

Smart FRP-OFBG bars and their application in reinforced concrete beams

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ABSTRACT: Fiber Reinforced Polymer (FRP) has become more and more popular as construction material in civil engineering due to its advantages of corrosion-resistance, high strength, nonmagnetic, fatigue-resistance and so on. Optical Fiber Brag Grating (OFBG) is now widely accepted as smart sensor due to its advantages of electric-magnetic resistance, small size, distributing measurement, durability, and so on. Combined the strength properties of FRP with the sensing properties of OFBG, a new kind of smart FRP-OFBG composite bars have been developed, and their mechanical properties, microstructures and sensing properties are also studied. The experiment of FRP-OFBG reinforced concrete beams under static load has been done, and the strain of FRP bars and cracking of concrete are monitored, especially the slip between FRP bars and concrete, and the strain distribution of the beams. The experimental results show that FRP-OFBG is a wonderful construction material for civil engineering. As smart sensing element, FRP-OFBG bars have overcome the difficulties of embedment installation in concrete structures, and can be conveniently used in reinforced concrete structures as sensors as well as reinforcing bars.

1 INTRODUCTION

Steel and concrete are the most important construction materials. Many concrete structures subjected to aggressive environment, such as bridge, dam and offshore exposed to deicing salts, combinations of moisture, temperature and chlorides reduce the alkalinity of the concrete and result in the corrosion of steel bars. The estimate of repair cost for existing highway bridges in the USA is over \$50 billion, and \$1 to \$3 trillion for all concrete structures. In Europe, steel corrosion has been estimated to cost about \$3 billion per year. To address corrosion problems, professionals have turned to alternative metallic reinforcement, such as epoxy-coated steel bars, cathodic protection, and increased concrete cover thickness. While effective in some situations, such remedies may still be unable to completely eliminate the problems of steel corrosion (ACI 440 2001).

Fiber reinforced polymer (FRP) materials are nonmetallic and noncorrosive, high-strength, nonmagnetic, high stiffness-to-weight ratios (density is 1/6~1/4 that of steel). America (Dolan, 1999), Canada (Rizkalla 1999), and Japan (Fukuyama 1999) have designed codes on FRP, and use FRP in bridge, seawall construction, substation reactor bases, airport runways, and electronics laboratories.

The tensile behavior of FRP bars is characterized by a linearly elastic stress-strain relationship until failure (Malvar 1995). Most FRP bars are relatively weak in shear behavior. The modulus of elasticity of FRP bars is 25%~70% that of steel bars. The deflec-

tion and crack width are larger than steel reinforced concrete (Razaqpur 2000). Brittle fracture, slip between FRP bars and concrete, creep fracture are the major research aspects in FRP bars application. Optical fiber brag grating (OFBG) sensors are nonmagnetic, small size, distributing measurement, noncorrosive, absolute measurement (Rao 1999). FRP bar embedded with OFBGs can't affect its mechanical properties because OFBG's diameter is relatively small compared with FRP bar's diameter. Kalamkarov embedded OFBG sensors in FRP bar during fabrication (Kalamkarov 2000a, b), and studied the properties of the FRP-OFBG bar sensing, fatigue, corrosive performances.

The OFBG is embedded in FRP bar with the fiber strands during production and carbon fiber reinforced polymer-optical fiber Bragg grating (CFRP-OFBG) bar and glass fiber reinforced polymer-optical fiber brag grating (GFRP-OFBG) bar are produced. The microstructure, mechanical and sensing properties are studied in this paper. The experiment of FRP-OFBG reinforced concrete beams under static load has been done, and the strain of FRP bars and cracking of concrete are monitored, especially the slip between FRP bars and concrete, and the strain distribution of the beams.

2 FABICATION OF FRP-OFBG BARS

Harbin Institute of Technology cooperate with Nation Resin Matrix Composites Engineering Technology Research Center in producing FRP bars. The OFBG in the center of die is pultruded with fiber

strands in the production of FRP bars, as shown in Figure 1. The CFRP-OFBG bars and GFRP-OFBG bars are shown in Figures 2 and 3. To improve the bond between FRP bar and concrete, the FRP bar surface deformations can be added by helically winding fiber strands and coating of sand particles.

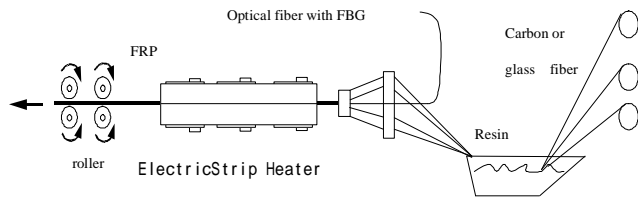


Figure 1. Technique of FRP-OFBG fabrication

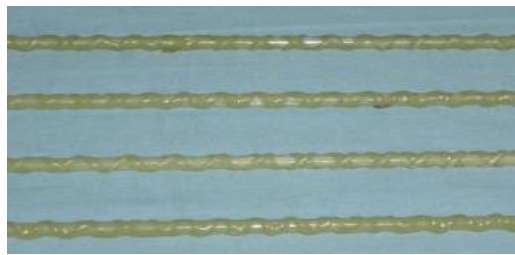


Figure 2. OFBG-GFRP bars

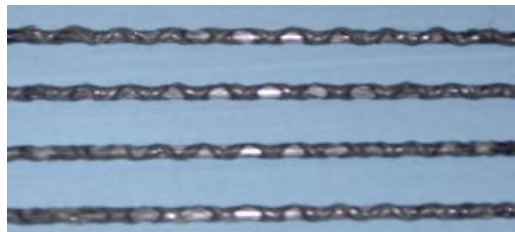


Figure 3. OFBG-CFRP bars

3 MICROSTRUCTURE AND TEST OF FRP-OFBG BARS

3.1 Microstructure of FRP-OFBG bar

The efficiency of monitoring the strain of FRP bars with OFBG depends on OFBG integrating with FRP. Figures 4 and 5 are the photographs of FRP-OFBG with scanning electronic mirror (SEM). OFBG is combined with FRP very well. Therefore FBG can sense the strain of FRP bar.

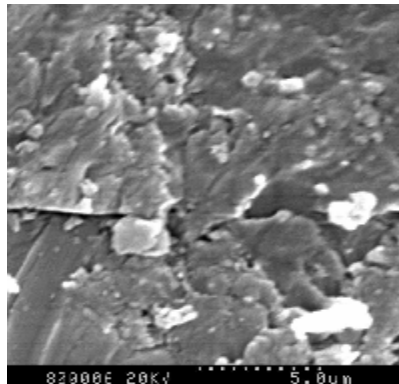


Figure 4. SEM of bare FBG and GFRP

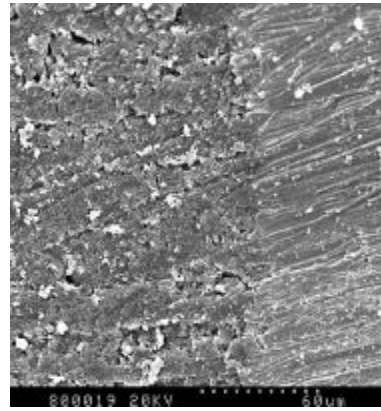


Figure 5. SEM of bare FBG and CFRP

3.2 Mechanical test of FRP-OFBG bars

The diameter of OFBG is about 2% that of FRP bar (diameter is 6 mm), and the area of section is about 0.04% that of FRP bar. The tensile test results of FRP-OFBG bar and FRP with same diameter are shown in Figures 6 and 7. Test results show that OFBGs don't affect the mechanical properties of FRP bars.

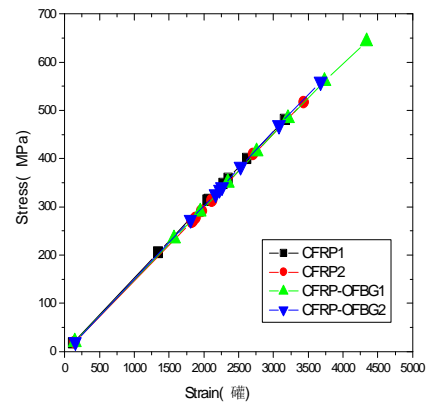


Figure 6. Comparison of CFRP-OFBG and CFRP bars under load

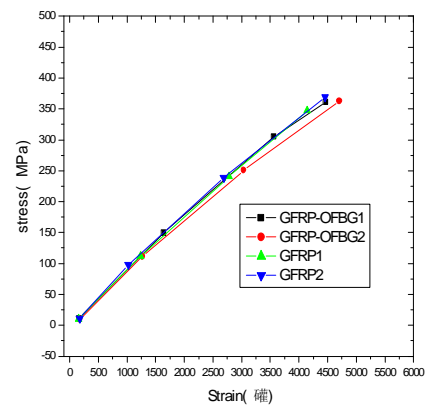


Figure 7. Comparison of GFRP-OFBG and GFRP bars under load

3.3 Strain sensing tests of FRP-OFBG bar

The sensing tests are carried out using universal testing machine. The internal load cell is used to monitor

the applied load. The load measurement precision is 0.001 kg. A 25-mm extensometer is used to measure the tensile strain of FRP-OFBG bar. The strain measurement precision is 0.001 mm. The wave length of OFBG is measured with FBG-SLI Interrogator of MICRON OPTICS. The load, tensile strain, and wave length of OFBG are recorded, as shown in Figures 8 and 9. The sensing coefficient of CFRP-OFBG and GFRP-OFBG bars are 1.21 pm/ $\mu\epsilon$ and 1.19 pm/ $\mu\epsilon$ respectively. The sensibility factor of OFBG is 1.20 pm/ $\mu\epsilon$. The difference is attribute to measurement precision of extensometer.

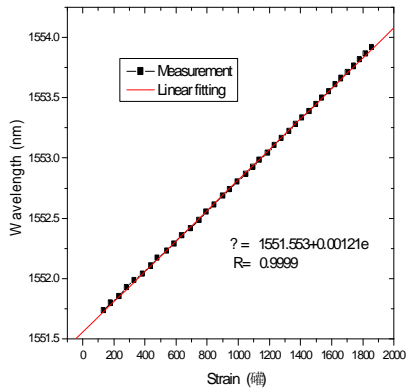


Figure 8. Strain sensing property of CFRP-OFBG bar

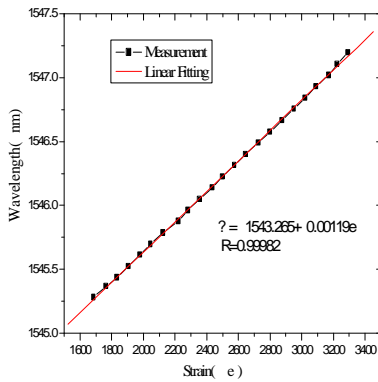


Figure 9. Strain sensing property of GFRP-OFBG bar

To verify repetitive property of FRP-OFBG bar, the specimens are load, unload with some loops. The test results reveal FRP-OFBG bar can work very well in load-unload loops because it is in elastic range, as shown in Figures 10 and 11.

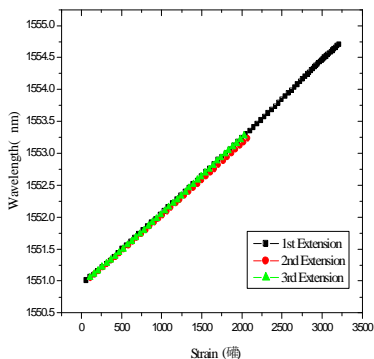


Figure 10. Repetitive property of CFRP-OFBG bar strain sensing

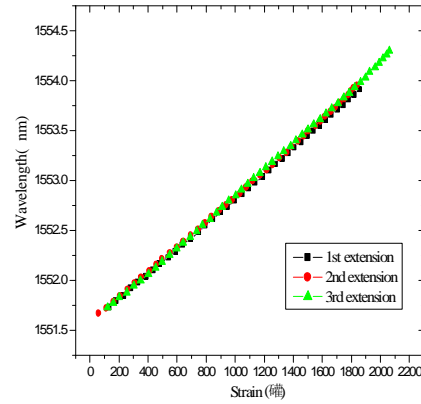


Figure 11. Repetitive property of GFRP-OFBG bar strain sensing

3.4 Temperature sensing tests of FRP-OFBG bar

The FRP-OFBG bars are placed in TYC-1 low temperature pool filled with alcohol and water. The test temperature margin is $-50\text{ }^{\circ}\text{C} \sim 80\text{ }^{\circ}\text{C}$, the temperature measurement precision is $0.01\text{ }^{\circ}\text{C}$. The temperature and wave length of OFBG are recorded. Test results are shown in Figures 12 and 13. In Figure 12, the temperature sensibility factor of GFRP-OFBG bar is $17.24\text{ pm}/^{\circ}\text{C}$, 1.84 times that of bare OFBG. The GFRP-OFBG bar enhances the temperature sensibility factor because the coefficient of thermal expansion of GFRP is larger than bare OFBG. In Figure 13, the temperature sensing coefficient of CFRP-OFBG bar is $8.68\text{ pm}/^{\circ}\text{C}$, 89% that of bare OFBG. The CFRP-OFBG bar reduces the temperature sensibility factor because the coefficient of thermal expansion of GFRP is smaller than bare OFBG.

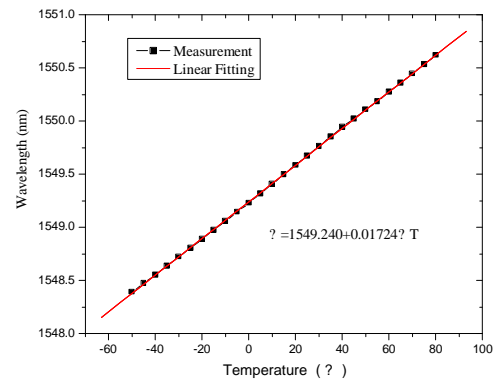


Figure 12. Temperature sensing of GFRP-OFBG

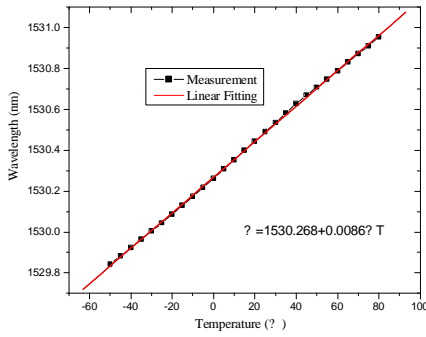


Figure 13. Temperature sensing of CFRP-OFBG

4 FRP-OFBG REINFORCED CONCRETE BEAM TESTS

4.1 Test design and preparation

The FRP-OFBG bars are embedded in twelve concrete beams to monitor the strain of FRP bars. The concrete compressive strength is 30 MPa and 40 MPa. The weight mixture ratio is cement: sand: gravel: water=381: 631: 1172: 195 kg and 454: 609: 1131: 195 kg respectively. The yield strength and modulus of elasticity of steel bar are 335 MPa, 200 GPa respectively. The steel stirrups (8 mm in diameter) are spaced by 50 mm for all beams to prevent shear failure. The details of concrete beam are shown in Figure 14.

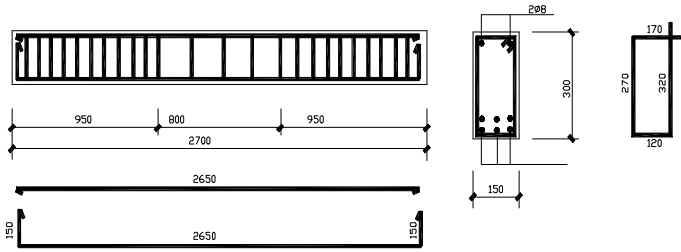


Figure 14. Structure specification of FRP concrete beam

The beams are subjected to third-point flexural bending testing, as shown in Figure 15. The strain gage is adhered to the concrete at the same height with FRP-OFBG bar. The load is applied to the beam step by step by means of one hydraulic jacks and is measured with load cell. The beams are instrumented with three linear variable differential transformer (LVDT) at supports and midspan to monitor deflection.

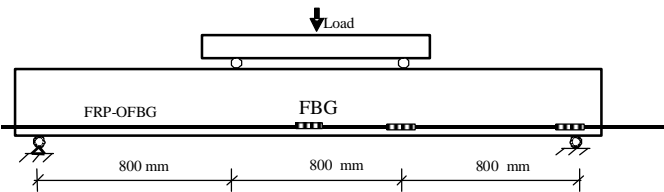


Figure 15. FRP-concrete beam under loader and the position of FBGs in FRP

4.2 Test results and discussion

At the end of each step, load, midspan deflection, strain gage reading and wave length are recorded. The typical test results are shown in Figures 16 and 17. The failure modes of concrete beams are shown in Figures 18 and 19.

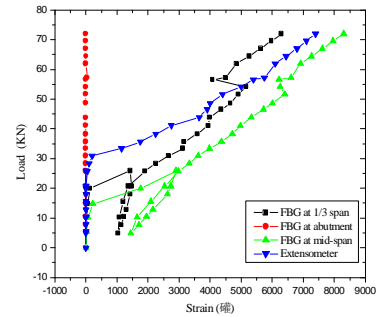


Figure 16. Load-strain relationship of CFRP-OFBG beam

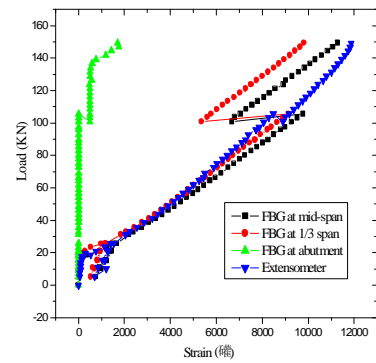


Figure 17. Load-strain relationship of GFRP-OFBG



Figure 18. Failure mode of CFRP-OFBG beams



Figure 19. Failure mode of GFRP-OFBG beams

The test results show that the FRP-OFBG bar strain is low, moderate and high in support, one-third span and midspan respectively. The maximum strain of FRP-OFBG bar is 1200 $\mu\epsilon$. When concrete uncracked the strain of FRP-OFBG agree well with concrete strain therefore they can work together. In load-unload loop the FRP-OFBG bar can work well. The FRP-OFBG bar can monitor the slip between FRP bar and concrete by means of the difference FRP strain and concrete strain.

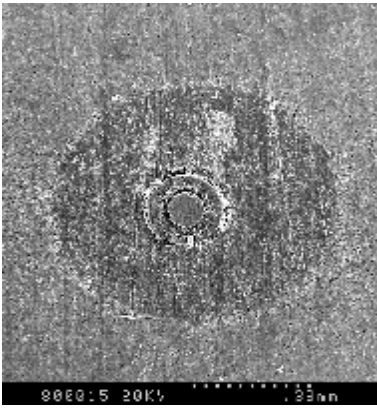


Figure 20. SEM of uncracked interface between CFRP-OFBG surface and FRP

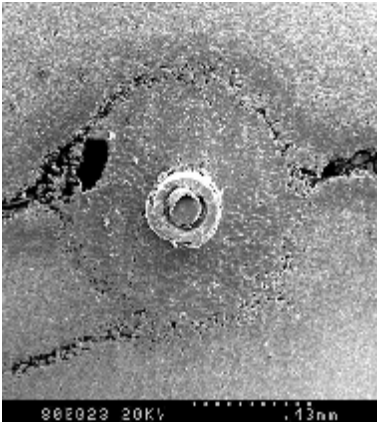


Figure 21. SEM of cracked interface between GFRP-OFBG and FRP

4.3 Microstructure of FRP-OFBG bar after beam failure

After concrete beams failure, the FRP-OFBG bars are taken out to investigate the interface between OFBG and FRP. The SEM photographs of uncracked CFRP-OFBG bar and cracked GFRP-OFBG bar are shown in Figures 20 and 21. In Figure 20, OFBG is combined with FRP very well at uncracked interface. Although GFRP-OFBG bar crack OFBG combine with FRP very well, therefore FRP-OFBG bar can monitor the strain of FRP bar until beam failure.

5 CONCLUSIONS

The FRP-OFBG bars are produced and its microstructure, mechanical, strain sensing, temperature sensing properties are studied. The concrete beams reinforced with FRP-OFBG bar are test under static loading. The strain of FRP bar, the cracking of concrete, and the slip between FRP bar and concrete are monitored. Based on this research the OFBG don't affect the mechanical properties of FRP bars because OFBG diameter is relative thin compared with FRP bar diameter. The sensibility factor of FRP-OFBG bar is same as bare OFBG in that OFBG embedded in FRP integrate with FRP well. The measurement precision is about $1\sim 2\mu\epsilon$, the maximum tensile strain is $1200\mu\epsilon$. The temperature sensing property of FRP-

OFBG bar is different with bare OFBG because the coefficient of thermal expansion of FRP differs from bare OFBG. FRP-OFBG bar can serve as both reinforcement and sensor. It can monitor the stain of FRP bar and the slip between FRP bar and concrete.

The FRP can protect OFBG from damage in laying out and improve the durability of OFBG. Furthermore FRP-OFBG bar can produced in any length and diameter as a sensor.

6 ACKNOWLEDGMENTS

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