Towards Structural Integrity and Material Quality Assurance of Aerospace Composite Structures

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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. Three research efforts consist of (a) an impact damage detection system of composite structures, (b) a PZT/FBG hybrid sensing system for bond-line monitoring in CFRP box structures, and (c) distributed strain sensing using the Brillouin optical correlation domain analysis (BOCDA). 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.

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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 three 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.

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.

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.

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

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 stain measurement technique called BOCDA, with high spatial resolution and dynamic 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.

**Figure 4.** Hybrid sensing system for Lamb wave detection

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.

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

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* JAXA: Japan Aerospace eXploration Agency
3. In-process monitoring and quality assessment of CFRP structures

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.

3.2 In-Process Material Characterization Methodology

Reference [6] developed a fiber-optic-based technique for in-process characterization of direction-dependent cure-induced shrinkage in thermoset fiber-reinforced composites. A procedure was established to embed FBG sensors in composite out-of-plane directions and to measure key through-thickness chemical cure shrinkage directly under practical curing conditions (Figure 9, T700SC/2592). Cure-shrinkage strain measured by FBG depends on the sensor tail length, which is the distance from the FBG to the edge of the optical fiber. This is attributed to the shear-lag effect at the edge of the optical fiber, and the material parameters for simulation, i.e., transverse cure shrinkage strain and stiffness change during curing, can be determined using this phenomenon.

![Life cycle monitoring of CFRP structures](image)

**Figure 8.** Life cycle monitoring of CFRP structures

![Innovative Structural Concept](image)

**Figure 9.** (Left) Surface of specimen with through-thickness FBG sensor. (Right) Transversely anisotropic shrinkage of unidirectional carbon/epoxy induced due to tool-part interaction. Measurement under practical curing condition is possible with this approach [6].
Figure 10 presents a summary of the proposed process simulation scheme based on in-process material characterization [7]. In previous work, cure shrinkage strain was measured by several dilatometric techniques (e.g., capillary dilatometer, gravimetric method, rheometer, and TMA), and stiffness change during curing was characterized using dynamic mechanical analyzer (DMA) or estimated from resin properties determined experimentally or numerically. However, most of the approaches were based on either measurement at ambient pressure or indirect estimation and thus could not evaluate the material parameters for simulation under realistic curing conditions.

<table>
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<tr>
<th>Previous works</th>
<th>This study</th>
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<tr>
<td>Stress model</td>
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<tr>
<td>ILE model</td>
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<tr>
<td>(Time-consuming)</td>
<td>(Well-balanced)</td>
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<tr>
<td>PDC model</td>
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<td>(Low accuracy)</td>
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<tr>
<td>Strain</td>
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<td>Degree of cure : $\alpha$</td>
<td>Tail length</td>
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<td>(Measured by DSC)</td>
<td>Long tail FBG sensor</td>
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<td>Elastic modulus</td>
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<tr>
<td>Measured by DMA</td>
<td>Tail length</td>
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<tr>
<td>Degree of cure : $\alpha$</td>
<td>Short tail FBG sensor</td>
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<tr>
<td>(Measured by DSC)</td>
<td>Determining by Shear-lag</td>
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<td>FEA $\theta$ Exp.</td>
<td>Shape distortion</td>
</tr>
<tr>
<td>FEA $\theta$ Exp.</td>
<td>Shape + Internal strain</td>
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</tbody>
</table>

**Figure 10.** Summary of proposed scheme and comparison with previous approaches [7]

In contrast, the material parameters in the proposed scheme are simultaneously determined by in-situ measurement using two FBG sensors with different tail lengths. This curing condition is more realistic than the previous approaches and large thermal analysis tests using high cost machines are not necessary. Furthermore, the simulation can be validated by in-situ internal-strain measurement (Figure 11). Therefore the validation is more elaborate and precise than the previous approaches based on shape comparison.

**Figure 11.** Determined material parameters (transverse cure shrinkage strain and stiffness change) and comparison between experiments and numerical simulation [7].
3.3 Skin-Core Effects of Thick Thermoplastic Composites

The influence of cooling rate on the residual strain of the carbon fiber/polyphenylenesulfide (PPS) unidirectional laminates was studied [8]. Three different cooling rates (300 degree/min, 100 degree/min and 10 degree/min) were applied to simulate a wide range of cooling conditions. The degree of crystallization in PPS depends on the cooling rate and affects the residual strain which induces the skin-core effects of thick CFPPS (Figure 12). The through-the-thickness strain distribution is well reproduced by the process simulation scheme proposed in Section 3.1 and the corresponding stress can be predicted (Figure 13) [9].

![Figure 12. Effects of Cooling Rates on Residual Strain and Skin-Core Effects of Thick CFPPS](image)

3.4 Processing Optimization of Out-of-Autoclave CFRP for Residual Stress Reduction

Vacuum-bag-only curing is an attractive out-of-autoclave method as an alternative to conventional autoclave curing. Previous extensive researches provided great insight into void formation during the vacuum-bag-only method and these findings are reflected in current vacuum-bag-only cure cycles to minimize void content. Cure process can be further improved by taking into consideration cure-induced residual stress/strain. We proposed a residual stress/strain reduction method and evaluated its effectiveness using a commercially available vacuum-bag-only material by fiber-optic-based in-situ strain monitoring and tensile tests (Figure 14) [10]. First, cure process monitoring and tensile tests were conducted for the manufacturer’s recommended cure cycle. Cure process monitoring showed that the material vitrifies during post-cure temperature dwell. Furthermore, the tensile test revealed that the vacuum-bag-only material has lower strength than conventional autoclave materials, suggesting the

![Figure 13. In-plane transverse strain development at each FBG point during fast cooling condition obtained by validation experiment and simulation](image)
importance of the effect of cure-induced residual stress/strain. Then, different cure cycles were proposed based on the findings from the manufacturer’s recommended cure cycle tests and a cure kinetics model. In the proposed cycles, resin vitrifies at a lower temperature than the manufacturer’s recommended cure cycle, leading to reduced residual stress/strain. Cure process monitoring and tensile test results for the new cycles showed that the residual strain was reduced by 12–18%, and the strength was increased by 26% in the best case (Figure 15). Moreover, void content was not significantly affected by changing the cure cycle.

![Figure 14. Proposed modified cycle for OoA prepregs](image1)

![Figure 15. Reduction of Residual Strain by Modified Cure Cycle and Transverse Cracks](image2)

### 3.5 Mechanisms of Shape Distortion in Complex-Shaped Parts and Quality Control

Residual deformation is induced in complex shaped CFRP laminates and causes residual stress and shape distortion after assembly or troublesome shimming. However, there still exit uncertainties including effects of thickness, boundary conditions and geometry, making the mechanisms unclear.

An in-situ strain monitoring method was proposed using two diagonally embedded FBG sensors (Figure 16) [11]. The method captures shear strain that was not measured by the conventional FBG technique. Then, 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 (Figure 17). The monitoring results showed that the deformation changed from shear dominated to bending dominated as cure proceeded. FEA was also carried out and revealed that the edge dams used to suppress resin flow insignificantly affect the internal strain condition. This is not obtained only with cured shapes, showing that the internal strain monitoring gives useful information. Meanwhile, thickness was shown to affect internal states and also residual deformation as pointed out in the previous researches. This
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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