STRAIN MEASUREMENT OF COMPOSITE LAMINATES USING FIBER BRAGG GRATING SENSORS

Chang-Sun Hong, Chi-Young Ryu, Chun-Gon Kim

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology(KAIST), 373-1 Kusong-dong, Yusong-gu, Taejon, 305-338, Korea

SUMMARY: Fiber Bragg grating(FBG) sensors, one of the fiber optic sensors(FOS), based on the wavelength division multiplexing(WDM) technology are ideally suitable for structural health monitoring of composite materials and structures. Proper monitoring of measurands in FBG sensor systems requires accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength. Thus we constructed a FBG sensor system by use of a wavelength-swept fiber laser(WSFL) in the present study. The quasi-static and dynamic strains were measured by the constructed FBG sensor system for investigation of the system performance. In addition a real-time signal processing program was made to measure strains. Three FBG sensors in an optical fiber were used to measure strains of the laminated composite panel under compressive axial loading. Experiments showed that the constructed FBG sensor system and the real-time signal processing program could successfully measure the strain of composite laminates.

KEYWORDS: Fiber Bragg grating sensor system, Strain measurement, Wavelength division multiplexing, Real-time signal processing, Strain monitoring

INTRODUCTION

In recent years, a lot of attention has been paid to the smart materials and structures. One or the combination of optical fiber sensors, piezoelectric film, shape memory alloy, and electro-rheological fluid may construct smart materials and structural systems. Optical fiber sensors are one of the promising sensor technologies for applications in smart materials and structures. They can be easily embedded into laminated composites and are not affected by the electro-magnetic field. Also, they have flexibility of the sensor size(μm~km) and very highly sensitive. These advantages of a FOS make it to be the potential solution for sensor systems of smart structures[1]. The development of smart composite structures with fiber optic sensing systems is a first necessary step in this field and will lead to advances in process control of composite material fabrication and to improvements in damage detection and health monitoring of composite structures.

There are several types of a FOS based on the intensity of light, interferometer and FBG methods. Two types of a FOS with the most promise at this time are interferometer sensors and FBG sensors. Michelson and Fabry-Perot(F-P) interferometer sensors are typical of interferometer sensors. Researches on the 1) simultaneous sensing of the strain and failure in composite beams with an embedded fiber optic Michelson sensor[2] and 2) signal characteristics in the composite specimen with an embedded fiber optic EFPI(extrinsic Fabry-Perot interferometer)[3] have been carried out. A FOS could measure strains and detect the failures of matrix crackings and delaminations of the laminated composites. Michelson and EFPI sensors showed excellent strain resolution and fast response time but some problems such as 2π ambiguity, automated fabrications, multiplexing and so on. Moreover signal drifting and beating problems occur especially in case of Michelson interferometer. On the other hand, FBG sensor is easy to be multiplexed and has many advantages of linear response, absolute measurement, etc.

FBG sensors based on the wavelength division multiplexing(WDM) technology attract considerable research interest and appear to be ideally suitable for structural health monitoring of composite materials and infrastructures. Proper monitoring of measurands in FBG sensor systems requires accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength especially in the structures under dynamic loading. Various interrogation schemes have been reported for the detection of small Bragg wavelength shifts based on the combination of a broadband source and a wavelength-dependent receiver. LED's, amplified spontaneous emission sources and ultrashort-pulse lasers are typically used as broadband sources. For wavelength-dependent receivers, scanning tunable filters[4] and unbalanced interferometers[5] have been employed. However, these schemes have shown some drawbacks associated with low signal powers by using a narrow spectral slice from a broad source spectrum. Moreover, these results showed poor spectral resolution determined by the resolution of the tunable filter or the spectrometer itself. Recently, the interrogation technique based on the WSFL was developed[6]. This technique offers several attractive features. First, it provides for high signal powers, since the full source output is available during the measurement of a given grating's Bragg wavelength. Second, the broad source tuning range and narrow instantaneous spectral line width allow for a large number of individual elements within the array.

In this study, we constructed a FBG sensor system using a WSFL and the signal processing program for real-time strain measurement. For verification of the system's performance, the experiments of quasi-static and dynamic strain measurement were carried out. Finally the strains of the composite laminated panel under compressive axial loading were effectively measured real-timely by the FBG sensor array.

A FIBER BRAGG GRATING SENSOR SYSTEM

Theory of Strain Measurement

A fiber Bragg grating is a periodic, refractive index perturbation that is formed in the core of an optical fiber by exposure to an intense UV interference pattern. Gratings can be formed in telecommunications compatible fibers to operate at any wavelength by the holographic technique[7]. However the holographic writing technique is not ideally suited to write gratings for a precise wavelength. A simpler technique for stable grating fabrication can be achieved using a phase mask. With this simpler method by Hill *et al.*[8], one can reproduce gratings of the same wavelength that is determined only by the mask's period, which is very important for mass production. We used FBG sensors fabricated by this phase mask technique. The Bragg wavelength that is retroreflected at each grating sensor can be written as following Bragg condition.

$$\lambda_B = 2n_e\Lambda \tag{1}$$

Where λ_B is the Bragg wavelength, n_e is the effective index of the fiber core, and Λ is the grating period. When temperature changes or mechanical strains are applied to the FBG sensor, Bragg wavelength is changed. The Bragg wavelength shift caused by temperature or strain can be expressed as following simple relation,

$$\Delta\lambda_B = \lambda_B\left[(\alpha+\xi)\Delta T + (1-p_e)\Delta\varepsilon\right] \tag{2}$$

$$p_e = \left(\frac{n^2}{2}\right)\left[p_{12} - \nu(p_{11}+p_{12})\right] \tag{3}$$

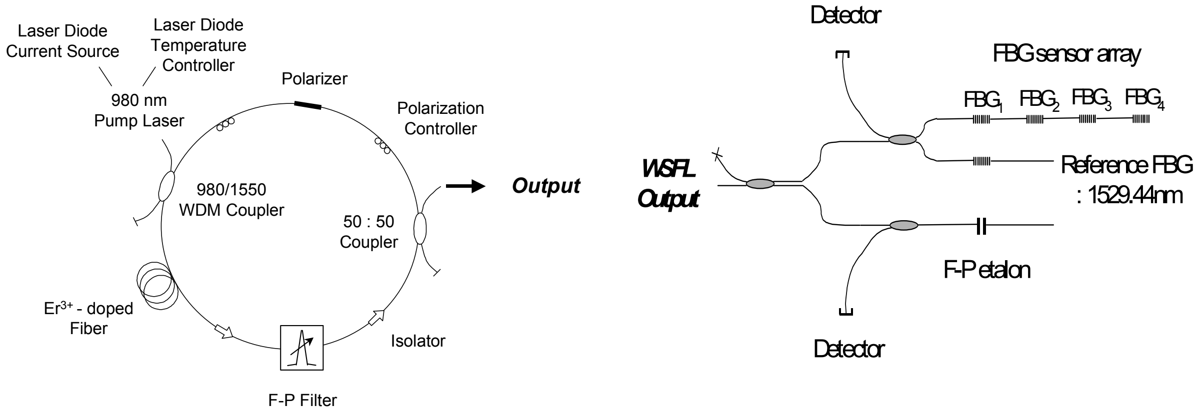
where α is the thermal expansion coefficient, ξ is the thermo-optic coefficient, p_e(=0.225) is the photoelastic constant and p_{11}, p_{12} are strain-optic tensors. Bragg wavelength shift by temperature is negligible, when environmental temperature does not change rapidly. It is generally known that 1.4 *nm* Bragg wavelength shift occurs by the change of temperature 100^{o}C. If FBG sensors are in the same environmental temperature, we can ignore the temperature dependent part in Eqn. 2. Considering this condition, the strain can be measured by detecting the Bragg wavelength shift. Finally the relation between strain and Bragg wavelength shift is conclusively as follows.

$$\varepsilon = \frac{1}{(1-p_e)}\frac{\Delta\lambda_B}{\lambda_B} \tag{4}$$

Construction of a WSFL and a Real-Time Signal Processing Program

The accurate detection of Bragg wavelength shift is important to strain measurement. For the purpose, the WSFL is constructed and employed to the present FBG sensor system. The WSFL has a scannig tunable filter in the cavity to sweep the laser output wavelength in time continuously and repeatedly over a range of a few tens of nanometers. When the WSFL output is directed to the grating array, the reflected optical signal consists of a series of pulses in the time domain whose timing relative to the start of the wavelength sweep is determined by both the Bragg wavelength of each corresponding grating and the position of each grating within the array. By measuring the reflected pulse timing characteristics and employing simple signal processing schemes based, for example, on time interval counting[6] or peak detection as in this study, one can deduce the instantaneous Bragg wavelength of the individual gratings within the array.

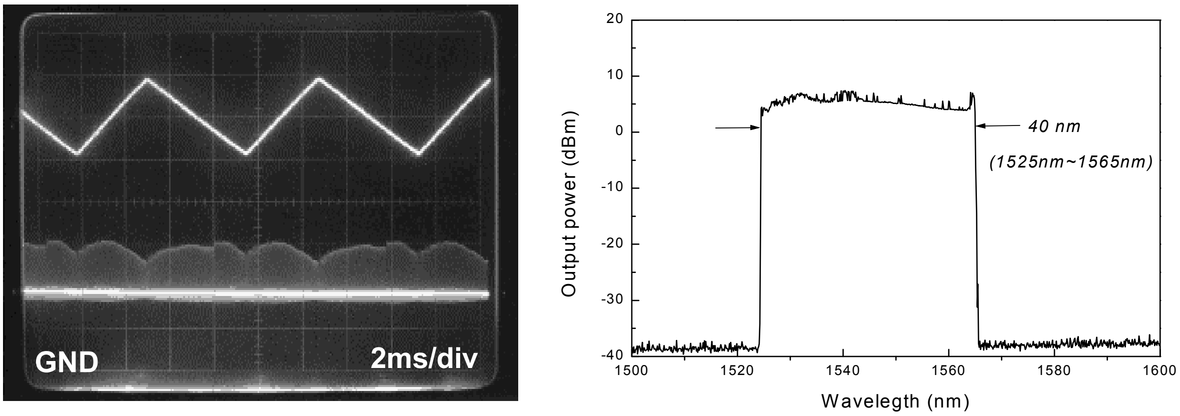
Fig. 1(a) shows a schematic of the configuration of the WSFL and (b) the grating array with a reference FBG and a Fabry-Perot(F-P) etalon. The WSFL was in a unidirectional ring configuration with isolators, a 3-dB output coupler, and an Er^{3+} - doped fiber pumped by a laser diode at 980 *nm*. A F-P tunable filter was used as the intracavity scanning filter and had a 3 *dB* bandwidth of 0.27 *nm* and a free spectral range of 58 *nm*. We modulate the F-P filter with a triangular waveform to produce a wavelength sweep over 40 *nm* from 1525 to 1565 *nm* at a 130 *Hz* repetition rate. The laser output was directed into an array of sensing gratings and a reference grating(λ_0=1529.4 *nm*) and a F-P etalon used the multi-beam interferometer with the interval of 1 *nm* via a 50% coupler.



(a) (b)

Fig. 1 : Configuration of (a) the wavelength-swept fiber laser and (b) the grating sensor array.

Fig. 2(a) shows the laser output signal seen with a fast(50 *MHz*) oscilloscope and detector system and illustrates the pulsed nature of the output; Fig. 2(b) shows the peak-hold optical spectrum. The triangular waveform shown in Fig. 2(a) is the 130 *Hz* electrical signal that was applied to the scanning filter. As the voltage of the signal was swept upward(downward), the output wavelength increased(decreased). By appropriate alignment of the intracavity polarization controllers, the fluctuations of the pulse peak power could be reduced by 5~7%. The average output power of the laser was 2.22 *mW* at a pump power of 43 *mW*, with a variation of less than 1 *dB* across the full wavelength sweep.



(a) (b)

Fig. 2 : (a) Triangular modulation signal(upper trace) and WSFL output seen on an analog oscilloscope. (b) Peak-hold optical spectrum.

When the WSFL output is directed to the reference FBG and an F-P etalon, the reflected optical signal is as like Fig. 3 with triangular modulation signal. Since the general PZT has hysteresis, the PZT of a F-P tunable filter may have non-linearity against linear modulation signal. Errors happen to be caused from this phenomenon could be corrected by an F-P etalon. The optical signal of multi-beam interference of an F-P etalon is used for a grid line that has a same spacing of wavelength. In this study, we manufactured an F-P etalon to have an interval of 1*nm* wavelength between valleys of the reflected signal. If an FBG known its Bragg center wavelength is located anywhere in the grid line of wavelength, a coordinate of wavelength could be generated. The information from the reference FBG and a F-P etalon is used for signal processing of strain measurement.

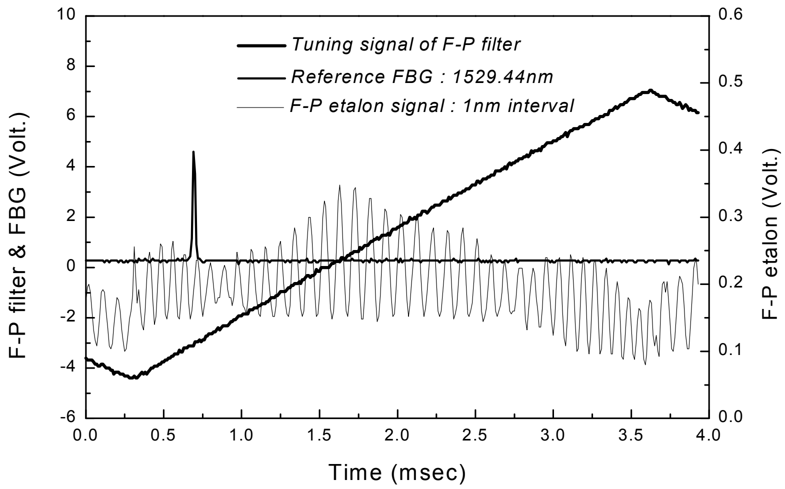


Fig. 3 : Tuning signal of F-P filter and optical signal of the refernece FBG and a F-P etalon.

The signal processing program of strain measurement using FBG sensors is summarized in Fig. 4. Program has two steps, 1) generation of fine grid points from F-P etalon's signal and 2) real-time signal processing of strain measurement. The fineness of the points is dependent on sampling frequency of acquired data. We considered the program to be able to select adequate sampling frequency as to types of strains(static or dynamic).

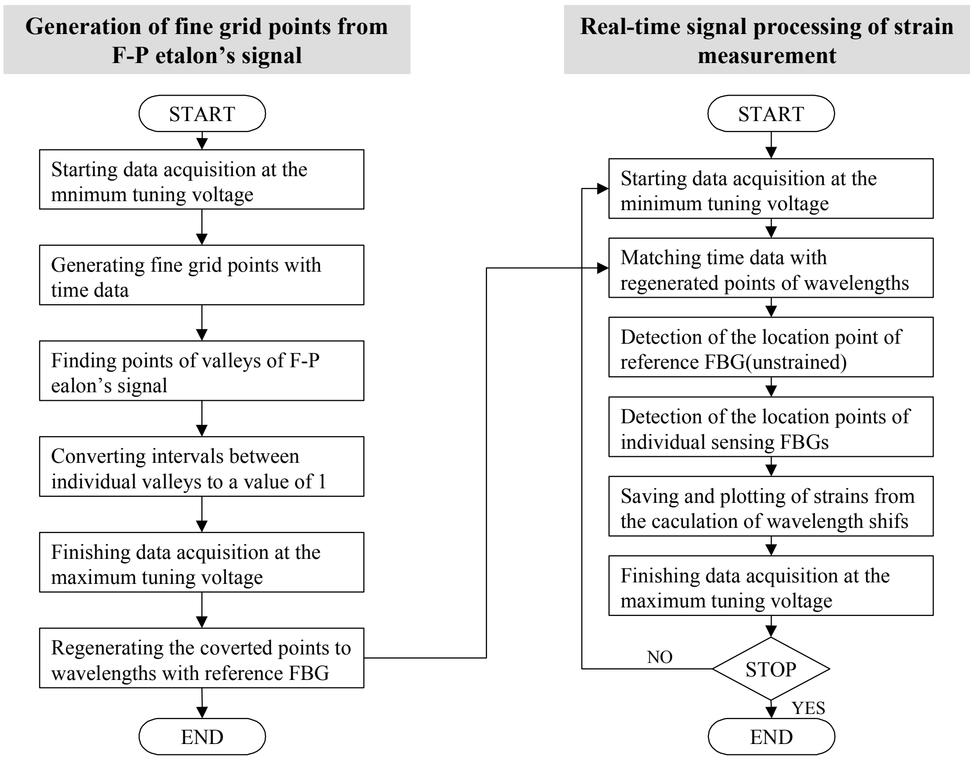
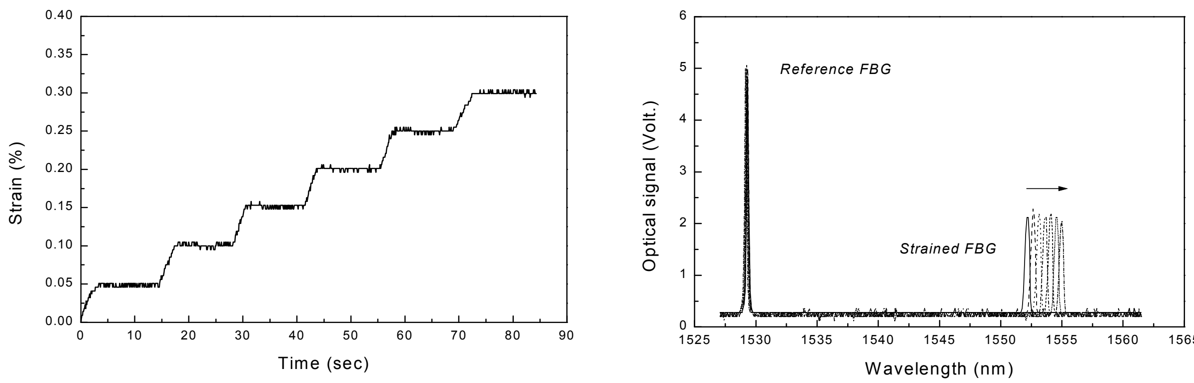


Fig. 4 : Schemes for real-time signal process of strain measurement using FBG sensors.

The Investigation Test of the FBG Sensor System

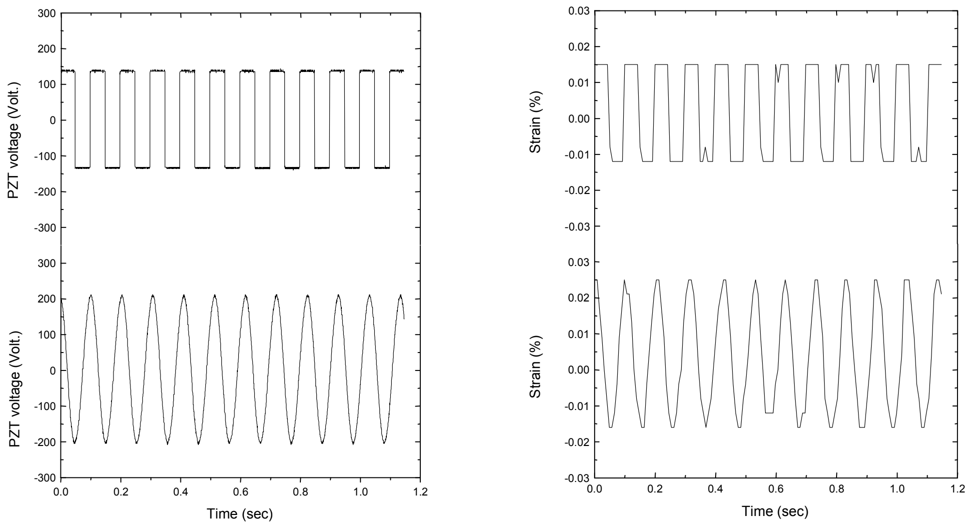
To investigate constructed FBG sensor system, experiments of measurement of quasi-static and dynamic strains were carried out. For a quasi-static strain test, the axial strain steps of 0.05% were carefully applied to a grating fiber of 1*m* length with Bragg wavelength of 1552.35 *nm* using a micro positioner that can control displacement up to 0.01 *mm* (corresponding to 0.001%). The experimental results are shown in Fig. 5. As can be seen from these results, the sensor system exactly measured the strains and the resolution of the system was 0.005%. Fig. 5(b) shows profiles of wavelength shift strained FBG acquired with digital storage oscilloscope(DSO).

To demonstrate dynamic strain measurement further, we applied rectangularly and sinusoidally varying strain to FBG sensors. Two FBGs(each Bragg wavelength is 1547.84 *nm* and 1552.23 *nm*) were bonded with FM73 adhesive film made by CYNAMID Co. on the surface of two piezo ceramics. Material properties of piezo ceramic made by Fuji Co.(model : Fuji C-82) are $E_1 = E_2 = 59$ *GPa*, $\nu_{12} = 0.34$, $\rho = 7400$ Kg/m^3, $d_{31} = d_{32} = -260 \times 10^{-12}$ *m/V* and its thickness is 0.4 *mm*. Piezo ceramics are modulated with square and sinusoidal waveform each other by a function generator. The voltage amplifier amplifies the signal of a function generator and this amplified signal modulates piezo ceramics. We detected this amplified signal via a 10:1 probe. When modulation speed is 10 *Hz*, the experimental results are shown in Fig. 6. Fig. 6(a) is the signal detected from piezo ceramic and (b) is the plotting of strain measured by FBG sensor system. These results show good agreement. The maximum frequency range for dynamic strain measurement without ambiguity was 65 *Hz*(half the sampling rate) when data was processed with a fast Fourier transform(FFT) analysis. Fig. 7 is a real-time strain measurement window by the signal processing program. The window could monitor real-timely dynamic strain states of the FBG sensors. The signal process and plotting windows of strains were constructed by use of LabVIEW software.



(a) (b)

Fig. 5 : (a) Experimental results for the quasi-static strain measurement. (b) Profiles of wavelength shift of strain-induced FBG sensor.



(a) (b)

Fig. 6 : (a) Voltage signals to the piezo ceramic. (b) Strains measured by FBG sensor system.

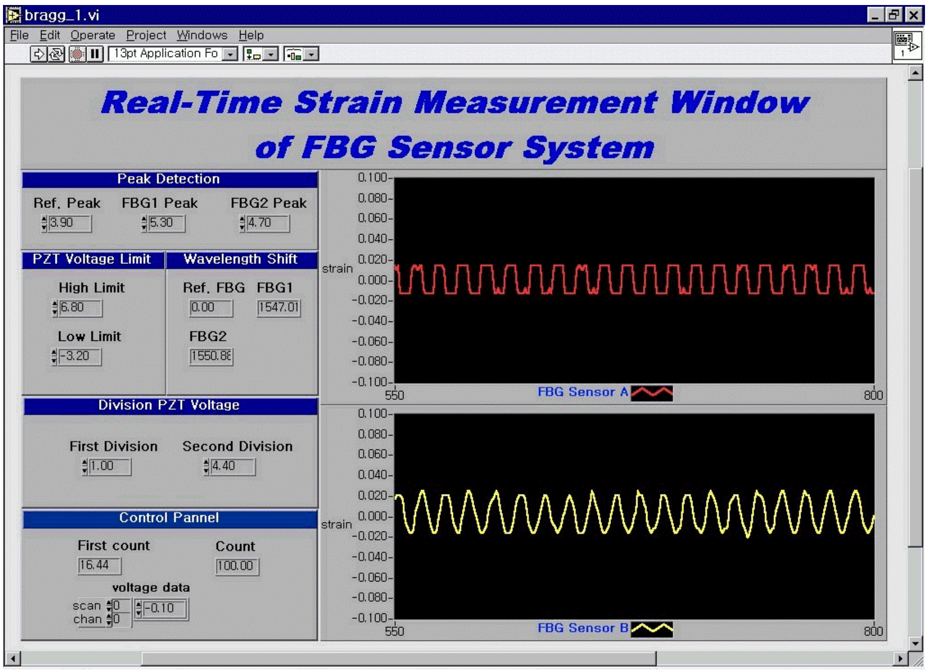


Fig. 7 : Real-time strain measurement window of FBG sensor system.

THE STRAIN MEASUREMENTS OF LAMINATED COMPOSITE

The experiments of strain measurement of laminated composite panel under compressive axial loading were carried out using a FBG sensor system. The composite panel was fabricated using graphite/epoxy prepreg, and its material properties are $E_1 = 130$ *GPa*, $E_2 = E_3 = 10$ *GPa*, $G_{12} = G_{13} = 4.85$ *GPa*, $G_{23} = 3.62$*GPa*, $\nu_{12} = \nu_{13} = 0.31$, $\nu_{23} = 0.52$, $X_T = 1933$ *MPa*, $X_C = 1051$ *MPa*, $Y_T = 51$ *MPa*, $Y_C = 141$ *MPa* and $S = 61$ *Mpa*. The geometry, dimensions and the boundary conditions of the composite panel are shown in Fig. 8. Three FBG sensors were bonded on the surface of the composite panel. The Bragg wavelengths are FBG1 = 1532.65 *nm*, FBG2 = 1546.01 *nm* and FBG3 = 1548.77 *nm*. In order to compare strains measured by

FBG sensors with those by electric strain gauges(ESG), ESG1 and ESG2 were symmetrically bonded to FBG1 and FBG2. ESG3 was bonded to FBG3 on the back of the panel.

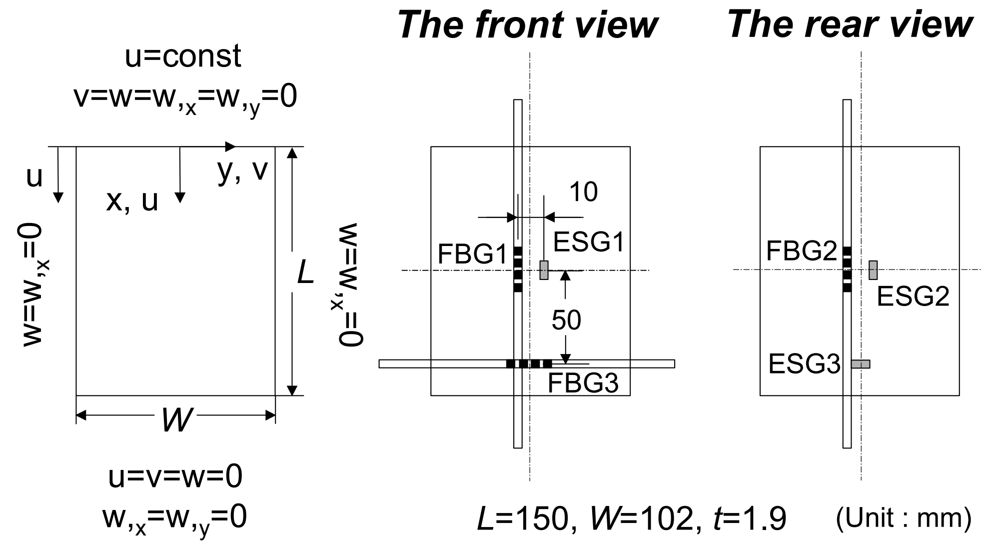


Fig. 8 : Configuration of the specimen.

Fig. 9 shows the schematic and photograph of the experimental setup for the buckilng test of the composite panel. Load was displacement-controlled, *0.5 mm/min*. FBG sensors were connected to one line of optical fiber by an arc fusion splicer. The behavior of the composite panel is simultaneously monitored by measuring strains using multiplexed FBG sensor array.

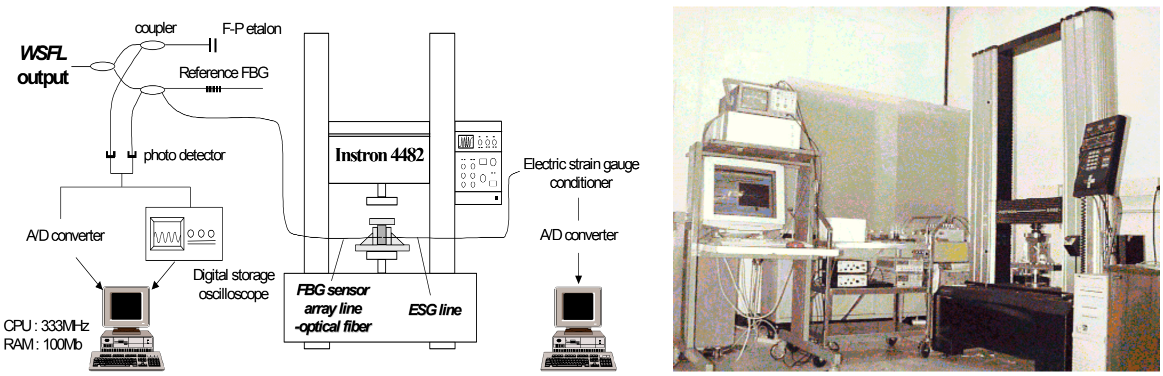


Fig. 9 : The schematic diagram and the picture of the experimental setup.

The strains measured by FBG sensors are compared with those by ESGs. As shown in Fig. 10, the strains measured by FBG1,2 sensors and ESG1,2 show good agreements up to final failure of the composite panel. FBG3 sensor and ESG3 were transversely bonded to compressive loading direction and on the the other side of the composite panel, therfore they were under the different strain states. Diffrences between strain from FBG1 and strain from FBG2 before buckling are caused by misalignment in the test or imperfection of the specimen. Buckling stress determined by mean value of strains from FBG1 and FBG2 was 35 *MPa*. Fig. 11 shows strains of FBGs to the time, which are monitored real-timely during an experiment.

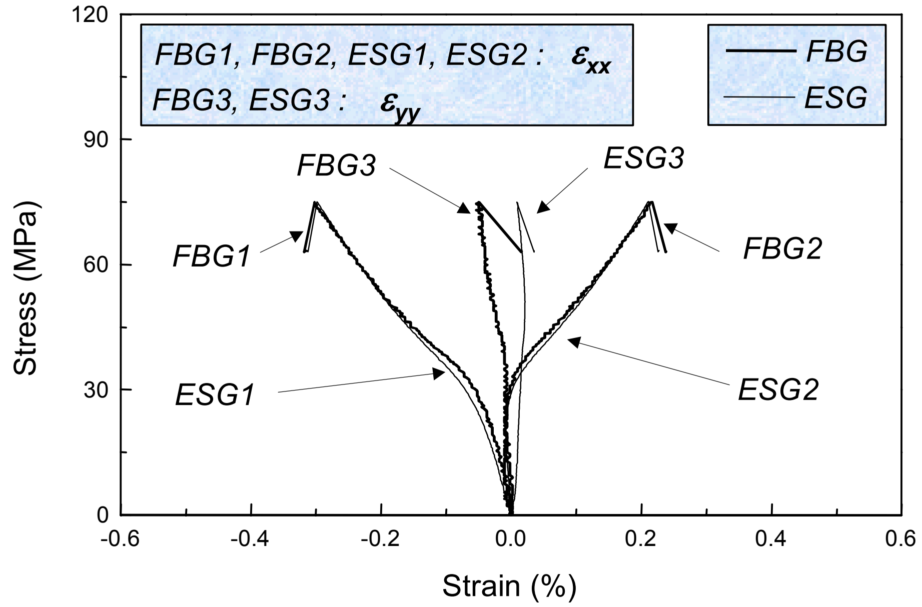


Fig. 10 : Comparison of strains measured by FBG and ESG.

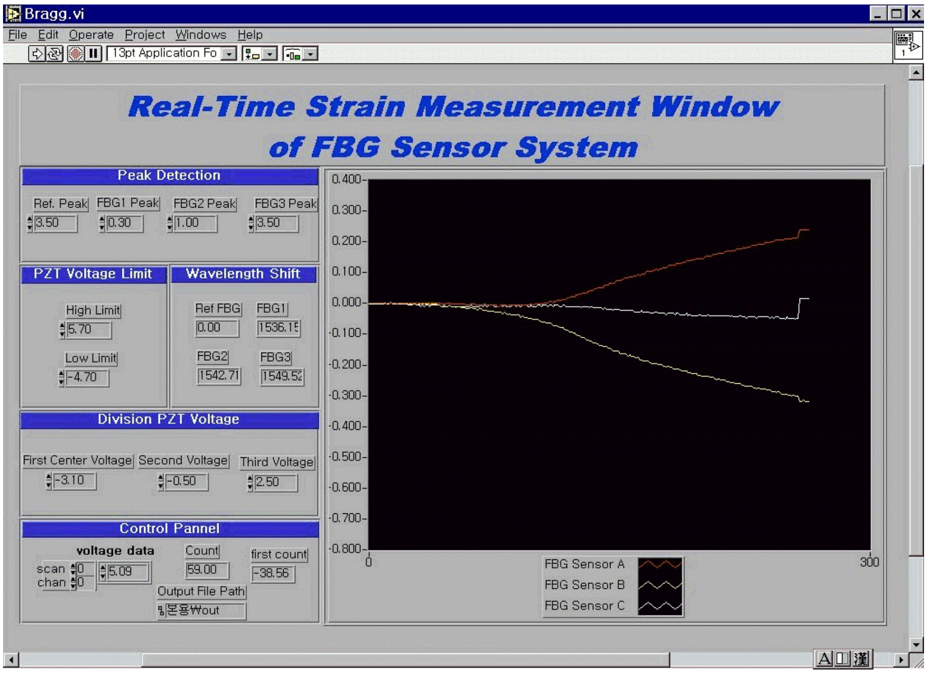


Fig. 11 : Real-time strain monitoring window during experiment.

CONCLUSIONS

We constructed an FBG sensor system by using a WSFL. The quasi-static and dynamic strains were measured by the constructed FBG sensor system, which turns out to show the effective system. Three FBG sensors in an optical fiber were used to measure strains of the laminated composite panel under compressive axial loading with multiplexing technique. Experiments showed that the constructed FBG sensor system and the real-time signal processing program could successfully measure the strains of multi-points in composite laminates.

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