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Simulation of curing process of carbon/epoxy composite during autoclave degassing molding by considering phase changes of epoxy resin

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Strain monitoring of a carbon/epoxy composite cross-ply laminate ($[0_5/90_5]_s$) during thermoforming was conducted by using fiber Bragg grating (FBG) sensors. The entire process was simulated by employing finite element analysis (FEA) by taking into consideration the phase changes of the epoxy resin. For the precise simulation of the curing process, a dielectrometry sensor was used to detect the epoxy-resin dissipation factor, which in turn was used to identify the curing point. To investigate the phase changes and consolidation of the composite laminate by employing FEA, modulus changes with temperature were measured by dynamic mechanical analysis (DMA), and the permeability was estimated by measuring the fiber volume fraction according to the curing temperature. As the epoxy resin changed from a liquid to solid phase, the strain generated along the carbon fibers dynamically changed, and the analysis results generally predicted the strain variation quite well. To apply this simulation technique to practical structures, a composite-aluminum hybrid wheel was analyzed and experimentally verified.

1. Introduction

The excellent mechanical properties of fibrous composites have enabled them to be applied to the design of various structures, in which their performance has been closely investigated [1–3]. However, a variation in some factors, particularly, residual stress—a crucial factor—during the forming process may ultimately affect the performance of the final product. In order to investigate the effect of material behavior during a forming process on the performance of the final product, significant research on thermoforming processes has been conducted, e.g., on a smart cure cycle for controlling temperature overshoot [4], simulation techniques for composite laminates, incorporation of consolidation and thickness variation [5,6], and forming techniques that take the resin viscosity into account [7–9].

In addition, intensive research into different forming processes has also been carried out. An optimal cure cycle to minimize residual stress and strain has been previously proposed [10,11], with strain variation during thermoforming being observed and closely investigated using fiber Bragg grating (FBG) optical sensors. This cycle takes into account the effect of thermal property differences between the composite laminate and the mold [12], the microstructures of fabric composites [13], boundary conditions [14], and differences in the coefficient of thermal expansion between different materials [15]. Health monitoring of composite structures [16,17] and cure monitoring of composite-metal hybrid structures [18,19] using various sensors have also been conducted to detect any material failures during service or forming conditions. Recently, the field of application of FBG sensors has been broadened to include real-time health monitoring of structures such as airplanes and ships [20–23]. The performance validation of FBG sensors, including their endurance limit, was also verified by comparing them with conventional sensors by performing various mechanical tests [24–29].

This paper presents the simulation of the curing of a carbon/epoxy laminate by taking into consideration the phase changes of the epoxy resin and the corresponding material property changes in the laminate. The strain and temperature change in the composite laminate was monitored during the curing process using FBG sensors, and the residual thermal strain also was measured. The simple technique for simulating the entire curing process with simple mechanical properties was developed using finite

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element analysis (FEA) with a user's subroutine, which predicted well the overall change in the generated strains in the composite laminate during the curing process. This technique may provide design guidance for composite structures, allowing durability to be enhanced by reducing the residual stress and strain of structures.

2. Experiments for determining parameters for the simulation

2.1. Materials and sensors

A carbon/epoxy prepreg (USN125, SK Chemical, Korea) was used to fabricate a laminate specimen. Vacuum bag degassing molding was then used to perform cure monitoring of the composite laminate, and all the materials used in the experiment are listed in Table 1. The material properties were obtained from a previous research [4–7].

Two types of sensors were used: FBG fiber optic sensors with an interrogator (Micron optics instrument, USA) were used for monitoring the strain and temperature of composite laminates during curing, and a dielectrometry sensor (see Fig. 1a; [11]) was used for detecting the degree of cure of the laminate. In order to accurately measure the strain variation with temperature in the composite laminate during curing, the sensor's coefficient of thermal expansion was compensated for in calculating equations:

$$\Delta\lambda_B = \lambda_0\left[\left(\alpha_f + \xi\right)\Delta T + (1 - p_e)\Delta\varepsilon\right] = K_\varepsilon\Delta\varepsilon + K_T\Delta T \quad (1)$$

$$\Delta\varepsilon = \frac{\Delta\lambda_B - K_T\Delta T}{K_\varepsilon} \quad (2)$$

where $\Delta\lambda_B$, λ_0, α_f, p_e, $\Delta\varepsilon$, ΔT, ξ, K_ε, and K_T are the wavelength shift, Bragg grating's peak reflection wavelength, FBG coefficient of thermal expansion (CTE), photo elastic constant of the optical fiber, strain change, temperature change of the FBG, Bragg grating's thermo-optical coefficient, sensitivity coefficient of strain, and sensitivity coefficient of temperature, respectively. The dielectrometry sensor detects the mobility of dipoles and ions of liquid polymers during the curing process. This sensor submerged in the liquid polymer was represented as an equivalent circuit as shown in Fig. 1a. Based on the phase of the polymer, the dissipation factor (DF) can be calculated by Eq. (3):

$$\mathrm{DF} = \left|\frac{I_R V_m}{I_c V_m}\right| = \left|\frac{I_R}{I_c}\right| = \left|\frac{Z_c}{Z_R}\right| = \frac{1}{\omega R_m C_m} \quad (3)$$

where I, Z, V_m, R_m, and C_m are the electric current, equivalent impedance, supplied voltage (which varies with the supplied frequency), equivalent resistance, and equivalent capacitance, respectively. The subscripts R and C represent the resistance and capacitance, respectively.

2.2. Measurement of the fiber volume fraction

To estimate the amount of resin extracted during vacuum bag degassing molding, the fiber volume fraction according to temperature was measured. Darcy's law [7] predicts the resin flow during the curing of composites based on the permeability (k_i) of the material, and it is closely related to the material void ratio [30] (e; Eq. (4)):

$$e = \frac{\mathrm{Vol} - \mathrm{Vol}_f}{\mathrm{Vol}_f} = \frac{\mathrm{Vol}}{\mathrm{Vol}_f} - 1 = \frac{1}{\mathrm{Vol}_f} - 1 \quad (4)$$

where Vol and Vol_f represent respectively the total volume and fiber volume of the composite laminate. At every target temperature, the mass of the composite laminate was measured, with the fiber mass also being measured after burning the matrix of the laminate. Based on the Kozeny–Carman theory [7], the permeability (k_i) can be expressed in terms of the void ratio (e):

$$k_i = \frac{r_f^2}{4c_i}\,\frac{e^3}{(1+e)} \quad (5)$$

where r_f and c_i are the fiber radius and Kozeny–Carman constant, respectively. The permeability of the composite laminate

Table 1
Material properties and measured values of various materials.

	Materials	Thermal conductivity (W/mK)	Specific heat capacity (J/kg K)	Density (kg/m^3)
Mechanical properties	Epoxy	0.2	1740	1210
	Fiber	85.0	700	1750
	Steel	60.0	450	8000
	Vacuum bag	0.24	1670	1140
	Breather	0.007	1350	260
	Teflon film	0.4	1050	2200

	Materials	Density (kg/m^3)	Young's Modulus (GPa)		Poisson's ratio		Elongation (%)
Mechanical properties	USN125	1480	E_1	131.0	ν_{12}	0.0226	1.8
			E_2	10.5	ν_{23}	0.0226	
			E_3	10.5	ν_{31}	0.4700	
	Aluminum	2700	68.9		0.33		17.0

	Materials		125 °C	105 °C	85 °C	65 °C	45 °C	25 °C
CTE for temperature (10^{-6}/°C)	USN125	L	−2.21	−1.85	−1.66	−1.49	−1.31	−1.09
		T	62.82	48.42	37.44	29.79	25.20	23.80
	Aluminum		23.76	23.49	23.29	23.09	22.91	22.86
	Steel		12.82	12.40	12.24	12.02	11.72	11.56

	Temperature (°C)	Fiber volume fraction	Permeability
V_f and permeability for temperature	25	0.55	0.8181
	55	0.56	0.7857
	80	0.58	0.7241
	100	0.60	0.6666
	125	0.61	0.6339