A paired CFRP FBG probe with low temperature sensitivity for structural health monitoring

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ABSTRACT

Fiber optic FBG(fiber Bragg grating) sensor probes are devised to monitor strain at the condition of low temperature sensitivity to use many probes in one optical fiber line. An FBG probe is fabricated with two FBGs inserted in CFRP (carbon fiber reinforced plastics) molded in epoxy resin. These probes are bonded on an aluminum plate to test the strain measurement performance. This specimen is inserted in a thermal heating chamber and tested in the heating condition of 24, 36, 56, and 76 °C. From this heating test, the temperature sensitivity of 1 mm thick CFRP FBG probe was determined as 2.39 pm/°C much lower than 11 pm/°C of the bare FBG probe. Also, the strain sensitivity of this probe was 0.35 pm/micro-strain, this sensitivity was also much lower than 1.1 pm/micro-strain of the bare FBG probe.

Keywords : Fiber optic FBG sensor probe, CFRP(carbon fiber reinforced plastics), epoxy resin, thermal heating condition, temperature sensitivity, strain sensitivity

1. INTRODUCTION

FBG sensors have very unique advantages to monitor structural status as electro-magnetic immunity, and durable in hash environment, and multiplexing capability through one sensing optical fiber line in Reddy (2010), Hwang (2010), Xiao (2001), Hsu (2006), and Kim (2013). However, the bare FBG probe of this sensor is generally fragile because FBGs are inscribed by a high power UV laser. Therefore, the bare FBG fiber should be molded by some plastic materials. Then, the temperature sensitivity of this molded FBG probe is much higher than that of the bare FBG probe. It limits multiplexing capability because one FBG probe needs wider wavelength range than that of the bare FBG probe. In order to solve this multiplexing limitation, we propose a

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method to reduce temperature sensitivity of a molded FBG probe. That can be accomplished by CFRP bonded on an FBG fiber. In this work, the FBG probes with low temperature sensitivity are fabricated with CFRP and epoxy resin and tested the sensitivity.

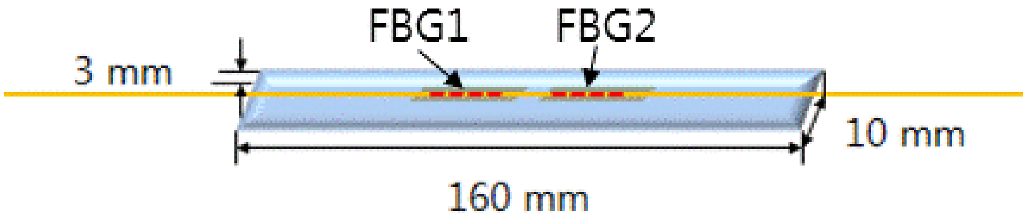


Fig. 1 Configuration of a paired CFRP FBG probe

2. A PAIRED FBG PROBE WITH CFRP

Fiber Bragg grating sensors are very useful and attractive for strain or temperature measurement, and they can measure at multiple positions through the use of multiplexing techniques. FBG sensor probes are designed as an epoxy molding type to give the convenience of installation in many cases. A CFRP FBG probe can also be molded with two FBGs in CFRPs in order to measure temperature and strain simultaneously shown in Fig. 1. FBG1 and FBG2 are bonded by CFRPs having different thicknesses. Therefore, the FBG1 and FBG2 have different coefficients of strain and temperature.

When the probe is applied on one point of structural material, the wavelength shifts of two FBGs are linearly related with strain and temperature of the point of structural material as following Eq. (1).

$$\begin{aligned} \Delta\lambda_{b1} &= K_{1\varepsilon}\Delta\varepsilon + K_{1T}\Delta T \\ \Delta\lambda_{b2} &= K_{2\varepsilon}\Delta\varepsilon + K_{2T}\Delta T \end{aligned} \qquad (1)$$

Where $K_{1\varepsilon}$, K_{1T} is the strain coefficient and the temperature coefficient of an FBG, also $K_{2\varepsilon}$, K_{2T} is the strain coefficient and the temperature coefficient of another FBG in one CFRP FBG probe. The Eq. (1) can be rewritten as a matrix form shown in Eq. (2).

$$\begin{pmatrix} \Delta\lambda_{b1} \\ \Delta\lambda_{b2} \end{pmatrix} = \begin{bmatrix} K_{1\varepsilon} & K_{1T} \\ K_{2\varepsilon} & K_{2T} \end{bmatrix} \begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} \qquad (2)$$

The temperature and strain is also determined by Eq. (3) reformulated from Eq. (2).

$$\begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} = \frac{\begin{bmatrix} K_{2T} & -K_{1T} \\ -K_{2\varepsilon} & K_{1\varepsilon} \end{bmatrix}}{\left| K_{1\varepsilon}K_{2T} - K_{2\varepsilon}K_{1T} \right|} \begin{pmatrix} \Delta\lambda_{b1} \\ \Delta\lambda_{b2} \end{pmatrix} \tag{3}$$

The temperature sensitivity of an FBG probe molded in epoxy resin is almost 4 times larger than that of a bare FBG probe. In order to decrease the temperature sensitivity of an epoxy resin molded FBG probe, CFRP is applied on the surface of the FBG fiber as shown in Fig. 1. Because the thermal expansion coefficient of CFRP is -0.5 ~ 0.5 micron, the CFRP FBG probe is to be operated at the condition of lower temperature sensitivity than the condition of the bare FBG probe.

3. FABRICATION OF FBG PROBES WITH CFRP

The fabrication procedure of a paired CFRP FBG probe is shown in Fig. 2. CFRPs are bonded on the surface of FBG1 and FBG2 fibers. These FBGs are located in the probe mold and the mixture of epoxy and hardener is poured into the mold. This mold with the FBGs is inserted into a thermal chamber and cured at the temperature of about 70 degree C during 2 hours. After curing this mold with FBGs in the thermal heating chamber, the CFRP FBG probe is pulled from the mold.

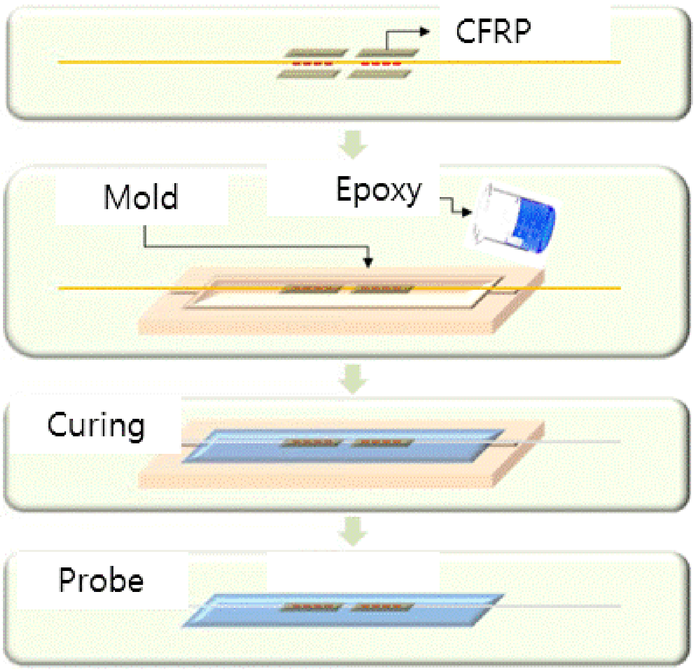
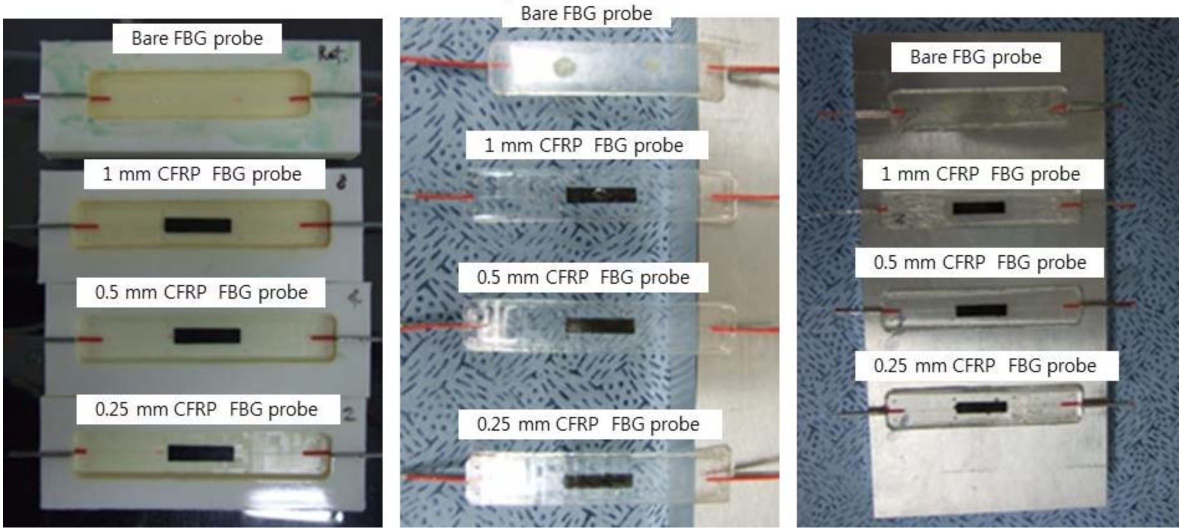


Fig. 2 Fabrication procedure of a paired CFRP FBG probe

Four kinds of FBG probes are prepared as a bare FBG probe, a 0.25 mm thick CFRP FBG probe, a 0.5 mm thick CFRP FBG probe, and a 1.0 mm thick FBG probe in order to verify the sensitivity of strain and temperature as shown in Fig. 3. A bare FBG fiber is located on the bottom of the mold frame and molded itself with epoxy resin. FBG fibers are embedded in the location of the thickness, 0.125, 0.25, 0.5 mm of the CFRP prepregs. These CFRP FBGs are located on the bottom of the mold frame and molded with epoxy resin shown in Fig. 3 (a). After thermal curing, the probes are pulled out from the mold frames shown in Fig. 3 (b). In order to do the thermal heating test, these probes are attached on the surface of an aluminum plate shown in Fig. 3 (c).



(a) (b) (c)

Fig. 3 CFRP FBG probes

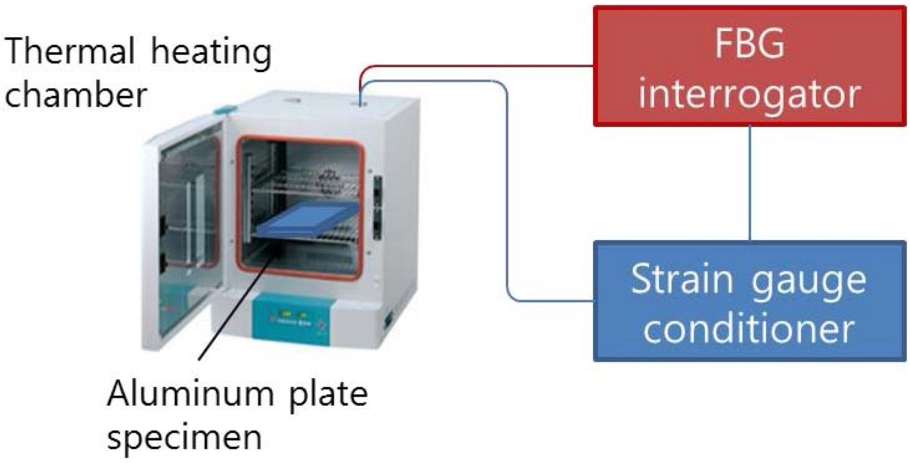


Fig. 4 Thermal heatingexperimental setup

4. STRAIN AND TEMPERATURE TEST OF CFRP FBG PROBES

In order to study the temperature and strain sensitivity of CFRP FBG probes, four probes attached on the aluminum plate are inserted in a thermal heating chamber shown in Fig. 4. The electrical strain gauge is also attached on the surface of the aluminum plate to measure the strain by thermal expansion shown in Fig. 4. The heating test is performed from the room temperature of 24 to 36, 36, 76 °C. The controlled temperature is maintained during 30 minutes to acquire the stable data. At every temperature states, the FBG probe signals are acquired by an FBG interrogator, and the strain of the aluminum plate is also measured by the electrical strain gauge using a strain gauge conditioner shown in Fig. 4.

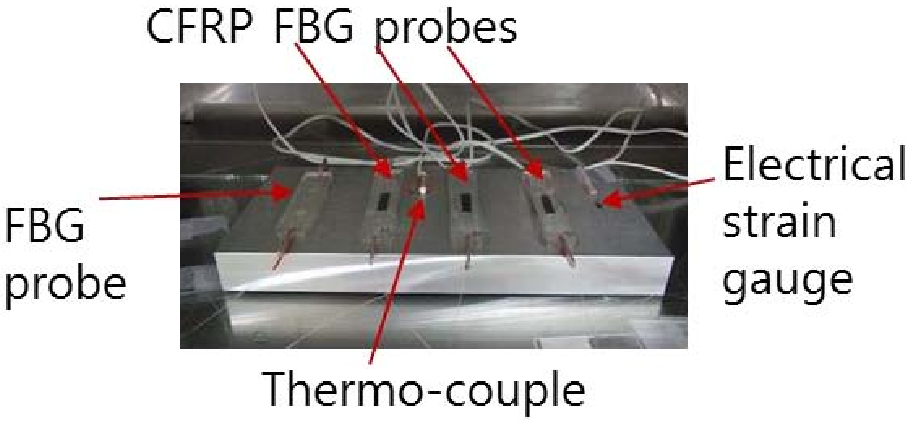


Fig. 5 Aluminum plate specimen with CFRP FBG probes

All of the data can be converted the digital data from the measured analog data by using an A/D converter embedded in the FBG interrogator. From this test, the wavelength shift data of CFRP FBG probes are obtained at every temperature state of four FBG probes as shown in table 1. In the test, the strain of aluminum plate specimen is also acquired and show in table 1.

Table 1 Heating test result of an aluminum plate with four CFRP FBG probes

Temperature from 24 °C (°C)	Bared FBG (pm)	FBG with 0.25 mm CFRP (pm)	FBG with 0.5 mm CFRP (pm)	FBG with 1 mm CFRP (pm)	Strain from ESG (micro-strain)
36	417	341	233	157	137
56	1860	1051	546	447	367
76	3810	1645	1006	774	570

In general, a bare FBG fiber has the strain sensitivity of 1.13 pm/micro-strain and the temperature sensitivity of 11 pm/°C. In order to check the temperature sensitivity differences between the CFRP FBG probes and the bare FBG fiber, the temperature sensitivities of the CFRP FBG probes are calculated from the wavelength shift influenced from the temperature divided by the temperature change. The wavelength shift from the temperature is determined by subtracting the wavelength shift calculated from the strain of the electrical strain gauge from the wavelength shift of each FBG probe. Following this procedure, the temperature sensitivity of the CFRP FBG probes are determined as shown in Fig. 5 (a). In this figure, the temperature sensitivity of the 1 mm thick CFRP FBG probe is smallest as 2.39 pm/°C.

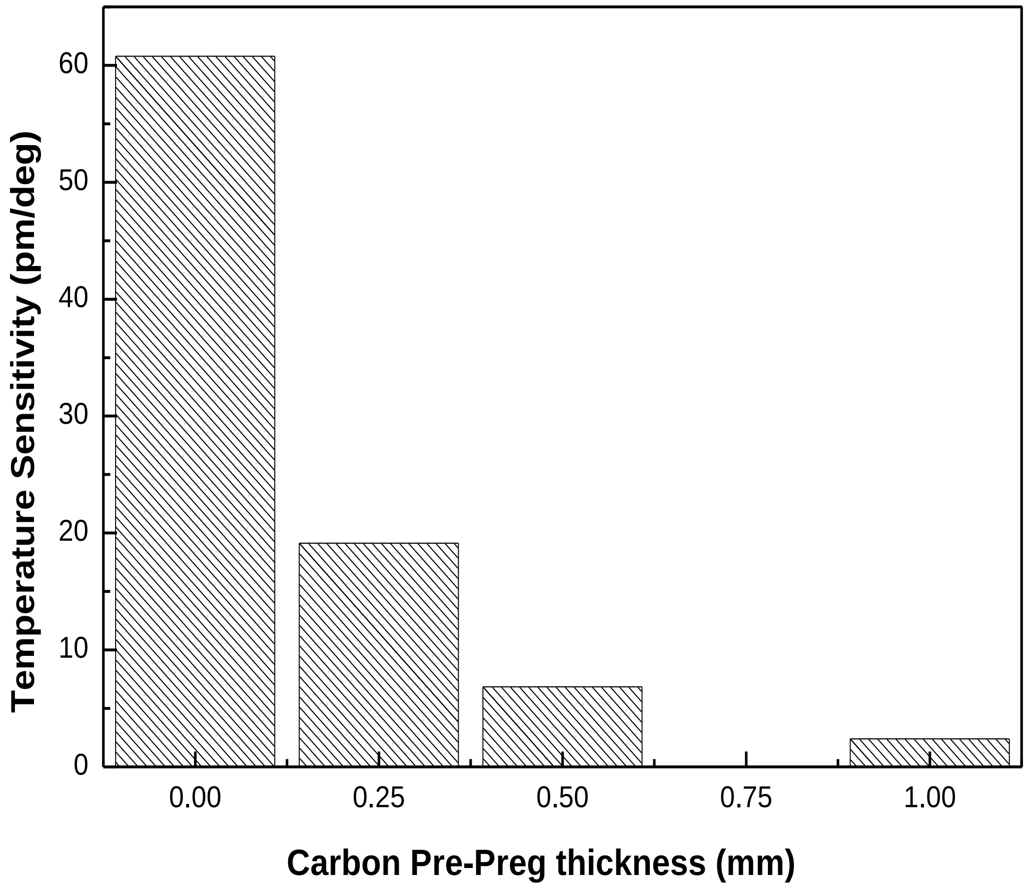


Fig. 5 Temperature sensitivity of CFRP FBG probes

On the one hand, in order to consider the change of strain sensitivity, the wavelength shifts of the probes influenced by the deformation are calculated by subtracting the wavelength shift of the bare FBG fiber influenced by heating from the wavelength shift of each CFRP FBG probe. Also, the wavelength shift of the bare FBG fiber influenced by heating is determined by multiplying the temperature sensitivity, 11 pm/°C, of the bare FBG fiber by the temperature change. The strain sensitivities of CFRP FBG probes are determined by dividing the wavelength shift of each probe by the strain change shown in Fig. 6. The strain sensitivity of 1 mm thick CFRP FBG probe is 0.35 pm/micro-strain, this sensitivity is also much lower than 1.1 pm/micro-strain of the bare FBG probe.

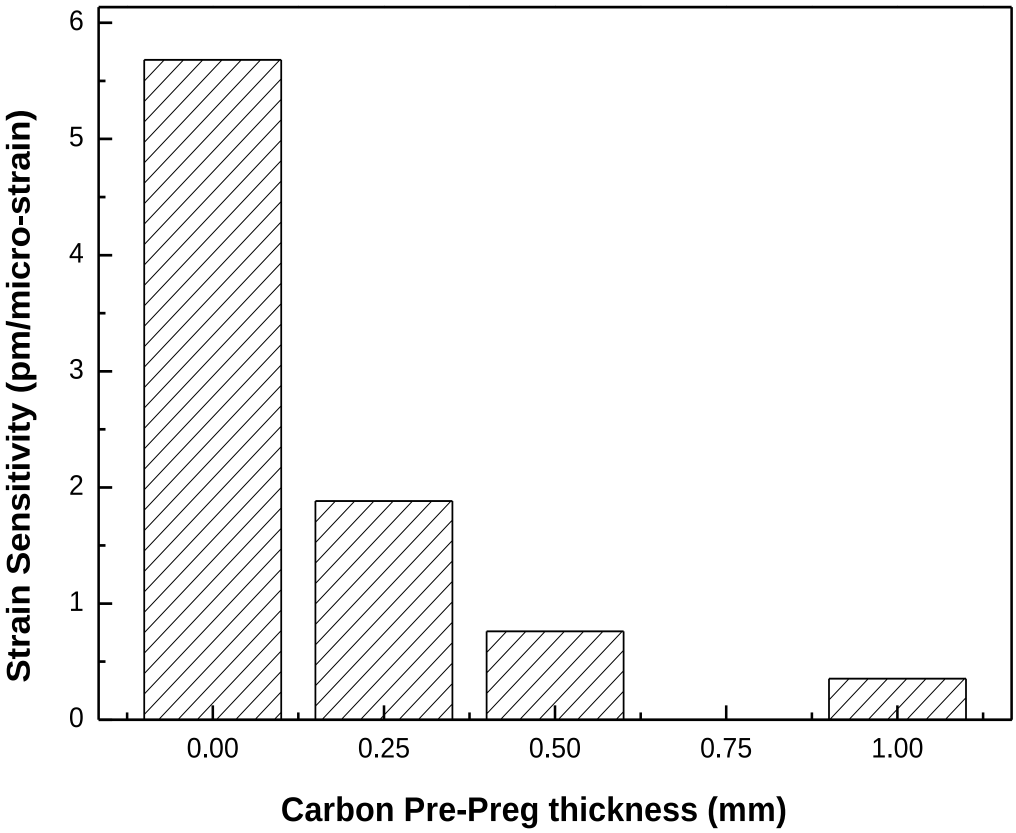


Fig. 6 Strain sensitivities of CFRP FBG probes

5. CONCLUSIONS

Fiber optic FBG(fiber Bragg grating) sensor probes are devised to monitor strain at the condition of low temperature sensitivity to use many probes in one optical fiber line. Four kinds of CFRP FBG probes are fabricated to study the change of the temperature sensitivity, and also the strain sensitivity from the bare FBG fiber. These probes are bonded on an aluminum plate to test the temperature sensitivity change. This specimen is tested by a thermal heating chamber. From this heating test, the temperature sensitivity of 1 mm thick CFRP FBG probe was determined as 2.39 pm/°C much lower than 11 pm/°C of the bare FBG probe. Also, the strain sensitivity of this probe was 0.35 pm/micro-strain, this sensitivity was also much lower than 1.13 pm/micro-strain of the bare FBG probe.

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