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Paper

Composite Fracture Detection Capabilities of FBG Sensor and AE Sensor

Cheol-Hwan Kim*, Jin-Ho Choi*†, Jin-Hwe Kweon*

ABSTRACT: Non-destructive testing methods of composite materials are very important for improving material reliability and safety. AE measurement is based on the detection of microscopic surface movements from stress waves in a material during the fracture process. The examination of AE is a useful tool for the sensitive detection and location of active damage in polymer and composite materials. FBG (Fiber Bragg Grating) sensors have attracted much interest owing to the important advantages of optical fiber sensing. Compared to conventional electronic sensors, fiber-optical sensors are known for their high resolution and high accuracy. Furthermore, they offer important advantages such as immunity to electromagnetic interference, and electrically passive operation. In this paper, the crack detection capability of AE (Acoustic Emission) measurement was compared with that of an FBG sensor under tensile testing and buckling test of composite materials. The AE signals of the PVDF sensor were measured and an AE signal analyzer, which had a low pass filter and a resonance filter, was designed and fabricated. Also, the wavelength variation of the FBG sensor was measured and its strain was calculated. Calculated strains were compared with those determined by finite element analysis.

Key Words: Buckling, FBG (fiber bragg grating), AE (acoustic emission), PVDF (polyvinylidene fluoride)

1. INTRODUCTION

The invisible inner damage of composite materials can be oriented by residual stresses during the curing process or by an overload during operation. These defects range from the submicron level to several millimeters in dimensions, and often have a great effect on the reliability and stability of the composite structures. It is very important to measure the sizes of these defects and to determine their tolerance ranges [1]. Also, if the generation, growth, and accumulation process of these defects within composite materials can be revealed by a micromechanical analysis and nondestructive tests, the strength, fracture toughness, and residual life can be evaluated more accurately [2-5]. AE (Acoustic Emission), can evaluate these defects by detecting the emitting strain energy when elastic waves are generated by the generation and growth of a crack, plastic deformation, fiber breakage, matrix cleavage, or delamination [6,7]. However, AE is very sensitive to any disturbances such as external vibration or noise. FBG sensors offer important advantages such as immunity to electromagnetic interference and electrically passive operation.

In this paper, the crack detection capability of the AE (Acoustic Emission) sensors was compared with that of FBG sensors under tensile and buckling tests of composite materials. The AE signal characteristics of the PVDF sensors were measured and an AE signal analyzer, which had a low pass filter and resonance filter, was designed and fabricated. Also, the wavelength variation of the FBG sensor was measured and its strain was calculated. Calculated strains were compared with those determined by the finite element analysis.

2. SIGNAL ANALYSIS OF FBG SENSOR

To analyze the basic signal characteristics of the FBG sensor, tensile testing was performed. Fig. 1 shows the shape of the tensile test specimen. Composite specimens, which had stack-

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*Research Center for Aircraft Parts Technology, School of Mechanical and Aerospace Engineering, Gyeongsang National Univesity
*†Research Center for Aircraft Parts Technology, School of Mechanical and Aerospace Engineering, Gyeongsang National Univesity, Corresponding author (E-mail: choi@gnu.ac.kr)

ing sequences of $[0]_4$ and $[90]_8$, were manufactured. USN 125 carbon epoxy prepreg supplied by SK Chemical Co. was used, and the maximum curing temperature was 120°C. The FBG sensor, with a central frequency of 1534.4 nm and a strain gauge was attached to the tensile specimen. The IFIS 100

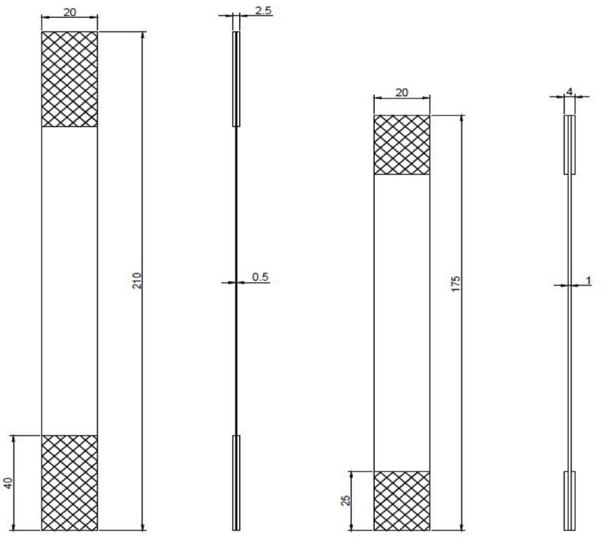


Fig. 1. Shape of the tensile test specimen

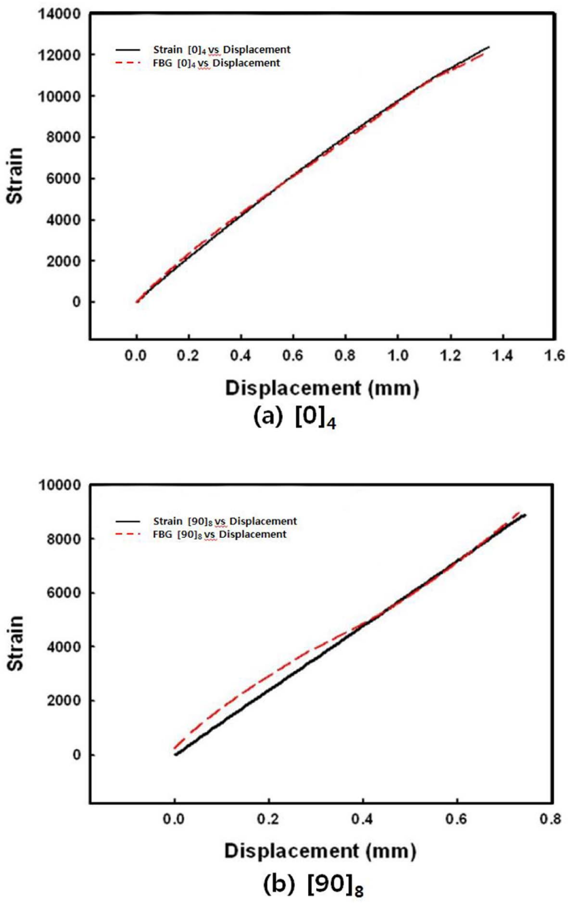


Fig. 2. Strain measured by FBG sensor and strain gauge

model of the FIBER PRO Co. was used for measuring the variation of the wavelength. A Universal Machine 8516 of the INSTRON Co. was used for the tensile tests of the specimens. The variation of wavelength, δλB, is proportional to the strain ε; the relationship of these two values was determined as follows.

The variation of wavelength was measured and the strain was calculated by Equation (1). Fig. 2 shows the strain measured by the FBG sensor and strain gauge during the tensile test. As can be seen in Fig. 2, the strains measured by the FBG sensor were almost the same as those determined with the strain gauge.

$$\delta\lambda_B = \lambda_B(1-P_e)\varepsilon \tag{1}$$

P_e: Photo-elastic constant, 0.22
λ_B: Central frequency of fiber Bragg grating

3. AE SIGNAL AND AE SIGNAL ANALYZER

The fracturing of the tensile test specimen was measured by the AE method. In the previous study [6], it was revealed that the fracture frequencies of the fiber and matrix in the composite materials were 100 kHz, 230 kHz, 300 kHz, and 400 kHz.

An AE signal analyzer, which can detect the fracture frequency of the composite materials, was designed and manufactured. Fig. 3 shows the electric circuit of the AE signal analyzer. As can be seen in Fig. 3, the amplified signal was input into the low-pass filter and the L-C resonator. The low-pass filter is for the impact detection and the L-C resonator is for the fracture detection. The cut-off frequency of the low-

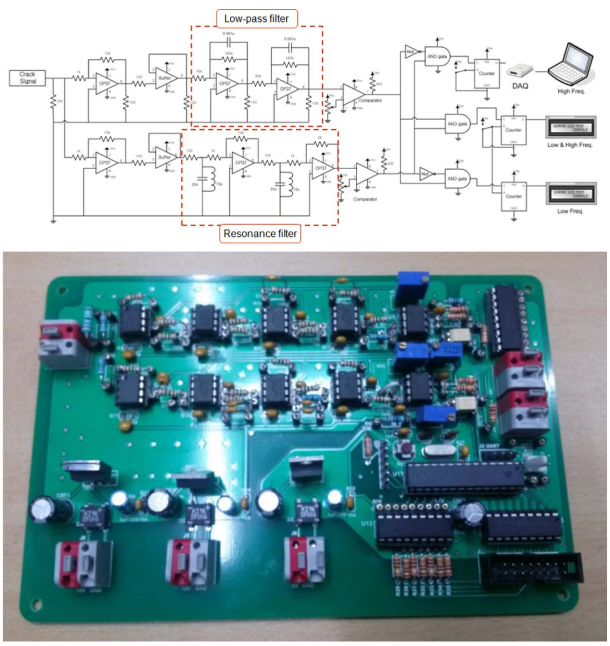


Fig. 3. AE signal analyzer

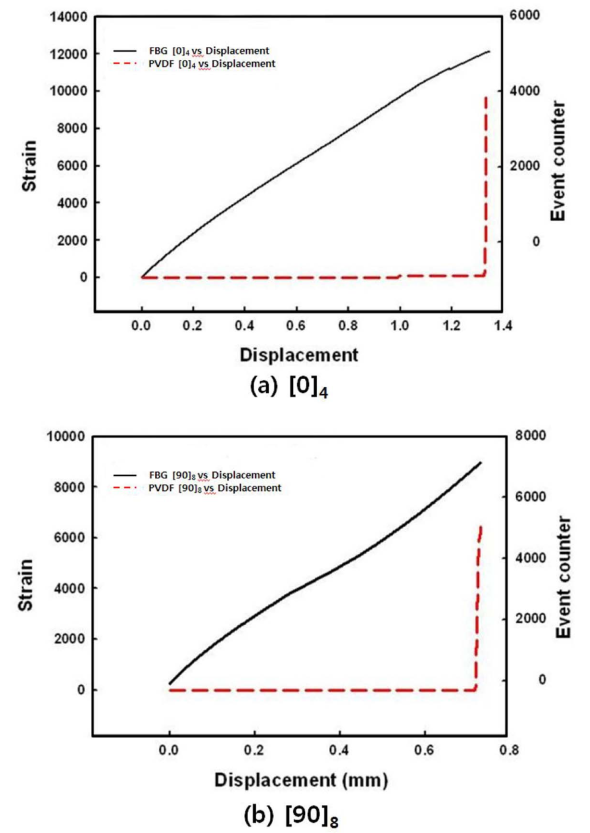


Fig. 4. Fracture detections by the FBG sensor and AE sensor

pass filter and the resonance frequency of L-C resonator were set to 700 Hz and 230 kHz, respectively. Since the fracture frequencies of the composite materials can be changed slightly in each test and can have a narrow band, the band pass filter can be used. The filtered signals are input into the comparator. Digital signals of 5 volts were produced by the comparator when the filtered signals were larger than the threshold voltage level. It was possible to adjust the threshold voltage level, and the digital signals were counted by the three counters. Each event count of low (impact) or high (fracture) frequency can be measured.

Fig. 4 shows fracture detections by the FBG sensor and AE sensor. As can be seen Fig. 4, the strains measured by the FBG sensor were increased and then abruptly dropped due to breakage of the FBG sensor when the tensile specimen was broken into two parts at the end of tensile test. Also, there was no event count until the tensile test specimen was broken, and then the event count of the fracture frequency was abruptly increased at the breakage of tensile test specimen in the AE method.

4. BUCKLING TEST

To evaluate the fracture detection capabilities of the FBG sensor and the AE sensor, a buckling test was performed and

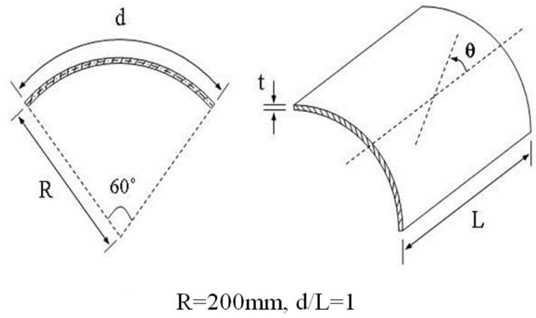


Fig. 5. Composite shell for the buckling test

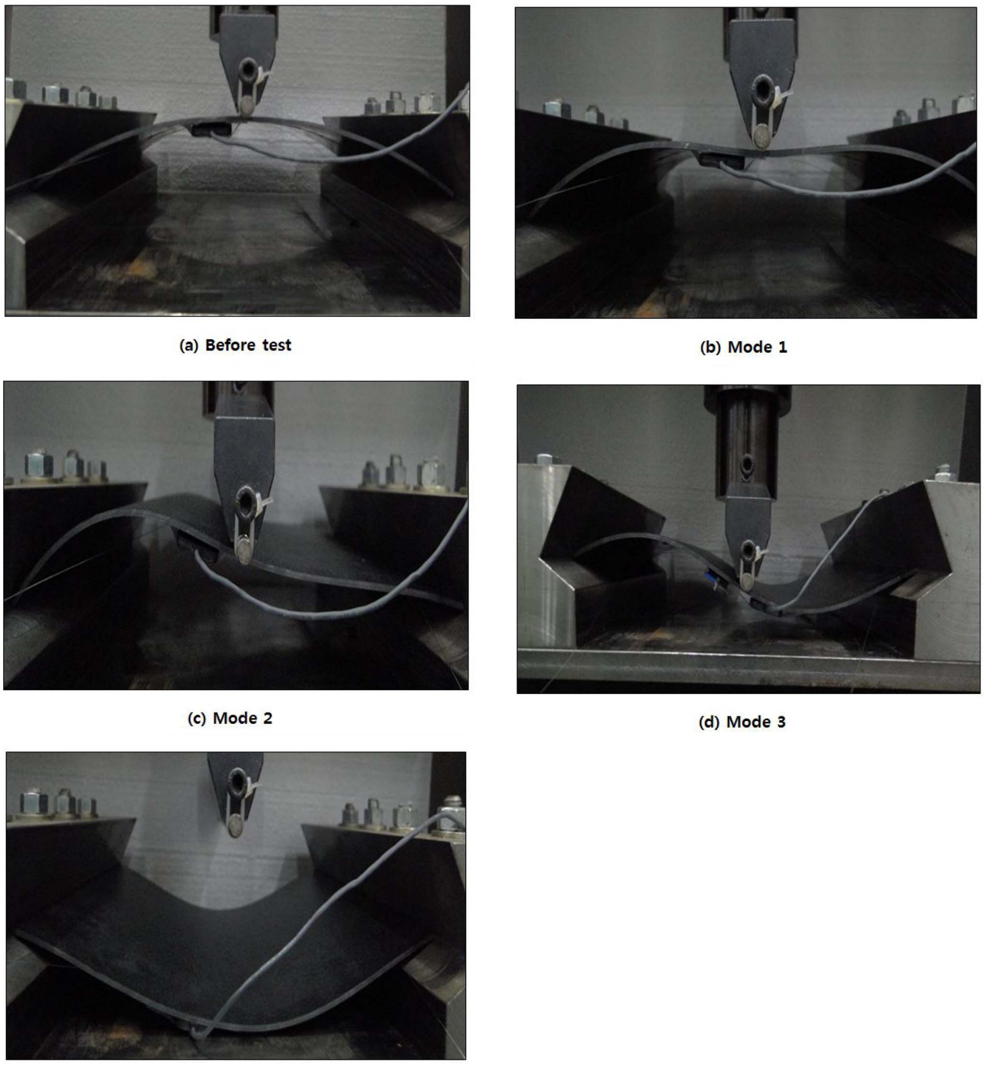
Fig. 6. Three FBG sensors attached to the composite shell

their capabilities were compared. Fig. 5 shows the composite shell for the buckling test. As can be seen in Fig. 5, the radius and length of the composite shell were 200 mm and 400 mm, respectively, and both ends were simply supported. The USN 125 carbon epoxy prepregs, which were fabricated from the same material as the tensile specimen, were used and their stacking sequence was $[02/902]_{2S}$. The AE sensor and the three FBG sensors were attached to the composite shell, as can be seen in Fig. 6. Several buckling modes were observed during the test and their shapes are shown in Fig. 7.

Fig. 8 shows the force-displacement curve and the FBG sensor signals during the buckling test. As can be seen in Fig. 8, the FBG signals of 1, 2 and 3 were abruptly changed around the 8mm displacement. These abrupt FBG signal changes around the 8 mm displacement were considered to occur due to mode change from symmetric mode to un-symmetric mode. However, no fracture signals from FBG sensors were detected and the composite shell was not broken into two parts after the buckling test.

To compare the strains measured by FBG sensors with those by analysis, the buckling analysis of the composite shell was performed. The ANSYS 10.0 was used for the analysis and the shell elements were used. Fig. 9 shows the finite element model and boundary condition of the composite shell. As shown in Fig. 9, the both ends were simply supported and the vertical loads were applied to the middle of the composite shell.

Fig. 10 shows the force-displacement curve calculated by buckling analysis. As shown in Fig. 10, the experimental buck-



(a) Before test

(b) Mode 1

(c) Mode 2

(d) Mode 3

(e) Snap-Through

Fig. 7. Buckling modes during the test

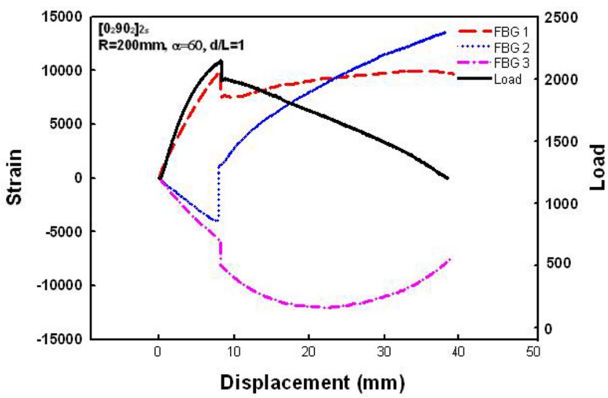


Fig. 8. Signals of FBG sensors during the buckling test

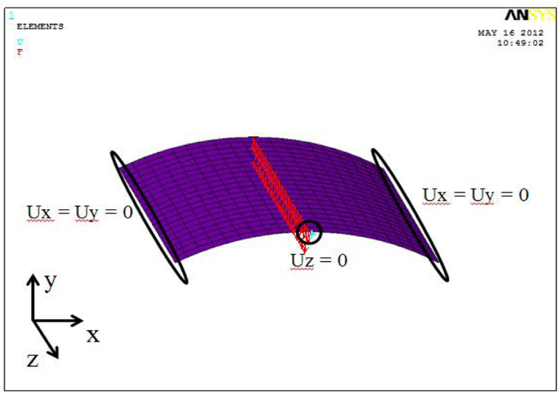


Fig. 9. Finite element model of the composite shell

ling force was lower than the calculated buckling force and the load drop of the analysis occurred earlier than that of the experiment. These experimental results are considered to be due to imperfection of specimen geometry or boundary con-

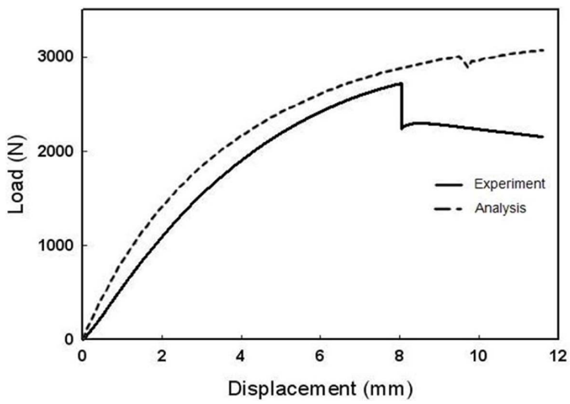


Fig. 10. Force-displacement curve calculated by the buckling analysis

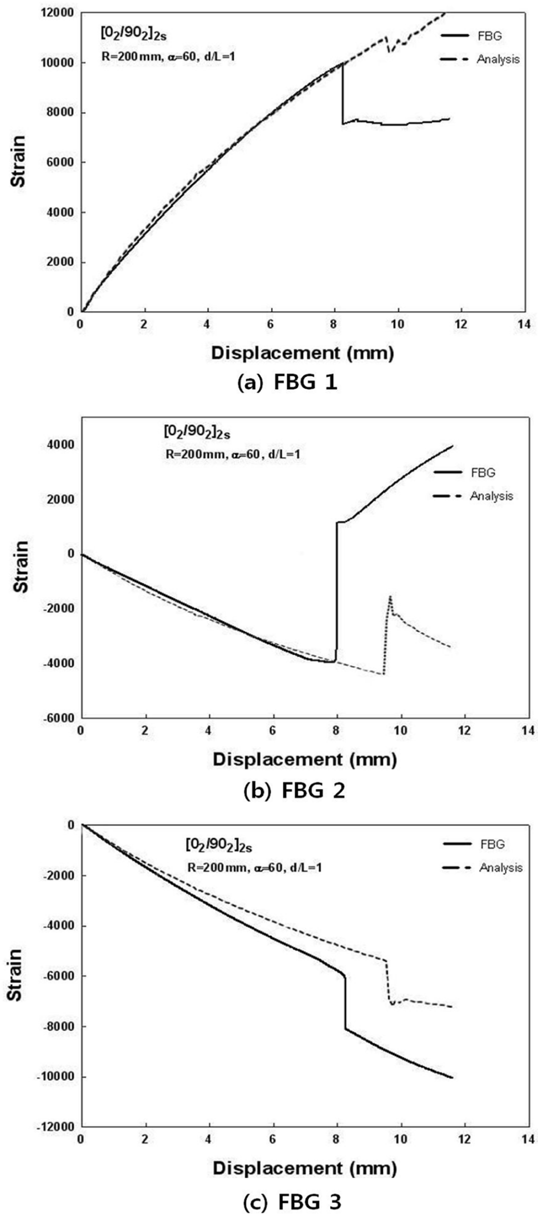


Fig. 11. Strains calculated by the buckling analysis

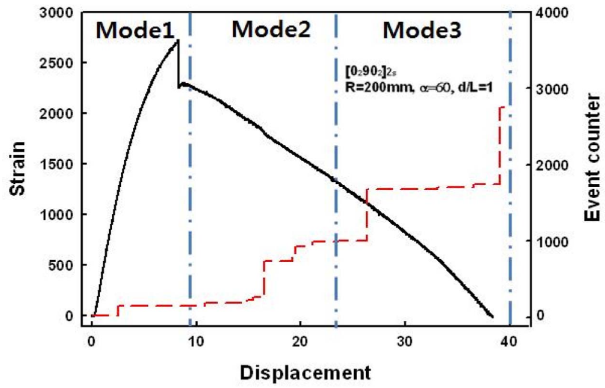


Fig. 12. Force-displacement curve and AE signals.

dition. The strains calculated by the buckling analysis were compared with strains measured by FBG sensors in Fig. 11. As shown in Fig. 11, the slopes of strains calculated by the buckling analysis were almost same as those of strains measured by FBG sensors except FBG 3.

From the tests, it can be concluded that the FBG sensors measure the multi-point strains effectively but cannot detect the fracture signal when the composite shell is not broken into two parts.

Fig. 12 shows the force-displacement curve and AE signals during the test. As can be seen in Fig. 12, the event count of the fracture frequency was abruptly increased around the 16.5 mm and 26.6 mm displacements. The strains between the 16.5 mm and 26.6 mm displacements were very high (over 12,000 μs) as shown in Fig. 8. Therefore, it was considered that the several layers of the composite shell were fractured around the 16.5 mm and 26.6 mm displacements, although the whole composite shell was not broken into two parts.

4. CONCLUSIONS

In this paper, the crack detection capability of the AE(Acoustic Emission) was compared with that of FBG sensor under the tensile test and buckling test of composite materials. From the tests, it can be concluded that the AE method can detect only the fracture point, and the FBG sensor can measure not only the fracture point but also the multi-point strains when the composite materials are broken into two parts. However, the FBG sensor couldn't detect the fracture signal when the composite materials were not broken into two parts.

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