26th International Congress of the Aeronautical Sciences
Anchorage, Alaska, USA, September 18, 2008

ICAS 2008

General Lecture

RECENT DEVELOPMENT OF STRUCTURAL HEALTH MONITORING TECHNOLOGIES FOR AIRCRAFT COMPOSITE STRUCTURES

Nobuo Takeda
The University of Tokyo

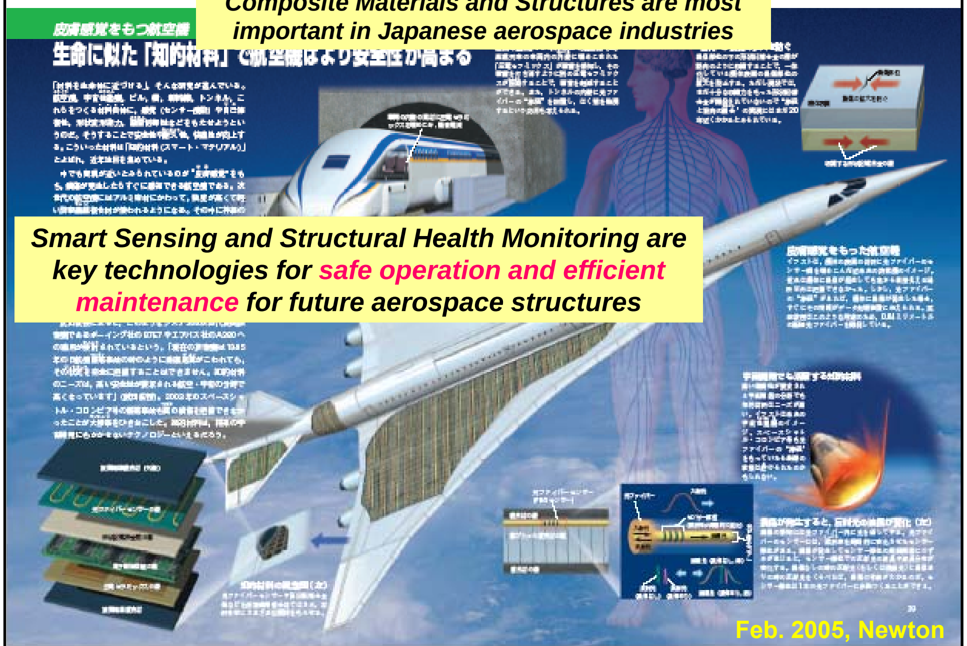
Dept. Advanced Energy, Graduate School of Frontier Sciences
and
Dept. Aeronautics and Astronautics, School of Engineering


Kashiwa Campus, the University of Tokyo

Increasing use of advanced composites in aerospace structures

More than 70% of carbon fibers are made in Japan

Composite Materials and Structures are most important in Japanese aerospace industries



Smart Sensing and Structural Health Monitoring are key technologies for safe operation and efficient maintenance for future aerospace structures

Feb. 2005, Newton

Outline

(1) Structural Health Monitoring Group, NEDO Smart Material/Structure System Program (FY1998-2002)

(2) Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures (ACS-SIDE) Project, METI Advanced Material & Processing for Next-Generation Aircraft Structure Program (FY2003-2007)

(3) Integrated High-Resolution Distributed Strain Monitoring with Embedded Optical Fibers in Composite Structures (FY2007-)

NEDO Smart Material/Structure System Program

5 Year Program
From April 1998
To March 2003

Approximately
5 Million US
Dollars per year

METI(Ministry of Economy, Trade and Industry)

NEDO(New Energy and industrial Technology Development organization)

RIMCOF(R&D Institute of Metals & Composites for Future Industries)

Health Monitoring
Univ. Tokyo
10 Companies

Active/Adaptive Structures
Nagoya Univ.
4 Companies
& Tokyo MMU

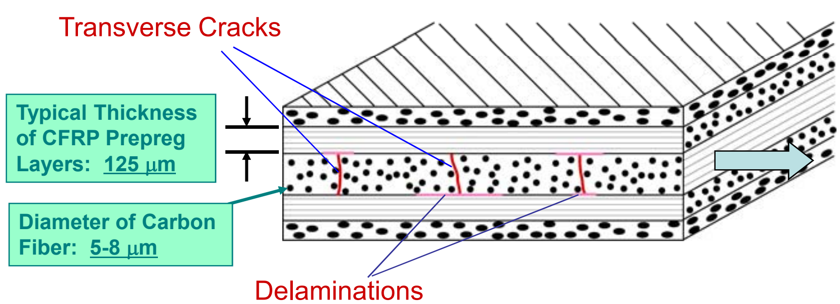
Demonstrator Program
4 Companies

Actuator Materials & Devices
Tohoku Univ.
4 Companies &
Univ. of Washington

Smart Manufacturing
Osaka City Univ.
2 Companies

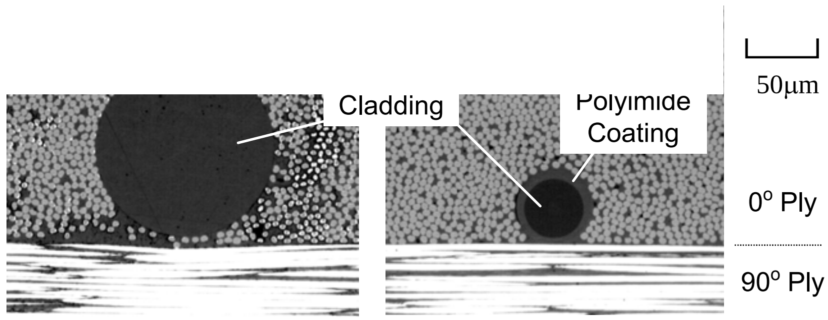
National Institute of Advanced Industrial Science and Technology
Smart Structure Research Center

Typical Damages in Composite Laminates



Small-diameter FBG sensors were developed for detection of transverse cracks or the delamination in CFRP laminates.

CFRP Laminates with Embedded FBG Sensors



Uncoated
normal FBG sensor

Polyimide-coated
small-diameter FBG sensor

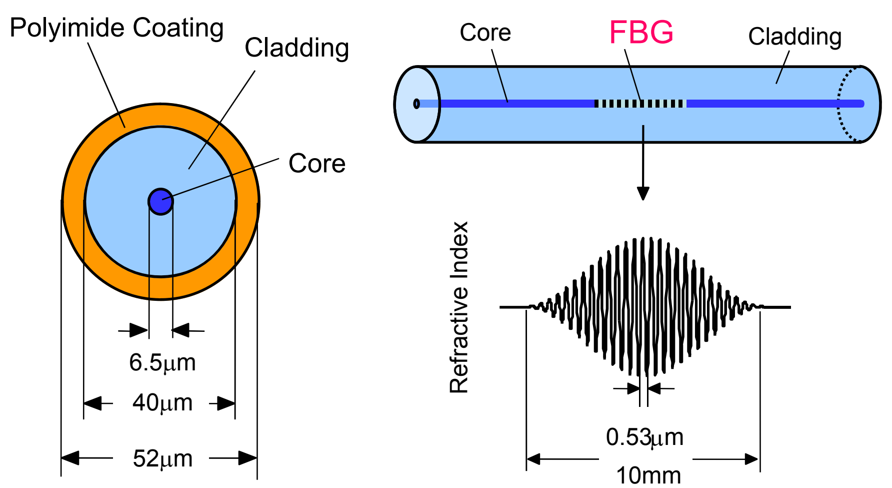
Cladding: ϕ125μm

Cladding: ϕ40μm
Polyimide Coating: ϕ52μm

Smart Composite System Laboratory — The University of Tokyo

Small-diameter Fiber Bragg Grating Sensor

- *Multi-Point Sensing (Strain, Temperature, etc)*
- *Free of Electro-magnetic Noises*



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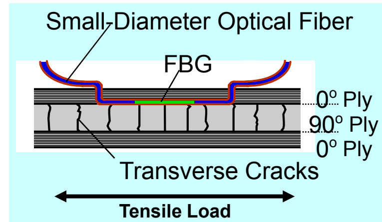
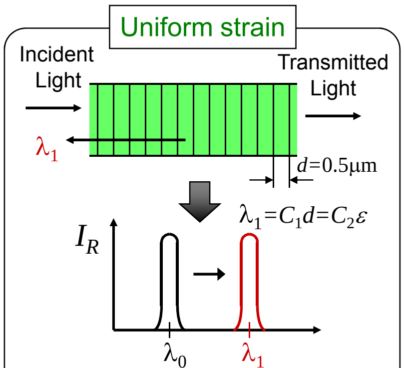
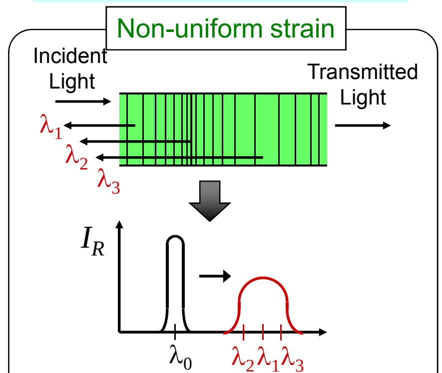
Response of FBG Sensor to Strain

Small-diameter FBG Sensors can be embedded close to transverse cracks without deteriorating the laminate.





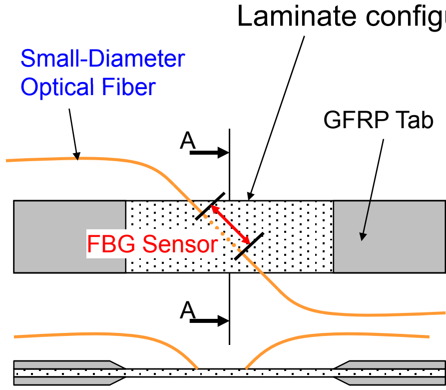
Reflection spectrum is *narrowband*.
Strain determined from wavelength shift.

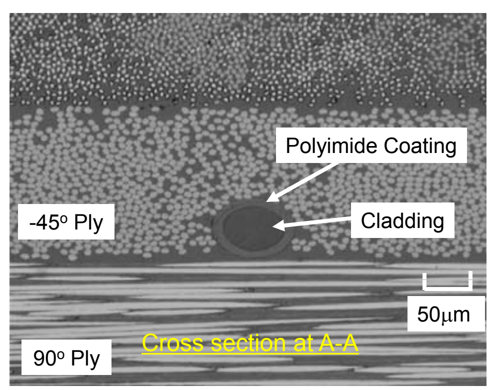


Reflection spectrum becomes *broadband*, which can be used for damage detection.

Detection of Transverse Cracks

CFRP: T800H/3631
Laminate configuration: quasi-isotropic $[45/0/-45/90]_s$



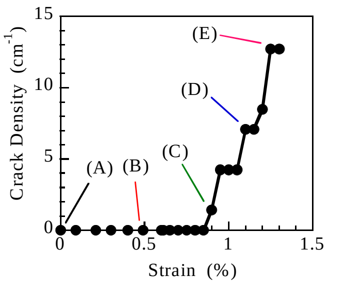


Embedded FBG sensor in –45° ply for detection of 90° transverse cracks

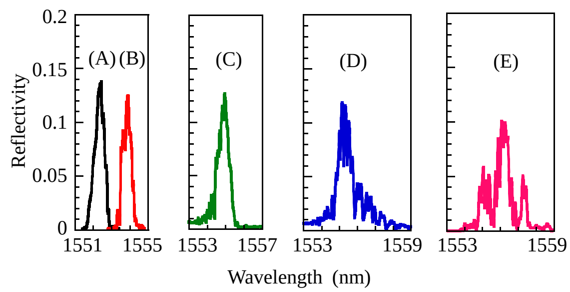
Detection of Transverse Cracks

Reflection Spectra at Various Tensile Strain Levels

(A) ε = 0.00%, ρ = 0.0cm^{-1} (D) ε = 1.10%, ρ = 7.1cm^{-1}
(B) ε = 0.49%, ρ = 0.0cm^{-1} (E) ε = 1.31%, ρ = 12.7cm^{-1}
(C) ε = 0.90%, ρ = 1.4cm^{-1}



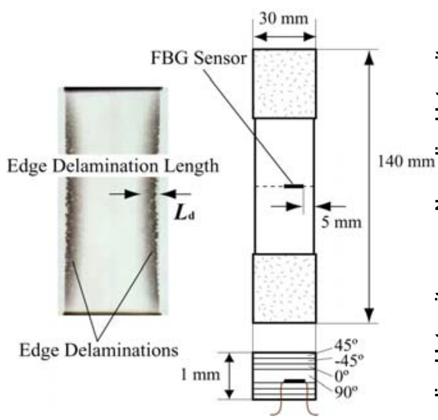
Crack density ρ vs. tensile strain ε.

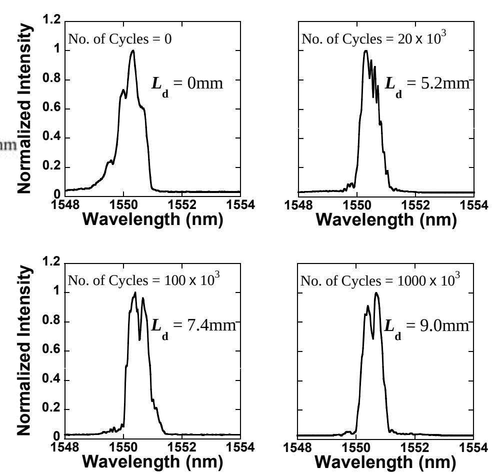


Reflection spectra measured under tensile loading.

Reflection spectrum was sensitively deformed with increase in crack density

Detection of Free-Edge Delamination in Composite Laminates with Embedded Small-Diameter FBG Sensor





Intensities of two peaks changed with the delamination growth

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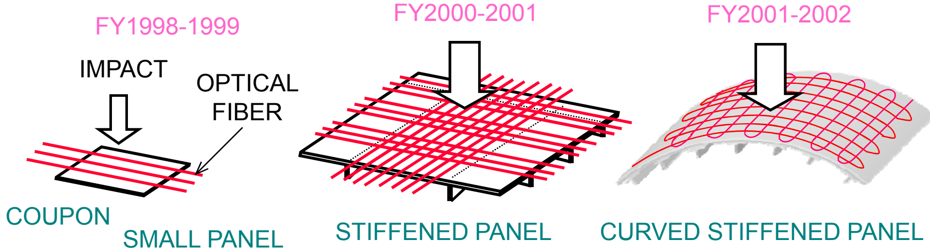
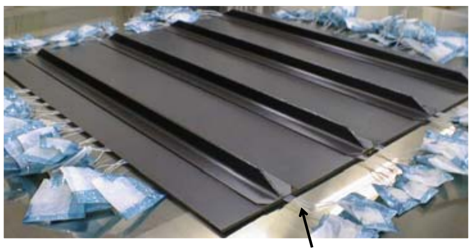
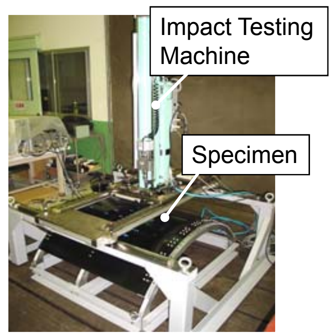
Impact Damage Detection in Composite Structures

- Building Block Approach -





SMALL-DIAMETER OPTICAL FIBER



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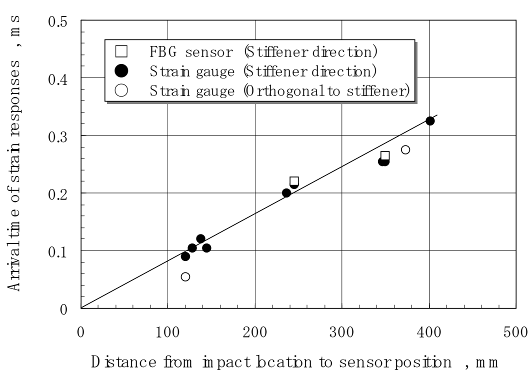
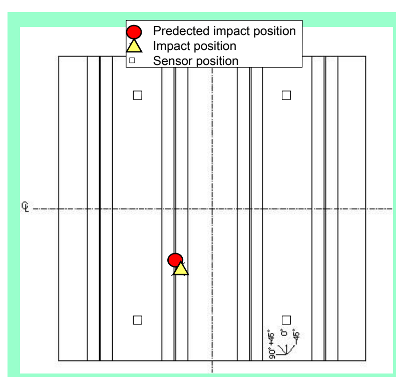
Prediction of Impact Point Using Dynamic FBG Response

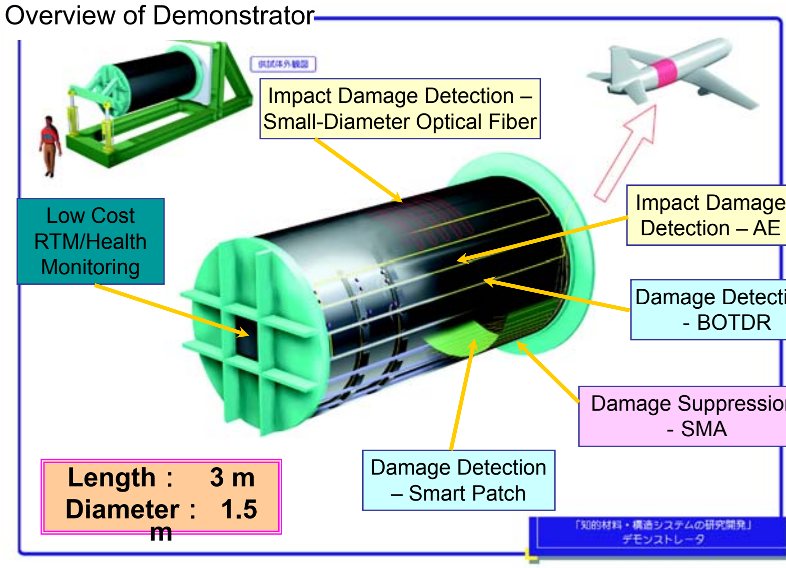


Arrival Time vs. Distance from Impact Point
(Impacted at Stiffener Flange)



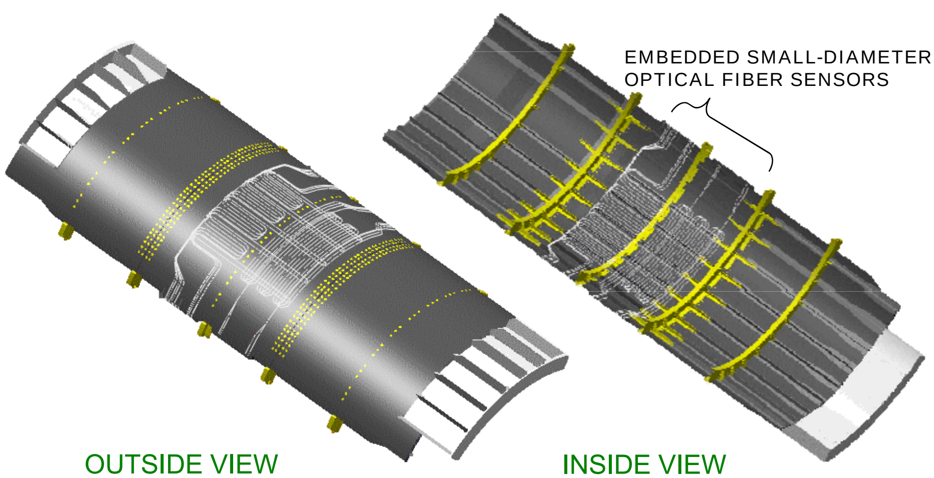
Predicted Impact Point
(Impacted at Stiffener Flange)

Damage Detection and Suppression Demonstrator



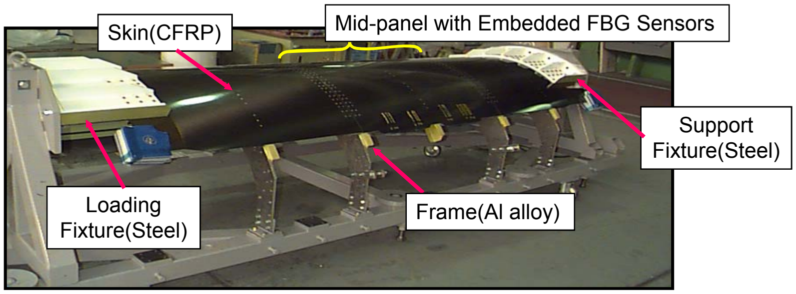
Arrangement of Small-Diameter Optical Fibers in Upper Panel for Impact Damage Detection

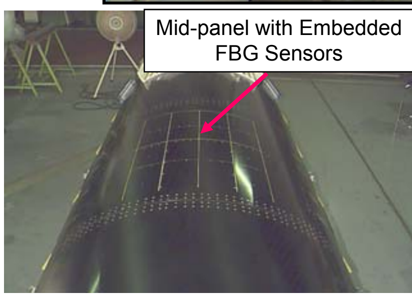
➢SKIN, STRINGER AND SKIN/STRINGER : 20 Optical Fibers including 6 FBG Sensors



Damage Detection and Suppression Demonstrator

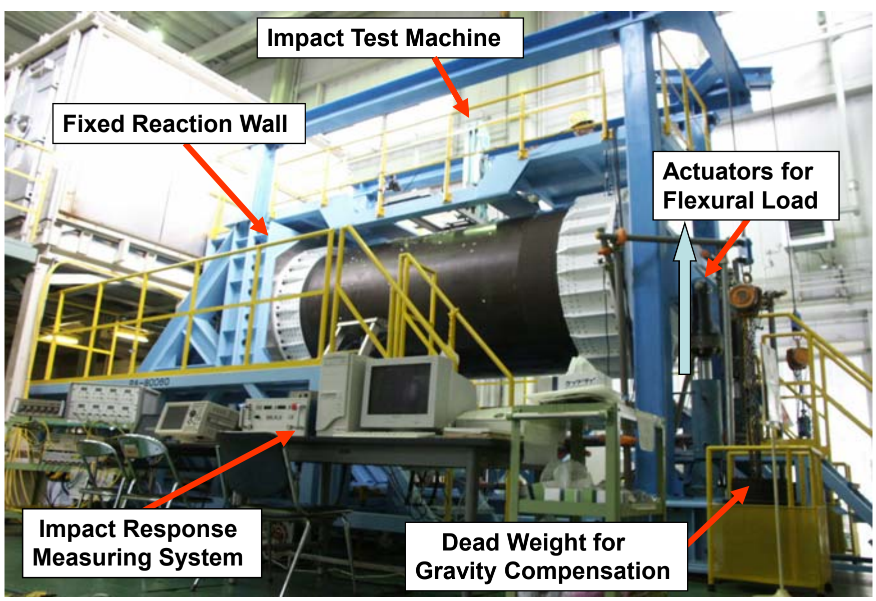
Upper Panel with Embedded Small-Diameter Optical Fiber Sensors



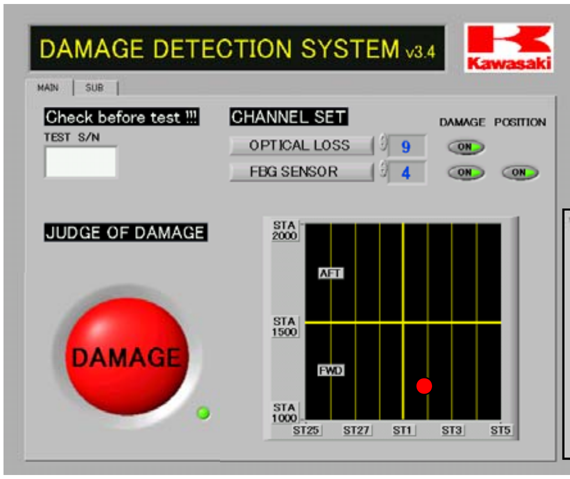


Impact Damage Detection Test

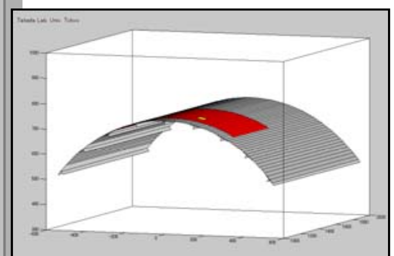
in Damage Detection and Suppression Demonstrator



Impact Damage Detection System



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



VISUALIZATION
(by Takeda Lab, Univ. Tokyo)

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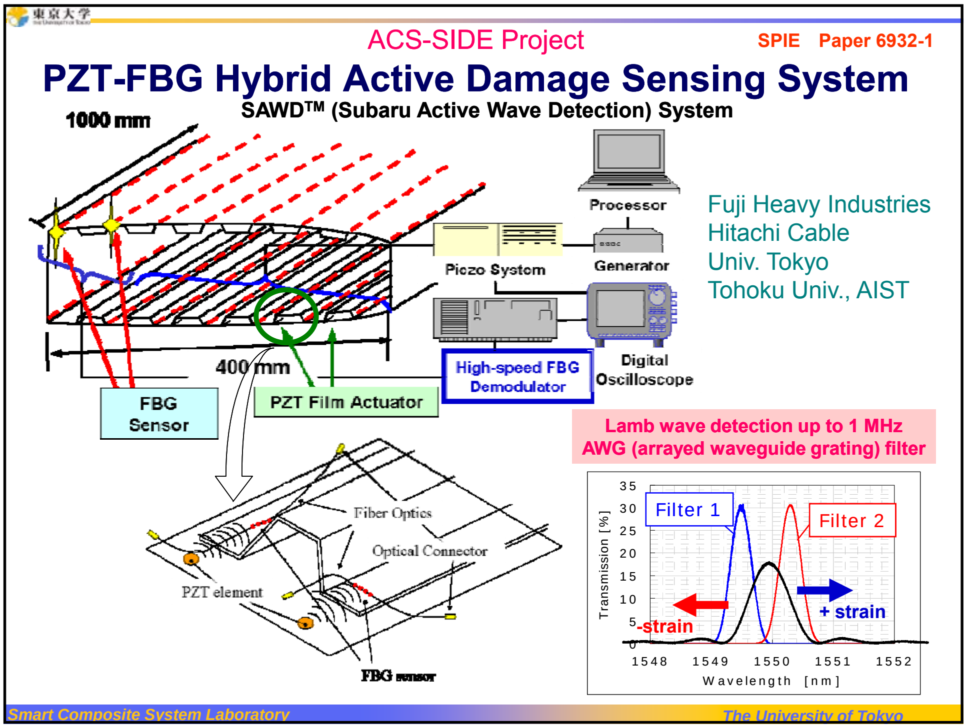
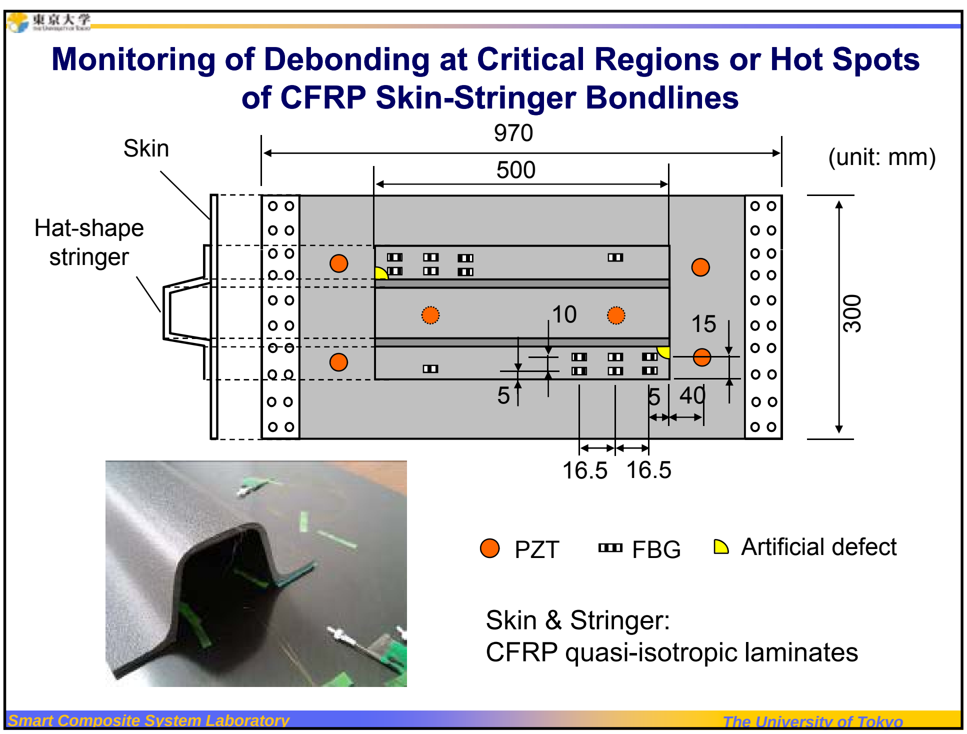


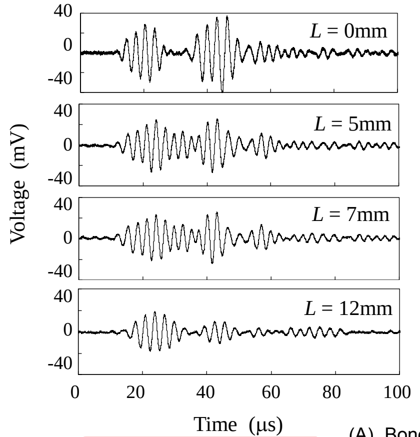
ACS-SIDE Project
SPIE Paper 6932-1
PZT-FBG Hybrid Active Damage Sensing System
SAWD™ (Subaru Active Wave Detection) System
1000 mm
400 mm
FBG Sensor
PZT Film Actuator
Piezo System
Processor
Generator
High-speed FBG Demodulator
Digital Oscilloscope
Fuji Heavy Industries
Hitachi Cable
Univ. Tokyo
Tohoku Univ., AIST
Lamb wave detection up to 1 MHz
AWG (arrayed waveguide grating) filter
Fiber Optics
Optical Connector
PZT element
FBG sensor
Filter 1
Filter 2
-strain
+ strain
Transmission [%]
Wavelength [nm]
Smart Composite System Laboratory
The University of Tokyo

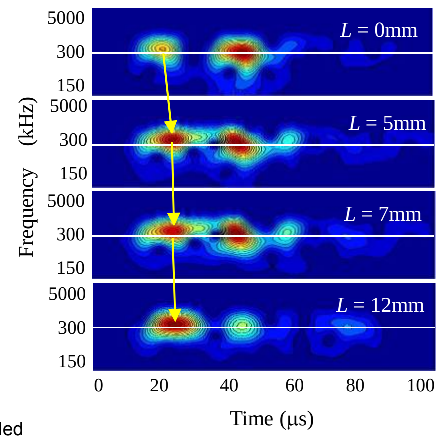


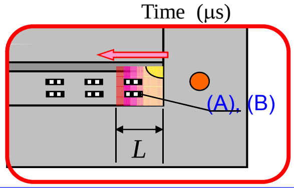
Monitoring of Debonding at Critical Regions or Hot Spots of CFRP Skin-Stringer Bondlines
Skin
Hat-shape stringer
970
500
(unit: mm)
300
10
15
5
5
40
16.5
16.5
PZT
FBG
Artificial defect
Skin & Stringer:
CFRP quasi-isotropic laminates
Smart Composite System Laboratory
The University of Tokyo

Detected Lamb Waves with Growing Debonding

(Bonded FBG (A))



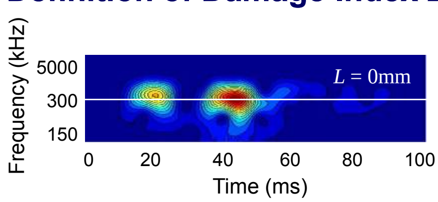


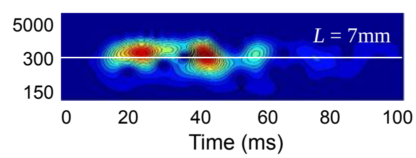


(A) Bonded
(B) Embedded

Arrival of the first peak became slower after debonding passed through FBG

Definition of Damage Index *DI* and Correlation Coefficient *c*





$\overline{x}_{ij}$: Standard wavelet coefficient

x_{ij} : Compared wavelet coefficient

Damage Index *DI*

$$DI = \frac{1}{N_d}\sum_{ij}\left(x_{ij} - \overline{x}_{ij}\right)^2$$

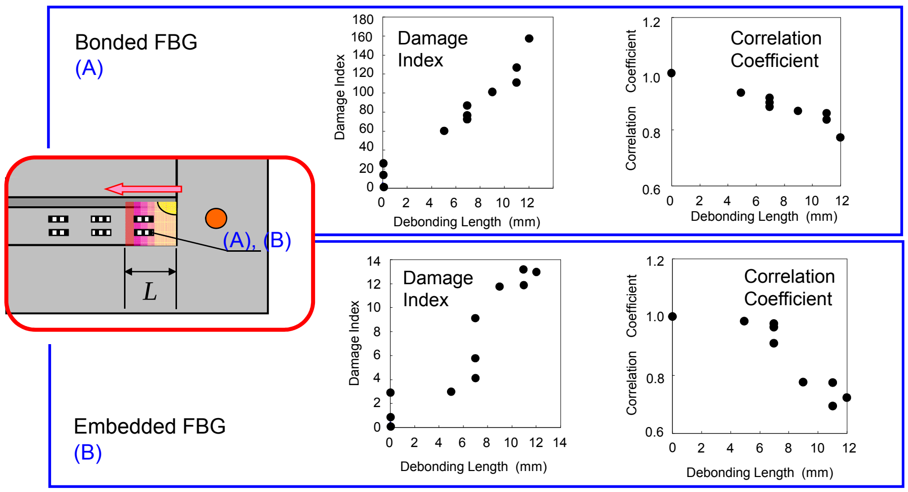
calculated from all the distribution of the wavelet coefficients

Correlation Coefficient *c*

$$c = \frac{\sum_{t=0}^{t=t_{max}} f(t)\cdot g(t)}{\sqrt{\sum_{t=0}^{t=t_{max}} f(t)^2}\sqrt{\sum_{t=0}^{t=t_{max}} g(t)^2}}$$

$f(t)$: Standard wavelet coefficient at 300kHz
$g(t)$: Compared wavelet coefficient at 300kHz

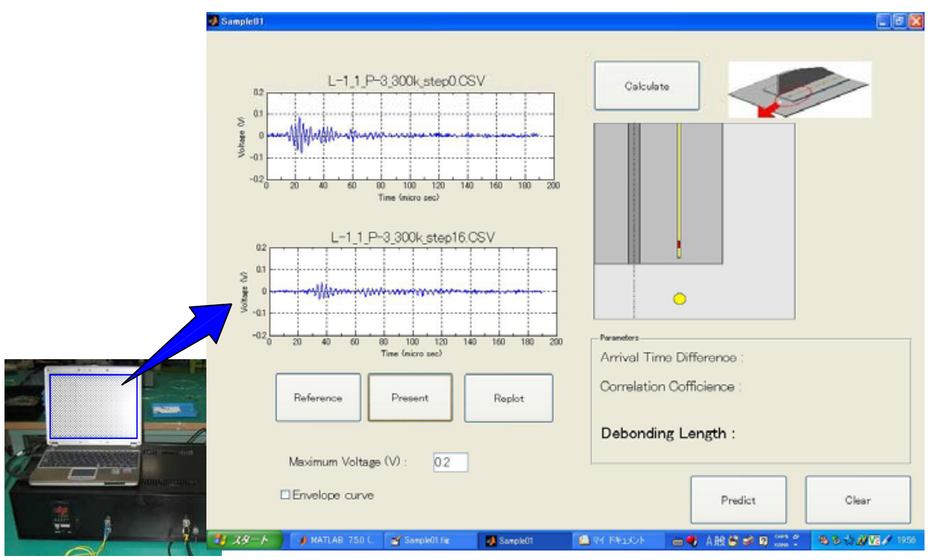
Damage Index *DI* and Correlation Coefficient *c* as Functions of Debonding Length



Results by embedded FBG (B) changes rapidly around *L* = 6mm, which indicates that the debonding passed above the FBG (B).

SAWD Damage Diagnosis Software

(1) Read the waveforms detected by the damage monitoring device



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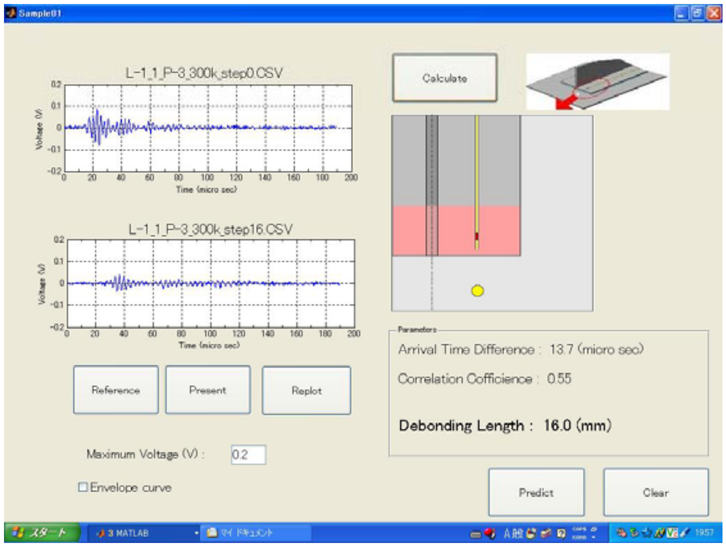
SAWD Damage Diagnosis Software

(2) Calculate the damage area by the damage diagnosis software



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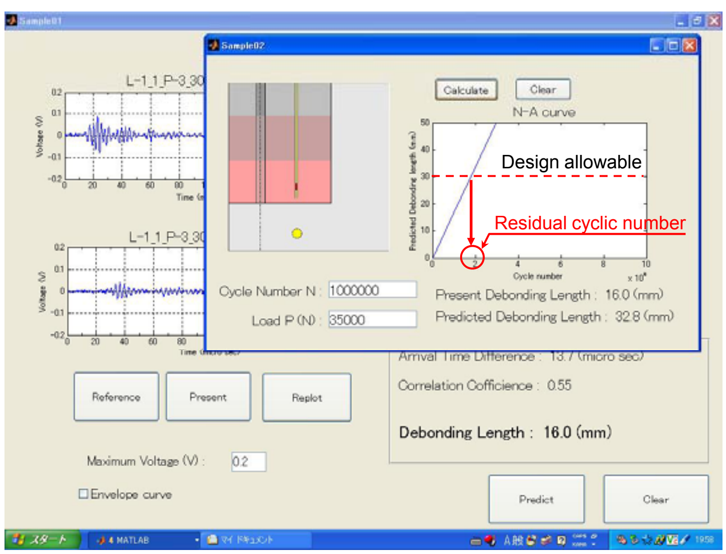
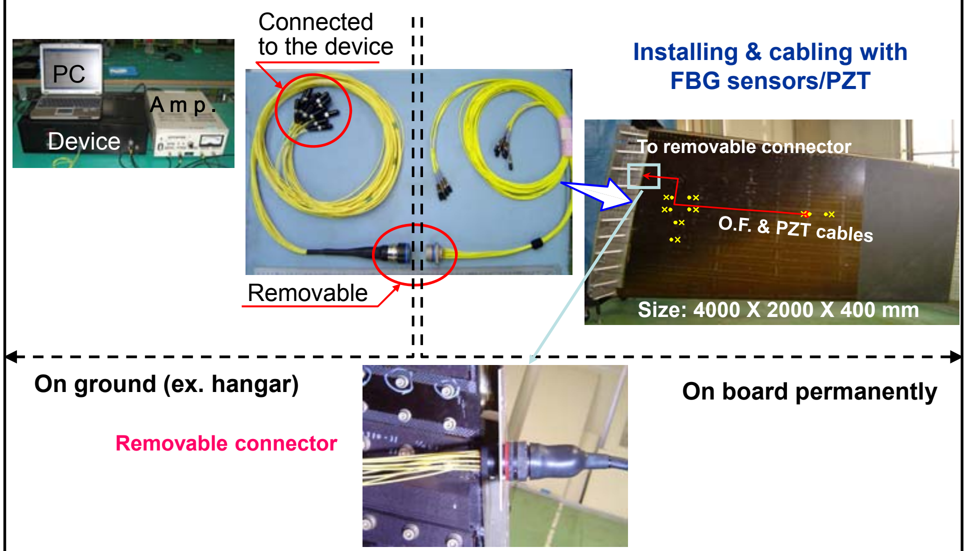
SAWD Damage Diagnosis Software

(3) Predict the damage growth by the residual life prognosis software



Verification by Sub-Structure Tests

The system set-up was simulated for practical use in inspection or maintenance field



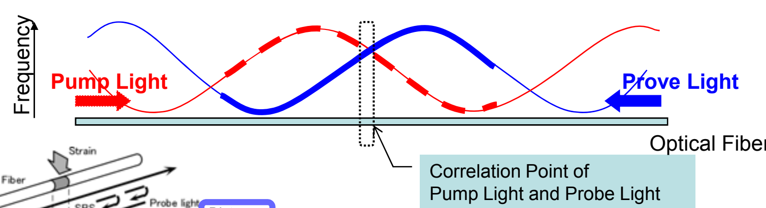
ACS-SIDE Project SPIE Paper 6933-29

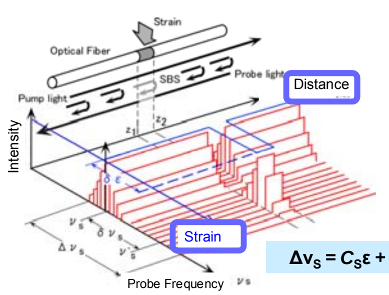
BOCDA High-Resolution Distributed Strain Measurement

Mitsubishi Heavy Industries, University of Tokyo

BOCDA Principle (Brillouin Optical Correlation Domain Analysis) developed by Professor Hotate

The phases of the pump and the probe light waves change periodically, it make the correlation peak position on the fiber. At the correlation peak position, the pump and the probe light waves are synchronously frequency modulated and maintain the frequency difference.





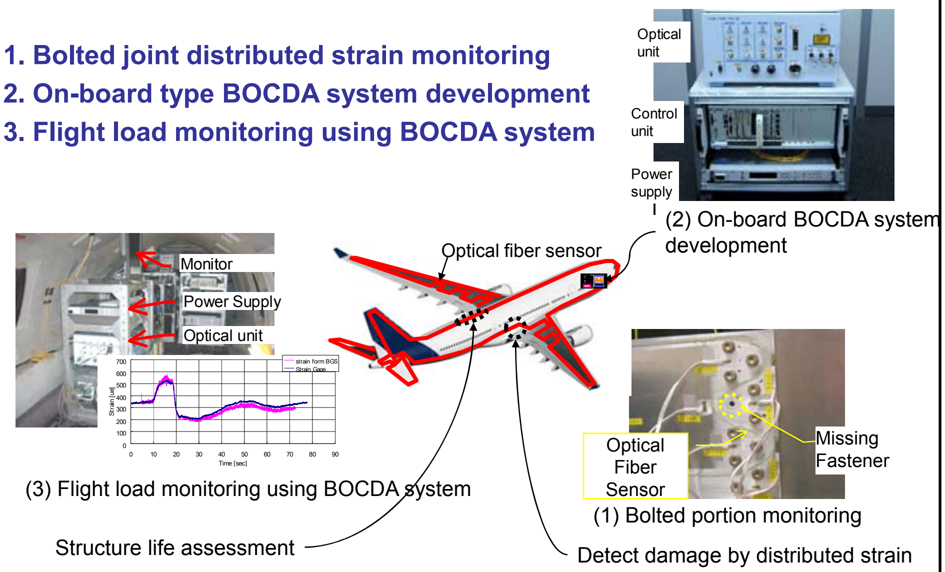
$\Delta\nu_S = C_S\varepsilon + C_T\Delta T$

➢Feature of BOCDA

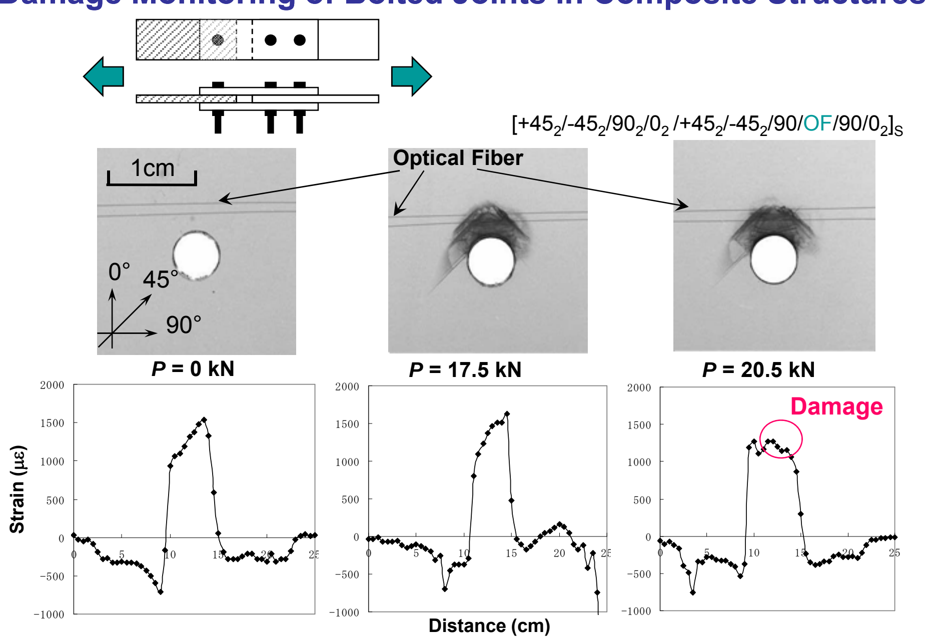
- ✓High spatial resolution
  - **(5 cm in length: Normal Mode)**
  - **(2 mm in length: HR Mode)**
- ✓High speed sampling rate **(10Hz)**
- ✓Multi-points strain sensing (random access)

BOCDA-SHM System Development

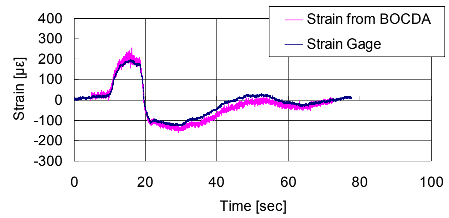
1. **Bolted joint distributed strain monitoring**
2. **On-board type BOCDA system development**
3. **Flight load monitoring using BOCDA system**



Damage Monitoring of Bolted Joints in Composite Structures

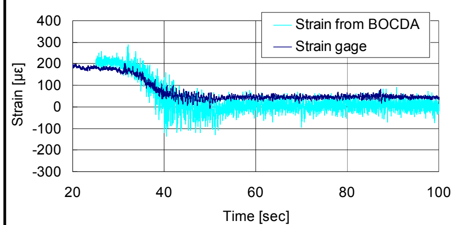


Dynamic Flight Load Monitoring



<Flight condition>
➤Pull up
➤Alt: 15,000ft

<Measuring Condition>
➤Dynamic sampling (60pt/sec)



<Flight condition>
➤Landing

<Measuring Condition>
➤Dynamic sampling (60pt/sec)

On-board BOCDA system was successfully operated during flight conditions to assess structural load history

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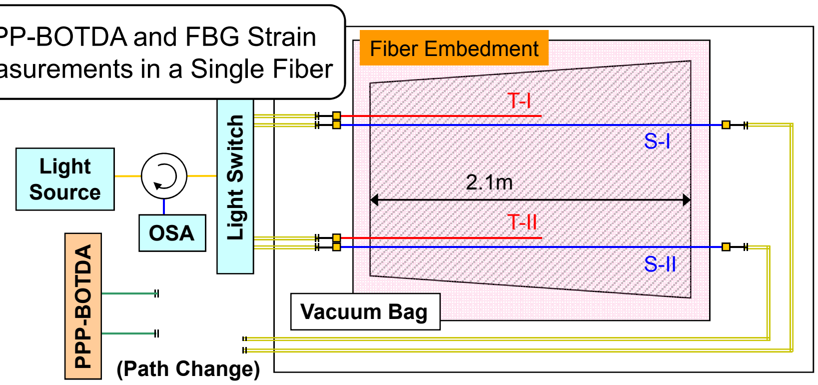
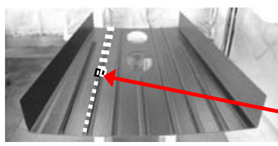
Strain Measurement During VaRTM (Vacuum-assisted Resin Transfer Molding) Process of CFRP Stiffened Structures

PPP-BOTDA and FBG Strain Measurements in a Single Fiber



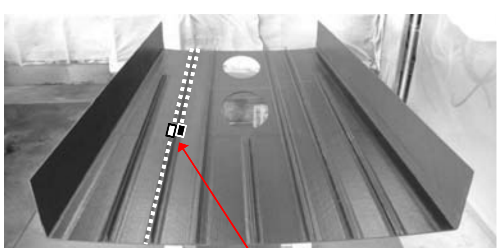
Small-diameter optical fiber with high refraction index difference was effective to reduce the optical loss due to embedment



Comparison of Strains by FBG and PPP-BOTDA Measurement

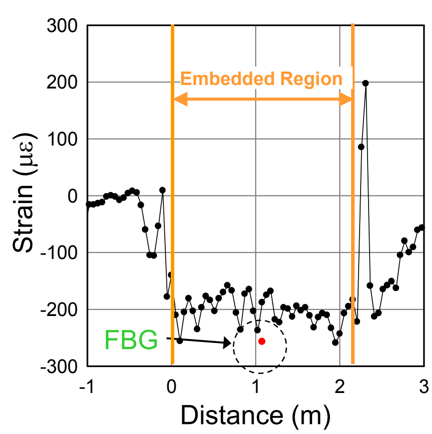
Strain Measurement During VaRTM (Vacuum-assisted Resin Transfer Molding) Process of CFRP Stiffened Structures

PPP-BOTDA and FBG Strain Measurements in a Single Fiber



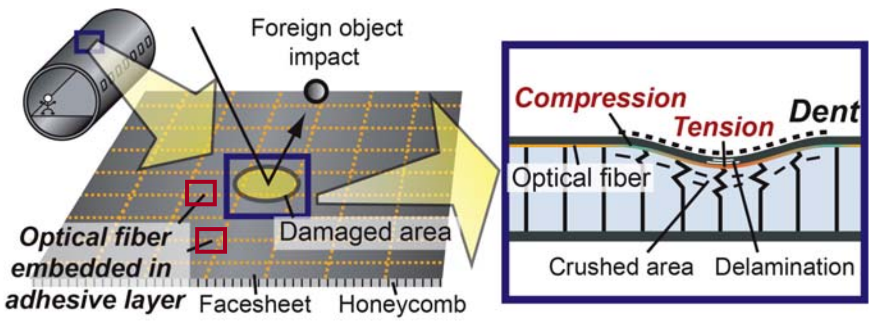
Comparison of Strains by FBG and PPP-BOTDA Measurement

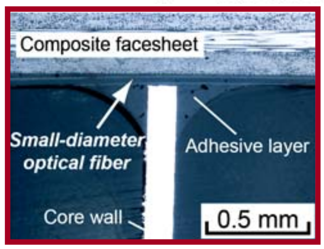
Residual Thermal Strain Distribution



Damage Detection in CFRP Sandwich Structures

Optical fiber acts as nerve to detect residual facesheet dent





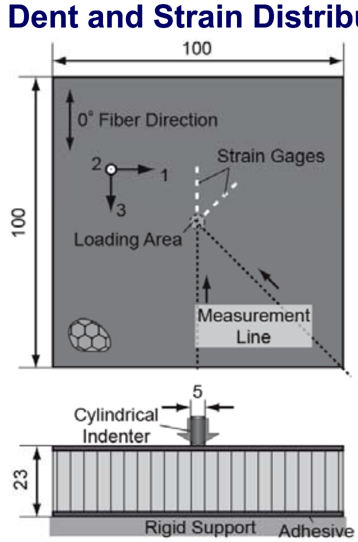
A limited number of optical fibers are sufficient to monitor whole structure

Key

1. **Non-uniform strain** is induced in optical fiber in damaged area
2. Facesheet dent is relatively **wide**

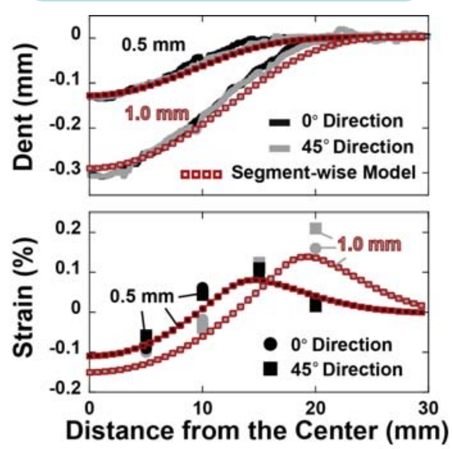
S. Minakuchi, et al., *Journal of Sandwich Structures and Materials*, 9 (1), pp 9-33, 2007.

Dent and Strain Distribution – Theory and Experiments



Facesheet: CFRP UT500/#135
(Toho Tenax Co.,Ltd., $[(0,90)_3]$)
Core : AL 3/16 5052-.001, Thickness : 20 mm
(Showa Aircraft Industry Co.)
Adhesive films : AF-163-2K (3M Co.)

Displacement rate : 0.5 mm/min
Maximum displacement : ***0.5, 1 mm***



Residual dent and strain was well reproduced

Response Simulation of Spectrum

How spectrum changes when damage is introduced?

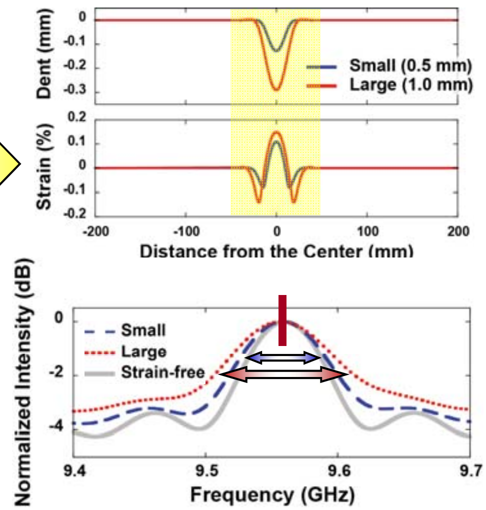
Simulation procedure

Damage right above embedded optical fiber

Calculate strain distribution along embedded fiber

Developed optical software

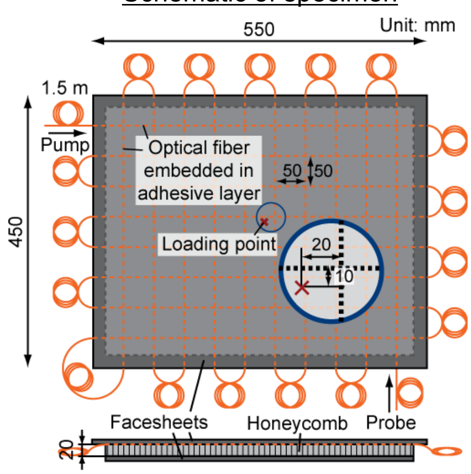
Calculate spectrum depending on measurement point



Width of spectrum depends on damage size

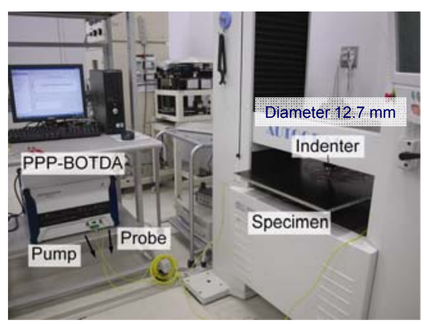
Damage Detection Test

Schematic of specimen



Facesheet: T700S/2500, $[0/90]_{3S}$
Core: Al 1/4-5052-.001

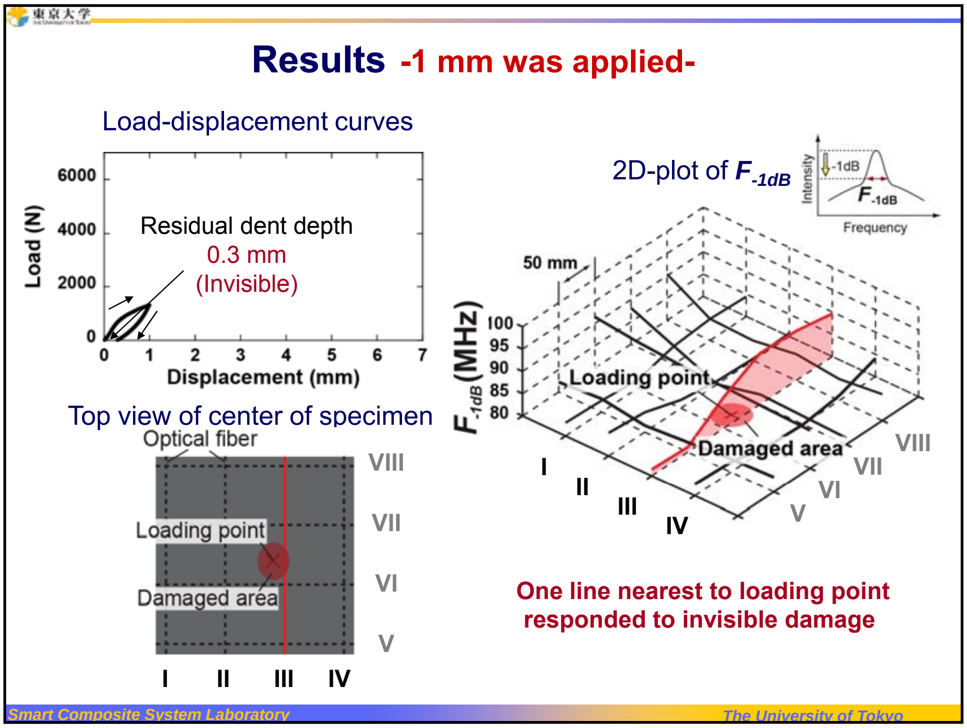
Experimental set-up



Quasi-static indentation loadings were applied to introduce simulated low velocity impact damage

Five kinds of maximum displacement : **1, 2, 3, 4, 6.5 mm**

Response depending on damage size was investigated


東京大学
Results -1 mm was applied-
Load-displacement curves
Load (N)
6000
4000
2000
0
0 1 2 3 4 5 6 7
Displacement (mm)
Residual dent depth
0.3 mm
(Invisible)
2D-plot of F_{-1dB}
Intensity
-1dB
F_{-1dB}
Frequency
50 mm
F_{-1dB} (MHz)
100
95
90
85
80
Loading point
Damaged area
I
II
III
IV
V
VI
VII
VIII
Top view of center of specimen
Optical fiber
Loading point
Damaged area
VIII
VII
VI
V
I II III IV
One line nearest to loading point
responded to invisible damage
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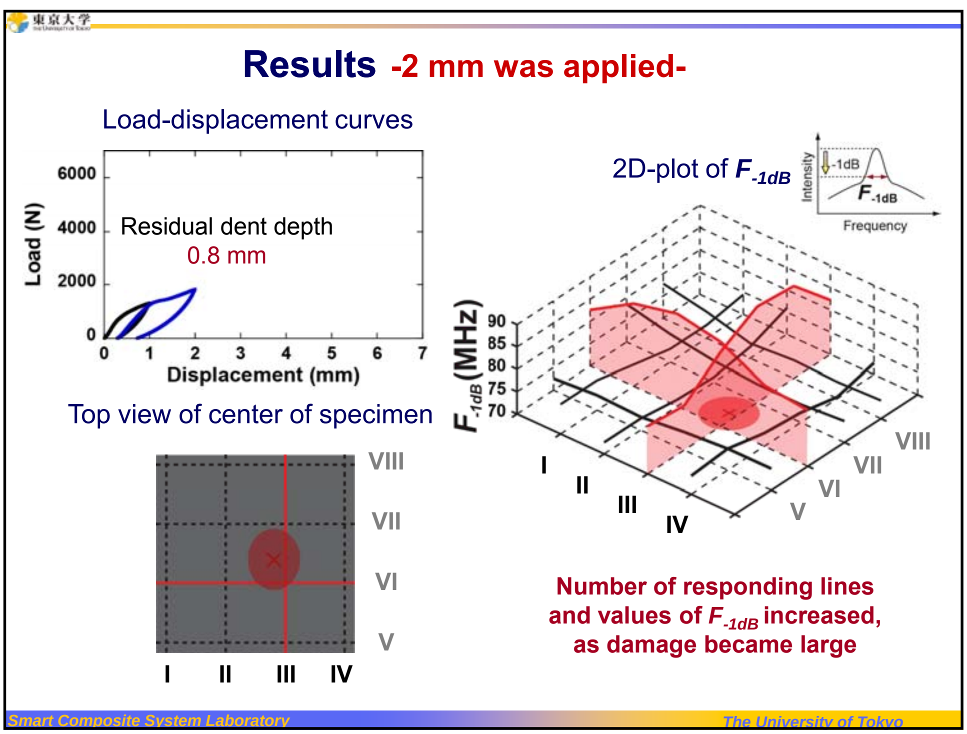
The University of Tokyo


東京大学
Results -2 mm was applied-
Load-displacement curves
Load (N)
6000
4000
2000
0
0 1 2 3 4 5 6 7
Displacement (mm)
Residual dent depth
0.8 mm
2D-plot of F_{-1dB}
Intensity
-1dB
F_{-1dB}
Frequency
F_{-1dB} (MHz)
90
85
80
75
70
I
II
III
IV
V
VI
VII
VIII
Top view of center of specimen
VIII
VII
VI
V
I II III IV
Number of responding lines
and values of F_{-1dB} increased,
as damage became large
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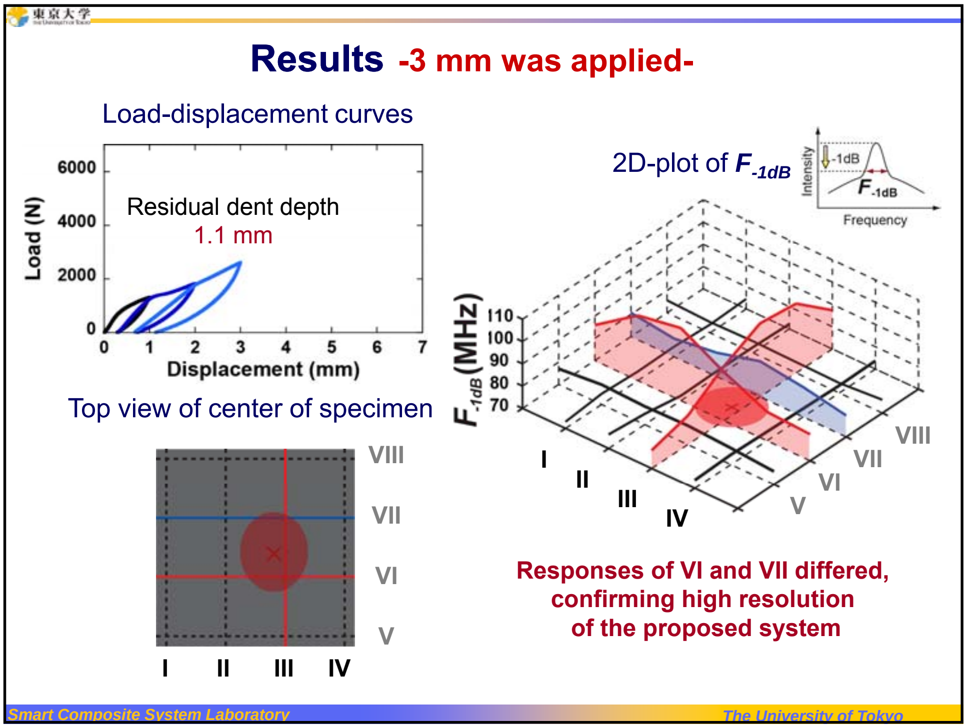
Results -3 mm was applied-
Load-displacement curves
Load (N)
6000
4000
2000
0
0 1 2 3 4 5 6 7
Displacement (mm)
Residual dent depth
1.1 mm
Top view of center of specimen
VIII
VII
VI
V
I II III IV
2D-plot of F-1dB
Intensity
-1dB
F-1dB
Frequency
F-1dB (MHz)
110
100
90
80
70
I
II
III
IV
V
VI
VII
VIII
Responses of VI and VII differed,
confirming high resolution
of the proposed system
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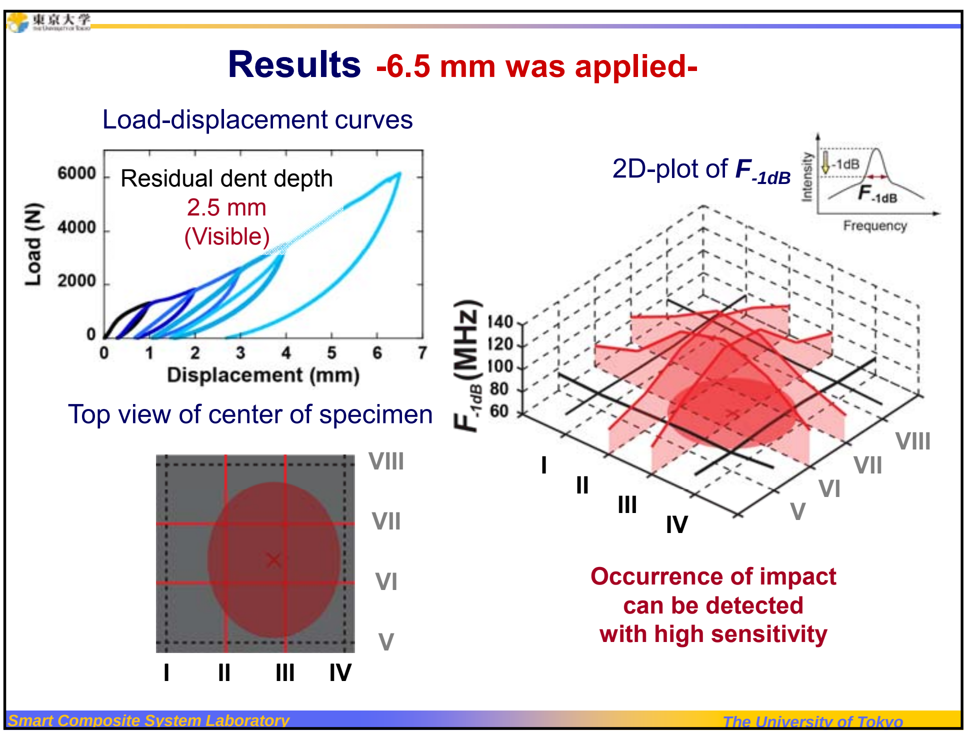
Results -6.5 mm was applied-
Load-displacement curves
Load (N)
6000
4000
2000
0
0 1 2 3 4 5 6 7
Displacement (mm)
Residual dent depth
2.5 mm
(Visible)
Top view of center of specimen
VIII
VII
VI
V
I II III IV
2D-plot of F-1dB
Intensity
-1dB
F-1dB
Frequency
F-1dB (MHz)
140
120
100
80
60
I
II
III
IV
V
VI
VII
VIII
Occurrence of impact
can be detected
with high sensitivity
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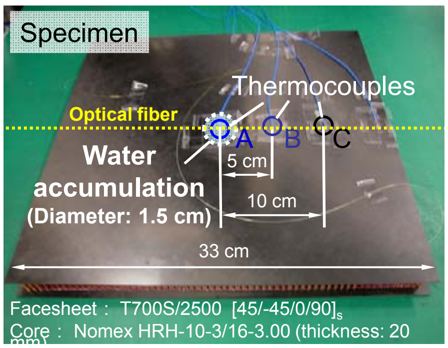
Water Detection in Honeycomb Sandwich Structures

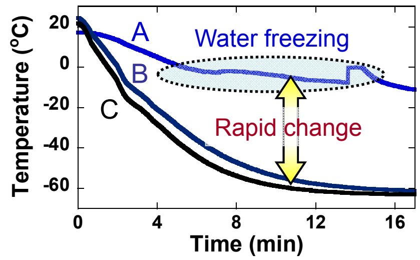
Water accumulation is difficult to detect for aircraft operators



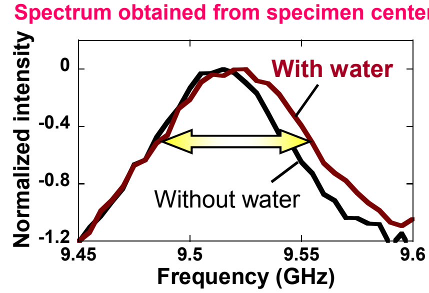
Optical fiber network was formed in adhesive layer between core and face

Temperature non-uniformity during takeoff (cooling) was utilized

Temperature change in condition simulating takeoff



Spectrum obtained from specimen center



(1) Structural Health Monitoring Group, NEDO Smart Material/Structure System Program (FY1998-2002)

(2) Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures (ACS-SIDE) Project, METI Advanced Material & Processing for Next-Generation Aircraft Structure Program (FY2003-2007)

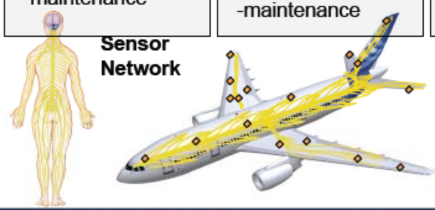
(3) Integrated High-Resolution Distributed Strain Monitoring with Embedded Optical Fibers in Composite Structures (FY2007-)

⇩

Application of SHM Technology to Near-Future Affordable Composite Aircraft and Spacesraft

Airbus Future Request – Structural Health Monitoring

Generation 0	Generation 1	Generation 2	Generation 3
• Structure testing application • Benefit: - Structure analysis & testing (e.g. A380)	• In-service aircraft, off-line sensor systems (TR: 2009) • Benefit: -maintenance	• In-service aircraft, on-line sensor systems (TR: 2013) • Benefit: -weight saving component level -maintenance	• In-service aircraft, fully integrated sensor systems (TR: 2018) • Benefit: -weight saving aircraft level -maintenance

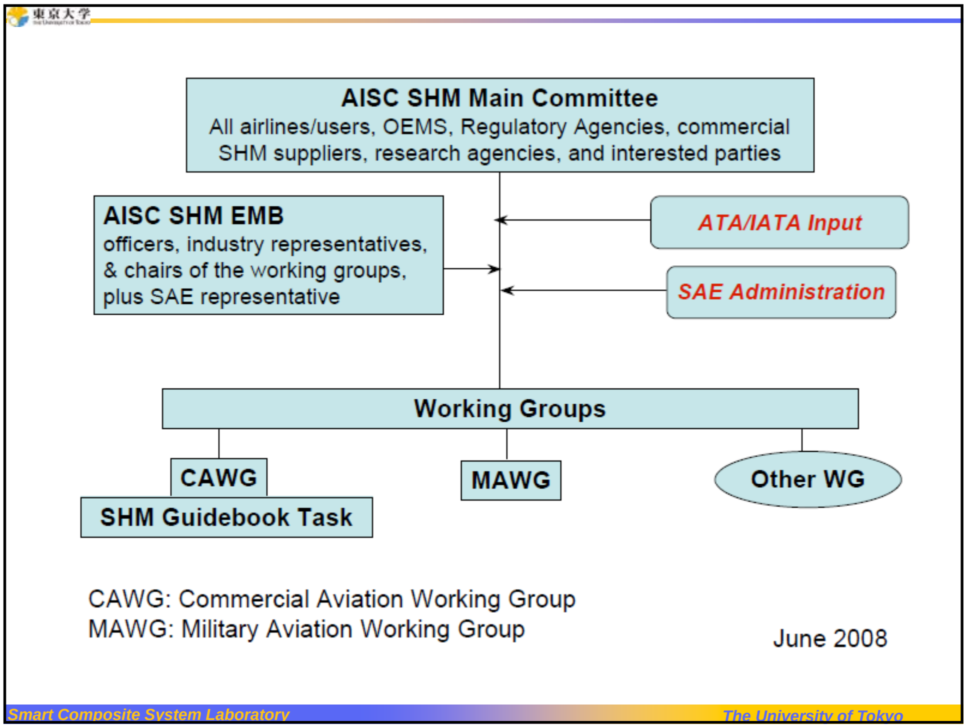


→ Stepwise approach towards SHM development
→ Global integration: Airlines/Authorities/Suppliers

Aerospace Industry Steering Committee (2006)

- Manufacturers:
  - Boeing
  - Airbus
  - EADS
  - Embraer
- System Integrators:
  - BAE
  - Honeywell
- Regulatory Agencies:
  - FAA
  - EASA
  - US AF
  - US Army
- Research Organizations:
  - Stanford University
  - Sandia National Lab
  - Air Force Research of Scientific Research
  - University of Tokyo
  - University of Sheffield
  - NASA
- Operators/Users:
  - ATA

"The roadmap to mature and commercialize aerospace SHM technologies is greatly encumbered by the lack of standards guiding how SHM should be implemented, certified and deployed to create value."


東京大学
AISC SHM Main Committee
All airlines/users, OEMS, Regulatory Agencies, commercial SHM suppliers, research agencies, and interested parties
AISC SHM EMB
officers, industry representatives, & chairs of the working groups, plus SAE representative
ATA/IATA Input
SAE Administration
Working Groups
CAWG
SHM Guidebook Task
MAWG
Other WG
CAWG: Commercial Aviation Working Group
MAWG: Military Aviation Working Group
June 2008
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