Fiber-Optic-Based Pressure and Residual Strain Monitoring in CFRP Bonding Process: Toward Realization of Secondary Bonding in CFRP Aircraft Structures

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FIBER-OPTIC-BASED PRESSURE AND RESIDUAL STRAIN MONITORING IN CFRP BONDING PROCESS: TOWARD REALIZATION OF SECONDARY BONDING IN CFRP AIRCRAFT STRUCTURES

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ABSTRACT

Applying secondary bonding to places where carbon fiber reinforced plastic (CFRP) structures are conventionally bolted leads to significant cost and weight saving. However, it has yet to be utilized due to difficulties in quality control. Lack of local pressure in bonding process has detrimental influence on the quality of the cured adhesive layer. Pressure detection is hence a key for controlling bonding quality, and a new quality assurance technique is urgently needed. This study established a fiber-optic-based pressure detection and quality assurance technique for secondary bonding process. Fiber Bragg grating (FBG) optical sensors were embedded in the adhesive layer and the reflected spectrum changes were monitored during the pressurizing stage to detect the applied pressure. Thermal residual strain after curing was also evaluated for further quality assurance. Good correlation was observed between the cure pressure, the CFRP quality and the FBG sensor response, confirming the validity of the proposed technique.

KEYWORDS : *CFRP, secondary bonding, process monitoring, FBG sensor*

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) has increasingly been applied to aerospace structures. Applying secondary bonding to places where structures are conventionally bolted leads to significant cost and weight saving [1]. However, it has yet to be fully utilized due to difficulties in quality control. Even though several non-destructive techniques have been developed to evaluate chemical state of bonding-surfaces, a new cure-pressure detection method is urgently needed for practical application of secondary bonding. Lack of local pressure can occur especially in complex-shaped parts due to cure-induced shape distortion, resulting in detrimental influence on the quality of the cured adhesive layer.

A fiber Bragg grating (FBG) [2] is a thin optical sensor that can be embedded in CFRP with minimal effects on the mechanical properties of base materials. We can obtain strain values from FBG reflection spectra. When an FBG sensor changes its cross-sectional shape by external force from a circle to an ellipse, the reflected spectrum broadens. This is known as the birefringence effect [3], and non-axisymmetric strain, the degree of asymmetric cross-sectional deformation of the FBG sensor can be evaluated from the broadness of the spectrum [4, 5].

This study proposes a fiber-optic-based novel pressure detection and quality assurance technique for secondary bonding process (Figure 1) [6]. It utilizes the birefringence effect of FBG sensors embedded in adhesive layers of CFRP specimens. First, non-axisymmetric strains of FBG sensors are evaluated at the moment of initial vacuuming phase before curing. The amount of

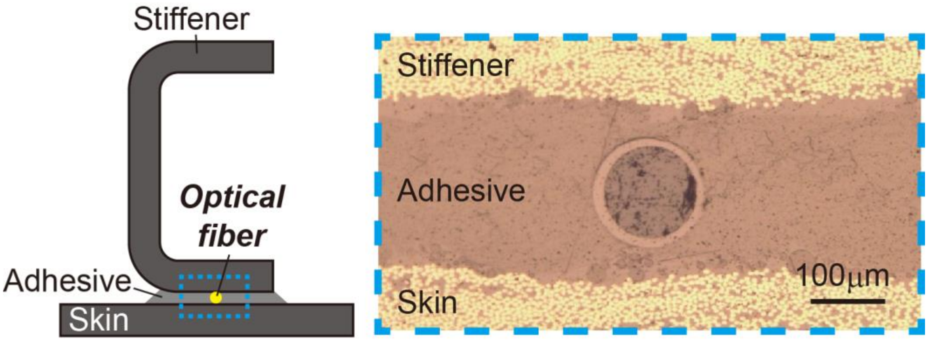


Figure 1: Optical fiber sensor embedded in adhesive layer of secondary bonded structure.

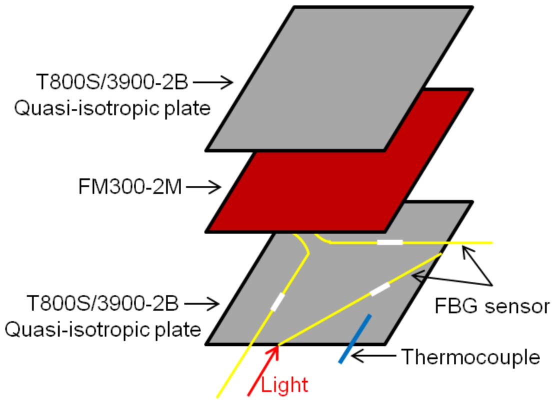


Figure 2: Schematic of Specimen.

pressure applied on the specimen is determined from the level of non-axisymmetric strain. Thermal residual strain is also measured after curing. And finally cured quality is correlated to the residual strain.

2. EXPERIMENTS

2.1 Methodology

Cured quasi-isotropic CFRP (T800S/3900-2B) plates were bonded with an adhesive layer (FM300-2M). Three FBG sensors were embedded under the adhesive as shown in Figure 2. The embedding directions were 0 degree, 45 degree, and 90 degree. A thermocouple was also embedded to measure temperature inside the adhesive layer.

The FBG reflection spectra and temperature were logged every minute. Experiments were conducted seven times with four different levels of cure pressure. Non-axisymmetric strain $\varepsilon_d = |\varepsilon_1 - \varepsilon_2|/2$ (Figure 3) of each sensor was calculated throughout the process by the following equation

$$\varepsilon_d = \frac{|\varepsilon_1 - \varepsilon_2|}{2} = \frac{|\lambda_p - \lambda_q|}{k} \tag{1}$$

where λ_p-λ_q is the wavelength difference of two peaks (Figure 4), and k is the constant [5].

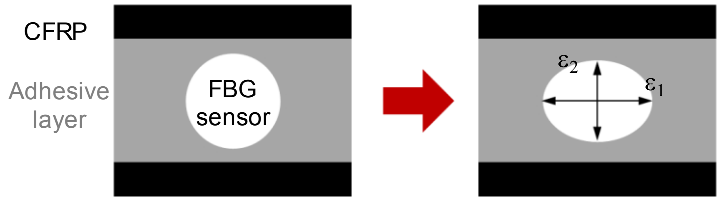


Figure 3: Non-axisymmetric deformation of FBG.

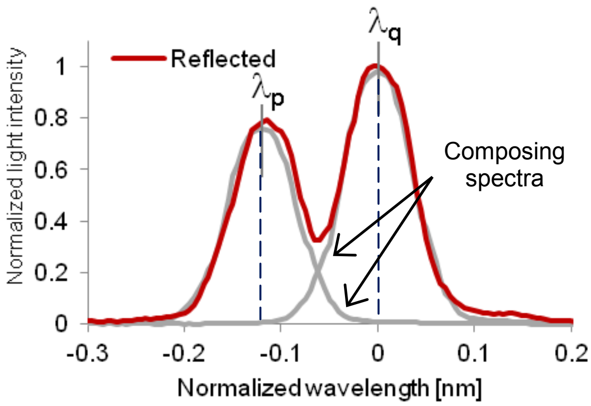


Figure 4: Two peaks in measured spectrum.

2.2 Initial Pressure Detection

When the specimens were vacuumed in the initial phase of bonding process, the FBG spectra deformed due to the birefringence effect (Figure 5). The applied through-thickness pressure deformed the FBG sensors sandwiched between the cured CFRP plates, and thus the pressure was successfully detected. Table 1 summarizes the calculated non-axisymmetric strain for each sensor immediately after vacuuming. Though values varied, considerable responses were seen in all sensors. After the transient deformation, however, the FBG spectra rapidly returned to their initial single-peak states (Figure 5). This attributes to stress relaxation caused by the softness of the adhesive before curing. Figure 6 depicts the relaxation of non-axisymmetric strain after vacuuming.

2.3 Quality Assurance

The FBG spectra after cure cycle also depended on the applied pressure. This attributes to the difference in the thermal residual strains that reflects the cured adhesive qualities. Figure 7 presents the relationship between the calculated thermal residual non-axisymmetric strain and cure pressure for the seven specimens. Significant positive correlation was obtained; for 0 degree FBG correlation factor r was 0.83, for 45 degree $r = 0.76$, and for 90 degree $r = 0.98$.

Cross sections of all specimens were observed to examine the cured qualities. Figures 8 to 10 show the cross sectional micrographs of specimens cured under three pressure conditions (1, 4, and 7 atm). Large voids can be observed in the specimen cured under insufficient pressure, 1 atm. Some small voids can still be seen in the specimen cured under 4 atm. No voids are visible in the specimen cured under manufacture’s recommended pressure, 7 atm.

Thicknesses and void area ratio were also measured to quantitatively examine the bondline qualities. Figure 11 shows the relationship between the two measures and the residual non-

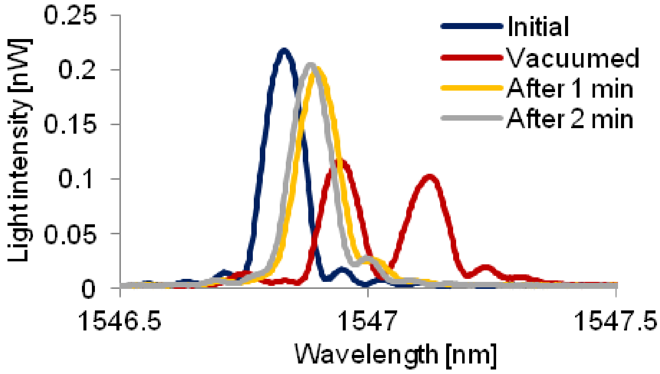


Figure 5: Deformation of spectrum.

Table 1: Non-axisymmetric strain when vacuumed.

Specimen	0 degree	45 degree	90 degree
a	181 με	168 με	344 με
b	552 με	527 με	481 με
c	0 με	150 με	152 με
d	305 με	518 με	326 με
e	199 με	252 με	194 με
f	296 με	279 με	106 με
g	283 με	394 με	269 με

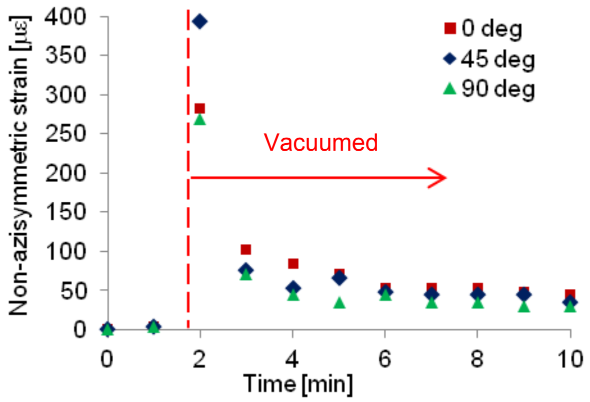


Figure 6: Relaxation of non-axisymmetric strain.

axisymmetric strain of FBG sensors embedded to the 90 degree direction. Non-axisymmetric strain is negatively related to void area. This indicates that the residual non-axisymmetric strain is positively related to adhesive quality, i.e., high strain means high quality and vice versa. This is consistent with the fact that cured adhesive quality closely depends on cure pressure.

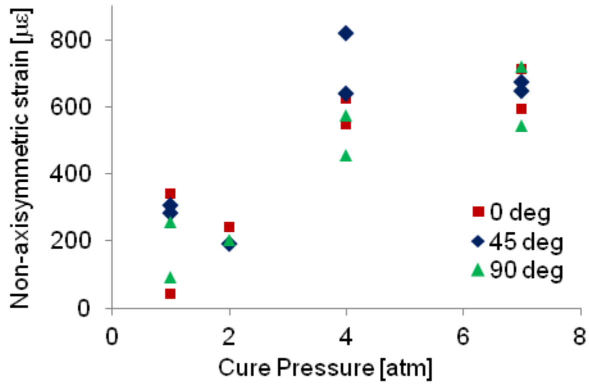


Figure 7: Residual strain and cure pressure.

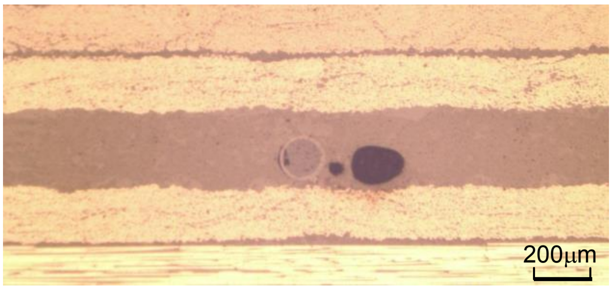


Figure 8: Cross sectional micrograph of specimen cured under 1 atm.

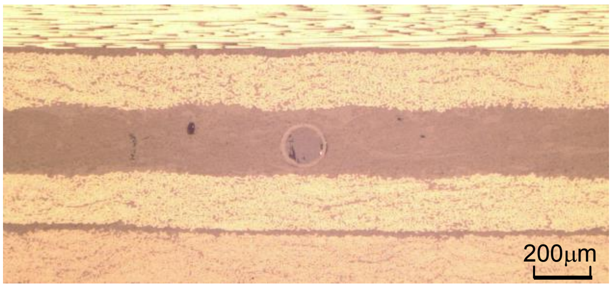


Figure 9: Cross sectional micrograph of specimen cured under 4 atm.

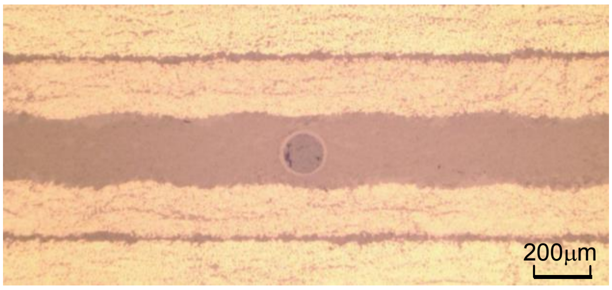
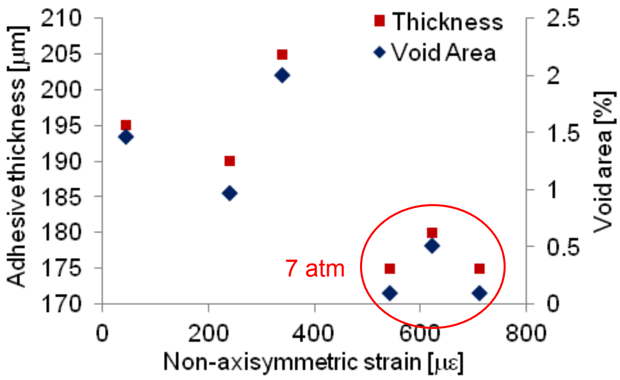


Figure 10: Cross sectional micrograph of specimen cured under 7 atm.



3. CONCLUSIONS

This study established a fiber-optic-based quality assurance technique for secondary bonding process of CFRP structures. Pressure was successfully detected by the proposed technique at the moment of vacuuming. Using this technique, manufacturing workers can know if there is any place with lack of pressure, allowing them to modify the setup before curing. This will significantly contribute to cost and time saving in secondary bonding process. However, non-axisymmetric strain after vacuuming relaxed rapidly. Thus it requires timely measurements. Future work will overcome this disadvantage.

Thermal residual non-axisymmetric strain after curing positively correlated with cured pressure and adhesive quality. With sufficient cure pressure, the residual strain exceeded 500με for all sensors. Adhesive thickness was below 175μm and void area rate was under 0.5% for every specimen cured under 7 atm. High bondline quality, associated with high cure pressure, can be assured by measuring thermal residual non-axisymmetric strain of FBG sensor after curing; if the residual strain exceeds a threshold, which was 500με in this study, cured adhesive has sufficient quality.

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