Recent Development of Optical Fiber Sensor Based Structural Health Monitoring (SHM) for CFRP Structures in Japan

Accomplishments and The Future

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Noriyuki SAWAI, Managing Researcher,
Nobuo TAKEDA, President, Prof.
R&D Institute of Metals and Composites for Future Industries (RIMCOF)

RIMCOF R&D Institute of Metals and Composites for Future Industries

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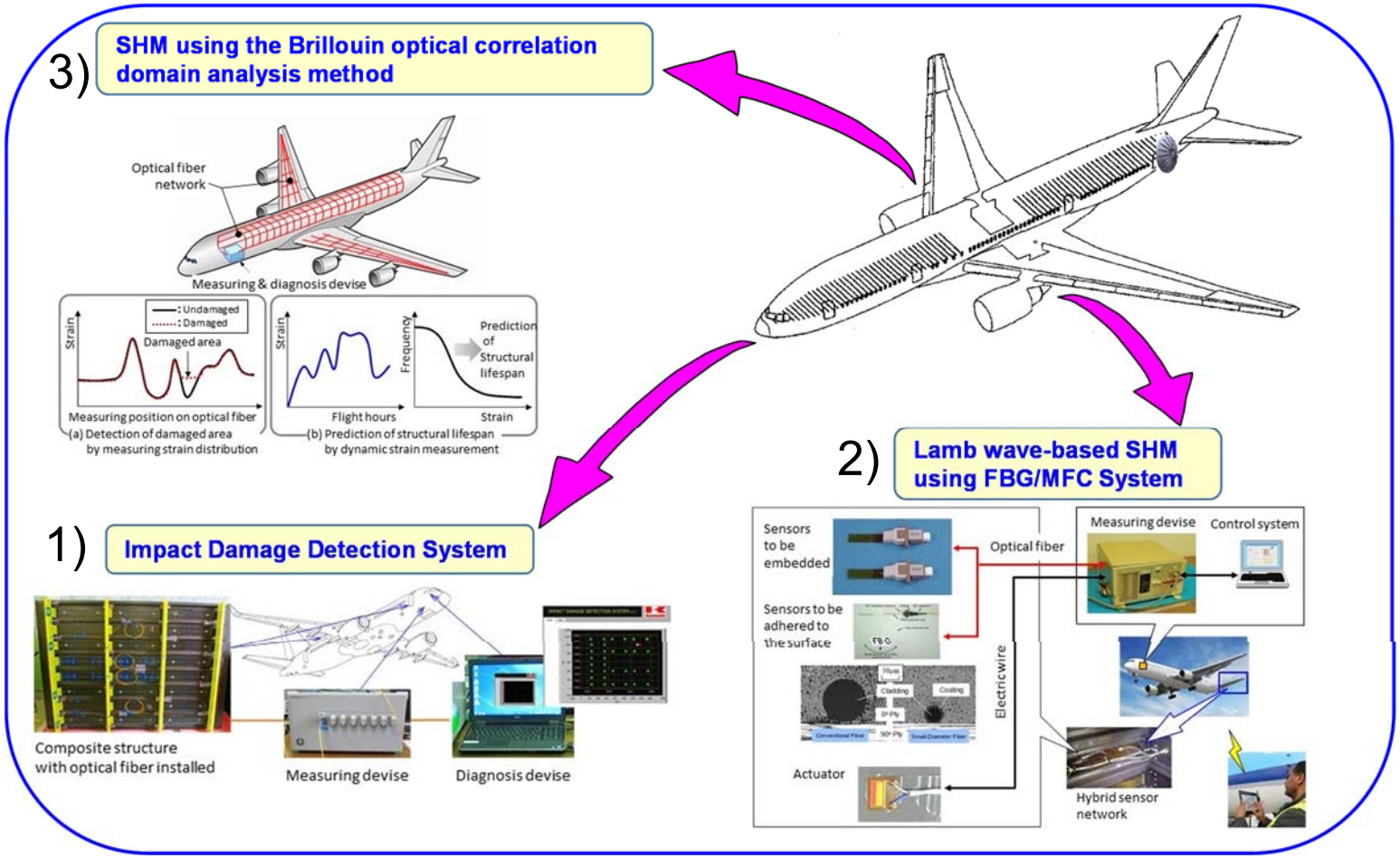
1. Three(3) - SHM Systems (1/4):

1) System Outlines (1/2):

+ Three(3) Structural Health Monitoring (SHM) Systems:

- Optical Fiber Sensor Based SHM Systems



1. Three(3) - SHM Systems (2/4):

1) System Outlines (2/2):

+ Three(3) Optical Fiber Sensor Based SHM Systems:

1) Impact Damage Detection System of Composite Structures
By Kawasaki Heavy Industries, Ltd. (KHI)

2) PZT / FBG Hybrid Sensing System Using Lamb-Waves
By SUBARU CORPORATION (SUBARU)
<Formerly: Fuji Heavy Industries Ltd. (FHI)>

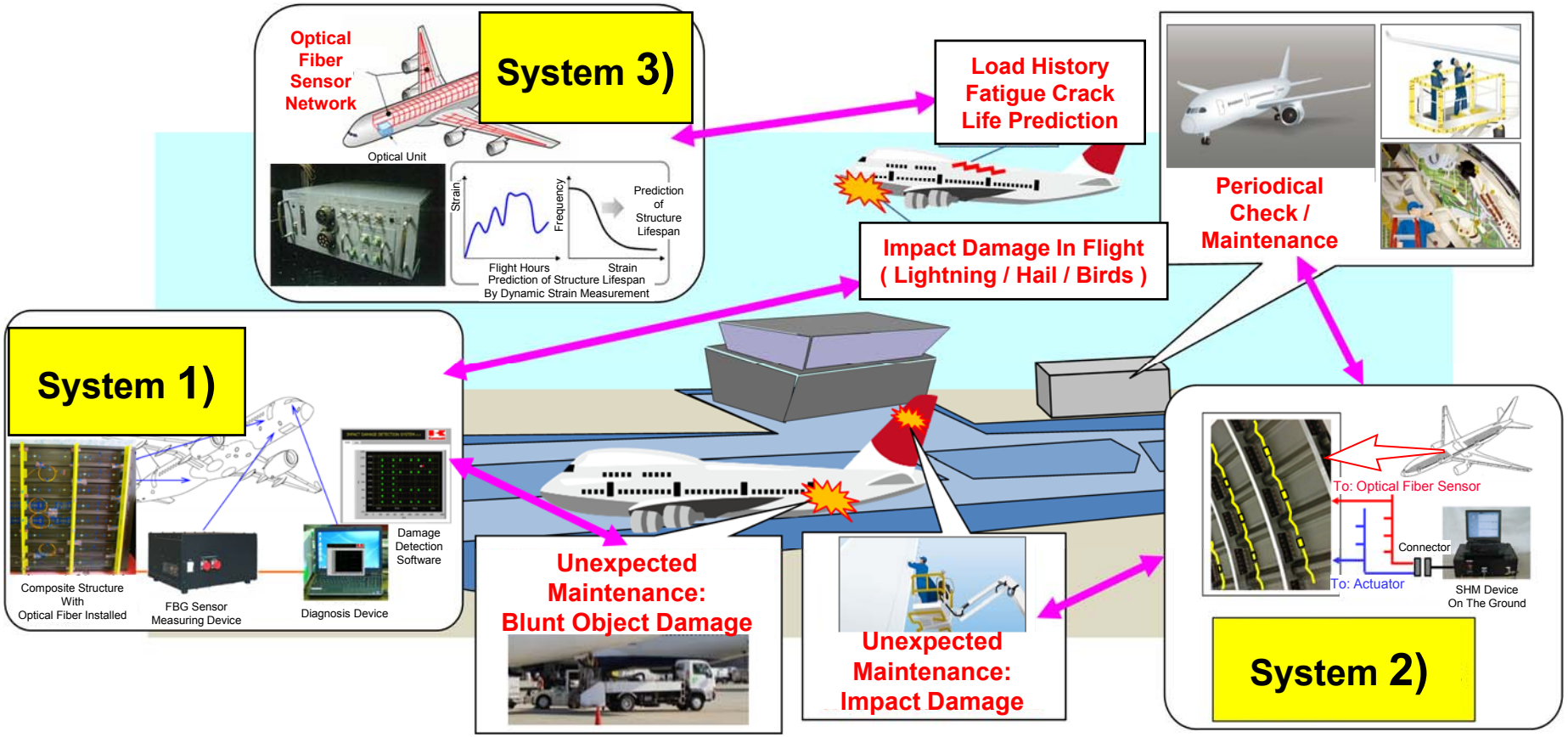
3) Distributed Strain Sensing
Using the Brillouin Optical Correlation Domain Analysis
By Mitsubishi Heavy Industries, Ltd. (MHI)

+ Optical Fiber Sensor:

- Very Useful for Monitoring Internal Strain and Temperature
- Light Weight
- Flexible and Strong
- Resistant to Heat
- Immunity to Electromagnetic Interface
- Multiplexing Capability

1. Three(3) - SHM Systems (3/4):

2) Long-Term Objective (1/2):
+ Total Solution for Effective Aircraft Operation:



1. Three(3) - SHM Systems (4/4):

2) Long-Term Objective (2/2):

+ Total Solution for Effective Aircraft Operation:

- Combination of Three(3) SHM Systems
  1) Impact Damage Detection System of Composite Structures
  2) PZT / FBG Hybrid Sensing Using Lamb-Waves
  3) Distributed Strain Sensing
     Using the Brillouin Optical Correlation Domain Analysis
- Supplement and/or Replacement to Existing NDT Methods
- The Right System in The Right Place
  - Coordination Among the Three(3) SHM Systems
  - Pre-Installed on Components: Maintenance
  - Retrofit on Components: Monitoring for Repaired Area
  - Hot Spot Monitoring
  - On The Ground (Batch Processing) and In Flight (Real-Time)
  - Embedded in Composite Structures (Future Plan)
- Condition Based Maintenance
  - Ultimate Target

2. Developmental Scheme (1/4):

1) RIMCOF (1/2):

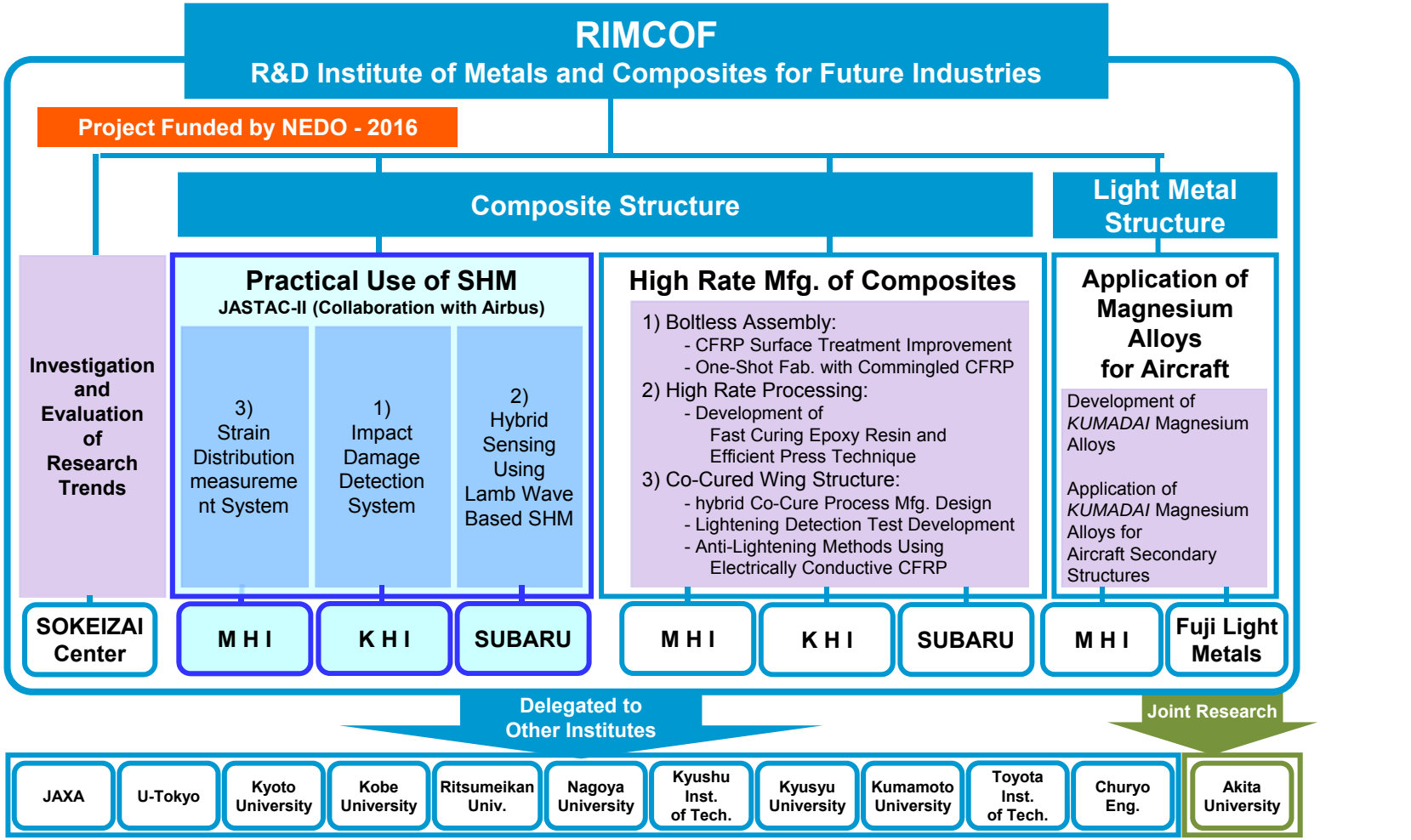
+ RIMCOF: R&D Institute of Metals and Composites for Future Industries
    - Consortium of Japanese Aerospace Industries for Developments
        President: Prof. Nobuo TAKEDA
            - SOKEIAI Center <Administration Office>
            - Mitsubishi Heavy Industries, Ltd. (MHI)
            - Kawasaki Heavy Industries, Ltd. (KHI)
            - SUBARU CORPORATION (SUBARU: Formerly FHI)
            - Fuji Light Metal Co., Ltd. <Light Metal Manufacturer>
    - Long History on Developments
            - 1981: Originally Established (Original Predecessor)
            - 1998: SHM Development Originally Started
            - 2016: Current Organization Established

+ Governmental Developments:
    - Funded by Japanese Government
            - Funds: Ministry of Economy, Trade and Industry (METI)
            - Contract: New Energy and Industrial Development Organization (NEDO)

2. Developmental Scheme (2/4):

1) RIMCOF (2/2):

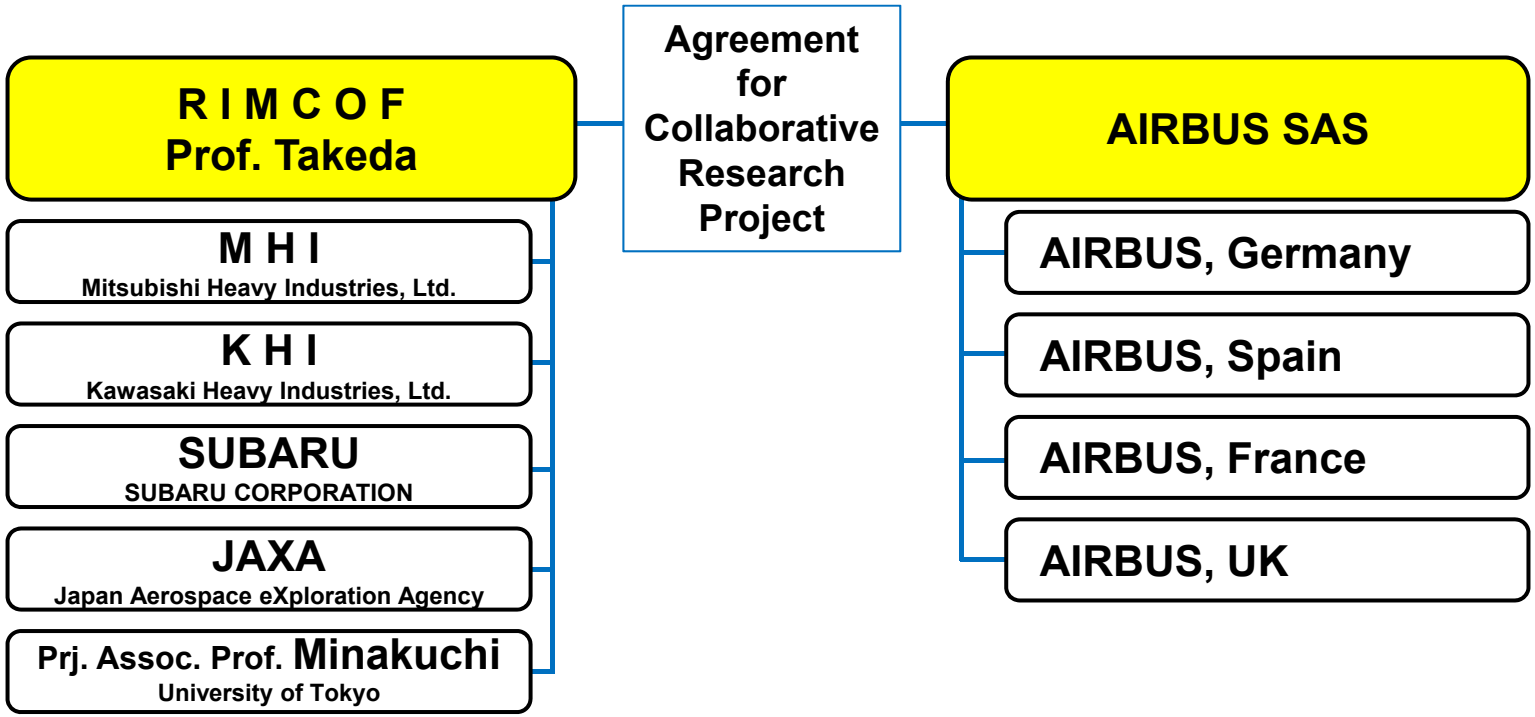
+ RIMCOF: R&D Institute of Metals and Composites for Future Industries



2. Developmental Scheme (3/4):

2) JASTAC (1/2):

+ JASTAC: Japan Airbus SHM Technology for Aircraft Composites
  - International Collaboration Between Airbus and RIMCOF
  - Successful Various Joint Activities Since 2006

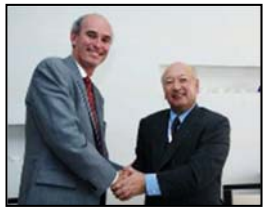


SUBARU : Formally " FHI : Fuji Heavy Industries Ltd. "

2. Developmental Scheme (4/4):

2) JASTAC (2/2):

+ Successful Long-Term Collaboration :



JASTAC-I	Jul.,	2006	Execution
	Dec.,	2009	Joint Test @AIRUBS, Germany
	Jun.,	2010	Extension for Two Years
	Oct.,	2010	Joint Test @AIRUBS, Spain
	Dec.,	2012	Expiration

JASTAC-II	Jun.,	2013	Execution
	Feb.,	2015	Joint Test @AIRBUS, Germany
	Dec.,	2015	Joint Test @AIRBUS, Spain
	Mar.,	2016	Joint Test @AIRBUS, Germany
	Mar.,	2016	Extension for Two Years
	Jul.,	2016	JASTAC Session @EWSHM
	Feb.,	2018	Joint Test @JAXA, Japan
	Jul.,	2018	Extension for Two Years

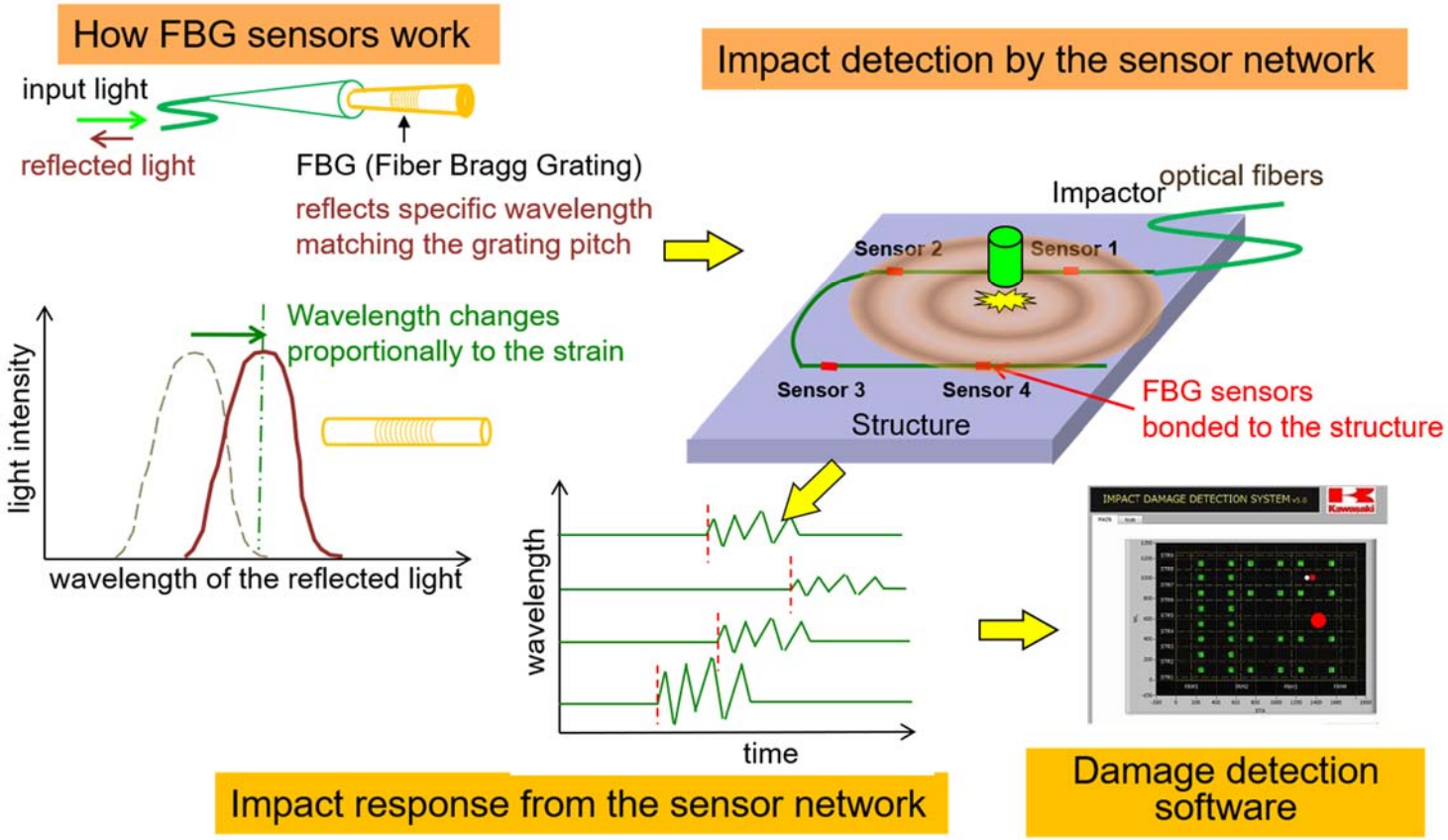
3. Accomplishments (1/11):

1) Impact Damage Detection System of Composite Structures (1/4):

+ Kawasaki Heavy Industries, Ltd. (KHI)

Lead By: Noriyoshi HIRANO, Senior Staff Officer

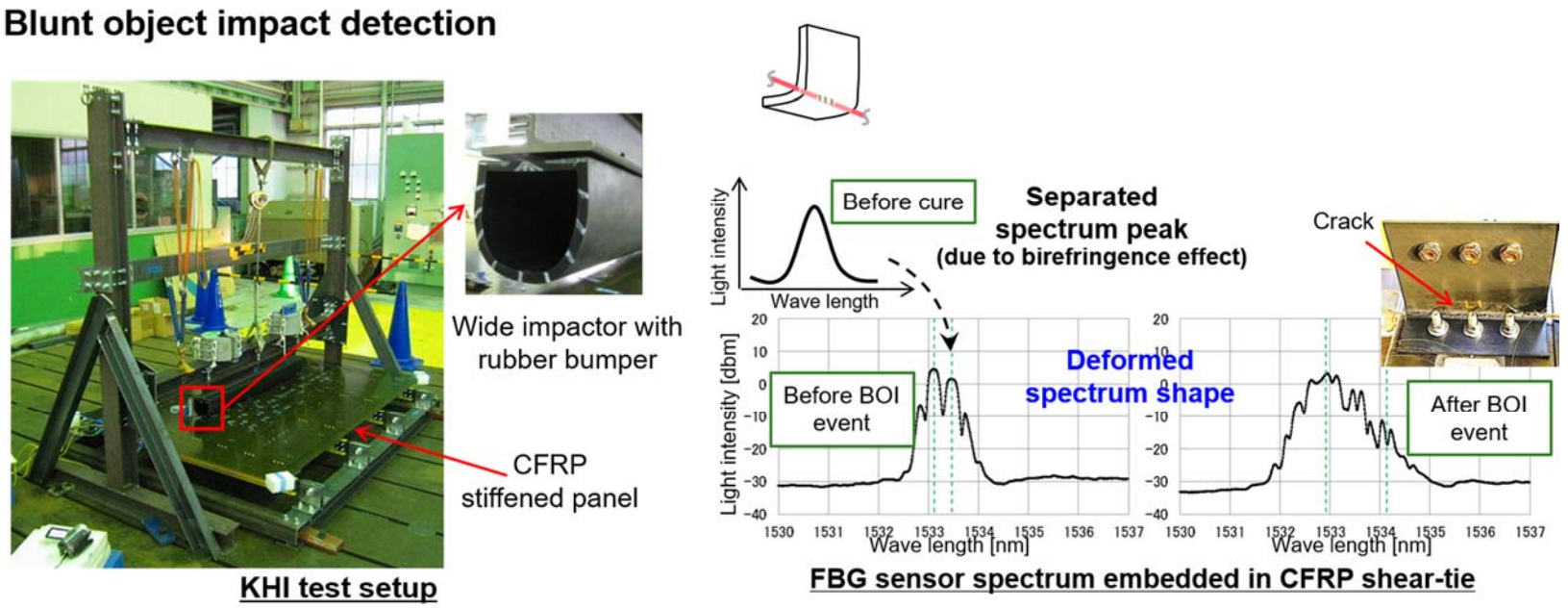
+ System Overview: Impact Detection System



3. Accomplishments (2/11):

1) Impact Damage Detection System of Composite Structures (2/4):

+ System Overview: Blunt Object Impact Detection System

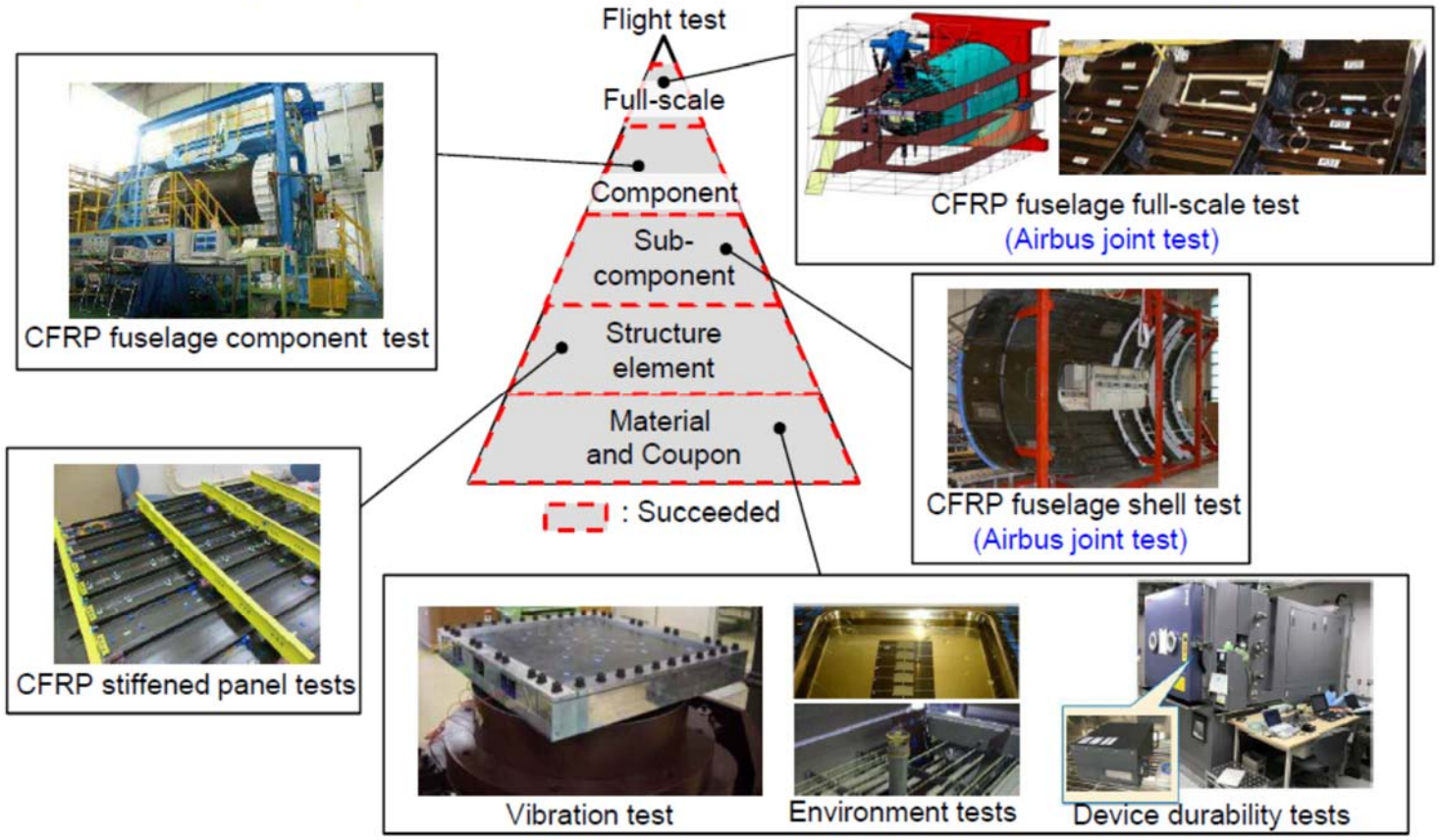


3. Accomplishments (3/11):

1) Impact Damage Detection System of Composite Structures (3/4):

+ Validity Demonstration: Building Block Approach

Detection capability has been evaluated through the validation test pyramid



3. Accomplishments (4/11):

1) Impact Damage Detection System of Composite Structures (4/4):

+ Durability Demonstration:

Demonstrated sufficient durability under all test conditions

- Coupon durability tests completed
  => Survived all conditions including the hydraulic fluid immersion

Load Conditions	Status
Static Test	Complete
Fatigue Test	Complete

Environment	Status
High / Low Temp.	Complete
Temp. Variation	Complete
Altitude / Pressure	Complete
Over Pressure	Complete
Decompression	Complete
Humidity	Complete
Flammability	Complete
Xenon (QUV)	Complete

Immersion	Status
Hydraulic Fluid	Complete
Salt Spray	Complete
Kerosene	Complete
Solvent	Complete
Toilet Fluid	Complete
Insecticide	Complete
Disinfectant	Complete
Fire Extinguisher	Complete
Water	Complete

- Durability of FBG measurement units has been tested.
- MTBF has been improved by modifying electronic parts.

Load Conditions	Status
Vibration	Complete
Shock	Complete

Environment	Status
Operating High / Low Temp.	Complete
Altitude / Pressure	Complete
Humidity	Complete
EMC (EMI and EMS)	Complete

Environmental test

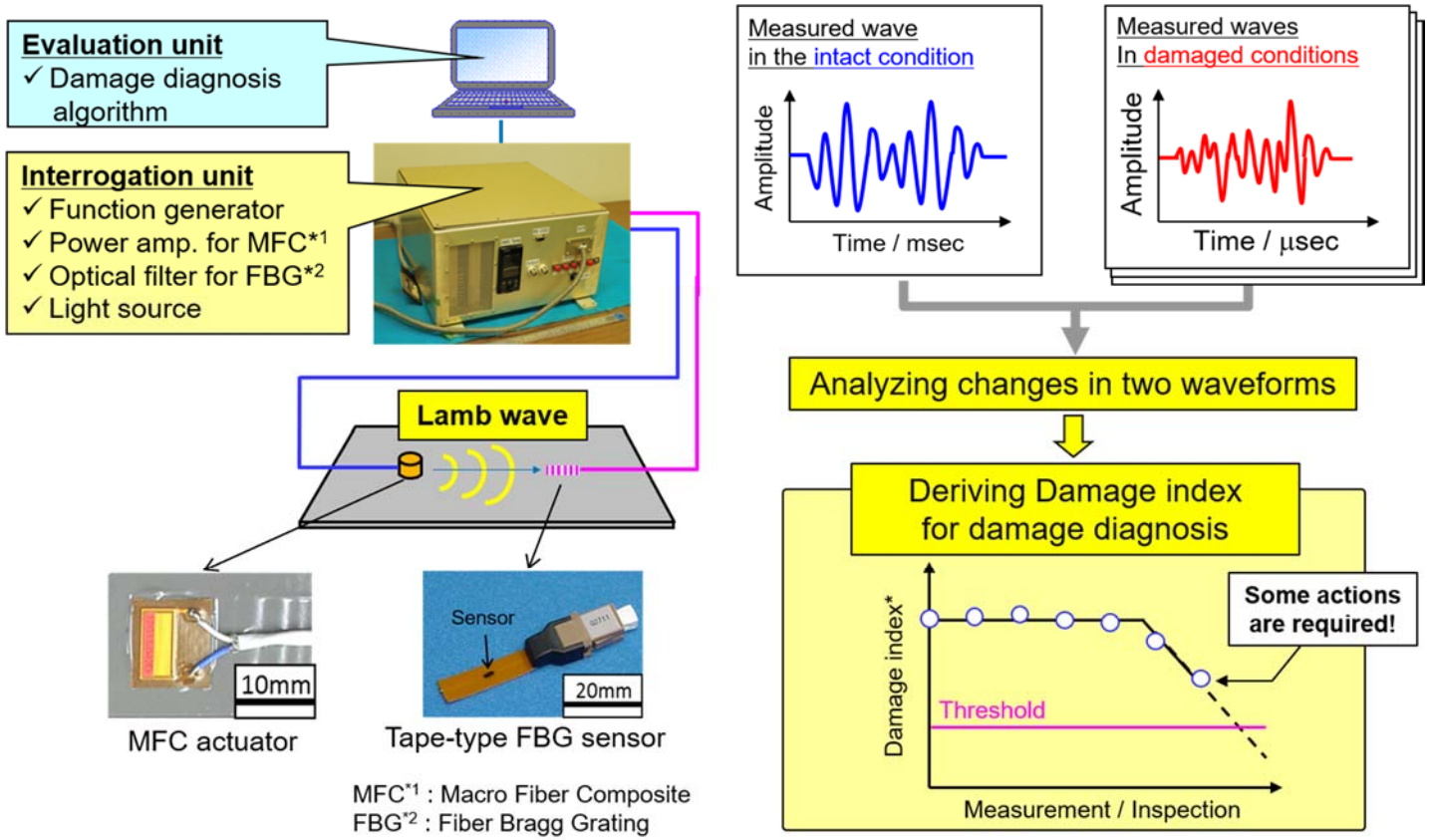
3. Accomplishments (5/11):

2) PZT / FBG Hybrid Sensing System Using Lamb-Waves (1/4):

+ SUBARU CORPORATION (SUBARU)

Lead By: Hideki SOEJIMA, Lead Engineer

+ System Overview: Hybrid Sensing System



3. Accomplishments (6/11):

2) PZT / FBG Hybrid Sensing System Using Lamb-Waves (2/4):

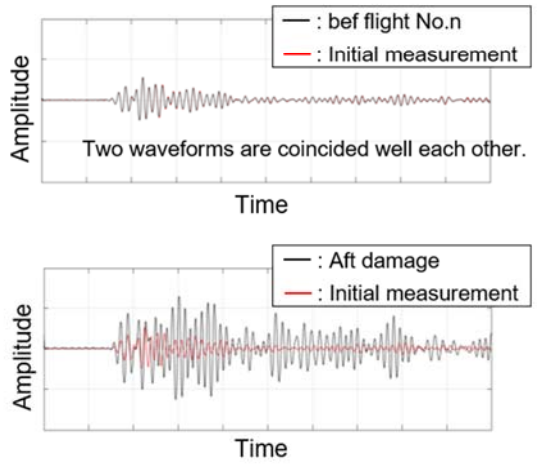
+ Flight Demonstration: "HISHO" - JAXA Flying Test Bed

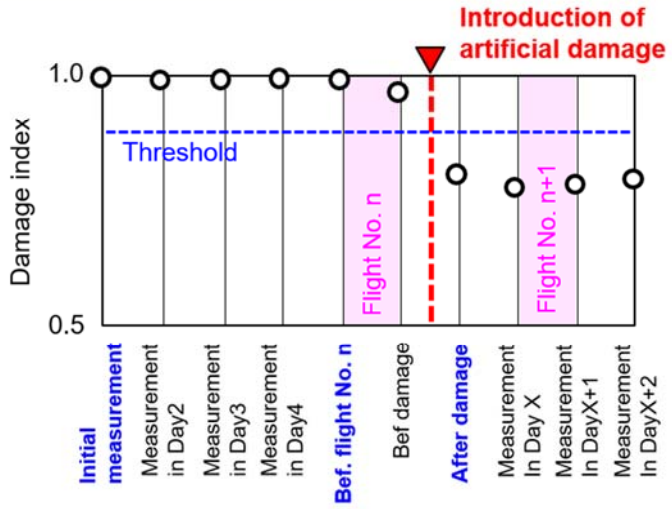
FTB owned by JAXA

Interrogation unit was installed in cabin.

Actuators / Sensors were installed on spar of wing box.

Maesured Lamb waves



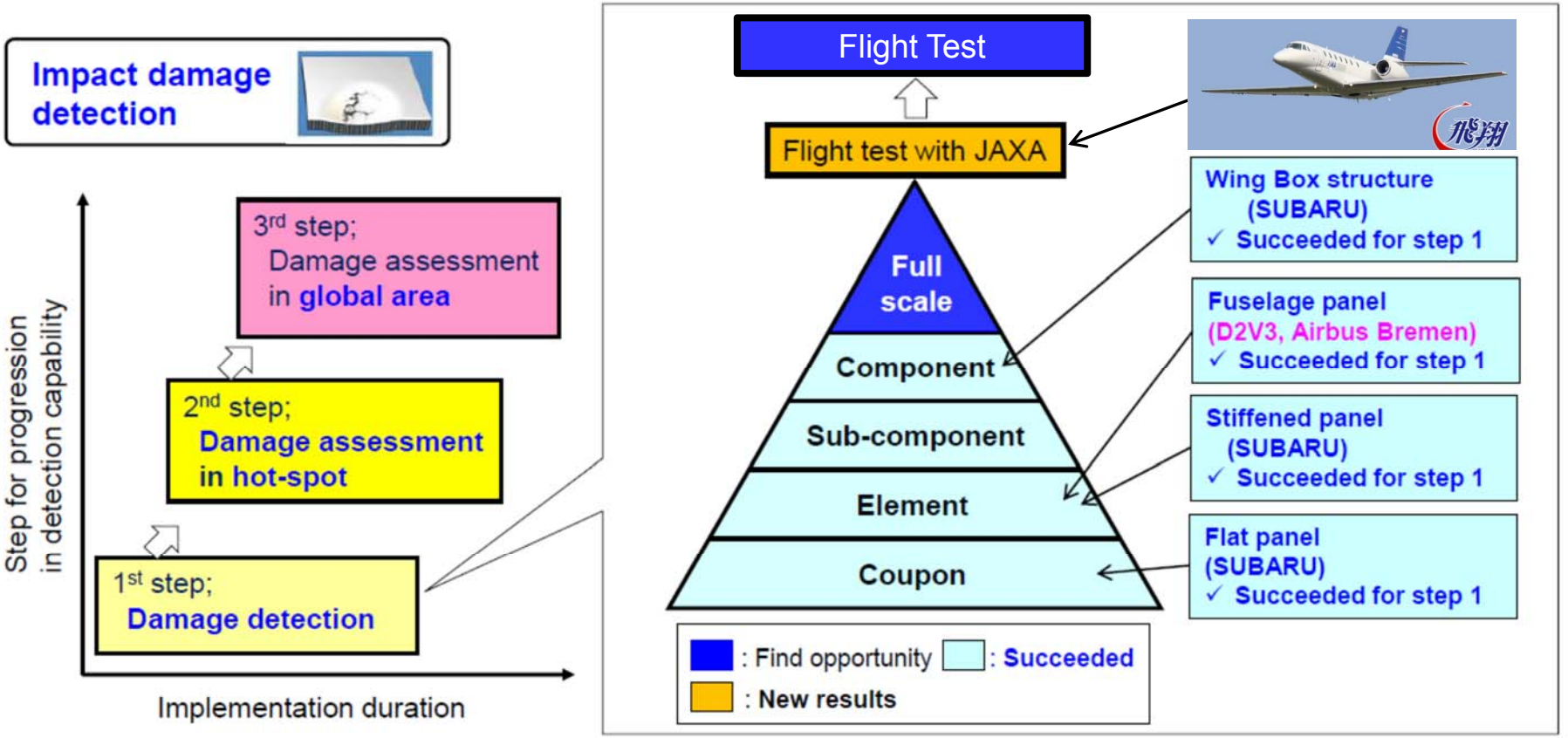


* JAXA: Japan Aerospace eXploration Agency

3. Accomplishments (7/11):

2) PZT / FBG Hybrid Sensing System Using Lamb-Waves (3/4):

+ Validity Demonstration: Building Block Approach



3. Accomplishments (7/11):

2) PZT / FBG Hybrid Sensing System Using Lamb-Waves (4/4):

+ Durability Demonstration:

No.	Test Items: Durability Only	Remarks
1	High Temperature	Successfully Completed.
2	Low Temperature	Successfully Completed.
3	High Pressure	Successfully Completed.
4	Low Pressure	Successfully Completed.
5	Decompression	Not Applicable.
6	Temperature Variation	Successfully Completed. (Measured at Room Temperature Only.)
7	Water Proofness	Not Applicable.
8	Humidity	Successfully Completed.
9	Fire	To Be Conducted In Accordance with RTCA DO-160.
10	Smoke Density & Toxicity	Specification Requeired for Testing.
11	Hot Distilled Water	Durability: Successfully Completed. / Lamb Wave Sensing: Requires Compensation Method.
12	Kerosene	Durability: Successfully Completed. / Lamb Wave Sensing: Requires Compensation Method.
13	Skydrol	Durability: Successfully Completed. / Lamb Wave Sensing: Requires Compensation Method.
14	Lubricant	To Be Conducted Upon Determination of Practical Application.
15	Solvent (MEK)	Successfully Completed.
16	Toilet Fluid	Successfully Completed.
17	De-Icing Fluid	Successfully Completed.
18	Isecticide	To Be Conducted Upon Determination of Practical Application.
19	Disinfectant	To Be Conducted Upon Determination of Practical Application.
20	Coland Dielectric Fluid	To Be Conducted Upon Determination of Practical Application.
21	Fire Extinguishant	Successfully Completed.
22	Salt Spray	Successfully Completed.
23	Xenon	To Be Conducted Upon Determination of Practical Application.
24	QUV	To Be Conducted Upon Determination of Practical Application.
25	Static	Successfully Completed.
26	Fatigue	Successfully Completed. (Tension - Compression In The Fuselage Condition.)

3. Accomplishments (8/11):

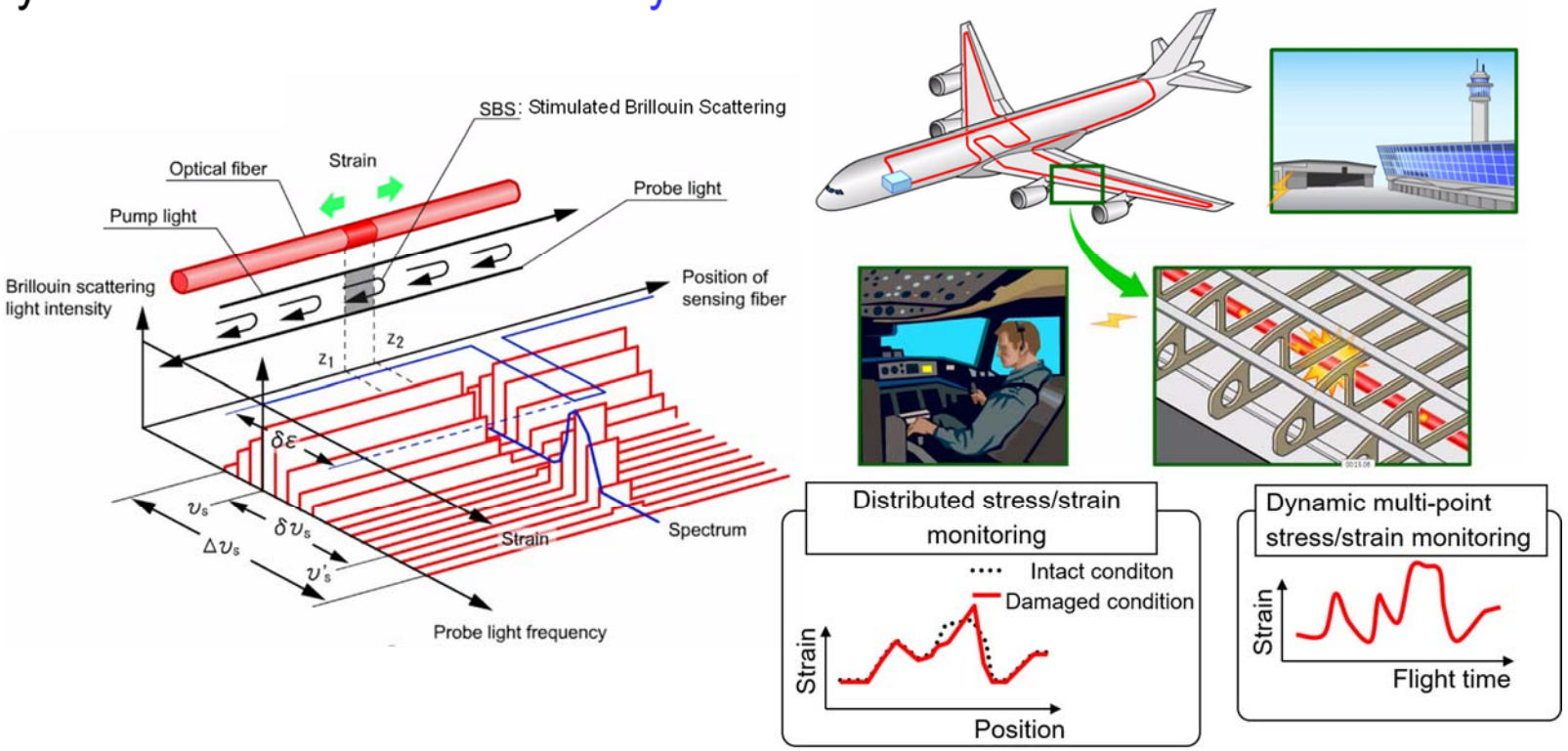
3) Distributed Strain Sensing

Using the Brillouin Optical Correlation Domain Analysis (1/4):

+ Mitsubishi Heavy Industries, Ltd. (MHI)

Lead By: Takashi YARI, Research Manager

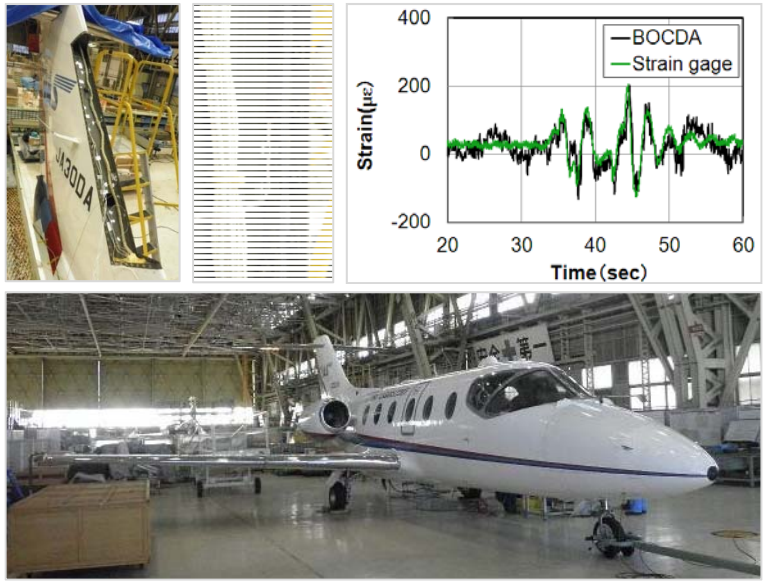
+ System Overview: BOCDA System



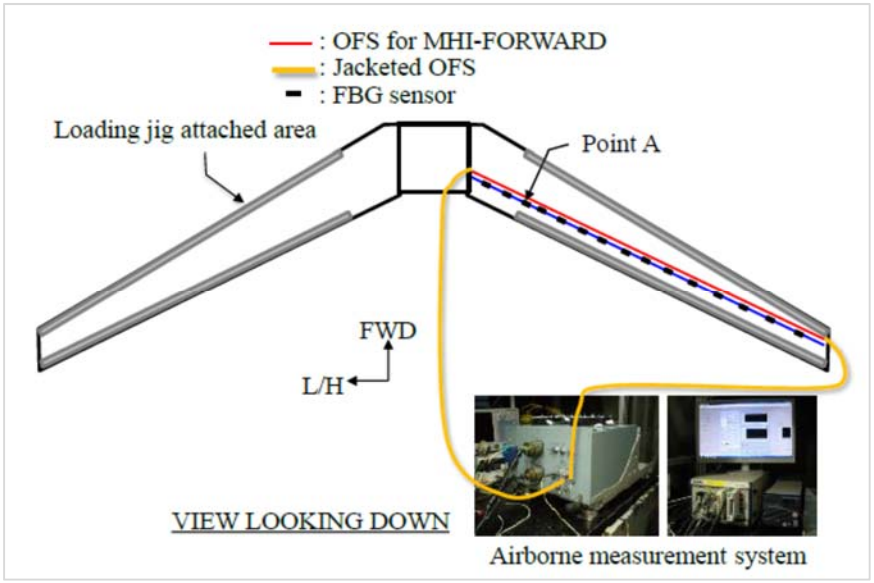
3. Accomplishments (9/11):

3) Distributed Strain Sensing
Using the Brillouin Optical Correlation Domain Analysis (2/4):

+ Full Scale Demonstration: BOCDA System



Flight Demonstration

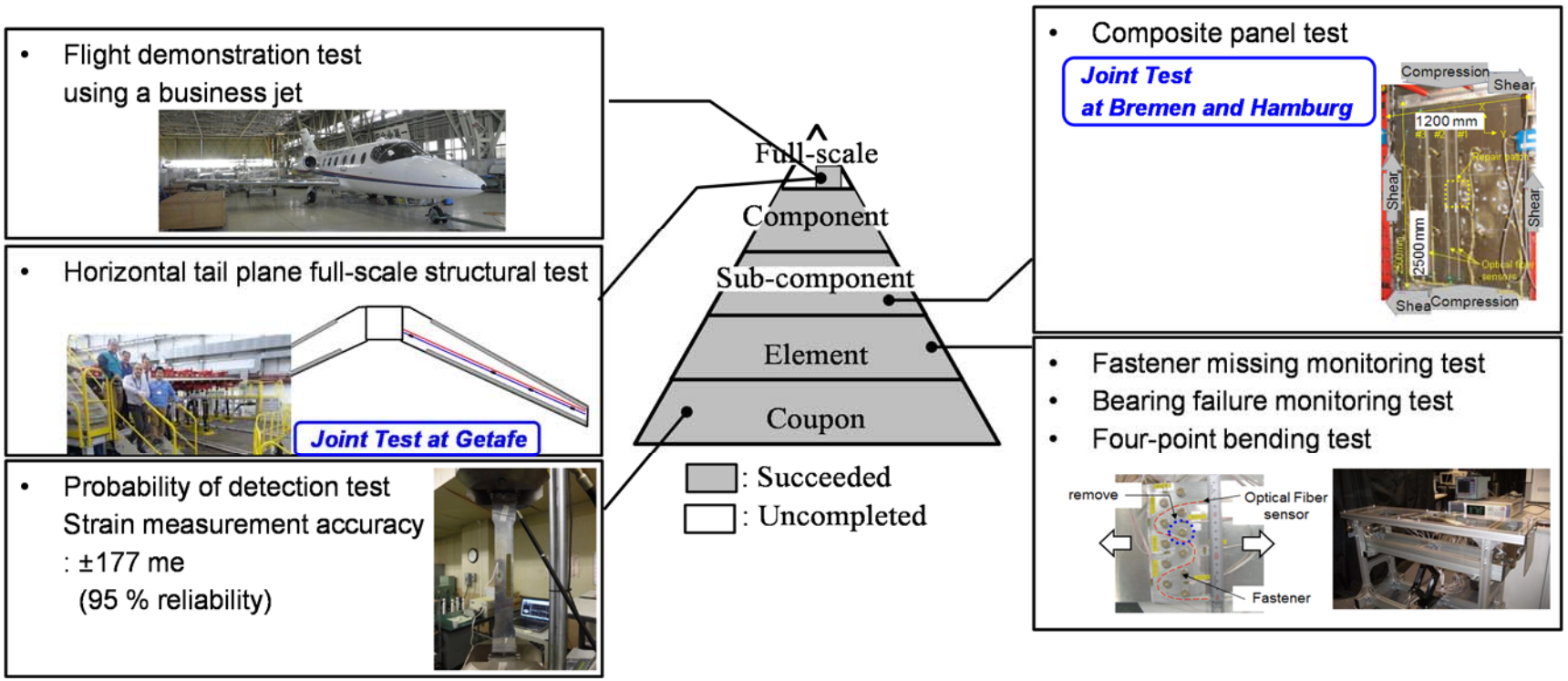


Horizontal Tail Plane
Full-Scale Structural Test

3. Accomplishments (10/11):

3) Distributed Strain Sensing
Using the Brillouin Optical Correlation Domain Analysis (3/4):

+ Validity Demonstration: Building Block Approach



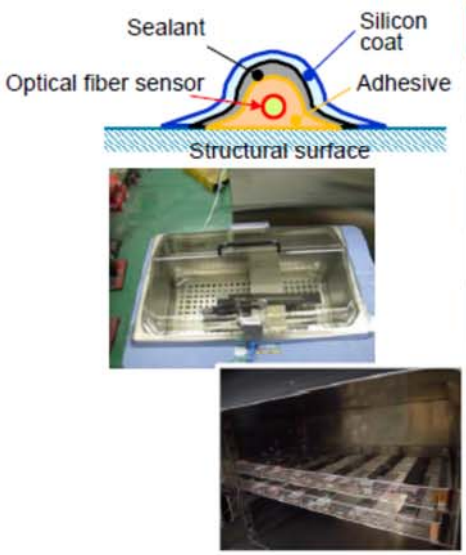
3. Accomplishments (11/11):

3) Distributed Strain Sensing

Using the Brillouin Optical Correlation Domain Analysis (4/4):

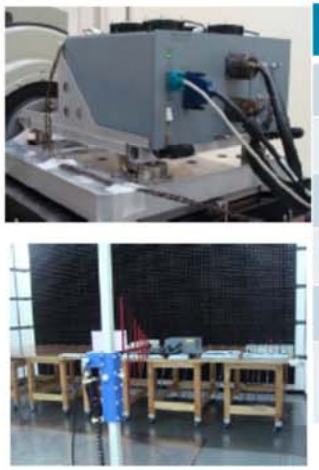
+ Durability Demonstration:

Durability verification test results of the sensor system



Title	Status
Altitude/Pressure	Completed
Decompression	Completed
Temperature variation	Completed
Humidity	Completed
Flammability	Completed
Kerosene	Completed
Static loading	Completed
Fatigue loading	Completed

Durability verification test results of the measurement device



Title	Status
Temperature	Completed
Altitude/Pressure	Completed
Decompression	Completed
Shock	Completed
Vibration	Completed
Electro-Magnetic Comparability	Partially Completed

Per: RTCA DO-160

4. Near-Term Future Plan (1/2):

1) Approach for Certification and Approval for Routine Use:

+ Sandia National Laboratories (SANDIA):
    - Supplement and/or Replacement to Existing NDT Methods
    - Collaboration with An Expert
    - Support for SHM Initiative by Dr. Dennis Roach
        - Participation: RIMCOF and Its Consortium Members
        - Technical Assistance
        - Planning Support
        - Guidance Production
        - Validation Testing Support
    - Referring / Following to Successful Example(s)
        - CVM Application on Delta Air Lines Fleet
        - Seeking for Practical Approach(es)

+ JASTAC-II Activities:
    - Continuing Collaboration

4. Near-Term Future Plan (2/2):

2) Seeking for Opportunities:

+ Flight Testing with Operational Airplanes:
  - A Major Element for Certification and Approval for Routine Use
  - More Flight Testing Opportunities, Firmer Possibilities
  - Continued Effort for Opportunities
    - JASTAC-II: Continued Determination for Practical Use
    - JAXA FTB "Hisho": General Study for Implementation

+ Hoping for New Collaboration:
  - Collaboration with Fleet Operators
    - Airline Companies
    - Air Freight Companies
    - Research Institutes
    - OEMs

+ RIMCOF Hopes and Welcomes New Collaboration:
  - Please Contact with RIMCOF at " mail@rimcof.or.jp " or " sawai@rimcof.or.jp ".

5. Conclusion / Acknowledgement / Reference (1/3):

1) Conclusion:

+ Optical Fiber Sensors - Promising Tools for SHM :
  - Suitable to Aerospace Composite Structures
  - Feasible Applications Demonstrated
    1) Impact Damage Detection System of Composite Structures
    2) PZT / FBG Hybrid Sensing System Using Lamb-Waves for Damage and Defect Monitoring of Structures
    3) Distributed Strain Sensing Using the Brillouin Optical Correlation Domain Analysis

+ Necessary Techniques For:
  - Safety & Reliability of Advanced Composite Structures
  - Reduction of Maintenance Cost for Practical Application

+ Continuing Efforts Required:
  - For Application in Real Aerospace Composite Structures
    - Enhancement of Durability and Reliability
    - Certification and Approval
  - Through International Collaboration

5. Conclusion / Acknowledgement / Reference (2/3):

2) Acknowledgement:

+ This study presented here was conducted as a part of
  - The "Civil Aviation Fundamental Technology Program - Advanced Materials and Process Development For Next-Generation Aircraft Structures" Project
    Commissioned by
    The New Energy and Industrial Technology Development Organization (NEDO),
    Funded by
    Ministry of Economy, Trade and Industry (METI), Japan
  - The "JASTAC" & "JASTAC-II" Projects along with AIRBUS, EU
  - The Joint Study with Japan Aerospace eXploration Agency (JAXA) for some of the Flight Tests.

+ Continuing Efforts by All of The Members in The Current Projects are Highly Appreciated.

5. Conclusion / Acknowledgement / Reference (3/3):

3) Reference

+ Related Recent Presentations:

+ **Recent Development of Optical Fiber Sensor Based Structural Health Monitoring and In-Process Monitoring of CFRP Structures in Japan**
  - 9th European Workshop on Structural Health Monitoring, July, 2018
  - Nobuo TAKEDA and Shu MINAKUCHI

+ **Outline of The Japanese National Project on Structural Health Monitoring System for Aircraft Composite Structures and JASTAC Project**
  - 8th European Workshop on Structural Health Monitoring, July, 2016
  - Akira ISOE, Hiroto KOJIMA, Kiyoshi ENOMOTO

+ **JASTAC - The Japan Airbus SHM Technology for Aircraft Composite**
  - 8th European Workshop on Structural Health Monitoring, July, 2016
  - Clemens BOCKENHEIMER, Carlos de MIGUEL, Pierre ZAHLEN, Christophe PAGET, Alexander WEISSER

+ **Development Overview of A Fiber Optic Based Distributed Strain Sensing Technology for Aircraft Structural Health Monitoring Applications**
  - 15th Japan International SAMPE Symposium and Exhibition, November, 2017
  - Nozomi SAIT, Takashi YARI, Kazuo HOTATE

+ **Optical Fiber Sensor Based Aircraft Structural Health Monitoring System**
  - 9th European Workshop on Structural Health Monitoring, July, 2018
  - Keisuke SAITO, Hiroshi MAMIZU, Toru ITOH, Noriyoshi HIRANO, Toshizo WAKAYAMA

+ **For The Practical Use of A Lamb Wave - Based SHM System**
  - 11th International Workshop on Structural Health Monitoring, September, 2017
  - Hideki SOEJIMA, Kohei TAKAHASHI, Megumi HIRAKI, Yoji OKABE

End of Presentation

Recent Development of
Optical Fiber Sensor Based
Structural Health Monitoring (SHM) for CFRP Structures
in Japan

Accomplishments and The Future

Thank You for Your Attention.

Noriyuki SAWAI, Managing Researcher,
Nobuo TAKEDA, President, Prof.
R&D Institute of Metals and Composites for Future Industries (RIMCOF)

RIMCOF R&D Institute of Metals and Composites for Future Industries