# Cure Monitoring of FRP by FBG Fiberoptic Sensors in RTM Molding Process

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**SUMMARY:** This paper describes an experimental study on cure monitoring by using a fiber Bragg grating (FBG) sensor in resin transfer molding (RTM) process. Extrinsic Fabry-Perot interferometric (EFPI) sensors were also used for the comparison because they have been proved as the strain sensor for cure monitoring in autoclave molding. In addition, the cyclic loading test was conducted to confirm the ability of the strain measurement in serve. The experimental results proved that the FBG sensors had a good performance to monitor the internal strain at the cooling stage of the curing process, while the reflected spectrum was deteriorated by the non-uniform thermal residual stress along the sensor caused by loose woven reinforcements. The cross-sectional observations of the molded composites showed that the embedding condition of FBG sensor was good but EFPI sensor formed a large void in the injection process. Then, it can be concluded that FBG sensors are usable for cure monitoring in RTM molding process. From the results of the loading test, it was also appeared that the embedded FBG sensor could be used for strain monitoring in service.

**KEYWORDS :** Cure monitoring, fiberoptic sensor, FBG sensor, RTM molding

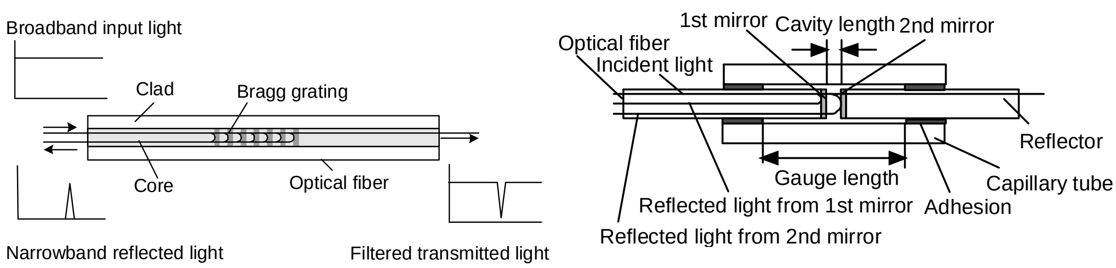
## INTRODUCTION

In liquid composite molding, preformed reinforcements are installed in a closed mold, and then liquid resin is injected. This molding method is suitable to manufacture large and complex-shaped parts made of fiber reinforced plastic (FRP) efficiently. The advantages of the molding method are good surface definition of products and healthy working environment compared with hand lay-up method. Resin transfer molding (RTM) is a popular process in the liquid molding. In RTM molding, liquid resin flows throughout the preform from the injection ports to the ejection ports by applying pressure to the resin. This injection process sometimes annoys us because the resin flow cannot be seen. Then, the inadequate pressure condition probably makes large voids at the corners of the mold or around the inserts. Large thermal residual stress in complex shaped composites is also a problem. To avoid these problems, the molding conditions specific with the products are essential. Since the conditions are obtained experientially, the initial cost of RTM molding rises price of the product. Then, the high-functional molding system with sensors and controllers has been desired in recent decades.

The high-functional molding system monitors the internal state of compoisites by using micro sensors and controls the pressure and the temperature in the molding processes. Several kinds of micro sensors, fiberoptic sensors, dielectric sensors, piezoelectric sensors and ultrasonic sensors, have been investigated as *in situ* sensors for the molding system. These sensors are mainly applied to cure monitoring, while some sensors can be used in pre-cure process. In RTM molding, the resin flow can be monitored by some sensors in the injection process [1,2]. The sensors give us various information of quality of products such as voids, defects, and residual strain after the cure process as well as the curing state. Then quality inspection process can be simplified because the quality is already assured at the end of the cure process. In addition, a time of the manufacturing process can be minimized by optimizing the cure cycle.

A cure monitoring technique using fiberoptic sensors is a most promising one and has been developed in a last decade. Advantages of the utilization of fiberoptic sensors in the cure monitoring are small size, high temperature resistance and a capability of the embedding. In addition, some of the fiberoptic sensors can be used in service after the implementation of products. Several kinds of fiberoptic sensors, spectroscopy-based sensors, fluorimetry-based sensors, refractive index-based sensors and strain/temperature sensors can be applied to the cure monitoring [3]. The near-infrared spectroscopy (NIRS)-based sensors and the fluorimetry-based sensors can monitor the chemical state of the resin. The refractive index-based sensor is utilized for the measurement of the refractive index changes of the resin. The embedded fiberoptic temperature sensors measure the local temperature in composites. The measurement of the residual strain, which is caused by the cure reaction and the thermal shrink, can be conducted by the embedded fiberoptic strain sensors. Many kinds of fiberoptic strain sensors, which are interferometric sensors, extrinsic Fabry-Perot interferometric (EFPI) sensors, fiber Bragg grating (FBG) sensors, Brillouin optical time domain reflectometric (B-OTDR) sensors, etc., can be used for the internal strain measurement.

For strain monitoring in molding process, FBG and EFPI sensors are suitable because the small gauge length and the high accuracy are required for the measurement of curing shrink and local stress. Figure 1(a) illustrates the construction of FBG sensors. FBG sensor has a fiber grating, which is a longitudinal periodic variation of the refractive index in the core of a single mode fiber. When a broadband light is incident into the grating, the narrowband light is reflected. The center wavelength, which is called Bragg wavelength, shifts when the fiber is stretched. Since the wavelength shift has a linear relation with the changes in the grating period, FBG sensors have a capability of absolute measurement of the axial strain.




(a) FBG sensor (b) EFPI sensor

Fig. 1 Construction of FBG sensor and EFPI sensor.

Figure 1(b) shows the construction of EFPI sensors used in this study. The EFPI sensor is constructed from two optical fibers, which are fixed with a capillary tube and have half mirrors at the ends of the fibers. The two mirrors compose an Fabry-Perot interferometer. There are two kinds of measurement systems for EFPI sensors. One uses a narrow-band light and another uses a broadband light. The former is a cheaper and high-speed system, but it depends on the optical power loss. On the other hand, the latter system is independent on the optical power loss due to the capability of the absolute measurement of the cavity length [4]. The loss may changes because applied pressure to FRP may vary in molding process. Therefore, the latter system is desirable for cure monitoring.

In the case of cure monitoring in RTM molding process, the sensors, which have smaller diameter than thickness of reinforcing fiber strands, are desired because the embedded sensors interrupt the resin flow. Thus, it is considered that FBG sensors are more suited than EFPI sensors because a diameter of EBG sensors is smaller. Although applications of FBG sensors to health monitoring of FRP can be seen in many literatures[5-8], the availability of FBG strain sensors in RTM molding has not been proved yet. In the present paper, the experimental research on the application of FBG sensors to the cure monitoring in RTM molding is mainly addressed. EFPI sensors were also used for the comparison because it has been proved as the strain sensor for cure monitoring in autoclave molding. In addition, the cyclic loading tests were conducted to know the availability of the embedded FBG sensors under mechanical loading in service.

## EXPERIMENTAL SETUP

The configuration of the RTM molding with *in situ* sensors is illustrated in Fig. 2. Twenty-five glass cloths were set in the mold as a preform. The fiberoptic sensor was knitted in the thirteenth cloth perpendicular to the direction of the resin flow. A dielectric sensor and a thermocouple were also embedded between thirteenth and fourteenth cloths of the preform. The fiberoptic sensor was drawn through the side slit of about 1 mm height and the other sensors were done through the ejection port as shown in Fig. 2. The side slit and the vacant space between the

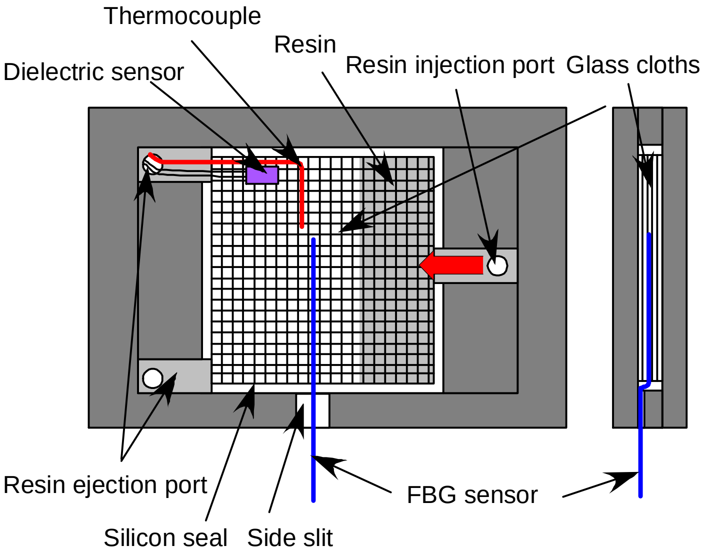



Fig. 2 Configuration of RTM molding with *in situ* sensors

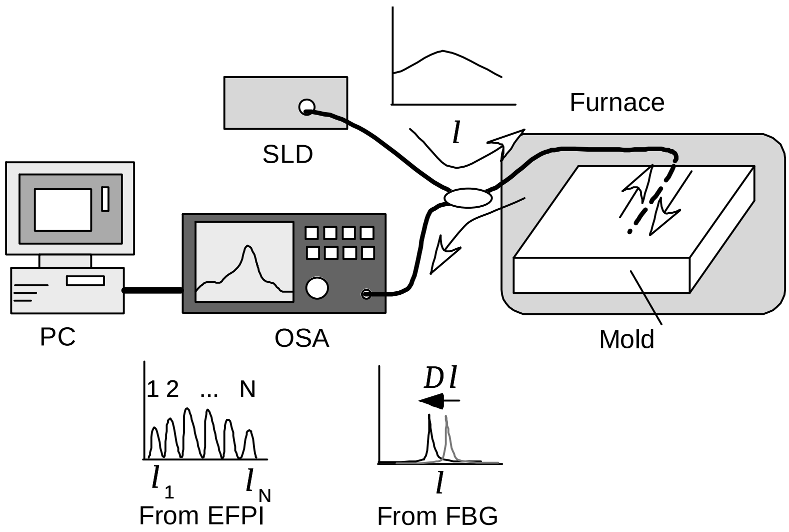



Fig. 3 The strain measurement system for FBG and EFPI sensors

preform and the mold were filled with silicon before the resin injection. The epoxy resin (EPIKOTE 807, Yuka Shell Epoxy, Co. Ltd.) was injected into the mold by applying pressure to the resin tank. After the finish of the resin injection, the fiberoptic sensor was connected to the strain measurement system and the dielectric sensor, to the dielectric measurement system (Numeric 100A, Micromet Instruments, Inc.). The composites were cured for 2 hours at 100 °C and for 4 hours at 175 °C in a furnace. Strain, temperature and dielectric constants were monitored in the curing process. After the end of the cure reaction, the mold was cooled to room temperature naturally. The molded FRP has the size of $19\times 18.5\times 5.1$ mm and the volume fraction of 36.5%. The composite was unmolded carefully so that the embedded optical fiber sensor was available for the loading test.

The strain measurement system for FBG and EFPI sensors was composed of a super luminescence diode (SLD), an optical spectrum analyzer (OSA), an optical directional coupler and a personal computer (PC) as shown in Fig 3. The measured spectra were sent to PC and then the software computed strain from them. The strain output $e_3$ of FBG sensor was obtained from the Bragg wavelength shift $\Delta l$ and the temperature variation $\Delta T$ by the following equation [5].

$$\begin{aligned}\frac{\Delta l}{l_0} &= \frac{\partial}{\partial e_3}\left(\frac{\Delta l}{l_0}\right)e_3 + \frac{\partial}{\partial T}\left(\frac{\Delta l}{l_0}\right)\Delta T \\ &= \left[1-\frac{n_0^{\ 2}}{2}\left\{p_{12}-n_s\left(p_{11}+p_{12}\right)\right\}\right]e_3 + \left(a_s + \frac{1}{n_0}\frac{dn_0}{dT}\right)\Delta T\,, \end{aligned} \tag{1}$$

where, $l_0$ is initial Bragg wavelength, $p_{11}$ and $p_{12}$ are Pockels constants, $a_s$ is coefficient of thermal expansion (CTE), $n_s$ is Poisson ratio, $n_0$ is refractive index at $\Delta T = 0$. All values belong to FBG sensor. In this paper, the sensor sensitivities to $e_3$ and $\Delta T$ were already measured for the strain calibration.

As for EFPI sensor, the cavity length $d$ was obtained by measuring $\Delta k$, which is the period of the transfer function of the reflected spectrum in wavenumber domain. When the peak positions were obtained from the spectrum as shown in Fig. 3, the cavity length can be calculated from $l_1$ and $l_N$ by the following equation.

$$d = \frac{1}{2\Delta k} = \frac{(N-1)}{2}\frac{l_1 l_N}{l_N - l_1} \tag{2}$$

The strain output of EFPI sensor can be represented as;

$$e_3 = \frac{\Delta d - d_0 a_S \Delta T}{L_G}, \tag{3}$$

where, $L_G$ is a gauge length, $d_0$ is an initial cavity length and $\Delta d$ is a variation of the cavity length. Most of commercial EFPI strain sensors have a low thermal sensitivity because the gage length is about as 20 times long as the cavity length. The EFPI sensors used in this study have the temperature sensitivity of about 0.00625 $10^{-6}$/°C.

## STRAIN MONITORING IN RTM MOLDING PROCESS

The typical behavior of the log ion viscosity measured by the embedded dielectric sensor is plotted against time with temperature in Fig. 4. The temperature-time profile had five stages, which were the first heating stage (I), the first isothermal stage (II), the second heating stage (III), the second isothermal stage (IV) and the cooling stage (V). The cure reaction of the resin started after the mixture of the resin with the cure agent and proceeded slowly at the resin injection process. Since it took a few hours to fill the mold with the resin, the ion viscosity was already high at the beginning of the measurement as shown in Fig. 4. The ion viscosity decreased at the stage I and then increased at the beginning of the stage II. This indicates that the speed of the cure reaction became faster over 100 °C. The convergence of the ion viscosity indicates the finish of the cure reaction at the end of the stage IV.

Figure 5 shows the experimental results of the internal strain measurements of the three specimens (Specimens A-C). It should be noted that these specimens had the same configuration and

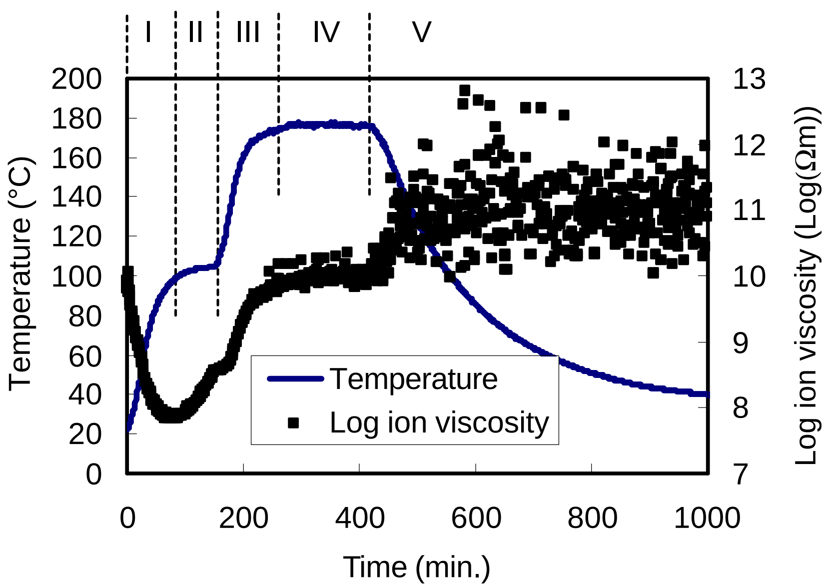



Fig. 4 Log ion viscosity and temperature as functions of time.

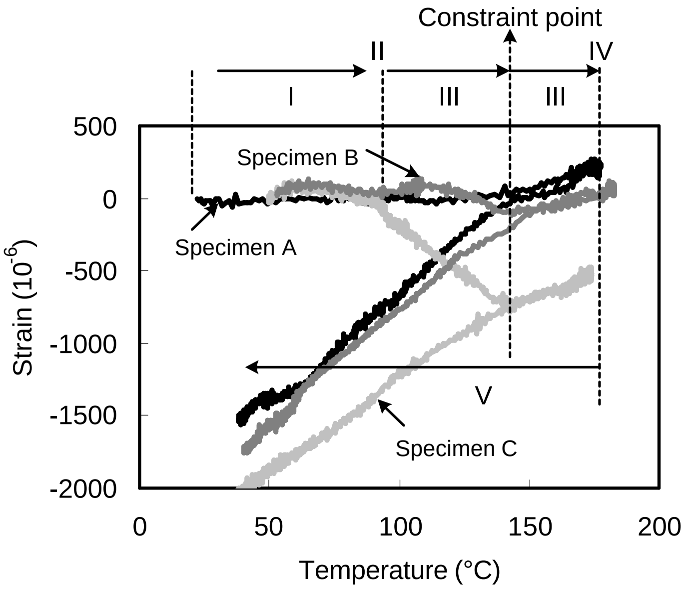



Fig. 5 Relations between strain from FBG sensors and temperature for the three different specimens.

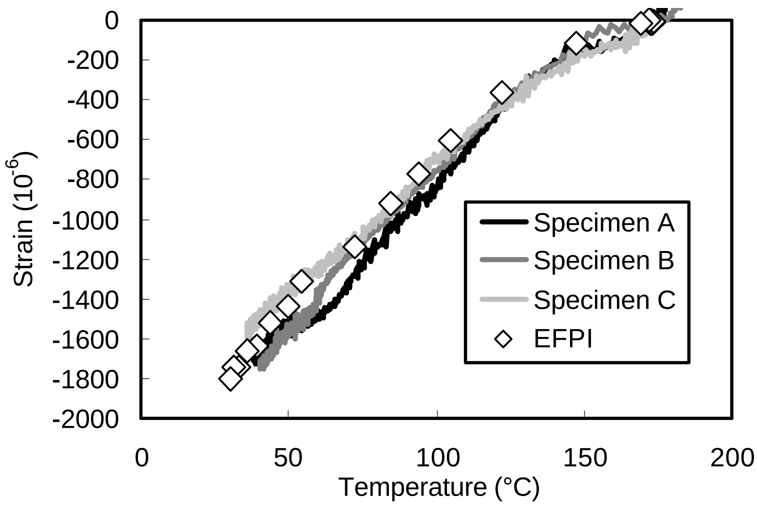



Fig. 6 Strain from FBG sensors and EFPI sensor and temperature as functions of temperature at cooling stage.

were molded under the same molding conditions. The x-axis represents temperatureand the y-axis does strain. The strain of all specimens was almost zero at the stage I. The knee points of the strain-temperature curves can be seen at the middle of the stage III. It is appered that the sensors were constrained by the reacting resin after this knee point because the sensors began to indicates tensile strain by heating. Then, the knee point was called constraint point in this paper. From the figure, it was appeared that the strain-temperature curve has poor reproducibility before the constraint of the sensor at the stage III. From the constraint point to the stage IV, the strain increased linearly with the temperature change. At the stage V, the strain decreased linearly with the temperature decreasing. To know the strain-temperature behavior at the stage V

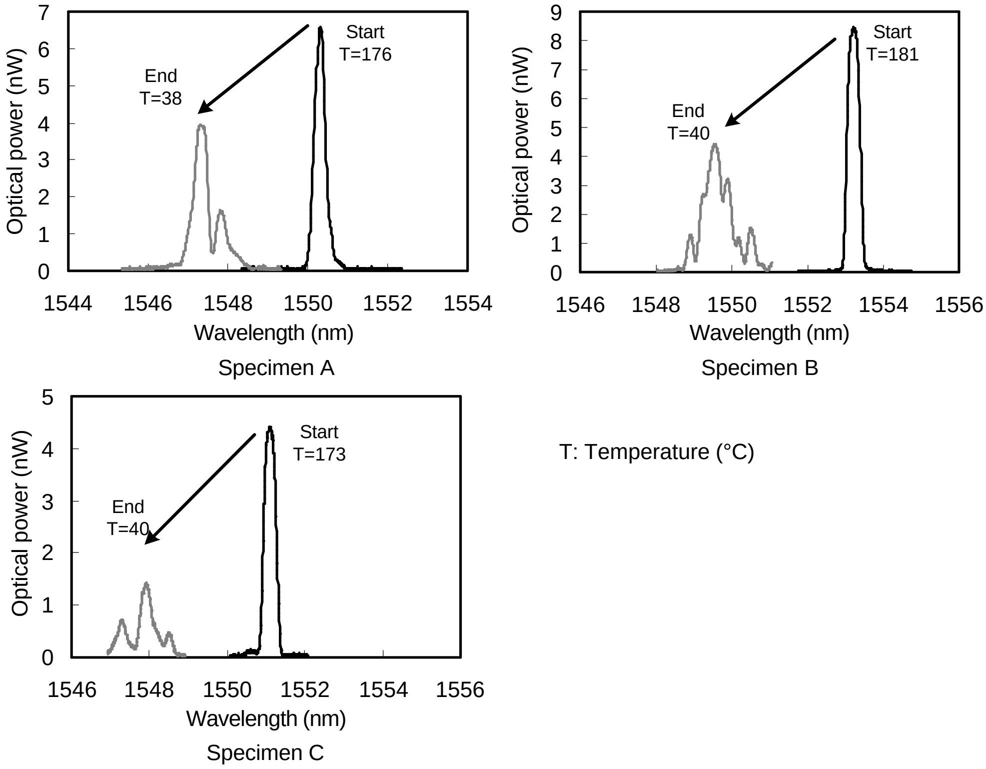



Fig. 7 Reflected spectra from embedded FBG sensors at cooling stage.

well, the baselines of the strain-temperature curves were shifted so that the curves matched to zero strain at 175 °C. The shifted strain-temperature curves obtained from the FBG sensors were shown with the results from the embedded EFPI sensor in Fig. 6. It was clear that the internal strain behaviors of the three specimens were almost same after the constraint of the sensors. Since the results from the FBG sensors agree well with those of the EFPI sensors, it is concluded that the strain measurement by the FBG sensors was reliable at the cooling stage.

## EMBEDDING CONDITION OF OPTICAL FIBERS

When a resin was cured at high temperature, it is thought that large thermal residual stress is generated around embedded fiberoptic sensors. Since FBG sensors are easily affected by the non-uniform stress distribution, the embedding condition of the FBG sensors can be investigated from the spectrum shapes. Figure 7 illustrates the changes of the reflected spectra from the embedded FBG sensors. From the figures, it was found that the reflected spectra were deteriorated after the cooling. This deterioration caused the reduction of the optical power, but it did not affect the precision of strain measurement seriously. However the mechanism of the deterioration should be investigated to know the optimal embedding condition.

The reason of the deterioration was though to be the two kinds of the residual stress distributions generated around the FBG sensor after the molding. One is the non-axisymmetric stress distribution resulting from the anisotropic CTE [6]. Two polarized waves, which have different Bragg wavelengths, were reflected corresponding to the normal stresses in the cross-sectional

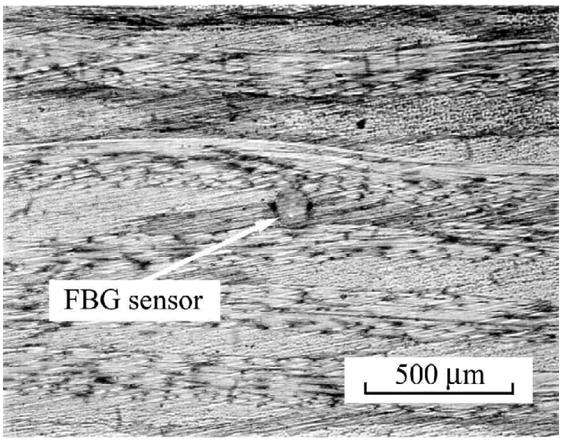



Fig. 8 Cross-sectional photographs of composites where FBGsensor embedded

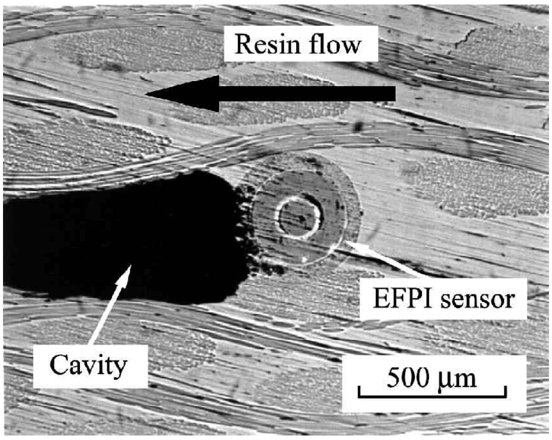



Fig. 9 Cross-sectional photographs of composites where EFPI sensor embedded

plane of the optical fiber and thereby the reflected spectrum has two peaks after the molding. Another is the non-uniform stress distribution along the FBG sensor caused by the inhomogeneity of the FRP. In this case, several peaks are probably observed in the reflected spectrum. The spectra of the specimen A showed only tow peaks, while the spectra of the specimens B and C have four and three peaks respectively. Therefore it can be concluded the embedded FBG sensors were affected strongly by the both stress distributions in this experiment. Stress analysis around the embedded sensor is necessary for more quantitative discussions.

After the experiments, the specimens were cut across the embedded optical fibers. Then the cross sections were observed by an optical microscope. Figures 8 and 9 show the cross-sectional photographs of the specimens, where FBG and EFPI sensors were embedded, respectively. Optical fibers embedded in composites across the reinforcing fiber strands usually form the resin rich region around it. This resin rich region may degrade the performance of the composites of high volume fraction. However, in the case of the loose-woven composites used in this study, that is not problem because the large resin rich region was distributed over the specimens. Figure 8 shows that the embedding condition of FBG sensor was good. On the other hands, a large void was observed near the EFPI sensor as shown in Fig. 9. In this study, the high viscous resin flew avoid the optical fiber sensors since the sensors were embedded perpendicularly to the direction of the resin flow. Then it was found that the dry spot was formed by the large diameter of the EFPI sensor. Low viscous resin is necessary for the use of EFPI sensors since the condition of formation of the dry spot depends on the viscosity of the resin as well as the diameter of the fiberoptic sensor. This fact indicates that FBG sensors are more suitable than EFPI sensors for the embedding in RTM molded composites.

## STRAIN MONITORING ON MECHANICAL LOADING TEST

The cyclic loading test of the specimen was conducted with measuring strain by the embedded FBG sensors and the attached foil strain gauges. Figure 10 shows the results of the cyclic loading test. Both the strain measured by the FBG sensor and the strain gauge was plotted against time. The total number of the cycles was 17. The FBG sensor was alive during the test. The

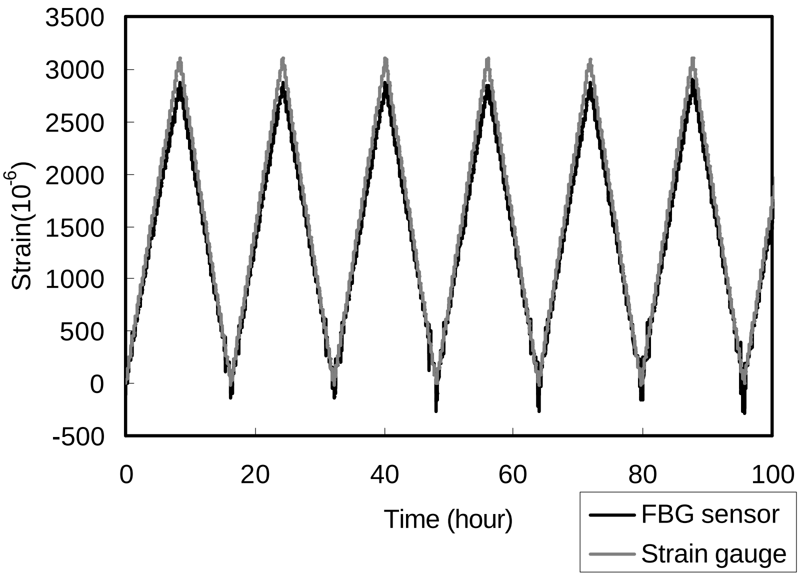



Fig. 10 Strain from FBG sensor and temperature as functions of time.

figure shows that the results of the FBG sensor had a good agreement with those of the strain gauge . Then it can be concluded that FBG sensors embedded in the woven FRP, whch are manufactured by RTM molding,  has a good potential of *in situ* strain monitoring in service while the spectrum was deteriorated by the thermal residual stress after the molding.

## CONCLUSIONS

Cure monitoring of GFRP by using embedded FBG strain sensors in RTM molding process was conducted. EFPI sensors were also used for the comparison because it has been proved as the strain sensor for cure monitoring in autoclave molding. After the molding, the stain measurement by the embedded FBG sensors was also carried out under mechanical loading. We can conclude this study as follows;

1. It was appeared that the strain from FBG sensors had a poor reproducibility until the sensor was constrained by the resin.
2. The strain behavior was almost same for the three specimens after the constraint of the sensors.
3. The comparison with the results of the embedded EFPI sensor proved that the embedded FBG sensors had a good performance to monitor the internal strain at the cooling stage of the curing process.
4. The cross-sectional observations of the molded composites showed that the embedding condition of FBG sensor was good but EFPI sensor formed a large void in the injection process due to the large diameter.
5. The reflected spectrum from the embedded FBG sensor was deteriorated at the cooling stage due to the non-uniform thermal residual stress caused by the anisotropy and the inhomogeneity of the loose-woven composites. However the deterioration did not affect the accuracy of the strain measurement seriously.
6. From the results of the loading tests, it was appeared that the embedded FBG sensors could be used in service while the spectrum was deteriorated.

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