Cure Monitoring of Composite Laminates Using Fiber Optic Sensors

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Abstract

In this paper, we present the simultaneous measurement of the strain and temperature during cures of various composite laminates using fiber optic sensors. Fiber Bragg grating/extrinsic Fabry-Perot interferometric (FBG/EFPI) hybrid sensors were used to measure those measurands. The characteristic matrix of the hybrid sensor is derived analytically and measurements can be done without sensor calibration experiments. For the fabrication of the three types of graphite/epoxy composite laminate, two FBG/EFPI hybrid sensors were embedded in each composite laminate in two mutually perpendicular different directions. We performed the real time measurement of fabrication strains and temperatures at two points within the composite laminates during cure process in an autoclave. Through these experiments, FBG/EFPI sensors are proven to be an efficient choice for smart monitoring of composite structures.

1. Introduction

Composite materials are increasingly being used as engineering materials in aircrafts, buildings, containers, and other structures. They are growing commoner because of high specific strength and specific stiffness over their metal counterparts, as well as excellent corrosion and fatigue resistance. Composite structures are fabricated by using a variety of techniques such as vacuum bag autoclave technique, hot press, resin transfer molding, pultrusion, and filament winding. Among these techniques, the vacuum bag autoclave molding is used extensively for production of high-quality aerospace structures.

Fabrication strains during cure can lead to significant problems such as warpage or spring-in, which presents difficulties in the assembly of composite structures. Residual stresses due to a difference in the thermal expansion coefficient between the fiber and matrix in the cooling stage can have intense effects on the mechanical properties of a composite product such as compressive and buckling strength, fracture toughness, and fatigue strength, since a “pre-loading” has been introduced[1]. Residual stresses may have a major effect on the micro-stresses within a composite material system and must be added to the stresses induced by the external mechanical loads[2,3]. A common manifestation of residual stresses is the warping of laminates with non-symmetrical layups. Several studies have been conducted to optimize the cure conditions for the reduction of process induced residual stresses of fiber[4-6] as well as matrix[7]. The quality of the final composite part is directly affected by cure conditions such as cure time, temperature, and pressure. To obtain the optimal cure conditions, there is a demand for sensors that are capable of monitoring the cure process in situ and at points remote from the surface.

A prerequisite of any in-situ sensor for composite materials is that it must not be detrimental to the operational requirements of the structure. A fiber optic sensor that can be easily embedded in composites is a good candidate for cure monitoring of composite materials. Furthermore, the dimensions and orientation of the optical fibers within the prepregs can be selected to have minimal impact on the mechanical properties of the composite. Also, the advantage of fiber optic sensor technology compared with other cure monitoring techniques such as electrical resistance and dielectric analysis is its low susceptibility to electromagnetic interference. Thus, fiber optic sensors can be used to monitor several parameters such as the fabrication strain and temperature during cure and to evaluate the structural integrity during service after cure.

For composite cure monitoring using fiber optic sensors, most research has been conducted only to measure the fabrication strain using various types of sensors such as the extrinsic Fabry-Perot interferometric (EFPI) sensor[8-11] and the fiber Bragg grating (FBG) sensor[12]. Several techniques, however, have been reported in recent years for the simultaneous measurement of strain and temperature using FOSs[13-17]. With these techniques, simultaneous monitoring of the fabrication strain and the cure temperature is possible with single fiber optic sensor.

In this paper, we present the simultaneous measurement of strain and temperature during cure of various composite laminates using fiber optic sensors. Fiber Bragg grating/extrinsic Fabry-Perot interferometric (FBG/EFPI) hybrid sensors were used to measure these measurands and the characteristic matrix of the sensor is derived analytically. For a unidirectional laminate, a symmetric cross-ply laminate, and a fabric laminate, two FBG/EFPI sensors are embedded in each graphite/epoxy composite laminate in different directions and different locations. They measured fabrication strains and temperatures within the composite laminates during the cure process in an autoclave.

2. Analytic Derivation of Relationship for FBG/EFPI hybrid sensor

For the simultaneous measurement of strain and temperature, we need two sensing elements that can supply two equations with respect to the two parameters. Many of the previous approaches have employed grating type sensosrs, a combination of interferometric and polarimetric techniques, fiber Bragg grating/Fabry-Perot interferometric hybrid sensors, and other hybrid type sensors. In most approaches, a number of experiments had to be performed to obtain the characteristic matrices of each sensor. These are time-consuming and may lead to inaccurate measurements. In our previous work, we analytically derived the relationship of strain and temperature to sensor outputs by the following procedure[17].

Figure 1 is a schematic diagram of the FBG/EFPI sensor. The FBG is encapsulated in a silica capillary tube to be isolated from the external strain. The EFPI cavity was formed between two cleaved fiber ends inserted into the capillary tube. The FBG is in strain-free condition and is only affected by the temperature change within the capillary tube, while EFPI is affected by both thermal and mechanical strains. When a broadband light illuminates this sensing element, the reflected spectrum of the Bragg grating element has a narrow bandwidth with high reflectivity whereas a sinusoidal wave with a fraction of the total optical power is reflected through the EFPI sensor, a low finesse interferometer.

For a FBG, the Bragg condition is given by $\lambda_B = 2n_e\Lambda$, 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 shift of Bragg wavelength due to the strain and temperature can be expressed as

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

where α_f is the coefficient of thermal expansion (CTE), ξ_f is the thermo-optic coefficient, and p_e is the strain-optic tensor of the optical fiber. For the FBG/EFPI sensor, because the FBG in a glass capillary tube is in a strain-free condition, $\varepsilon = 0$, (1) can be simplified in terms of only the temperature change as

$$\Delta\lambda_B = \lambda_B\left(\alpha_f + \xi_f\right)\Delta T . \tag{2}$$

Therefore, we can measure the temperature change from the wavelength shift as

$$\Delta T = \frac{1}{\alpha_f + \xi_f} \cdot \frac{\Delta\lambda_B}{\lambda_B} . \tag{3}$$

The response of the absolute EFPI(AEFPI) sensor comes from thermal strain as well as the applied strain of a structure. When the sensor is perfectly bonded to structure, the thermal expansion of the sensor is constrained to take on the effect of CTE of the host structure. Therefore, the thermal expansion of FOS bonded to or embedded in a material becomes that of the structure itself. The cavity length, d_i, at any measuring instant can be measured from the peaks of the reflected spectrum as

$$d_i = \frac{m\lambda_1\lambda_2}{2\left(\lambda_2 - \lambda_1\right)} \qquad i = 0, 1, 2... \tag{4}$$

where λ_1 and λ_2 are two wavelengths that are $2m\pi$ out of phase and m is an integer. *i* is the number of the measuring instant, and in the case of initial state, *i=0*. If the EFPI sensor has a gage length of *L*, the applied strain can be expressed as

$$\varepsilon = \frac{d_n - d_0}{L} = \frac{\Delta d}{L} \tag{5}$$

where Δd is the change of cavity length, and d_n, d_0 are the final and initial cavity lengths, respectively. When temperature change and strain are applied to the structure with an embedded or attached FBG/EFPI sensor, the lengths of internal optical fibers in the capillary tube change with temperature variation only depending upon its CTE while an external capillary tube is subject to both thermal and mechanical strains of the structure. Therefore, we can measure the total strain applied to a structure through the variation of a reflected spectrum caused by the difference of length change between the sum of two internal fibers in the tube and the capillary tube. The strain measured from the EFPI interferometric signal, ε_{mea}, can be described by

$$\varepsilon_{mea} = \varepsilon_{tot} - \varepsilon_{f,T} = \frac{\Delta d}{L} \tag{6}$$

where ε_{tot} is the sum of the mechanical and thermal strains of a structure, and $\varepsilon_{f,T}$ is the thermal strain of the internal optical fibers. We want to obtain the total strain of the structure, that is, the strain of the capillary tube. From (6) we can obtain the equation for total strain as

$$\varepsilon_{tot} = \frac{\Delta d}{L} + \varepsilon_{f,T} = \frac{\Delta d}{L} + \frac{L - d_0}{L} \cdot \alpha_f \cdot \Delta T\,. \tag{7}$$

Substituting (3) into (7) leads to

$$\varepsilon_{tot}=\frac{\Delta d}{L}+\frac{L-d_0}{L}\cdot\frac{\alpha_f}{\alpha_f+\xi_f}\cdot\frac{\Delta\lambda_B}{\lambda_B}. \tag{8}$$

By combining (3) and (8), we can yield the relationships of the sensor outputs to measurands as

$$\begin{aligned}\begin{Bmatrix}\varepsilon\\ \Delta T\end{Bmatrix}&=\begin{bmatrix}\dfrac{1}{L} & \dfrac{L-d_0}{L}\cdot\dfrac{\alpha_f}{\alpha_f+\xi_f}\cdot\dfrac{1}{\lambda_B}\\ 0 & \dfrac{1}{\alpha_f+\xi_f}\cdot\dfrac{1}{\lambda_B}\end{bmatrix}\begin{Bmatrix}\Delta d\\ \Delta\lambda_B\end{Bmatrix}\\ &=\begin{bmatrix}P_{1\varepsilon} & P_{2\varepsilon}\\ P_{1T} & P_{2T}\end{bmatrix}\begin{Bmatrix}\Delta d\\ \Delta\lambda_B\end{Bmatrix}\end{aligned}. \tag{9}$$

From (9), it should be noted that the characteristic matrix of a sensor can be determined by sensor specifications such as gage length, initial cavity length, the Bragg wavelength of FBG, and the CTE and thermal-optic coefficient of the optical fibers. The strain and the temperature can be easily determined by measuring the change of cavity length for the strain and the wavelength shift for the temperature. In the conventional method, all sensors with different specifications must be calibrated to obtain the characteristic matrix before field use. However, we can simply generate the matrix with known specifications of sensors using (9). The strain and the temperature of structures can be measured directly and simultaneously. In our previous work, also, we verified the validity of the proposed relationship, (9), by performing experiments.

3. Experimental Details

3.1 Fabrication of composite laminate with embedded fiber optic sensor

A 10 *mm* long FBG was encapsulated in a silica capillary tube(140/300 *μm*) to be isolated from the external strain. The EFPI cavity was formed between the fiber end face near to the FBG and a gold-coated fiber end surface inserted into the opposite end of the capillary tube. Specifications of the sensors embedded in composite laminates are shown in Table 1. Substituting the specifications of the sensors in Table 1 into (9), we can obtain analytically the components of the characteristic matrices of the sensors, as shown in Table 2.

Figures 2, 3, and 4 show schematic diagrams of composite laminates, such as a unidirectional laminate, a symmetric cross-ply laminate, and a fabric laminate, indicating directions and locations of fiber optic sensors and thermocouples. The laminates were made of CU-125 NS graphite/epoxy prepreg (HFG Co.). The stacking sequences of the laminates were chosen as $[0_{12}/\{0,90\}/0_{12}]_T$, $[0_3/\{0\}/0_3/90_6/\{90\}/90_6/0_6]_T$, and $[\text{Fabric}_8/\{0,90\}/\text{Fabric}_8]_T$ where '{}' marks the location of an embedded sensor. Two fiber optic sensors were embedded in each laminate with a thermocouple. Sensor 1 and sensor 2 were embedded in the center of the $[0_{12}/\{0,90\}/0_{12}]_T$ laminate between the 12th and 13th plies. Sensor 1 was embedded parallel and sensor 2 was embedded perpendicular to the reinforcing fibers, respectively. Sensor 3 was embedded between the 21th and 22th plies and sensor 4 was embedded between the 12th and 13th plies of the $[0_3/\{0\}/0_3/90_6/\{90\}/90_6/0_6]_T$ laminate so that both sensors could be embedded parallel to reinforcing fibers. Sensor 5 and sensor 6 were embedded in the center of the $[\text{Fabric}_8/\{0,90\}/\text{Fabric}_8]_T$ laminate between the 8th and 9th plies. K-type thermocouples were embedded to control the temperature during cure and to serve as a reference source for the temperature.

3.2 Test apparatus and method

The experimental arrangement for cure monitoring is depicted in Figure 5. Figure 6 shows a typical curing cycle of graphite epoxy composite in the autoclave molding. Generally, the curing cycle of graphite/epoxy (GR/EP) composite consists of 3 stages as following. In stage I, the temperature of the laminate is increased to an intermediate temperature (80℃) and held for half an hour to decrease the viscosity of the resin. In stage II, the temperature is increased to the final cure temperature (130℃) and held for two hours. And in the final stage (stage III), the composite is cooled to room temperature. During a chain of curing stages, the composite laminate experiences severe temperature changes and the fabrication strain develops.

Each composite laminate was placed in an autoclave and fabricated by the curing cycle. Two optical fibers and a thermocouple line were extracted through holes in the wall of the autoclave and connected to the data acquisition and processing system. The reflected signals of the fiber optic sensors were acquired through a DAQ board, and processed and saved by a signal-processing program written in LabVIEW® software. A wavelength-swept fiber laser (WSFL)[18] was used as a light source to supply high signal power[19]. The sensor signals were acquired at 3-minute intervals.

4. Results and Discussions

The plots of strains and temperatures measured by the FOSs during the cure of the unidirectional laminate are given in Figures 7 and 8. Figure 6 presents (a) the strain in the 0° direction measured by sensor 1 and (b) the strain in the 90° direction measured by sensor 2. The compressive strains developed abruptly in the transverse direction during cooling stage, while the strain variation in the fiber direction was small. The final compressive strains in the longitudinal and transverse direction were approximately –140 $\mu\varepsilon$ and –4000 $\mu\varepsilon$, and the compressive strains during cooling stage were –130 $\mu\varepsilon$ and –4200 $\mu\varepsilon$, respectively. From this result, it is shown that the strain in the transverse direction is significantly larger than that in the longitudinal direction. This is because the properties in the transverse direction are dominated by the epoxy matrix which should exhibit large thermal and chemical deformations during cure. As shown in figure 8, the temperatures measured by FOSs have good agreement with the temperature measured by a thermocouple.

Figure 9 presents (a) the strain measurement, (b) the temperature measurement by FOSs during the cure of the symmetric cross-ply laminate. The final compressive strains in the 0° and 90° direction were approximately –410 $\mu\varepsilon$ and –470 $\mu\varepsilon$, and the compressive strains during cool-down period were –280 $\mu\varepsilon$ and –380 $\mu\varepsilon$, respectively. The temperatures measured by FOSs have good agreement with that measured by thermocouple as shown in figure 9(b).

Figure 10 presents (a) the strain measurement, (b) the temperature measurement by FOSs during the cure of a fabric laminate. The final compressive strains in the 0° and 90° direction were approximately –210 $\mu\varepsilon$ and –240 $\mu\varepsilon$, and the compressive strains during cool-down period were –360 $\mu\varepsilon$ and –350 $\mu\varepsilon$, respectively. Good correlations were found between temperatures measured by FOSs and thermocouple as shown in figure 10(b).

In our previous work[20], we measured the fabrication strain and temperature during the cure of an unsymmetric cross-ply laminate, which had the stacking sequence of $[0_6/\{0\}/0_6/90_6/\{90\}/90_6]_T$. In this experiment, we could find that the final compressive strains in the 0° and 90° direction were approximately –440 $\mu\varepsilon$ and –520 $\mu\varepsilon$, and the compressive strains during cool-down period were –330 $\mu\varepsilon$ and –320 $\mu\varepsilon$, respectively.

The strains measured by sensors up to 2nd temperature raising stage can be occurred due to volume change and resin flow of low viscosity matrix by pressure and chemical shrinkage of matrix. These strains may not affect the residual stress because of the stress relief due to the low viscosity of the matrix. Therefore, data taken in this region should be interpreted carefully. Most residual strains develop during the cool-down period and these strains become residual strains. Table 3 shows the residual strains occurred during cool-down period for four types of the composite laminates. As you can see in Table 3, since the unidirectional composite plies have the anisotropic property, they will shrink more in the transverse direction than in the reinforcing fiber direction due to thermal and chemical shrinkage. On the other hand, the residual strains of other composite laminates that were reinforced in two orthogonal directions were similar each other. Also, they were larger than the strain in the reinforcing fiber direction and less than the strain in the transverse direction of the unidirectional laminate. These residual strain values can be used to calculate residual stresses.

As you can see from the experimental results, a lower cure temperature is more desirable to decrease the residual strain (stress) since the residual strain (stress) is induced by the thermal expansion mismatch between the reinforcing fiber and matrix, and matrix shrinkage during cure and the cool-down period. However, the low cure temperature for reducing residual stresses requires longer curing time but long cure time is not economical. Consequently, these two parameters must be compromised[7].

As shown in figures 8, 9(b), and 10(b), the temperatures measured by fiber optic sensors have good agreement with the temperature measured by the thermocouple. Therefore we can use this FOS technology to control and monitor the cure process of composite materials in situ and at points remote from the surface. Through these experiments, we can provide a basis for the efficient smart processing of composites.

5. Conclusions

We performed a simultaneous monitoring of strain and temperature during the cures of various composite laminates using FBG/EFPI hybrid sensors. Two FOSs were embedded in two mutually perpendicular directions of each composite laminate with a thermocouple. The unidirectional composite plies showed very large compressive strain in the transverse direction while small strain in the reinforcing fiber direction. On the other hand, the residual strains of other composite laminates that were reinforced in two orthogonal directions were similar each other. Also, they were larger than the strain in the reinforcing fiber direction and less than the strain in the transverse direction of the unidirectional laminate. The temperatures measured by fiber optic sensors have good agreement with the temperature measured by the thermocouple. From the experimental results, we can find that the FOSs can be used to monitor several parameters such as the fabrication strain and temperature during cure. FOS method will be able to supply the informations about cure process and be used to find the optimal cure condition.

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