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DEVELOPMENT OF FBG SENSORS FOR STRUCTURAL HEALTH MONITORING IN CIVIL INFRASTRUCTURES

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Abstract: In recent years, FBG (Fiber Bragg Grating) has been accepted as a new kind of sensing element for structural health monitoring (SHM) in civil infrastructures. Cost of FBG fabrication, high-quality FBG demodulation system, practical encapsulation (package) techniques and indirect FBG-based sensors, and practical applications are the cores for FBG to be widely popularized in infrastructures. In this paper, firstly, the FBG fabrication and demodulation system are briefly introduced and the practical needs from infrastructure are pointed out; Secondly, the practical encapsulation (package) techniques and indirect FBG based sensors from Harbin Institute of Technology (HIT), have been conducted; Thirdly, some practical applications, taken as examples, are carried out; Finally, the future studies and problems are also set forth. Researches and practical applications show that FBG sensors have become one of the key sensors in SHM instead of some conventional electrical sensors.

Key words: FBG, sensor, structural health monitoring, civil infrastructure.

1. INTRODUCTION

After almost 10 years' development, SHM has currently become the highlight of researches and applications in civil infrastructures all over the world. And its core is damage detection and identification. As is known, it is a big challenge to perform accurate damage analysis, especially the damage location, via global information. Local damage monitoring seems paramount. Generally speaking, local damage behaves as crack, fatigue, slip, debonding, effective force-resistance area loss, and so on. Strain is an alternative parameter which can be used to describe deformation, study the crack opening and even detect the slip and bonding, so high-quality strain sensor has always been pursued by the structural researchers. However, infrastructures are generally large, long span and serve for a very long time, so the local durable and reliable sensors are the foundation of successful health monitoring systems. Optical fiber sensors, especially the sensors based on FBG, show distinguishing advantages: electro-magnetic resistance, small size, resistance to corrosion, multiplexing a large number of sensors along a single fiber, etc. FBG has more and more become the most prominent sensors for structural monitoring.

In this paper, aiming at the practical application of FBG sensors in infrastructures, the FBG fabrication and demodulation system are introduced briefly and the practical needs from infrastructure are pointed out. Then, the practical encapsulation (package) techniques and indirect FBG based sensors, especially from Harbin Institute of Technology (HIT), have been conducted. And some practical applications from HIT taken as examples are carried out. Finally, the future studies and problems are also set forth. By and large FBG sensor is predicated that have become one of the key sensors in SHM instead of some conventional electrical sensors.

2. FBG FABRICATION AND DEMODULATION

2.1 FBG fabrication

Due to the great potential of FBG’s applications, more research was conducted on the fabrication methods of FBG. Currently, there are two major methods for fabricating Fiber Bragg Grating: holographic method and phase mask method (Hill, 1993). In 1989, Meltz used holographic interference setup to write FBG, and the grating was written from the side of fiber. Away from G. Meltz’s two UV beams interference, other methods were given to improve the stability during the fabrication process, such as using a prism to split the UV beam and then interference. The advantage of the Holographic method: it is easy to adjust the angle between two beams to create different periods, therefore, to fabricate FBG with difference wavelengths. The disadvantage of this method is that a more stable setup is needed and a good coherence light source is also requested in the meantime.

In 1993, Hill et al gave another easy method to fabricate FBG by phase mask. Phase mask is a piece of diffractive grating with depth modulation on fused silica. The phase mask were designed to suppress 0^{th} order diffraction efficiency (<5%) and increase +/-1^{st} order efficiency (>35%). When a UV beam incident on phase mask, the +/- 1^{st} order beam will credit an interference pattern, this pattern will write the FBG on the fiber. The period on FBG is the half of phase mask. The advantage of Phase Mask method: it is simple with great repeatability as well as the disadvantage of Phase Mask: each mask can only generate one wavelength of FBG.

2.2 FBG demodulation

Currently, interrogators for multiple Bragg grating sensors fall into two main categories: time division multiplexing (TDM) and wavelength division multiplexing (WDM). TMD discriminates between many sensors on a single optical fiber by gauging the time required for a pulse of light to return to the detection system. TDM systems must be designed to balance the sensor-sampling rate with the distance of the sensor from the light source and detection system. Blue Road Inc. has successfully developed FBG interrogators based on such idea. The most popular approach is WDM. WDM systems discriminate individual sensors by wavelength. That is, several sensors may have nominal center wavelengths separated by a few nanometers. Each sensor is tracked simultaneously as its center wavelength changes due to environmental changes like strain, temperature or pressure. Most WDM systems are designed using the basic configurations: broadband source and swept detector (BSSD) or laser source and broadband detector (LSBD). BSSD systems generally use an ASE, LED or SLED source coupled with a tunable filter and broadband detector. Micron Optics Inc. has developed such kind of interrogators as FBG-IS and Sm220. Whereas LSBD overcomes the sensor limitation with much more optical power and laser-based interrogators can illuminate more than 100 sensors per channel, whose limiting factor is usually wavelength range. Micron Optics Inc. has developed high-quality interrogators based on its FFP-TF (fiber F-P tunable filter) technology like SI425.

2.3 Needs from civil infrastructures

General speaking, infrastructures are large, long span and serve for a very long time. Sometimes it is hard to judge the definite positions where the local damages will take place. So in order to assure the reliability of health monitoring system, we can do nothing but install local sensors as many as possible. Unfortunately, it conflicts much with the cost of FBG sensors and interrogators. In order to popularize of FBG sensors in infrastructures, high-quality and effective FBG fabrication techniques should be developed. And the best way is to produce FBG by batch, which can drop down the cost. 3 kinds of FBG interrogators should be developed urgently due to the needs of quality control of construction, real-time and long- term heath monitoring system, and FBG-based sensors calibration and quality-control. The first kind of interrogator should be small size, high-precision, portable and battery based, which does not need high frequency and multi-channel. The second should be high frequency (> 100Hz), multi channels (>16 channels) and durability (> 10 years). The third should be high precision (< 2 *pm*) and revolution (< 0.5 *pm*). The 3 kinds of FBG interrogators are the base of FBG popularization in civil engineering.

3. SENSORS BASED ON FBG FOR INFRATRUCTURES

Bare FBG shows good compatibility with infrastructures, but due to its fragility, bare FBG without encapsulation (package) is not proper to be directly applied in practical infrastructures. Otherwise, we have to develop special in-situ installation and protection techniques for bare FBGs. Unfortunately, the "perfect" installation techniques often conflict with the in-situ construction, or it can not meet the demand of critical schedule of construction. Besides, in order to make full use of FBG, we should develop indirect sensors device based on FBG and combine the FBG and construction materials. Many sensors based on FBG have been developed. Under the support of several projects related to heath monitoring, Harbin Institute of Technology, China, has developed some practical packaged FBG sensors, indirect sensor devices and FRP-combined sensors, which are commercially available.

3.1 Encapsulated FBG strain sensor for embedment

In order to overcome the embedment of FBG strain sensor in concrete structures, HIT has developed the technique of mental tube encapsulated FBG strain sensor, depicted as figure 1.

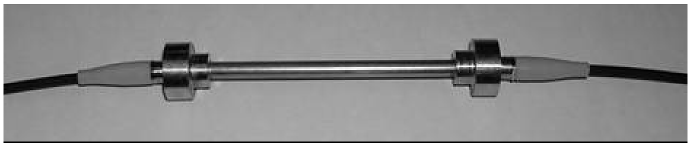


Figure 1 Picture of mental tube encapsulated FBG strain sensor

3.2 Encapsulated FBG strain sensor for surface strain measurement

In order to overcome the installation of FBG strain sensor on surface of steel or concrete structures, HIT has developed the technique of mental slice encapsulated FBG strain sensor, depicted as figure 2.

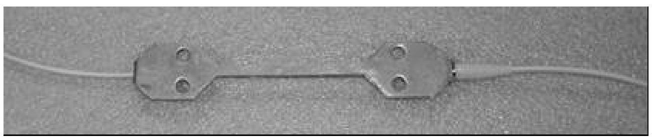


Figure 2 Picture of mental slice encapsulated FBG strain sensor

3.3 Encapsulated FBG temperature sensor

In order to overcome the installation of FBG temperature sensor on or inside structures, HIT has developed the technique of encapsulated FBG temperature sensor, depicted as figure 3.

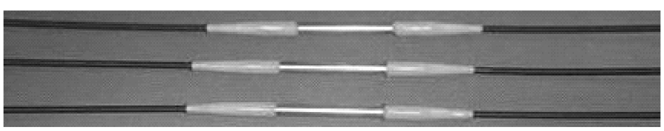


Figure 3 Sketch for steel capillary encapsulation for FBG temperature sensor

3.4 Smart rebar based on FBG sensors

FRP is now more and more accepted as a kind of important construction material. To make full use of FRP's strength properties and FBG's sensing properties, Prof. OU has developed the fabrication technique of FRP-OFBGs bars and gotten the products, shown as Figure 4.

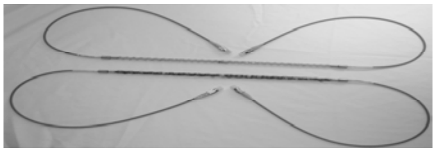


Figure 4 FRP-OFBG sensors

3.5 Indirect sensor devices based on FBG

1) Ice pressure sensing device based on FBG

Ice load is important force acting on offshore platforms in the high-latitude district. Conventional ice pressure meter is based on electrical strain gauge, whose durability is very bad. A novel ice pressure sensing device based on dual FBGs is developed by HIT. Its inside structure is shown as figure 5. The main idea for the ice pressure sensing device is based on cantilever with dual FBGs installed up and down the surface and the load transfer structure. When load acting the device, we can get it by the dual FBGs, which is self-temperature compensation and the measurement results is not relative to the acting position. Such kind of ice pressure sensing device is proper for practical application.

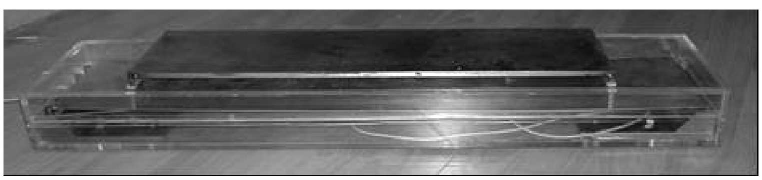


Figure 5 Structure of ice load sensing device based on dual FBG

2) Smart cable based on FBG

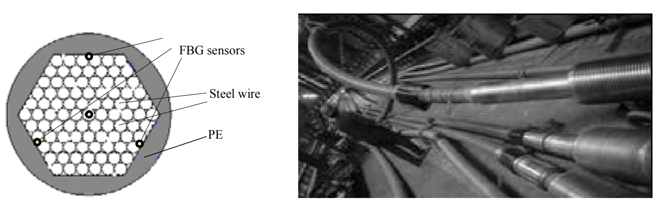


Figure 6 Smart cables based on FBGs

Cables are the key member of cable-stayed bridges, suspension bridges, hanging bridges and so on. The bridge cables in service are easily damaged due to the factors of environment corrosion, fatigue, materials aging, stress redistribution, etc. How to evaluate the damage or stress state of the cables in service has always still been a big challenge for civil engineers. HIT has developed a new kind of cables installed with FBGs during manufacture of the cables, shown as figure 6. The feasibility and advantages of smart bridge cable based on FBGs are test. This kind of cables has been applied in Luoguo Bridge in Panzhihua, and Binzhou Yellow River Bridge in Shangdong, China.

3) Smart weight in motion

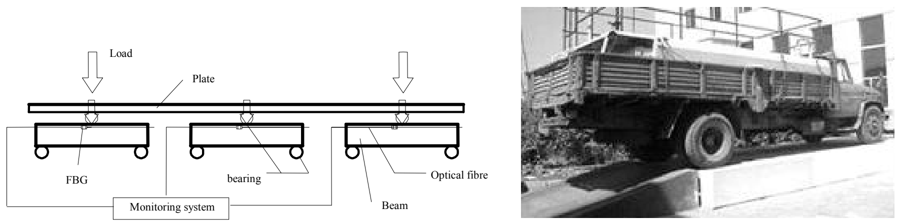


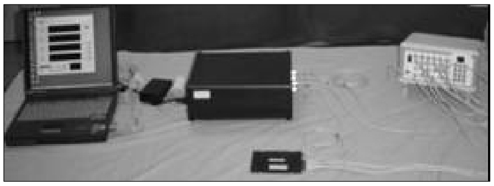
Figure 7 Weight in motion based on FBG

Based on the sensing properties of FBG, a new kind of smart weigh in motion, namely smart FBG weighbridge, has been developed, shown as figure 7. The smart FBG weighbridge is based on the principle that the traffic weight can be gotten from the deformation of the reinforced concrete beam with embedded FBG strain sensors which measure the deformation. This kind of weighbridge shows the features of simplicity, convenience, high precision, good durability, low cost and so on.

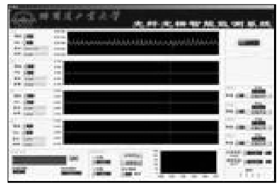
4. APPLICATIONS OF FBG SENORS

FBG sensors have been applied in many infrastructures. HIT have developed intelligent monitoring system based FBG and applied it in several projects as follows. And more than 2000 FBGs has been used

4.1 Intelligent monitoring systems based on FBG



(a) Practical devices for monitoring system based on FBG sensors



(b) Software of intelligent monitoring system based on FBG sensors

Figure 8 Intelligent monitoring system based on FBG sensors

The intelligent monitoring system based on FBG sensors include FBG sensors, optical coupler (optical switch), FBG interrogator, transmission cable, jumpers and relative software, which shown as figure 8 (a) and (b).

4.2 FBG sensors applied in Bridges

Due to that the bridges is the key part of transportation, lots of large-span bridges are under construction in developing countries as well as China. With the development of structural health monitoring, the bridge owners realize the importance of adding structural health monitoring system to the bridges under construction in order to avoid disastrous tragedy to happen. OU has developed several structural health monitoring systems based on FBG sensors to be applied in the several large-span bridges, shown as figure 9-12, to monitor the performance of the bridges under construction and in service.

Figure 9 Songhua River Bridge in Heilongjiang (2003, over 50 FBGs uses)

Figure 10 Dongying Yellow River Bridge in Shandong (2003, over1800 FBGs used)

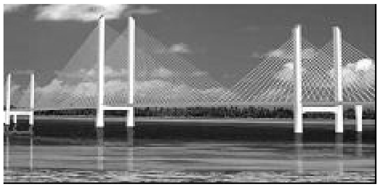


Figure 11 Binzhou Yellow River Bridge in Shandong (2002, over 130 FBGs used)

Figure 12 Nanjing third Yangtze river Bridge (2003, over 300 FBGs used)

4.3 FBG sensors application on offshore platform

Offshore platform is the key infrastructures for oil exploitation, which serve in extremely bad environments with wind, wave, ice and ocean current, even corrosion, so the life of the offshore platform are very short, 20 years or so. It is in great need to real-time evaluate the safety and predict the remaining life of the platform.

Under the support of 863 High Tech. Research Program, OU and Duan (2002) have developed a large real time structural health monitoring system to monitor the global and local performances of the platform, such as acceleration, strain, temperature and crack and so on, and even the environment load mentioned above by the ocean weather observation station. According to the monitoring information and the designed model, the safety state of the platform can be given real time. CB32A located in Bohai Bay is the application demonstration of the project achievement, shown as *Figure 13*, where the intelligent monitoring system based on FBG sensors is applied. And more than 350 FBGs has been used.

Figure 13 CB32A platform in Bahai bay (more than 350 FBG used)

5. CONCLUSIONS AND REMARKS

FBG (Fiber Bragg Grating) has been accepted as a new kind of sensing element for structural health monitoring (SHM) in civil infrastructures. FBG sensors' key research areas include FBG fabrication, FBG demodulation, FBG encapsulation, indirect sensing device based on FBG and practical applications. The core problems focus on reliable FBG standardized encapsulated sensors and the multi-channels, high frequency, and high precision low-cost demodulation devices. Researches and practical applications show that FBG sensors have become one of the key sensors in SHM and will take the place of some conventional electrical sensors.

As a new kind of sensor for structural health monitoring system, popularization of FBG is still a challenge for researchers. Following problems should be the directions of future studies on FBG: 1) Develop low-cost standard bare FBG with stable sensing coefficient; 2) Effective temperature compensation techniques for FBG strain sensors used in long-term monitoring systems; 3) How to develop standardized FBG encapsulated sensors; 4) How to develop smart devices based on FBG to detect special parameters of infrastructures, such as corrosions, slip, debonding, and so on; 5) How to avoid the damage of the FBG sensors and cables during constructions; 6) How to develop low-cost multi-channel interrogators when we have to face the embarrassment that we have no choice but to cut down the number of FBG sensors along one cable, even sometimes one sensor on one cable, which makes us not able to make full use of the advantages of FBG; 7) How to develop large integrated FBG monitoring system and make it become the important part of the Structural Health Monitoring System and give useful information for damage identification.

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