Measurement of material properties of composites under high temperature using fiber Bragg grating sensors

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Abstract. Composite materials are widely used for aircraft, satellites, and other structures due to their good mechanical and thermal characteristics such as high specific stiffness and strength, a low coefficient of thermal expansion, and good heat-resistance. However, for the use of composites under high temperature, their material properties must be measured and verified at high temperatures. In this study, the material properties of T700/Epoxy were measured through a tension test of composite specimens with an embedded fiber Bragg grating sensor in a thermal chamber at temperatures of room temperature, 100 ^oC, 200 ^oC, 300 ^oC, and 400 ^oC. The effects of an optical fiber on the material properties of the composites were investigated through a pre-test of embedding an optical fiber. Finally, the material properties of composites, parallel to and perpendicular to the reinforcing fiber, were successfully shown to vary according to increases in the temperature.

Introduction

Composite materials are increasingly being used as engineering materials in aircrafts, buildings, and other structures. Compared to conventional aluminum alloys, composites have many advantages such as high specific stiffness and strength, a low coefficient of thermal expansion, and good heat-resistance. However, composite materials can also be locally heated to a high temperature because of several causes like the aerodynamic heating. Composite materials that are available at a high temperature are therefore necessary. Several studies related to composites have been published [1,2]. Although some materials can endure high temperature, their material properties degrade as the temperature increases. For this reason, and for a better application of composite materials under high temperature, studies on the way material properties change with temperature should be verified.

An electric strain gage (ESG) has mainly been used to measure the material properties of composite materials. However, electromagnetic waves affect their performance and, when the temperature is very high, their ability to measure strain is limited. Additionally, the strain gage also needs a bridge circuit to compensate for the thermal strain of the gage itself. Fiber-optic sensors can be easily embedded into structures because of their small size, wide temperature ranges, and electromagnetic immunity. Unlike many fiber-optic sensors, fiber Bragg grating (FBG) sensors can simply measure strain and temperature, just by detecting changes in the reflected wavelength. The FBG sensors also have better multiplexing capabilities than many other sensors. Many studies on the strain measurement of composite structures and on applications under various temperature conditions have already been conducted using FBG sensors [3,4]. For these reasons, FBG sensors are considered very appropriate as a strain sensor under high temperature, and their application potential is being gradually expanded.

In this study, we used an embedded FBG sensor to measure the changes in the material properties of the T700/Epoxy composite materials that were used to fabricate filament-wound pressure tanks at the temperatures of room temperature (RT), 100 ^oC, 200 ^oC, 300 ^oC, and 400 ^oC. The stacking sequences of the used specimens were $[0/\{0\}/0]_T$ and $[90_2/\{0\}/90_2]_T$. Material properties of each specimen were measured through tension test in a thermal chamber with an embedded FBG sensor, located in the center of the specimen. We also confirmed the effects of embedded optical fiber on the material properties of the composites through a pre-test in which optical fiber was embedded into the composite. From the experimental results, the material properties of composites were successfully shown to vary according to increases in the temperature.

Fiber Bragg grating sensor

Fiber Bragg grating is composed of periodic changes of the refractive index that are formed from exposure to an intense UV interference pattern in the core of an optical fiber. This grating structure results in the reflection of light at a specific narrowband wavelength, called the Bragg wavelength. The Bragg condition is expressed as $\lambda_B = 2\, n_e \Lambda$ where λ_B is the Bragg wavelength of FBG; n_e is the effective index of the fiber core; and Λ is the grating period. The wavelength, which is determined by the Bragg condition, reflects at the Bragg grating part and the other wavelengths pass through it. Figure 1 shows this process.

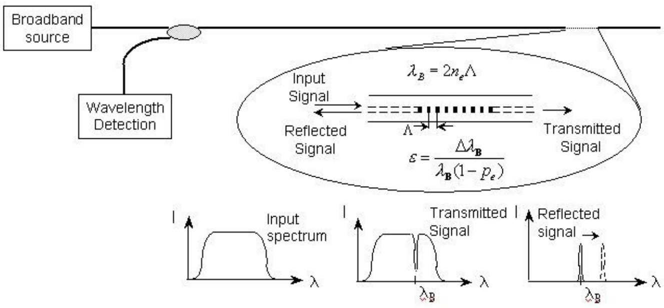


Fig. 1 Fiber Bragg grating sensor wavelength-encoding operation.

The Bragg wavelength is a function of the refractive index of the fiber core and the grating period. If the grating is exposed to external environmental procedures, such as strain and temperature, the Bragg wavelength changes. By measuring the wavelength change accurately, we can measure material properties like strain and temperature, - this is the fundamental principle that allows fiber Bragg grating to be used as a sensor. The shift of a Bragg wavelength due to strain and temperature can be expressed as equation 1, where α_f is the coefficient of thermal expansion (CTE), ξ_f is the thermo-optic coefficient, and p_e is the strain-optic coefficient of the optical fiber. The value of p_e(=0.227) was measured experimentally and used for this study.

$$\Delta\lambda_B = \lambda_B\left[\left(\alpha_f + \xi_f\right)\Delta T + \left(1 - p_e\right)\varepsilon\right] \tag{1}$$

$$\varepsilon = \frac{1}{1 - p_e}\frac{\Delta\lambda_B}{\lambda_B} \tag{2}$$

Using the above equation, assuming there is no temperature change, we can measure the strain from the wavelength shift as equation 2. From Eq. 2, the strain can be easily calculated just by measuring the wavelength shift. We can also measure the strains at many positions in a single optical fiber by multiplexing capabilities of FBG sensors, like wavelength division multiplexing (WDM), because FBG sensors that have different Bragg wavelengths do not influence one another.

Estimation of the effects of embedded optical fiber

Even a very small amount of optical fiber embedded into a composite material can affect the properties of the material. To verify the effects of embedded optical fiber on the material properties, three types of specimens were fabricated. The first type was a specimen for a normal tension test; its measurements were used as reference data for the material properties. The second type was protected by a stainless tube with the diameter of 6 *mm*. The third type was protected with a polyvinyl chloride (PVC) jacket at the ingress/egress point of the specimen. The laminates were made from CU125-NS graphite/epoxy prepreg (HFG Co.), and the stacking sequences were chosen as $[0_8]_T$ and $[90_{16}]_T$. An optical fiber was embedded into the center of each specimen.

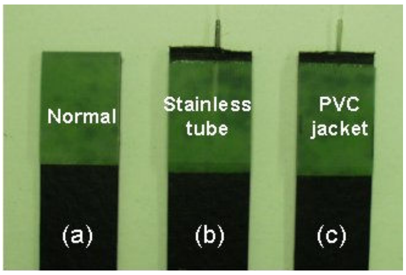


Fig. 2 Verification test specimens of the sensor embedding affection.

After fabrication of the test specimens, a suitable ingress/egress method was selected. For the stainless tube specimens, some irregularities were observed on the surface of the specimens, as shown in Fig. 2. As a result, a groove had to be made on the tab surface when attaching tabs to the specimen. This process weakened the adhesiveness between tab and the surface of the specimen, thereby them to separate. This tendency was also shown in the $[90_{16}]_T$ specimen. However, for the specimen with the PVC jacket, the jacket was assimilated well with the composite materials during the cure and no irregularities were observed on the surface of the specimen after the specimens had been fabricated. The tension tests for the three specimens were conducted using electric strain gages (FLA-5-11, TML) and, from the results, the material properties such as stiffness and strength were almost the same for each specimen. With respect to the effectiveness of fabrication, the PVC jacket is the best ingress/egress method for embedding the sensors without degrading the material properties.

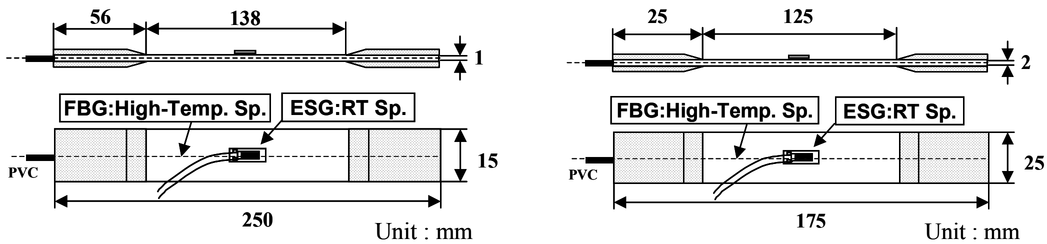
Fabrication of test specimens

The curing cycle of the T700/Epoxy specimen has several characteristics such as the high temperatures and long duration of the first holding and second holding steps. The fabrication procedure is as follows:

- First, hoop winding on the mandrel is performed using reinforcing fiber (T700, Toray Co.) with high temperature epoxy resin (MY0510, HFG Co.).
- Second, prepreg tapes are finally produced, by spreading sheets extracted from the cylinder.
- Third, the β-stage cure is performed in a thermal chamber.

Using the prepreg tapes, test specimens were fabricated in an autoclave, and the staking sequences were $[0/\{0\}/0]_T$ and $[90_2/\{0\}/90_2]_T$, where '{}' marks the location and the figure in '{}' marks the direction of an embedded sensor. One FBG sensor was embedded parallel to the reinforcing fiber in the $[0/\{0\}/0]_T$ specimen and perpendicular to the reinforcing fiber in the $[90_2/\{0\}/90_2]_T$ specimen. Specimens were fabricated in terms of ASTM D 3039/D 3039M. The grating part of the fabricated FBG sensors was recoated with arcylate using a recoating machine, and the ingress/egress point of each specimen was protected with the PVC jacket.

We fabricated two specimens, the 0^o specimen and the 90^o specimen. Each specimen was divided into five portions corresponding to each of the following temperatures: RT, 100 ^oC, 200 ^oC, 300 ^oC, and 400 ^oC. Because every specimen was extracted from the same laminate in order to diminish the fabrication errors, the number of specimens for each kind was limited to two. The configurations of the specimens and sensor positions are shown in Fig. 4. An ESG was attached on the surface of the RT specimen and an FBG sensor was embedded into every high-temperature specimen. The measurements from the ESG were used as a reference for the material properties, and characterizations of the property changes were based on the data from the FBG sensors. The reflected signals of the FBG sensors were acquired through a data acquisition board; they were then, processed and saved by a signal-processing program written with a software application called LabVIEW® [5]. A wavelength-swept fiber laser (WSFL) was used as a broadband light source to supply high signal power. The FBG sensor signals were acquired at intervals of 5 Hz.



(a) $[0/\{0\}/0]_T$ (b) $[90_2/\{0\}/90_2]_T$

Fig. 4 Configurations of test specimens.

Measurement of material properties at high temperatures: 0^o specimen

The tension test of the 0^o specimens was conducted at RT so that the experimental data of the tests could be used as a reference for the material properties. The test was conducted using an ESG attached to the surface. However, the experimental data measured at the high temperatures of 100 ^oC, 200 ^oC, 300 ^oC, and 400 ^oC were obtained with an FBG sensor embedded into each specimen. The FBG sensor was used because the data measured with it agree well with the results of many other studies that used strain gages. All the tests were conducted in a thermal chamber equipped in an *Instron* 4505, with a displacement control of 1 mm/min. The experimental apparatus is depicted in Fig. 5.

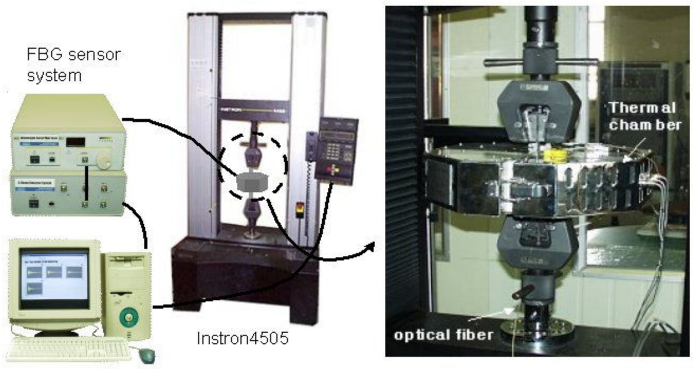


Fig. 5 Experimental setup for tension test at high temperatures.

In Fig. 5, the test specimen was fixed on the grip of the *Instron*, and the temperature of the thermal chamber was set to a desired temperature. A tensile load was applied after the set temperature was completely saturated.

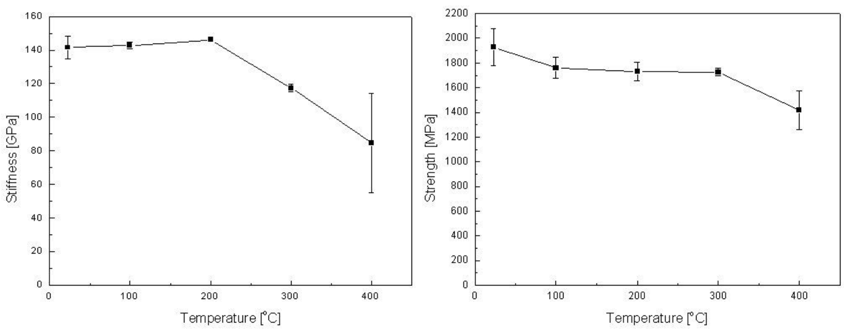
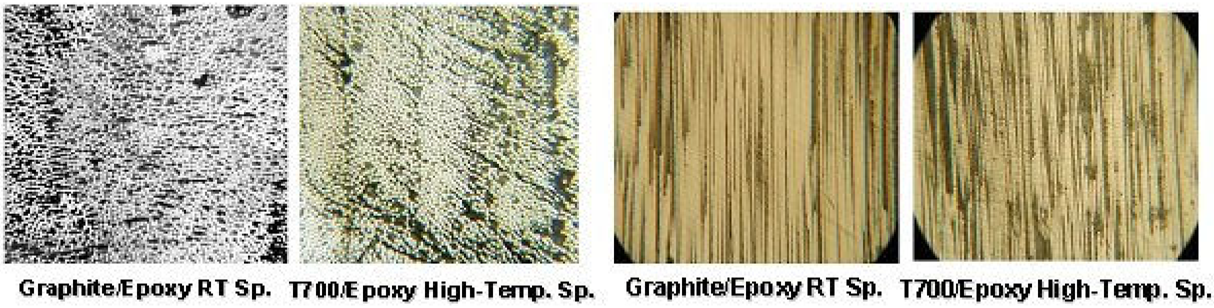


Fig. 6 Material property change of $[0_2]_T$ with temperatures.

Figure 6 shows that, the stiffness of the 0^o specimen was maintained from RT to 200 ^oC and it gradually decreased above 200 ^oC. On the other hand, the strength of the 0^o specimen decreased slightly from RT to 100 ^oC but was maintained from 100 ^oC to 300 ^oC. Above 300 ^oC, the strength decreased again. As shown in Fig. 6, the stiffness and strength have different tendencies when the temperature increases. In Fig. 6, a large deviation is found in the measurements as a result of irregularities in the fabrication of the specimens. For each specimen, microphotographs of the cut end were taken with a microscope (PME3, Olympus), parallel to and perpendicular to the reinforcing fiber, as shown in Fig. 7.



(a) perpendicular to the reinforcing fiber (b) parallel to the reinforcing fiber

Fig. 7 The microphotographs of the cut end of specimens.

In Fig. 7, the fiber arrangement of the T700/epoxy specimen is clearly more irregular than that of the graphite/epoxy specimen. An image processing program was used to calculate the fiber volume fraction, for each of the three specimens, and the measurements of each specimen were taken at two different sections. The results show that the deviation in the measurements of the T700/epoxy specimen is about twice as large as that of the graphite/epoxy specimen, even though the averages are almost the same. In short, the specimen that was fabricated with the reinforcing fiber partly wrinkled. The material properties at 400 ^oC, however, show a huge deviation, even when the irregularities of the specimen are considered. As shown in Fig. 8, the deviation is explained by the failure shapes of the specimens at each temperature.

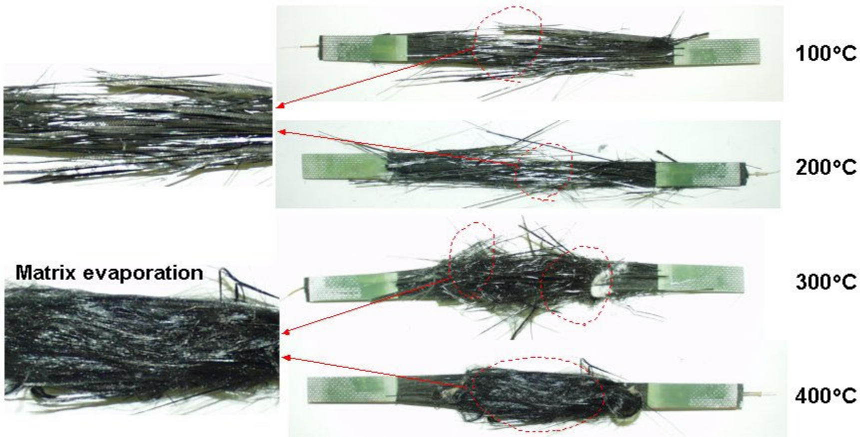


Fig. 8 Failure shapes of specimens at each temperature.

In Fig. 8, the failure shapes of the specimens at 300 ^oC and 400 ^oC prove that the matrices of the specimens are burned and evaporated, while those at 100 ^oC and 200 ^oC are definitely normal. The thermal strain and fiber slippage induced by the matrix evaporation could generate some measurement errors in the FBG sensors. Additionally, the induced thermal strain is dependent on the saturation time of each temperature for each specimen. The thermal strain that an FBG sensor induces upon itself during the evaporation of a matrix should therefore be measured to reduce the measurement errors.

Measurement of material properties at high temperatures: 90° specimen

The material properties of the 90° specimens were measured using the same procedure as in the previous section. Contrary to the results of the 0° specimens, the stiffness and strength both decrease continuously as the temperature increases. However, obtaining a strain measurement over 300 ^{o}C is impossible because the matrix cannot bear the load due to the evaporation of the matrix. When the temperature is less than 200 ^{o}C, the material properties show an exponential decrease with the temperature increase, as shown in the Fig. 9. The stiffness and strength both show a similar tendency and, as shown in Fig. 9, the evaporation point of the epoxy resin appears to exist in a temperature range between 200 ^{o}C and 300 ^{o}C. These results confirm that the FBG sensors were successfully used to quantitatively measure the material properties of composites under high temperature. They also confirm that, for precise measurement, the thermal strain should be also measured above a particular temperature because of the evaporation of the matrix.

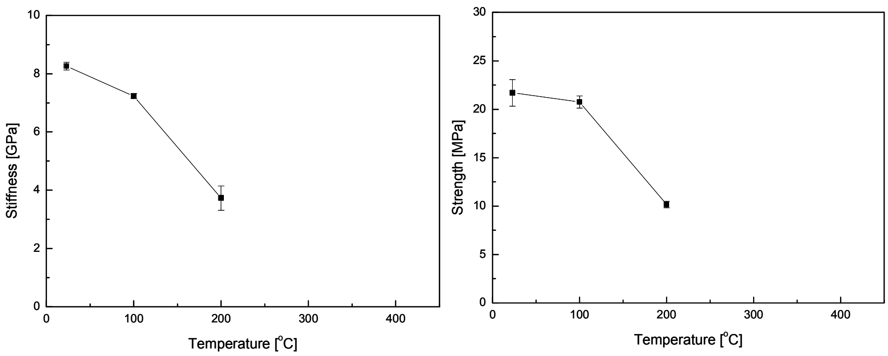


Fig. 9 Material property change of $[90_4]_T$ with temperatures.

Conclusion

The conclusions obtained from this research are as follows. FBG sensors are suitable for measuring the material properties of composites without any degradation of material properties at high temperatures. When the effectiveness of fabrication is considered, a PVC jacket is the best means of protecting the ingress/egress point of composites. The material properties of composites that are perpendicular, and parallel to the reinforcing fiber can be measured using embedded FBG sensors at high temperatures.

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