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Guided Wave-based System for Real-time Cure Monitoring of Composites using Piezoelectric Discs and Phase-shifted Fiber Bragg Gratings

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Abstract

A real-time, in-process cure monitoring system employing a guided wave-based concept for carbon fiber reinforced polymer (CFRP) composites was developed. The system included a single piezoelectric disc that was bonded to the surface of the composite for excitation, and an embedded phase-shifted fiber Bragg grating (PS-FBG) for sensing. The PS-FBG almost simultaneously measured both quasi-static strain and the ultrasonic guided wave-based signals throughout the cure cycle. A traditional FBG was also used as a base for evaluating the high sensitivity of the PS-FBG sensor.

Composite physical properties (degree of cure and glass transition temperature) were correlated to the amplitude and time of arrival of the guided wave-based measurements during the cure cycle. In addition, key state transitions (gelation and vitrification) were identified from the experimental data. The physical properties and state transitions were validated using cure process modeling software (e.g., RAVEN®).

This system demonstrated the capability of using an embedded PS-FBG to sense a wide bandwidth of signals during cure. The distinct advantages of a fiber optic-based system include multiplexing of multiple gratings along a single optical fiber, small size compared to piezoelectric sensors, ability to embed or surface mount, utilization in harsh environments, electrically passive operation, and electromagnetic interference (EMI) immunity. The embedded PS-FBG fiber optic sensor can monitor the entire life-cycle of the composite structure from curing, post-cure/assembly, and in-service creating “smart structures”.

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Keywords

Polymer-matrix composites (PMCs); Curing; Thermomechanical properties; Ultrasonics; Cure monitoring; Smart Structures

1. Introduction

1.1 Cure monitoring techniques

Dielectric analysis (DEA) is an in-process cure monitoring technique that utilizes a loss factor, ϵ'' , to monitor different stages (liquid, rubbery, and glassy) of cure [1]. An expanded discussion of DEA is provided in McIlhagger, et al. [2] and Hardis, et al. [3]. One of the primary advantages of DEA is the potential to implement in-situ cure monitoring during production. Analogous trends have been observed between DEA and guided wave-based cure monitoring, including the identification of minimum viscosity and gelation [4, 5]. Conventional bulk wave ultrasound in the low MHz frequency range is a technique utilizing wave phenomena to interrogate the curing process. The trends of attenuation/amplitude and velocity have been shown to be consistent with newly developed guided wave-based systems [4–6]. Using bulk wave ultrasound (both contact and non-contact) for cure monitoring is dependent on an accurate measurement of thickness to determine wave velocity in the resin and/or composite. In addition, bulk wave ultrasound only senses the data in the near vicinity of the transducer. However, the shorter wavelength (relative to guided waves) due to higher ultrasonic frequency results in a smaller diffraction limit that allows for smaller defects to be detected.

1.2 Fiber Bragg gratings (FBGs)

1.2.1 Bragg wavelength and strain sensing—A periodic variation of refractive index is inscribed into the core of the fiber using an intense ultraviolet (UV) light source. This periodic variation of the refractive index acts as a filter for a specific wavelength of light (the Bragg wavelength, λ_B) based on the grating pitch [Eq. (1)].

$$\lambda_B = 2n_{eff}\Lambda$$

(1)

where n_{eff} is the effective refractive index of the grating in the fiber core and Λ is the grating pitch. Figure 1 illustrates the general concept of the input, reflected, and transmitted spectrums from a single FBG with a Bragg wavelength of 1580 nm.

Strain-based cure monitoring techniques using embedded FBGs have been investigated extensively for over twenty years [7–13]. A relatively low sampling period (every 30 s to 1 min) is used since strain and temperature change gradually during cure.

1.2.2 FBGs for ultrasound sensing—FBGs have been used to sense ultrasound, guided wave, and acoustic emission by several groups. The fiber-optic system presented in Betz et al. [14] validated experimentally that FBGs can detect ultrasonic Lamb waves at a center actuation frequency of 150 kHz. This showed its feasibility as an ultrasonic sensing technique. FBGs have also been used for ultrasonic wave sensing up to the MHz range [15]. Takahashi et al. [16] used FBGs as an underwater acoustic sensor. Perez et al. [17] used FBGs bonded onto the surface of aluminum plates to detect acoustic emissions from pencil lead breaks, gentle knocks on the plate surface, and ultrasonic transducers. For an acoustic wavelength significantly greater than the length of the FBG ($L \approx 2\text{--}10\text{ mm}$), the strain across the grating is considered constant. This leads to a linear dependence between the Bragg wavelength and the strain based on standard grating theory [18].

1.3 Phase-shifted fiber Bragg gratings (PS-FBGs)

1.3.1 Principle of operation of PS-FBGs—PS-FBGs can be produced by a phase mask (as can FBGs). This is done by using a UV light to inscribe a periodic variation, with a phase-shift at a specific location along the grating, of the refractive index in the fiber core. When a π -phase shift of the refractive index is inscribed at the center of the grating, a narrow central transmission peak opens up in the center of the stop band of the grating [19], as shown in Figure 2. This peak acts as a transmission filter for light whose bandwidth (with respect to wavelength) is much narrower than a traditional FBG. Agrawal and Radic [20] provided a detailed mathematical derivation of the PS-FBG spectrum. Liu and Han [21] performed a numerical analysis on the response of PS-FBGs. The results indicated the first minimum of wavelength sensitivity occurs at an ultrasonic wavelength approximately twice the grating length. This provides a reasonable estimate for the minimum wavelength that should be detected when designing a detection system. A longer grating has higher intensity sensitivity due to a sharper slope, but is more directionally dependent and less sensitive at higher frequencies. Figure 2 shows a plot of signal output from a traditional FBG alongside a PS-FBG. The narrow central transmission peak in the PS-FBG spectrum creates a steeper slope at the Full Width Half Maximum (FWHM) wavelength (λ_{FWHM}), $m_{PS-FBG} \gg m_{FBG}$.

1.3.2 PS-FBGs for ultrasound sensing—PS-FBGs have only recently been developed for use in ultrasonic sensing. The Okabe group [19, 22–27] has extensively utilized PS-FBGs for ultrasound sensing. PS-FBGs have several intrinsic advantages. PS-FBGs have a very wide bandwidth (applied to acoustic emission at 1.5 MHz and 2 MHz for nonlinear ultrasonics). The sensitivity of a PS-FBG is up to 1000 times greater than conventional FBGs and on the same order [within 3 dB ($\frac{1}{2}$)] of piezoelectric sensors [19, 22–27]. This is due to the sharp slope of the grating spectrum created by a phase-shift in the periodic variation of the refractive index at a specific location along the grating (usually half-way). As with most fiber optic sensors, PS-FBGs can withstand high temperatures and be embedded. The Okabe group, however, has traditionally used surface mounted PS-FBGs for their work. One drawback of PS-FBGs compared to piezoelectric sensors is the signal-to-noise ratio (SNR). PS-FBGs typically require twice the number of averages than piezoelectric sensors for similar SNR.

1.4 Proposed system

The system developed in this work was designed to determine the feasibility of using embedded FBGs/PS-FBGs measuring guided wave-based signals as a viable technique for cure monitoring. “Guided wave-based” refers to the setup of the actuator and sensor in a pitch-catch configuration at a distance of at least ten times the thickness with an actuation frequency between 60 kHz to 1 MHz. This configuration is typical for guided wave measurements in solid media. Since the resin of the composite transitions from the prepreg through liquid, rubbery, and gelled glass to the final composite, the type of wave propagating throughout the entire cure cycle may not be the classically understood definition of a guided wave [28].

A previous system was composed of a robust linear array of high temperature piezoelectric transducers [4, 6]. In this system, the linear array of high temperature piezoelectric transducers was replaced by either a single FBG, or a single PS-FBG. Since the optical fiber remains embedded in the composite, the sensor can detect wave signals during cure and in-service, enabling life cycle monitoring. Embedding fiber optic sensors is becoming a more attractive option as the size of optical fibers decrease. Current, small-diameter FBGs (diameter of 40–52 μm) [29] are approximately ten percent of the area of traditional FBGs (diameter of 125 μm). In fact, multiple sensors can be placed along the same optical fiber using a technique called wavelength division multiplexing.

2. Material and methods

2.1 Panel descriptions

Two identical 305 mm $\times$ 305 mm, twenty-four ply, unidirectional panels were laid up by hand from HexPly® IM7/8552 unidirectional prepreg (35% resin content, 190 g/m²) from Hexcel®. The only difference between these two panels was the sensor used, a traditional FBG (Experiment 1) and a PS-FBG (Experiment 2). For the first panel (Experiment 1), a polyimide coated FBG [MicronOptics (Model: os1100) with a nominal Bragg wavelength (λ_B) of 1580 nm, a bandwidth at FWHM of 0.25 nm, and a grating length of 10 mm] was placed 38.1 mm from the center of the composite between plies eighteen and nineteen perpendicular to the carbon fiber direction. For the second panel (Experiment 2), an acrylate coated PS-FBG (QPS Photonics with a nominal λ_B of 1543 nm, a bandwidth at FWHM of 0.003 nm, and a grating length of 10 mm) was placed 38.1 mm from the center of the composite between plies eighteen and nineteen perpendicular to the carbon fiber direction. A piezoelectric disc actuator [APC International, Ltd. (piezo material 850, $\varnothing$ 6.35 mm, thickness: 0.254 mm, Curie point: 360 °C)] was bonded to the top ply 38.1 mm from the center of each composite panel in the opposite direction of the sensor resulting in a propagation distance of 76.2 mm (Figure 3). A high temperature adhesive (Loctite EA 9394 QT AERO Part A and Part B) was used to bond the piezoelectric disc onto the surface of each composite allowing for proper coupling of the ultrasonic waves into the composite. For a fully embedded system, the piezoelectric disc actuator could be embedded in the composite, although feedthrough wiring would have been difficult. Fluorinated ethylene propylene (FEP) release film (Airtech International) was placed on the top and bottom of the composite panels. A breather cloth and vacuum bag covered the panel and full vacuum was

applied. The panels were cured under vacuum in an oven using a two stage cure with a B-stage hold. The temperature was increased to 107 °C at 2.8 °C/min, held constant for one hour, increased to 177 °C at 2.8 °C/min, held constant for two hours, then cooled down.

2.2 Guided wave-based measurements using piezoelectric disc actuation and FBG/PS-FBG sensing

The panels were interrogated during the entire cure cycle through the use of guided wave-based sensing and strain measurements. A wave was excited into the plate using a five-cycle, Hanning windowed, sinusoidal tone-burst signal emitted from a waveform generator (Agilent Technologies: 81150A) to an amplifier (Krohn-Hite Corporation: Model 7602M) to a piezoelectric disc. The amplifier magnified the input signal to a peak-to-peak voltage of approximately 120 V. The guided wave-based signal was recorded by the FBG/PS-FBG using an optical power meter (Agilent Technologies: N7744A) and a tunable laser (Santec: TSL-710) (Figure 3). The Santec TSL-710 has a wide wavelength range (1480–1640 nm) with wavelength resolution of 0.1 pm, high wavelength accuracy (± 2 pm at operating temperature), and a narrow linewidth (100 kHz with coherence control off).

The automation code for the system was written as a combination of MATLAB® and LabVIEW® scripts and functions. The sweep processing unit recorded the full spectrum of the FBG/PS-FBG. The FWHM wavelength (λ_{FWHM}) and λ_B were identified from the spectrum. The output wavelength of the tunable laser was set to the FWHM wavelength of the grating. The center frequency of the five-cycle, Hanning windowed, sinusoidal tone-burst signal was set using the waveform generator. During each iteration, the center frequency was cycled through a predefined set of center frequencies (80, 100, 150, 200, 250, and 300 kHz). The number of frequencies (six) and number of averages per measurement (five) were set based on the rate at which the spectrum shifted during the temperature ramps and the measurement cycle time. When the wave propagated past the FBG/PS-FBG, the local strain at the sensor caused an oscillation of the wavelength spectrum resulting in a fluctuation of the output power measured by the optical power meter. In the linear range of the FBG/PS-FBG, the change in optical power measured was linearly related to the change in wavelength spectrum, and linearly related to the strain at the sensor (Figure 4).

Through the use of MATLAB®, it was possible to constantly monitor λ_B and the FWHM wavelength of the FBG/PS-FBG, ensuring the proper peak and slope were selected throughout the cure. After recording all the necessary data from the cure cycle, the data was processed through a bandpass filter and analyzed using MATLAB®.

2.3 Strain sensing using embedded FBG/PS-FBG

Using the same embedded FBG/PS-FBG, strain was recorded almost simultaneously with the guided wave-based signals. For temperature compensation, a reference FBG/PS-FBG and thermocouples were utilized. The reference FBG/PS-FBG, placed outside of the vacuum bag, was assumed to be strain free ($\epsilon_{ref} = 0$) throughout the cure. The strain in the embedded sensor was calculated by Eq. (4).

$$\frac{\Delta\lambda_{B, sen}}{\lambda_{B, sen}} = C_\epsilon \epsilon_{sen} + C_T \Delta T = C_\epsilon \epsilon_{sen} + C_T (T_{sen} - T_0)$$

(2)

$$\frac{\Delta\lambda_{B, ref}}{\lambda_{B, ref}} = C_\epsilon \epsilon_{ref} + C_T \Delta T = C_T (T_{ref} - T_0)$$

(3)

Solving for ϵ_{sen} from Eq. (2) and Eq. (3),

$$\epsilon_{sen} = \frac{\frac{\Delta\lambda_{B, sen}}{\lambda_{B, sen}} - \frac{\Delta\lambda_{B, ref}}{\lambda_{B, ref}} - C_T (T_{sen} - T_{ref})}{C_\epsilon}$$

(4)

where $\lambda_{B, sen}$ were the values recorded from the FBG/PS-FBG embedded in the composite and $\lambda_{B, ref}$ were the values of the reference FBG/PS-FBG. λ_B is the change in λ_B during the experiment [Eq. (5)].

$$\Delta\lambda_B = \lambda_B - \lambda_{B_0}$$

(5)

T_{sen} was the temperature of the embedded grating measured by the use of two thermocouples (averaged) that were attached to the composite during the cure cycle, and T_{ref} was the temperature of the reference grating (measured by the use of a thermocouple outside the vacuum bag alongside the reference grating). T_0 was the temperature of the gratings before the initiation of the cure cycle (i.e., room temperature). C_ϵ is the strain coefficient for the FBG/PS-FBG (0.76), and C_T is the coefficient of temperature for the optical fiber sensors. C_T was determined through a series of calibration tests using strain-free FBG/PS-FBG sensors.

3. Results and discussion

3.1 Cure kinetic simulations with the semi-empirical material model using RAVEN®

To validate the experimental studies, simulations of the cure response were performed using RAVEN® composite process simulation software. The material model utilized in RAVEN® was a semi-empirical material model [30] based on lab-scale tests [e.g., Differential Scanning Calorimetry (DSC) and rheology]. RAVEN® simulations were conducted for both experiments. Since the simulation results were very similar, only the simulations for Experiment 1 are shown in Figure 5. Hudson et al. [4, 5] provides a detailed explanation of the equations on which the simulations were based. The shaded regions corresponding to the state of the resin in the composite were determined from the cure kinetic simulations. The degree of cure and glass transition temperature (T_g), related by the DeBenedetto equation, followed an S-shaped curve (Figure 5a). The cure rate is the time derivative of the degree of cure and reached a maximum just before gelation at a cure time around 150 minutes. The majority of cure occurred during the second temperature ramp (to 177 °C) and the early part of the 177 °C temperature hold (from around cure time 125 minutes to 195 minutes).

During the first temperature ramp (to 107 °C), the viscosity dropped and the resin became a liquid. The resin reached minimum viscosity during the second temperature ramp (to 177 °C) prior to gelation. Upon gelation, the viscosity spiked (Figure 5b).

3.2 Guided wave-based measurements using piezoelectric disc actuation and FBG/PS-FBG sensing

3.2.1 Data collection—By assembling data for each individual waveform at a particular actuation center frequency, the full time-history of the composite response can be viewed as a three-dimensional surface plot. This can be seen for the guided wave-based signals of the 80 kHz actuation throughout the cure process up to cool down in Figure 6a for Experiment 1 (FBG) and Figure 6b for Experiment 2 (PS-FBG). Each guided wave-based measurement is one “slice” of the full time-history.

For guided wave-based sensing, the change in power of the FBG (Figure 6a) was two orders of magnitude lower than the PS-FBG (Figure 6b) due to the steeper slope, $m_{FBG(PS-FBG)}$, at the FWHM wavelength (Figure 2). The steeper slope caused the same change in x (shift of spectrum due to wave passing the sensor) to result in a higher change in y (optical power) for the PS-FBG. The advantage of the PS-FBG compared to the FBG was obvious from Figure 6a (FBG) and Figure 6b (PS-FBG) by observing the change in power each sensor recorded. Figure 7 plots the change in power measured by the FBG in Experiment 1 on the same scale as the change in power measured by the PS-FBG in Experiment 2. The SNR for the PS-FBG was also greater than that of the traditional FBG [Figure 6a/Figure 7 compared to Figure 6b and Figure A.1 compared to Figure A.2 (Appendix)]. Also, it was noticed at 200, 250, and 300 kHz center frequency excitation the S_0 wave mode was not captured with the traditional FBG but was captured by the PS-FBG [Figure A.1 and Figure A.2 (250 kHz center frequency excitation)].

From these results, it was observed that the onset of vitrification was marked by the cure time at which there was a significant increase in peak change in power (i.e., amplitude) of

the waves. This occurred early in the second temperature hold (177 °C) at a cure time around 170 minutes.

3.2.2 Data analysis

3.2.2.1 Peak change in power (Amplitude): The average normalized peak change in power, $\Delta P_{avg, norm, peak}$, was selected as the metric for amplitude of the guided wave-based signals. It was calculated by finding the peak change in power, ΔP_{peak} , from every measurement [Eq. (6)], normalizing across cure time [Eq. (7)], and averaging across center actuation frequency [Eq. (8)].

$$\Delta P_{peak}(CT_i, f_{c_k}) = \max_l [\Delta P(CT_i, f_{c_k}, t_l)]$$

(6)

$$\Delta P_{norm, peak}(CT_i, f_{c_k}) = \frac{\Delta P_{peak}(CT_i, f_{c_k})}{\max_i [P_{peak}(CT_i, f_{c_k})]}$$

(7)

$$\Delta P_{avg, norm, peak}(CT) = \frac{1}{p} \sum_{k=1}^p \Delta P_{norm, peak}(CT, f_{c_k})$$

(8)

where P is the change in power measured by the optical power meter at measurement time, t_l , and CT_i and f_{c_k} denote the discrete cure time, and center frequency of actuation at which the measurement was taken, respectively.

As the system looped through the actuation center frequencies, measurements at different actuation center frequencies occurred at slightly different cure times (typical cycle times were two minutes for the entire loop). Thus, the normalized peak change in power was first interpolated at defined cure times before averaging across center actuation frequency [Eq. (8)]. The averaging across center actuation frequency removed frequency variation in the results, allowing for cleaner interpretation and communication of the effect of curing on the

amplitude of the guided wave-based signals. The average normalized peak change in power for Experiments 1 and 2 are displayed below (Figure 8).

Since rubbery state has increased damping, more energy is dissipated from the mechanical wave as it travels from the actuator to the sensor. This resulted in the average normalized peak change in power spike during the transition to the glassy state (vitrification) for both experiments.

In addition, a distinguishable increase in average normalized peak change in power occurred near gelation (transition from liquid to rubbery state) during Experiment 2. A similar trend was observed in additional experiments [5]. The suspected cause for this was greater strain transfer in the rubbery state compared to the liquid state, as the wave passes by the sensor, from the composite to the PS-FBG. The amplitude of the waves was not visibly significant in the liquid state (compared to glassy state) for this setup. However, further testing with quasi-isotropic layups has shown higher amplitudes in the liquid region, due to greater strain transfer into the sensors due to the fiber bed [5].

3.2.2.2 Time of arrival (TOA): The TOA was identified by finding the measurement time at which P_{peak} occurred. The TOA was then averaged across center actuation frequency at defined cure times [Eq. (9)]. As with peak change in power, the TOA values were interpolated at defined cure times before averaging since measurements at each actuation center frequency occurred at slightly different cure times.

$$TOA_{avg}(CT) = \frac{1}{p} \sum_{k=1}^p TOA(CT, f_{c_k})$$

(9)

The average TOA for the six excitation center frequencies (80, 100, 150, 200, 250, and 300 kHz) are shown in Figure 9 for Experiment 1 and 2.

For both experiments, the average TOA of the waves decreased as the composite entered its glassy state. The initial point at which the TOA was determined (during the 177 °C temperature hold) occurred near the vitrification point of the composite. In addition, the average TOA was inversely proportional to the degree of cure and T_g predictions from the semi-empirical model simulations. In the glassy state, as the mechanical properties of the composite increased, the speed of the wave increased (i.e., the TOA decreased).

3.3 Strain sensing using embedded FBG/PS-FBG

3.3.1 Strain sensing during cure and residual strain—Figure 10 shows the strain measured by the embedded sensor throughout the cure cycle for Experiments 1 and 2. In both experiments, the fiber optic sensor was perpendicular to the composite's carbon fiber direction resulting in compressive strain. The strain resulted primarily from two sources: 1) chemical cure shrinkage and 2) coefficient of thermal expansion (CTE). Thermally induced

strain primarily results from cooling of the composite (i.e., composite vitrifies at high temperature then cools to room temperature). It can also arise due to mechanical boundary conditions such as CTE mismatch between the tool and the composite.

3.3.2 Change in FBG/PS-FBG spectrum—The transmitted spectrums before and after cure for Experiments 1 (FBG) and 2 (PS-FBG) are shown in Figure 11. The grating spectrums changed from the beginning to the end of the cure resulting in a reduction of light reflected/filtered by the FBG/PS-FBG, and the formation of double and/or additional peaks. The formation of additional peaks within the sensors' spectrum evolved over time during the cure cycle. This phenomenon occurred primarily during the cool down stage of the cure cycle. Non-axial residual strain was considered a likely cause of the extra peaks.

4. Conclusions

In summary, a preliminary cure monitoring system employing piezoelectric discs and PS-FBGs was developed to interrogate composite panels during cure. The experimental guided wave-based measurement trends for the average normalized peak change in power (amplitude) and time of arrival (TOA) correlated well with the simulation predictions of the cure kinetics using the semi-empirical material model (RAVEN®). The semi-empirical material model utilized experimental data from material characterization tests (e.g., DSC, rheology) coupled with a cure kinetics model. From the guided wave-based measurements, the state transitions (gelation and vitrification) can be identified and a metric for degree of cure and T_g was presented. During both experiments, the amplitude spiked during the transition to the glassy state (vitrification). In addition, a distinguishable increase in amplitude was observed at gelation in Experiment 2. The TOA was inversely proportional to the degree of cure and T_g because of the increased mechanical properties. As the mechanical properties increased, the wave arrived at the sensor sooner.

The PS-FBG sensor provided increased sensitivity for performing wave measurements compared to the traditional FBG sensor, due to higher change in optical power (signal) under identical conditions resulting in a higher SNR. A higher SNR for the PS-FBG sensor allows the sensor to detect a smaller magnitude of the wave mode (longer propagation distances), enhances ability to sense all wave modes (e.g., S_0 , A_0), and increases the probability of collecting data throughout the entire cure cycle (liquid, rubbery, and glassy states).

An automated monitoring system with embedded PS-FBG sensors could be the future of smart structures. Together with in-situ cure monitoring, the system could enable life-cycle monitoring of the composite structures. During life-cycle monitoring, these structures could have both usage/loads monitoring and impact/damage detection capabilities, almost in real time. Using the same embedded fiber optic sensor(s), usage and loads monitoring would be feasible due to the ability to measure strain, and impact/damage detection would be achievable due to the ability to record ultrasonic guided waves and/or acoustic emission. This system could provide a cost effective and accurate method for cure monitoring during production and structural health monitoring during the life-cycle of the part.

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8.: Appendix

Figure A.1.

3-D surface plot of recorded signals for 250 kHz center frequency actuation measured by an FBG from beginning of cure until beginning of cool down (Experiment 1).

Figure A.2.

3-D surface plot of recorded signals for 250 kHz center frequency actuation measured by a PS-FBG from the beginning of cure until beginning of cool down (Experiment 2).

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Figure 1.
FBG reflected and transmitted spectrums with Bragg wavelength of 1580 nm.

Figure 2.
Comparison of FBG and PS-FBG transmitted spectra.

Figure 3.

(a) PC for hardware control, data collection, and data analysis. Waveform generator and amplifier for excitation. (b) Tunable laser, optical power meter, and sweep processing unit for guided wave-based sensing and strain measurements. (c) Experimental setup inside oven. (d) Locations of piezoelectric disc actuator and embedded FBG/PS-FBG.

Figure 4.

(a) Transmitted spectrum of a PS-FBG and (b) fluctuation in optical power measured due to shift in wavelength spectrum as the wave propagates past the PS-FBG.

Figure 5.

(a) Part temperature (outside left axis), T_g (outside left axis), degree of cure (outside right axis), and cure rate (inside right axis) and (b) part temperature (outside left axis) and resin viscosity (outside right axis) as predicted by Hexcel® 8552 material model [30] using RAVEN® composite process simulation software (Experiment 1).

Figure 6. 3-D surface plot of recorded signals for 80 kHz center frequency actuation measured by (a) an FBG (Experiment 1) and (b) a PS-FBG (Experiment 2) from the beginning of cure until beginning of cool down.

Figure 7.

3-D surface plot of recorded signals for 80 kHz center frequency actuation measured by an FBG in Experiment 1 on the same scale as Experiment 2 using PS-FBG (Figure 6b).

Figure 8.

Average normalized peak change in power from six excitation center frequencies (80, 100, 150, 200, 250, and 300 kHz) for (a) Experiment 1 (FBG) and (b) Experiment 2 (PS-FBG).

Figure 9.

Average time of arrival for six excitation center frequencies (80, 100, 150, 200, 250, and 300 kHz) for (a) Experiment 1 (FBG) and (b) Experiment 2 (PS-FBG).

Figure 10. Strain measured by (a) an FBG (Experiment 1) and (b) a PS-FBG (Experiment 2) throughout cure.

Figure 11.
Transmitted spectrum of (a) an FBG (Experiment 1) and (b) a PS-FBG (Experiment 2) before and after cure.