Recent development of optical fiber sensor based structural health monitoring and in-process monitoring of CFRP structures in Japan

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Abstract

Optical fiber sensors are very useful to monitor the internal strain and temperature during manufacturing as well as in practical operations exposed to external loads. The authors have been using both multi-point and distributed strain monitoring techniques to characterize the structural integrity and quality control of advanced composite structures. This presentation first covers optical fiber based structural health monitoring (SHM) technologies for aircraft composite structures being conducted these ten years in Japan as national and international projects. Then, some recent developments on process and life-cycle monitoring (LCM) are presented as a promising method for intrinsic quality control of advanced composite structures with embedded optical fiber sensor systems.

1. Introduction

Structural health monitoring (SHM) technologies have been studied extensively in order to assess the safety and the durability of the structures [1]. In addition, for weight saving of airplanes, carbon fiber-reinforced plastic (CFRP) laminates are extensively being used for the primary structures. However, the maintenance cost of the structures may increase because of the complicated fracture process of the CFRP laminates. A new technological innovation to reduce the maintenance cost is a health monitoring or management system. At present, optical fiber sensors (OFSs) are most promising among all [2, 3]. This is because optical fibers have enough flexibility, strength, and heat resistance to be embedded easily into composite laminates. Furthermore, OFSs have some advantages when compared with previous sensors, such as immunity to electromagnetic interference and multiplexing capability. Among various types of OFSs, we have used multi-point fiber Bragg grating (FBG) sensors and distributed OFS, which seem most suitable for SHM of aerospace composite structures. Then, some recent developments on process and life-cycle monitoring (LCM) are presented as a promising method for intrinsic quality control of advanced composite structures with embedded optical fiber sensor systems.

2. Current status of ACS-SIDE project

2.1 Introduction

This chapter describes a summary of current status of the Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures (ACS-SIDE) project in Japan managed by Research Institute of Metals and Composites for Future Industries
(RIMCOF) and funded by Ministry of Economy, Trade, and Industries (METI), Japan. The main goal of this project is to establish the following four SHM technologies for prototype applications in advanced aircraft composite structures: (a) an impact damage detection system of composite structures (Kawasaki Heavy Industries), (b) a PZT (lead-zirconium-titanate)/FBG hybrid sensing system for bond-line monitoring in CFRP box structures (SUBARU Corporation), (c) distributed strain sensing using the Brillouin optical correlation domain analysis (BOCDA) (Mitsubishi Heavy Industries). These systems (Fig. 1) are highly demanded to assure the safety and reliability of advanced composite structures and to reduce the maintenance cost as well.

Figure 1. Overview of ACS-SIDE project.

Figure 2. Impact detection system.
2.2 Impact damage detection system of composite structures

Development of real-time detection of impact damage with embedded small-diameter OFSs has been conducted. The principle of the impact detection system is summarized in Fig. 2. Recent results on blunt object impact are summarized in Fig. 3.

![Blunt object impact detection](image)

Figure 3. Blunt object impact test and results.

2.3 PTZ/FBG hybrid sensing system using Lamb waves

A hybrid sensing system with PZT actuators and FBG sensors has been developed. The main focus is laid on the bond-line monitoring (debonding at inaccessible bonded areas) in CFRP box structures. Such structures can be realized only with a reliable SHM system. Lamb waves generated by actuators can travel some distance and are influenced by damaged or debonded regions. Then, these Lamb waves are measured by a high-speed optical wavelength interrogation system using an arrayed waveguide grating (AWG) filter (Fig. 4). Figure 5 shows the latest results of flight verification tests.
In the flight test campaign with JAXA*, it was confirmed the following things.

- Ultrasonic Lamb waves can be measured during in-flight conditions as well as on ground conditions by the system installed in wing spar.
- Damage index derived from ultrasonic Lamb waves can tell us the damage occurrence.

The BOTDR is the most popular method of the distributed optical fiber sensing system to measure the strain distribution along an optical fiber, but the special resolution has been limited up to 1m long. The measurement along the whole optical fiber length took typically 20–30 min. Hotate et al. [4, 5] have been developing a novel distributed strain measurement technique called BOCDA, with high spatial resolution and dynamic

**Figure 5. Flight demonstration for hybrid sensing system.**

### 2.4 Distributed strain sensing Brillouin optical correlation domain analysis (BOCDA)

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**Figure 6. Overview of BOCDA system**
measurement capability. The development of a prototype BOCDA system has been conducted, which operates with 20mm spatial resolution and 15 Hz sampling speed. (Fig. 6) The high-speed sampling at a certain point in an optical fiber was also demonstrated during a flight test. The demonstration flight test was conducted to obtain in-flight data and to understand important problems for use in practical flight conditions. Figure 7 shows a building-block approach to demonstrate the validity of the system.

3. In-process measurement and numerical analysis of cure induced strain in curved composites

3.1 Introduction

This section demonstrates a fiber-optic-based sensing system to monitor the internal state of composite structures. Since this system can measure axial strain and temperature at an arbitrary point along the optical fiber, a limited number of optical fibers are sufficient to cover the whole structure. And an embedded fiber-optic network, formed during the lay-up process, can be used to monitor the internal state of a composite structure all through its life (Fig. 8). Despite these considerable researches over the past two decades, the experiments revealed several inconsistencies and uncertainties including the effects of thickness, geometry, boundary conditions and tool-part interaction. Therefore, fundamental mechanisms for spring-in are still unclear. It is partially because the previous researches mainly focused on the final cured shapes and internal state development during cure has not been measured. Thus, this research aims to propose an in-process strain monitoring technique and to investigate the mechanisms of residual deformation in complex shaped CFRPs based on the internal state and numerical results. Our previous study developed a direction-dependent strain measurement method using optical fiber sensors and proposed a research scheme based on the internal strain measurement [6, 7]. This approach is extended in the present work to capture the shear stain using optical fibers embedded in two diagonal directions.

Figure 7. BOCDA building-block approach for system validation.
Since the tool-part interaction complicates the mechanisms of residual deformation, the present work focused on the effect of cure induced chemical and thermal shrinkages by minimizing the effect of the tool-part interaction [8, 9].

3.2 Fiber-optic-based in-process strain monitoring

Fiber Bragg grating (FBG) are usually utilized to monitor the in-plane normal strain. However, the present study developed a new method to evaluate the through-thickness normal and shear strains using two FBG sensors embedded into the ±45° diagonal directions. The FBGs are cut near the grating areas to be inserted into the diagonal directions (Fig. 9). The distance between the edge and the grating of the FBG sensor is called tail length [5,6]. Note that the strains measured by the diagonally embedded sensors would be smaller than the strain induced in the CFRP due to the shear-lag effect near the end of the optical fiber especially when the resin modulus is low. The measured strain differential $\Delta \varepsilon$ is written as:

$$d\varepsilon = \alpha(C(t), l) \cdot d\varepsilon,$$

where $d\varepsilon$ is the strain differential in the composite in the sensor direction, $t$ is the time and $\alpha$ is the shear-lag coefficient that depends on the composite stiffness $C$ and tail length of the FBG sensor $l$. The shear-lag coefficient increases from 0 to 1 during cure with increasing composite stiffness $C$. Meanwhile, the composite strains induced in the ±45° diagonal directions are calculated by the inplane normal strain $\varepsilon_c$, and out-of-plane normal and shear strains, $\varepsilon_c^2$ and $\gamma_{12}$:

$$\varepsilon_c^{\pm45} = (\varepsilon_c^1 - \varepsilon_c^1 + \varepsilon_c^2) / 2 \equiv (-\gamma_{12} + \varepsilon_c^2) / 2$$

$$\varepsilon_c^{\pm45} = (\varepsilon_c^1 + \varepsilon_c^1 + \varepsilon_c^2) / 2 \equiv (\gamma_{12} + \varepsilon_c^2) / 2.$$
The in-plane strain $\varepsilon_{1}^c$ is assumed to be zero because a cross-ply layup was used in this research. Eqs. (1) and (2) lead to strain differentials measured by the $\pm 45^\circ$ sensors $d\varepsilon_{+45}$ and $d\varepsilon_{-45}$:

\[
\begin{align*}
    d\varepsilon_{+45} &= \alpha(C(t), l) \cdot (-d\gamma_{12} + d\varepsilon_{2}) / 2, \\
    d\varepsilon_{-45} &= \alpha(C(t), l) \cdot (d\gamma_{12} + d\varepsilon_{2}) / 2.
\end{align*}
\]

Eq. (3) leads to the following ratio.

\[
\frac{\dot{\varepsilon}_{+45}(t) - \dot{\varepsilon}_{-45}(t)}{\dot{\varepsilon}_{+45}(t) + \dot{\varepsilon}_{-45}(t)} \equiv -\frac{d\gamma_{12}(t)}{d\varepsilon_{2}(t)} = \frac{d\gamma_{12}(t)}{d\varepsilon_{2}(t)}
\]

where $\varepsilon'$ represents the time derivative of strain $\varepsilon$ and $\gamma'$ is defined as minus $\gamma$ (i.e., $-\gamma$). This ratio expresses the shear strain increment induced by a unit amount of through-thickness normal strain. Hence, the value is called shear/normal strain ratio. It should be noted that the ratio is independent of the shear-lag coefficient $\alpha$, showing that the composite internal state can be directly captured by the sensor responses. The shear/normal strain ratio is an indicator of cure induced state at a certain time. The present study evaluates the internal state development using the ratio.

![Schematic of embedment](image1)

**Figure 9. Two diagonally embedded FBG sensors.**

### 3.2 Mechanisms of shape distortion in complex-shaped parts and quality control

L-shaped CFRPs were fabricated and the internal strain (out-of-plane normal and shear strains) states were monitored using the proposed in-situ measurement. The monitoring results showed that the deformation changed from shear dominated to bending dominated as cure proceeded. Thickness was shown to affect internal states and also residual deformation as pointed out in the previous researches (Fig. 10).
Figure 10. Comparison of out-of-plane normal/shear strain ratios between thin and thick CFRP laminates.

Figure 11 compares the effect of thickness on the shear/normal strain ratio. The experiment result is well consistent with the numerical result without the edge constrains, confirming that the edge dams insignificantly affect internal strain states for each thickness. This technique was extended to more complex CFRP structures such as U-shaped parts and ply drop-off parts [8].

4. Conclusions

OFSs including FBG are promising as tools for SHM of aerospace composite structures, as found in this review. Some recent results in the current ACS-SIDE project were also presented on optical fiber-based SHM for some feasible applications in aerospace composite structures, which include (a) an impact damage detection system of composite structures, (b) PZT/FBG hybrid sensing system for bond-line monitoring in CFRP box structures, (c) distributed strain sensing using the Brillouin optical
correlation base analysis. These techniques are necessary to assure the safety and reliability of advanced composite structures and to reduce the maintenance cost as well for practical use. Further continuing efforts are necessary for implementing them in real aerospace composite structures. Moreover, some recent developments on process and life-cycle monitoring were presented as a promising method for intrinsic quality control of CFRP structures with embedded optical fiber sensor systems.

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