Workshop on Next Generation Transport Aircraft
University of Washington, Seattle, WA
Friday 29th March, 2013

GRADUATE SCHOOL OF FRONTIER SCIENCES
THE UNIVERSITY OF TOKYO

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

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(Todai-JAXA Center for Composites)
Graduate School of Frontier Sciences
The University of Tokyo

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

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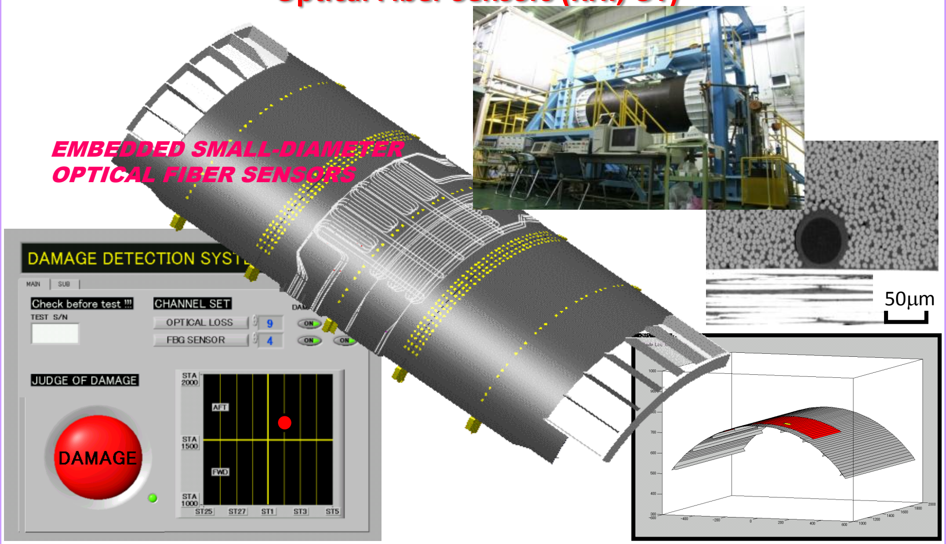
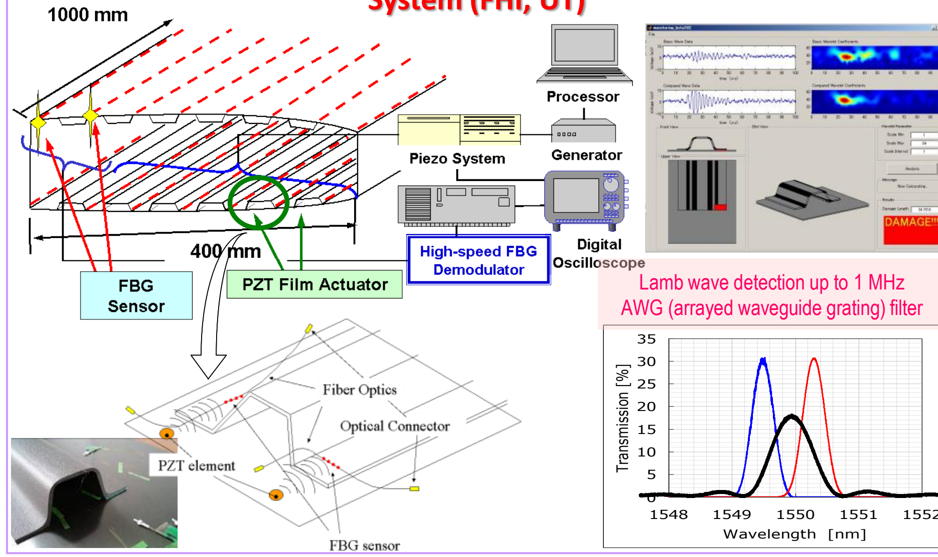
Development of Optical Fiber Based SHM System

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

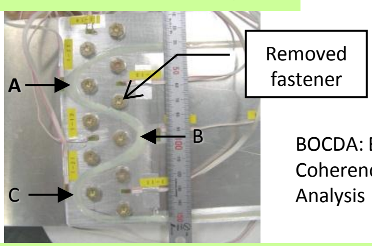


Debond Monitoring Using PZT-FBG Hybrid Active Damage Sensing System (FHI, UT)



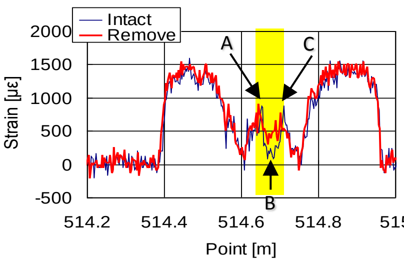
Distributed and Dynamic Strain Measurement by BOCDA Technique (MHI, UT)

Fastener Joint Monitoring



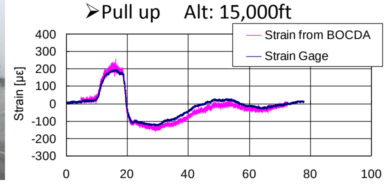
BOCDA: Brillouin Optical Coherence Domain Analysis

Current Status
Length Resolution: 1-5 cm
Dynamic Response: 10 Hz

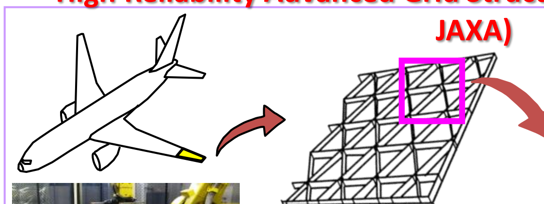


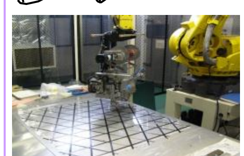
Flight Test Bed and On-board BOCDA system

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

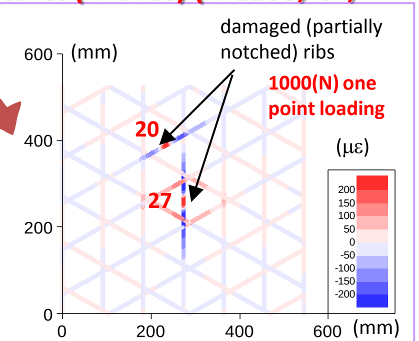


High Reliability Advanced Grid Structures (HRAGS) (MELCO, UT, JAXA)



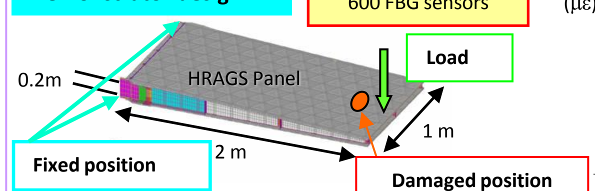


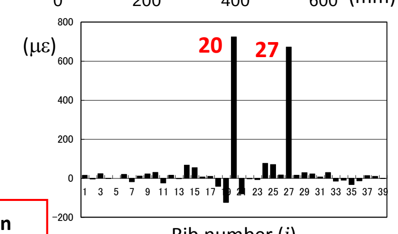
6 axis controlled robot
(Tape prepreg & Optical fiber)



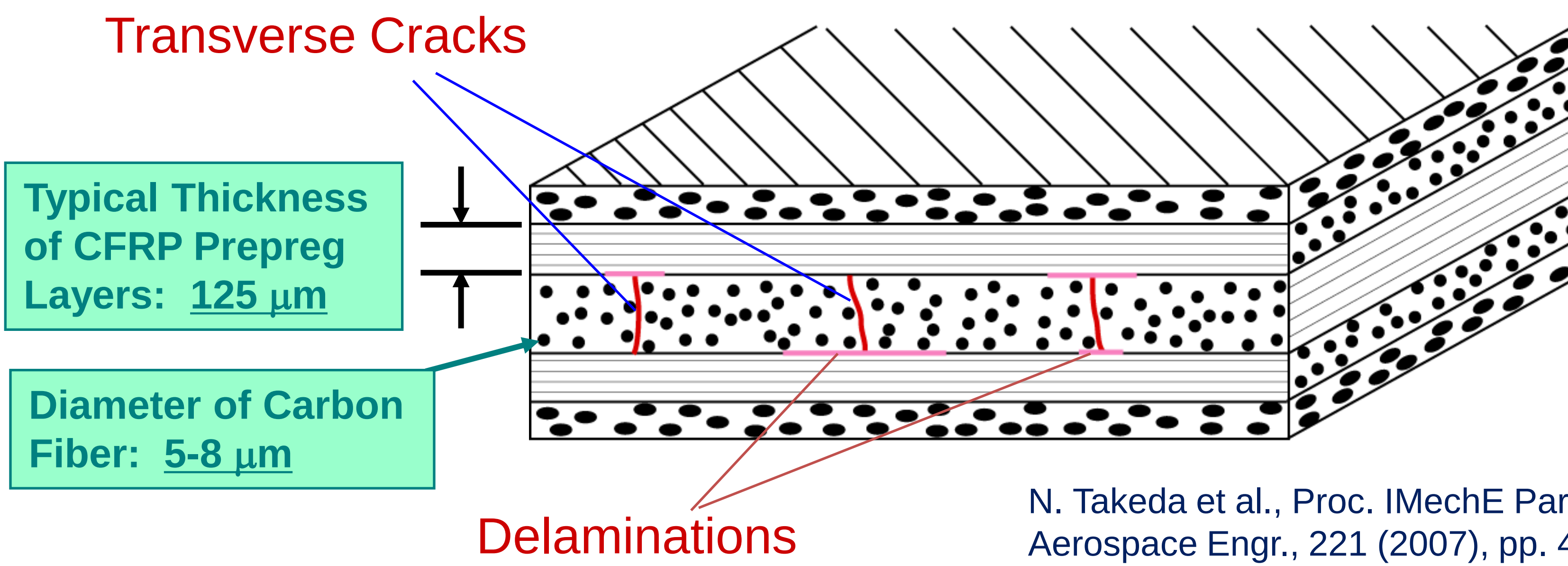
Demonstrator design

BOX structure
600 FBG sensors



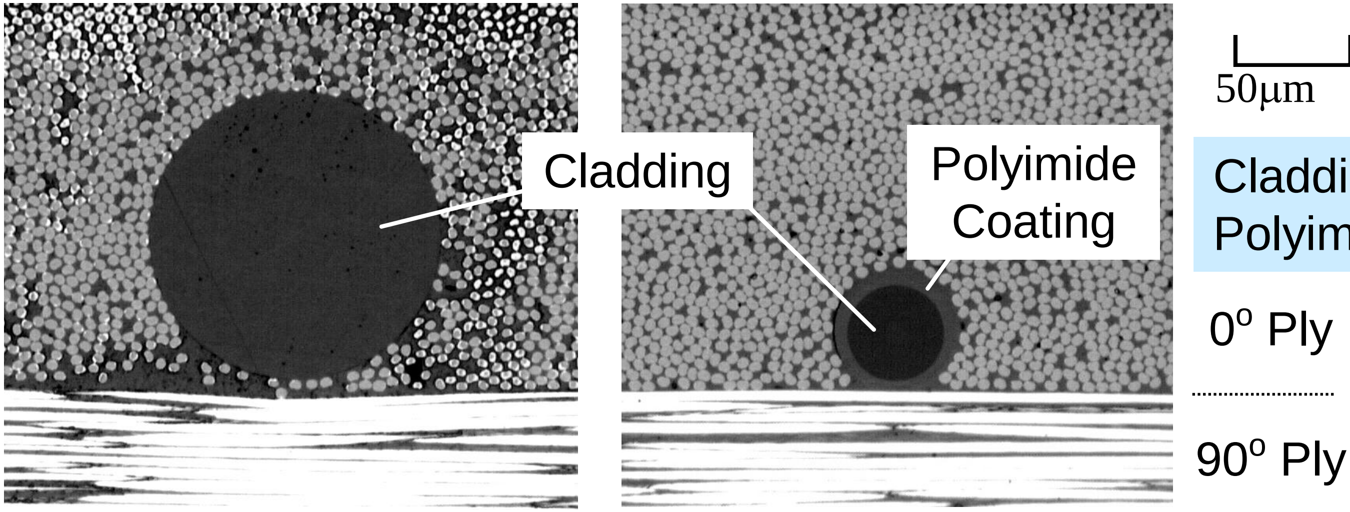


Development of Small-Diameter Optical Fiber Sensor



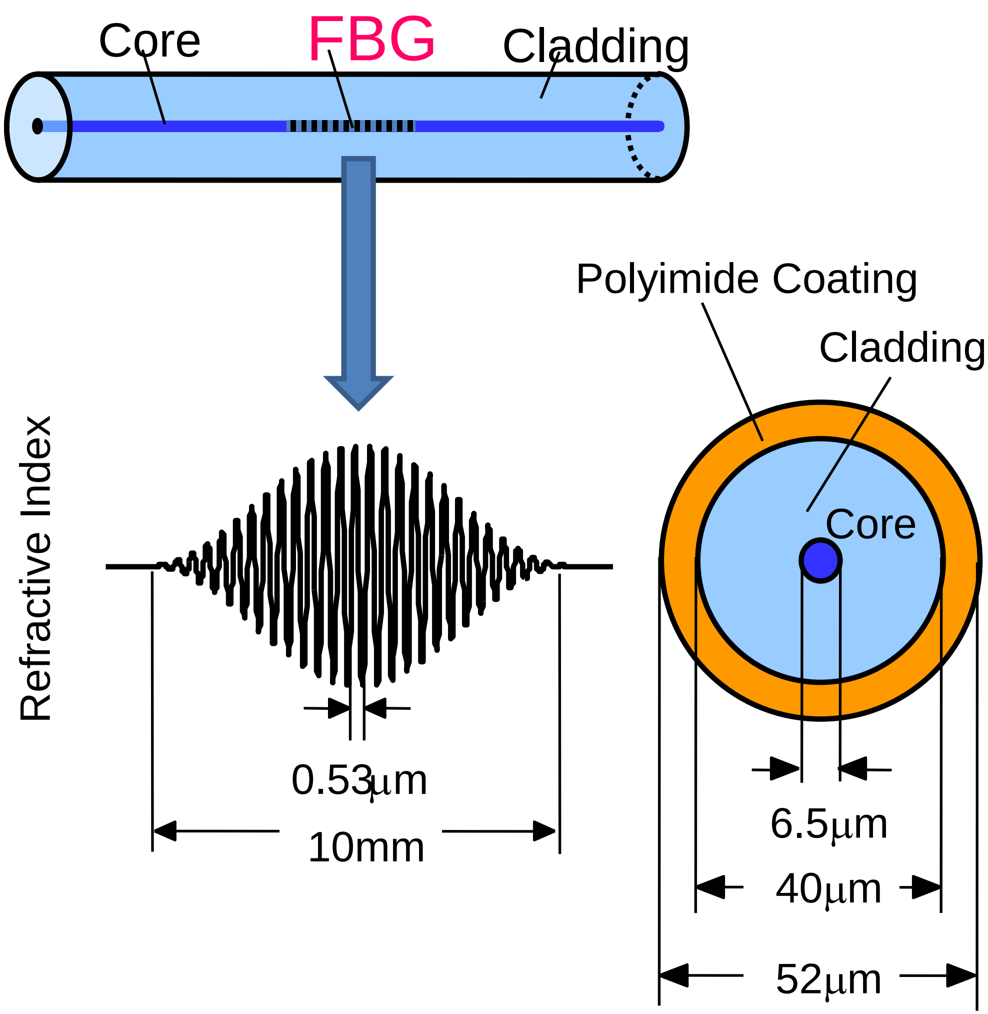
N. Takeda et al., Proc. IMechE Part G: J. Aerospace Engr., 221 (2007), pp. 497-508.

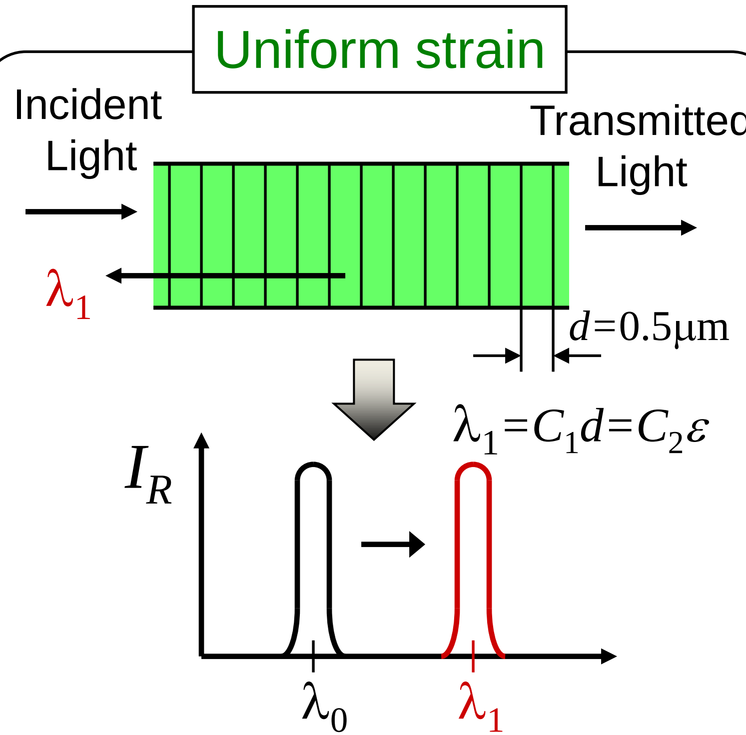
Small-diameter FBG sensors for detection of transverse cracks or delamination



Cladding: ϕ 40μm
Polyimide Coating: ϕ 52μm

Small-Diameter Optical Fiber Sensor





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

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

ppp-BOCDA – Distributed Strain Sensing

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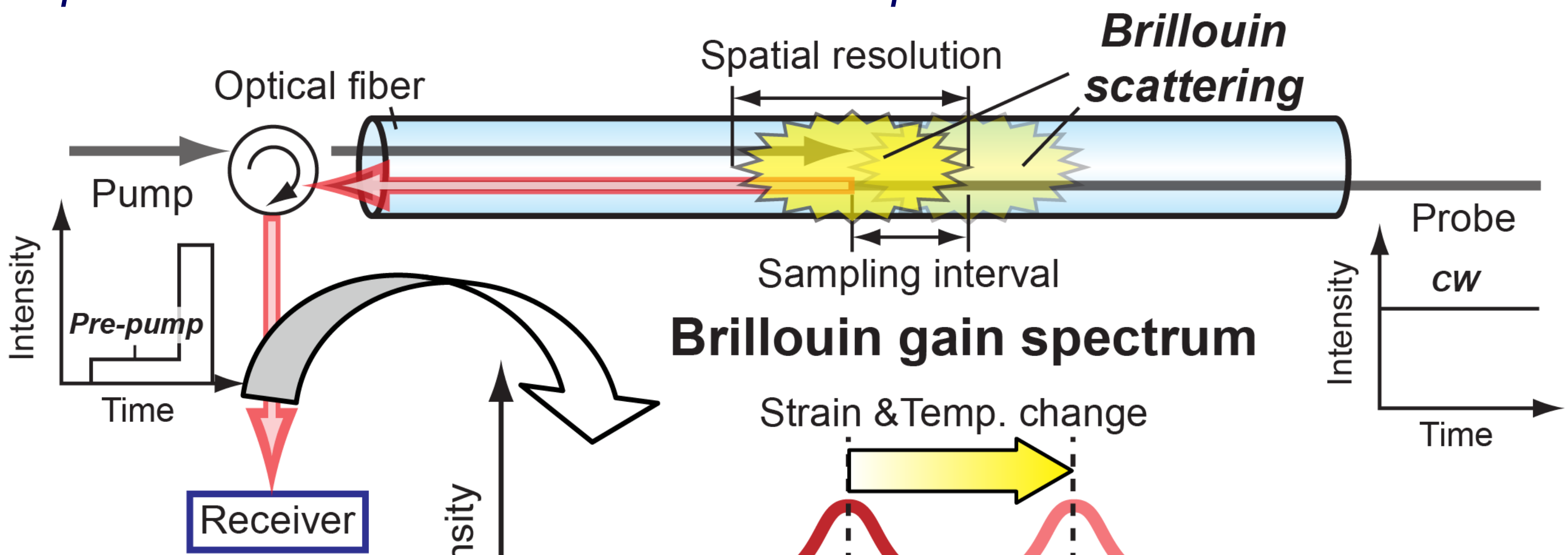
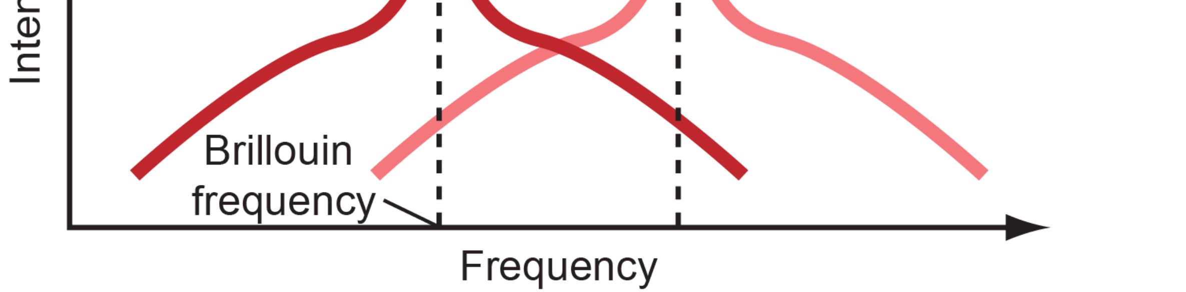
Pre-**p**ump **P**ulse **B**rillouin **O**ptical **T**ime **D**omain **A**nalysis

High spatial resolution distributed strain/temperature measurement





Neubrescope
(Neubrex Co., Ltd)

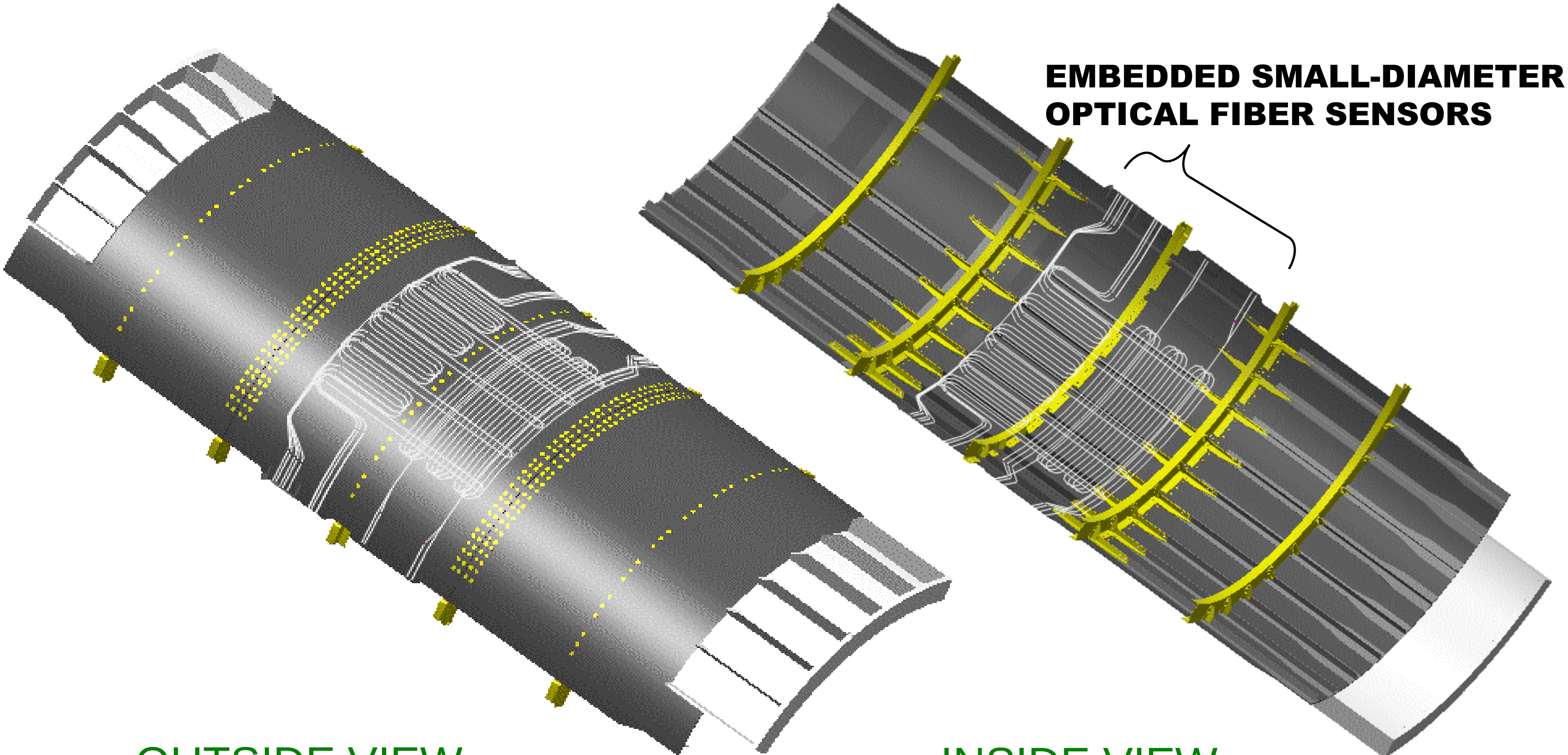
Spatial resolution: **2 cm** Sampling interval: 5 cm

Sensing range: > 1 km (whole length of optical fiber)

Simultaneous temperature and strain measurement is possible

Arrangement of Embedded Small-Diameter Optical Fibers

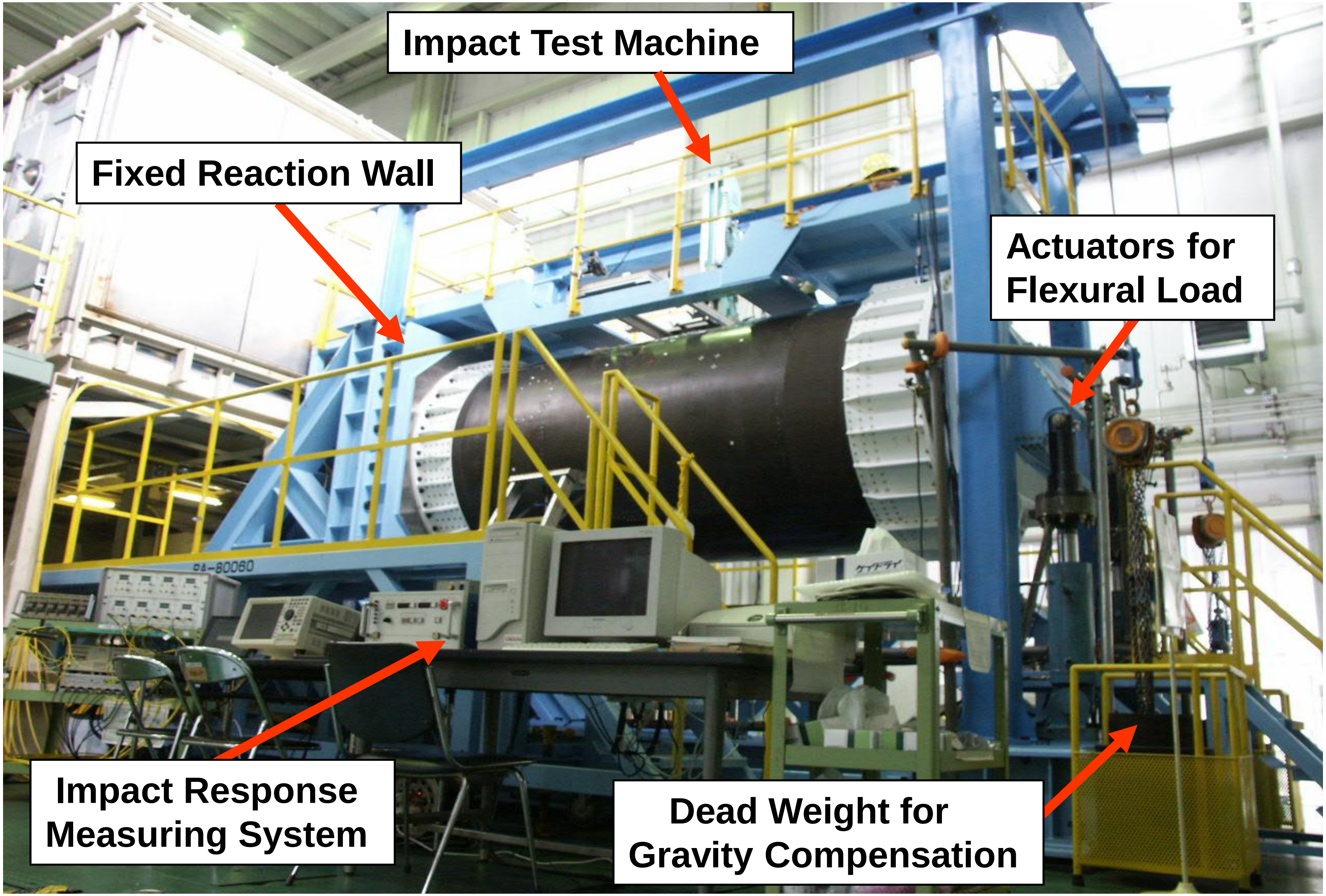
- SKIN, STRINGER AND SKIN/STRINGER : 20 Optical Fibers including 6 FBG Sensors



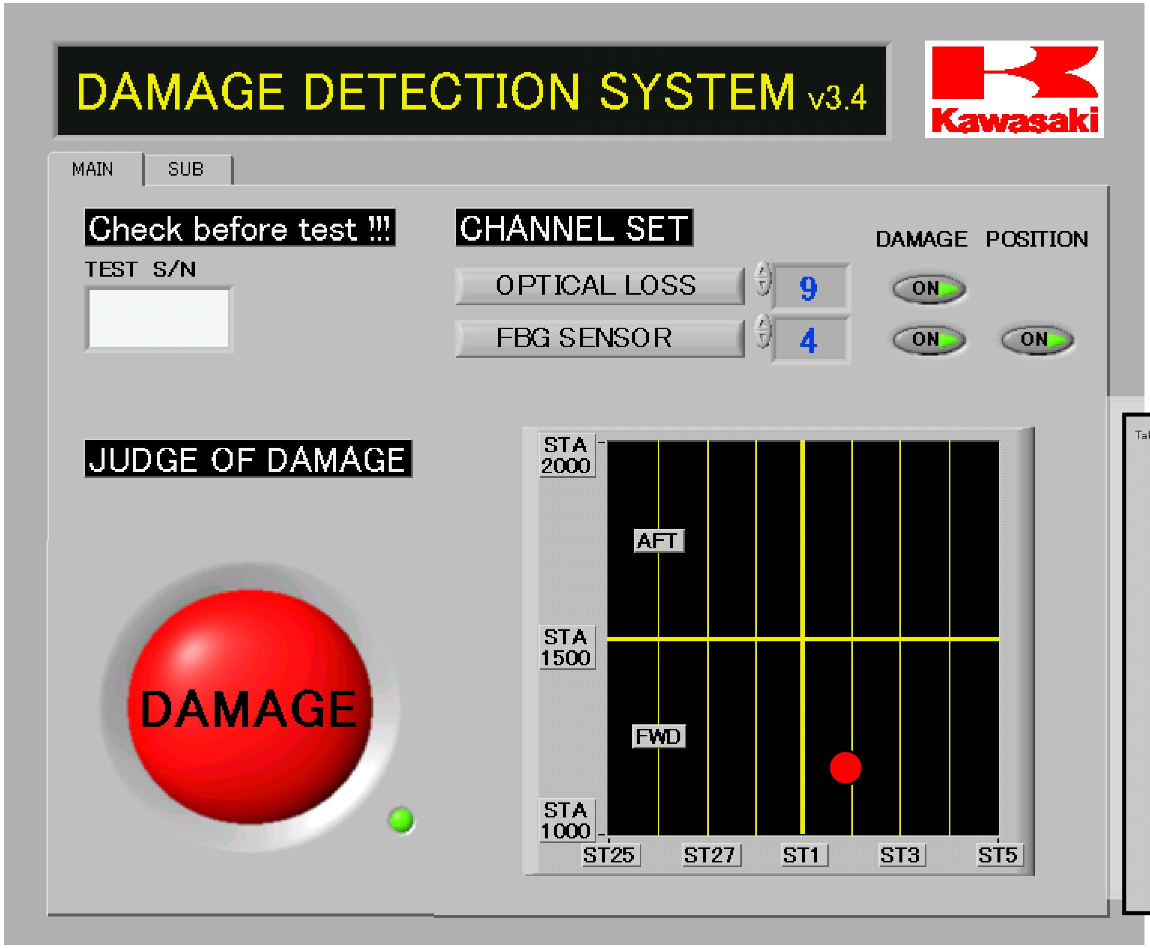
OUTSIDE VIEW

INSIDE VIEW

Impact Damage Detection Test

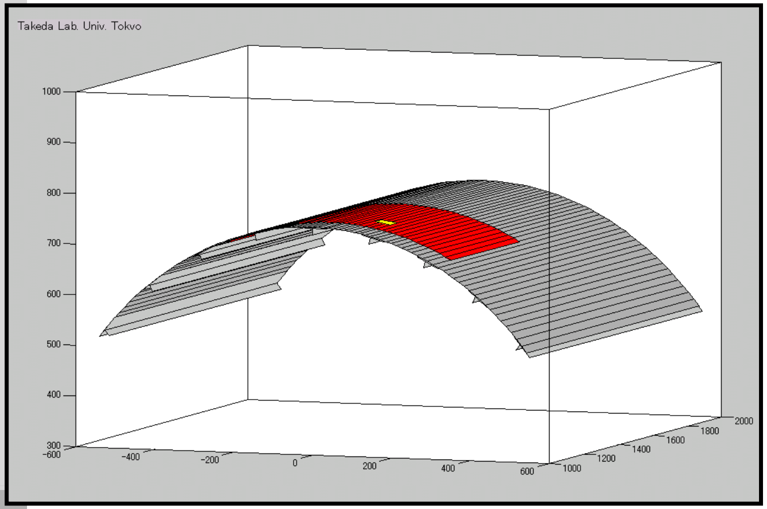


Impact Damage Detection System



ANALYSIS/EVALUATION

(by Kawasaki Heavy Industries, Ltd.)



VISUALIZATION

(by Takeda Lab, Univ. Tokyo)

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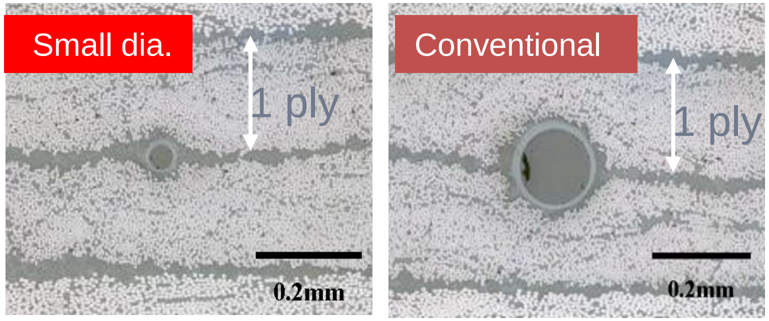
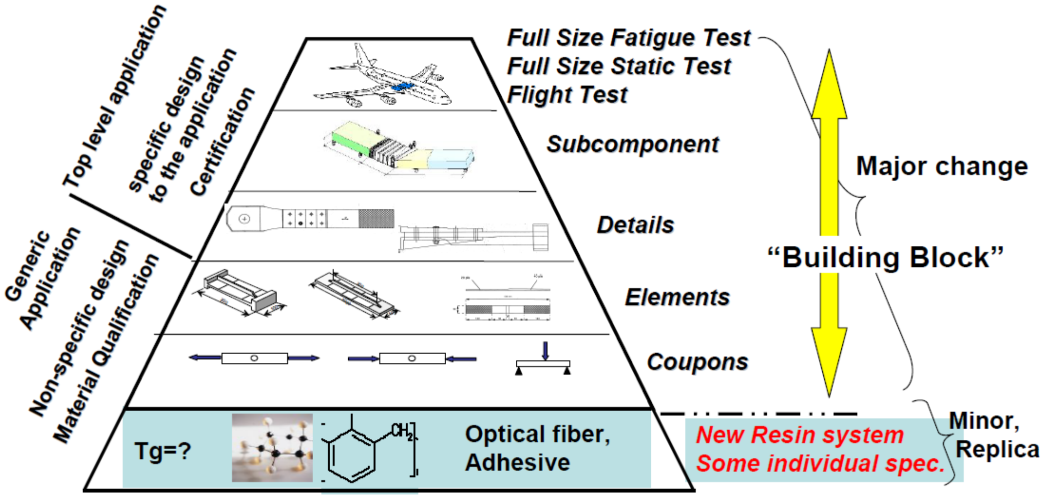
- No disturbance concept
  - No strength reduction due to optical fiber embedment



Cross section of the embedded O.F.



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

Some type of specimens, such as co-cure, co-bonding and 2ndary bonding are required in some items, in which adhesive properties are evaluated.

Preparation of SHM Guidebook for Aircraft SAE G-11SHM Committee

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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(Lufthanza, Delta, ANA)
Research Organization (Stanford Univ., Univ. Tokyo, Cranfield Univ., RIMCOF)

Application of Optical Fiber Sensors for Repair

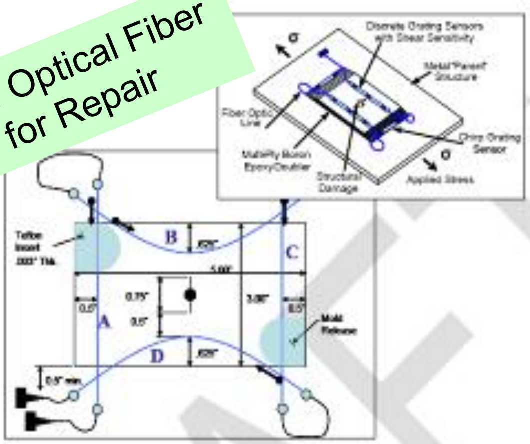

FIGURE 19 - FIBER BRAGG GRATING SENSOR LAYOUT AND ENGINEERED FLAWS IN BONDED COMPOSITE REPAIR TEST SPECIMENS

FIGURE 20 - FIBER OPTIC SENSORS IN ADHESIVE BONDLINE AND FO MONITORING EQUIPMENT

SAE Aerospace An SAE International Group

AEROSPACE RECOMMENDED PRACTICE

SAE ARP6461

Issued Proposed Draft 2012-11-28

Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

RATIONALE

The development of Structural Health Monitoring (SHM) technologies to achieve Vehicle Health Management objectives in aerospace applications is an activity that spans multiple engineering disciplines. It is also recognized that many stakeholders: Regulatory Agencies, Airlines, Original Equipment Manufacturers (OEM), Academia and Equipment Suppliers are crucial to the process of certifying viable SHM solutions. Thus a common language (definitions), framework of solution types, and recommended practices for reaching those solutions, are needed to promote fruitful and efficient technology development.

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Manufacturing Issues in Large-Scale Composite Structures

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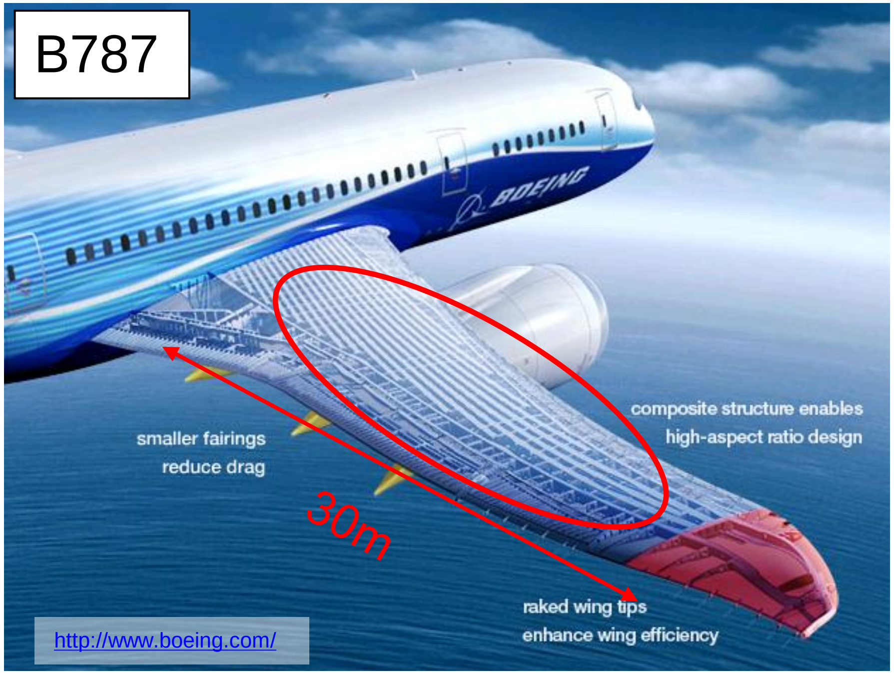
Wing panel of Boeing 787 manufactured by MHI



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

Life Cycle Monitoring (LCM)

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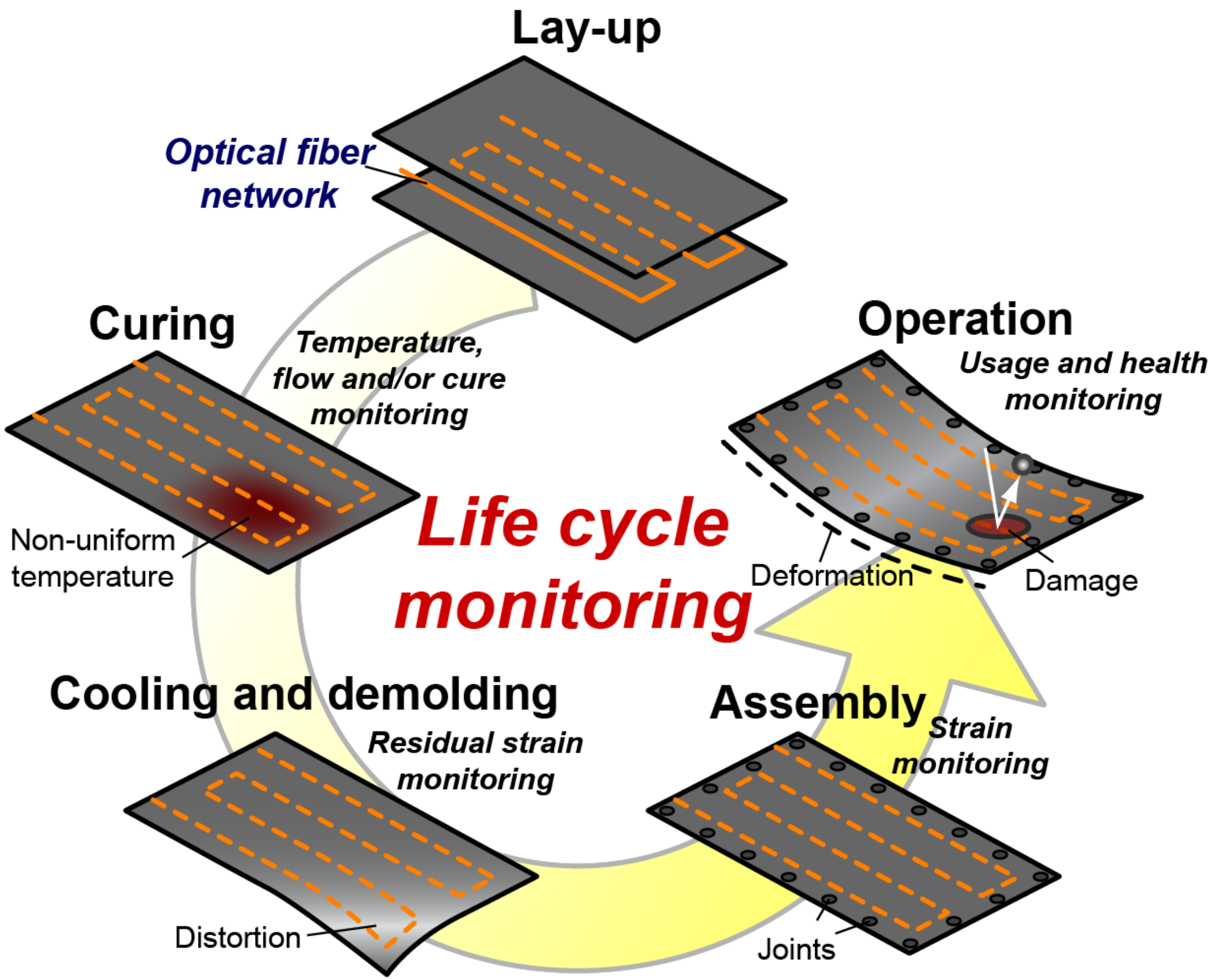
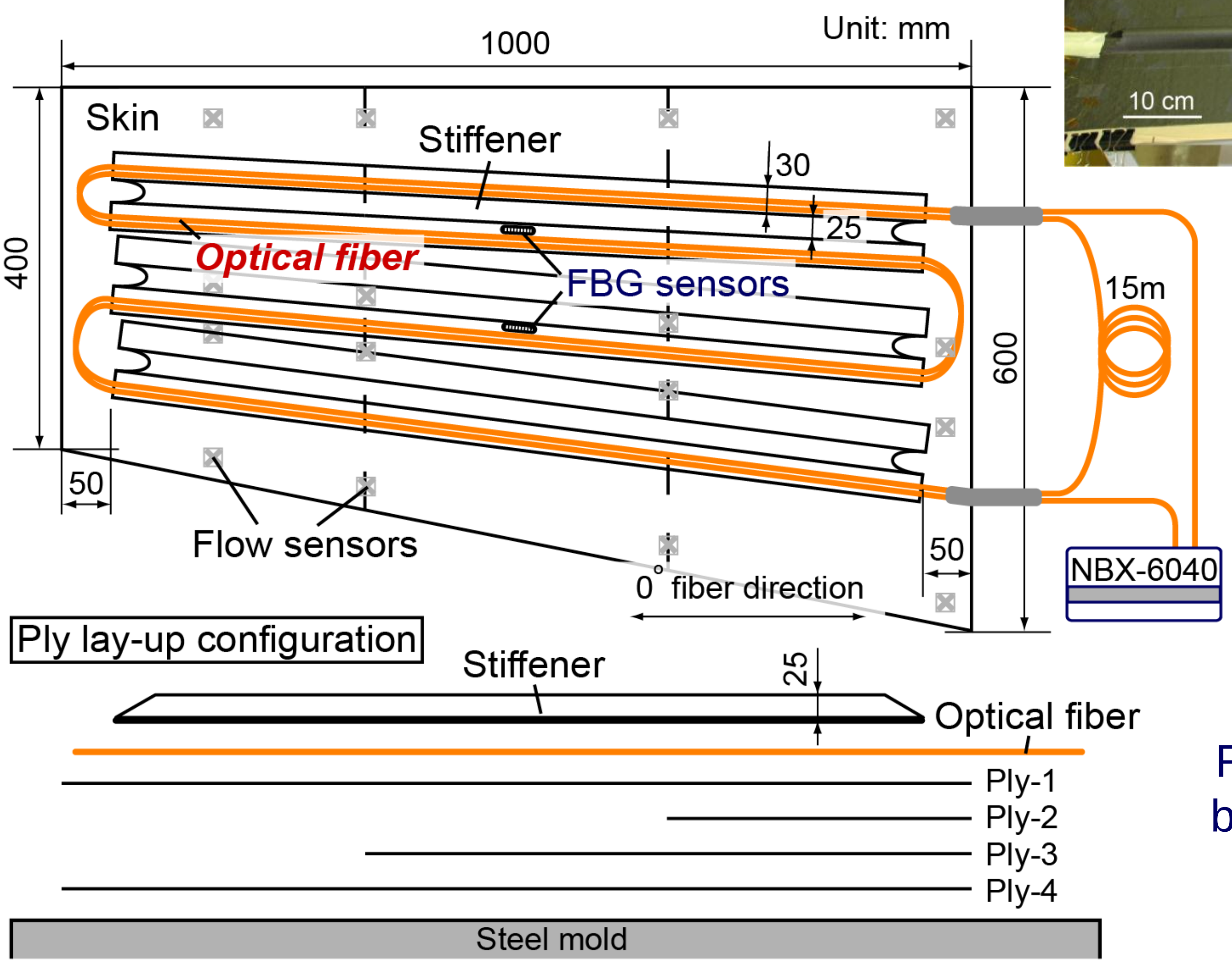
Embedded fiber-optic network, formed during lay-up as biological neuron, continuously monitors internal state of composite structure throughout its life

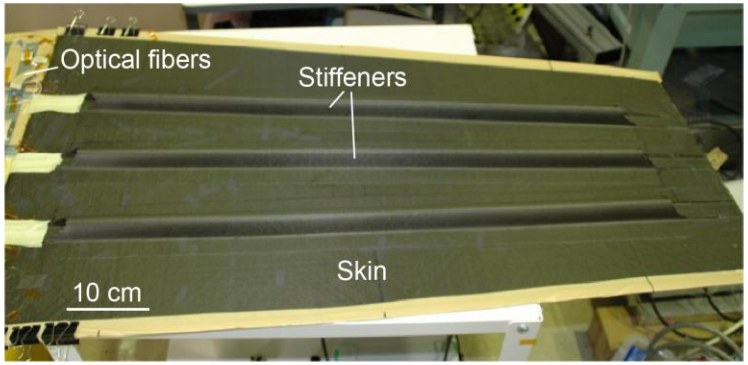


Optical Fiber Distributed Strain Monitoring

S. Minakuchi et al., Composites: Part A, 42 (2011), pp. 669-676.

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

Thermal Residual Strain Distribution

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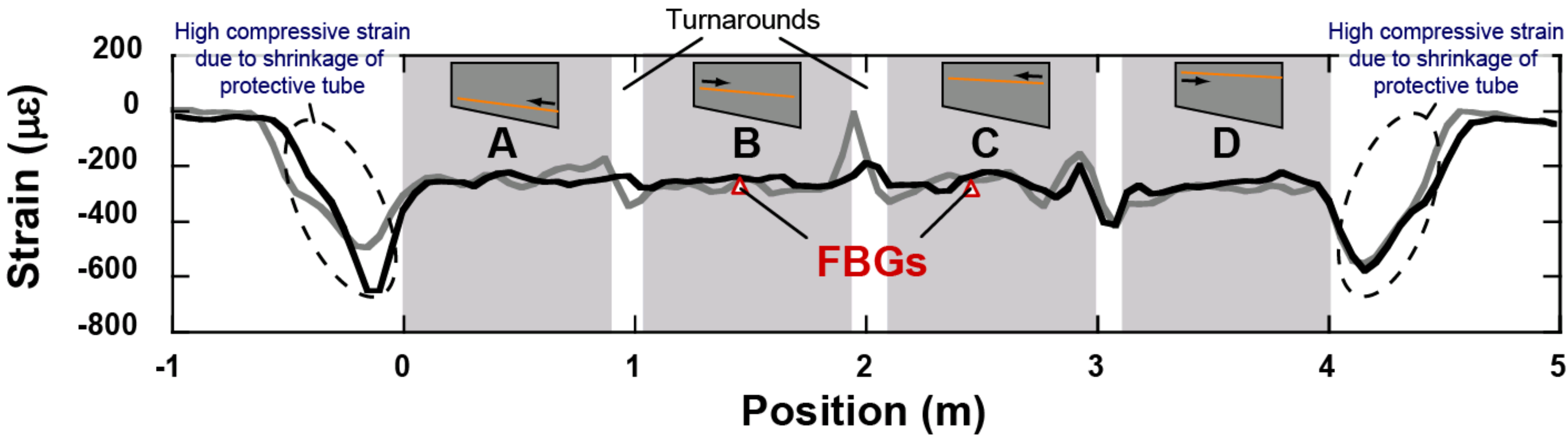
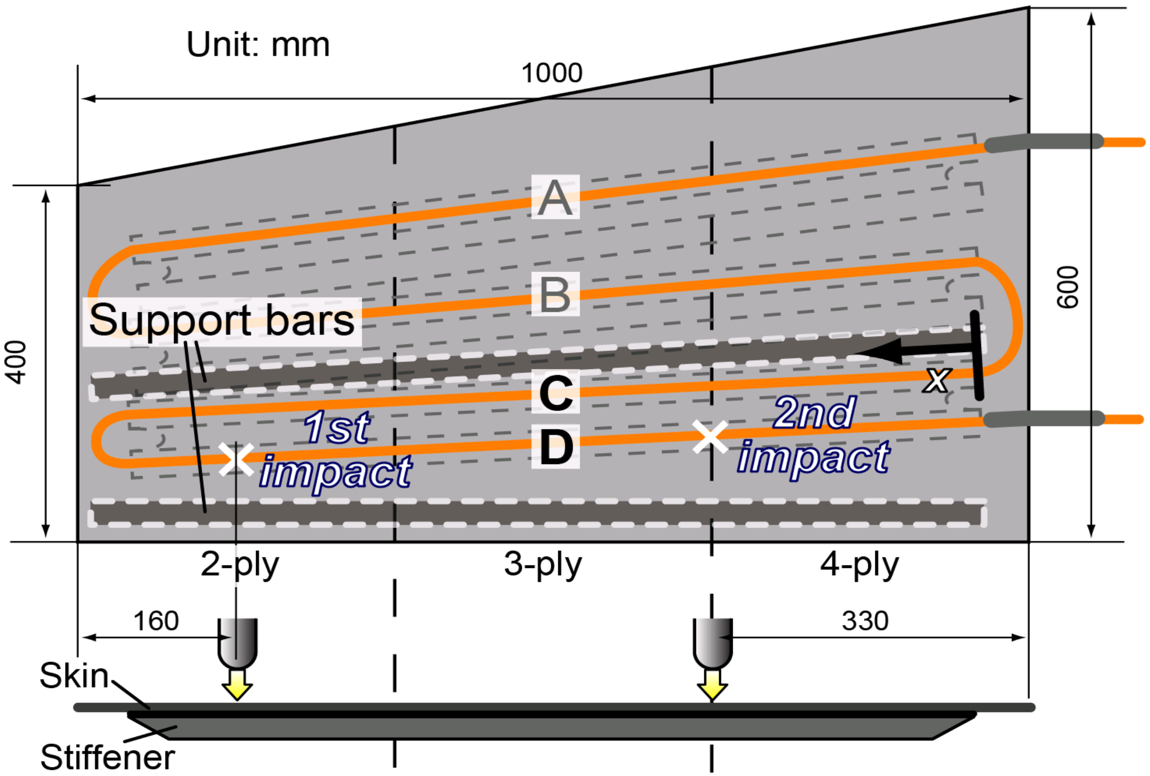


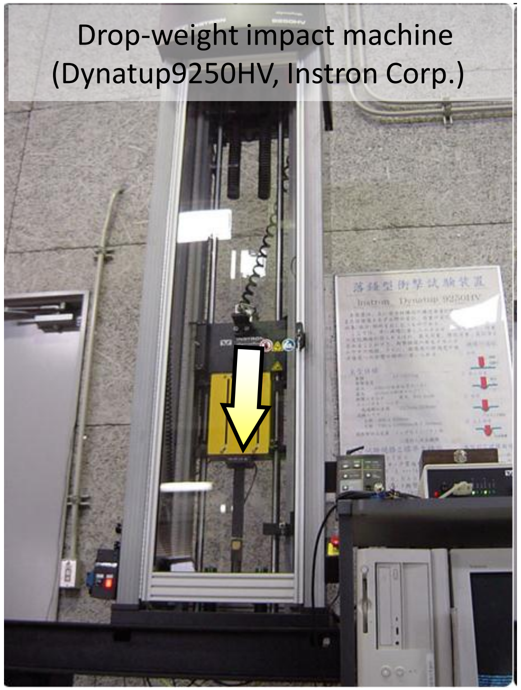
•Two lines again measured quite similar strain distributions

•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.

Assembly and Impact Tests





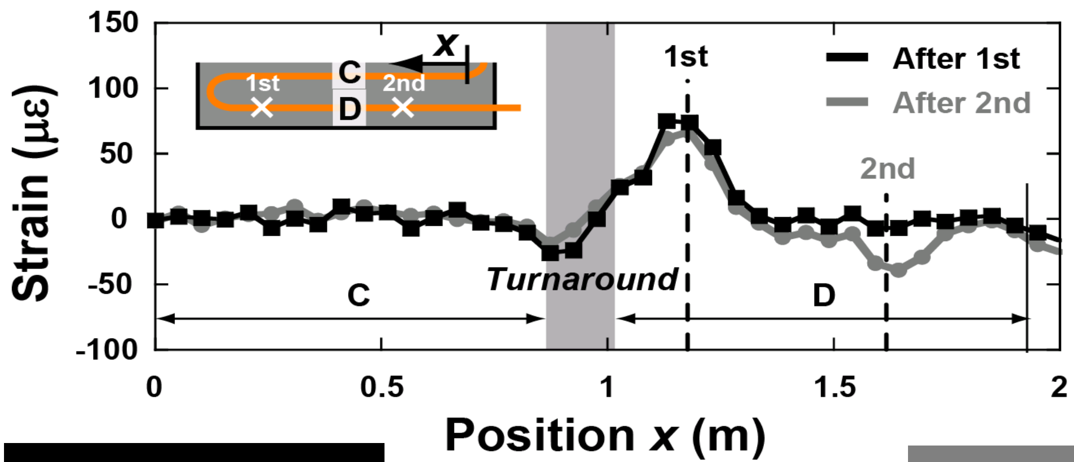
1st: 60J, 2nd: 90J

•First the specimen was fully clamped on steel bars (simulated assembly)

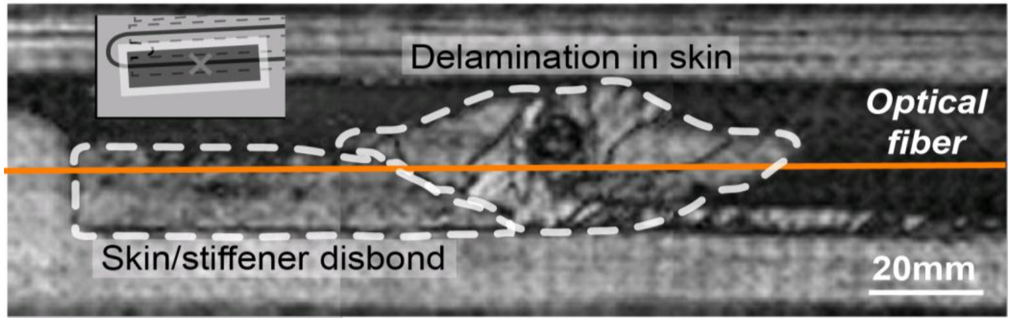
•Low velocity impact loadings were then applied directly above foot of stiffener by a drop-weight impact machine

Strain changes due to simulated assembly and impact damages was evaluated

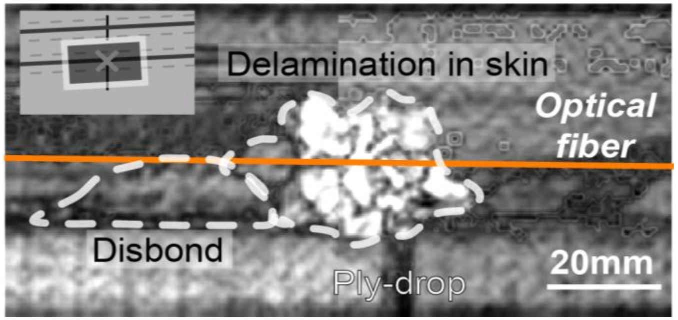
Ultrasonic Images v.s. Strain Distribution



1st impact (60J)



2nd impact (90J)



•Strain increase at <u>1st impact point</u> can be explained as resulting from releasing compressive thermal residual strain by skin/stiffener disbond

•Strain decrease induced around <u>2nd impact point</u> can be attributed to visually-observed concave deformation of impacted area

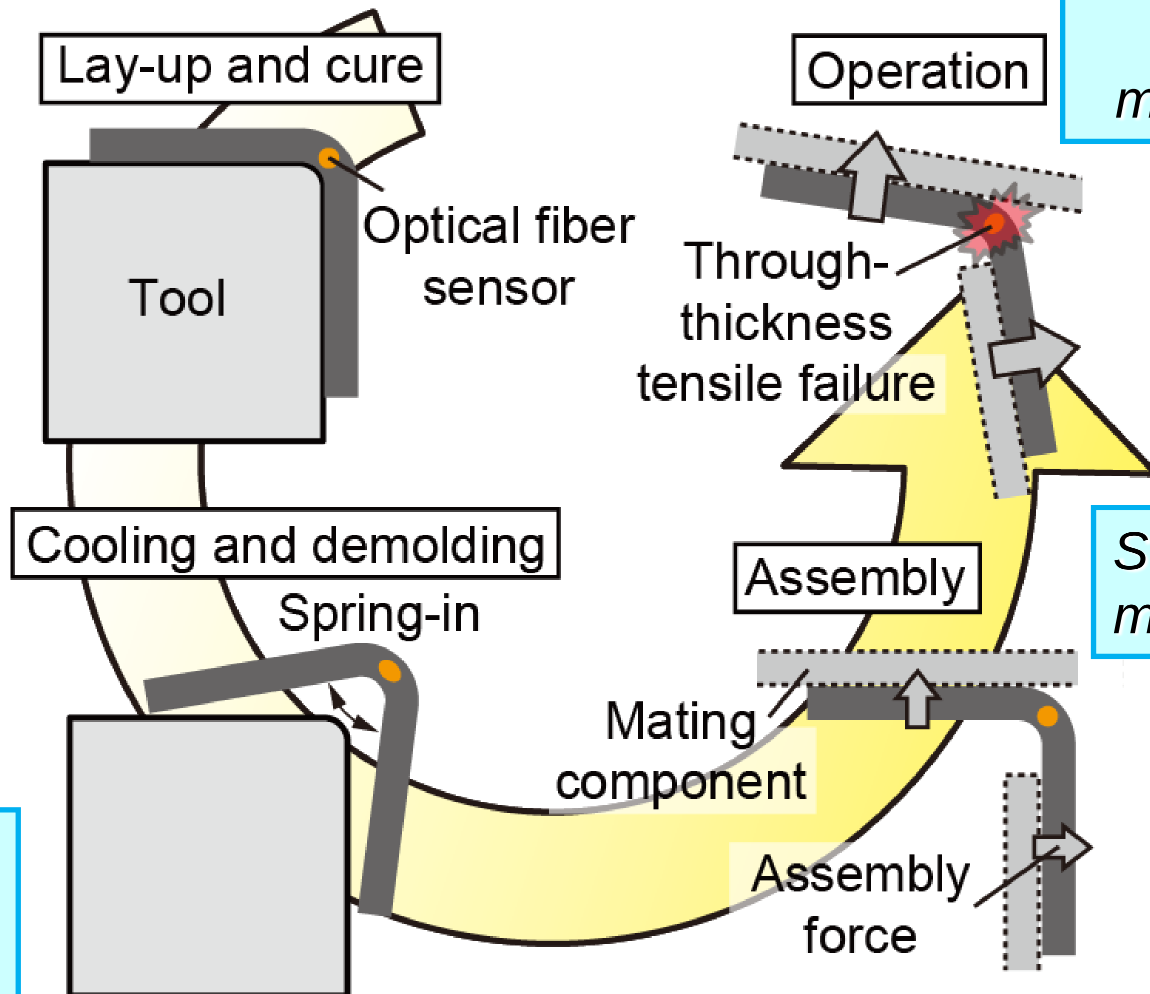
After impact tests, embedded fiber-optic system still worked correctly and mechanical strain distribution around damaged area could be obtained

Life Cycle Monitoring of Curved Panel - Spring-in

S. Minakuchi et al. Composites Part A, Vol. 48 (2013), pp.153-161.

Life Cycle Monitoring

Usage and health monitoring



Strain monitoring

Residual strain monitoring

Spring-in of Curved Panel

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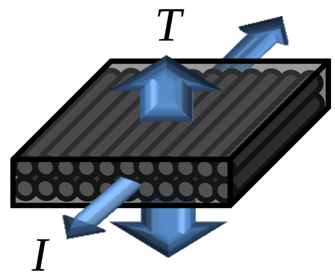
Residual Strain

- Cure shrinkage
- Heat contraction depending on material direction

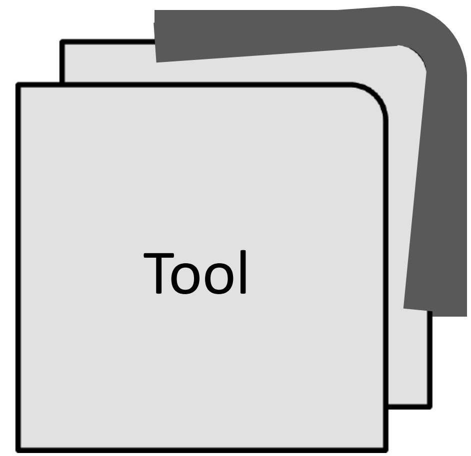
Spring-in

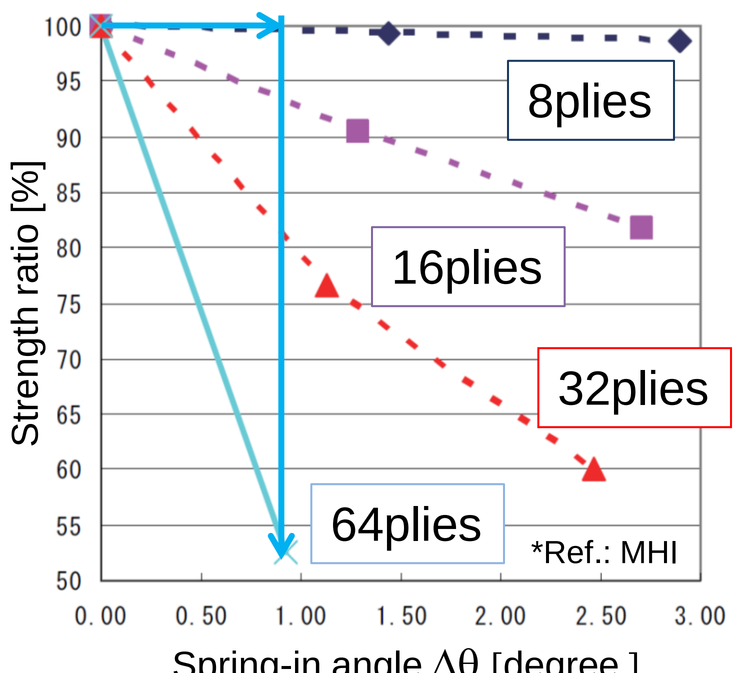
$$\frac{\Delta\theta}{\theta} = (\alpha_I - \alpha_T)\Delta T + (\beta_I - \beta_T)$$

α : Thermal expansion coefficient
β : Curing contraction rate



L-shaped CFRP





- 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-

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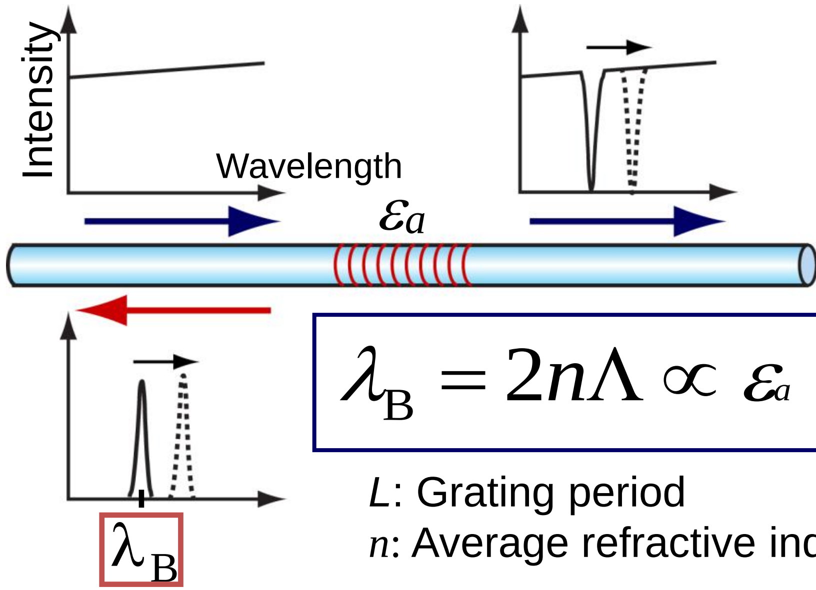
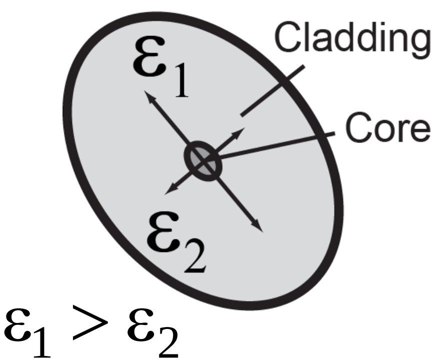


$$\lambda_B = 2n\Lambda \propto \varepsilon_a$$

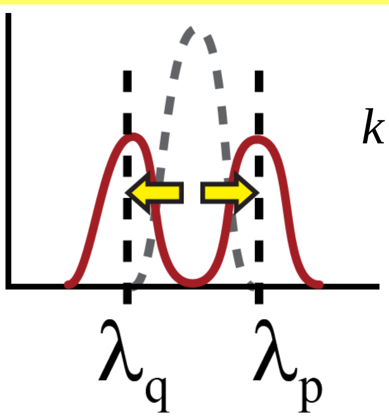
L: Grating period
n: Average refractive index

Birefringence Effect

Sectional view



Reflection Spectra



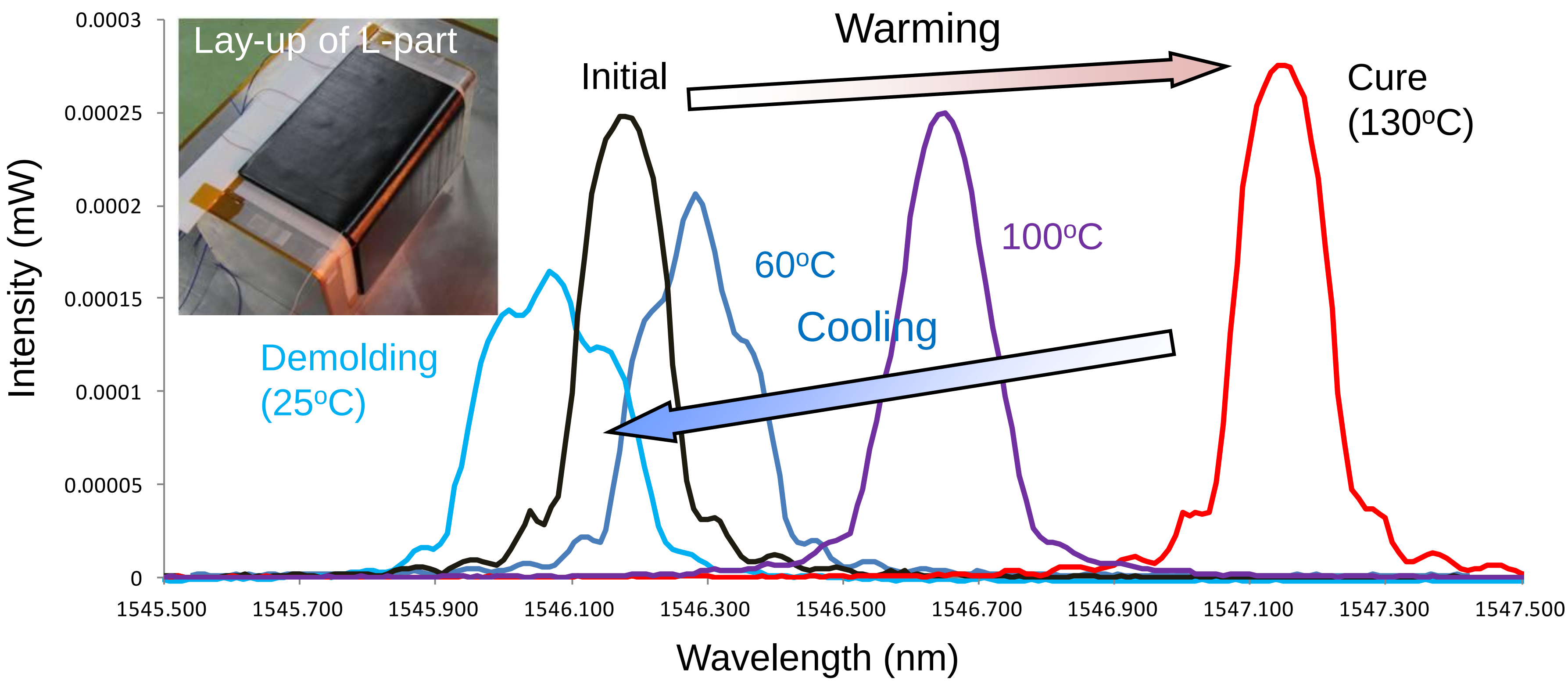
$$\lambda_p - \lambda_q = k\,(\varepsilon_1 - \varepsilon_2)$$

$$k = \frac{n_0^2 \lambda_0}{2}\left(p_{12} - p_{11}\right)$$

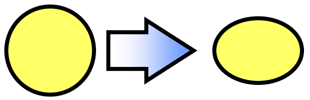
n_0: Initial average refractive index
λ_0: Initial wavelength
p_{11}, p_{12}: Photoelastic constants

Peak wavelength difference is proportional to non-axisymmetric strain $\varepsilon_d = (\varepsilon_1 - \varepsilon_2)/2$ in optical fiber section

Change in Reflection Spectra during Curing Process



Spectral shape changed during cooling and demolding process due to cross-sectional deformation of optical fiber (birefringence effect)



Using spectral shape, we can <u>quantitatively</u> evaluate non-axisymmetric strain ε_d or through-the-thickness stain

Non-axisymmetric Strain during Cooling/Decompressing Process

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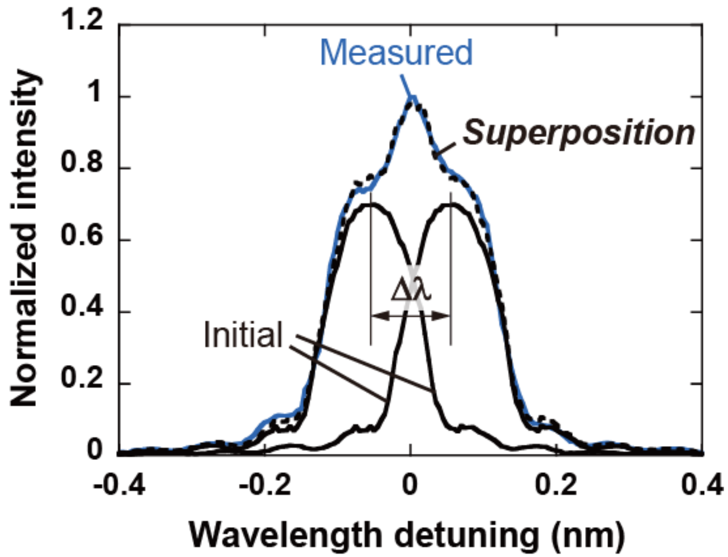

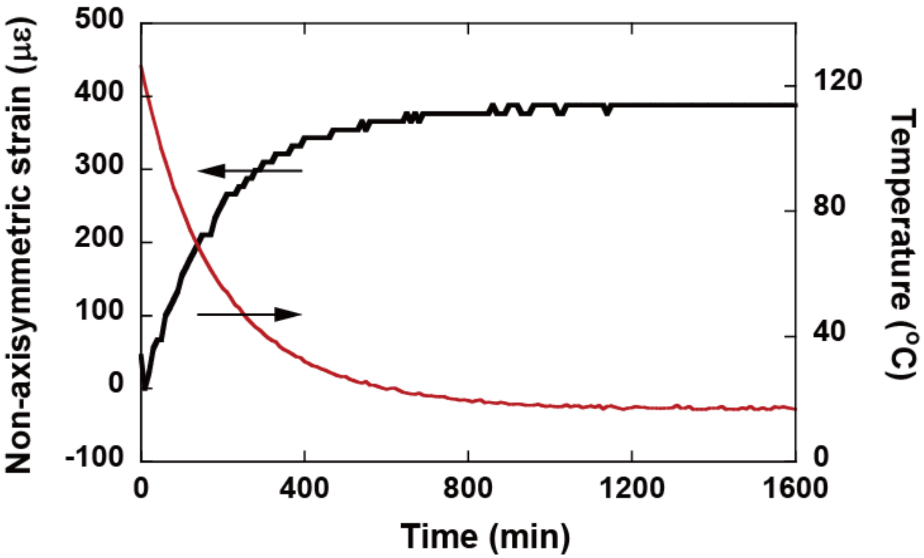

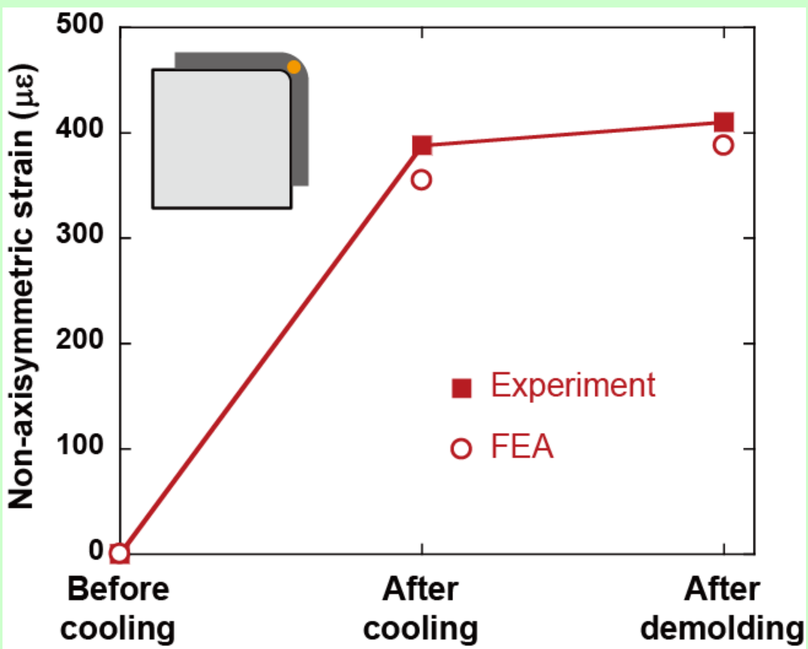

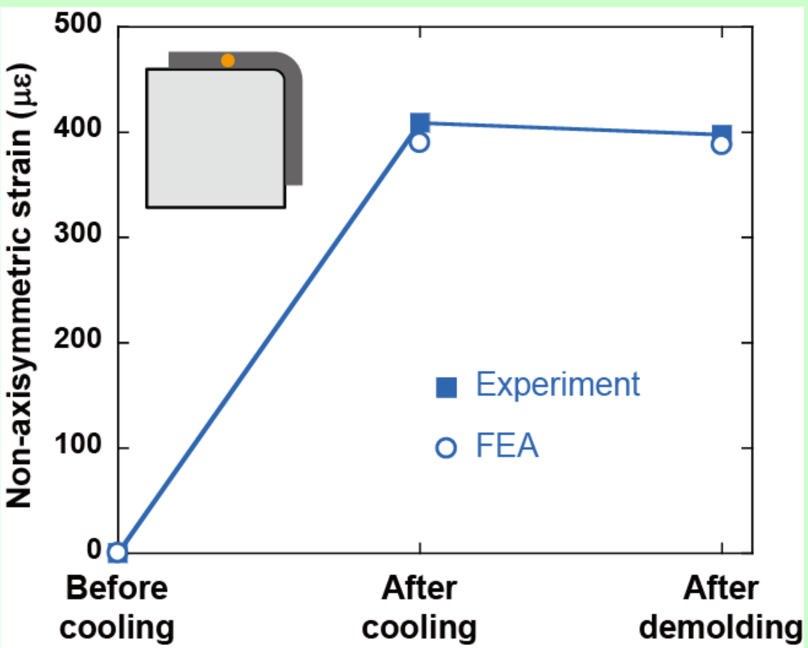

Strength v.s. Spring-in Angle

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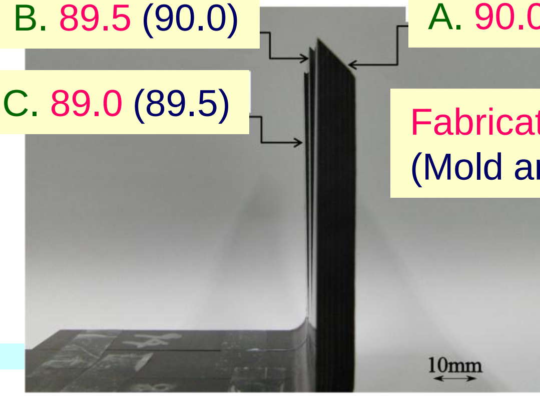
Specimens with different corner angles fabricated with different-angled molds

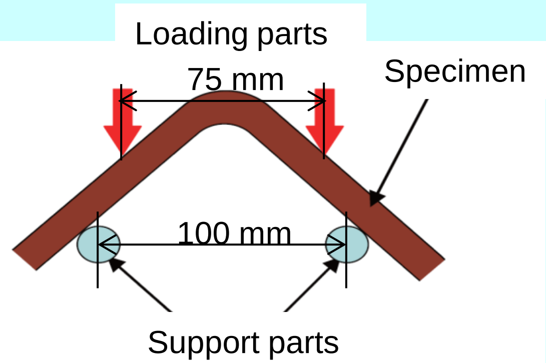
B. 89.5 (90.0)

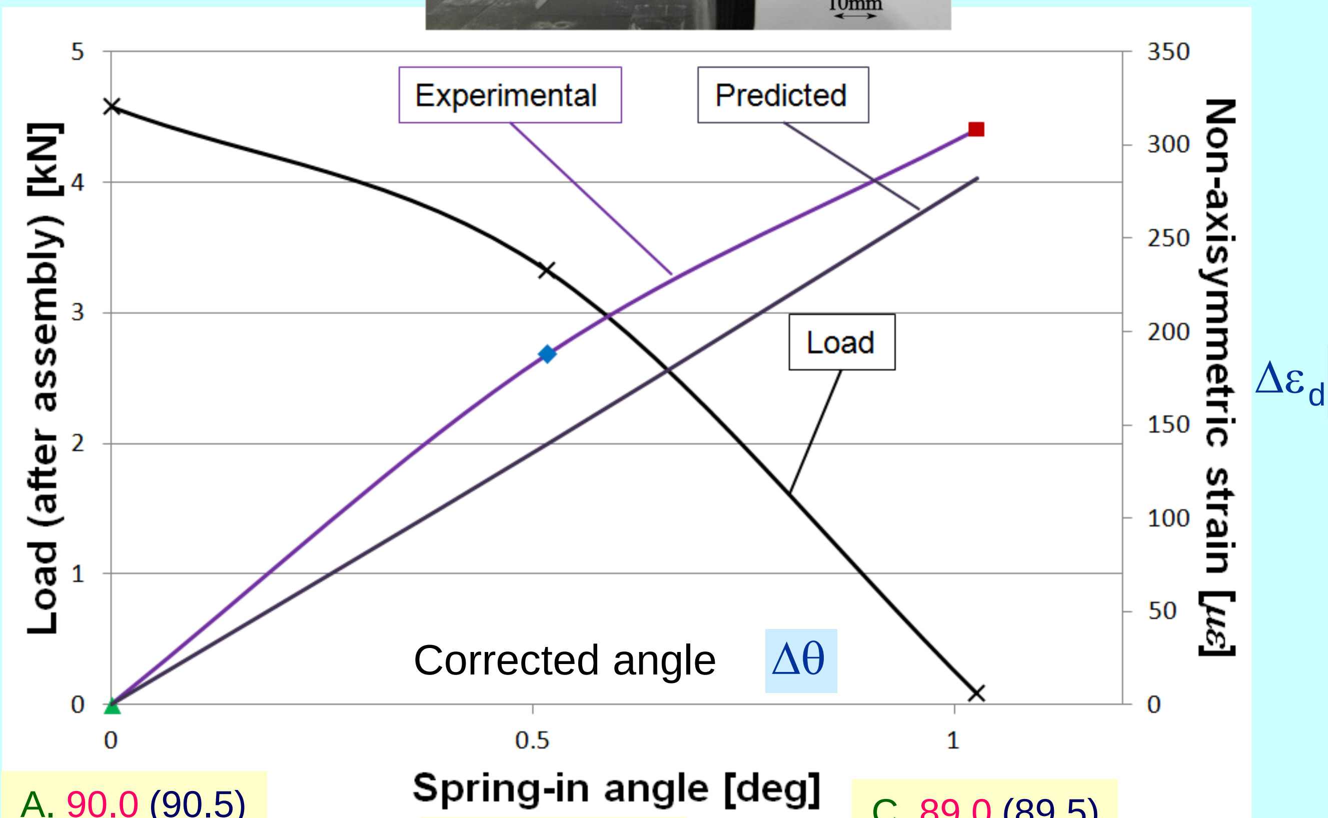
C. 89.0 (89.5)

A. 90.0 (90.5)

Fabricated corner angle (Mold angle)







A. 90.0 (90.5)

B. 89.5 (90.0)

C. 89.0 (89.5)

Acknowledgement

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