Reduction of Development Costs of Full Composite Aero-Structure :A Proposal from a Research Sector

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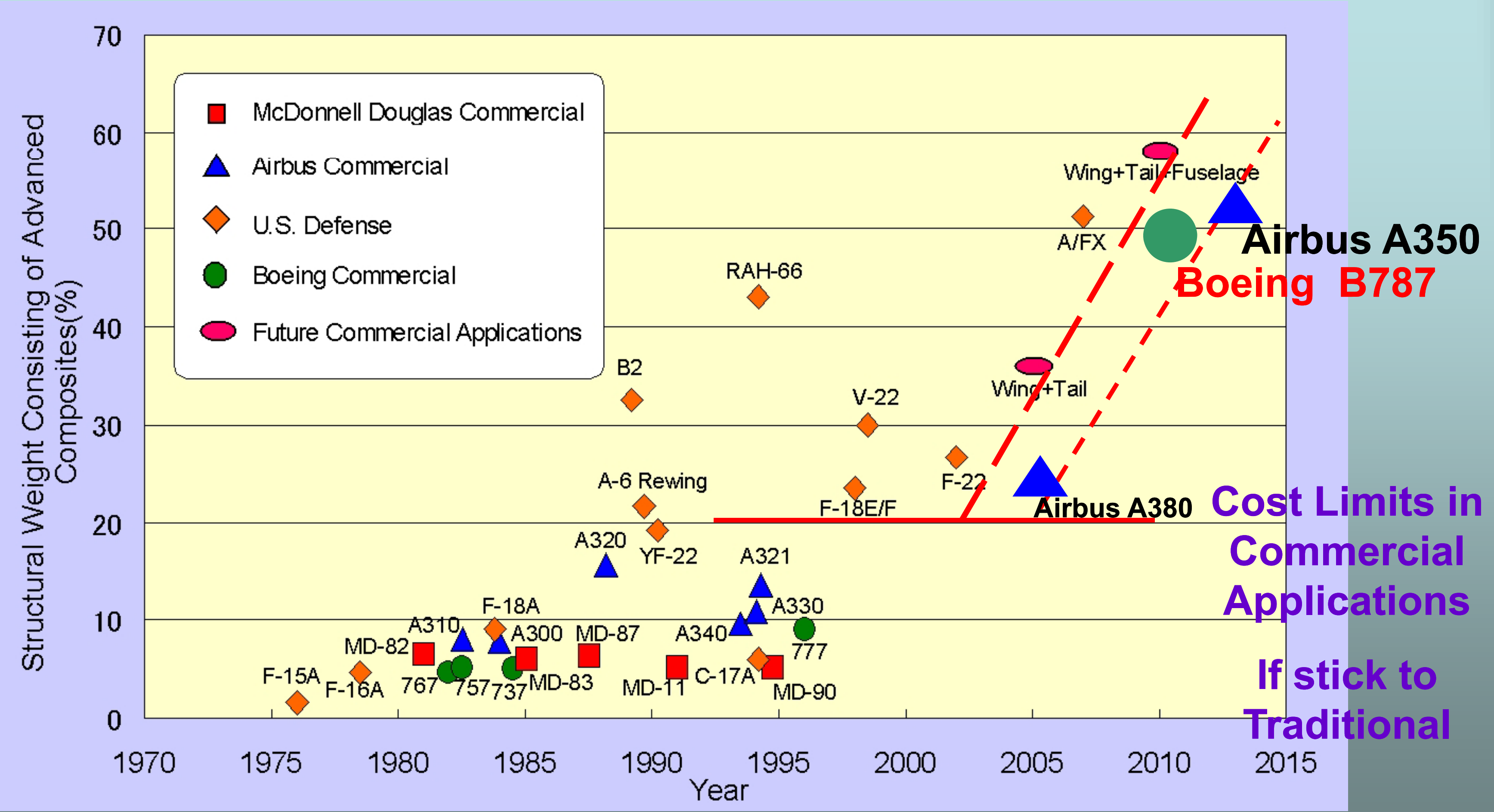
B-787 First Wing Roll-Out: Courtesy of Website of Mitsubishi Heavy Industries Co. Ltd.

Outline of the Presentation

- Increase of composites percentage in aero-structures
- Recent two major challenges: B-787 and A350
- Precious lessons learned: Delay and cost issues,
  Unexpectedly low weight reduction, increase?
- Proposal for Development Cost Reduction
  - Substitution of some steps in BBA by "Virtual testing"
    - Essential difficulty: Progressive failure simulation
  - Reduction of trial fabrication by "Virtual processing"
    - [Out of scope, today]
- Example: Lower panel test of VaRTM wing, predictable
- Example: Lightening strike damage, only at gateway
- If fails, industries may return to aluminum structures
- Conclusions

History of Composites Application to Aircraft



Two Major Challenges to Full Composite Aero-Structures A Case of Boeing B-787

Picture of B-787 in ANA Painting

(Courtesy of New Release of Boeing Japan: May 26/2011

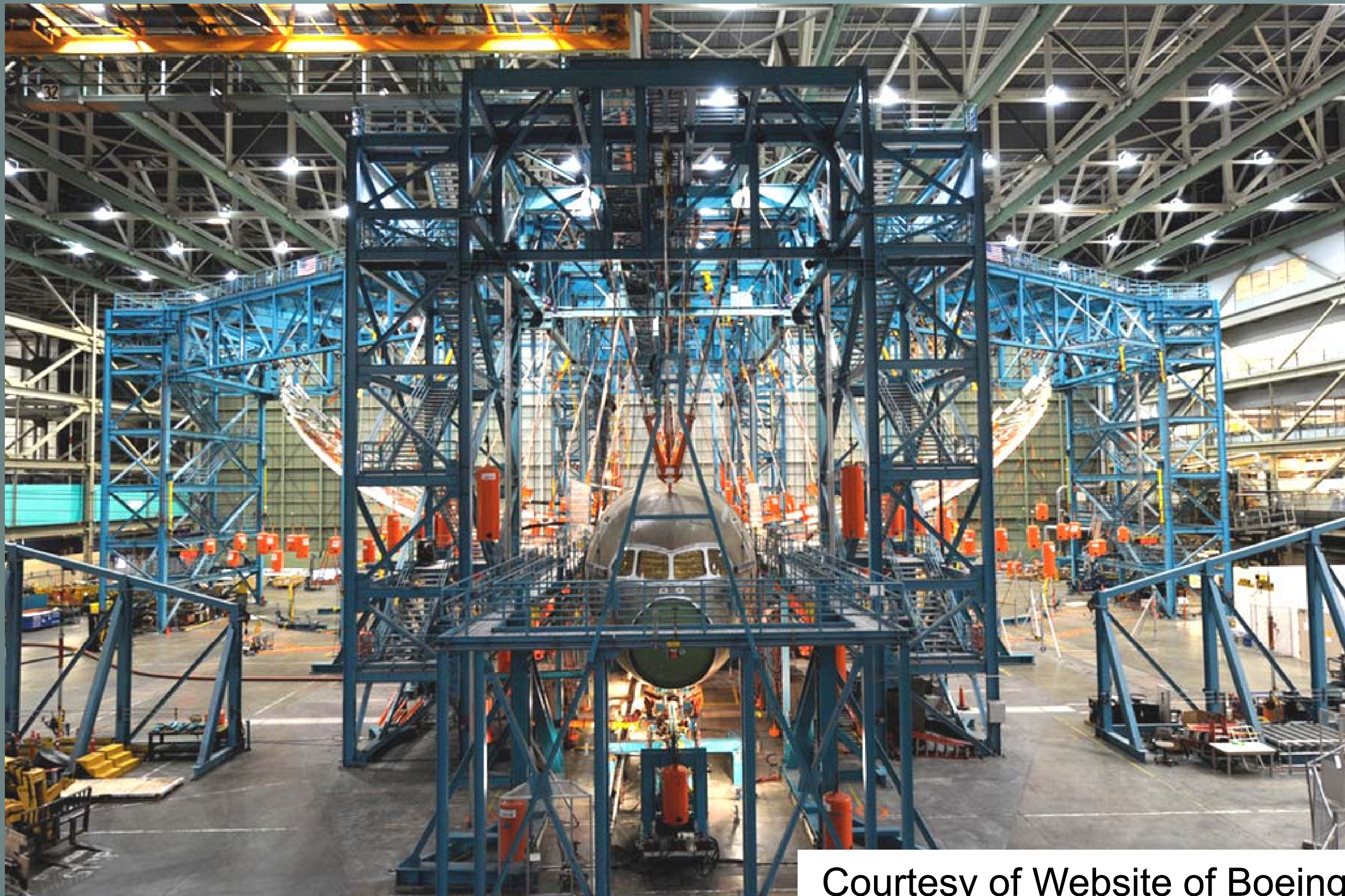
Pictures of B-787at Farnborough Air Show in 2010

Picture of B-787 Main Wing at Roll-out Ceremony at MHI O-e Plant

Courtesy of Website of MHI Co. LTD

Using Toughened Epoxy Prepreg:
Auto tape lay-up machines are used in lamination process of wing skin

Successful Design Ultimate Test of B-787 Main Wing



Courtesy of Website of Boeing Co.

Picture of Full Composite Fuselage of B-787

Precious Lessons Learned

▲Difficulty in the processing

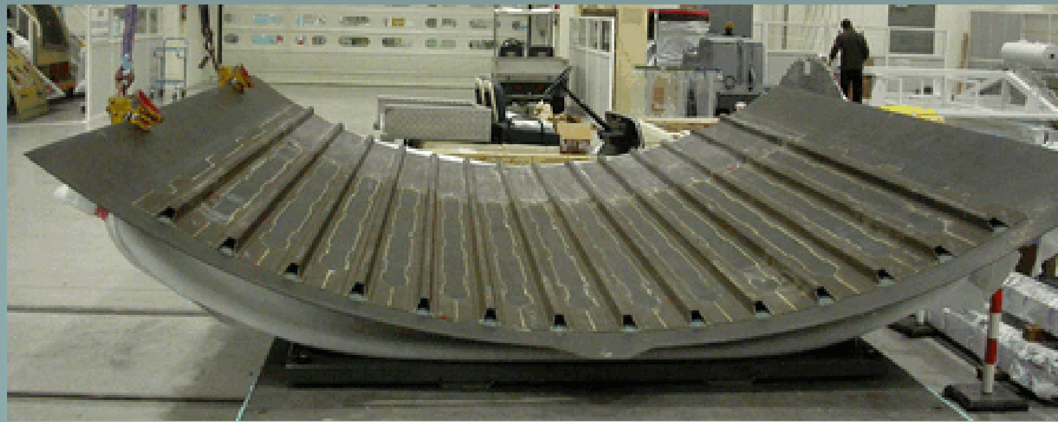
Demo Parts:
In the production, Work share by Kawasaki Heavy Ind. (KHI), Japan and Alenia, Italy.

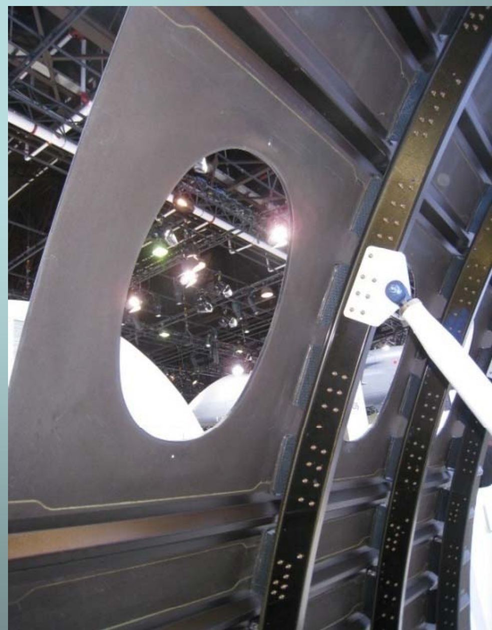
Great Advantage of Composite Fuselage

- **Absolutely No Corrosion**
- **Contribution to Passenger Amenity**

Two Major Challenges to Full Composite Aero-Structures A Case of Airbus A-350 XWB

Full Composite Fuselage of A350 XWB
above: Upper Panel, below: Demo Parts of Side Panel





Lessons Learned: Delay of Development, Cost Issues?

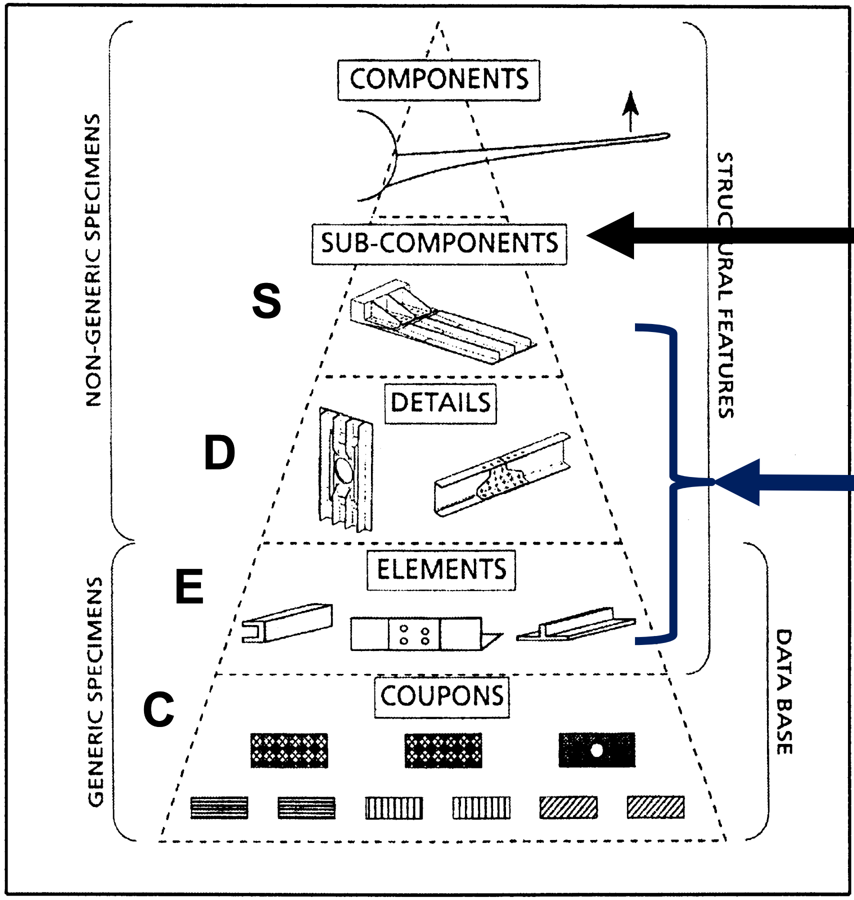
Proposal for Development Cost Reduction of Full Composite Aero-Structure

- ***Substitution of Some Steps in Building Block Approach by High Accuracy Numerical Simulation of Tests [Virtual Testing]:***
  Consideration of Damage Propagation in the Failure Process = Essential Point
- ***Reduction of Trial Fabrication by High Accuracy Numerical Simulation of Processing [Virtual Processing]:***
  Out of Today's scope

Established Procedure of Type Certification of Composite Aero-Structure

Building Block Approach (BBA)

BBA is considered as inevitable approach. However, as a research sector, two questions can be raised.



Two Basic Questions

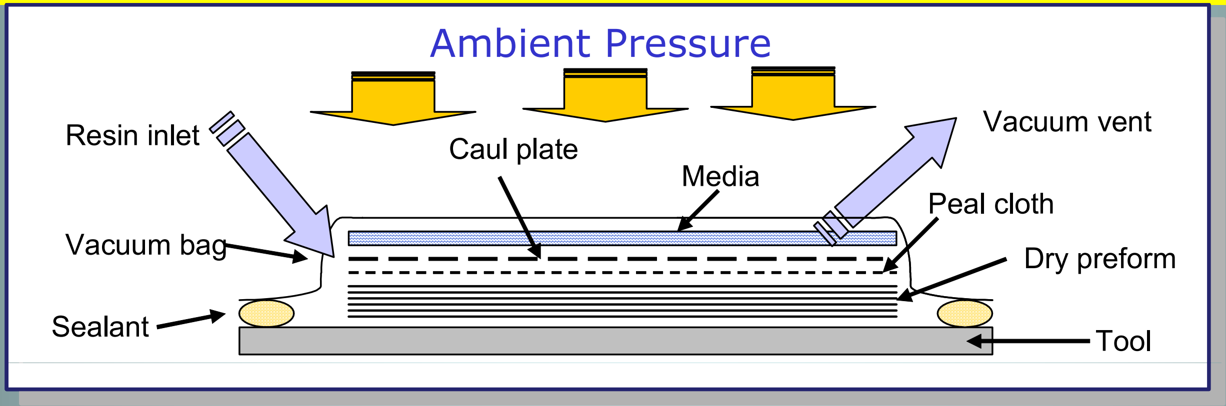
1. Sub-Components must be close in size to "Components"?

2. Some steps like elements and details can be replaced by numerical predictions?

"Virtual Testing"

JAXA pursues Development of VaRTM Composite Aero-Structures

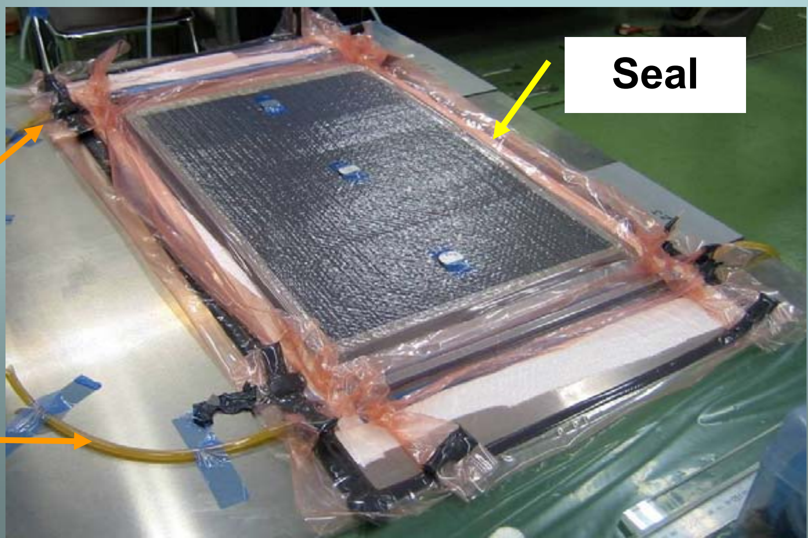
Outline of technology for Low Cost Composite Manufacturing



VaRTM :(Vacuum assisted Resin Transfer Molding)

Resin supply

Vacuum pump



A Good Example of Virtual Test for Predicting Damage Propagation

Shown in this Color Bar Slide

Fabrication of 6m Full Size Panel

(Bagging and vacuuming）

Heat Insulation Panel

Needless costly autoclave!

Fan heater blower

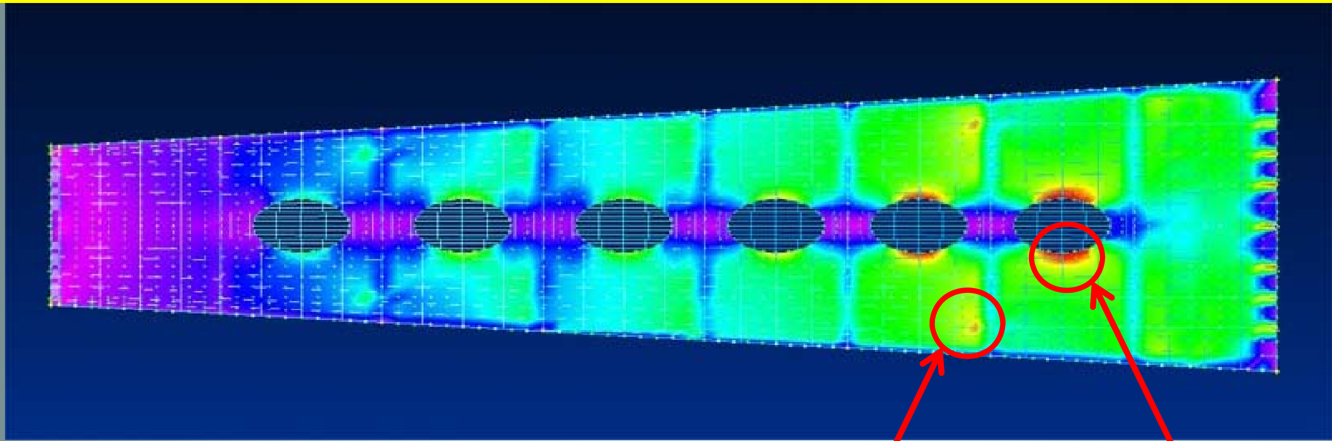
Simulation of Fabrication Process =
Virtual Processing: One Point of Proposal
Omitted in Today's Presentation

6m Full Size Wing Box in the Test Rig

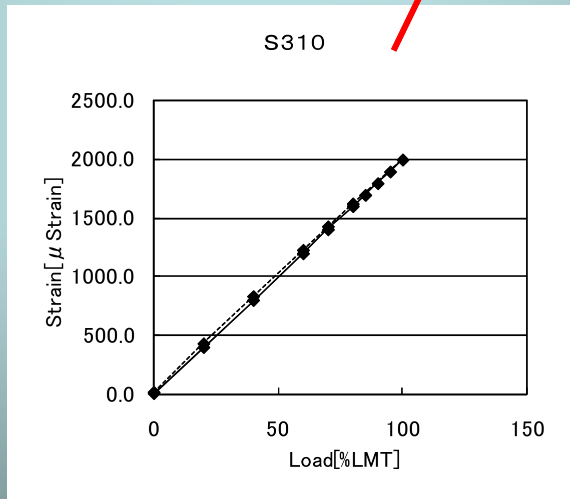
Photo of Static Load Test (100%)

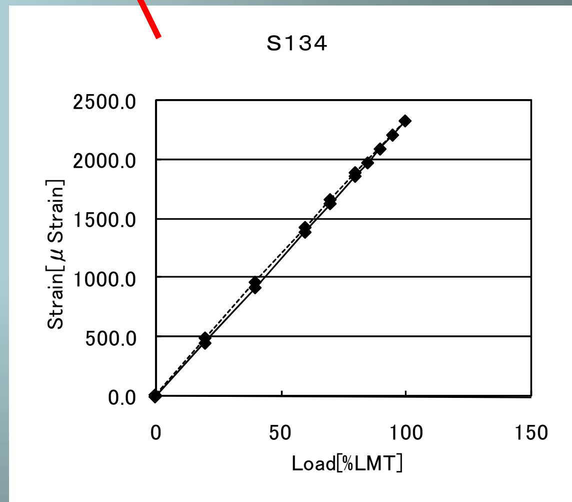
Two life fatigue test of this box was finished

Comparison of calculated (FEM) and experimental strain level at limit load test [at lower panel]



	S310	S134
FEM	2006	2260
Measured	1990	2331
Error [%]	0.8	3.0





Easy Work before the Progressive Failure : in Design Limit Load Test

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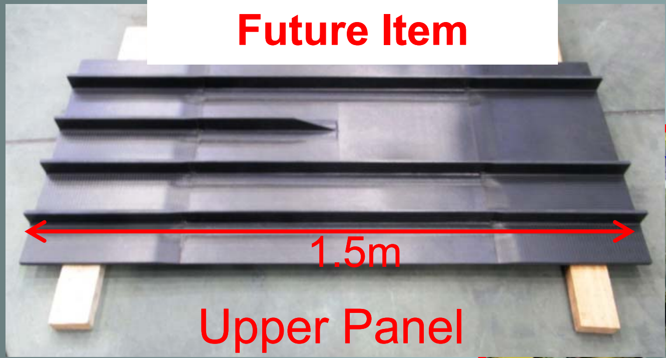
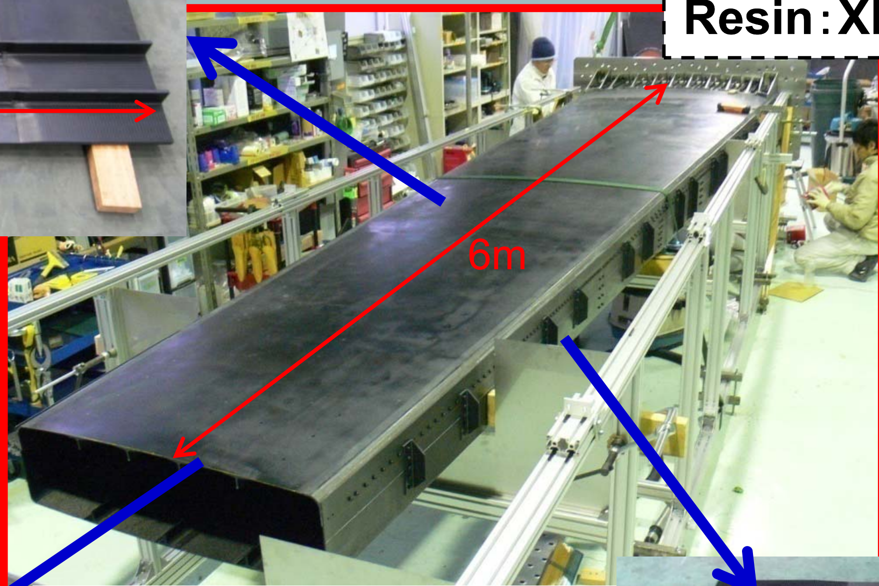
Fatigue Test of VaRTM Structure : Specimens

Fiber : T800SC-24k (Skin)
Saertex NCF(Stringer)
Resin : XNR6809

Future Item

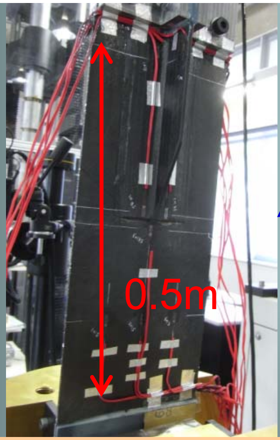


Finished



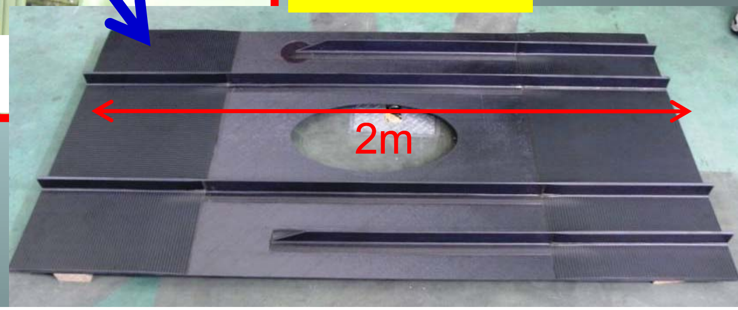
Full Size Main Wing Box

Future Item



Element of Stringer Run-out

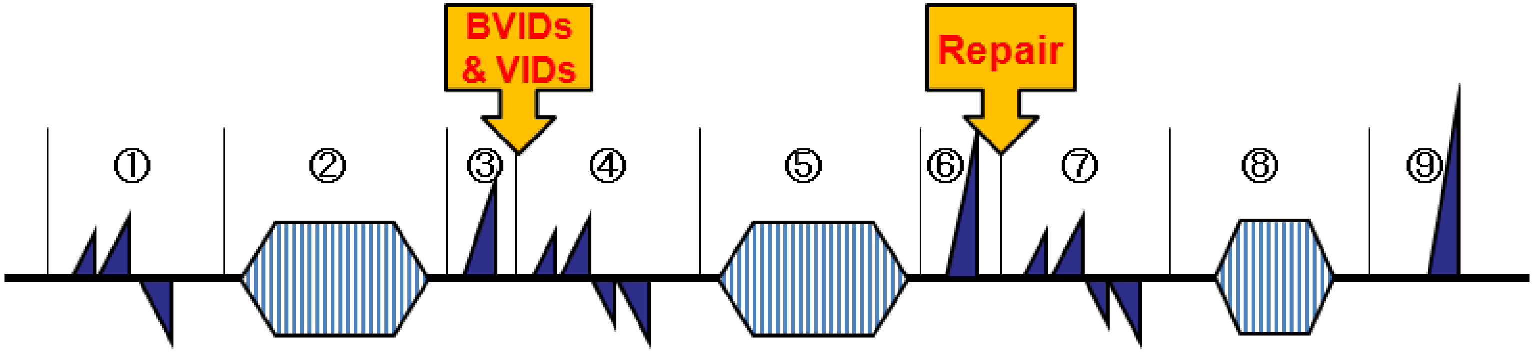
Finished



Lower Panel: Sub-component of Wing

From this slide, an early example of "Virtual test"

Fatigue Test of VaRTM Structure: Test Plan



① Initial strain survey

② **Fatigue spectrum – 1 DSO with LEF=1.18, Life factor = 1.0**

– Evaluate **disbonding of stringer run-out**

③ 100% DLL Verification

④ Strain survey (static behavior of BVIDs, VIDs)

⑤ **Fatigue spectrum – 1 DSO with LEF=1.18, Life factor = 1.0**

– Evaluate **impact damage growth and disbonding of stringer run-out**

⑥ 150% DLL Verification

⑦ Strain survey (effects of repair part)

⑧ Fatigue Spectrum- 2 inspection Intervals with LEF and Life factor

– Evaluate DT of repaired part

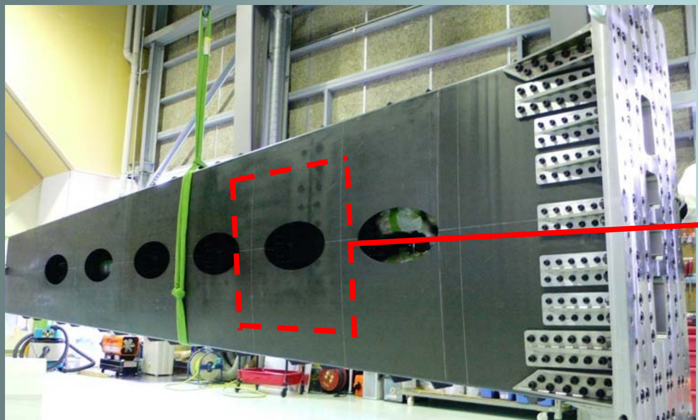
⑨ Destruction Test

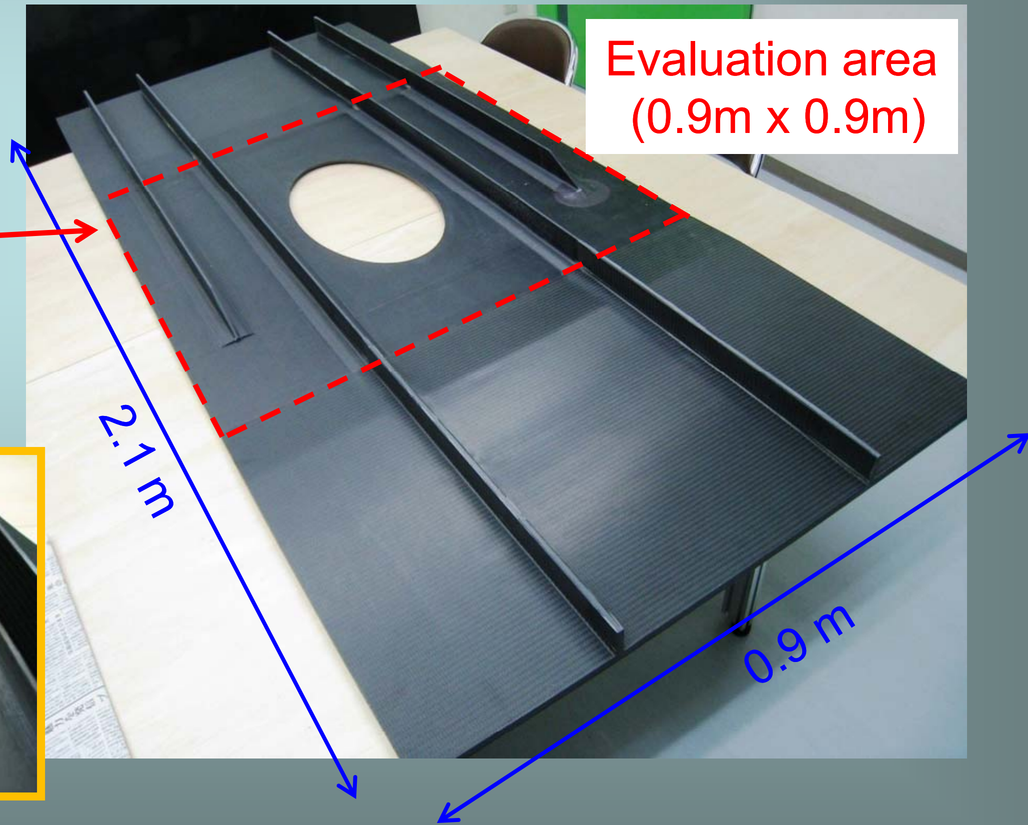
DSO: Design service objective
LEF: Load enhancement factor (Considering Scatter of Fatigue Strength)
DLL: Design limit load

Aviation Program Group

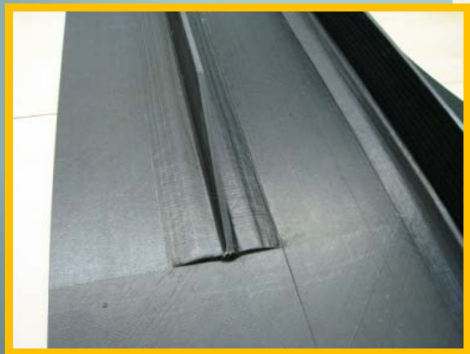
Fatigue Test of VaRTM:
Lower Panel as Sub-component of Main Wing

- **Dimension: 2.1m in Length x 0.9m in Width**
- **Critical Portion: Edge of Stringer Run-out, Maintenance Hole**

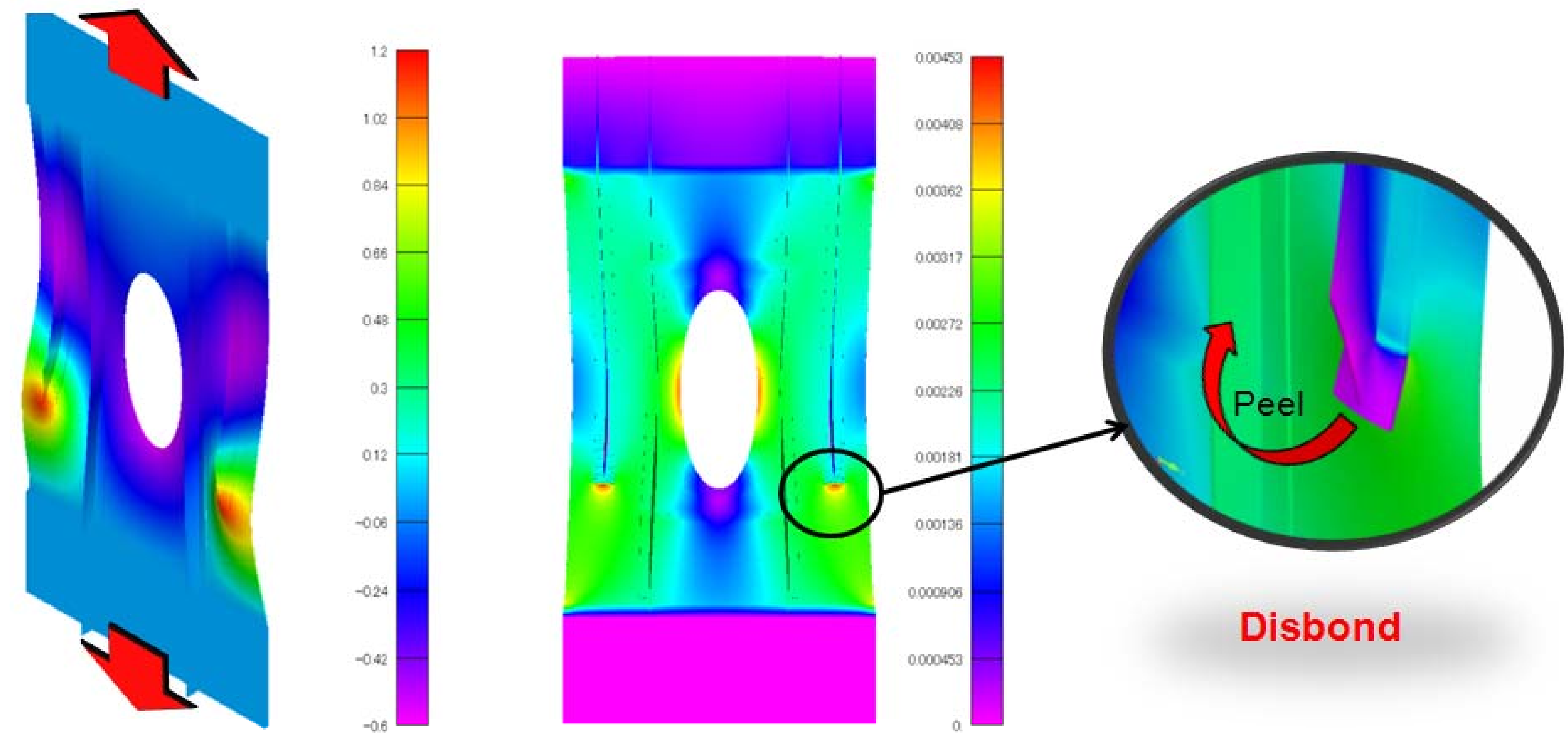




Region of interest: Stringer run-out



Fatigue Test of Lower Panel:
Pre-test Analysis for Static Tension



Out-of-plane displacement

Principal strain

Design Strain (@100%DLL)←OHT Critical

●Stringer: 2,200μ

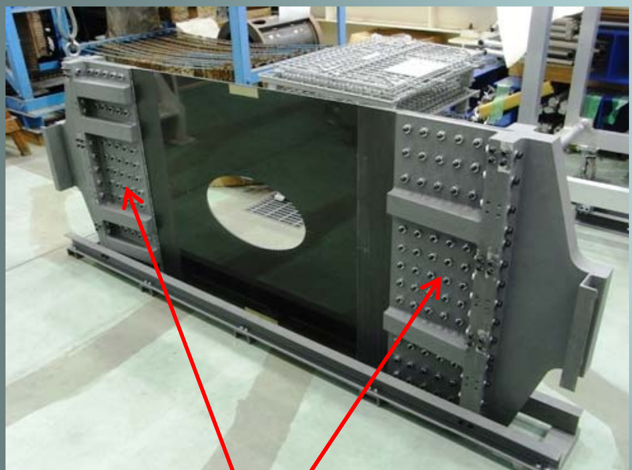
●General Skin: 2,300μ

●Edge of Maintenance Hole: 4,000μ

Designed for the most critical in-plane strengths to load conditions (environment factor: considered)

Fatigue Test of Lower Panel: Preparation Procedure

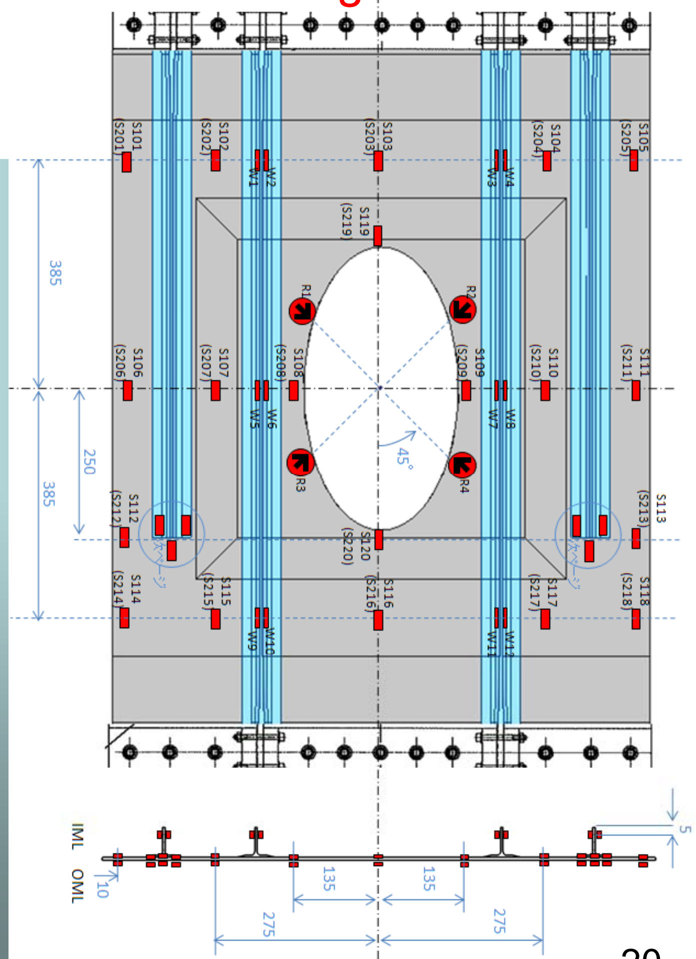
- Fitting of Steel Loading Fixture to 2 Ends
- Loading: 2,500kN High Speed Actuator (MTS)
- Strain Channels: 76,
  Deflection Measurement Points: 4
- 3-D Optical Deformation Measurement (DIC)



Fitting by Bolts and Adhesion

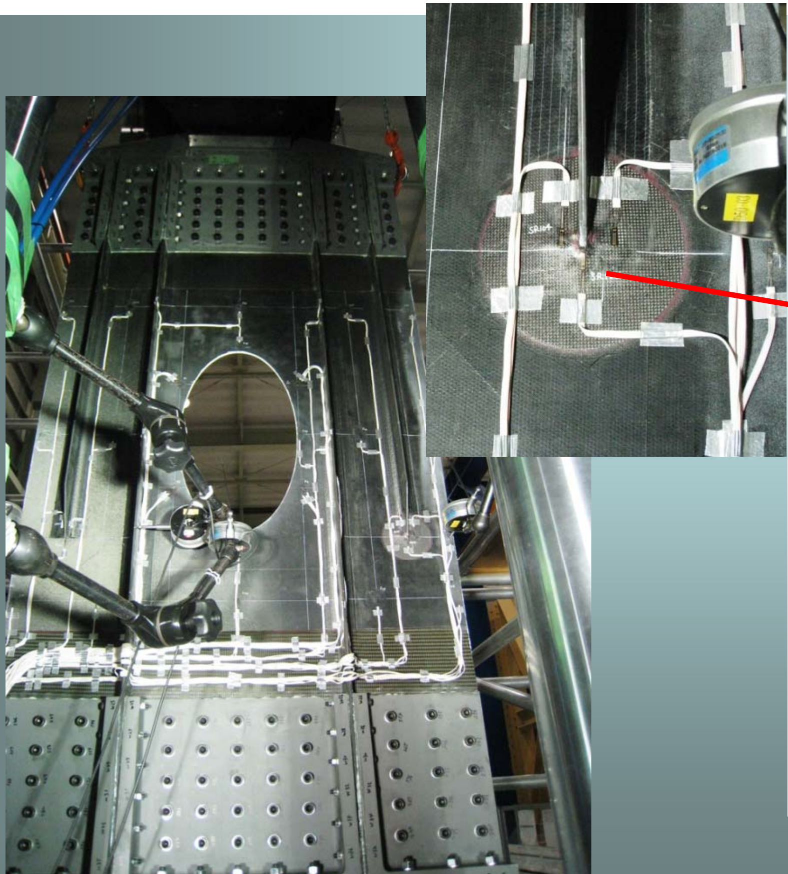
2,500kN Machine

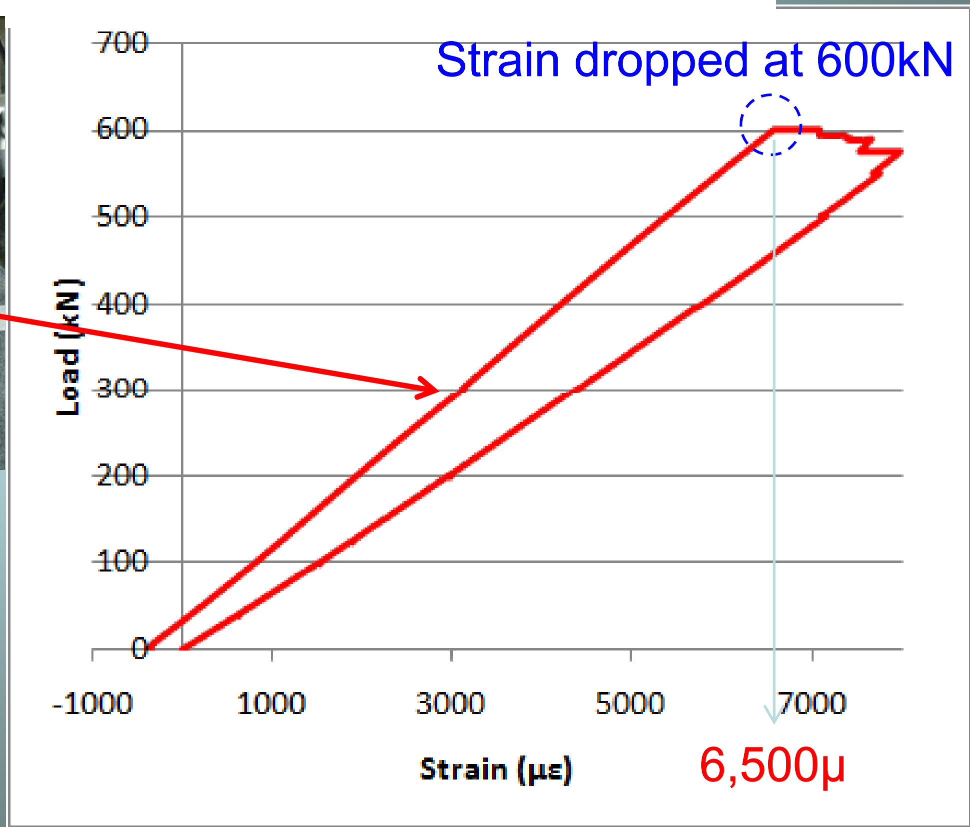
Strain Gage Locations



Fatigue Test of Lower Panel: Strain Survey as the 1st Step

- Initial Adaptation of Fixture, Check of Measurement System, Comparison with Analysis
- Bestowment of Initial Damage at Edge of Stringer Run-out
  - ⇒ Created at 82% DLL: Peel Force by Local Bending
  - ⇒ No Detrimental Residual Deformation

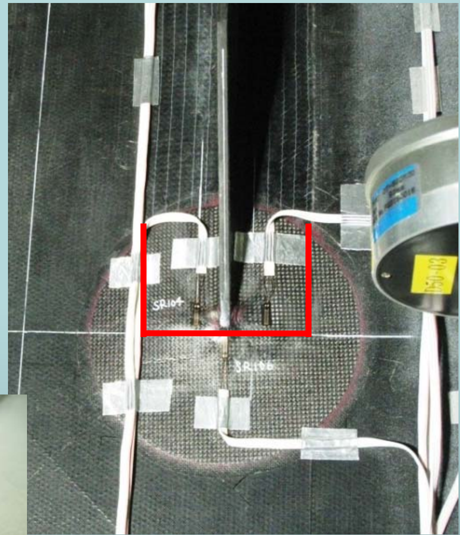


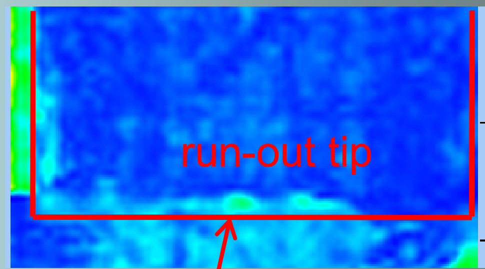


Fatigue Test of Lower Panel:
Inspection after Strain Survey

- **Non-Destructive Inspection by Using Array Probe Ultrasonic C-Scan**
  ⇒Small Delamination at Tip of Stringer Run-out (5mm x 2mm)

64ch x 5MHz linear array sensor

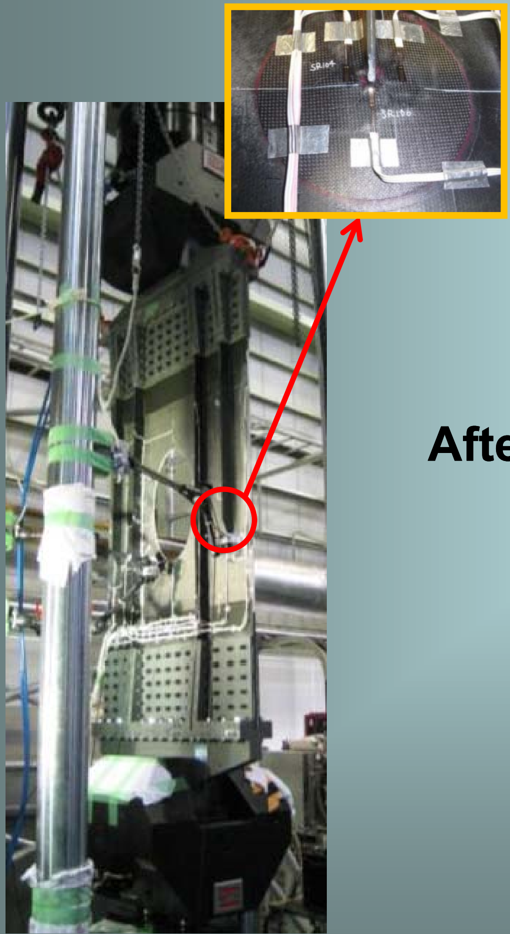


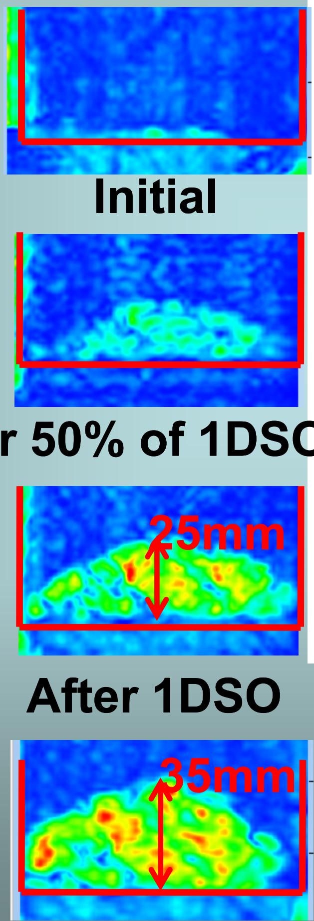


Disbonding (5mm x 2mm)

Fatigue Test of Lower Panel: Evaluation of Delamination Growth

- Inspection Interval: at Every 4,000 Flight (every 10% of DSO)
  - By Human Eye: No Finding
  - **NDI: Growth of Delamination at Stringer Run-out Tip**



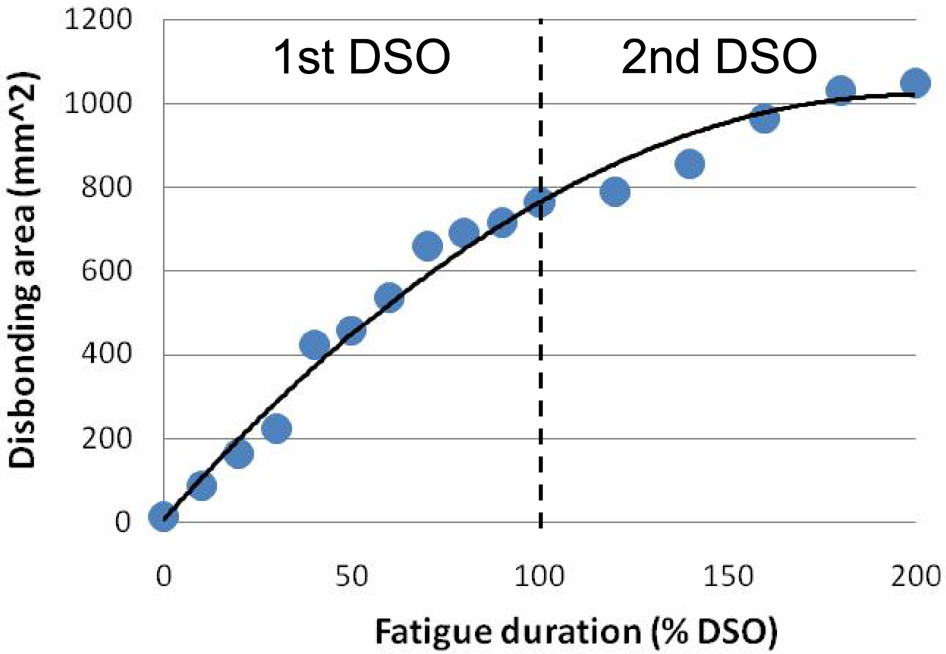


Initial

After 50% of 1DSO

After 1DSO

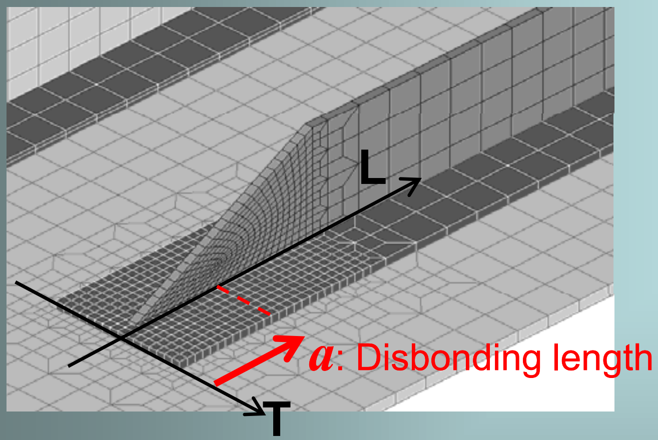
After 2DSO

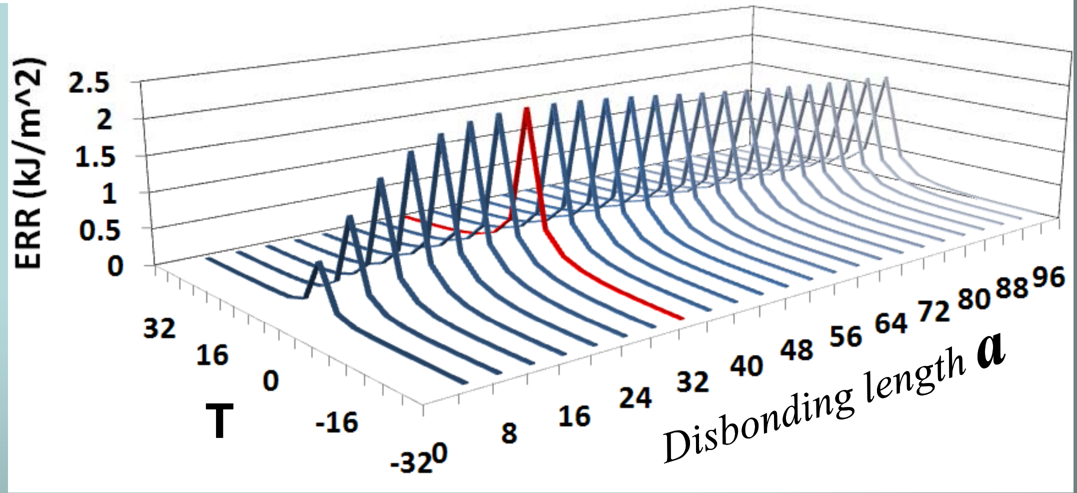


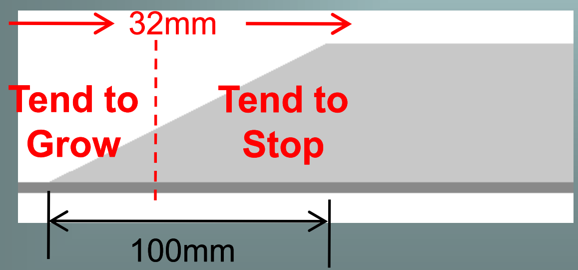
- Stable Growth during 1 DSO (slow growth)
- No Effect on Whole Structural Integrity at 100% DLL Test after 1 DSO

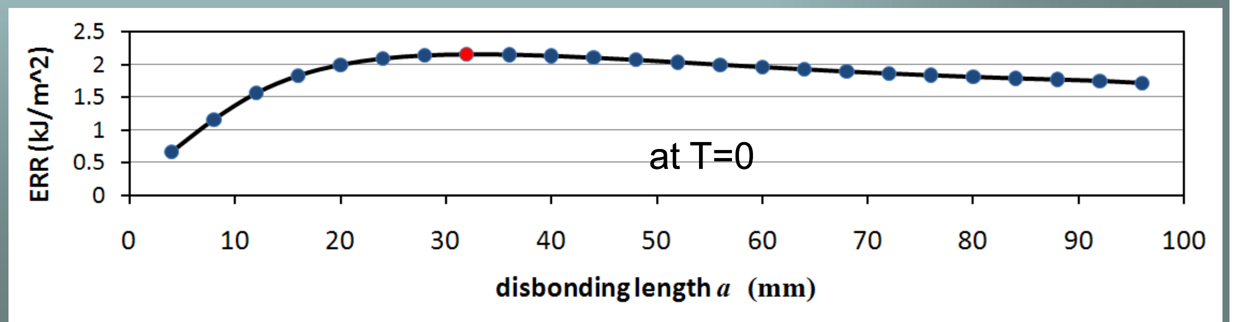
Fatigue Test of Lower Panel:
Numerical Analysis of Damage Growth

- Obtained Relationship between Delamination Length a and Energy Release Rate Distribution at Tip ⇒ Mode I Dominant (GI >> GII, GIII)
- Energy Release Rate Distribution
  - Width-wise (T)：Maximum at the Center(= below Web)
  - Length-wise (L): Increase within a < 32mm → Tend to Grow
    : Decrease over a > 32mm → Tend to Stop



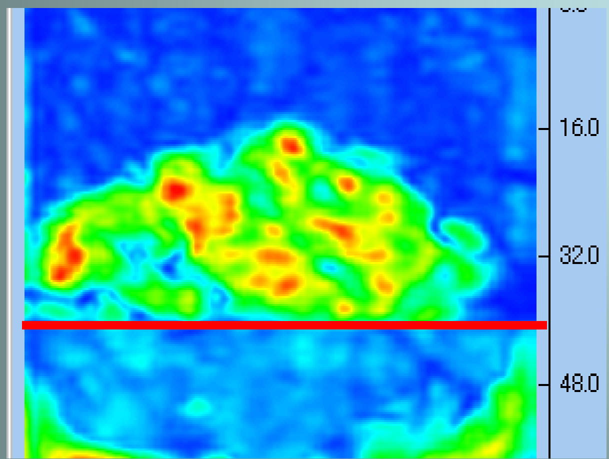




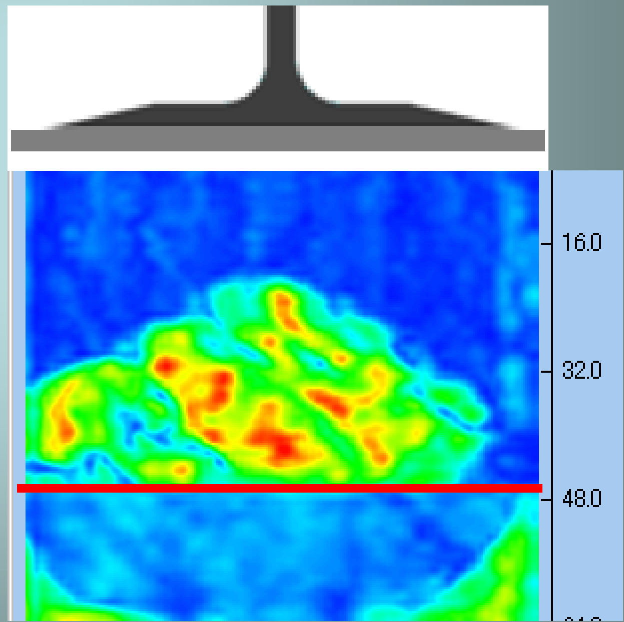


Fatigue Test of Lower Panel:
Damage after Ultimate Load Test

- Loading to 150% DLL, Keep for 3 Seconds
- Slight Growth of Delamination at Stringer Run-out, No Finding other Detrimental Residual Deformation or Rigidity Reduction
- No effect on Structural Integrity



Before 150% DLL test



After 150% DLL test

If numerical prediction is successful, this test can be eliminated.
Current simulation level: not 100% complete, future task

Research of Lightening Strike to Aircraft Composite Structure: Background

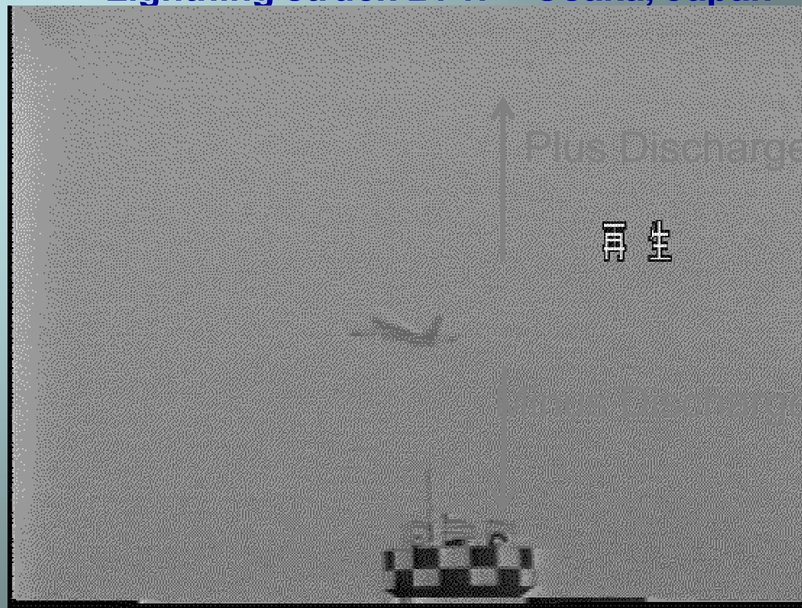
Increase of CFRP application: Main wing

Topics
- Damage mechanism by lightening
- Residual strength and durability after strike
- Method of repair/ strength after repair
- Spark problems in integral fuel tank

Japan Sea coast line in winter: Meteorological anomaly

➡ **High energy, frequent lightening**

Lightning struck B747 Osaka, Japan



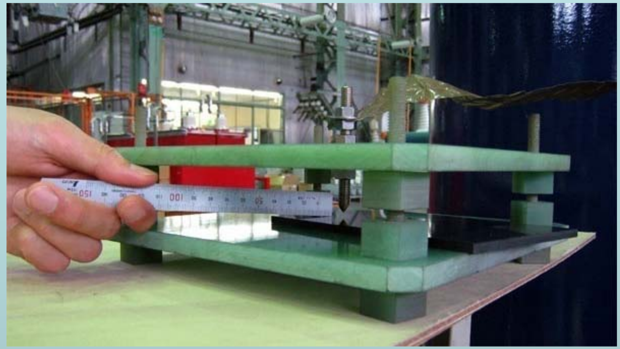
Courtesy of website of Dr. Kawasaki （Osaka Univ.）:（ http://zenk.sblo.jp）

Simulated Artificial Lightening Test
Final Goal: Elimination of Costly Test

Lightening Strike to Regular Compression after Impact Specimen

High Voltage Impulser, by HAEFELY Co.
(Owned by Nisshin Electric Co. Ltd [Japan])

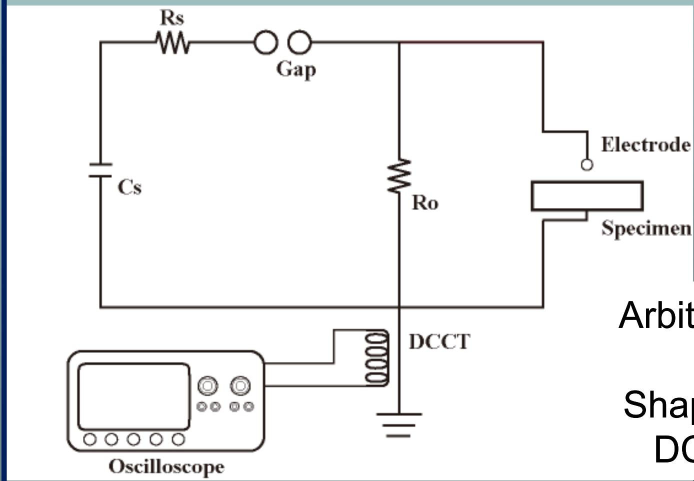
Maximum capability: 2400kV 120kJ
Time Parameter for Impulse Currency Pattern:
4/10μs, 8/20μs, 0/350μs
Maximum Currency: ±40kA (±20kA)



Fixture for specimen

Specimen
ASTM D7131 (CAI)

IM600/133
[45/0/-45/90]4s (n=4)
t = 4.7 [mm]
100×150mm



Arbitrary pulse shape by adjusting R, Cs
Shape data acquired by DCCT, Oscilloscope

Image of Impulser Circuit

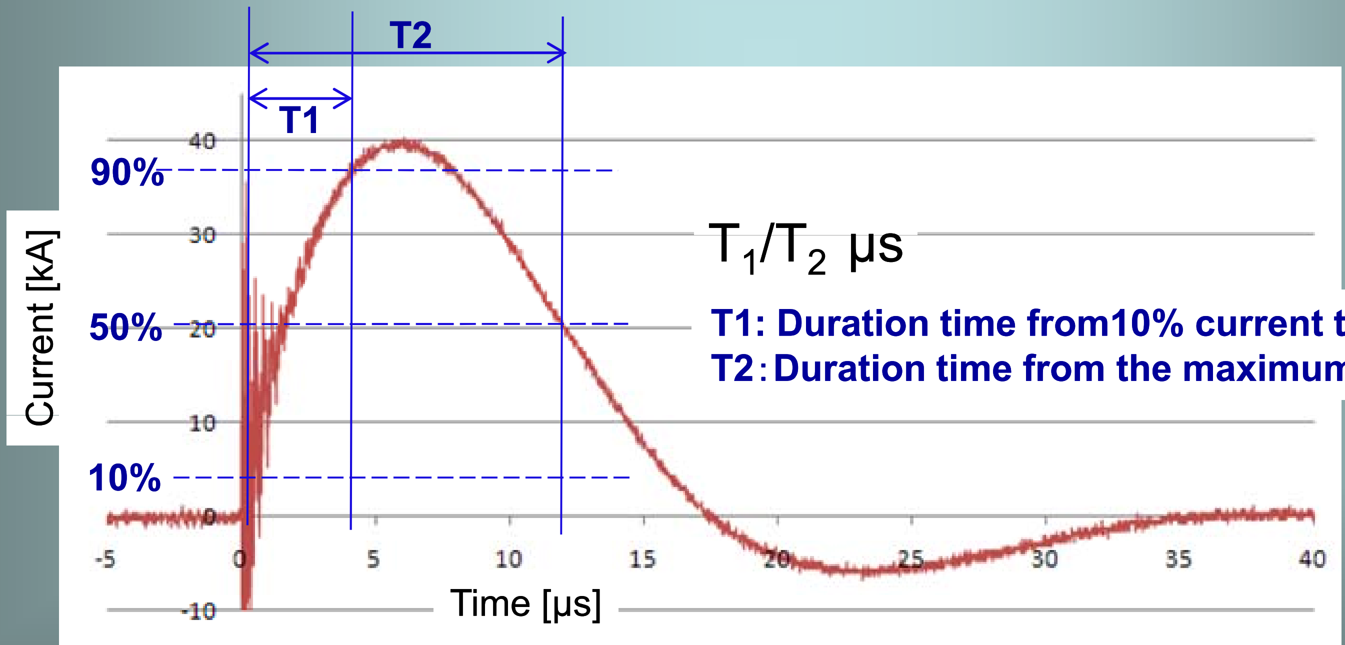
Lightening Impulse Test Parameters

Discharge condition

	Waveform [μs]	Peak Current [kA]	Electrical Charge [C]	Action Integral [A^2s]
I	2.6/10.5	20	0.20	2831.38
II		30	0.31	6273.28
III		40	0.41	11440.90
IV	4/20	20	0.42	5444.82
V		30	0.63	12350.97
VI		40	0.82	20887.35

Electrical charge $Q = \int i\,dt$

Action Integral : AI (Specific current energy) $AI = \int i^2\,dt$



T_1/T_2 μs

T1: Duration time from10% current to 90% current
T2：Duration time from the maximum to 50% current

Obtained impulse current shape at simulated lightening test(4/20, 40kA)

Observed Damage Geometry

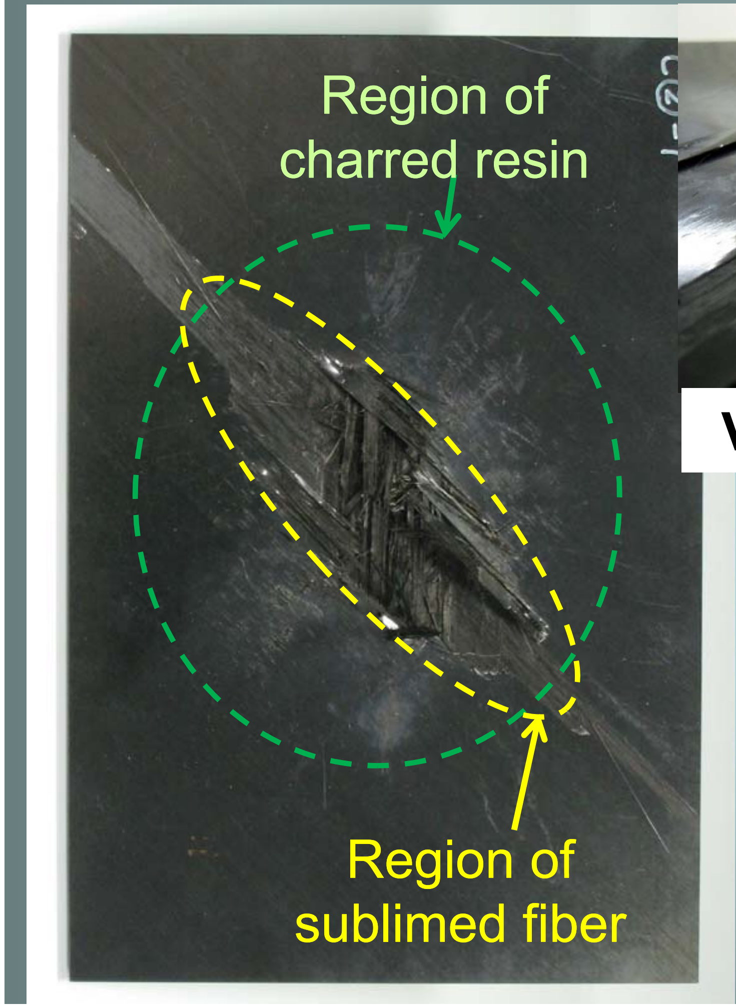


Photo of damaged specimen

Vicinity of impulse contact point

Wave profile ：4/20μs
Peak current：40ｋA
Action Integral：2×10^4[A^2s]
thickness：4.7mm

Observed two damage modes

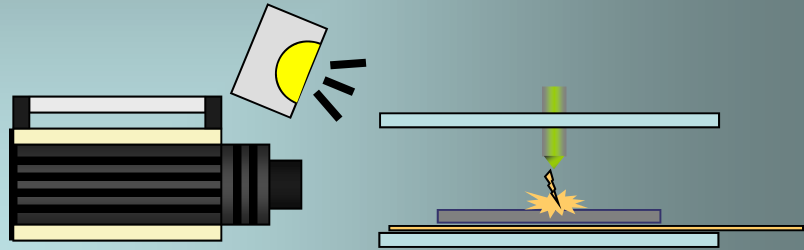
- □Surface damage
  - □Sublimation of fibers in some plies
  - □Delamination under surface ply
- □Charred or sublimed resin: circular area

Estimated scenario: Created super high temperature by Joule heat due to high electric current
⇒Explosive sublimation of fiber or resin

Understanding of Mechanism by Using Ultra-High Speed Video

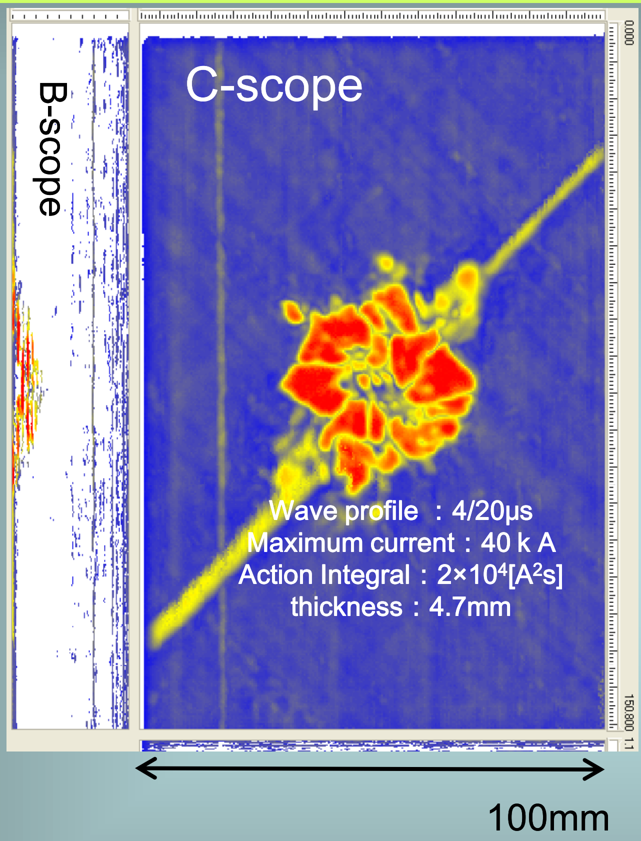
Wave profile : 7/150[μs]
Max. current : 20[kA]
Action Integral (AI) : 3×10^5[A^{2}s]
Thickness : 4.7[mm]

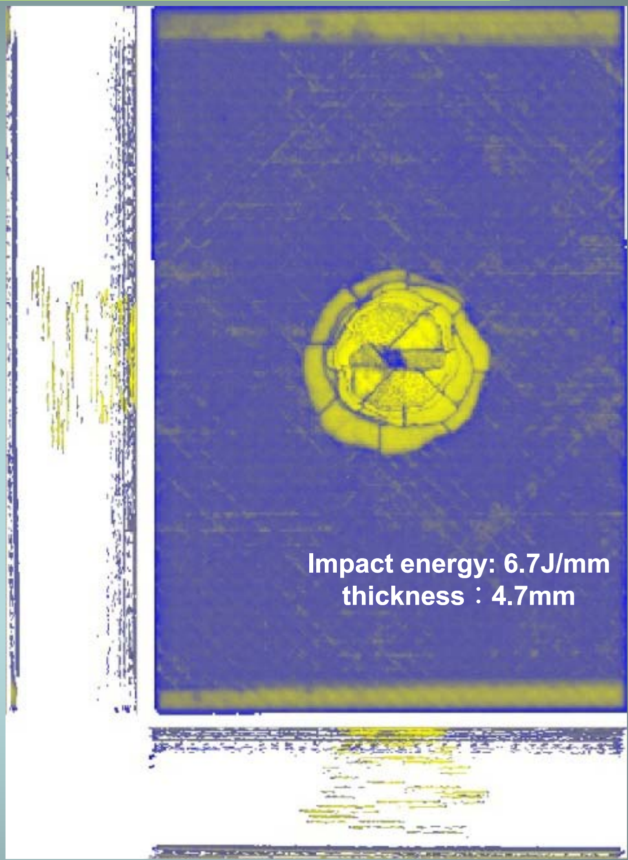
High-speed camera by Shimadzu Co. Ltd
HPV-1 (1,000,000fps max.)



Frame rate : 500,000 fps
Record duration : 200 μs

Internal Damage Pattern by Ultrasonic C-scan

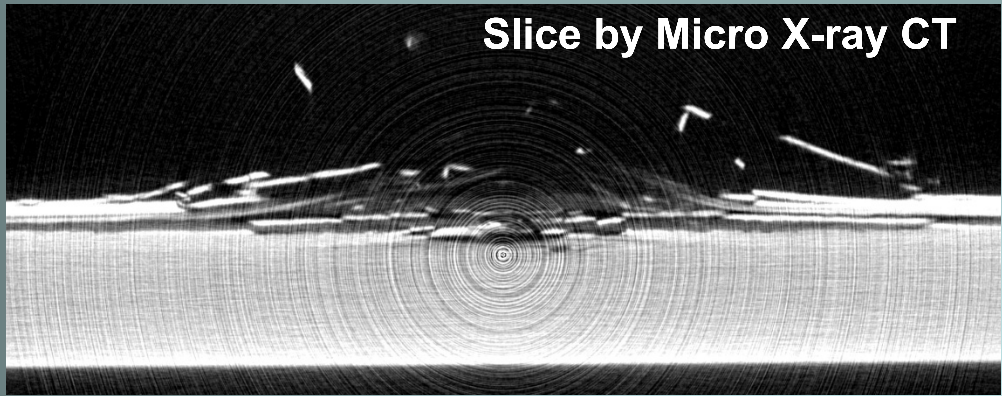


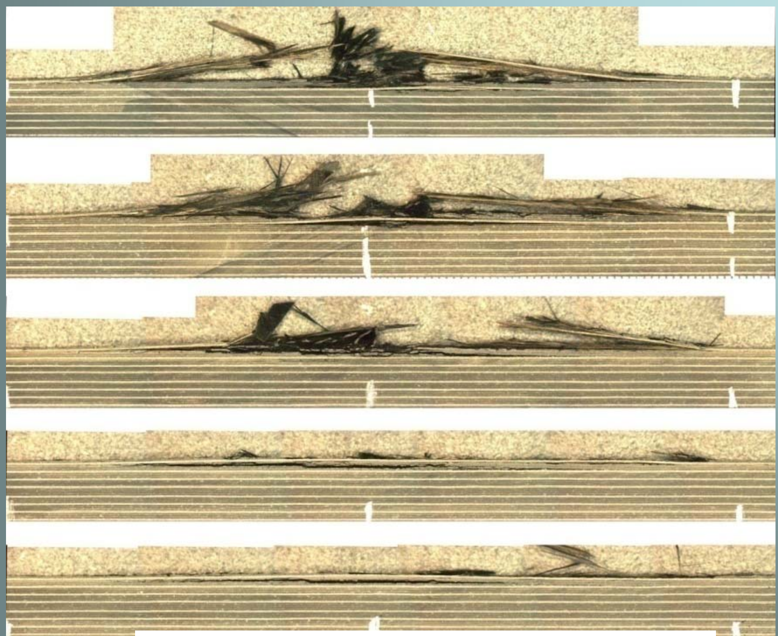


	Damage by lightening	Damage by mechannical impact
Delamination	Delamination between each ply: A pair of fan-like shape	
Cause of growth	Thermal & electrical anisotropy	Mechanical anisotropy
Thickwise extent	A few plies near impulse point	Whole in the thickness

Internal Damage Pattern by X-ray CT Scan and Actual Cutting

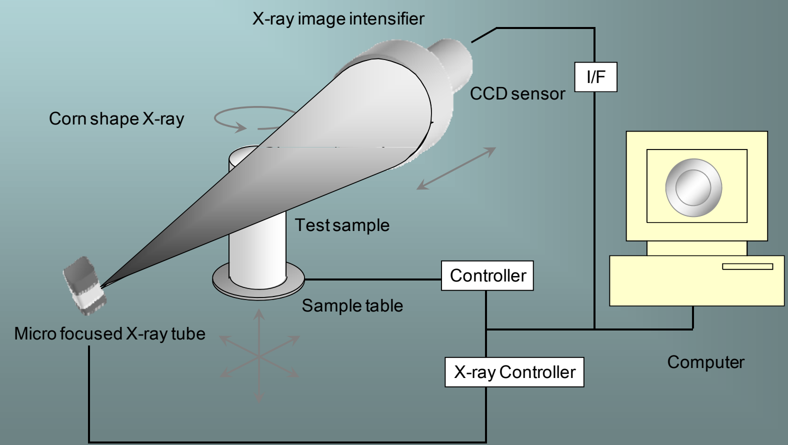
Slice by Micro X-ray CT





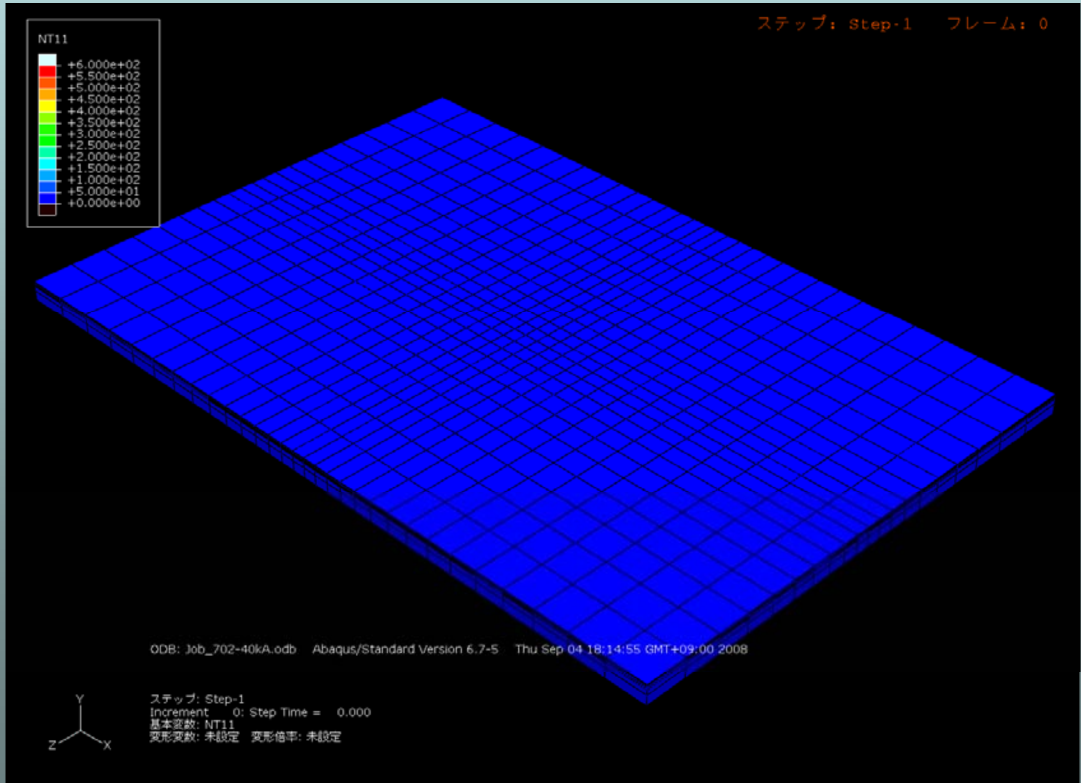
Pictures of cut sections

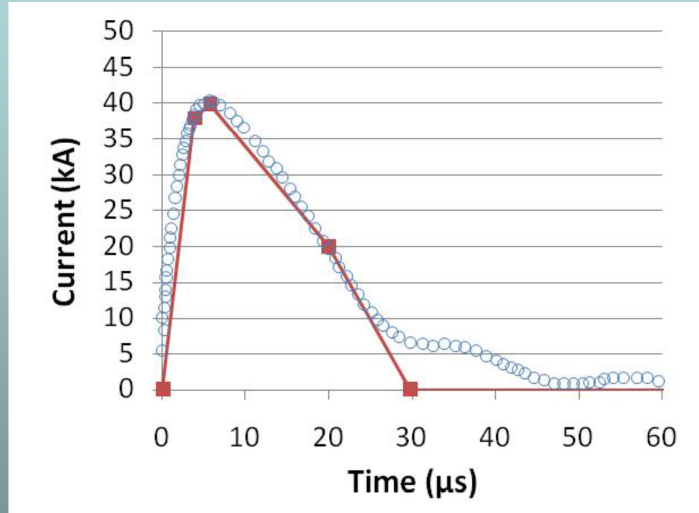
Photo of Micro X-ray CT Scanner



Results of Numerical Temperature Simulation (During and just after Lightening)

- **Peak Current: 40kA, Wave Time Parameter: T1/T2=4/20**
  During Lightening: 0～30 μsec., After Lightening: 30～50μsec.
- **Gray Color Region Indicates over 3000℃**
  （Decomposition→Delamination→Sublimation）

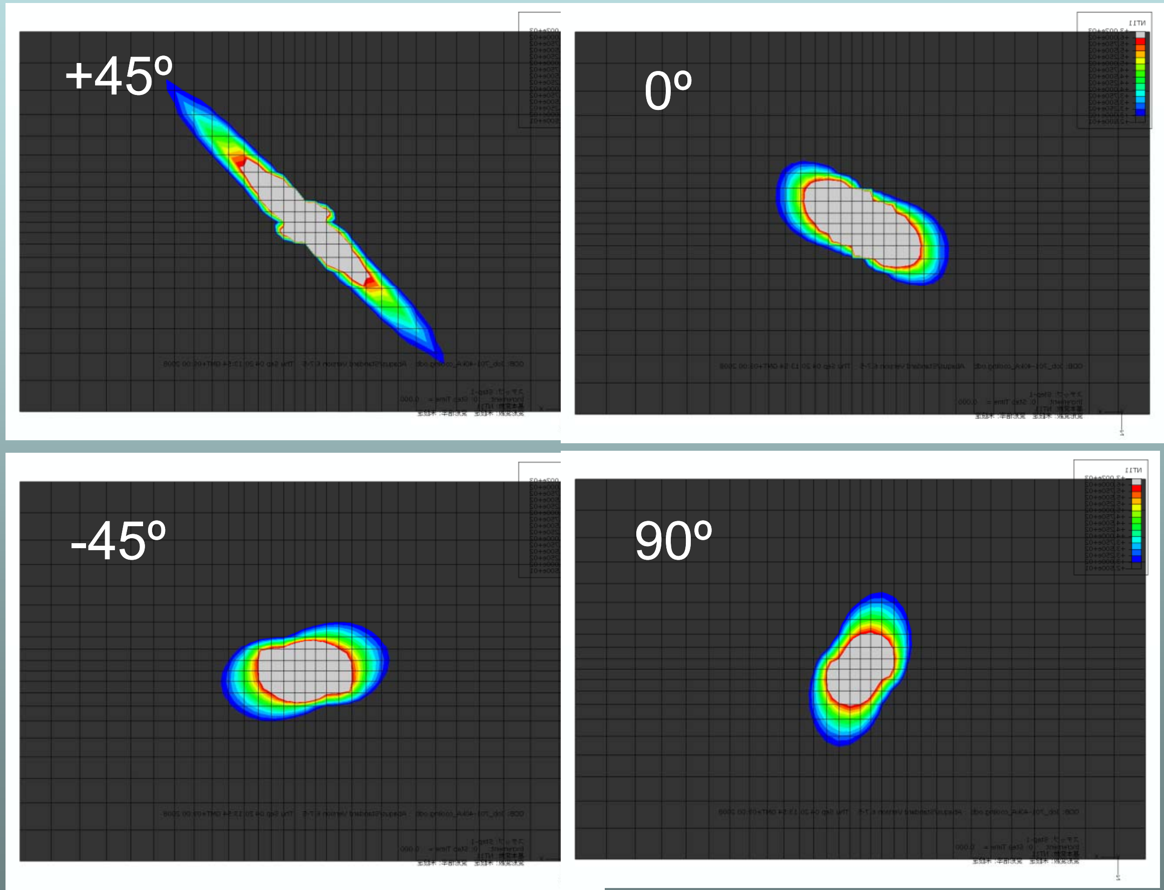


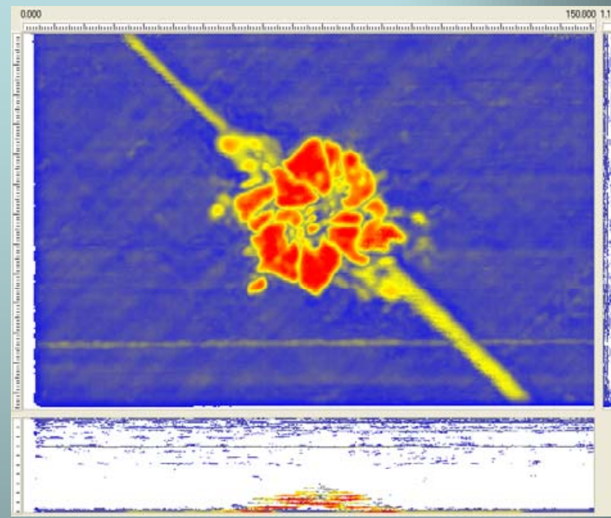


0～50 μsec

Temperature Distribution at Each Ply
Current Simulation Level: Qualitative

- **Peak Current: 40kA, Wave Time Parameter: T1/T2=4/20**
- **Regions over 300℃ : Indicated**
- **Distribution Shape: Affected by Heat Conduction after Lightening**





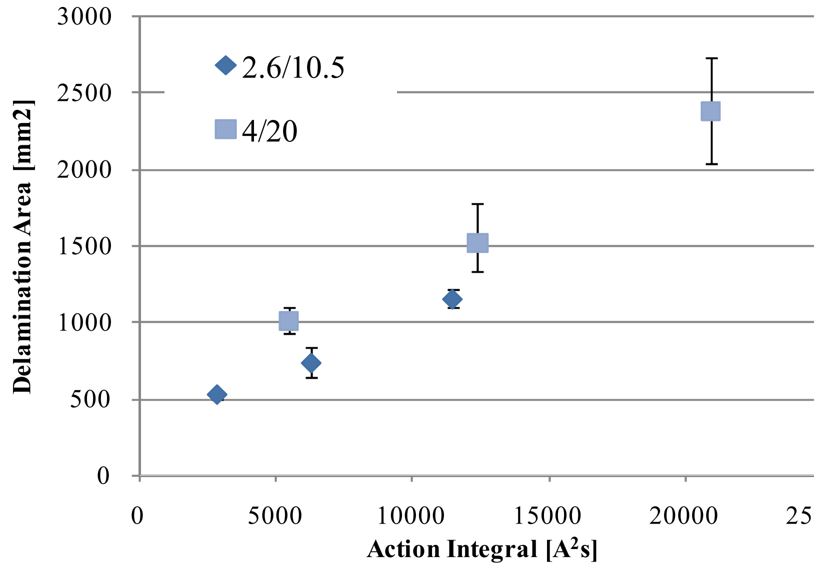
Ultrasonic C-Scan from the Backside of the Specimen

Level of numerical simulation: only at a gateway

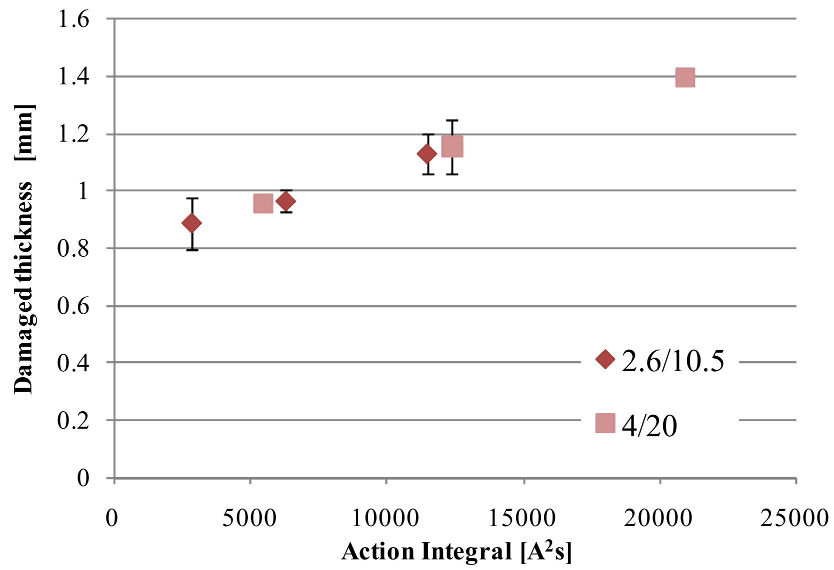
Relationship between Lightening Energy and Damage Extent

- Delamination area (in projection)
  - Fiber damage
  - Resin char
- Damage depth (Mainly delamination)

Next Step: More Quantitative EME Based Analysis



Projected delamination area vs AI



Damage depth vs AI（by Micro CT）

Almost linear relationships between AI (Specific current energy) and delamiantion area and AI and damage depth

Summary

JAXA Japan Aerospace Exploration Agency

- Increase of composites percentage in aero-structures
- Recent two major challenges: B-787 and A350
- Precious lessons learned: Delay and cost issues, Unexpectedly low weight reduction, increase?
- Proposal for Development Cost Reduction
  Substitution of some steps in BBA by "Virtual testing"
  "Virtual processing" : Out of scope, today
- Example: Lower panel of VaRTM wing test, potential of future substitution of BBA steps by simulation
- Example: Lightening strike damage: difficult & costly tests, at a gateway of accurate numerical simulation
- If high development costs remain in composites, aircraft industries may go back to aluminum again!