Optic fiber Bragg-grating-based sensing technologies and their applications in structural health monitoring*

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ABSTRACT

Optical fiber Bragg grating (FBG) has been appreciated as prominent high-durable local monitoring sensor and largely applied in structural health monitoring (SHM). However, it is still a big problem how to develop the feasible FBG-based sensors to fully meet the practical SHM for infrastructures. Many recent advances of FBG sensors for SHM in Harbin Institute of Technology, P.R. China are introduced in this paper, which include direct FBG-based sensors, indirect FBG-based sensors; FBG based smart structures, and the applications of FBG sensors in some typical civil infrastructures. Finally, some directions of researches and applications have been recommended. Researches and practical applications show that FBG sensors are becoming one of the key sensors in long-term SHM instead of some conventional electrical sensors.

1. INTRODUCTION

SHM has currently become the highlight of researches and applications in civil infrastructures all over the world. However, infrastructures are generally large, long span and serve for a very long time, so the durable and reliable sensors are the base of successful SHM systems. As one of the most important inventions in measurement field in the late 20th century, optical fiber Bragg grating (FBG) has been greatly recognized and largely applied in long-term structural health monitoring (SHM) (Mufti 2003; Ou & Zhou 2002~2005) due to that optical FBG shows distinguishing advantages: electro-magnetic resistance, small size, resistance to corrosion, multiplexing a large number of sensors along a single fiber, etc. However, it is still a big problem how to develop the feasible FBG-based sensors to fully meet the practical SHM for infrastructures.

Aiming at the practical needs from large infrastructures, Harbin Institute of Technology (HIT) has made some progress on research and development of FBG-based sensors. In this paper, many recent advances of FBG sensors for SHM in HIT are introduced, which include direct FBG-based sensors, indirect FBG-based sensors, FBG based smart structures, and the applications of FBG sensors in some typical civil infrastructures. Finally, some directions of researches and applications have been recommended.

2. IRECT FBG SENSORS

2.1 Direct FRP-packaged FBG strain sensors

Due to bare FBG's fragility, it is very difficult to apply bare FBG without package in practical infrastructures under rough construction conditions or harsh environment. However, if the FBG is packaged by glue and metal, a new "short life" problem will come out due to that the creep and aging defection of the glue will restrict the high durability of FBG sensors. Making full use of FRP's of durability and pseudo–elastic constitution, HIT has developed various FBG strain sensors by

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combining the FBG sensors and FRP, which shows wonderful strain sensing properties and long-term durability. The sensors are depicted as figure 1. The sensing properties show that measure range is above 5000με, even to 10000με; resolution is 1~2με or so (depended on FBG interrogator); repeatability error is less than 0.5%; linearity error is less than 0.8%;

sensitivity coefficient is about 7.8E-7 and the hysteresis error is less than 0.5%; Fatigue life is over 2×10^6 times at 3000±1000με. After 12 months' corrosion test, the sensors still keep their strain sensing properties. Such types of packaged FBG strain sensors can be designed according to the needs of the customers and are proper for long-term SHM for large infrastructures.

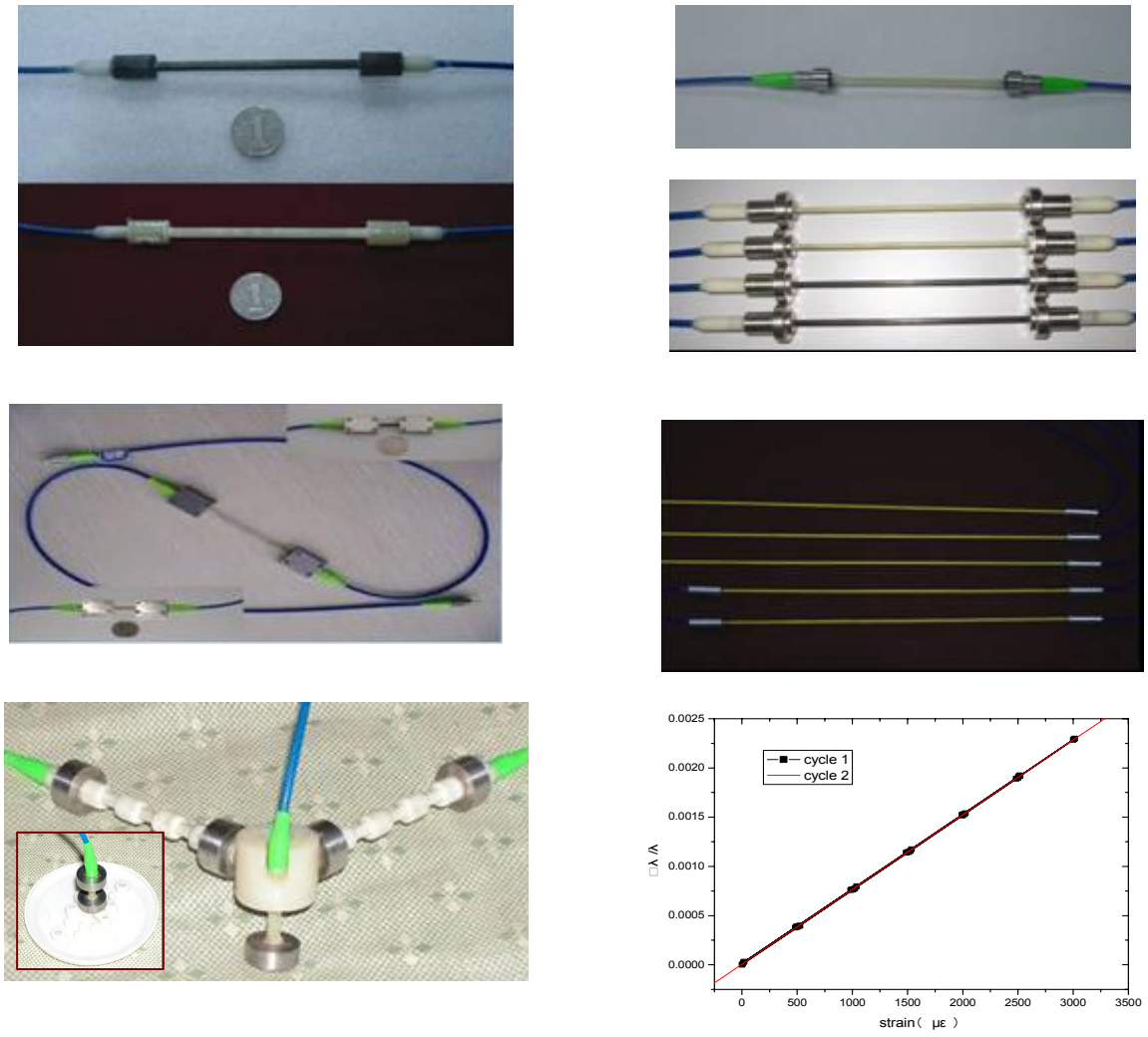


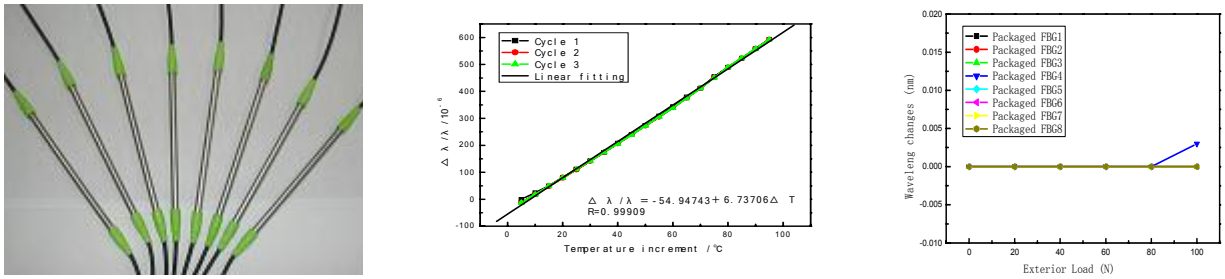
Figure 1. Various FRP-Packaged FBG strain sensors

Besides, in order to detect the large strain, much bigger than 15000με, or high resolution, less than 0.5με, a new kind of sensitivity-increasing or decreasing technology has been developed in HIT. Such kind of FBG-based sensors can be easily designed and fabricated according to the practical applications.

Figure 2. Sensitivity adjustable FBG-based sensors

3. DIRECT FBG-BASED TEMPERATURE SENSORS

Ordinary packaged FBG temperature sensor is easily influenced by exterior load and results in crossing-sensing errors. Novel FBG temperature sensor without exterior load influence over 80N has been developed. The sensor and its sensing properties are given as figure 3.



a) Sensor picture b) Sensing property c) Loading resistance

Figure 3. Novel FBG temperature sensors without exterior load influence

4. INDIRECT FBG-BASED SENSORS

4.1 High durable FBG-based steel rebar transducer

The FBG-based steel rebar transducer is developed by the technique of strain isolation and the product shows the properties like that of Bare FBG, which is given as Figure 4.

Figure 4. High durable packaged FBG steel rebar meter

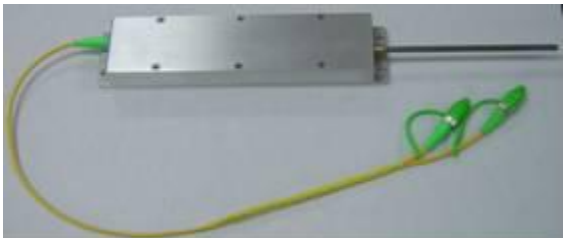
4.2 FBG-based crack sensor (large strain sensor)

General speaking, the bare FBG can only stand 3000~5000$\mu\varepsilon$, so it is impossible to use bare FBG to detect large strain, especially the cracks. HIT has developed such sensors by technique of sensitivity-decreasing, shown as figure 5. The large FBG strain sensor can detect 100000με at maximum, almost 20mm crack at the calibration length of 20 centimeter and the accuracy can reach 0.002mm.

Figure5. FBG crack sensor (large strain sensor)

4.3 FBG displacement transducer

The FBG displacement transducer depicted as figure 6 is developed by technique of sensitivity-decreasing, which can detect 0.01mm at the calibration length of 10cm.



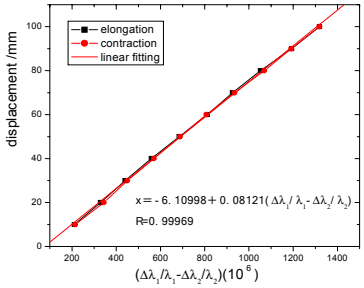
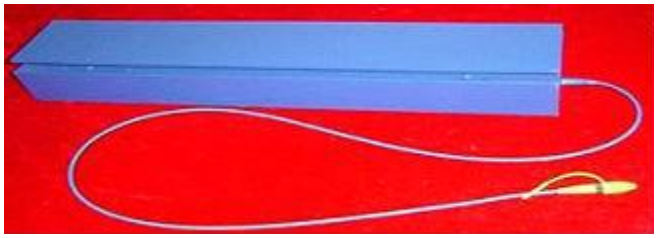


Figure 6. FBG displacement transducer developed at HIT

4.4 Novel ice-load cell based on dual FBGs

Ice load is important for offshore platforms and bridges across rivers in the high-latitude area. A novel ice pressure sensor based on dual FBGs has been developed at HIT, given as figure 7. The FBG-based ice load cell is independent of loading position and temperature changes.



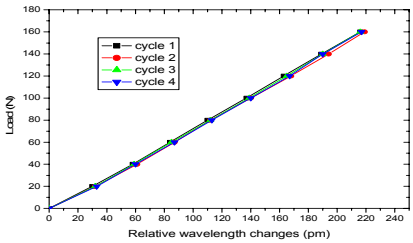


Figure 7. Novel ice load cell based on dual FBGs

4.5 FBG-based cable load cell

Cables are the main load-bearing components for stayed-cable bridges and its stress status is very important for safety evaluation when bridges under construction and in-service. A FBG-based load cell has been developed, shown as figure 8, which is suitable for stay cables.

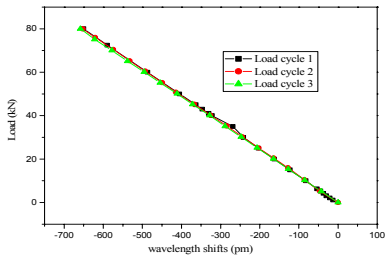
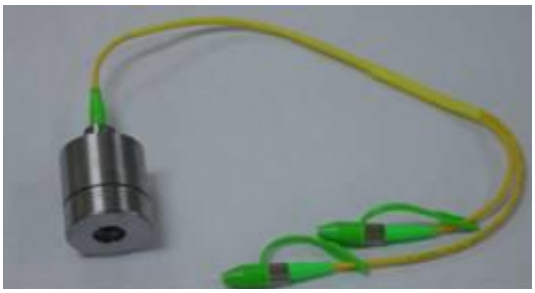


Figure 8. Novel ice load cell based on dual FBGs

4.6 FBG-based osmometer

Traditional ohmmeters are based on vibrating string or strain gauge, whose durability can not meet the need of long-term monitoring of soil hydraulic pressure under harsh environment. A novel FBG-based osmometer has been developed in HIT, shown as figure 9.



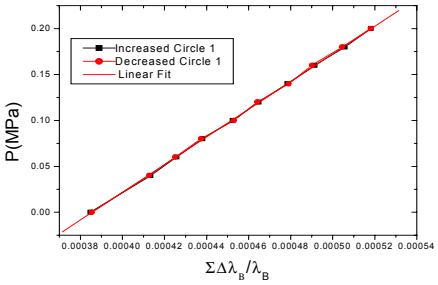


Figure 9. FBG-based osmometer

4.7 FBG-based simultaneous displacement and load transducer

Displacement and load are useful information for safety evaluation in some particular situation. A FBG-based simultaneous displacement and load transducer has been developed in HIT, shown as figure 10.

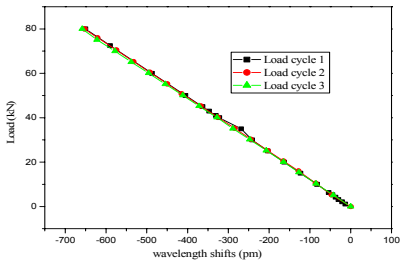


Figure 10. Novel ice load cell based on dual FBGs

4.8 FBG-based soil-pressure transducer

The durability and stability are the factors for soil pressure sensor under rough condition. A high-durable FBG-based soil pressure transducer has been developed in HIT, shown as figure 11.

Figure 11. Novel ice load cell based on dual FBGs

5. SMART FBG-BASED STRUCTURES

Combined FBG and other structures (or special material), new kinds of smart structures with high sensing properties can be developed. Aiming at possible practical applications, HIT has developed several smart structures based on FBG, such as FRP-OFBG rebar, board, tube and sheets; smart cables and weigh-In-Motion based on FBG.

5.1 FRP-OFBG rebars/board/ tube and sheets

Fiber Reinforced Polymer (FRP) has shown advantages of corrosion-resistance, high strength, nonmagnetic, fatigue-resistance and so on. Combined the FRP with OFBG, new kind of smart FRP-OFBG composite rebars/board/ tube and sheets have been developed. The FRP-OFBG can act as strain sensors and reinforcing components simultaneously, which can be used to detect slip and crack in RC structures. The developed FRP-OFBG rebars are given as figure 12.

Figure 12. FRP-OFBG rebars and their sensing properties

5.2 Smart FBG-based cables

Cables are the key components of cable-stayed bridges, suspension bridges, hanging bridges and so on. They are easily damaged due to the factors of environment corrosion, fatigue, materials aging, stress redistribution, etc, which may result in that the cables can not stand as long as originally designed. The installation techniques and the sensing properties of FBGs in three kinds of cables: FRP cables, common steel-wire cables and extruded-anchor cable are studied. In order to dissolve the practical problem of how to effectively install FBG sensors on bridge cables, a novel simple and effective solution is brought forward to develop smart bridge cables using FRP-OFBG bars. The FRP-OFBG bars in the cable act as components of the cable and can be regarded as well-protected sensors. The deformation of FRP-OFBG bars in the smart cables can be consistent with that of the cables and give the load and damage information of the cables. The developed FBG-based cables are shown as figure 13.

Figure 13. Smart cables based on FBG

5.3 Smart FRP anchor based on FBG

FRP has become the alteration material of steel in civil engineering. However, the anchor is the baffle for FRP's applications because the interface between FRP and anchor is not fully understood without proper measurement technique to get the inner strain distribution. HIT has developed smart FRP anchor based on FRP-OFBG, given as Figure 14, which can supply important information to FRP anchor design and can also monitor the anchorage system, which is useful for the application of FRP in civil engineering.

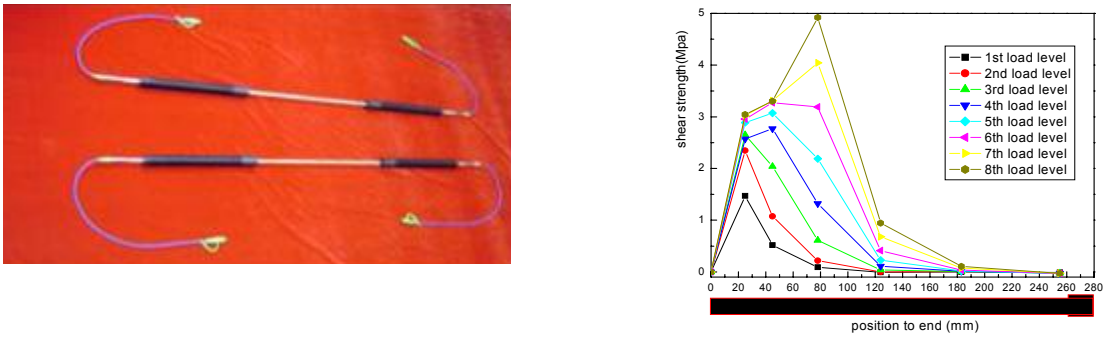


Figure 14. Smart FRP anchor based on FBG

5.4 Smart FBG-based Weigh-In- Motion

Durability is the key problem of traditional traffic Weigh-In-Motion (WIM) based on electrical gauges. A new kind of high durable traffic WIM has been studied and developed using up-supported load transducer based on FBG, shown as figure 15.

Figure 15. Smart FBG-based Weigh-In-Motion

6. APPLICATIONS OF FBG SENSORS IN SHM OF INFRASTRUCTURES

Under supports of some projects, HIT has applied large number of FBG sensors in more than 10 practical infrastructures, such as Yonghe River Bridge in Tianjin, Binzhou and Dongying Yellow River Bridges and Tailai High-way Road in Shangdong Province, Songhua River Bridge, Hulan River bridge and NiutouShan bridge in Heilongjiang Province, Nanjing third Yangtze river Bridge, Maocaojie Bridge in Hunan Province, Erbian bridge in Sichuan and Guangyangdao Bridge in Chongqing, CB32A offshore platform, Olympic Swimming Center in Beijing, and so on.

7. CONCLUSIONS AND REMARKS

In this paper, various optical FBG-based sensors developed in HIT are introduced. The main contents include direct FBG-based sensors, indirect FBG-based sensors and FBG-based smart structures. Optical fiber Bragg grating (FBG) based sensors have been greatly recognized and largely applied in long-term structural health monitoring (SHM). However, following problems are still challenges for FBG's popularization: Durable package techniques for FBG to be used to develop new kinds of sensors to meet the needs of long-term SHM system; FBG sensors guideline or standardization for long-term SHM; High performance, low cost, multi channel FBG interrogators; integrated system of FBG for long-term SHM and so on.

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