Signal Characteristics in the Delaminated Composite Specimen with Fiber Optic Sensor

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ABSTRACT

Delamination problems are one of the most important issues affecting the applications of composite laminates. Delamination reduces overall structural performance of composite laminates such as stiffness, strength, and buckling load. Therefore, it is necessary to identify the influence of delamination failure on composite laminates. The delaminated unidirectional composite specimens subjected to the compressive load were tested to study the characteristics of fiber optic sensor (FOS) signals when the buckling and the growth of delamination occurred. Extrinsic Fabry-Perot interferometers (EFPI) were used in this study. EFPI was embedded in the delaminated composite specimen or attached on the surface of specimen. As the specimens were buckled, the signals of FOS were analyzed. In addition, when the delamination growth occurred, the characteristics of FOS signal and data aliasing caused by the sampling time were investigated. The effects of the delamination length were discussed.

KEY WORDS: composite, delamination, buckling, fiber optic sensor (FOS)

1. INTRODUCTION

Composite materials have been widely used in many structures since they have higher specific stiffness and strength than those of metal materials. Damages in composites, such as matrix cracks, delamination and fiber breakage, may occur as a result of excessive load, fatigue, low-velocity impact, etc. The failure of composites can not be exactly defined since the damage of composites appears as the combined damage mode. In the early stage of damage, the matrix failure mainly occurs since the properties of matrix are weaker than reinforcement. Composites can continuously endure the applied load after the early fracture of composites. Matrix failure can be usually classified into the matrix cracking and delamination.

With the increasing use of composite laminates, the compression behavior of delaminated structures has drawn more and more attention in recent years. The delamination reduces the compressive strength and buckling load of the composite structures.[1] Finally, the delamination leads to global structural failure at a lower load than that of the undamaged composite structures. The detection of delamination growth and the prediction of the delaminated composite structures are very important to estimate the overall performance of composites and to improve the reliability of composite structures.

The advantages of the fiber optic sensor are the potential solutions for sensing of smart structures.[2] The fiber optic sensors can be easily embedded into composites and are not affected by the electro-magnetic field. Also, they are small size and very highly sensitive. They have more potential capability for multiplexing than other commercial sensors. The integrated sensor system can be easily constructed by FOS.

The buckling test of the delaminated unidirectional composite laminates was performed to detect the buckling load and the delamination growth using FOS to study the characteristics in FOS signals. The used FOS in this study was the extrinsic Fabry-Perot interferometer (EFPI).[3]

2. FIBER OPTIC SENSOR

For the interferometric FOS, the relation between phase of FOS and deformation can be written as follows:[4]

$$\frac{\Delta\phi}{\Delta L} = \frac{4\pi n}{\lambda_0}\left\{1 - \frac{n^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right]\right\} \tag{1}$$

where $\Delta\phi$ means the cumulative phase-shift caused by the deformation in FOS. ΔL is the length change of the embedded optical fiber due to structural deformation. n is the refractive index of FOS in the gage length, λ_0 is the wavelength of laser diode in vacuum state, 1310 *nm*. p_{ij} is the strain-optic tensor of the optical fiber. For the EFPI, there is no change of refractive index in the gage length since the light medium of EFPI is air ($n \cong 1$). Eq. (1) can be described as follows:

$$\frac{\Delta\phi}{\Delta L} = \frac{4\pi n}{\lambda_0} = 0.9593 \times 10^7 \ (rad/m) \tag{2}$$

The signal of FOS is converted into the strain by the detection of $\Delta\phi$. If N is the number of the half waves of the sinusoidal signal of FOS, $\Delta\phi$ can be written as follows:

$$\Delta\phi = N\pi \tag{3}$$

From Eq. (2) and Eq. (3), the interferometric signal of FOS is transformed into the strain of the deformed structure.

$$\begin{aligned}\varepsilon &= \frac{N\pi}{0.9593 \times 10^7 L} \\ &= 3.275 \times 10^{-7} N/L\end{aligned} \tag{4}$$

3. EXPERIMENTS

3.1 *Fabrication of the delaminated specimen with the embedded EFPI*

Figure 1 shows the schematic diagram of the manufactured EFPI. The ends of silica capillary tube were bonded to the single mode and multi mode fibers with epoxy in order to make EFPI as shown in Figure 1. The Fresnel reflection from glass/air interface at the front of the air gap (s) and the reflection from the glass/air interface at the far end of the air gap interfere in the input/output fiber. L means the gage length of EFPI. The gage length of EFPI was about 5 *mm* and the gap separation (s) was about 10 ~ 50 μm.

The delaminated specimens were made of CU-125 NS graphite/epoxy prepreg (HFG Co.). Material properties are as follows:

E_1 = 135.4 GPa, $E_2 = E_3$ = 9.6 GPa, $G_{12} = G_{13} = G_{23}$=4.8 GPa, $\nu_{12} = \nu_{13} = 0.31$, $\nu_{23} = 0.52$.

Teflon film was utilized to form the delamination and inserted into mid-plane of specimen. Figure 2 shows the configuration of specimen. 'a' is the length of delamination. In case of the surface attachment of FOS, the stacking sequence of specimen was $[0_8//0_8]_T$ where '//' means the position of delamination. In case of the embedding of FOS, the stacking sequence of specimen was chosen as $[0_8//0_6/\{0\}/0_2]_T$ where '{}' means the direction of the embedded EFPI. The egress of EFPI in specimen was reinforced using metal tube that had the outer diameter about 1 *mm*. Three strain gages were attached on the front and back surfaces of the specimen for the load alignment.

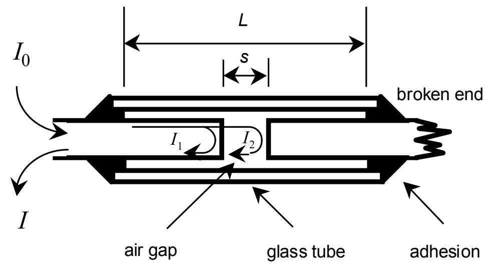


Figure 1. Schematics of EFPI

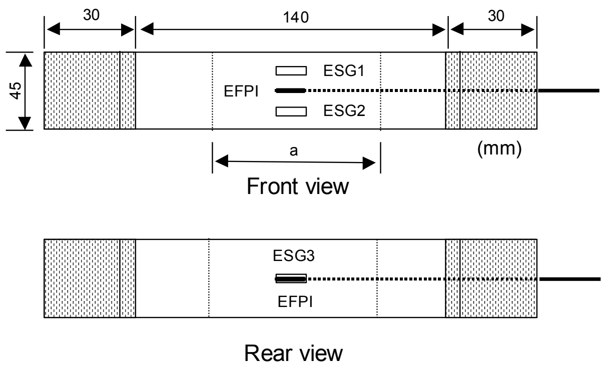


Figure 2. Configuration of specimen

'$\bar{a}$' is the normalized delamination length ($\bar{a} = a$ / length of test section). Specimens had the different delamination lengths, $\bar{a} =$ 0.2, 0.3, 0.5 and 0.7.

3.2 *Experimental device and procedure*

Fiber optic sensor system was composed of the light source (1310 *nm*, LD), photo-detector, isolator, coupler, etc. The digital storage oscilloscope (DSO) was used for the detection of the instant when the delamination growth occurs. In addition, A/D converter card was utilized for the data acquisition during the whole time of experiment.

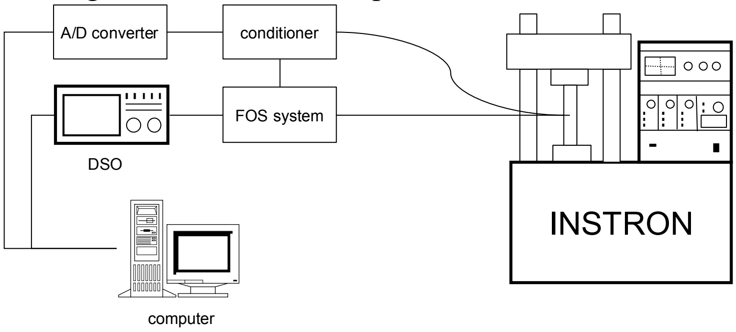


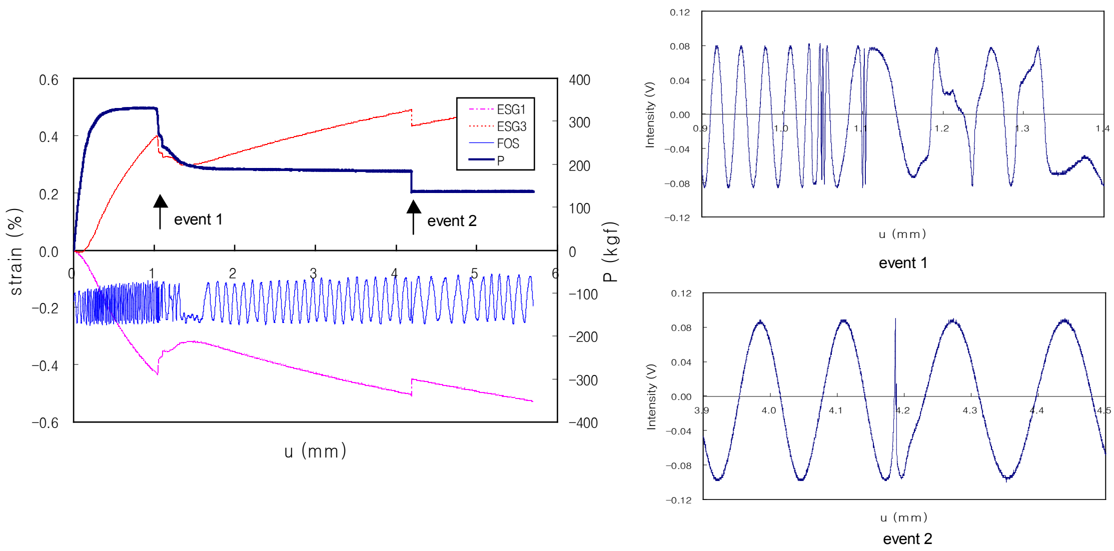
Figure 3. Overall view of the experimental setup

The experimental data obtained from EFPI was transmitted to DSO (Tektronix, TDS-420). The data obtained from strain gage was transmitted to the A/D converter. For the post-processor, all signals were stored in PC through a GPIB (IEEE 488). The arc-fusion-splicer (Fujikura, FSM-30S) was used for the connection between specimen and FOS system. It is shown the overall view of the experimental setup in Figure 3. Buckling test was performed about the delaminated composite beams with an embedded (or surface attached) EFPI using a static test machine (INSTRON, 1350). The static test machine was operated at the 1 *mm/min* stroke rate. The sensor signals were processed using MATLAB.

4. EXPERIMENTAL RESULTS AND DISCUSSION

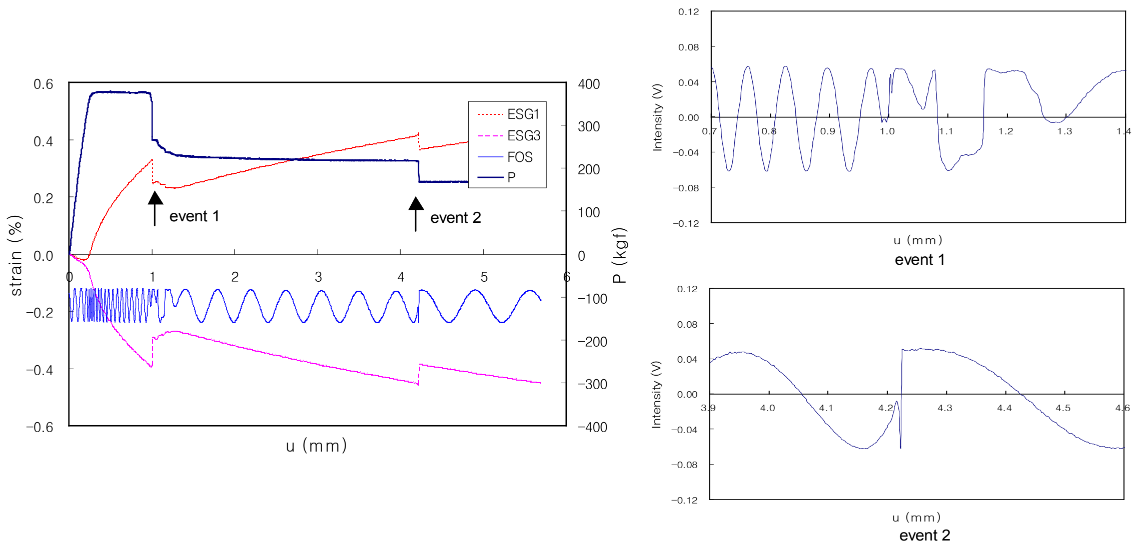
4.1 *Effects of the FOS location and delamination growth*

The effects of FOS location on the FOS signal are shown in Figure 4 and Figure 5. The FOS signal in Figure 4 is obtained from FOS attached to the specimen surface and that in Figure 5 is from the embedded FOS.



(a) signals up to failure (b) zoomed FOS signal at event 1, 2

Figure 4. Signals of ESG, load and FOS up to failure ($\bar{a}$ = 0.5, surface attachment)



(a) signals up to failure (b) zoomed FOS signal at event 1, 2

Figure 5. Signals of ESG, load and FOS up to failure ($\bar{a}$ = 0.5, embedding)

For the surface attached FOS, the number of the interferometric fringe is higher than that of the embedded case since the strain distribution through the thickness is linear. However, the results of Figure 4 and Figure 5 show the disagreement with those by the thickness ratio of FOS location. This means that FOS location is moved to the mid-plane during the curing process of specimen.

When the delamination grew, the leakage of FOS signal appeared due to the rapid change in frequency as shown in Figure 4 (b) and 5 (b). Then, the leakage of the FOS signal means the delamination growth. Delamination did not grow until the ultimate failure in the specimen of which the delamination length is $\bar{a} = 0.2$. In case of $\bar{a} = 0.3$, delamination growth occurred in higher load and also the specimen endured up to failure. However, as the delamination length increases, the buckling load and the delamination growth load decrease rapidly. In case of $\bar{a} = 0.7$, the delamination growth load differs little from the buckling load.

4.2 *Detection of buckling*

The plate and shell structures such as the laminated composite structures have the lower buckling stress than compressive strength. Then the prediction and assessment of buckling are very important for the damage tolerance design of composite structures. Figure 6 shows the signals of load, strains, FOS when the buckling occurred. Strains of front and rear surface gages began to bifurcate each other, and deviates from linearity and almost constant until the growth of delmiantion.

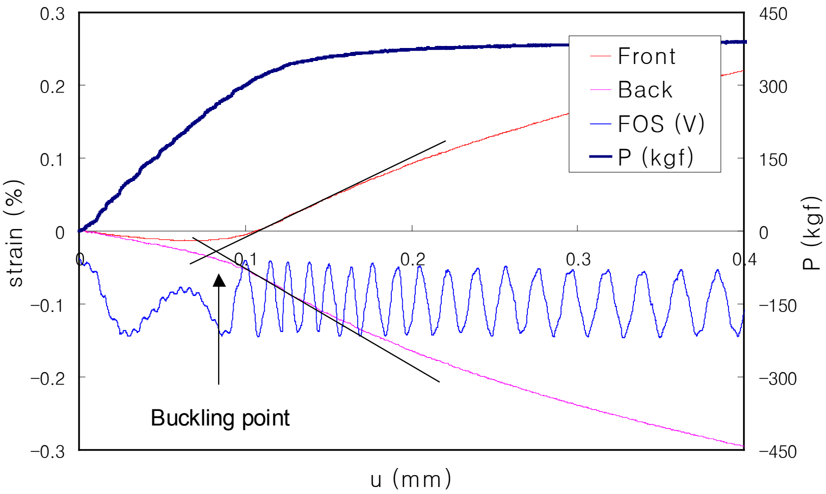
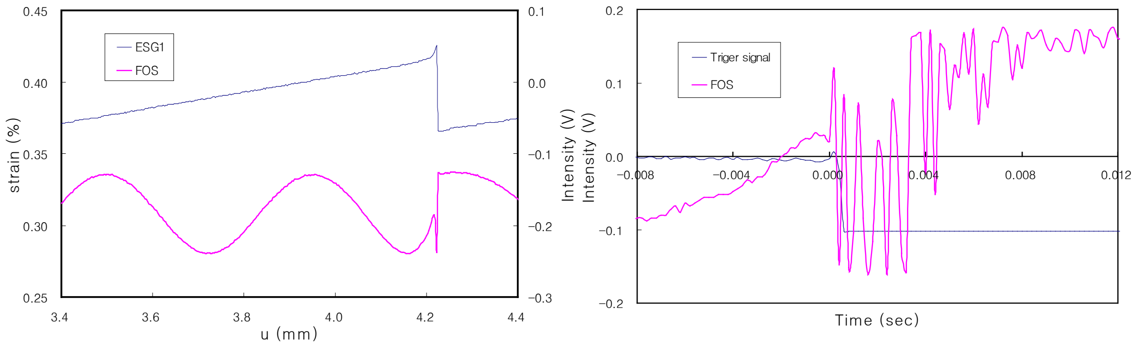


Figure 6. Signals of ESG, load cell and FOS when specimen was buckled

There are many methods to decide the buckling load. It was decided by the crossing of tangential lines at the bifurcated part of the strain curves in this study as shown Figure 6. The FOS signal was low in frequency but there was a rapid change in frequency since the strains rapidly changed after the buckling. The abrupt change of FOS signal can be easily distinguished in the determination of buckling. FOS expresses the deformation of the structure in the sinusoidal interferometric fringes. And so, FOS has the advantage of the detection of buckling in comparison with the electrical strain gage. Under the constant stroke control, FOS signal gives the information of the buckling occurrence by observing the frequency change of FOS signal.

4.3 *Data aliasing*

The interferometric fringes of FOS are converted into strain and so the data of FOS should be exactly acquired. But as shown in Figure 4 (b) or 5 (b), FOS signals were leaked due to the improper selection of the sampling time. These leakage of data causes error in the calculation of the strain. In Figure 7 (a), the sampling frequency, f_S, was 500 Hz and then Nyquist frequency, $f_N = f_S/2$, has the value of 250 Hz. To avoid the phenomenon of data aliasing, the adequate sampling time should be selected in the abrupt change of strain when the delamination growth occurred. In Figure 7 (b), the ESG signal by the AC setting in DSO was used as the trigger signal to acquire the FOS signal. The sampling frequency, f_S, is 10 kHz and this sampling frequency can exactly describe the information of signal up to 5 kHz. Figure 7 (b) shows that f_S should be more than 10 kHz at least to avoid the data aliasing. This means that FOS signal is more than 5 kHz when the delamination grows.



(a) aliasing of FOS signal caused by the delamination growth (Ts = 0.002 sec, fs = 500 Hz)

(b) FOS signal detected by DSO when the delamination growth (Ts = 0.0001 sec, fs = 10 kHz)

Figure 7. Aliasing of FOS signal when specimen was buckled

5. REMARKS

The unidirectional composite laminates with FOS (surface attachment or embedding) were performed to detect the buckling and the delamination growth. FOS could successfully detect the buckling and crack growth by the frequency change of FOS signal. As the delamination length increase, the buckling load and the delamination growth load decrease rapidly. Sampling time should be more than 10 kHz to avoid the data aliasing of FOS signal when the delamination growth occurs.

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