Various types of optical FBG sensors and their applications in SHM

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ABSTRACT: As one of the most important inventions in measurement field in the late 20th century, optical fiber Bragg grating (FBG) based sensors have been greatly recognized and largely applied in long-term structural health monitoring (SHM). In this paper, various types of optical FBG sensors and applications in SHM are introduced. The main contents 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 have become 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) based sensors have 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. By now, it is time to develop practical popular techniques to make FBG easy to be understood and applied, and drop down the cost of FBG systems for civil infrastructures.

Aiming at the practical needs from large infrastructures, Harbin Institute of Technology (HIT) has made some progress on the durability problem for the package of FBG sensors based on the basic theory of strain transfer, creep effect and the optimization design. And various FBG-based sensors and smart structures have been developed in HIT.

In this paper, various types of optical FBG sensors and applications in SHM are introduced. The main contents 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.

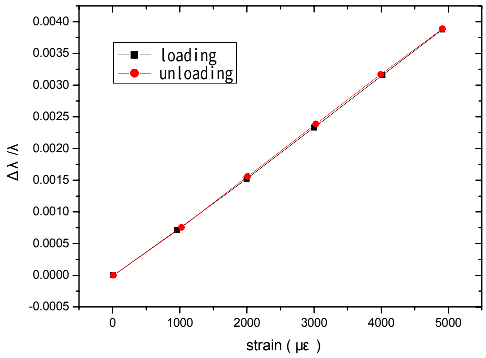
2 VARIOUS FBG-BASED SENSORS

2.1 *Direct FBG-based 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 combining the FBG sensors and FRP, which shows wonderful strain sensing properties and long-term durability.

Six types of FRP packaged FBG strain sensors are given as follows, depicted as figure 1~6. The sensors are packaged without any short-life materials. Their common sensing properties show that measure range is above 5000$\mu\varepsilon$, even to 10000$\mu\varepsilon$; accuracy is 1~2$\mu\varepsilon$ or so (decided by 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 higher than 1×1,000,000 times at 1000 $\mu\varepsilon$. After 4 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.

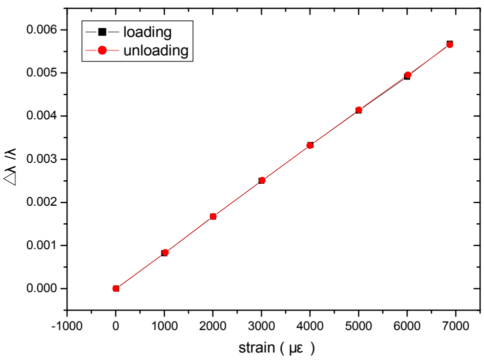
a) Sensor picture



b) Sensing properties

Figure 1. CFRP packaged embeddable strain sensor with 80~100 mm calibration length

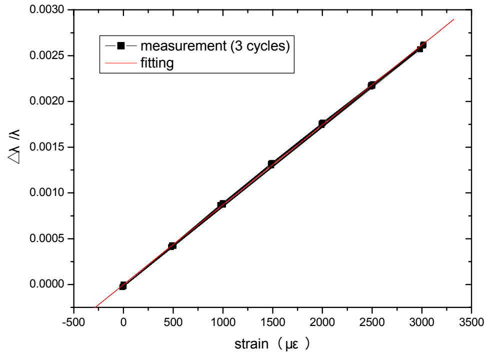
a) Sensor picture



b) Sensing properties

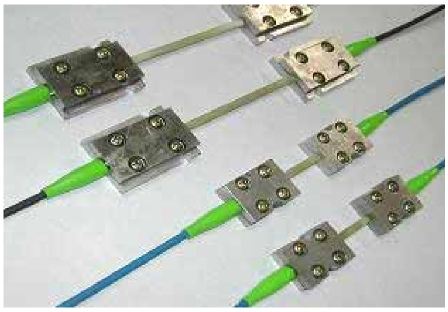
Figure 2. GFRP packaged embedded strain sensor

a) Sensor picture

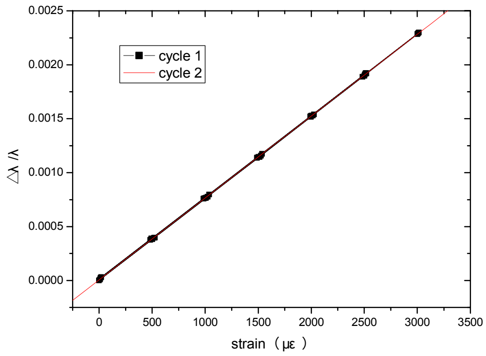


b) Sensing properties

Figure.3 FRP-packaged embeddable FBG strain sensor with enlarged end

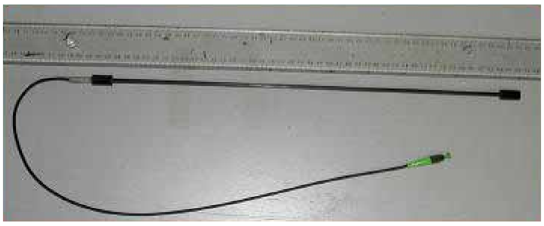


a) Sensor picture

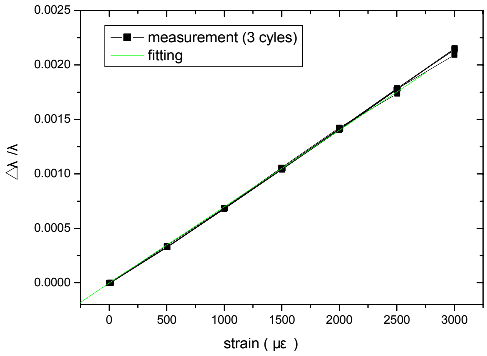


b) Sensing properties

Figure 4. GFRP (CFRP) packaged weldable strain sensor

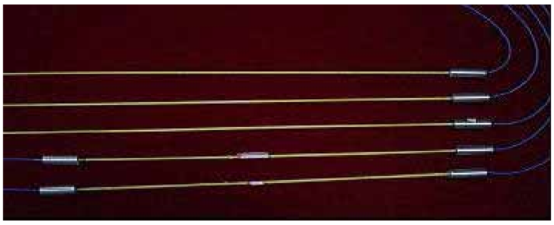


a) Sensor picture

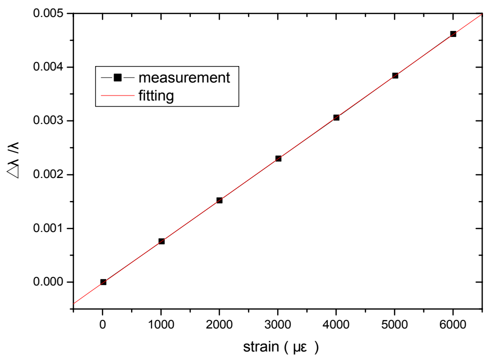


b) Sensing properties

Figure 5. FRP packaged embeddable long gauge FBG strain sensor



a) Sensor picture



b) Sensing properties

Figure 6. FRP-packaged embedded long gauge FBG strain sensor

Moreover, In order to calibrate the FBG strain sensors, HIT has developed the convenient device for all kinds of FBG strain sensors including the embeddable and weldable ones, which is shown as Figure 7.

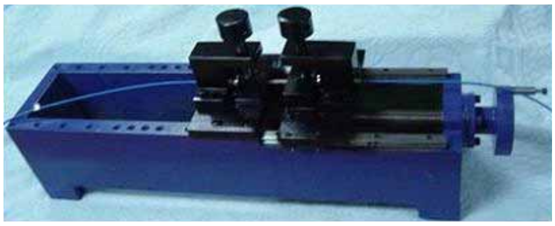
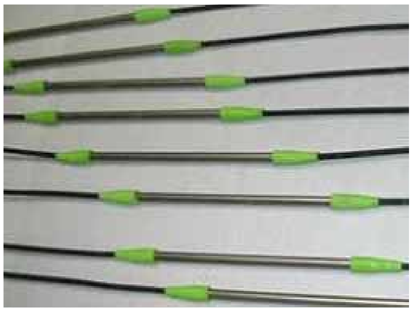


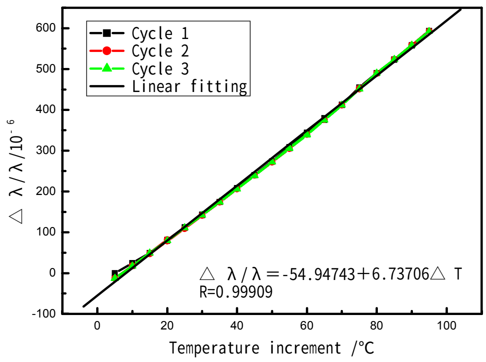
Figure 7. FBG strain sensors calibration device

2.2 *Direct FBG-based FBG temperature sensors*

Common packaged FBG temperature sensor is easily influenced by exterior load and results in errors. Novel packaged FBG temperature sensors without load influence by prototype and sensitivity-increasing package techniques are developed, respectively. The sensitivity coefficients of prototype-packaged FBG temperature sensor and sensitivity-increasing packaged FBG temperature sensor are 1 and 2.86 times of that of the bare FBG, respectively. Moreover, the packaged FBG temperature sensor's wavelength is not changed under load of 80N when the environment temperature remains the same. Such kinds of package technique are proper for FBG temperature sensors under possible loading condition. The developed sensors and their sensing properties are given as figure 8 and 9. And the loading effection result is given as figure 10.



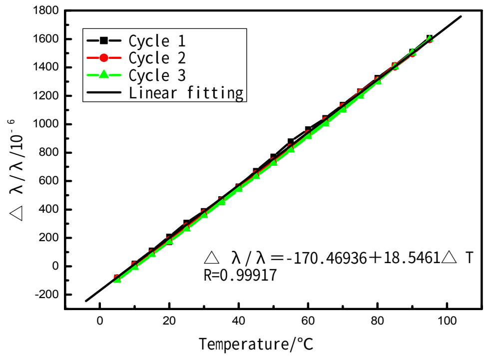
a) Sensor picture



b) Sensing properties

Figure 8. Prototype packaged FBG temperature sensors without exterior loading influence

a) Sensor picture



b) Sensing properties

Figure 9. Sensitivity-increasing Packaged FBG Temperature sensors without exterior loading influence

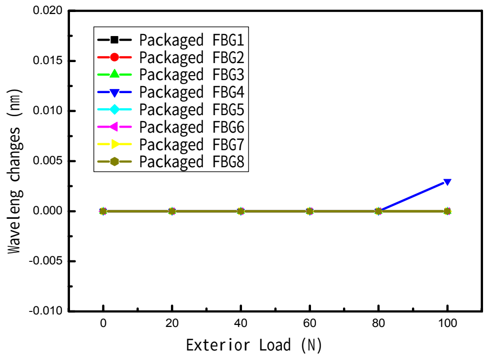


Figure 10. Influence of exterior loading on packaged FBG temperature sensor

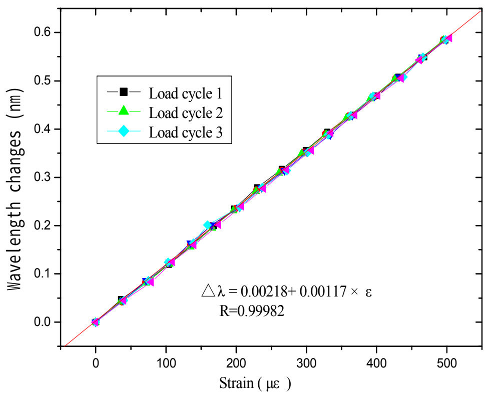
2.3 *Indirect FBG-based sensors*

There are so many necessary parameters to measure. HIT has developed various indirect FBG-based sensors, such as FBG steel rebar meter, FBG crack meter, FBG displacement transducer, cable and ice load cells.

2.3.1 *High durable FBG steel rebar meter*

The FBG steel rebar meter is developed by the technique of strain isolation and the products shows the properties like that of Bare FBG, which is given as Figure 11.

a) Sensor picture



b) Sensing properties

Figure 11. High durable packaged FBG steel rebar meter

2.3.2 *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 12. The large FBG strain sensor can detect 100000$\mu\varepsilon$ at maximum, almost 20mm crack at the calibration length of 20 centimeter and the accuracy can reach 0.002mm.

Figure. 12 FBG crack sensor (large strain sensor)

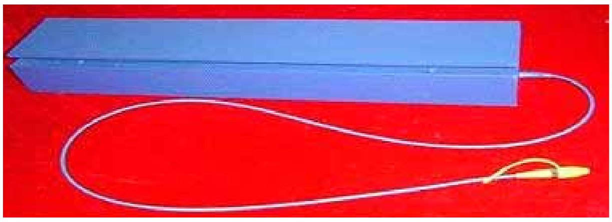
2.3.3 *FBG displacement meter*

The FBG displacement meter depicted as figure 13 is developed by technique of sensitivity-decreasing, which can detect 0.01mm at the calibration length of 10～20cm.

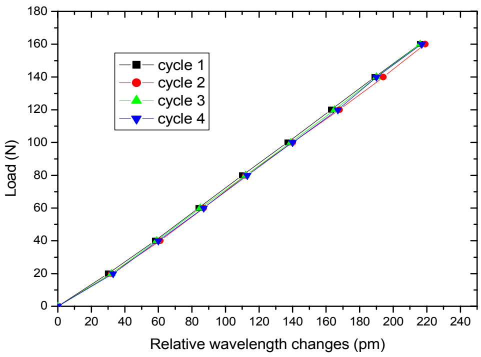
Figure 12. FBG displacement meter developed at HIT

2.3.4 *Novel ice-load cell based on dual FBGs*

Ice load is important for offshore platforms and bridges across rivers in the high-latitude area. Traditional ice-pressure monitoring device based on electrical strain gauge is easy to be damaged. A novel ice pressure sensor based on dual FBGs has been developed at HIT, given as figure 13. The FBG-based ice load cell is independent of loading position and temperature changes and shows good linearity and repetition. Its resolution and accuracy can be adjusted according to the needs of practical structures. Such kind of FBG-based ice load sensor can be used to monitor ice pressure of offshore platform conveniently.



a) Sensor picture

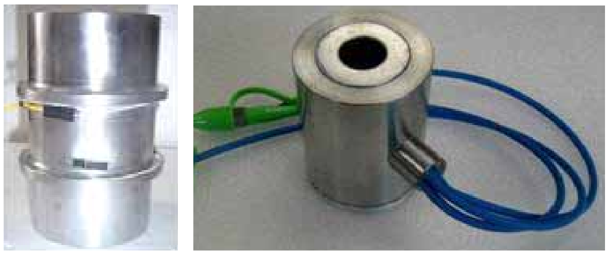


b) Sensing properties

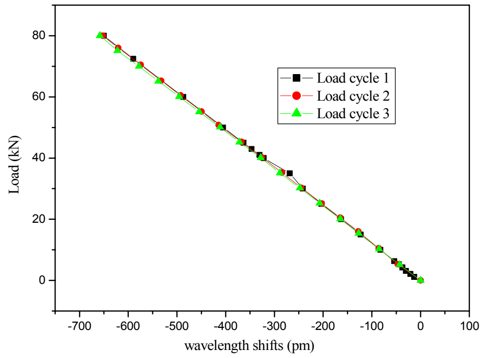
Figure 13. Novel ice load cell based on dual FBGs

2.3.5 *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 14, which is suitable for stay cables.



a) Sensor picture



b) Sensing properties

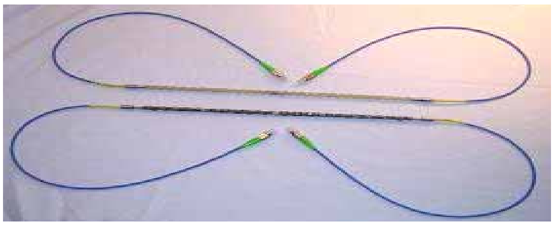
Figure 14. FBG-based load cell for cables

3 SMART FBG-BASED STRUCTURES

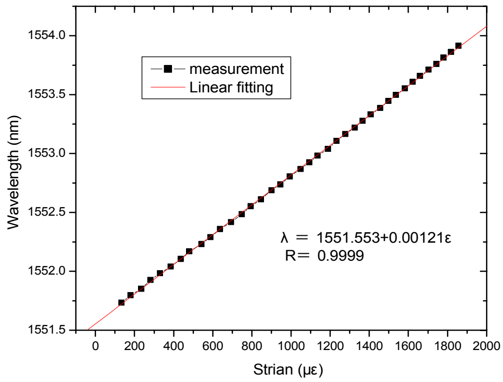
Combined FBG and other structures (or special material), new kinds of smart structures with high sensing properties can be developed. Aiming at possible practical applications, HIT has developed several smart structures based on FBG, such as FRP-OFBG rebar, board, tube and sheets; smart cables and weighbridge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

3.1 *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 15.



a) Sensor picture



b) Sensing properties

Figure 15. FRP-OFBG rebars and their sensing properties

3.2 *Smart FBG-based cables*

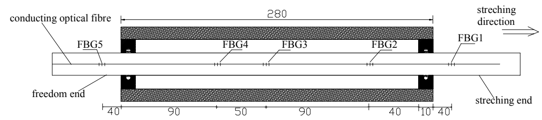
Cables are the key components of cable-stayed bridges, suspension bridges, hanging bridges and so on. They are easily damaged due to the factors of environment corrosion, fatigue, materials aging, stress redistribution, etc, which may result in that the cables can not stand as long as originally designed.

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 cabes, 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.

Figure 16. Smart cables based on FBG

3.3 *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 Figure17, 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.



a) Sensor picture

b) Sensing properties

Figure 17. Smart FRP anchor based on FBG

3.4 *High Durable Traffic Weighbridge based on FBG sensors*

Durability is the key problem of traditional traffic weighbridge based on electrical gauges. A new kind of high durable traffic weighbridge based on FBG has been studied and developed. The principle of the smart FBG-weighbridge is based on that the traffic weight can be gotten from the deformation of the sensing beam with embedded FRP (Fiber Reinforced Polymer) - packaged FBG strain sensors. The results from the tests and calibration analysis show that this kind of weighbridge features high durability, simplicity, convenience, low cost, etc, which is possible to replace the traditional traffic weighbridge for long-term monitoring of traffic load.

Figure 18. High durable traffic Weighbridge based on FBG sensors

4 APPLICATIONS OF FBG SENSORS IN SHM OF INFRASTRUCTURES

Under supports of some projects, HIT has applied large numbers of FBG sensors in more than 10 practical infrastructures, such as Binzhou and Dongying Yellow river bridges 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. Here only 4 different types of bridges and an offshore platform are briefly introduced.

4.1 *Application of FBG sensors in Hulan River bridge*

Hulan River Bridge is located in Hulan county of Heilongjiang province, China. The length of the bridge is 420 meters. There are seven 42-meter spans along the bridge and each span consists of five prestressed concrete box girders. In order to monitor the deformation and temperature of box girders under construction and in service, we have installed 3 FBG temperature sensors and 12 FBG strain sensors on the tendons of 2 box girders in 2001. In order to test the durability of FBGs and compare the measurement results, we have also embedded strain gauges at the close points where the FBGs locate.

After the bridge was completed one year later, the FBGs are still working, but the strain gauges almost died out. We have monitored the strain and temperature course of Hulan River Bridge in service, depicted as figure19~21, which agrees well with the practical situation.

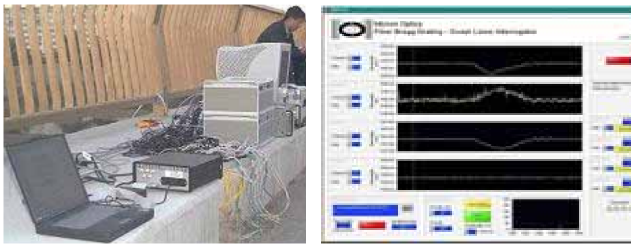


Figure 19. Monitoring of Hulan river bridge

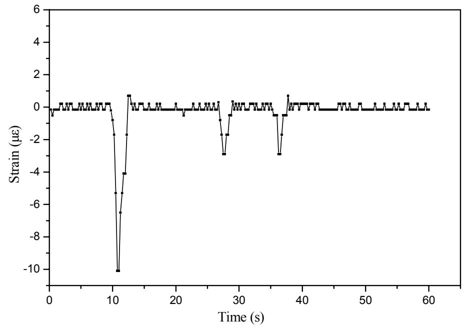


Figure 20. Strain monitored by embedded FBGs sensors when the bridge under traffic load

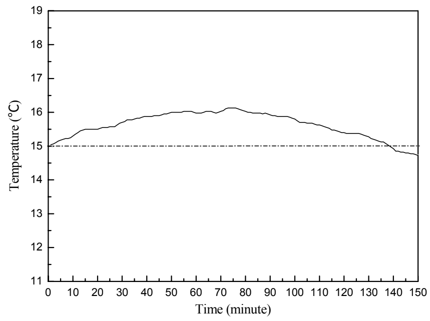


Figure 21. Bridge's temperature-time relationship monitored by the embedded FBG at noon

4.2 *Application of FBG sensors in Binzhou River bridge*

Binzhou Yellow River Bridge is a cable-stayed bridge with three towers, 84+300+300+84m span distribution and located in Binzhou city, Shandong of China, as shown in figure 22. From 2002, 138 FBG sensors has been installed on the bridge during construction and a real-time monitoring system consisted of FBG interrogator, optical switch and coupler has also developed, shown as figure 23 (OU , 2003,2004).

Figure 22. Binzhou Yellow River Bridge under monitoring

Figure 23. FBG monitoring system for Binzhou Bridge

Figure 24 and 25 show the strain and temperature monitoring results from the FBG sensors when the bridges under traffic load test and in service, respectively.

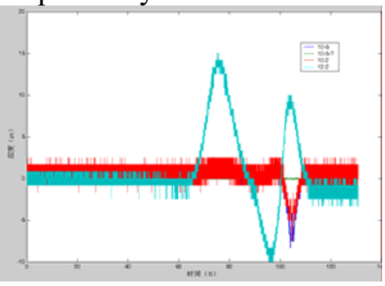


Figure 24. Strain monitoring of FBG under traffic test

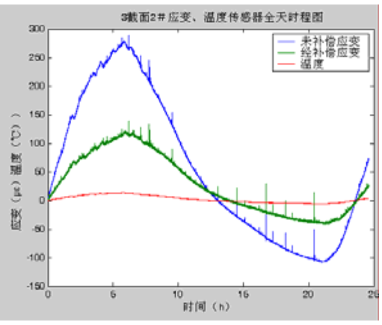


Figure 25. Strain and temperature monitoring of bridge in service

4.3 *Application of FBG sensors in Nanjing third Yangtze River Bridge*

Nanjing 3rd Yangtze River bridge is a cable-stayed bridge with two towers, 648m main span and located in Nanjing city, Jiangsu of China, as shown in figure 26. Because the water with depth of over 20 meters flows very fast at the position where the bridge lies, the method of offshore platform construction is adopted and the construction control is carried out by use of FBG sensors. From 2003, 397 FBG sensors have been installed on the bridge to monitor the stress state of steel protective tube, piles and even the temperature of large mass concrete structures during construction. Some monitoring results are given as figure 27 and 28.

Figure 26. View of Nanjing 3rd Yangtze River bridge

Figure 27. Construction monitoring for steel protective tube

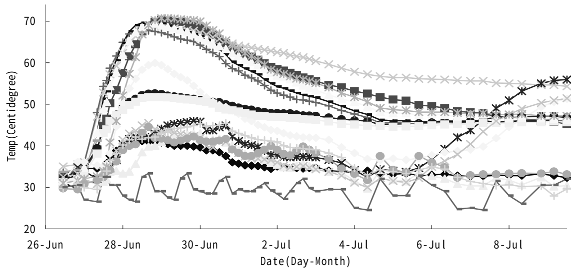


Figure 28. Temperature monitoring of large mass concrete

4.4 *Application of FBG sensors in CB32 offshore-platform in Shengli oil field*

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.

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. offshore platform

The CB32A Platform with jacket height 24.7m was built in 2004 and located in water depth 18.2m. 259 FBGs has been installed during construction, shown as figure 29. This project is still going on and the monitoring system will be open by the end of 1005.

Figure 29. CB32A platform in Bahai bay to be monitored real time

5 CONCLUSTIONS AND REMARKS

In this paper, various types of optical FBG sensors and applications in SHM are introduced. The main contents include direct FBG-based sensors, indirect FBG-based sensors, FBG-based smart structures, and the applications of FBG sensors in some typical civil infrastructures.

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; 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

6 ACKNOWLEDGEMENT

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