STRAIN MEASUREMENTS OF COMPOSITE LAMINATES USING FIBER BRAGG GRATING SENSOR

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Abstract: Fiber optic sensors(FOS) are currently being investigated as strain monitors in smart structures. Fiber Bragg grating(FBG) sensor, one of the fiber optic sensors, based on the wavelength division multiplexing technology is ideally suited for structural health monitoring of composite materials as they have the potential of offering many distinct advantage over the conventional strain gage. Proper monitoring of measurands in FBG sensor systems requires the accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength. Thus a tunable fiber Fabry-Perot filter as a demodulator for FBG sensors was used in the present study. Two FBG sensors in an optical fiber were constructed to measure longitudinal and transverse strain of the laminated composite under the tensile loading. And real-time signal processing program was constructed to measure strains. The strains measured by FBG sensor system were compared with those by the conventional strain gage. Experiments showed that the constructed FBG sensor system and the real-time signal processing program could successfully interrogate wavelength division multiplexed FBG sensors.

Key words: *FBG sensor system, Real-time signal processing program, Strain measurement, Laminated composite*

1. INTRODUCTION

In recent years, a lot of attention has been paid to the smart materials and structures. The development of smart composite structures with fiber optic sensing systems is a necessary first 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.

The advantages of FOS make them to be the potential solutions for sensor systems of smart structures[1]. 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.

There are several types of FOS based on the intensity of light, interferometer and FBG methods. The two types of FOS with the most promise at this time are interferometer sensor and FBG sensor. Michelson and Fabry-Perot 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[2,3] and 2) signal characteristics in the composite specimen with an embedded fiber optic EFPI(extrinsic Fabry-Perot interferometer)[4,5] were carried out at our lab. FOS could sense strains which makes good agreement with conventional strain gage and detect the failures of matrix crackings and delaminations of the laminated composites throughout research. Michelson and EFPI sensors showed excellent strain resolution and fast response time but some problems like as 2π ambiguity, automated fabrications, multiplexing and so on. Moreover signal drifting and beating problems are occurred 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 sensor based on the wavelength division multiplexing(WDM) technology attracts considerable research interest and appears to be ideally suited for structural health monitoring of composite materials and civil engineering applications. Proper monitoring of measurands in FBG sensor systems requires the accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength especially in the structures under dynamic loading. Thus for more accurate and faster performance than optical spectrum analyzer, a lot of Bragg wavelength interrogation systems have been reported and demonstrated[6,7]. In this paper, we constructed FBG sensor system with a tunable FFP filter as a demodulator, and real-time signal processing program. Longitudinal and transverse strains were successfully measured for the composite laminate under tensile loading.

2. FIBER BRAGG GRATING SENSOR

2.1. Theory

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. It was first shown in 1978 by Hill *et al.*[8] that reflective gratings could be photorefractively formed in the core of germanium doped silicate fibers. Gratings can be formed in telecommunications compatible fibers to operate at any wavelength by the holographic technique[9]. 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.*[10], 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.

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

Here λ_B is the Bragg wavelength, n_e is the effective index of the fiber core, and Λ is the grating period.

When light from a broadband source is coupled into the fiber that transmits the light to the grating elements, wavelength by the Bragg condition is only reflected and the other wavelength is transmitted in the grating part. This process is shown in Fig. 1.

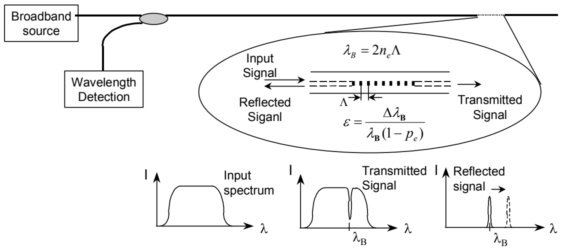


Fig. 1 FBG sensor wavelength-encoding operation.

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,

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

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

Here α is the thermal expansion coefficient, ξ is the thermo-optic coefficient, p_e is the photoelastic constant, and p_{11}, p_{12} are strain-optic tensors.

It is generally known that 1.4*nm* Bragg wavelength shift occurs by 100°C temperature changing. Bragg wavelength shift by temperature is negligible, when environmental temperature do not change rapidly. Moreover FBG sensors are in the same environmental temperature within a little degree deviation as present experiment, we can ignore temperature dependent part of the eqn. (2). Considering this condition, the strain can be measured by detecting the Bragg wavelength shift. The relation between strain and Bragg wavelength shift is conclusively as follows.

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

2.2. Measurement of Photoelstic Constant, p_e

If fiber is made by different drawn tower or treated with different conditions just like as Ge-doped or Hydrogen loaded fiber, the photoelastic constant, p_e, may have different value. It is generally known that the value of p_e is 0.22 for silica glass(SiO_2)[11]. From eqn. (4), we must know accurate value of p_e of the fiber for precise measurement of strain.

Three Hydrogen loaded fibers made by LG Cable Co. were used to measure the p_e. The center wavelengths of three FBG sensors are 1533.8*nm*, 1545.4*nm* and 1555.3*nm*. Fig. 2 is experimental setup.

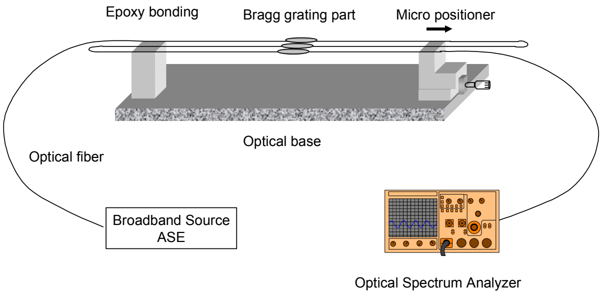


Fig. 2 Experimental setup for measuring p_e.

The same axial strain was carefully induced to three grating fibers of 1*m* length using micro positioner that can control displacement up to 0.01*mm*. The shifts of center wavelength due to the given strain were measured using optical spectrum analyzer with the resolution of 0.05*nm* wavelength. We used an amplified spontaneous emission(ASE) of an LD-pumped Erbium-doped fiber (EDF) as a broadband light source. Fig. 3 shows center wavelength shift vs. strain.

Photoelastic constant p_e calculated by these results differ in its value from the reference one[11]. The p_e of the fiber made by LG Cable Co. was 0.257. Therefore it is necessary to measure the value of p_e of the fiber used in the FBG strain sensing experiment.

Using above results the strain was measured in the present FBG sensor system.

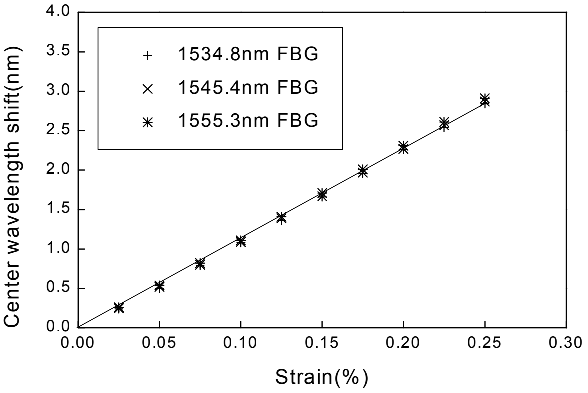


Fig. 3 Center wavelength shift vs. strain induced to optical fiber.

3. EXPERIMENTS

The experiment measuring two components of strain, longitudinal and transverse directions, of the laminated composite under tensile loading was carried out by FBG sensor system. The experimental system is shown schematically in Fig. 4.

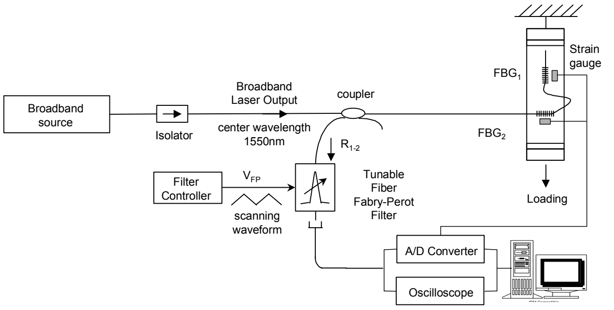


Fig. 4 Schematic diagram of the FBG sensor system.

The portable broadband source was an LD-pumped Er-doped fiber superfluorescent source with a 45*nm* bandwidth (1525~1570*nm*). Fig. 5 shows a constructed broadband source.

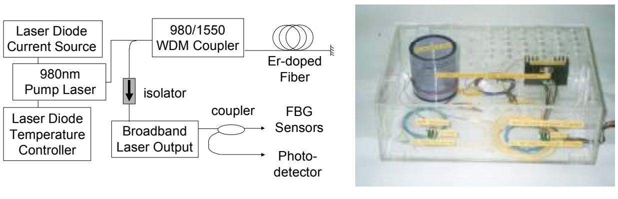


Fig. 5 Schematic diagram and photograph of broadband source.

The FBG_1 sensor with 1534.3*nm* center wavelength and the FBG_2 sensor with 1547.4*nm* center wavelength were attached to the composite laminate. Electrical strain gages(ESG) were also attached near the FBG sensors to compare strain measured by FBG sensors. CU-125 NS Gr/Ep prepreg (HFG Co., material properties : E_1=135.4GPa, E_2=E_3= 9.6GPa, G_{12}=G_{13}=G_{23}= 4.8GPa, ν_{12}=ν_{13}=0.31, ν_{23}=0.52) was used for test specimen. Configuration of the test specimen is shown in Fig. 6.

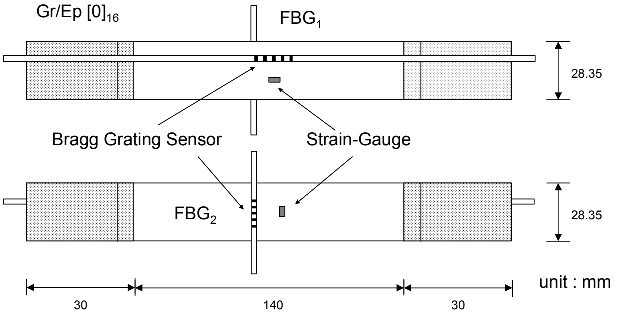


Fig. 6 Configuration of the tensile test specimen.

The scheme of the present FBG sensor system to detect the Bragg wavelength shift is based on Kersey *et al.*'s one[12]. This scheme is very efficient in multiplexing and tracking rapid shifts of wavelength shift. The reflected light from FBG1 and FBG2 passes through an electrically tunable fiber Fabry-Perot(FFP) filter with a FWHM of 0.3nm. The sensors are scanned by the tunable FFP with PZT that was driven with a ramp waveform. This excitation sweeps the filter's narrow pass-band through its 40nm Free Spectral Range(FSR). The detected optical signal by a tunable FFP filter and a ramp waveform voltage signal are shown in Fig. 7.

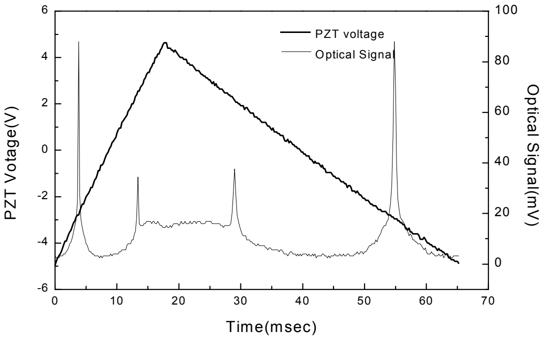


Fig. 7 Optical signal and PZT voltage to time.

The acquired data was processed and converted real-timely to strain using LabVIEW software from National Instruments. And the plots of the strain were displayed.

4. EXPERIMENTAL RESULTS

Fig. 8 shows the Bragg wavelength shifts of FBG sensors under tensile loading. The center wavelength of FBG_1 sensor shifted to long wavelength region and the center wavelength of FBG_2 sensor shifted to short wavelength region.

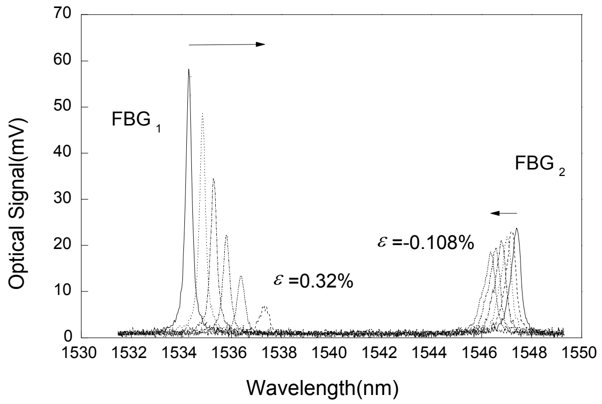
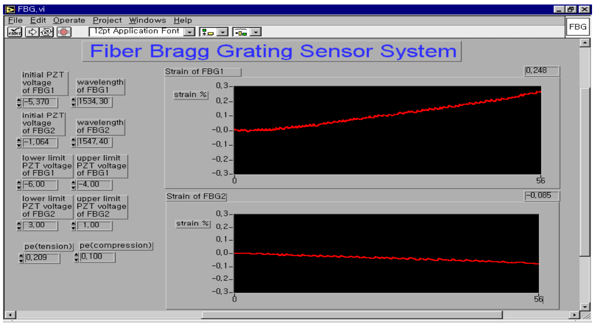


Fig. 8 Strain induced wavelength shift profiles of FBG sensors.

The intensity of reflected light of FBG sensors attached on the surface of the specimen was varied and the peak was broadened by strain increase.

These phenomena are caused from high local shear stresses at the fiber-specimen interface and the birefringence effect occurrence[13]. If sensor is embedded in the composite laminates, these intensity variations do not occur. When FBG sensor is attached to the structures, we must consider these phenomena.

Fig. 9 shows real-time strain monitoring display. This window displayed plots of strain history for two FBG sensors. The user was able to use optionally more plots of the FBG sensors with any Bragg center wavelength. And these plots were simultaneously saved on the hard drive of PC.



initial PZT voltage of FBG1: -5.370
wavelength of FBG1: 1534.30
initial PZT voltage of FBG2: -1.064
wavelength of FBG2: 1547.40
lower limit PZT voltage of FBG1: -6.00
upper limit PZT voltage of FBG1: -4.00
lower limit PZT voltage of FBG2: -3.00
upper limit PZT voltage of FBG2: -1.00
pe(tension): 0.209
pe(compression): 0.100
Strain of FBG1: 0.248
Strain of FBG2: -0.085

Fig. 9 Real-time strain monitoring display.

Fig. 10 shows strain histories by the FBG sensor and ESG under the tensile loading. The transverse strain measured by FBG2 sensor had one third value to the longitudinal strain measured by FBG1 sensor. This result corresponds to poisson's ratio of the specimen. The strain measured by the FBG sensor was in good agreement with that by the ESG. As discussed above, a little error is caused from peak broadening from birefringence effect.

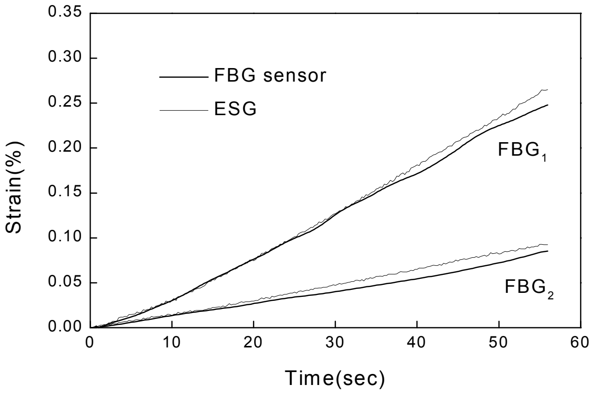


Fig. 10 Comparison of strain measured by FBG sensors and ESG.

5. CONCLUSIONS

The strain of the laminated composites under tensile loading was real-timely measured by the constructed FBG sensor system. The measured strain by the FBG sensor system was in good agreement with that by the ESG.

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