A CHALLENGE FOR STRUCTURAL HEALTH MONITORING USING FIBER OPTIC SENSOR

- Simultaneous Measurement and Monitoring of Smart Composite Structures Using Fiber Optic Sensor System

Chang-Sun Hong

President, Korea Advanced Institute of Science and Technology 373-1, Kuseong-dong, Yuseong-gu, Daejeon, 305-701, Korea

ABSTRACT

Fiber optic sensors are the key elements for structural health monitoring. In this paper, fiber optic sensors are introduced and the trend of the sensor technology is reviewed. Especially, the health monitoring of composites using the fiber optic sensors is focused through the reviews of several cases of applications. Finally, it shows that the fiber sensor technology is useful and prospective through the several applications of real structures.

INTRODUCTION

Most of the conventional damage-assessment and nondestructive inspection methods are time-consuming and they are often difficult to implement on hard-to-reach-parts of the structure. For these reasons, built-in assessment system must be developed to monitor constantly the structural integrity of critical components. Measuring structural response in the form of strains and deflections is of great interest. Recently, fiber optic sensors have been introduced into many structures, especially composite structures [1,2]. Fiber optic sensors have shown a potential to serve real time health monitoring of the structures because of many advantages such as ease of embedding, flexibility of sensor size, high sensitivity, wide temperature range, multiplexing and etc. Of many fiber optic sensors, the strain measurement using FBG (Fiber Bragg Grating) sensors based on WDM (wavelength division multiplexing) technology are attracting considerable research interest and appears to be ideally suitable for structural health monitoring of smart composite structures. FBG sensors can be easily multiplexed and has many advantages such as linear response, absolute measurement, etc. As the spectral response of the FBG sensor signal renders the measurement free from intensity fluctuations, it guarantees reproducible measurements despite optical losses due to bending or connectors.

The research fields covered in this paper using fiber optic sensors are as follows: strain monitoring of smart wing box and filament wound composite tank, cure monitoring of smart composites, simultaneous monitoring of smart composites and damage detection systems for smart composites. Several kinds of sensor systems were developed and verified through the above monitoring tests.
Especially, we constructed an improved FBG sensor system using a WSFL and a signal-processing board with an electrical circuit for the test. In order to monitor the structural strain real-timely, the signal-processing program was also constructed using LabVIEW® software for storage and visualization of the data. Experiments showed that the constructed FBG sensor system and the real-time signal-processing program could successfully execute several monitoring tests. It was successfully demonstrated that the constructed FBG sensor system could be useful one for the large structures that require a large number of sensor arrays. Additionally, a fiber Fabry-Perot interferometric sensor system was also improved to detect acoustic emission fracture signals without a fade-out problem.

**FIBER OPTIC SENSOR (FOS)**

Fiber optic sensors can be classified into various types. For the classification of fiber optic sensors, several criteria can be applied. In this section, three categories are adopted for the classification; sensing region, light media of sensing part and modulation principle.

Regarding the size of sensing region, fiber optic sensors are divided into point-, quasi-distributed- and distributed-types. The point type fiber optic sensor can be used as conventional strain and temperature gauges with superior performance compared with conventional gages. Quasi-distributed-types are also possible to be composed by multiplexing fiber optic sensors of the point-types. Otherwise, a long optical fiber itself becomes a sensing part in case of the distributed-type such as OTDR (optical time domain reflectometry).

Fiber optic sensors can also be assorted into intrinsic and extrinsic sensors depending upon light media of the sensing part of the optical fiber. In case of the intrinsic sensor, the sensing takes place within the optical fiber itself, but in a zone outside the fiber for the extrinsic sensor. The medium of sensing part in the extrinsic sensor is different from that of the optical fiber of light transmission. Figure 1 shows the difference between extrinsic and intrinsic sensors.

![Figure 1. extrinsic and intrinsic fiber optics sensors](image)

Finally, fiber optic sensors can be categorized by the measurement parameters and principles. Among these parameters, strain and acoustic emission play an important roles in structural health monitoring. FBG, FFPI (fiber Fabry-Perot interferometer), OTDR and BOTDA (Brillouin optical time domain analysis) sensors are mainly used for strain and damage monitoring.

Moreover, the technology and the applications of fiber optic sensors have grown up rapidly. From the
expansion of product lines, the optical components of the fiber optic sensor system get cheaper and the quality of the key components become higher. As a result, the market share of fiber optic sensors is also enlarged. Figure 2 shows the trend of fiber optic sensor technology [3].

![Figure 2. Trend of fiber optic sensor technology](image)

**HEALTH MONITORING OF COMPOSITES USING FOS**

**Strain Monitoring of Smart Wing Box**

Advanced composites are being extensively used for aerospace structures due to the high stiffness to weight and high strength to weight ratios. The stiffened wing boxes made of composite materials can be applied to aircraft fuselage or wing structure. As a practical application of aircraft structures, the composite wing box composed of two spars, four stiffeners, and two skins was fabricated [4]. Both the ends of the wing box were designed for clamping. Both the spars and the skins had the same stacking sequences of [0/90/±45]s, and stiffeners had the stacking sequence of [0/90/45/0/−45]s. The upper skin and two I-stiffeners were cured as one part. The lower skin and two I-stiffeners constituted the other part. These two co-cured stiffened skins were then secondary bonded by adhesive film with two spars. Total 24 FBG sensors were embedded in the composite wing box. FBG_A, FBG_B, and FBG_D lines were embedded in the upper skin, while, FBG_C line was embedded in the front spar. Figure 3 shows notation and location of the embedded FBG sensors. The selection of location of sensors was determined using the analytic results by the general-purpose finite element code, ABAQUS. The local buckling points of severe strain change were selected as the sensing points under bending load. A load cell was attached to the loading end. Electrical strain gages (ESG) were bonded on the surface of the
wing box in order to compare the measured strain with that by FBG sensors. A LVDT (Linear Variable Differential Transformer) was used to measure vertical displacement.

![Figure 3. Location and notation of FBG sensors](image)

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![Figure 4. Strains measured by FBG sensors – Line B and C](image)

Figure 4. Strains measured by FBG sensors – Line B and C

Strain vs. time curves by FBG sensors are shown in Figure 4. In the sensor line B and C, pop-in (knee-point) phenomena were definitely observed at 920 seconds after the start of constant rate loading. These were caused by transient strain-release due to the failure of spar that plays a role of bearing the most of bending load. For the sensor lines A and D that were relatively far apart from the spar, strain-release effect from the spar was weakly propagated. The strains measured by FBG sensors were compared with strains by ESG and analytical results. At the previous strain vs. time curves, strain curves of FBGB and FBGC definitely branched into two paths. As a result, we were successfully able to measure the internal strains and determine the buckling point of the wing box using FBG sensors embedded in the wing box.

**Strain Monitoring of Filament Wound Composite Tank**

The use of filament wound composite tanks is increasingly prevalent because of high specific strength and specific stiffness over their metal counterparts, as well as excellent corrosion and fatigue resistance. Filament wound composite tanks are finding their use in the applications such as fuel tanks,
pressure tanks, and motor cases of aerospace structures. Figure 5 shows the experimental setup of filament wound composite tank, which is to be used as the 3rd stage kick motor case of a 3-stage Korea Sounding Rocket (KSR) [5]. The composite tank was fabricated through a dry winding process using tow prepreg. The tow prepreg is the composite prepreg tape with wide bandwidth of 8.5mm in helical direction and 9.0mm in hoop direction. The dome parts consist of 12 layers (helical winding layers) with ±22° winding angle and the cylinder part are made of helical layers and several hoop layers(90°) inserted between the helical layers. The helical winding layer is 0.198 mm thick per 2 layers (+22°/−22°) and the hoop winding layer is 0.168 mm thick per single layer. The 1st skirt and 2nd skirt have [±30°/90°/±30°/90°], and [90°/±15°/90°/±15°/90°] lay-up, respectively.

![Figure 5. Experimental set-up.](image1.png)

![Figure 6. Strain results measured by FBG and ESG.](image2.png)

Twenty FBG sensors were attached on the domes and cylinder part of the filament wound composite tank to measure the strains in real time during hydrostatic pressurization (intervals of 100 psi up to 1000 psi).

The data from the FBG sensors, strain gauges and a pressure transducer were acquired and processed by computers in real time and displayed by a signal-processing program written in LabVIEW® software.

As shown in Figure 6, FBG sensors attached on the cylinder and the skirt showed close agreement with strain gauges, while the agreement of the two types of sensors on domes was not good. Since the peak splittings of some FBG sensor signals during pressurization made the strain measurement impossible, the compensatory manufacturing methods of the sensor heads are needed to prevent the peak splitting of the FBG sensor signal. From the experiment, it was successfully demonstrated that the FBG sensor system could be useful for the strain monitoring of large structures that require a large number of sensor arrays.

**Cure Monitoring of Smart Composites**

Fabrication strains during cure can lead to warpage or spring-back, which presents difficulties in the assembly of composite structures and residual stresses due to differences of thermal expansion
coefficients between fiber and matrix in cooling stage can have intense effects on the mechanical properties of the composite product. The quality of the final composite part is directly affected by cure time, temperature and pressure. The knowledge of cure process is very helpful to obtain high quality composites at reduced producing cost. Therefore, sensors capable of monitoring the cure process are desired and fiber optic sensors are the good candidates for cure monitoring of composite materials.

![Experimental setup for cure monitoring.](image)

Fig. 7. Experimental setup for cure monitoring.

In this paper, we presented the simultaneous monitoring of the fabrication strain and temperature during the composite cure process by using fiber optic sensors. Fiber Bragg grating/extrinsic Fabry-Perot interferometric (FBG/EFPI) hybrid sensors were used to monitor those measurands. The characteristic equation matrix of the sensor was analytically derived and measurements could be done without sensor calibration for each experiment. A wavelength-swept fiber laser was utilized as a light source. FBG/EFPI sensors were embedded in graphite/epoxy composite laminates at different direction and location. We performed the real time monitoring of fabrication strains and temperatures at two points of composite laminates during cure process in an autoclave. Through this experiment, we were able to provide a basis for the efficient smart processing of composites.

![Strain and temperature measurements in the [012/012]T laminate.](image)

Fig. 8. Strain and temperature measurements in the [012/012]T laminate.
Simultaneous Monitoring of Smart Composites

To perform the real-time health monitoring of the smart composite structures, two fiber optic sensor systems are proposed, which can measure the strain and detect the moment of fracture simultaneously. The two types of the coherent sources were used for the detection of fracture signals – EDFA (Erbium Doped Fiber Amplifier) with FBG and EDFA with Fabry-Perot filter. These sources were coupled to EFPI sensors embedded in composite specimens to monitor the fracture behavior of composites.

![Diagram](image)

**Figure 9.** Fiber optic sensor system for strain and fracture monitoring

In order to understand the characteristics of matrix cracking signals, we performed tensile tests using surface attached PZT sensors. This paper describes the implementation of time-frequency analysis such as short time Fourier-transform (STFT) for the quantitative evaluation of the fracture signals like matrix cracking.

![Graph](image)

(a) AE signal  (a) Strains measured by ESG and FOS

**Figure 10.** AE fractural signal and strain measured by FOS

From the test of tensile load monitoring using fiber optic sensor systems, the measured strain agreed well with the value of electric strain gage and the fracture detection system could find out the moment of damage with high sensitivity to recognize the onset of micro-crack fracture signals.
Damage Detection Systems for Smart Composites Using EFPI

The acoustic emission (AE) fractural signal could be produced under dynamic loading and the external temperature changing as the cavity length changes continuously. The effect of temperature or quasi-static strain produces phase shifts much greater than $\pi$. Therefore, the EFPI sensor will not remain in quadrature point and the sensitivity in the interferometer will also vary as a sinusoidal function. As a result, one of the basis issues with the interferometer is the compensating demodulation technique to maintain the sensitivity at the quadrature point. We developed a stabilization control sensor system that is composed of an EDFA (erbium-doped fiber amplifier) source, a F-P (Fabry-Perot) tunable filter and a control-circuit board as shown in Figure 11. The circuit board was developed to control the FP tunable filter through which the proper wavelength can pass.

![Stabilization control system](image)

Figure 11. Closed-loop stabilization control system to compensate the phase shift by controlling the Fabry-Perot tunable filter

As an application of the FOS sensor system, we performed the fracture test of the composite specimen on which an EFPI was attached in order to detect AE signals induced by several fracture modes such as matrix cracks, debondings and fiber breakages. As a result, most AE signals were successfully detected in spite of the presence of applied low frequency strains by using the stabilization control system as shown in Figure 12.

![Stress-strain curve](image)

Figure 12. A stress-strain curve of the composite specimen Gr/Ep [03/903], and an accumulated event curve and acoustic emission signal detected at crack initiation point.
APPLICATION OF FOS TO REAL STRUCTURES

As the FOS technology has grown up and several commercial products have been developed very well, many applications have been carried out in several fields of infrastructures, airplanes, automobiles, etc. In this section, we will introduce several applications of FOS systems to real structures performed in Korea.

The first application is the monitoring of Nam-Hae suspension bridge using FBG sensors. This structure has three parts separated by two main towers. It had been constructed by HYUNDAI Inc. (Korea) in 1973. When this bridge was reinforced in 1999, S. B. Lee et al. (Korea Institute of Science and Technology) applied FBG sensor system to the 400m long main span of the bridge at 8 points to test the reliability of that work. In the sensor system EDFA was used as a broadband light source. Light emitted from EDFA was incident to temperature compensated FBG array through a circulator. The performance of this system depends on the line resolution and scanning speed of the wavelength variable filter. In addition, this system has $\pm 2 \mu \varepsilon$ error rate.

The second is a vehicle monitoring system in a driver’s license examination office. This system was developed by ICES Inc. (Korea) and it was simply composed of a microbend optical fiber sensor. It showed that the FOS system was better than traditional air switch and road tube because of reducing the error from the background temperature through the actual test.

As a last application, I. B. Kwon et al. (Korea Research Institute of Standards and Science) developed fiber optic BOTDA (Brillouin Optical Time Domain Analysis) sensor system to be able to detect an intrusion effect through several kilometer optical fiber. Fiber optic BOTDA sensor was constructed with one laser diode and two electro-optic modulators. The intrusion detection experiment was performed by the strain inducing effect. In the result of this experiment, the intrusion effect was well detected as the distance resolution of 3m through the fiber length of about 4.81km during 1.5 seconds.

In these days, many other engineers and researchers are also willing to apply FOS systems to several other real structures. Therefore, FOS systems will be popular and prospective as sensor systems for the health monitoring of every kind of structures.

COMMERCIAL PRODUCTS OF FOS SYSTEMS

The market volume of fiber optic sensors was US$305 million in 1997 and is supposed to rise to US$550 million in 2002 [6]. The growth rate is to rise from 10% to about 15%. The US share that is dominating the world market for fiber optic sensors declined from 60%~70% in the late 1980s to 43% in 1997. The market shares of Europe and Asia have grown to 25% each and this trend is expected to continue over the next few years [6]. For the commercialized product of FBG sensor system, several US and European companies such as MICRON OPTICS Inc. and AOS Inc. have introduced some FBG interrogation systems having the precision of 1-μstrain resolution. In Korea, FIBERPRO Inc. has produced commercialized FBG sensor system, IS7000, through the industry-university cooperation.
program with KAIST. Different from other products, this FBG system uses WSFL (wavelength swept fiber laser) broadband light source. Compared to other light sources such as EDFA and SLD, it provides relatively high signal powers and flattened source profile, since the full source output is available by scanning the high power fiber laser.

CONCLUSIONS

In this paper, fiber optic sensors were introduced and classified into several categories. Then the trend of the sensor technology was reviewed. The health monitoring of composites using the fiber optic sensors was particularly focused through the reviews of several cases of applications, such as strain-monitoring of a smart wing box and a filament wound composite tank, cure monitoring and damage detection of composites, etc. Moreover, it shows that the fiber optic sensor technology is useful and prospective through the several applications into real structures. As a result, fiber optic sensor is a key technology for a structural health monitoring.

REFERENCES


