The Progress of Smart Structures Using Fiber Optic Sensors in Korea

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ABSTRACT

This paper summarizes briefly the research activities on smart materials and structures technology using fiber optic sensors (FOS) in Korea. The smart material/structural system, as an interdisciplinary discipline, is somewhat in its infancy and recently attracts some attention of mechanical and aerospace engineering research groups in Korea. About 10 research groups are active in fiber optics and smart structures. This paper presents some results of fiber optic sensors that are currently under investigation in Korea.

INTRODUCTION

The technology of smart materials and structures is highly interdisciplinary in its nature. Smart materials and structural systems may be constructed by one or the combination of optical fiber sensor, piezoelectric film, shape memory alloy, and electro-rheological fluid. Physicists have studied fiber optics and the optical fiber is manufactured mainly for tele-communications in Korea. Recently, the accumulated knowledge on fiber optics made the application to smart structures possible. Current research fields on smart structures using FOS are as follows:

- Real time health monitoring of infrastructures such as bridges and buildings
- Damage detection, real time monitoring and curing monitoring of composite structures
- Sensor development such as intrinsic Fabry-Perot sensor, extrinsic Fabry-Perot sensor, fiber bragg grating sensor, etc

Fiber optic sensors are one of the promising sensor technologies for applications in smart materials and structures. One of the advantages of optical fiber sensors is easy to embed within composite structures (or concrete structures) to provide in-situ measurements of composite cure (or concrete cure) as well as health monitoring during the service of structures. Some research organizations, which devote to the investigation of smart material/structure systems in Korea, are as follows:

- Research institutes:
  Ssangyong Cement Industrial Co., Korean Air, KIST
- Educational institutes:
  KAIST, POSTECH, Inha University

1. *Research institutes*

Ssangyong Cement Industrial Co.

The safety diagnosis of a bridge was done using the FOS and comparative sensors. They performed the visual inspection first, then chose three spans for the system identification of the bridge. They applied a number of strain gages, acceleration sensors and deflection gages as well as intrinsic Fabry-Perot sensors (IFPI). Static and dynamic loads were applied to the bridge with 30-ton weigh trucks. The fiber optic sensor system showed good responses to the static and dynamic loading with a resolution of approximately 0.12 $\mu\varepsilon$. The fiber optic sensors can be used as elements of bridge monitoring system.

Korean Air

Fiber bragg grating (FBG) sensor technology based on wavelength division multiplexing (WDM) topology appears to be ideally suited for structural health monitoring of composite materials and civil engineering applications as they have the potential of offering many distinct advantages over conventional electrical sensors. FBG sensor is known to be very promising one to realize multiplexing. The Korean Air research center executed cure monitoring of composite structures using FBG sensor in cooperation with UTRC (United Technology Research Center).

Korea Institute of Science and Technology (KIST)

The Photonics Research Center at the Division of Electronics and Information Technology fabricated FBG sensors using the in-house facilities. They can design and fabricate various FBG sensors for diverse uses. For example, they made polarization-maintaining FBG sensor to detect pressure and dual-wavelength FBG sensor to detect strain and temperature independently.

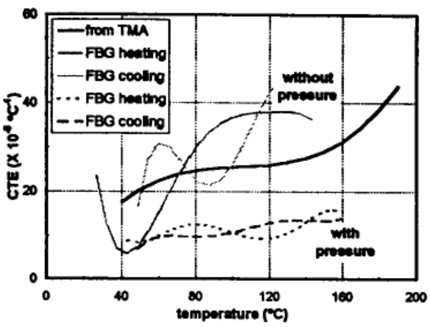

Figure 1. Calculation of CTE using FBG sensor (Korean Air)

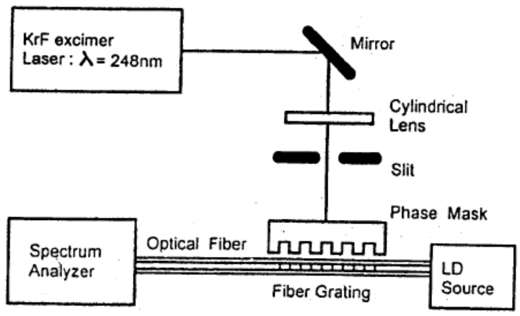

Figure 2. Schematic diagram of fabrication of FBG sensor (KIST)

2. *Educational institutes*

Researches in POSTECH on smart structures are mainly devoted to active control of structures using piezoelectric materials and fiber optic smart structures are started very recently

The Researches on smart structures using FOS at KAIST have been performed mainly in Department of Aerospace Engineering and Department of Mechanical Engineering. KAIST has strong research groups in fiber optics and optical fiber communication in Department physics and Department of Electronics. The progress of the performed researches on the fiber optic smart structures at KAIST is as follows:

- Evaluations of the mechanical behavior of structures with embedded optical fibers
- Quasi-Static load

- Michelson interferometer
- Extrinsic Fabry-Perot interferometer (EFPI)

- Dynamic load
  - The 3x3 passive demodulated fiber Michelson interferometer
  - Phase shifted EFPI by two probes
- Data Processing
- Failure Detection of composite structures
  - Simultaneous sensing of the strain and failure
  - Detection of matrix cracking
  - Low velocity impact characteristics
  - Detection of buckling load and crack growth
- Real-time Monitoring

Researches on the smart composites with embedded optical fiber sensors are being actively performed because they have several advantages over other type of sensors. But, the embedded optical fiber sensors may deteriorate the mechanical properties of composite structures. The effects of embedded optical fiber sensors on mechanical properties of composite structures were investigated. Though the embedded optical fiber sensors introduce geometrical discontinuity and stress concentration, they do not affect significantly on the mechanical properties of structures such as stiffness, strength and Poisson's ratio or the formation and growth of matrix cracks under static loads like tension or compression. The effect of FOS on the damage size and growth behavior due to low velocity impact and the interlaminar fracture toughness at the plane that the optical fibers are embedded is also not significant. As shown in Figure 3 and 4, the fatigue life of unidirectional laminates does not show remarkable reduction by the embedding of the optical fiber sensors, but that of cross ply laminates may reduce seriously. The fatigue limit of embedded optical fiber sensors themselves is much lower than that of laminates in which they are embedded. Therefore, in order to ensure the structural and sensorial integrity of smart structures embedded optical fiber sensors, their fatigue behavior must be considered in their design and manufacturing. Using the fracture characteristics of embedded optical fiber sensors, the kind and extent of damage can be predicted.

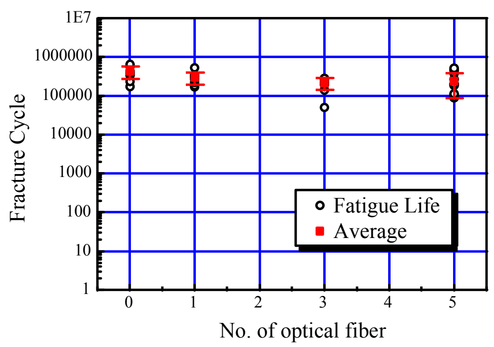

Figure 3. The fatigue life for unidirectional specimens

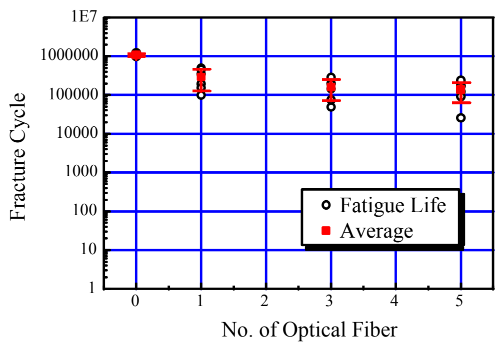

Figure 4. The fatigue life for cross ply specimens

As the first step in the application of the optical fiber sensor (FOS) to composite structures, strain was measured for a composite beam under uniaxial tensile loading. Michelson interferometer and EFPI were used as FOS. The fiber optic Michelson interferometer and EFPI were embedded in the graphite/epoxy laminates.

Under the quasi-static loading, strains measured by Michelson sensor and EFPI showed good agreement with those by the electrical strain gage (ESG). The signals of EFPI sensor were compared with those of Michelson interferometer. For the EFPI sensor, the method to distinguish the loading directions using the envelope of the interferometric fringe in the quasi-static state was proposed. Since the fiber optic interferometric sensor has the 2π ambiguity, it is necessary more information that is needed to decide the loading direction. The 3x3 passive demodulated Michelson sensor and the phase-shifted EFPI having the two probes can overcome this limitation by giving the information of change in loading direction through appropriate signal processing. The result of Michelson sensor with the passive demodulated technique is shown in Figure 5. Also, the research by the phase-shifted EFPI was performed to solve these problems. The experimental results of the phase-shifted EFPI are shown in Figure 6[1].

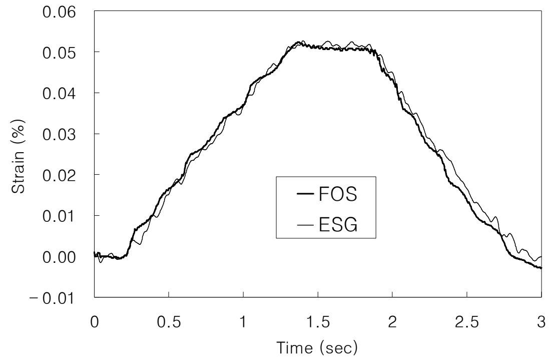

Figure 5. Result of the 3x3 passive demodulated Michelson interferometer

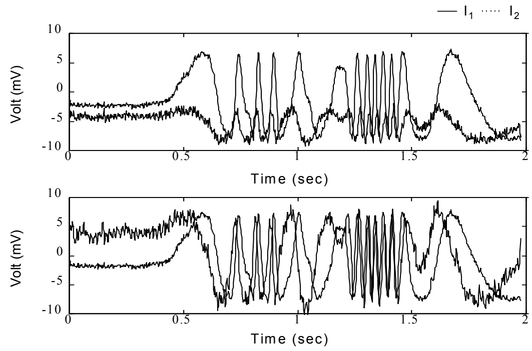

Figure 6. Results of the phase-shifted EFPI

In the fiber optic interferometry, the signal processing is very important to quantitative the FOS signal. Using the proper filter set, the strain and failure instants in composite beam were simultaneously sensed[2].

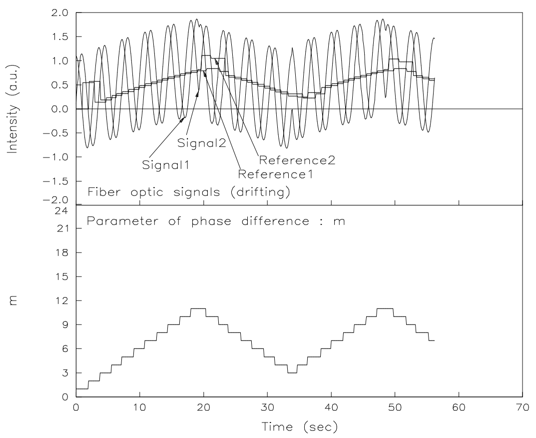

Figure 7. Modified reference moving method in Michelson sensor

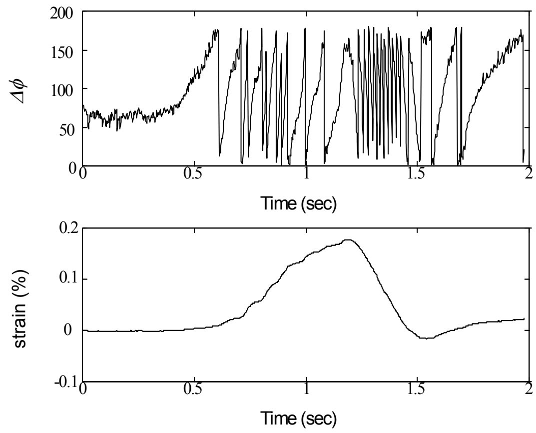

Figure 8. Results processed by arc-tangent method

In the case of the Michelson sensor, demodulation is difficult since the beating and drifting of signal were caused by the change of polarization axis in the sensing part. The method was suggested to overcome these disadvantages through the adaptive tracking of the moving mean value of the light intensity envelope (Figure 7)[2]. In the passive demodulation of FOS signal, the arc-tangent method and phase-unwrapping technique[1] were used. In Figure 8, $\Delta\phi$ is $\tan^{-1}(I_1/I_2)$ where I_1 and I_2 are the intensities of two probes of the phase-shifed EFPI.

The most frequently encountered first ply failure mode in laminated composites is the matrix cracking. Matrix cracks can be detrimental to the structural reliability and durability of laminated composites. Recently, the fiber optic sensors are studied to detect matrix cracking. An optical fiber sensor based on the Michelson interferometer was embedded into a composite laminated specimen and loaded to detect AE (acoustic emission) signal due to matrix. The captured FOS signal was AE signal due to the matrix cracking under tensile loading by cross-ply laminated composites, which was confirmed by the edge-replica method. Figure 9 shows the AE signal detected by the optical fiber sensor and the power spectrum of the original signal. In the frequency analysis of AE signal for matrix cracking, the signal spans up to 120 kHz in frequency [3]. The survivability of optical fiber sensors was examined experimentally. The experiment showed that it was advantageous to embed an optical fiber in the direction of the reinforcing fibers of the composite laminates to protect the optical fiber from matrix cracks of various types. Also, the effects of the embedded direction of the optical fiber were investigated [3].

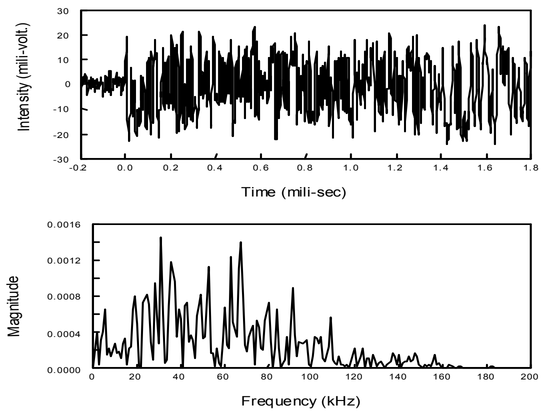

Figure 9. AE signal and power spectrum detected by FOS

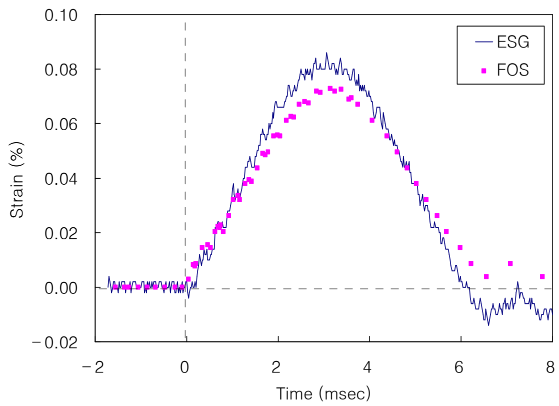

Figure 10. Transient response of FOS and ESG subject to the low-velocity impact

Low-velocity impact is one of the important issues in composite structures. The mechanical behavior of composite panel with embedded FOS was investigated under impact loading. The embedding location of FOS was decided using the finite element analysis. The composite laminated specimen had an ESG on the surface and FOS located 2 layers away from the mid plane. The two signals from ESG and FOS agree well each other and compared in Figure 10, in which the FOS signal was linearly extrapolated to the surface strain[4].

Delamination is the critical failure mode for a laminated structure under compressive loading. Delamination reduces the overall structural performance of composite laminates such as stiffness, strength, and buckling load. So, it is necessary to identify the delamination failure of 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. The signals of FOS were analyzed for the whole span of loading up to failure. When the delaminated specimen buckles, the frequency of the FOS signal suddenly changes due to abrupt growth in out-of-plane deformation. And also when the delamination crack grows, the characteristics of FOS signal and data aliasing caused by the sampling time were investigated (Figure 11)[5].

Recently, a great attention has been paid to the fiber optic sensor, as the monitoring of structural health becomes important. The structural strains due to external loading have to be measured to monitor the structural health. For this purpose, the real-time system that can sense deformation of structures immediately is essential. The real-time strain measurement system was constructed with a 3x3 passive fiber optic Michelson interferometric sensor and a signal processing program was user-friendly written in Visual Basic. The signal-processing program converts the signal of FOS to the strain in real time. For the validation of the signal processing program, it was performed the off-line simulation that compared the strain by FOS with that by ESG subjected to the tensile loading/unloading.

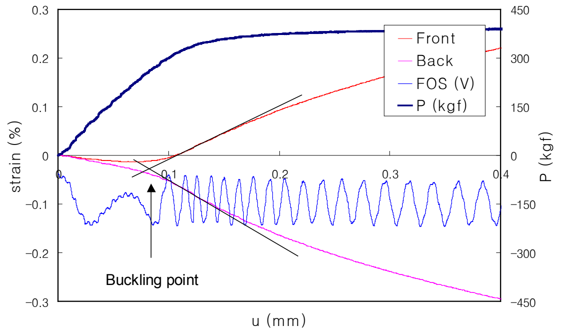

Figure 11. Signals of ESG, load cell and FOS when specimen was buckled

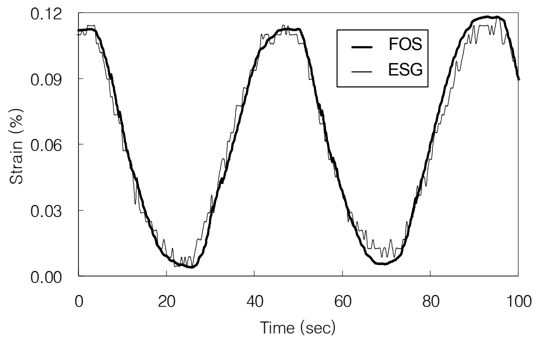

Figure 12. Real-time monitoring of the structural strain subject to the dynamic load

Figure 12 shows the result measured by the real-time monitoring strain measurement system using FOS subject to the dynamic compression-compression load. Since the real-time strain measurement system could successfully detect the structural dynamic strain, it can be used to measure the strain of a structure subjected to general loads in real situations[6].

REMARKS

In this paper, researches on smart structures using FOS in Korea have been briefly summarized. Researches on smart structures using FOS are getting active and great attention. Many topics, such as failure detection of composite structures and evaluations of the mechanical properties of structure with embedded FOS, curing monitoring of composite, health monitoring of infrastructures and so on, have been studied in the various organizations in Korea. FOS systems based on the basic researches are being gradually applied to the real structures such as infrastructures, composite wing parts of an airplane.

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