Optical Fiber Based Process and Structural Health Monitoring of Aerospace Composite Structures

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Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures (ACS-SIDE) Project (FY2003-2012)

**Development of Optical Fiber Based SHM System**

**Impact Damage Detection Using Embedded Small-Diameter Optical Fiber Sensors (KHI, UT)**

**Debond Monitoring Using PZT-FBG Hybrid Active Damage Sensing System (FHI, UT)**

**Distributed and Dynamic Strain Measurement by BOCDA Technique (MHI, UT)**

**High Reliability Advanced Grid Structures (HRAGS) (MELCO, UT, JAXA)**

- **Damaged position**
- **Fixed position**
- **Demonstrator design**

- **BOX structure**
- **600 FBG sensors**

**Flight Test Bed and On-board BOCDA system**

- **6 axis controlled robot** (Tape prepreg & Optical fiber)

- **Load**

- **1000(N) one point loading**

**Eye-catching points**

- Lamb wave detection up to 1 MHz
- AWG (arrayed waveguide grating) filter

**Key technologies**

- EMBEDDED SMALL DIAMETER OPTICAL FIBER SENSORS
- Fastener Joint Monitoring
- Demonstrate design

**Current Status**

- Length Resolution: 1-5 cm
- Dynamic Response: 10 Hz
Transverse Cracks

Typical Thickness of CFRP Prepreg Layers: 125 µm

Diameter of Carbon Fiber: 5-8 µm

Delaminations

Small-diameter FBG sensors for detection of transverse cracks or delamination

Cladding: φ 40 µm

Polyimide Coating: φ 52 µm

0º Ply

90º Ply

Small-Diameter Optical Fiber Sensor

- Multi-point Strain
- Free from Electromagnetic Noise
- Small size

Reflection spectrum is narrowband. Strain determined from wavelength shift.
Pre-pump Pulse Brillouin Optical Time Domain Analysis

High spatial resolution distributed strain/temperature measurement

Spatial resolution: **2 cm**  
Sampling interval: 5 cm  
Sensing range: > 1 km (whole length of optical fiber)

Simultaneous temperature and strain measurement is possible
Arrangement of Embedded Small-Diameter Optical Fibers

- **SKIN, STRINGER AND SKIN/STRINGER**: 20 Optical Fibers including 6 FBG Sensors

OUTSIDE VIEW

INSIDE VIEW
Impact Damage Detection Test

Impact Test Machine

Fixed Reaction Wall

Actuators for Flexural Load

Impact Response Measuring System

Dead Weight for Gravity Compensation
Impact Damage Detection System

DAMAGE DETECTION SYSTEM v3.4

Check before test !!!
TEST S/N

CHANNEL SET
OPTICAL LOSS 9 ON
FBE SENSOR 4 ON ON ON

DAMAGE POSITION

JUDGE OF DAMAGE

DAMAGE

ANALYSIS/EVALUATION
(by Kawasaki Heavy Industries, Ltd.)

VISUALIZATION
(by Takeda Lab, Univ. Tokyo)
Towards Certification of Embedded OFS

- No disturbance concept
  - No strength reduction due to optical fiber embedment

Cross section of the embedded O.F.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of tests</th>
<th>Test spec.</th>
<th>RT</th>
<th>HW</th>
<th>LTD</th>
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<tbody>
<tr>
<td>B-1</td>
<td>Non Hole Tension(0°Lamina)</td>
<td>EN 2561 A</td>
<td>v</td>
<td>v</td>
<td>v</td>
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<tr>
<td>B-2</td>
<td>Non Hole Tension(90°Lamina)</td>
<td>EN 2597 B</td>
<td>v</td>
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<tr>
<td>B-3</td>
<td>Non Hole Compression(0°Lamina)</td>
<td>EN 2850 B</td>
<td>v</td>
<td>v</td>
<td>v</td>
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<tr>
<td>B-4</td>
<td>Non Hole Compression(90°Lamina)</td>
<td>EN 2850 B</td>
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<td>v</td>
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<tr>
<td>B-5</td>
<td>In plane shear strength(±45°)</td>
<td>AITM 1-0002</td>
<td>v</td>
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<td>v</td>
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<tr>
<td>B-6</td>
<td>GILS</td>
<td>ASTM D 3846</td>
<td>v</td>
<td>v</td>
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<tr>
<td>B-7</td>
<td>Non Hole Tension(Quasi-isotropic)</td>
<td>AITM 1-0007</td>
<td>v</td>
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<td>B-8</td>
<td>Non Hole Compression(Quasi-isotropic)</td>
<td>AITM 1-0008</td>
<td>v</td>
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<td>v</td>
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<tr>
<td>B-9</td>
<td>Open Hole Tension(Quasi-isotropic)</td>
<td>AITM 1-0007</td>
<td>v</td>
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<tr>
<td>B-10</td>
<td>Open Hole Compression(Quasi-isotropic)</td>
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<tr>
<td>B-11</td>
<td>CAI(Quasi-isotropic)</td>
<td>AITM 1-0010</td>
<td>v</td>
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<td>B-12</td>
<td>Filled hole tensile strength</td>
<td>AITM 1-0007</td>
<td>v</td>
<td>v</td>
<td>v</td>
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<tr>
<td>B-13</td>
<td>Filled hole compression strength</td>
<td>AITM 1-0008</td>
<td>v</td>
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<tr>
<td>B-14</td>
<td>Bearing Strength(Quasi-isotropic)</td>
<td>AITM 1-0009</td>
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<tr>
<td>B-15</td>
<td>Double Lap Shear(Quasi-isotropic)</td>
<td>ASTM D3528</td>
<td>v</td>
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<tr>
<td>B-16</td>
<td>ILSS</td>
<td>EN2563</td>
<td>v</td>
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<td>B-17-1</td>
<td>GIC, Adhesive line</td>
<td>AITM 1-0005</td>
<td>v</td>
<td>v</td>
<td>v</td>
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<td>B-17-2</td>
<td>GIC, Two layers below adhesive line</td>
<td>AITM 1-0005</td>
<td>v</td>
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<td>v</td>
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<td>B-18-1</td>
<td>GIC, Static</td>
<td>AITM 1-0006</td>
<td>v</td>
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<td>v</td>
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<td>B-18-2</td>
<td>GIC, Fatigue</td>
<td>AITM 1-0006</td>
<td>v</td>
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<td>v</td>
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<td>B-19</td>
<td>Flatwise</td>
<td>ASTM C 297/C 297M-04</td>
<td>v</td>
<td>v</td>
<td>v</td>
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<td>B-20</td>
<td>Fatigue(Quasi-isotropic), Tension—Tension</td>
<td>TBD</td>
<td>v</td>
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<td>v</td>
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<tr>
<td>B-21</td>
<td>Fatigue(Quasi-isotropic), Tension—Compression</td>
<td>TBD</td>
<td>v</td>
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<td>v</td>
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<tr>
<td>B-22</td>
<td>Fatigue(Double lap shear), Tension—Tension</td>
<td>ASTM D3528</td>
<td>v</td>
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<td>v</td>
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</tbody>
</table>

Some type of specimens, such as co-cure, co-bonding and secondary bonding are required in some items, in which adhesive properties are evaluated.
Preparation of SHM Guidebook for Aircraft  
SAE G-11SHM Committee

AISC-SHM (Aircraft Industries Steering Committee of SHM)  
OEM (Boeing, Airbus, EADS, Bombardier, Embraer, BAE)  
Systems (Honeywell, Goodrich, GE Aviation)  
Regulatory Agents (FAA, EASA, US Air Force, Navair)  
Airlines (Lufthansa, Delta, ANA)  
Research Organization (Stanford Univ., Univ. Tokyo, Cranfield Univ., RIMCOF)

Application of Optical Fiber Sensors for Repair

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Manufacturing Issues in Large-Scale Composite Structures

Wing panel of Boeing 787 manufactured by MHI

Difficulties in manufacturing large-scale co-cured CFRP structures

- Non-uniform temperature in autoclave
- Thermal distortion
- Joining distorted parts

Urgent need to **continuously monitor** internal states of composite structures in order to improve design, processing technologies and maintenance
Embedded fiber-optic network, formed during lay-up as biological neuron, continuously monitors internal state of composite structure throughout its life cycle.

Life Cycle Monitoring (LCM)
Optical Fiber Distributed Strain Monitoring

Vacuum assisted resin transfer molding (VARTM)

Preform: Quadraxial carbon non-crimp fabric (Hexcel Co.)
Resin: HexFlow RTM 6 (Hexcel Co.)

Resin saturating preforms bonded stiffeners and skin

Two lines again measured quite similar strain distributions.

Almost uniform compressive strain of 250 $\mu\varepsilon$ was induced in whole structural area, indicating that specimen was perfectly injected and cured.

The results also agreed well with the measurement by the two FBG sensors, validating the measurement accuracy of the distributed sensing.
First the specimen was fully clamped on steel bars (simulated assembly).

Low velocity impact loadings were then applied directly above foot of stiffener by a drop-weight impact machine.

Strain changes due to simulated assembly and impact damages was evaluated.
Strain increase at 1st impact point can be explained as resulting from releasing compressive thermal residual strain by skin/stiffener disbond.

Strain decrease induced around 2nd impact point can be attributed to visually-observed concave deformation of impacted area.

After impact tests, embedded fiber-optic system still worked correctly and mechanical strain distribution around damaged area could be obtained.
Life Cycle Monitoring of Curved Panel - Spring-in

S. Minakuchi et al.
Spring-in of Curved Panel

Residual Strain
- Cure shrinkage
- Heat contraction depending on material direction

\[
\frac{\Delta \theta}{\theta} = (\alpha_I - \alpha_T) \Delta T + (\beta_I - \beta_T)
\]

\( \alpha \): Thermal expansion coefficient
\( \beta \): Curing contraction rate

Spring-in angle \( \Delta \theta \) [degree]

Strength ratio [%]

- Structural strength is significantly decreased
- Technical difficulties to prevent spring-in due to many parameters involved

Necessity of prediction methodology
**Fiber Bragg Grating (FBG) Sensor - Birefringence Effect**

**Birefringence Effect**

**Sectional view**

- Cladding
- Core
- \( \varepsilon_1 > \varepsilon_2 \)

**Reflection Spectra**

- \( \lambda_p - \lambda_q = k (\varepsilon_1 - \varepsilon_2) \)

- \( k = \frac{n_0^2 \lambda_0}{2} (p_{12} - p_{11}) \)
  - \( n_0 \): Initial average refractive index
  - \( \lambda_0 \): Initial wavelength
  - \( p_{11}, p_{12} \): Photoelastic constants

Peak wavelength difference is proportional to non-axisymmetric strain

\( \varepsilon_d = (\varepsilon_1 - \varepsilon_2)/2 \) in optical fiber section

\[ \lambda_B = 2n\Lambda \propto \varepsilon_a \]

- \( \Lambda \): Grating period
- \( n \): Average refractive index

**symbols and equations**

- \( \varepsilon_a \)
- \( l \)
- \( k \)
- \( p_{11}, p_{12} \)
- \( n_0 \)
- \( \lambda_0 \)
- \( \lambda_B \)
- \( \lambda_p, \lambda_q \)
- \( \varepsilon_1, \varepsilon_2 \)
Spectral shape changed during cooling and demolding process due to cross-sectional deformation of optical fiber (birefringence effect).

Using spectral shape, we can quantitatively evaluate non-axisymmetric strain $\varepsilon_d$ or through-the-thickness strain.
Non-axisymmetric Strain during Cooling/Decompressing Process

- **Graph 1:**
  - X-axis: Wavelength detuning (nm)
  - Y-axis: Normalized intensity
  - Measured and Superposition curves
  - Initial and Δλ peaks

- **Graph 2:**
  - X-axis: Time (min)
  - Y-axis: Non-axisymmetric strain (με)
  - Temperature (°C)

- **Graph 3:**
  - Before cooling
  - After cooling
  - After demolding
  - Experiment (red) and FEA (orange)

- **Graph 4:**
  - Before cooling
  - After cooling
  - After demolding
  - Experiment (blue) and FEA (white)
Specimens with different corner angles fabricated with different-angled molds

Fabricated corner angle (Mold angle)

A. 90.0 (90.5)
B. 89.5 (90.0)
C. 89.0 (89.5)

Corrected angle

A. 90.0 (90.5)
B. 89.5 (90.0)
C. 89.0 (89.5)

Strength v.s. Spring-in Angle

Experimental

Predicted

Load (after assembly) [kN]

Load

Non-axisymmetric strain [\(\mu\)]

\(\Delta \varepsilon_d\)

Spring-in angle [deg]

\(\Delta \theta\)
This study was partly conducted as a part of the ‘Civil Aviation Fundamental Technology Program– Advanced Materials and Process Development for Next-Generation Aircraft Structures’ project under contract with RIMCOF and funded by METI, Japan. Continuing efforts of the members in the current ACS-SIDE project are highly appreciated.

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