Optical fiber sensor-based smart structures

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Abstract. With the rapid growth of civil infrastructures, it has been significant to develop life-cycle monitoring of structures from their inception throughout construction, until final commission and elimination. This paper presents the use of built-in optical fiber sensors and prefabrication methods with the support of Building Information Management (BIM) for the life-cycle issue. Optical fiber-based sensors (OFs) are integrated into the material to produce OF-based intelligent components and systems. The latest progress on the built-in OFs materials, components, and integrated systems with the functionality of self-sensing ability to detect any kind of changes occurring in structures being concerned are presented. Finally, case studies of the project in China using existing developed smart components are also presented. The integration of optical fiber sensors into material and component level ease and improve the structural health monitoring by detection of local and distributed damage with high accuracy throughout the lifespan of the structure.

1. Introduction
The significant growth of civil engineering structures (high-rise buildings, bridges, tunnels, etc.), the changes in external conditions (climate, natural disasters), unspecified decreases in material properties, and the mechanism of aging effects, could lead to diverse scale of damage to structural components and systems. Moreover, corrosion of steel-based structure (reinforced concrete, metallic structure, etc.) remains a doubt and huge challenge in civil engineering construction. Structural health monitoring ensures the safety and provides the health state of the structure during service via the installation of different sensors by using diverse methods. However, obtaining information of civil infrastructures from its inception throughout construction and service, until decommission and elimination is vital to improve the construction management and give an early decision whether repair or maintenance is needed.

Fiber reinforced polymer (FRP) composites have been used worldwide to upgrade deteriorated structures or even to replace certain steel reinforcement [1]. With the advantage in small size and low cost of optical fiber-based sensors, some researchers have proved that the Optical fiber Bragg-grating sensors (OFBGs) packaged into FRP is efficient to detect strain and temperature of structures compare to conventional transducers [2].

Nowadays, countries including China are seeking a new construction method based on prefabrication to reduce the time consuming during construction. Although these new materials (FRP

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composites, transparent concrete, and so on.) seem advantageous over conventional ones, they can also present drawbacks such as the sudden rupture for FRP, which could limit their applications in civil infrastructures by consequently affecting the quality of the pre-assembled structural elements [3]. Moreover, construction manager might not notice changes and damage to prefabricated components during manufacturing and transportation, which could delay the construction progress and even affect the quality of the infrastructure built. Therefore, combining novel materials with OF-based sensors could be a breakthrough for life-cycle monitoring.

This paper summarizes the recent achievements on the life cycle monitoring of civil infrastructure based on OF-intelligent prefabricated systems. The latest development on the smart materials, components, and systems developed by our research group are given. Built-in sensors in the smart components and systems can play a key role in building information modeling (BIM) by providing a lifecycle information for structural health monitoring of the structures from inception throughout construction and service, until decommission and elimination.

2. OF-based smart materials

Due to a wide variety of optical fiber, high diameter plastic fibers are used and integrated into concrete to produce smart transparent concrete. The material produced could perform as a light transmitter (energy saving), optical fiber sensing, infrared alarm, as well as a fiber-reinforced transparent concrete block materials. Figure 1 shows the final smart material obtained. Additionally, optical fiber sensor is built-in with steel rebar using cement mortar to produce smart steel rebar for corrosion monitoring (see figure 2).

![Figure 1. Transparent concrete block with built-in plastic fiber.](image1)

![Figure 2. Smart rebar with built-in FBG.](image2)

3. OF-based smart components

3.1. Description, manufacturing, and characterization.

Smart components are key elements of civil infrastructures manufactured with a built-in optical fiber sensor method. The components are designed to sustain specified loading, as well as having a self-sensing ability. The intelligent elements could be made of fully FRP with built-in optical fiber sensors such as intelligent FRP rebar, smart carbon plate, and self-sensing FRP tube; or fabricated by hybridization method of FRP and steel such as smart steel strand, cable bridge, anchor, etc. The built-in optical fiber sensors and the FRP packaging material are perfectly bonded to form a cohesive part. Therefore, the value of changes (strain, temperature, etc.) obtained from the optical fiber sensors corresponds to the deformation of the FRP material. For components based on hybrid FRP-steel, it is assumed that the deformation on the FRP with a built-in OF bar (FRP-OF) and the steel materials are coherent. Thus, the value of strains obtained from the incorporated FRP rebar is considered as the strain developed in the component. Different optical fiber sensing techniques could be used during the manufacturing of the smart components. Therefore, components with a local, distributed, or even both local and distributed sensing functions are available. The OFs are integrated during pultrusion, or wet lay-up process to manufacture the smart FRP-based components.

To characterize the sensing and mechanical performance of the smart components, calibration tests under corresponding loading case were performed for each manufactured element before any related application. Conventional strain gages are used for comparison as strain is considered as main measurement parameter. Test results reveal that each component performs well to measure strain and temperature with stable and accurate values. The linearity of the measurement and sensitivity nearly equal to a simple FRP-packaged OFs are proved for each type of smart components [4].
3.2. Available OF-based smart components, advantages, and properties
The entire FRP-based components with built-in OF are smart FRP rebar, intelligent Carbon plate, built-in FBG tube, and FRP cable-stayed bridge. Some available components are illustrated in figure 3 to 4.

- **Figure 3.** OF-based smart FRP rebar.
- **Figure 4.** OF-based CFRP plate.
- **Figure 5.** Smart strand Prototype.
- **Figure 6.** OF-based self-sensing anchor.

The intelligent hybrid FRP-steel component is also produced by replacing one or several pieces of steel-based components by the built-in OF-FRP. Figure 5 to 6 show some examples and prototypes of smart components available at ZhiXing Ltd, Nantong, China.

4. OF-based smart systems
Smart system is a prefabricated part of building, road, or other infrastructure where OF-based intelligent components and materials listed in previous section are used to provide useful information in BIM for life-cycle monitoring. A smart system could be an assembly of one or more intelligent components/materials forming one system. Several smart systems have been developed by our research group, including RC beam, a segment of Highway Bridge, strengthened intelligent beam, etc.

To ease prestressed beam construction, and to successfully detect its life-cycle prestress loss, prefabricated smart prestressed beam (Figure 7) with smart steel strands installed instead of conventional steel strand was proposed. Smart FRP rebar are optional that could replace conventional reinforcement in RC. The built-in OF steel strands can play a key role for the lifetime prestress loss monitoring of the prefabricated beam. Moreover, a prefabricated intelligent beam externally reinforced with built-in OF carbon plate (figure 8) is proposed to enhance the load capacity of conventional RC beam. The number and the length of the carbon plate strengthening the beam can vary in function of the structural demand. With additional smart FRP internal reinforcement, a full life-cycle monitoring is possible by using data gathered from components with built-in OF.

- **Figure 7.** Prefabricated prestressed Beam with Smart steel strand.
- **Figure 8.** Intelligent externally strengthened assembled beam.

5. Case studies
The OF-based intelligent components and systems described previously have been deployed in several construction projects for monitoring and strengthening purpose. Numerous construction projects such as the suspension Aizhai Bridge, the National Swimming Center in Beijing, and so on have seen the application of the proposed systems. The intelligent carbon plate component is used for rehabilitation
and strengthening purpose of new and deteriorated structure. Up to date, we have deployed several lengths of smart CFRP plates for different projects such as factory and highway bridges (see figure 9).

**Figure 9.** Deployment of smart CFRP plate: (a) on a large car factory, (b) G55 Highway bridge with 43.5 meters of CFRP plate.

Another important case study is the contribution to the monitoring of the Hutiao River Viaduct in Guizhou, China. The viaduct consists of prestressed concrete box Beam Bridge (figure 10) with a total span of 1957.74 meters, which is an important hub on the Shanghai-Kunming expressway (G60). Intelligent external prestressing cable system of the bridge was undertaken by ZhiXing S&T Ltd. to ensure the safety of the bridge. The system (Figure 11) includes eight (08) smart prestressed cables, FBGs demodulator device, and data analysis software. Results showed that the use of the intelligent prestressed cable could meet the design requirement, as well as simplify the cable force monitoring. The project has completed the relevant check on September 2016 and is operating in good condition.

**Figure 10.** Hutiaohe Bridge in Guizhou, China.

**Figure 11.** Installation of smart cable on box girder.

**Acknowledgment**

The authors would like to acknowledge the project from National Science Foundation of China (No. 61328501), and the financial support from China Government Scholarship Council (CSC) under Grand No. 2012450T21.

**References**

1. Xiao, Y., S.A. Sheikh, and Z.X. Li, *Applications of FRP composites in concrete columns*. Frp Composites in Civil Engineering, Vols I and II, Proceedings, ed. J.G. Teng. 2001, Amsterdam: Elsevier Science Bv. 731-740.
2. Ou, J.P. and Z. Zhou, *Optic fiber Bragg-grating-based sensing technologies and their applications in structural health monitoring - art. no. 659503*, in Fundamental Problems of Optoelectronics and Microelectronics III, Pts 1 and 2, Y.N. Kulchin, et al., Editors. 2007, Spie-Int Soc Optical Engineering: Bellingham. p. 59503-59503.
3. Hollaway, L.C., *A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties*. Construction and Building Materials, 2010. 24(12): p. 2419-2445.
4. Zhou, Z., Y.W. Sasy Chan, and J.P. Ou, *Advances in FRP-Based Smart Components and Structures*, in Structural Health Monitoring of Composite Structures Using Fiber Optic Methods. 2016, CRC Press. p. 371-413.