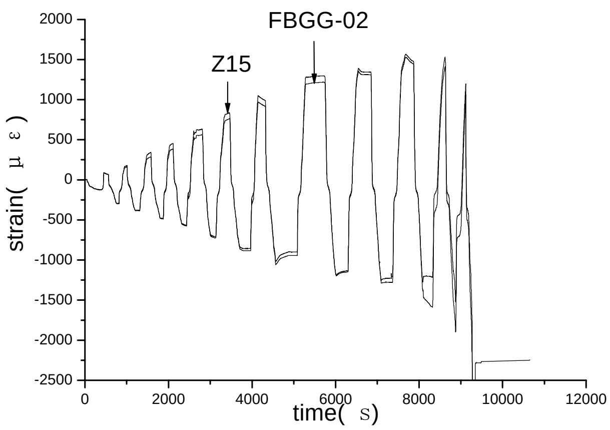

Figure 9. Outpt of FBGG-02 and Z15

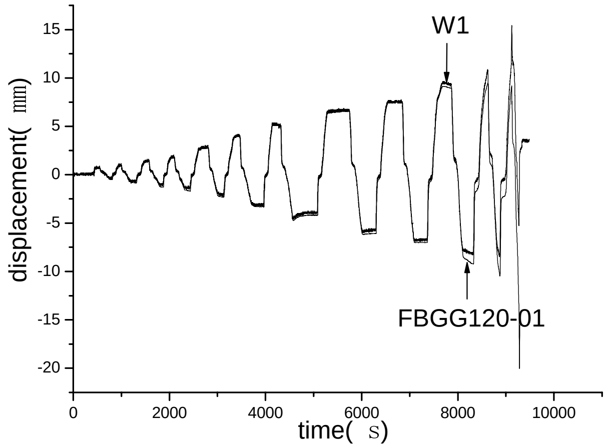

Figure 10. Outpt of FBGG120-01 and W1

3.2 *The LuPu Bridge*

LuPu Bridge (see Figure 11), a 550-m-long-main-span steel arch bridge, provides a direct highway link between PuDong and PuXi in Shanghai . It was known as “the longest arch bridge in the world”, which was built in June, 2003. Before the LuPu bridge would be open to traffic, ten FBG strain sensors (see Figure 12) were symmetrically placed in the same section, and the ten FBG strain sensors were linked together using a single fiber. The twice measurement were separately finished in October 20, 2003 and in January 30, 2004. The two results show that the FBG sensor was used successfully on actual structures and can provide excellent performance for both short term measurement and long term measurement. Furthermore, the style of vehicles can elementarily be distinguished from the time history of strain. The higher the value of the strain is, the more heavy the traffic is (see Figure 13).

Figure 11. Lupu Bridge

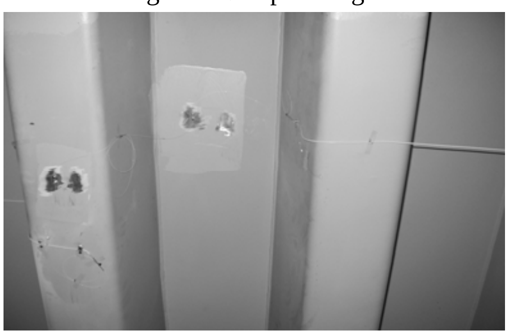

Figure 12. FBG sensors being placed

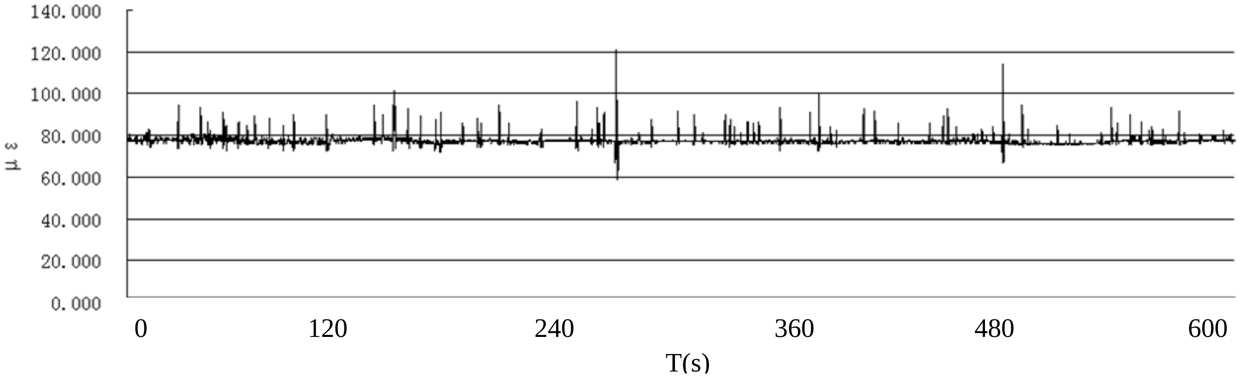

Figure 13. The time history of strain form the FBG sensor

4 FBG ACCELEROMETER

Instead of using a single FBG, we have placed a second FBG into the mechanical structure (mass-spring system). Because of the symmetrical structure of the spring-mass system one grating is stretched while the other one contracts when the sensor is accelerated. So the two Bragg wavelengths always move into opposite directions, and it doesn't need any temperature compensation schemes. In addition, we infused a damping liquid with some viscosity into the mechanical structure and adjust it to make sure of a damping radio $\xi = 70\%$. Thus the accelerometer shows high performance over the frequency range $0 < \overline{w} < 0.6w_o$. At the same time, its life cycle will be prolonged accordingly by infusing a damping liquid. The mechanism of the new FBG accelerometer is shown in Figure 14. At present, we finished the optimum structural design. The next step is that we choose appropriate material, manufacture a prototype FBG accelerometer and examine it.

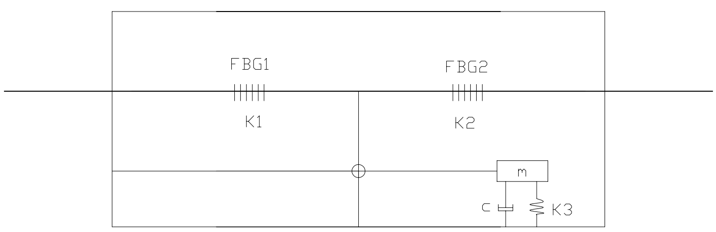

Figure 14. The mechanism of the new FBG accelerometer

5 CONCLUSION

In recent years, the fiber-optic sensors, particularly FBG sensors, have attracted a lot of interests and are being used in numerous applications. The SHM in-service is very important and definitely demanded for safely working of engineering structure. The FBG sensors have some high performances of workability and durability over the conventional sensors in the long-term monitoring. As the SHM system based on FBG, a demodulation device, which converts the wavelength shift, can be used in detecting and inspecting the measurement of environmental parameter such as strain, crack, deflection, pressure, temperature, vibration, chemical concentration and electromagnetic field. Thus many novel FBG sensors will be invented and fabricated. The paper demonstrates a novel design of FBG accelerometer for the civil structure with low frequency.

6 REFERENCES

Akira Mita, Isamu Yokoi, Fiber Bragg grating accelerometer for buildings and civil infrastructures. Proceedings of SPIE Vol. 4330, 479-486 (2001).

Austin, T., Singh, M., Gregson, P., Dakin, J., and Powell, P. Damage Assessment in Hybrid Laminates Using an Array of Embedded Fibre Optic Sensors, Smart Structures and Materials 1999: Smart Systems for Bridges, Structures, and Highways, Proceedings of SPIE, Vol. 3,671, 281–288 (1999).

Berkoff, T. A. and Kersey, A. D. Experimental Demonstration of a Fiber Bragg Grating Accelerometer, IEEE Photonics Technology Letters, Vol.8, 1677-1679 (1996).

Davis, M., Bellemore, D., Berkoff, T., Kersey, A., Putnam, M., Idriss, R., and Kodinduma, M. Fiber-Optic Sensor System for Bridge Monitoring with Both Static Load and Dynamic Modal Sensing Capabilities. Proceedings of SPIE, Vol. 2,946, 219–232 (1996).

Hill, K. O., Fujii, F., Johnson, D. C. and Kawasaki, B. S., Photosensitivityon optical fiber waveguides: Application to reflection filter fabrication. Appl. Physics Lett., Vol. 32, 647–649, (1978).

Joan R.Casas and Paulo J.S.Cruz, M. Fiber optic sensors for bridge monitorin. journal of bridge engineering, VOl,8. ASCE,362-373(2003)

Todd, M. D., Johnson, G. A., Althouse, B. A. and Vohra, S. T., Flexural Beam-Based Fiber Bragg Grating Accelerometers, IEEE Photonics Technology Letters, Vol.10, 1605-1607 (1998).