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Smart structural members with embedded FBG sensor

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ABSTRACT: Most sensors for structural health monitoring should have a protector for damage prevention and can hardly measure the inside change of a member because they are usually attached on surface. If a sensor was inserted into inside of a member, the sensor is almost free from external damage, the inside change of a member can be monitored and it can be smart. Smart member means the one has a structurally integrated sensing system and can monitor the state of itself throughout its working life. In this study, for making structural members smart, experimental feasibility tests were performed. FBG sensor was embedded in steel bar, anchor head and fiber reinforced polymer bar and tested by tensioning. Through tensile tests, feasibility that the structural members could be smart with FBG sensor was checked.

1 INTRODUCTION

Structures such as bridge, building, nuclear power plant in service suffer from repeated loads, aggressive environments, and so on. It is important to diagnose and cure structures like human body because such structures, if they lost designed performance, may threaten human life and individual/public property. Therefore, structures in service are in great need of structural health monitoring (SHM) systems in order to assure structural safety, integrity, and durability.

SHM generally consists of a lot of sensors and data acquisition equipment, signal processing, and information processing. And there are various types of sensor for required response. Among them, electrical resistance type is used widely for measuring strain. It is said that this sensor has a few limits such as noise by electromagnetic waves which might cause reading error, low durability and brazing lead wires, and one-to-one matching between sensor and lead wire.

Optical fiber sensor has been emerging as a promising sensor in civil engineering field due to various advantages such as small size, high durability, greater sensitivity, electrical passiveness, freedom from electromagnetic interference, wide dynamic range, and both point and distributed configuration over the conventional electrical resistance strain gages (Bashir et al., 2005). Since optical fiber is extremely small compared with other strain measuring devices, it can be embedded into structural elements without influencing the mechanical properties and stress conditions of the host material (Lau et al., 2001).

The objective of this study is to check the feasibility of making structural members smart. Smart member means the one has a structurally integrated sensing system and can monitor the state of itself throughout its working life. Using the feature of small size of optical fiber sensor, sensor was embedded in FRP and steel bar, anchor head. The type of optical fiber sensor was FBG (Fiber Bragg Grating) and tensile tests were performed to observe the response. Consequently, it is certain that FBG sensor could make structural members smart.

2 FBG SENSOR

Among of optical fiber sensors, it is considered that the FBG sensor is one of excellent developments in recent years. FBG is made by laterally exposing the core of a single-mode fiber to a periodic pattern of intense ultraviolet light. It has a special advantage that the measured signal is encoded directly in terms of the wavelength. This is an absolute parameter and does not suffer from disturbances of the light paths (Berkoff et al., 1994). Hence, the output signal does not depend on the intensity of the source, and losses in the connecting fibers and couplers. Furthermore, multiplexing is another exciting feature due to unique wavelength of each reflected signals. This makes it possible for optical fiber to have many sensors and to measure them simultaneously.

Figure 1 shows the principle of FBG. When a source of light enters into an optical fiber, wavelength component satisfying Bragg condition is reflected and the others are transmitted. Spectra of incident, reflected, and transmitted are expressed in Figure 1.

The reflected wavelength is known as the Bragg wavelength, λ_{Bragg}, and is given by

$$\lambda_{Bragg} = 2n\Lambda \tag{1}$$

where n is the effective refraction index of the fiber core, Λ is the period of the index modulation. The reflected Bragg wavelength is a function of the effective refraction and period index depending on external physical quantities such as temperature and strain. Thus, by monitoring the resultant changes in reflected wavelength, unknown physical quantity is to be obtained with following equation (2).

$$\Delta\lambda_{Bragg} = \lambda_{Bragg}[(\alpha + \xi)\Delta T + (1 - P_e)\Delta\epsilon] \tag{2}$$

where $\Delta\lambda_{Bragg}$ is the Bragg wavelength, α and ξ are the thermal expansion coefficient and thermo-optic coefficient of the fiber material respectively, and ΔT and $\Delta\epsilon$ are the change of temperature and strain respectively.

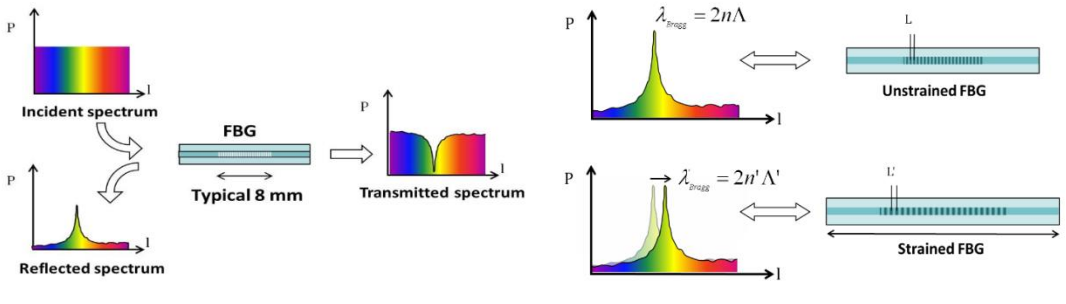


Figure 1. Working principle of FBG and FBG response as function of strain. (http://www.fbgs.com)

3 EXPERIMENTAL STUDY

3.1 FRP bar with embedded FBG sensor

3.1.1 FRP bar

FRP bar used in this study was fabricated with combining process of pultrusion and braiding method as seen in Figure 2 (You et al., 2007). This process makes it possible to increase of producing speed (finally related with cost) and form deformation similar to that of steel reinforcement.

This bar consists of E-glass fiber, vinyl-ester resin, hardener, and thinner and the fraction of it was 60.72% and 78.01% by volume and weight, respectively. Tensile capacity of FRP rebar with 12.7 mm in diameter performed with a hydraulic loading machine according to CSA standard (2002) showed 1,059 MPa and 46.5 GPa with 99.87% of confidence level for tensile strength and elastic modulus, respectively.

3.1.2 Test preparation

As mentioned above, FBG sensor is written in a strand of fiber which is a main material to consist FRP bar. There were no any other effort to fabricate FRP bar with FBG sensor except for a device which kept the center position of fiber in the section of bar.

FRP bar has weaker transverse stiffness than that of steel bar so it might not be evaluated properly when same device for steel bar is used. For solving this problem, steel cylinders were equipped at both ends of FRP bar for tensile test.

A FBG sensor was embedded in bar and an electric resistance type of gauge, so called foil type, was attached on the surface of bar for comparing results. Supplemental two LVDTs were installed on FRP bar for measuring tensile strain by special device as seen in Figure 3.

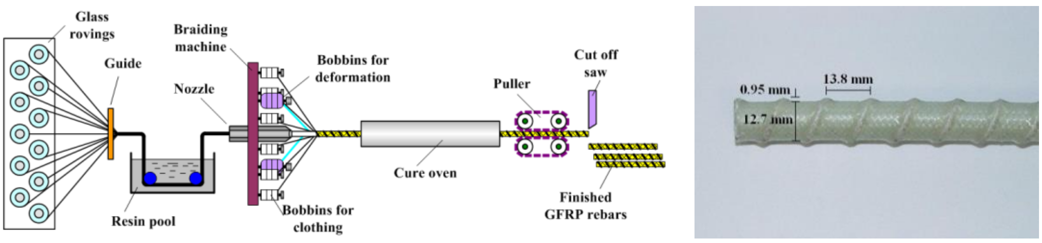


Figure 2. Braidtrusion process and fabricated FRP bar.

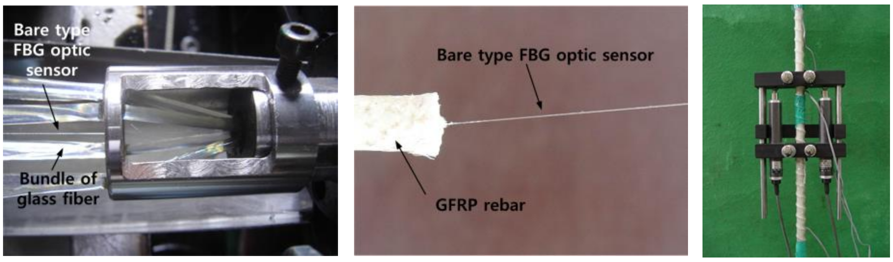


Figure 3. Inserting FGB sensor, FRP bar with FBG sensor, and measurement.

3.1.3 Test results

Figure 4 shows the response of foil gauge, FBG sensor, and LVDTs according to force. Foil gauge attached on the surface of FRP bar showed non-linear response. However, as known well, FRP has a material property which behaviors linearly for load and deformation. Therefore there could be something wrong for foil gauge. A photo in Figure 4 shows the state that foil gauge is installed. Foil gauge should be installed straightly and flatly for accurate measuring but it was installed with round shape. Consequently, this seemed to cause non-linear behavior.

On the contrary, LVDTs and FBG embedded in FRP bar showed good agreement and strong linearity. The coefficient of determination of response of FBG sensor was close to one. Strong linearity for response is one of the most important features required as a sensor. Obtained elastic moduli of LVDT and FBG sensor were 50.2 GPa and 49.5 GPa, respectively. So it is certain that LVDTs and FBG sensor show coincident response as seen in Figure 4. This result shows that FRP bar could be smart with embedded FBG sensor.

3.2 Steel bar with embedded FBG sensor

3.2.1 Test preparation

A tensile test was performed to check the feasibility making steel member like PS bar smart. Specimen was a steel bar with 3000 mm in length and 42 mm in diameter. This has threaded ends with 300 mm in length as seen in Figure 5.

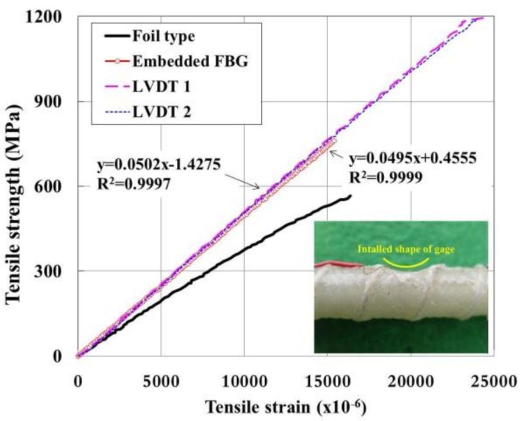


Figure 4. Tensile test results of FRP bar.

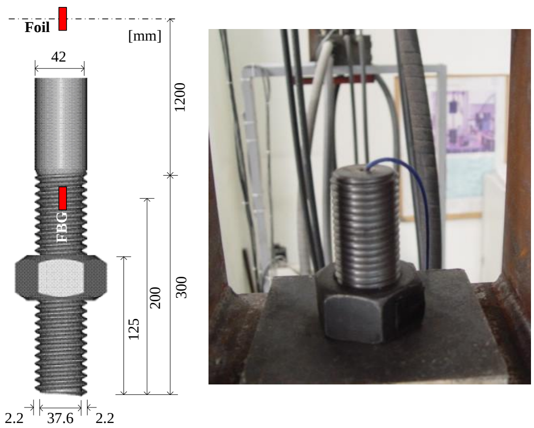


Figure 5. Steel bar and installed FBG sensor.

Figure 5 also shows embedded FBG sensor. A FBG sensor was inserted into the steel bar and cured with resin after boring the center of it. Installed point was 200 mm from the end of bar. The steel bar was tensioned by UTM with 1000 kN capacity for length of 2400 mm of it. In order to verify the response of FBG sensor, a foil gauge was attached on the surface of bar in the middle.

Tensile force was loaded up to about 400 kN and unloaded. During test, the responses of foil gauge and FBG were measured by data logger and interrogator.

3.2.2 Test results

Measured data from foil gauge and FBG sensor were synchronized for loaded force.

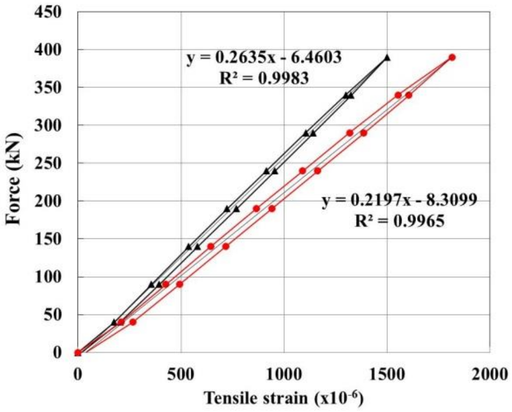
Figure 6 shows the response of foil gauge and FBG sensor according to force. As seen in the graph, the response of FBG sensor was different a little from that of foil gauge. There could be many causes for this phenomenon like installing errors. However this might result from the difference of cross section of steel bar. The installed point of FBG sensor was in range of tensioning but it was still in thread length so that areas of cross section where foil gauge and FBG sensor were installed were different.

Even though there is a small gap between loading and unloading, each sensor has strong linearity. The coefficient of determination of response of FBG sensor was close to one, of course, that of foil gauge was about one. This result shows that steel bar could be smart with embedded FBG sensor.

3.2.3 FEM analysis

FEM analysis was performed to examine the difference of responses between foil gauge and FBG sensor. Linear analysis was performed for half model with axisymmetric element. Threaded part was modeled as round shape with 37.6 mm in diameter without thread.

Analysis results are plotted with measured values of each sensor in Figure 7. In Figure 7, blank figures are by FEM. Values by FEM at the same positions where foil gauge and FBG sensor installed are obtained differently and are exactly same with measured values. Therefore the different slopes of response of foil gauge and FBG sensor resulted from the different areas of measured point and consequently steel bar could be smart with embedded FBG sensor.



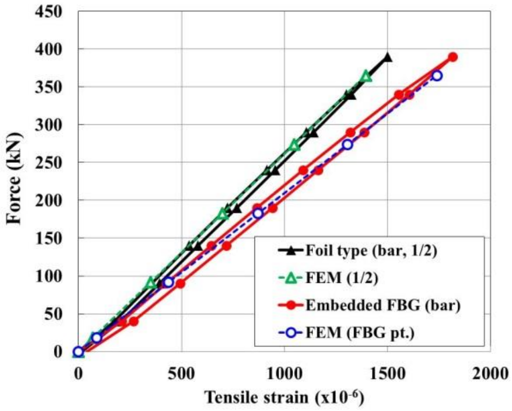


Figure 6. Responses of sensors for steel bar.

Figure 7. Plot of measured and analyzed results.

3.3 Anchor head with embedded FBG sensor

3.3.1 Test preparation

To overcome a problem that it is not easy to measure the strain of PS tendon directly, acquiring the strain of PS tendon indirectly by measuring that of anchor head with embedded FBG sensor was proposed. This idea started from the fact that the material of anchor head is steel and it has linear property.

The feasibility of smart anchor head was checked first by finite element method. Anchor head has a diameter of 180 mm and 65 mm depth. There are twelve wedge holes in anchor head with

29 mm diameter on upper side (wedge insert face) and 17 mm on lower side (contact face between structural member and anchor head). Analysis was perform for the case that one strand in a hole among three in center was tensioned (You et al., 2011).

Even though the anchor head is made with steel, it has many holes like cone and this resulted in non-linear strain distribution along the depth as seen in Figure 8. However there was a noticeable fact as seen in Figure 9. Figure 9 shows that a depth where strains occur for increased loads is same. For example, if an expected strain for a given load is 100x10^{-6}, then a depth is about 43 mm from Figure 8. As like this way, strains can be acquired for increased loads and the depths are same with 43 mm. This means there is a possibility to use the linear property of steel and to get constant response for loading.

Figure 10 and Figure 11 shows a tensile test set-up and result for anchor head. Responses of FBG installed at measuring point 10 (MP 10) in Figure 8 in depth with 32.5 mm were acquired for three times loading and unloading. The regression line of measurements shows strong linearity and this means it is possible to estimate the strain of PS tendon by measuring the deformation of anchor head.

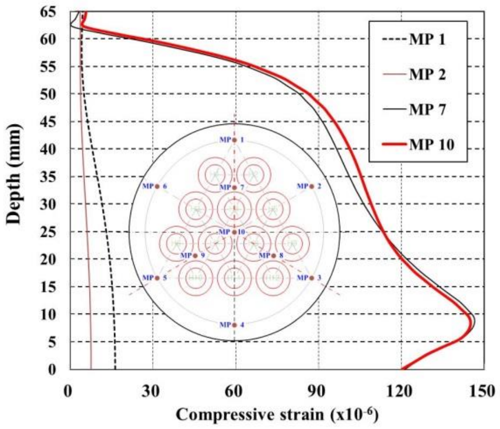


Figure 8. Strain distribution along depth.

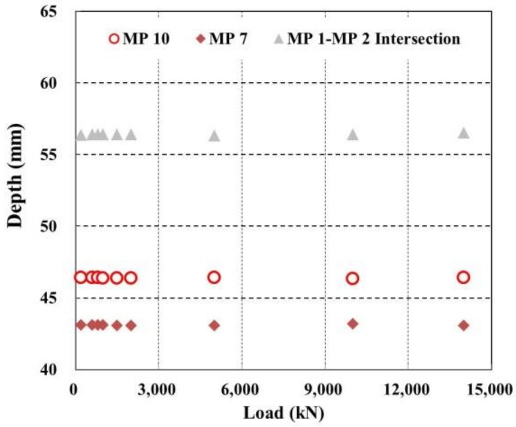


Figure 9. Strain at fixed depth.

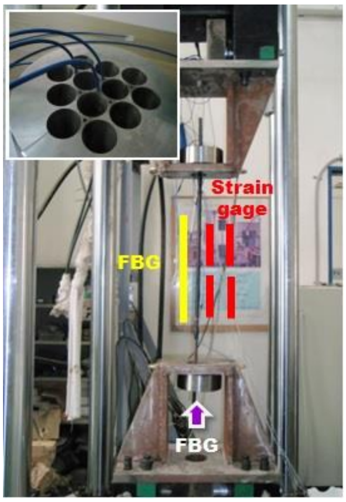


Figure 10. Tension test for PS strand and anchor head.

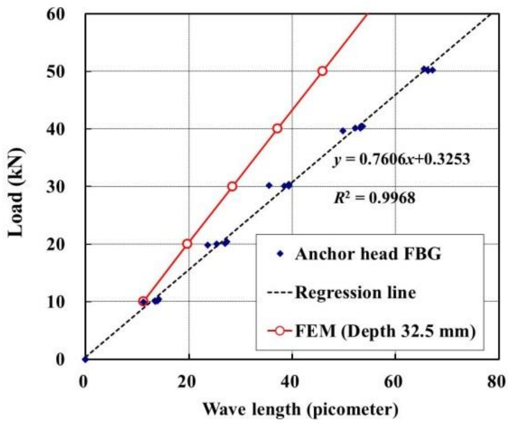


Figure 11. Comparison of Exp. and FEM.

Unfortunately, there was some gap in response between the results of FEM and test. However, this could be solved by applying calibration factor because both results show strong linearity.

4 CONCLUSIONS

This study is for checking the feasibility whether structural members could be smart. FBG sensor was embedded in steel and FRP bar and anchor head. Tensile tests were performed to observe the response of it and drawn conclusions are as follows:

To install foil gauge for measuring strain of a member, there needs close attention because it could give inaccurate readings when the surface where it was attached is round.

FBG in FRP and steel bar and anchor head showed strong linearity and accurate readings. Therefore, those structural members could be smart member with embedding FBG sensor into them.

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