Aging Effects Evaluation of A Beechcraft Starship and a Decommissioned Boeing CRFP 737-200 Horizontal Stabilizer

Research Team (Beechcraft Starship)

- Principal Investigators & Researchers
  - Dr. John Tomblin, Wichita State University
  - Lamia Salah, Wichita State University
- FAA Technical Monitor
  - Curtis Davies
- Other FAA Personnel Involved
  - Peter Sheprykevich, Larry Ilcewicz
- Industry Participation
  - Ric Abbott

Outline

- Objective/ Methodology
- Background
- Test Article Description
- Teardown
- Investigative Plan
- NDI Evaluation after Teardown
- Summary/ Ongoing Efforts

Objective / Methodology

- To evaluate the aging effects on the composite structure of a beechcraft starship after 12 years of service (1827 hours)
- Non-Destructive Inspection to identify flaws induced during manufacture/ service (delamination, disbonds, impact damage, moisture ingression, etc…)
- Coupon level static and fatigue testing to investigate any degradation in the mechanical properties of the material.
- Physical and thermal tests to validate design properties, identify possible changes in the chemical properties of the material
- Full scale durability and damage tolerance tests to validate the structure's design philosophy

Background

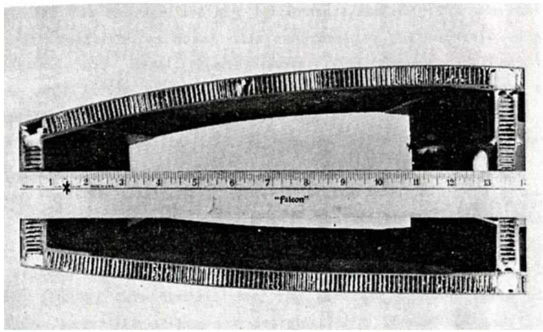
- The starship program was officially launched in 1982.
- Objectives were to produce the most advanced turboprop business airplane feasible at the time and to promote the use of composites in a business aircraft
- Benefits: to achieve elaborate contours through composite molding, lower part count, manufacturing simplicity, use composite's resistance to corrosion, good fatigue properties, weight savings.
- 70% of the airframe by weight is composite (main and forward wing, pressure cabin and tip-sail are nomex honeycomb sandwich construction)

Background

- The first beechcraft starship was flown on February 15th, 1986. The second joined the test flight program in June 1986, and the third was ready for flight in the early spring of 1987. In the course of a two-year flight test program, they flew almost 2,000 hours, and on June 14th the Starship received type certificate from the FAA.
- A total of 53 airframes were built but only a handful ever sold. In 2003, the OEM decided to retire the entire Starship fleet except four that were still flying as of October 2006.
- Certification: the starship was certified to FAA part 23 regulations plus special conditions: damage tolerance methods instead of fatigue life or fail safe methods traditionally required for part 23 airplanes

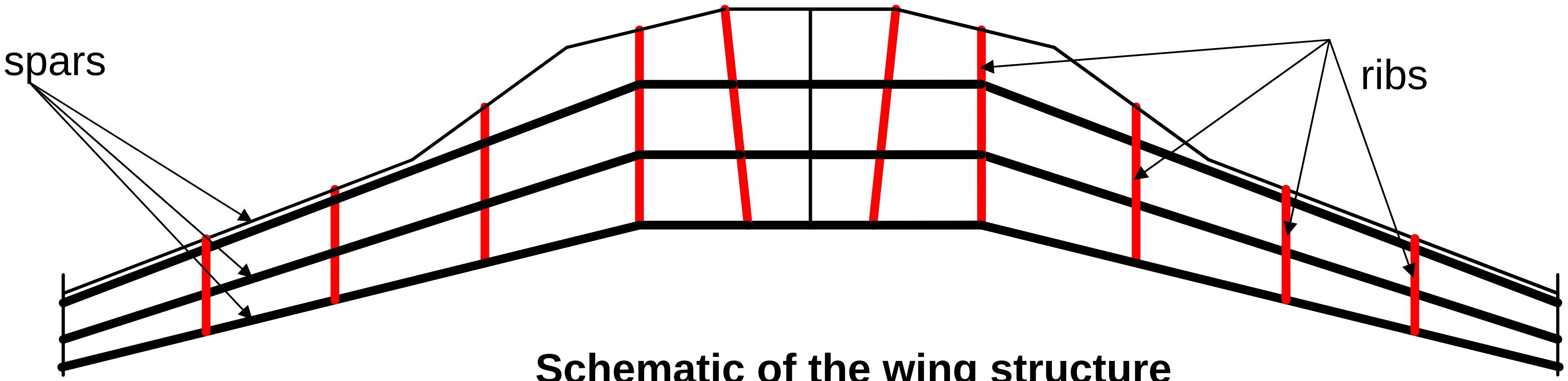
Test Article Description (Main Wing)

- Monocoque structure with three spars and five ribs
- The wing skins are cured in one piece 54 feet tip to tip
- The wing skins are secondarily bonded to the spars and ribs using paste adhesive
- Lightning Protection achieved through the use of hybrid woven graphite/ aluminum fabric as the surface ply in all exterior surfaces
- Materials used was HITEX/ E7K8 12K/ 280 and 145 tape and AS4 E7K8 3K/195 PW fabric. Material qualification was conducted per Military Handbook 17 specifications. Lamina and Laminate testing was conducted to generate tension, compression, shear strength, stiffness and ultimate strain in cold/dry, room temperature/dry, room temperature/ wet, and hot-wet environmental conditions.



Test Article Description (Main Wing)

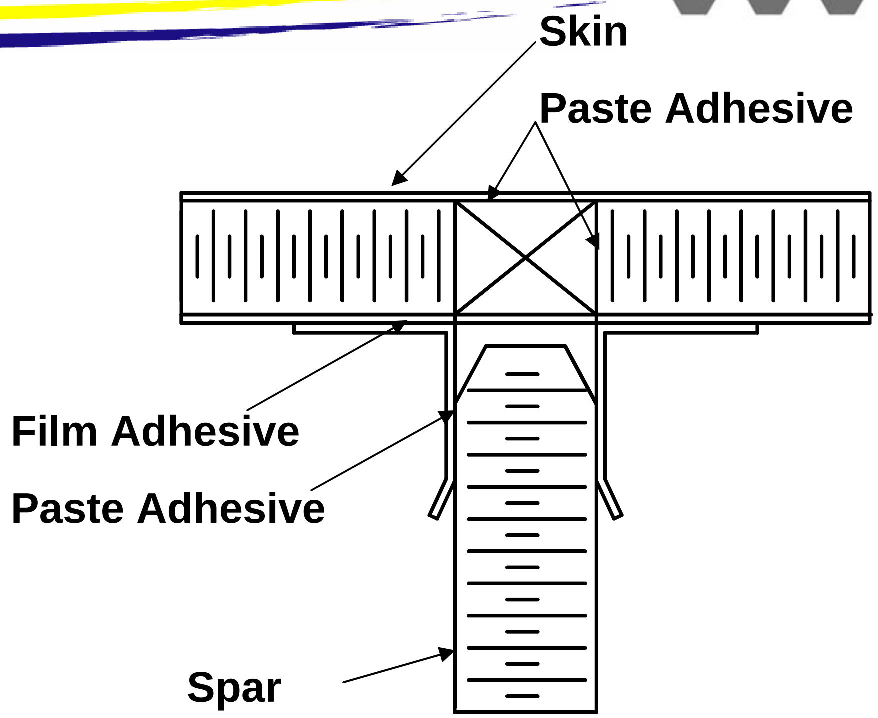
- Spars: 3 full span spars, fabricated from graphite/epoxy facesheets separated by Nomex honeycomb core
- Ribs: the aft wing has five ribs, symmetric about the aircraft centerline. The ribs are also sandwich construction
- Wing Box Assembly joints: 3 types of secondary bonded joints were used to bond the skins to the spars and ribs, the H-joint, the V-joint and the shear clip joint



Schematic of the wing structure

Test Article Description (Main Wing)

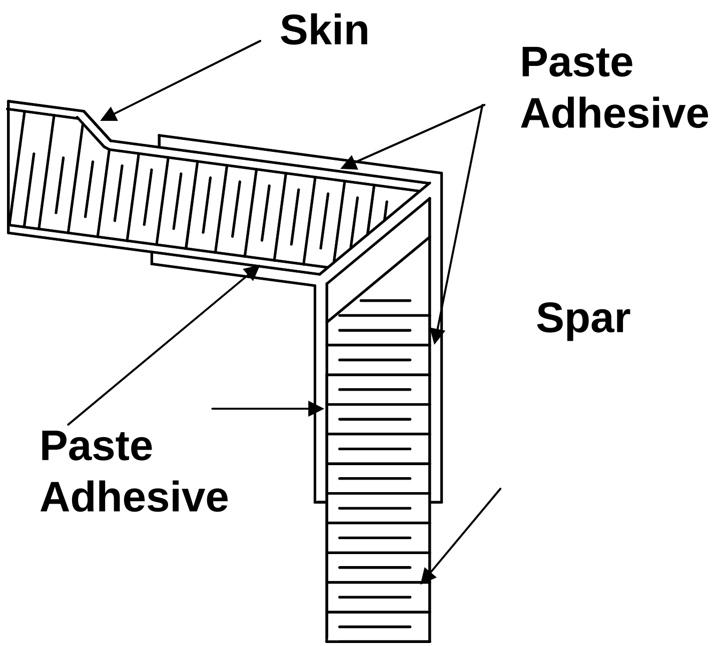
- H-Joint: used to join the upper and lower skins to the spars
- A cutout is first routed in the skin prior to bonding the joint to the skin.
- The joint is then secondarily bonded to the skin using paste and film adhesive
- The spars are finally bonded to the assembly using paste adhesive



H-Joint Cross Section

Test Article Description (Main Wing)

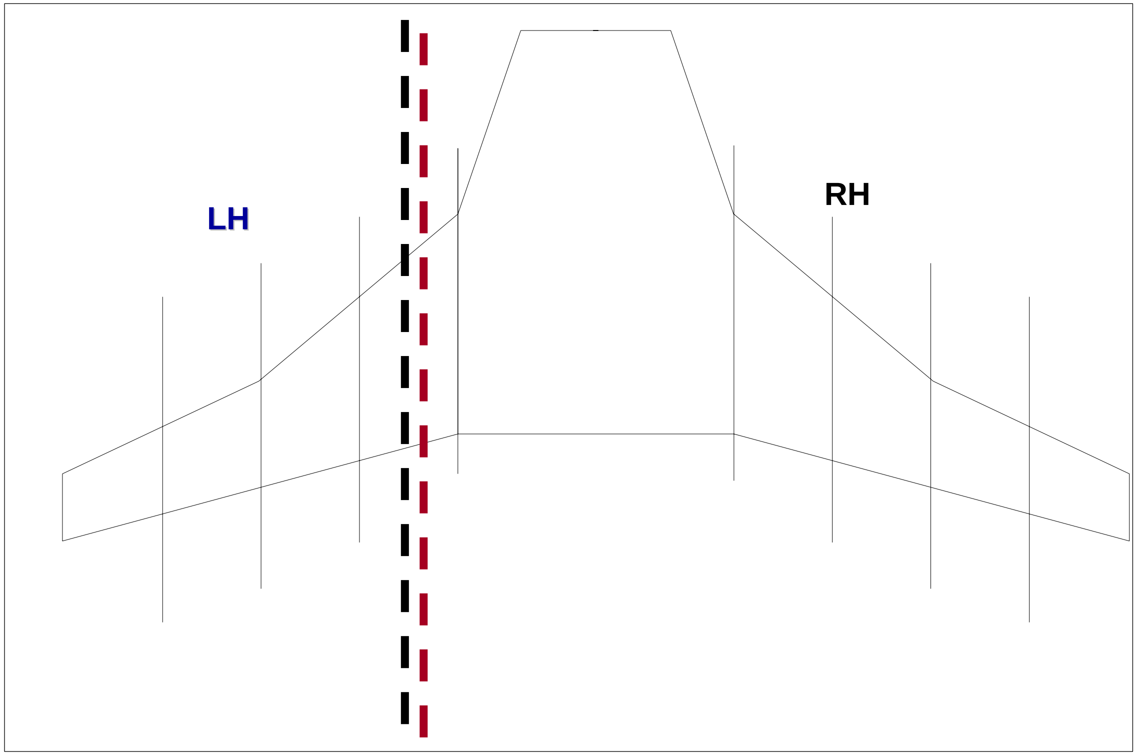
- V-Joint: used to bond the upper and lower wing skins to sections of the forward and aft spars
- The pre-cured graphite epoxy joint is secondarily bonded to the wing skin first using paste adhesive
- After this process is completed, the assembly is subsequently joined to the spars using paste adhesive



Disassembly

Main components disassembled (fuselage, forward wing, main wing, nacelles, fuel tanks)

Main wing cut in two pieces for ease of transportation



Disassembly

Main wing was demated from the fuselage at the 4 fuselage attachment points shown below

Wing to fuselage attach points

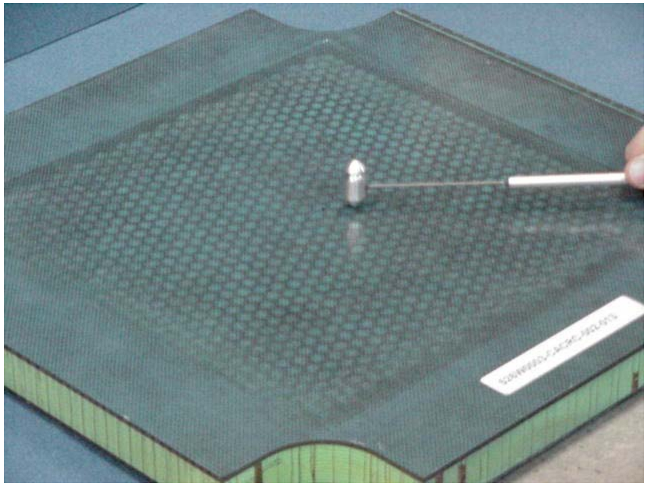
LH wing used for detailed destructive testing

RH used as a full scale static and fatigue article

Non-destructive Inspection Methods

Several NDI methods are being used to inspect the structure in its current state but also to monitor flaw growth during fatigue testing

- **Full Scale Test Article**
  Tap Testing, Visual Inspection, TTU and PE when necessary
- **Wing LH used for detailed destructive evaluation (TTU used for inspection)**



Tap Hammer (AANC-SNL)

TTU Equipment (WSU)

Investigative Plan

Destructive Evaluation:

Image Analysis will be used to determine void content and inspect the structure for microcracks

Thermal/ Physical Tests
Differential Scanning Calorimetry (DSC)
Dynamic Mechanical Analysis (DMA), to evaluate Tg, degree of cure

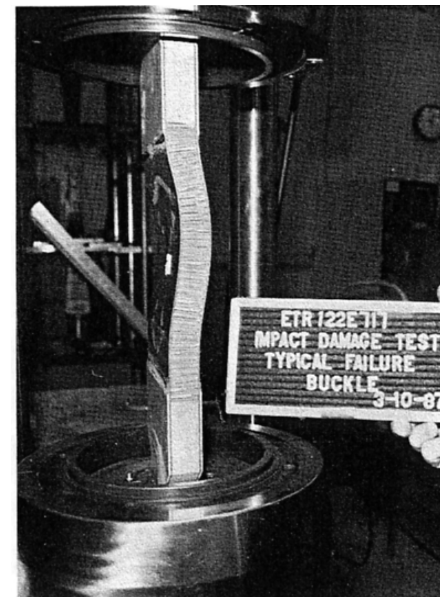
Resin and fiber mass ratios, void content (D3171, D2734), to evaluate fiber volume fractions, porosity levels and compare them to the design values

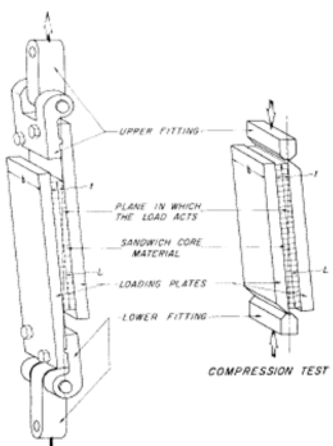
Moisture Content By Weight Loss/gain (ASTM D5229) to evaluate moisture levels in the structure

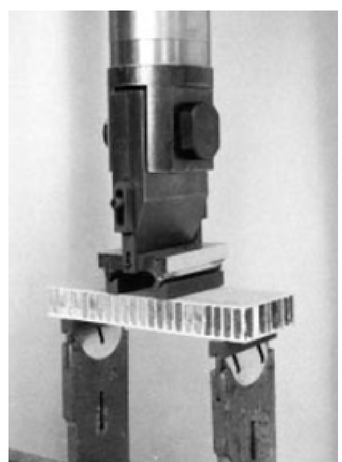
Investigative Plan

Coupon/ Element Mechanical Testing

- Compression after impact
- Compression and tension static and cyclic flaw growth
- ASTM C273 to determine possible changes in core shear properties
- ASTM C297 to determine possible changes in core flatwise tension properties
- ASTM C393 to determine possible changes In the sandwich flexural properties

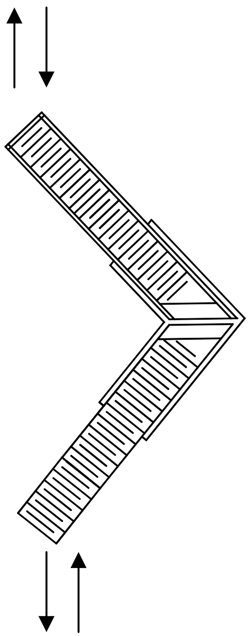




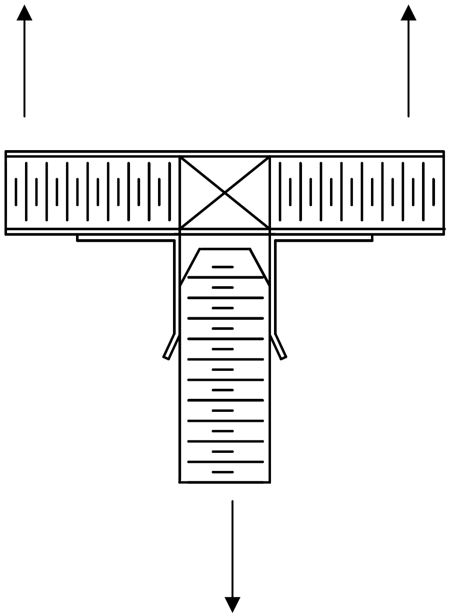


Investigative Plan

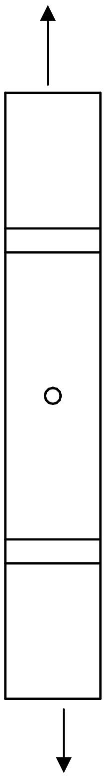
Element Mechanical Testing



V-joint Static/ Cyclic Tension/ Compression



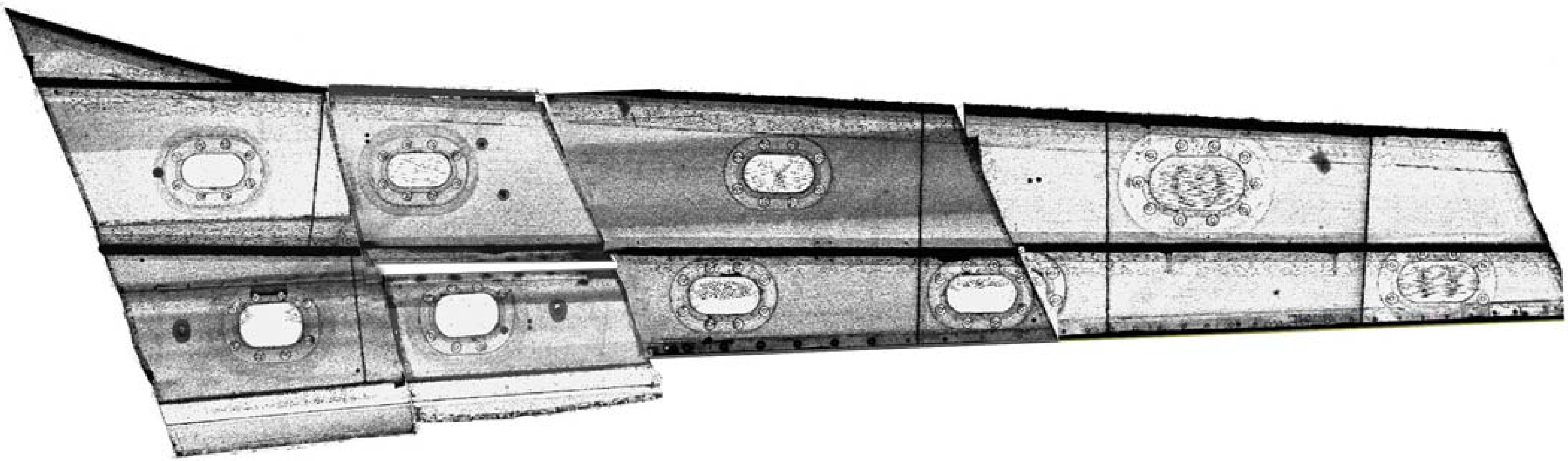
H-joint Static/ Cyclic Tension



FHT Testing

Non-destructive Inspection-LH

Preliminary TTU Non-Destructive inspection showed no evidence of flaws induced during manufacture or service in the skins



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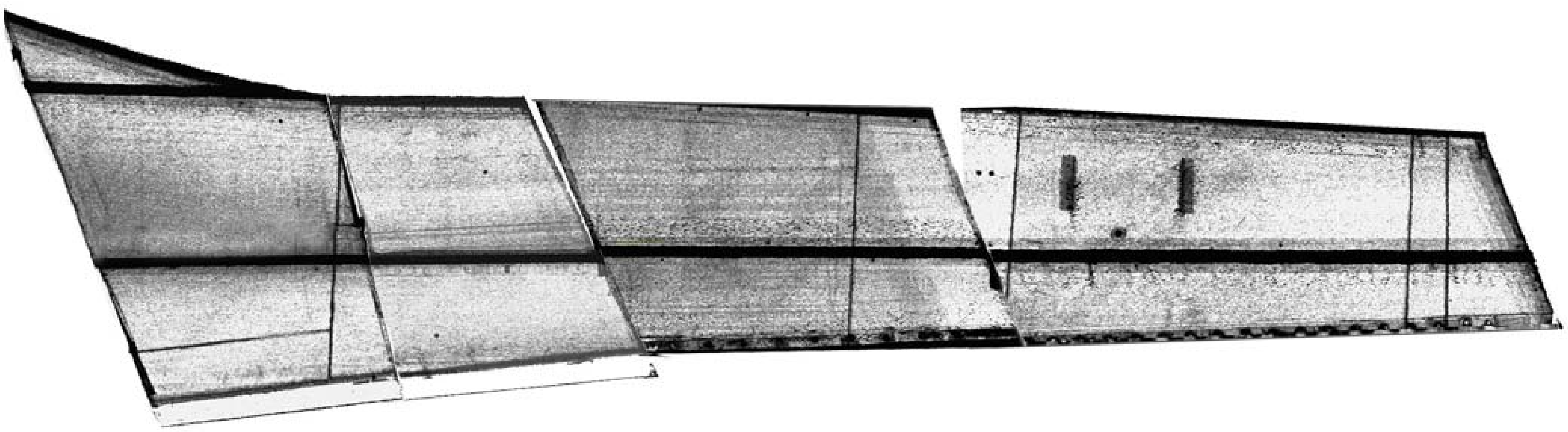
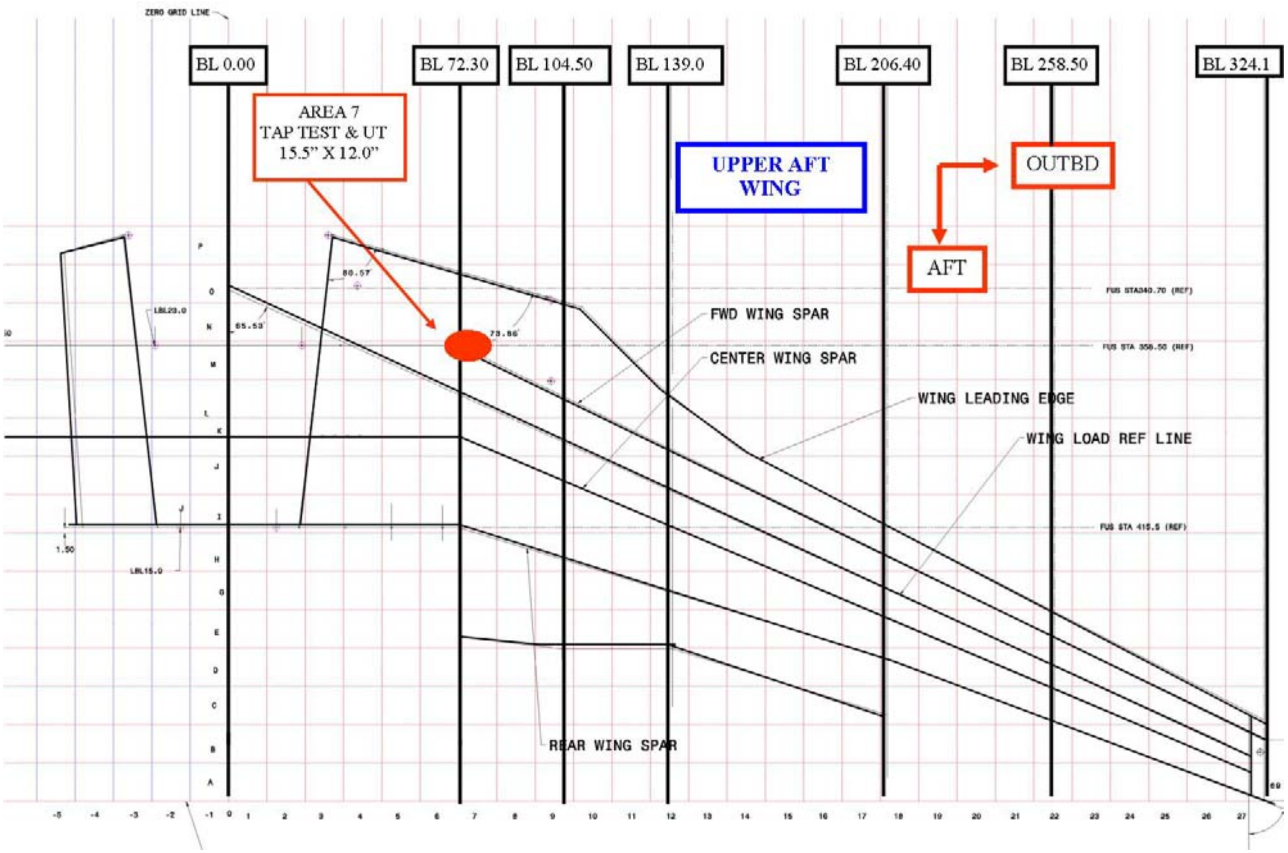


Full Scale Structural Test

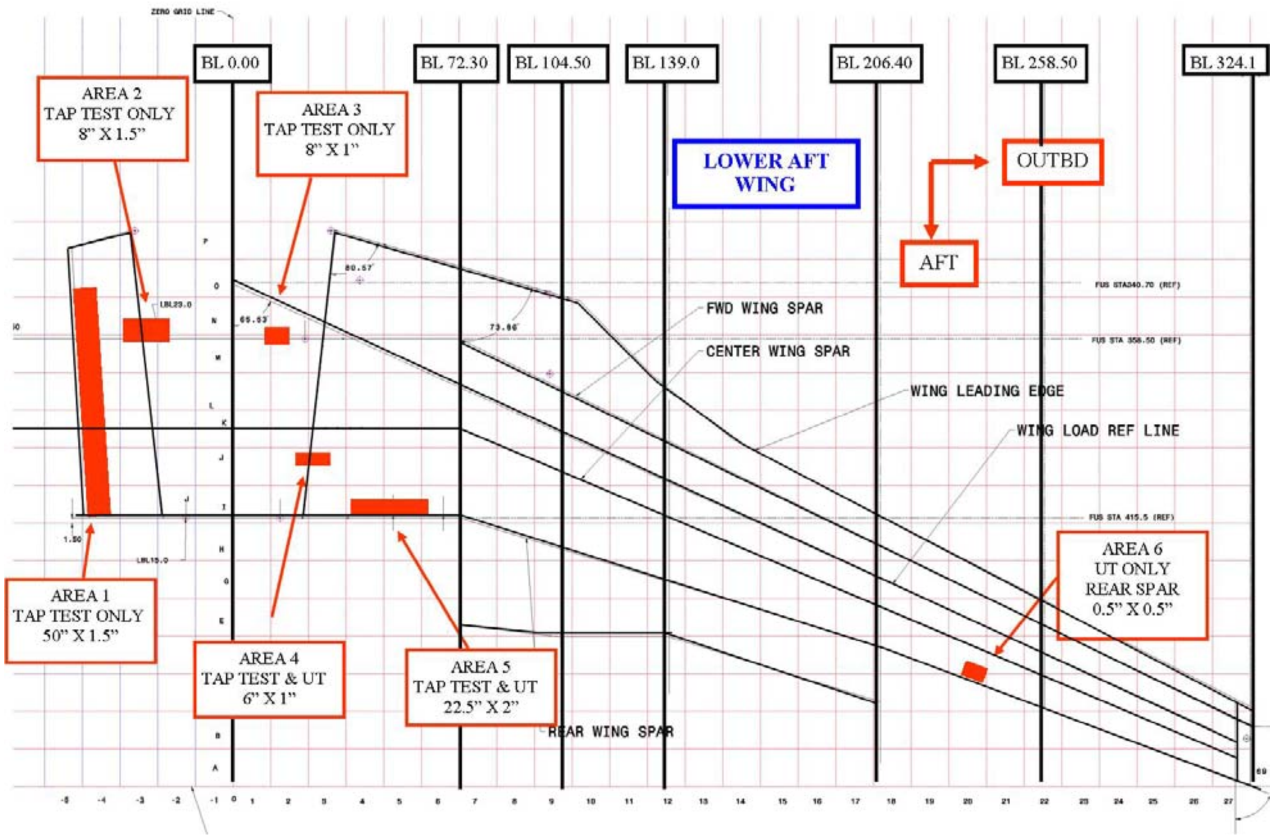
- A baseline Non-Destructive Inspection scan has been conducted prior to conducting the full scale test in order to identify possible manufacturing flaws or defects induced during service
- NDI standards have been built, probes and an NDI grid has been drawn on the structure for ease of inspection and flaw growth monitoring
- The OEM has supplied engineering reports that define the wing load reference line for subsequent full-scale static and fatigue tests.
- A fixture has been built to simulate inertia loads induced by the engines.
- A fixture has been built to simulate rudder tip deflections
- Limit Load full-scale test preparation in progress

Full Scale Structural Evaluation



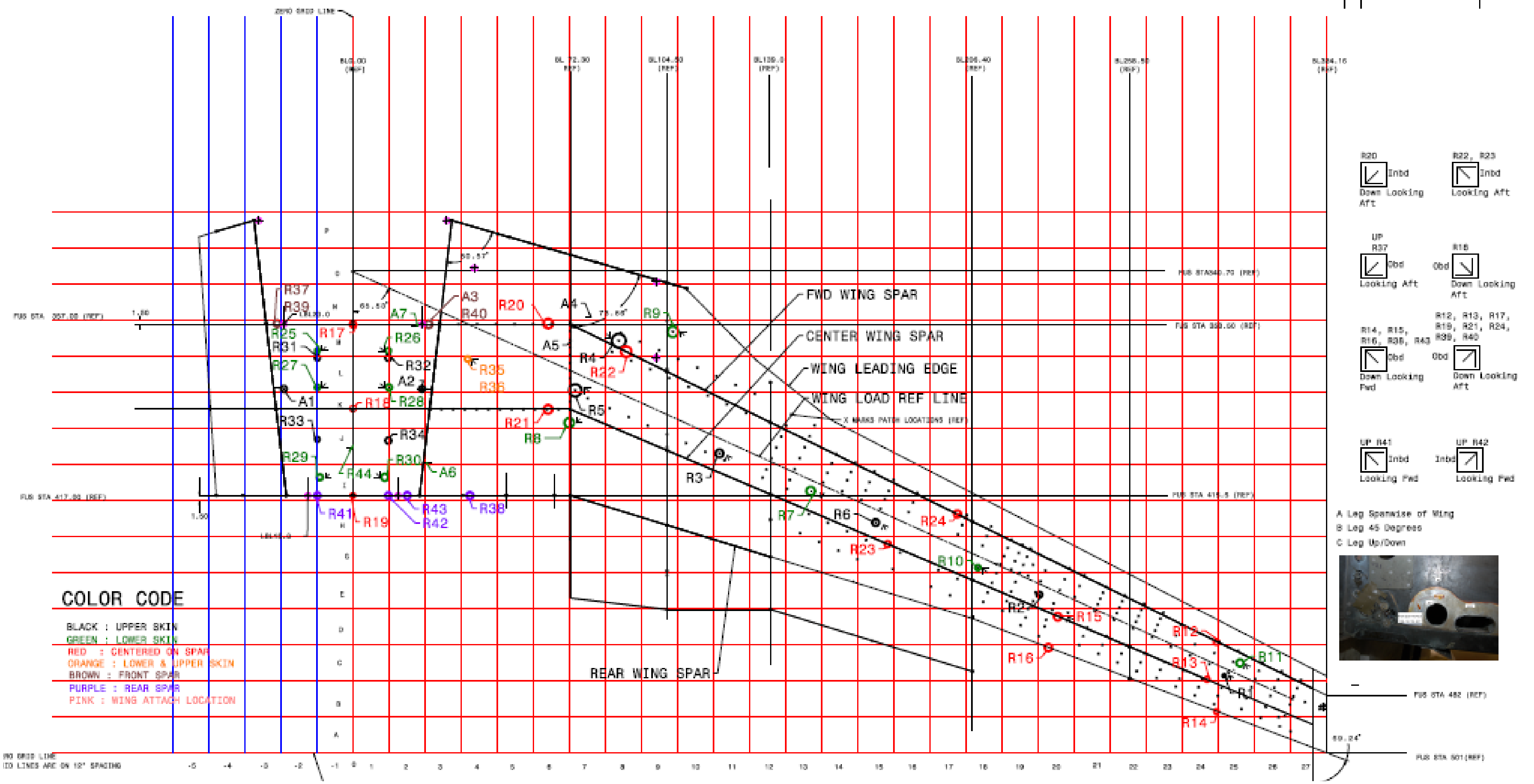
NDI results of the Left Upper Aft Wing of the Starship

Full Scale Structural Evaluation



NDI results of the Left Lower Aft Wing of the Starship

Full Scale Structural Test



Full Scale Structural Evaluation

Baseline NDI Inspection after 1800 hours of service

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Limit Load Test-1 condition

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Durability Test at original levels Scatter factor of 1.151/ different LEF
- Inspection of exposed airframe components every 600 hours
- Significant Structural items inspection every 2500 hours

↓

Limit Load Test-1 condition
- Strain Surveys to document changes in compliance

↓

Damage Introduction
Delaminations/ disbonds, impact damage

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Damage Tolerance Test
- Flaw growth Monitoring/ strain survey
- Repair Implementation
- Inspection every 5000 hours

↓

Limit Load Test to demonstrate Residual Strength

Summary/ Ongoing Efforts

- LH TTU non-destructive inspection, complete
- Thermal Analysis, Image Analysis, physical tests and mechanical tests

- RH baseline skin NDI, complete
- Strain gage installation complete
- Full scale static and fatigue test final set-up in progress

- Aging effects will be evaluated at the bottom of the building block (coupon tests) but also at the top of the pyramid using a full scale structure

Research Team (B737)

- Principal Investigators & Researchers
  - Dr. John Tomblin, Wichita State University
  - Lamia Salah, Wichita State University
- FAA Technical Monitor
  - Curtis Davies
- Other FAA Personnel Involved
  - Peter Sheprykevich, Larry Ilcewicz
- Industry Participation
  - Dr. Matthew Miller, The Boeing Company
  - Dan Hoffman, Jeff kollgaard, Karl Nelson, The Boeing Company

Outline

- Objective/ Methodology
- Background: ACEE program/ Boeing 737 HS Fleet Status
- Test Article Description
- Teardown: Procedure/ Preliminary Findings
- Non Destructive Inspection Prior to and after teardown
- Destructive Evaluation after Teardown
- Physical Test Results
- Thermal Analysis Results
- Image Analysis
- Mechanical Tests
- Conclusions/ Value of the Teardown
- Acknowledgments

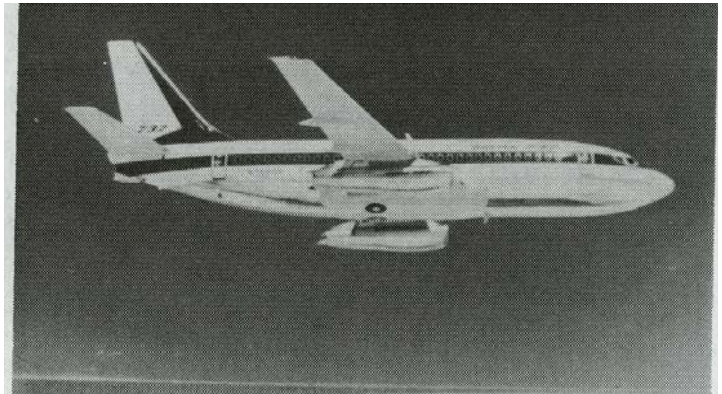
Objective / Methodology

To evaluate the aging effects of a (RH) graphite-epoxy horizontal stabilizer after 18 years of service (48000 flights, 2/3 of DSO)

- **Non-Destructive Inspection to identify flaws induced during manufacture or service**
- **Mechanical testing on coupons extracted from the structure to investigate any degradation in the mechanical properties of the material**
- **Physical, thermal and image analysis to quantify porosity and moisture levels in the structure, characterize its thermal properties and its state at the micro-structural level (microcracks, etc…)**

Background

- The B737-200 CRFP stabilizer was built as part of the NASA ACEE (Aircraft Energy Efficiency) program initiated in late 1975
- The purpose was to develop new technologies to reduce fuel consumption in aircraft structures
- The ACEE program was subdivided into four development areas: laminar flow systems, advanced aerodynamics, flight controls and composite structures
- The ACEE Composites program focused on redesigning existing structural components using lighter materials
- A building block approach was followed where composite structure development would start with lightly loaded secondary components followed by medium primary components and finally wing and fuselage development

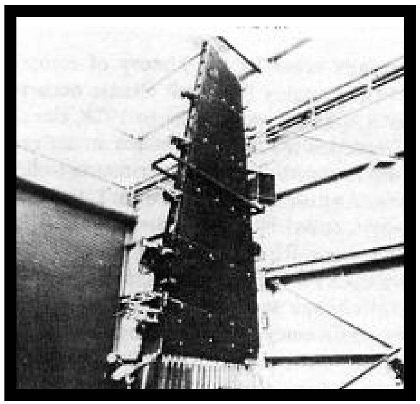

BOEING 737 COMPOSITE HORIZONTAL STABILIZER

DC-10 VERTICAL STABILIZER

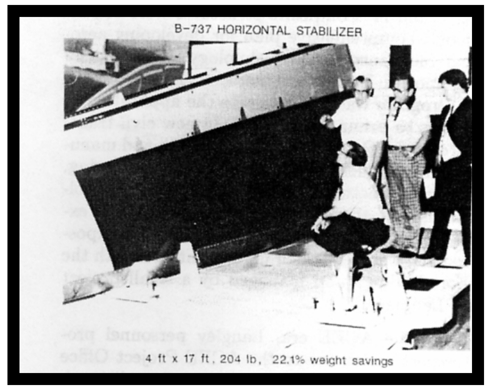
7 ft x 23 ft,780 lb, 22.6% weight savings

Background

- Six aircraft secondary and medium primary components were redesigned using composite materials
- ACEE program was ended before the implementation of advanced materials in wing and fuselage components



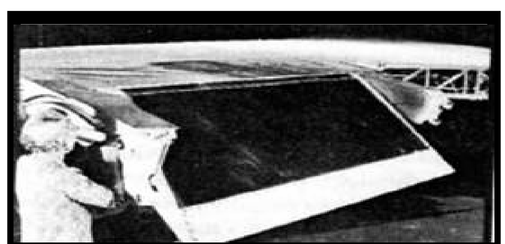
L1011 Vertical Fin



B-737 Horizontal stabilizer

DC 10 Vertical Stabilizer

DC-10 Upper Aft Rudder



L1011 Inboard Aileron

B 727 Elevator

Background

- The OEM redesigned, manufactured, certified, & deployed five shipsets of 737-200 horizontal stabilizers using graphite-epoxy composites
- Certification was achieved in 1982 and all shipsets were introduced into commercial service in 1984
- The OEM closely monitored the performance of the stabilizers for 7 years. Outstanding performance was demonstrated with no in-service incidents attributed to aging of the composite structure

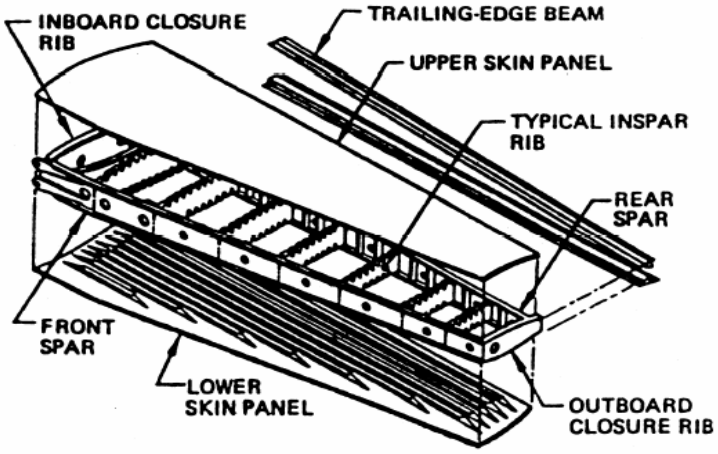
Boeing 737 Fleet Status

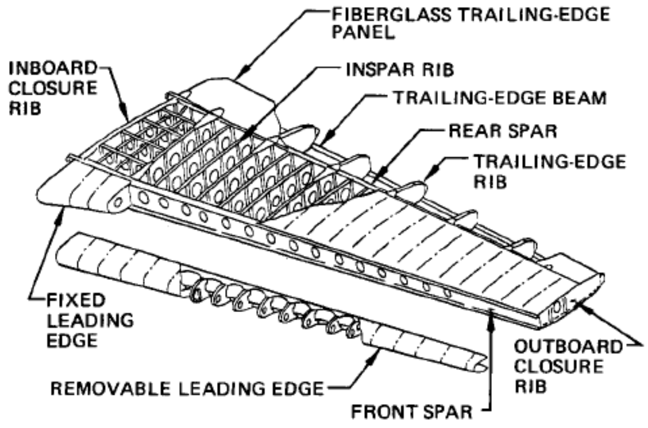
- DSO of 75000 flights
- Upper Skin Inboard delaminations at stringer runouts due to maintenance personnel walking on a no-step zone

Shipset / Production Line #	Entry into Service	Airline	Status as of October, 2006
1 / 1003	2 May 1984	A	Removed from service (60000 hours, 45000 flights)
2 /1012	21 March 1984	A	Removed from service (61000 hours, 47000 flights)
3 / 1025	11 May 1984	B	Damaged beyond repair 1990; partial teardown completed in 1991 (17300 hours, 19300 flights)
4 / 1036	17 July 1984	B & C	Stabilizers removed from service 2002 (approx. 39000 hours, 55000 flights); partial teardown of R/H unit at Boeing
5 / 1042	14 August 1984	B & D	Stabilizers removed from service 2002 (approx. 52000 hours, 48000 flights); teardown of L/H unit at Boeing; teardown of R/H unit at NIAR, Wichita State

Horizontal Stabilizer Description

- Designed such that it is interchangeable with the metal structure in terms of geometry, aerodynamic shape to meet control effectiveness and flutter requirements
- 21.6% weight savings/ metal structure
- Material: NARMCO T300/5208
- Stiffened skin structural box arrangement with co-cured I stiffeners
- Honeycomb ribs for cost efficiency, fastened to the skins using shear ties
- Spars are I beams consisting of two pre-cured C channels and two pre-cured caps subsequently bonded together
- Root lugs used steel plates bonded and bolted to a pre-cured graphite epoxy chord





Composite vs. Metal Stabilizer

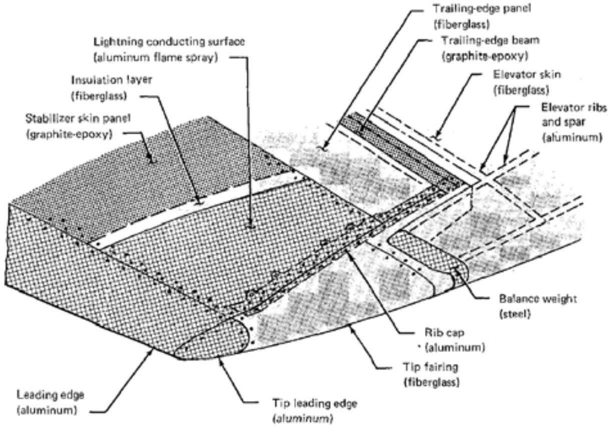
Corrosion / Lightning Protection Scheme

Corrosion Protection Scheme

- **Corrosion protection by co-curing a fiberglass ply onto the graphite-epoxy structure or painting the surface with primer and epoxy enamel**
- **All aluminum structure was anodized or alodine treated, primed and enameled**
- **Fasteners were installed with wet polysulfide sealant**

Lightning Protection Scheme

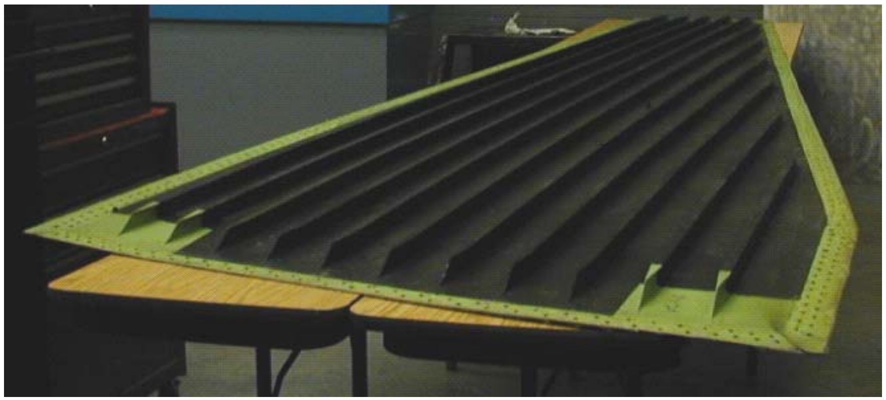
- **Lightning protection scheme provided an electrical path around the perimeter of the structure. Bonding straps were used to connect the aluminum leading edge, the aluminum rib cap of the outboard closure rib, the aluminum elevator spar and the spar lugs**
- **An Aluminum flame spray was used on the stabilizer's critical strike area. The outboard skin panels were insulated using a layer of fiberglass. Mechanical fasteners were used to electrically connect the aluminum flame area to the metal cap of the outboard closure rib**



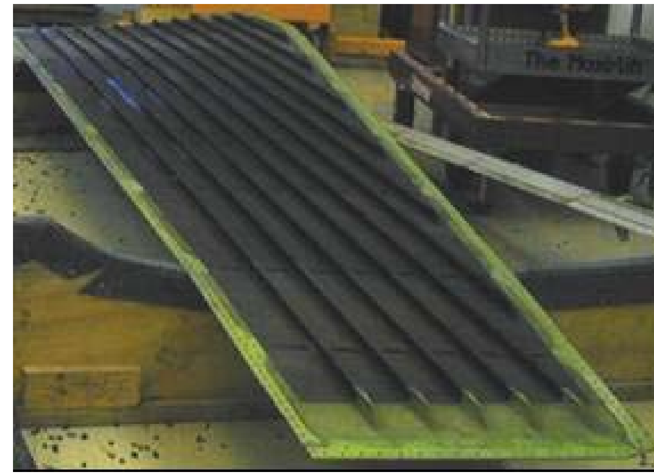
Disassembly

- Upper skin assembled using Inconel “Big Foot” blind fasteners
- Lower skin assembled using titanium Hi-Lok fasteners with corrosion resistant steel collars and washers
- The upper skin was disassembled first by drilling out the blind fasteners using a Monogram fastener removal kit: the fastener head was drilled out until the shank could be driven out of the structure
- Once the upper skin was dismantled, the lower skin’s Hi-Lok fasteners were disassembled

Disassembly/ Preliminary Findings



Upper Skin (RH)



Lower Skin (RH)

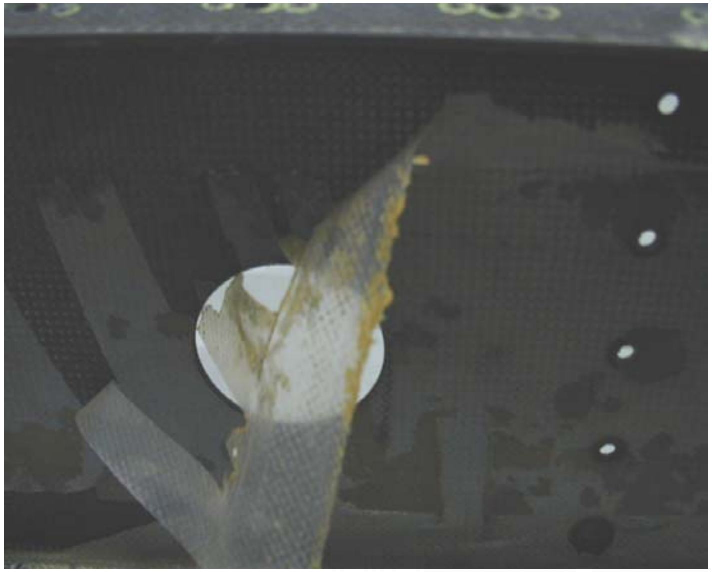
Center Box (RH)

- **Structure held very well**
- **No evidence of pitting or corrosion as would be observed in a metal structure**
- **No residual strains compared to the LH**

Disassembly/ Preliminary Findings

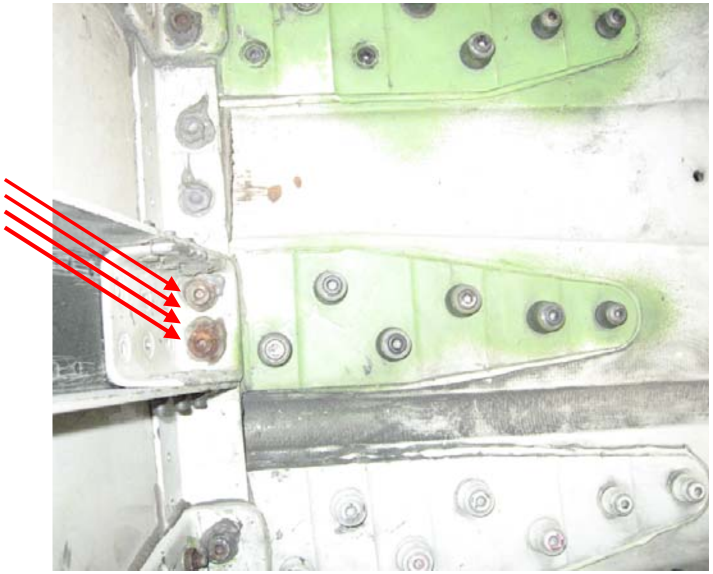
Front and Rear Spars after disassembly

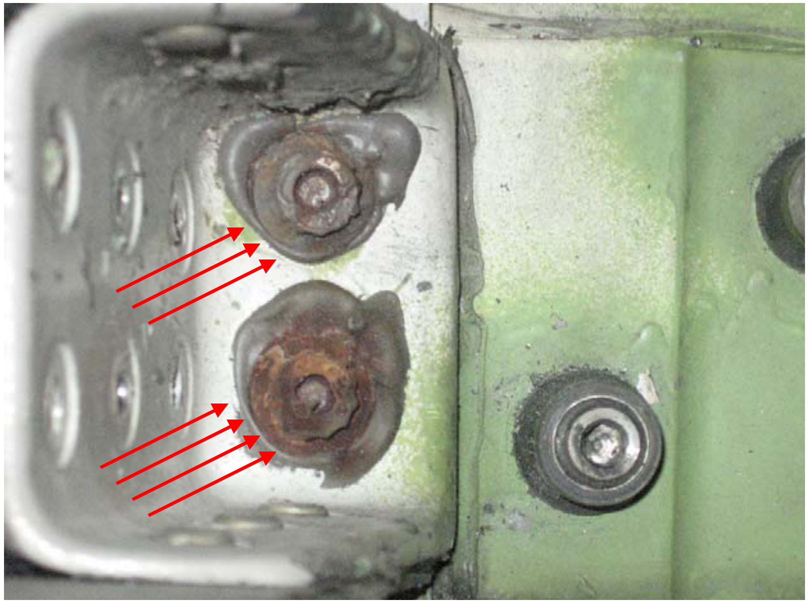
Visual Inspection



Degradation of Tedlar Moisture Barrier film

Visual Inspection

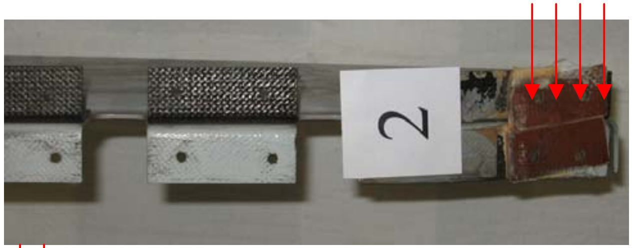


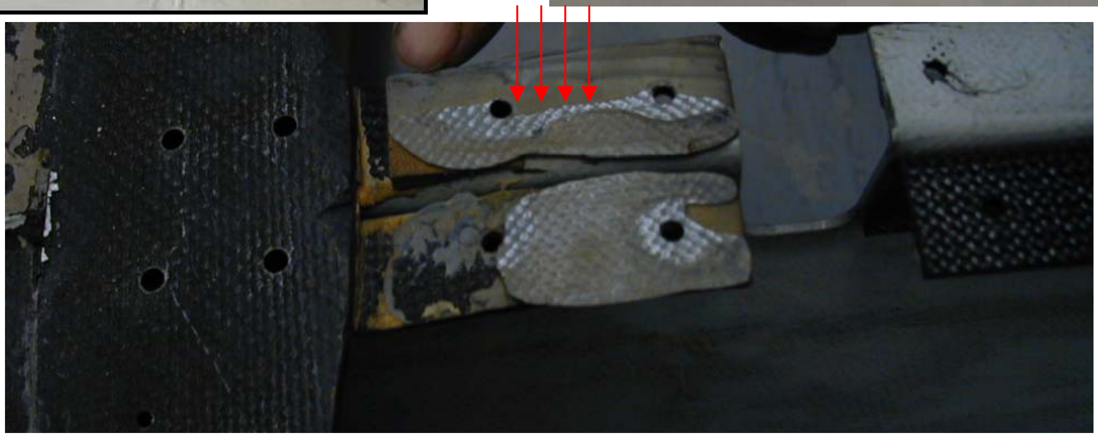


A few corroded fasteners due to sealant deterioration

Visual Inspection

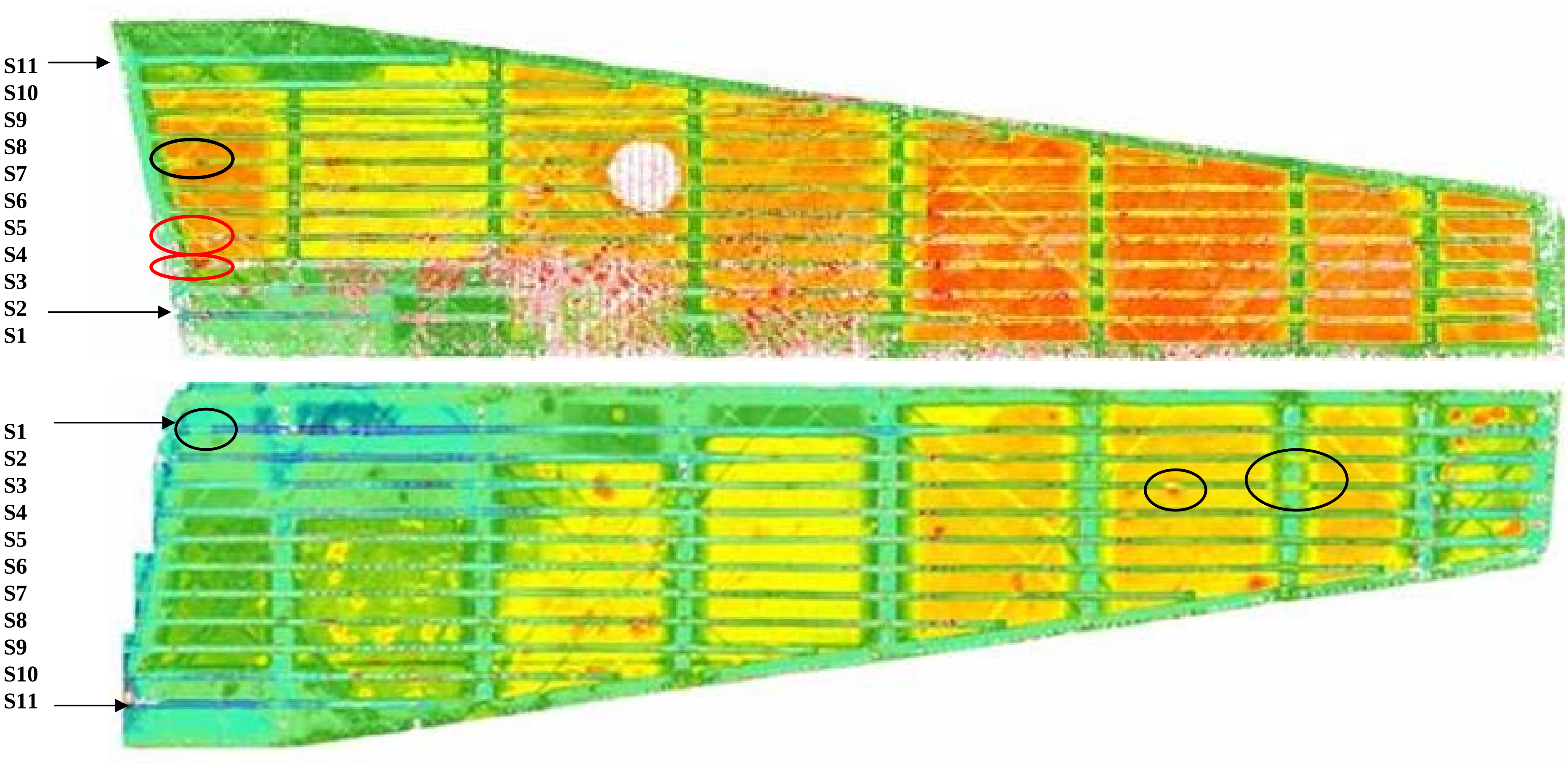
Phenolic shims used to fill gaps between skin and ribs





Liquid Shims used to fill gaps between the upper skin and the stabilizer ribs

Non-Destructive Inspection Prior to teardown

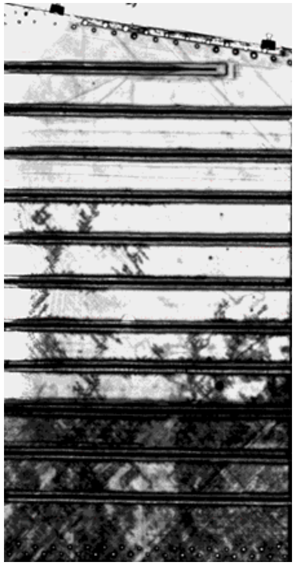


Rapidscan™ analysis (pulse echo time of flight data) of the R/H of the B737 stabilizer (Courtesy of Sandia National Laboratories and NDT solutions ltd. UK)

Non-Destructive Inspection after Teardown

- Pulse-echo and through-transmission non-destructive methods were used to inspect the stabilizer using 2.25 Mhz frequency transducers
- Both methods confirmed the large amounts of porosity in the upper skin
- Pulse-echo results obtained confirmed the existence of delaminated stringers and demonstrated the increased accuracy/ sensitivity of the current inspection methods compared to those used in the 1980's

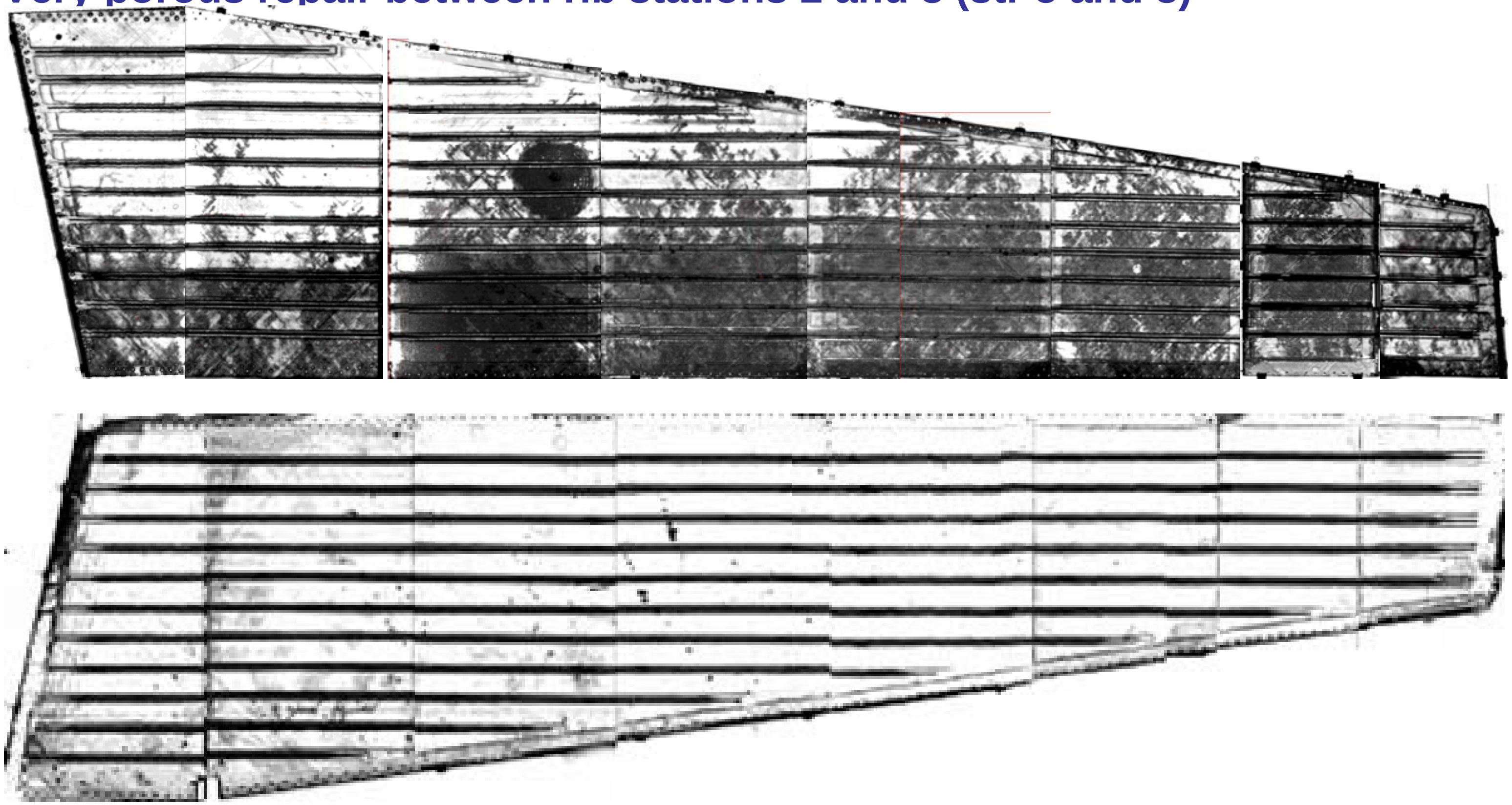
1980's sensitivity



Today's sensitivity

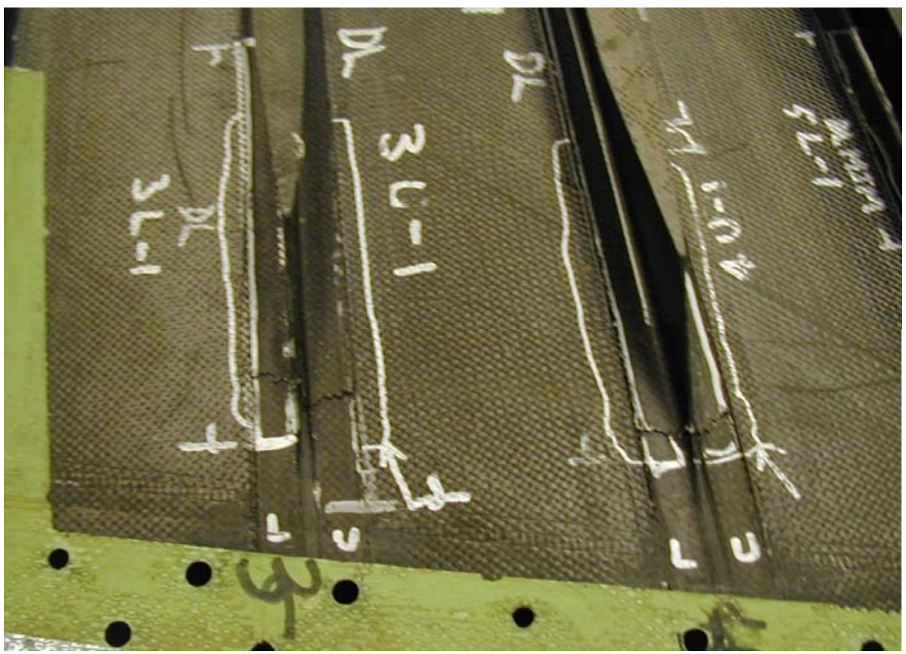
Non-Destructive Inspection

- NDI pulse echo inspection showed significant levels of porosity in the upper skin compared to the lower skin (tooling and process variability)
- Porosity levels have been quantified using image analysis/ physical tests
- Very porous repair between rib stations 2 and 3 (str 5 and 8)



Non-Destructive Inspection

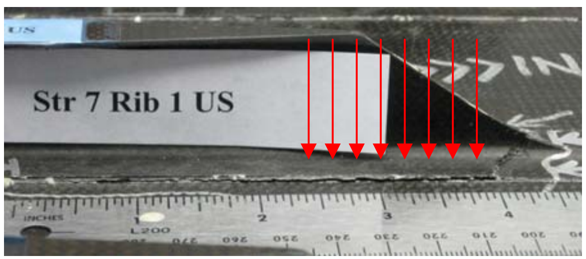
- Manual Pulse-echo was performed to inspect the skin/ stringer co-cured bonds and identify areas with delaminated stringers

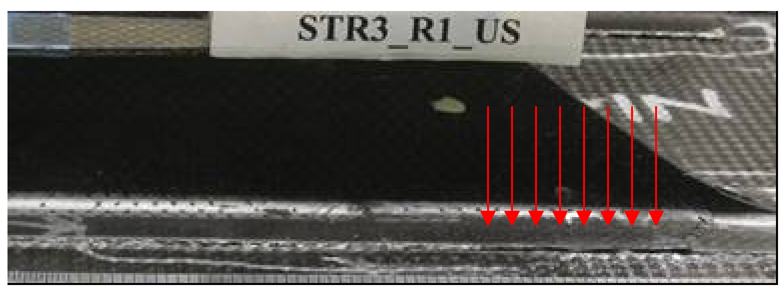


Upper skin Inboard delaminations at stringer runouts

Destructive Evaluation

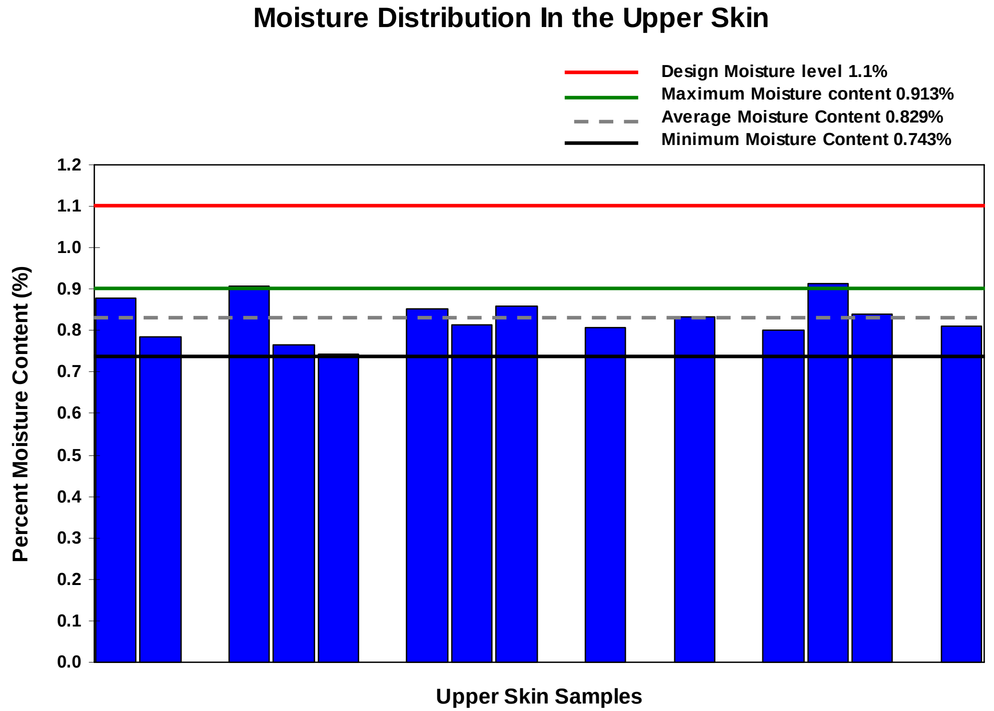
- Destructive evaluation has been conducted on sections of the stabilizer identified as disbonds from the NDI inspection to verify the existence of these delaminations. Destructive evaluation confirmed the results.



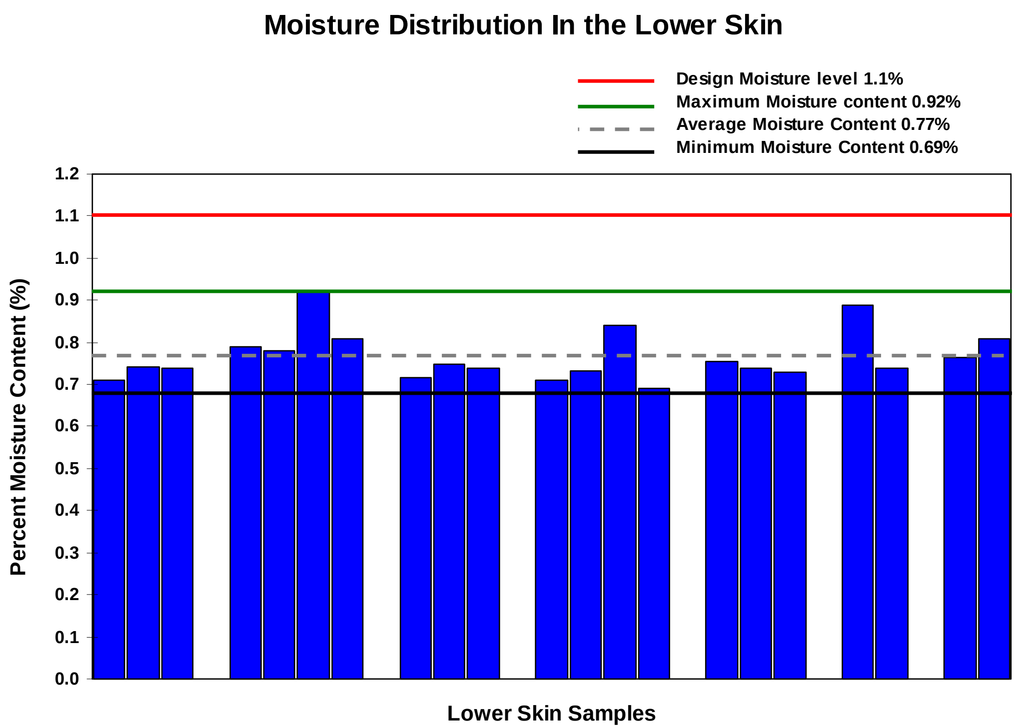


Moisture Content Evaluation

- Moisture content in the aged structure has been quantified per ASTM D5229: specimens were extracted from different locations in the upper skin and lower skins of the stabilizer and have been dried to evaluate the moisture content of the structure.
- The results showed that the moisture content in the upper skin varied from 0.743 to 0.913% (design moisture level of 1.1%)



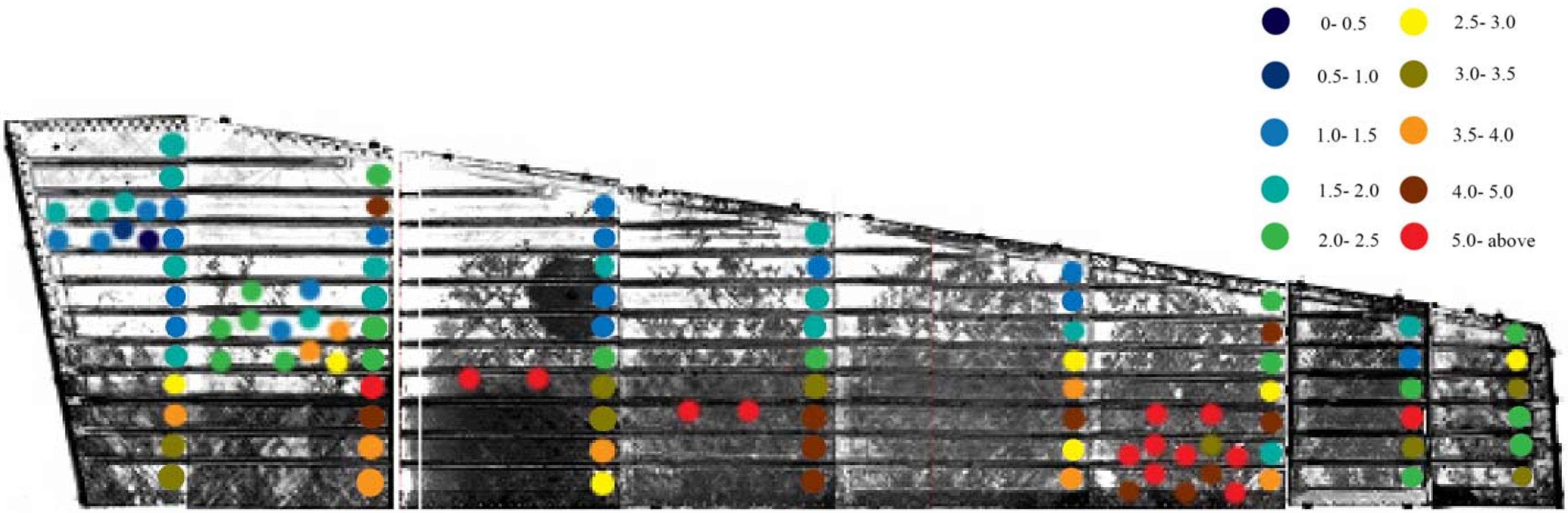
Moisture Content Evaluation



- The moisture content in the lower skin varied from 0.69 to 0.92% (design moisture level of 1.1%)

Physical Tests Results-US

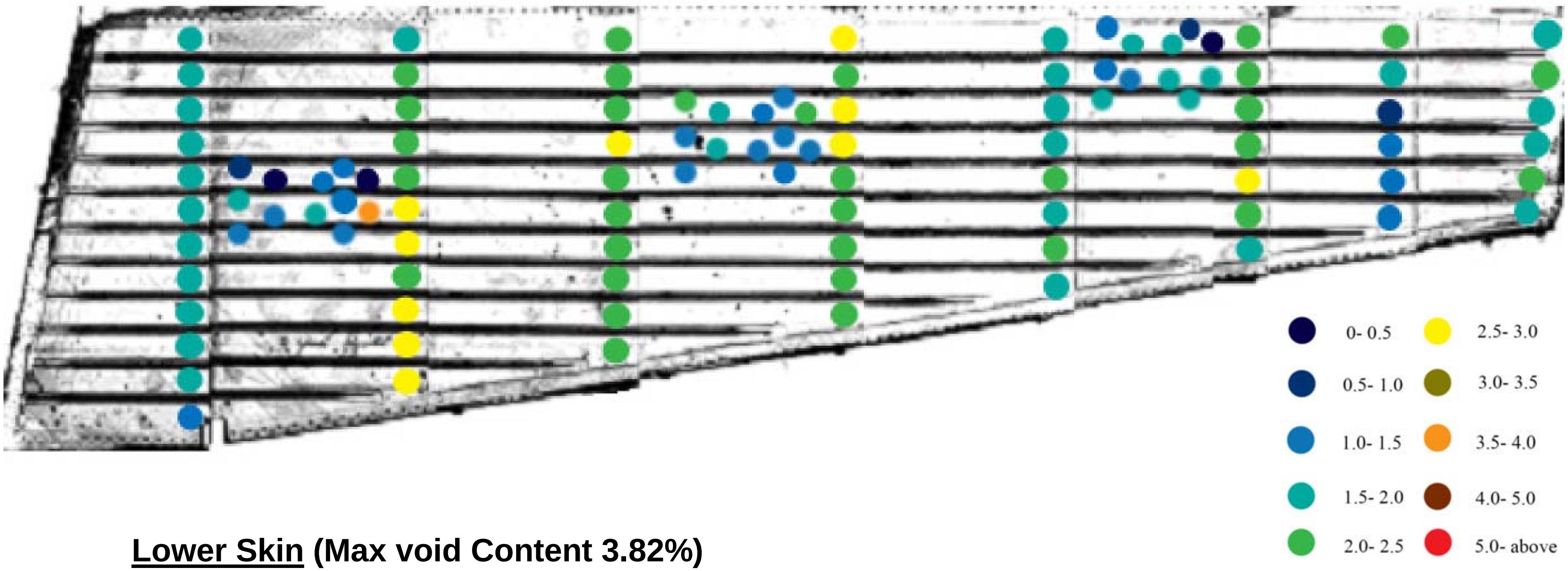
- Physical tests were conducted per ASTM D3171 to quantify porosity levels in both skins



<u>Upper Skin</u> (Max void Content 7.26%)

Physical Tests Results-LS

- Physical tests were conducted per ASTM D3171 to quantify porosity levels in both skins

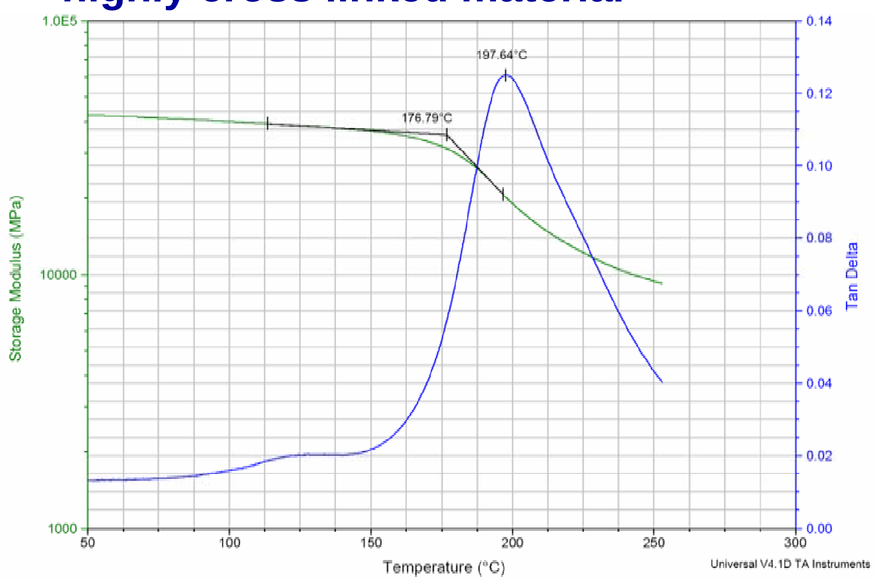


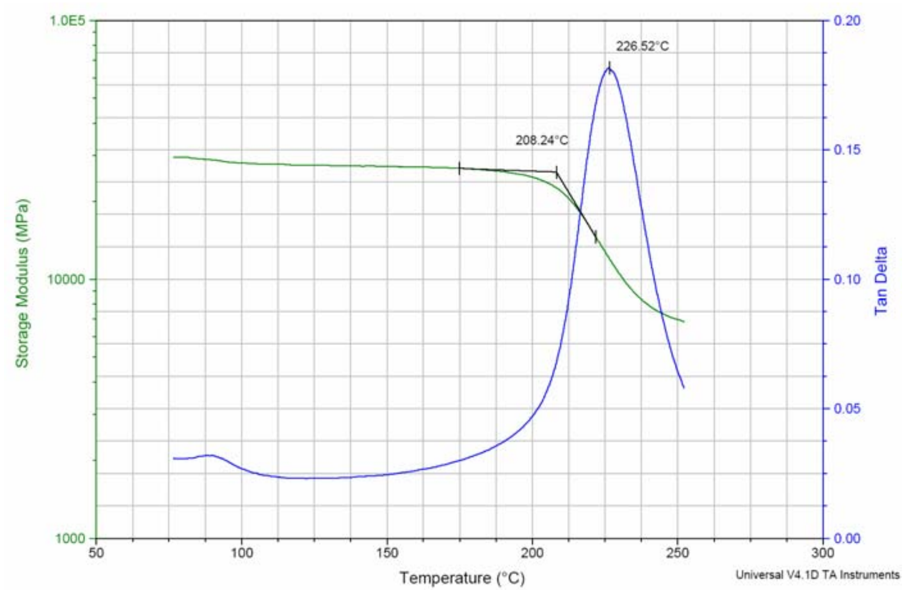
Lower Skin (Max void Content 3.82%)

Front and Rear Spars (Less than 1.14% and 1.67% void content)

Thermal Analysis

- DMA technique to determine the glass transition temperature of the aged material for coupons extracted from both the upper and lower skins
- Thermal analysis was conducted on coupons with actual in-service moisture content and dried coupons to compare the difference between the in-service Tg with respect to the dry Tg.
- Storage Modulus is an indication of the stiffness of the material, tanδ is a measure of the damping of the material
- DMA curves with a shallow storage modulus transition and a narrow tanδ indicate a highly cross linked material

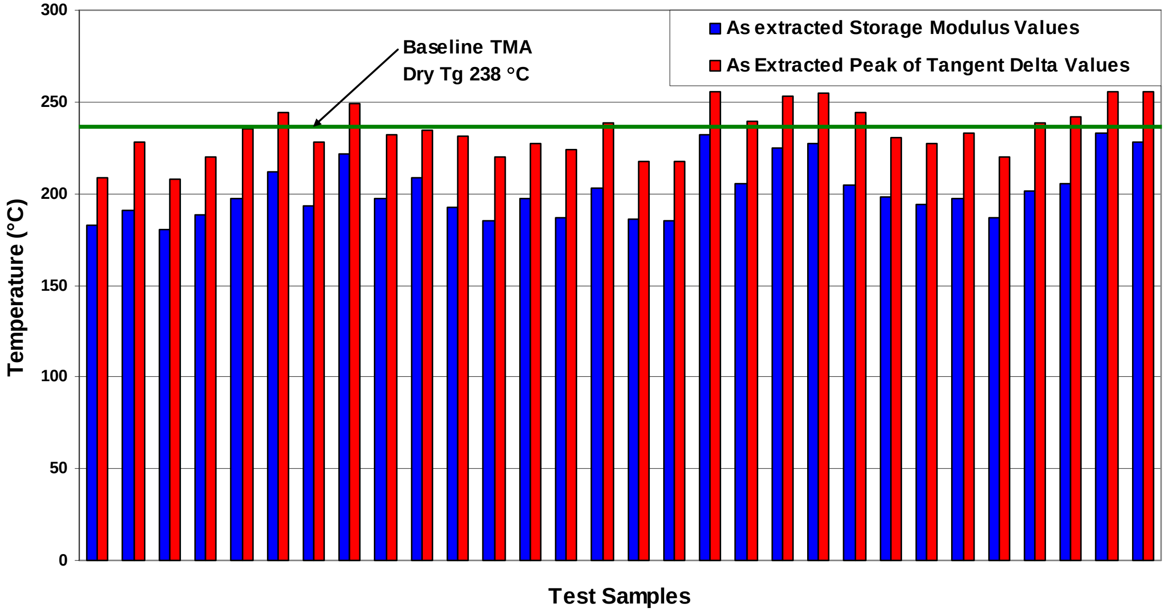




Thermal Analysis

- Tg values consistent and comparable to LH Results (Courtesy the Boeing Co) average values for RH (201°C/233°C)
- DMA test parameters vary/ Tg obtained is a "wet" Tg (at least 0.69% moisture content)

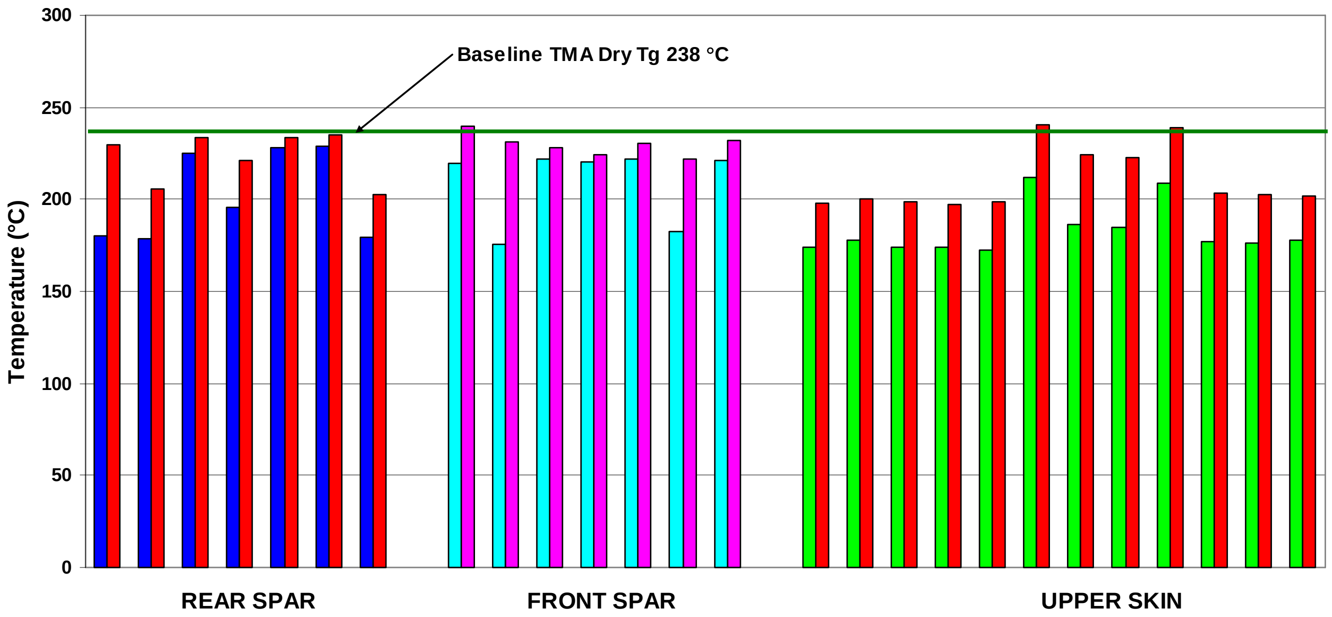
DMA Results for coupons excised from the upper skin of the B-737 Horizontal Stabilizer (Boeing Method)



Thermal Analysis- Spar Skin Comparison

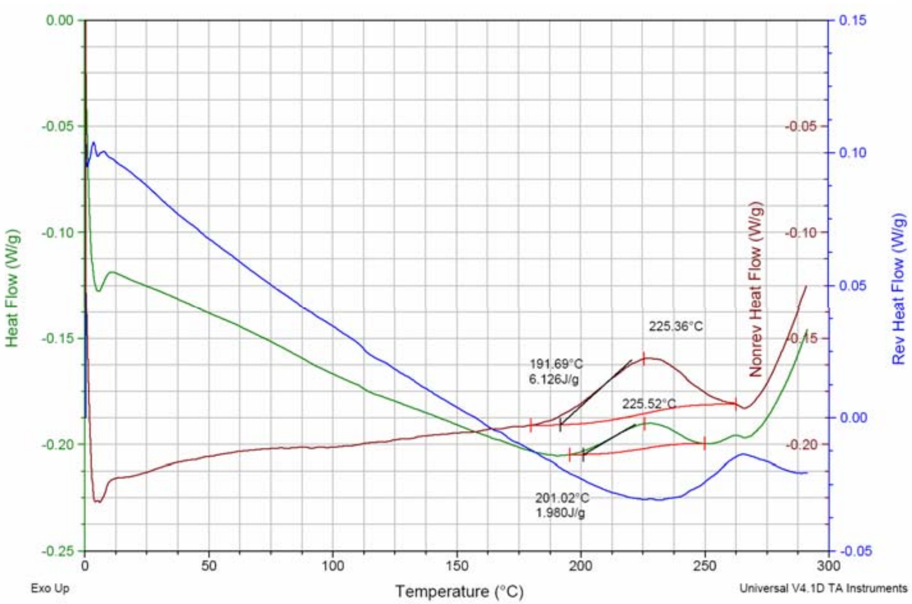
- Spar Tg is about 18°C higher than the skin Tg. (1 cure cycle for skin, 2 for spars)

DMA Results Comparison for coupons excised from the upper skin and the front and rear spars of the B-737 Horizontal Stabilizer (ASTM Standard)

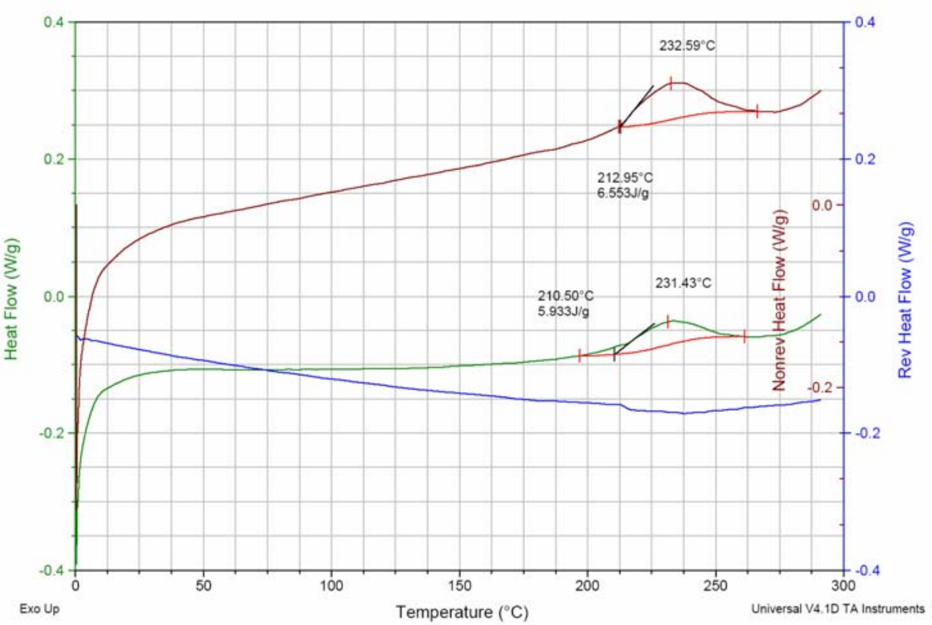


Thermal Analysis / DSC

- Non-Reversing heat flow curves reveal exotherms/ chemical reactions
  DSC heat of reaction values are extremely small (<6J/g) indicating a highly cross linked material (fully cured)
- Reversing heat flow curves reveal Tg
- Drying the specimen increased the cure onset (water acts as a plasticizer)
- Water content does not affect the degree of cure



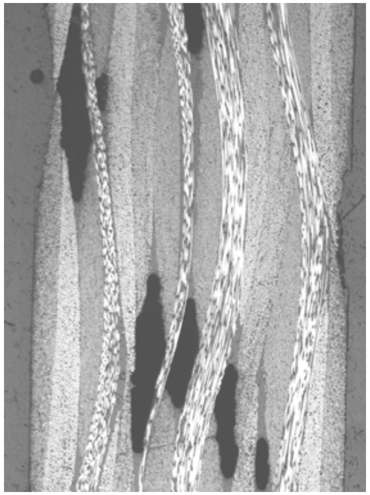
DSC, Rib 7, as extracted

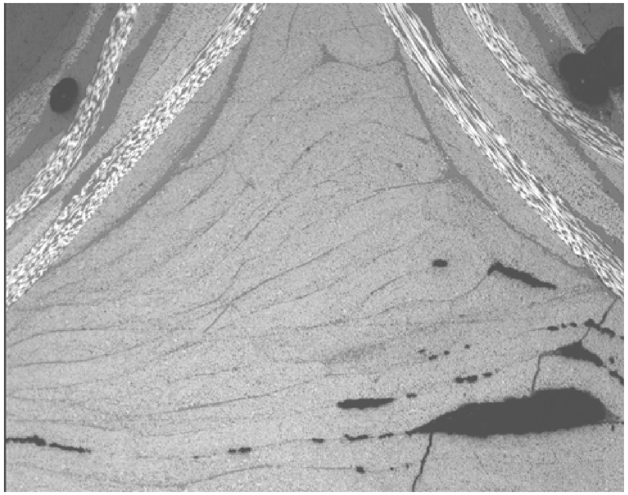


DSC, Rib 7, dry

Microscopy/ Image Analysis

- Image analysis was performed to detect porosity/ micro-cracking and any evidence of aging in the structure.
- Both images show evidence of porosity embedded in the laminate. The flange cross section also shows evidence of microcracking initiating in the void areas.





X-section of stringer 2, rib station 2 at a magnification of 50x stringer web (left image) and flange (right image).

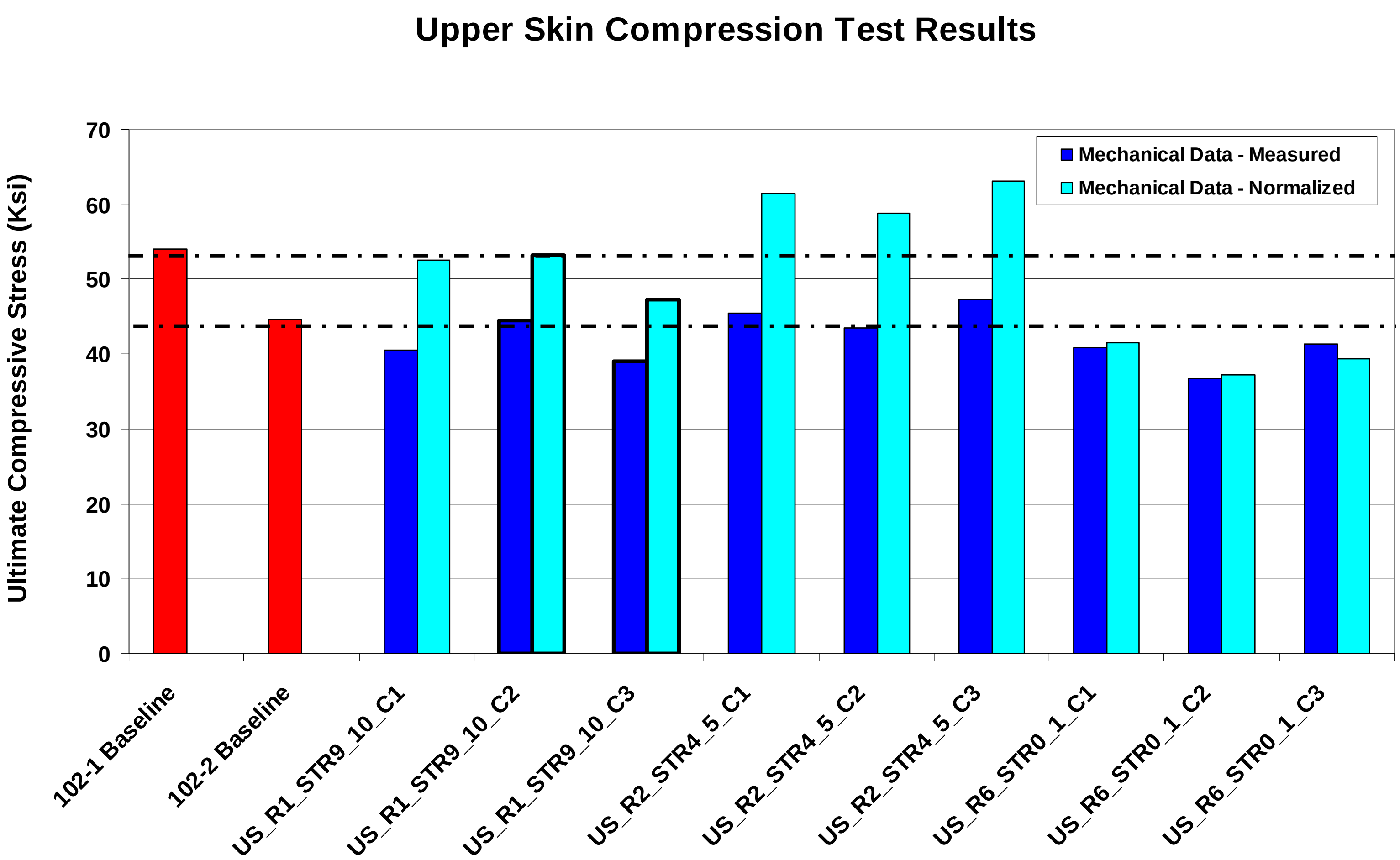
Mechanical Tests

Mechanical Tests were conducted according to the 1980’s requirements/ standards

Tested Upper Skin Compression Coupons

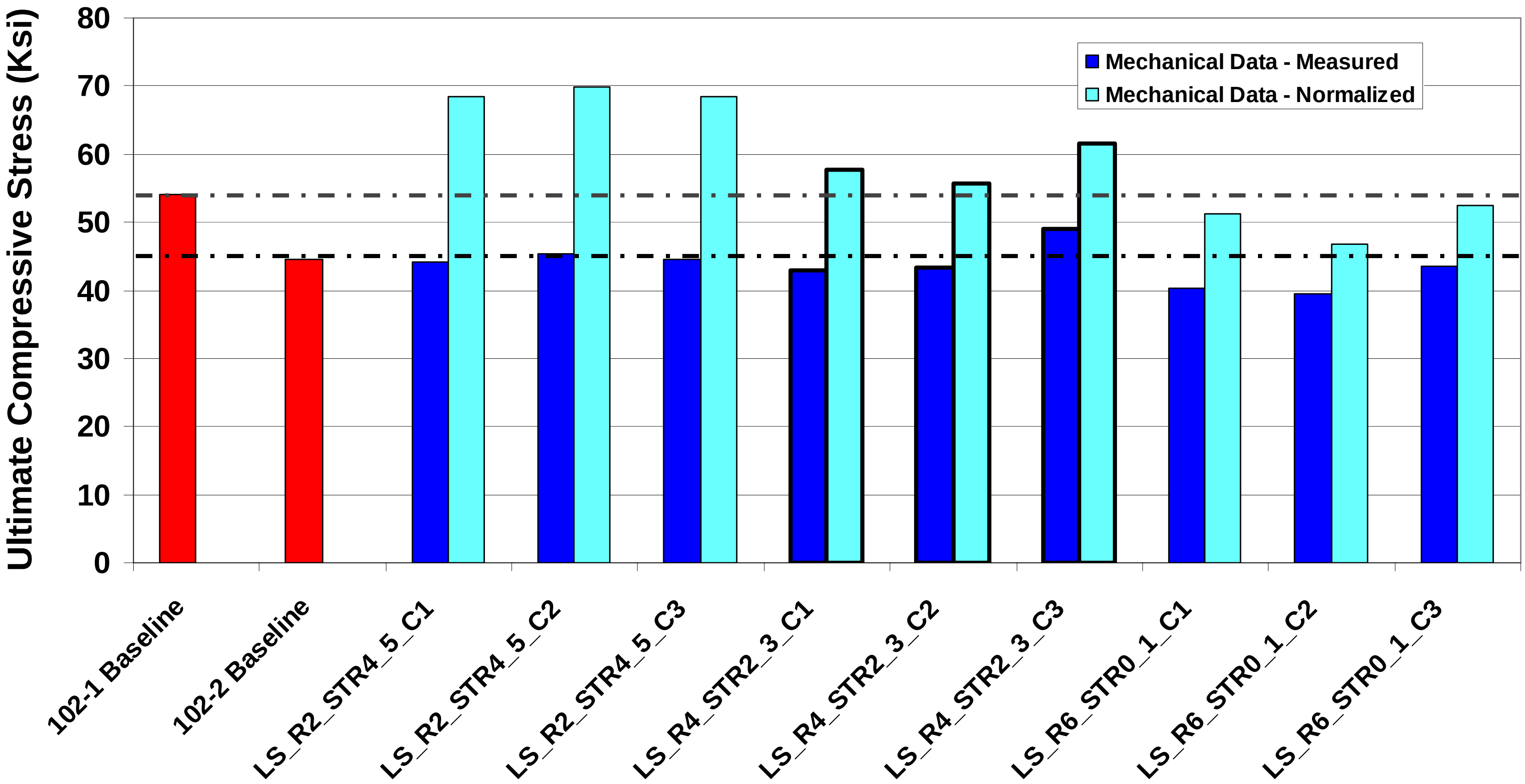
Compression Test Set-up

Mechanical Tests Results



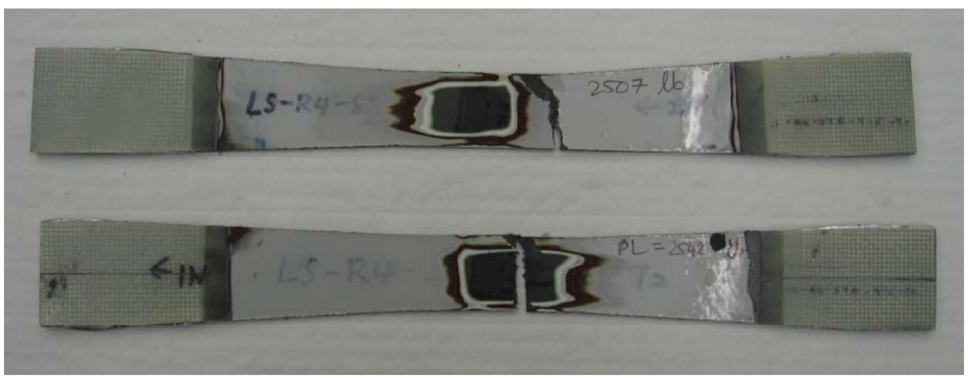
Mechanical Tests Results

Lower Skin Compression Test Results



Mechanical Tests

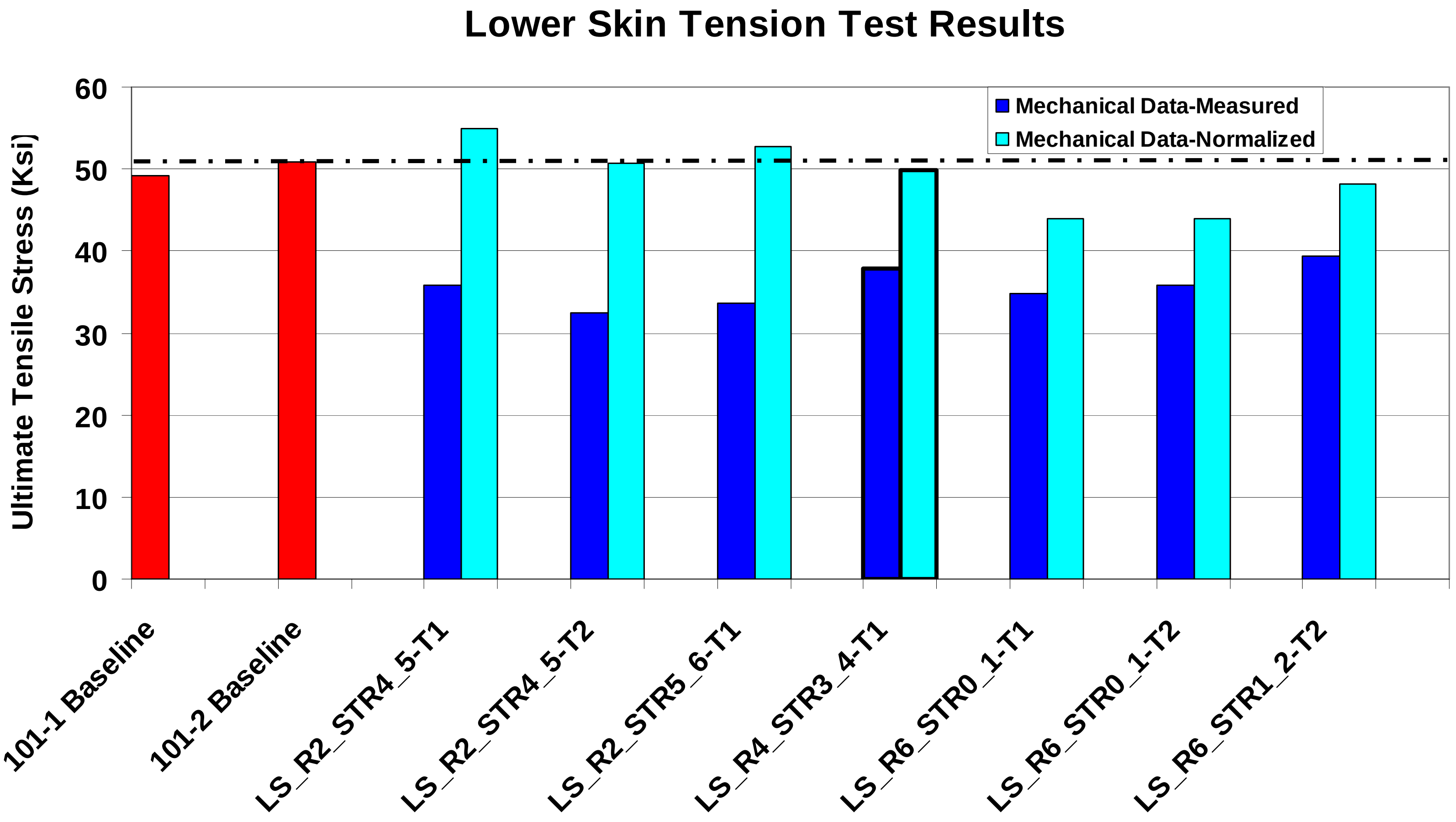
Mechanical Tests were conducted according to the 1980's requirements/ standards



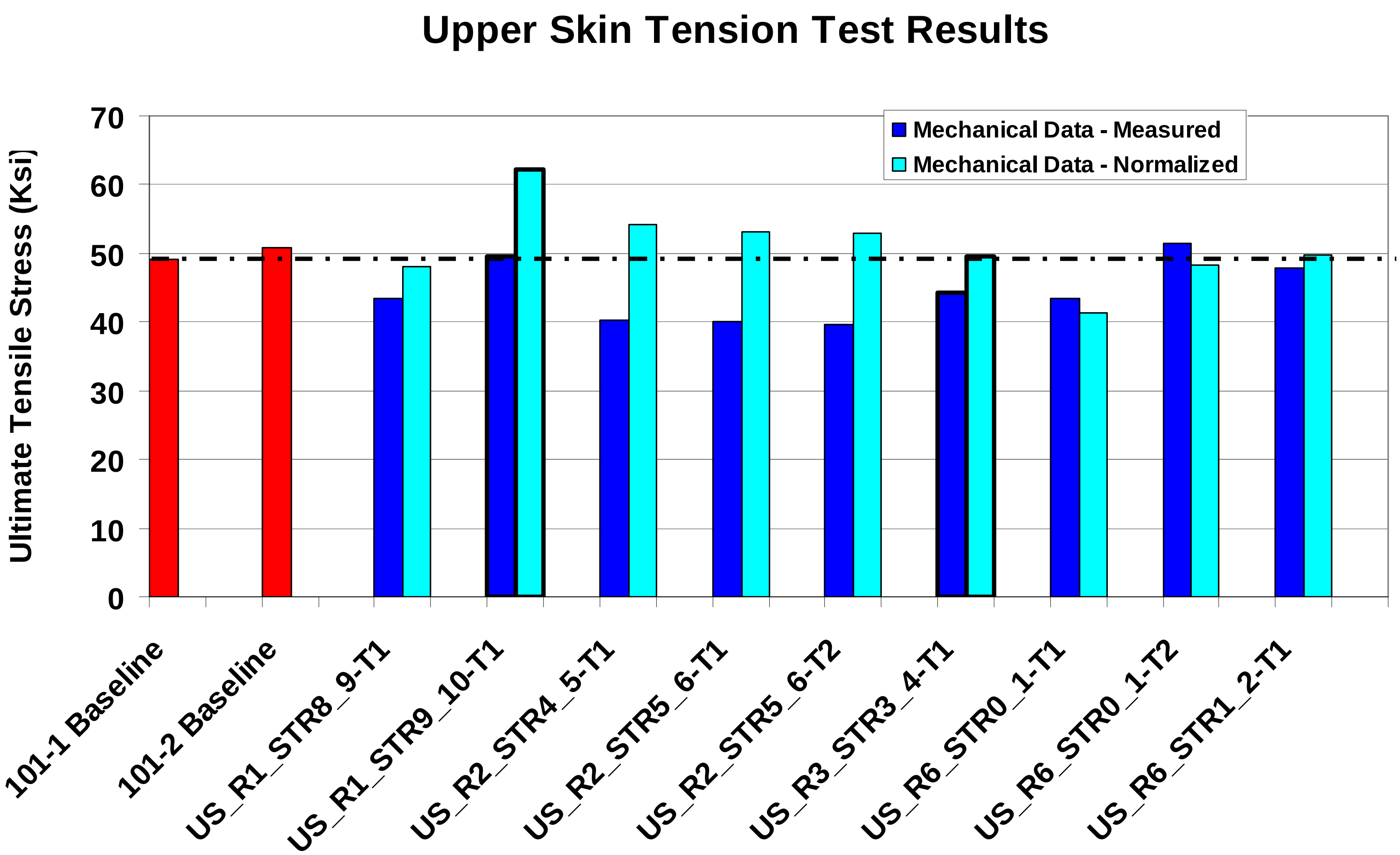
Tested Lower SkinTension Coupons

Tension Coupon Test Set-up

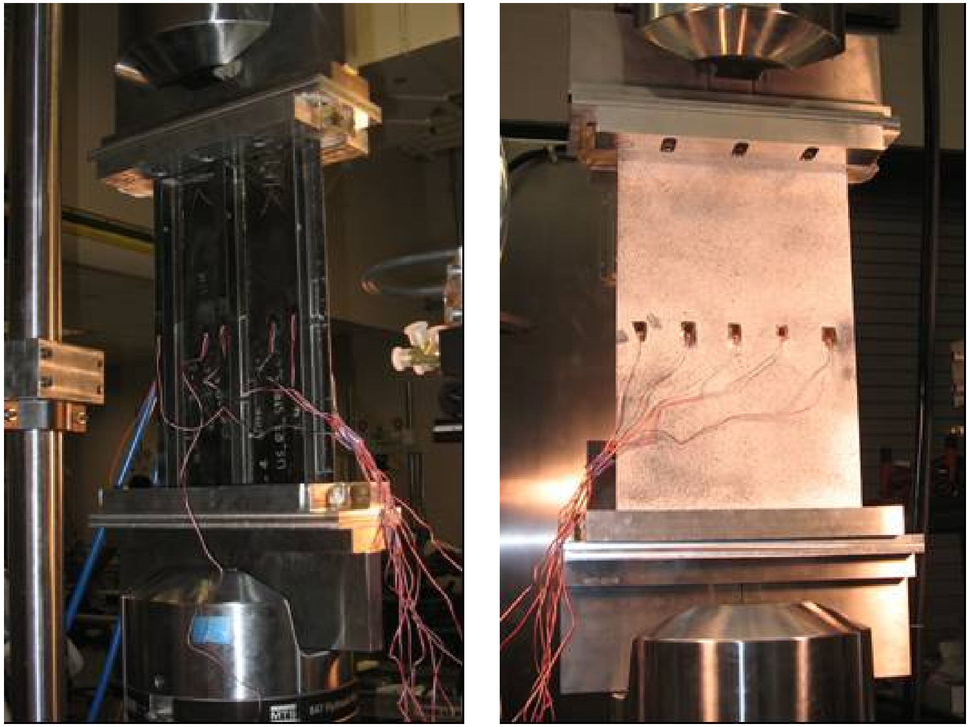
Mechanical Tests Results



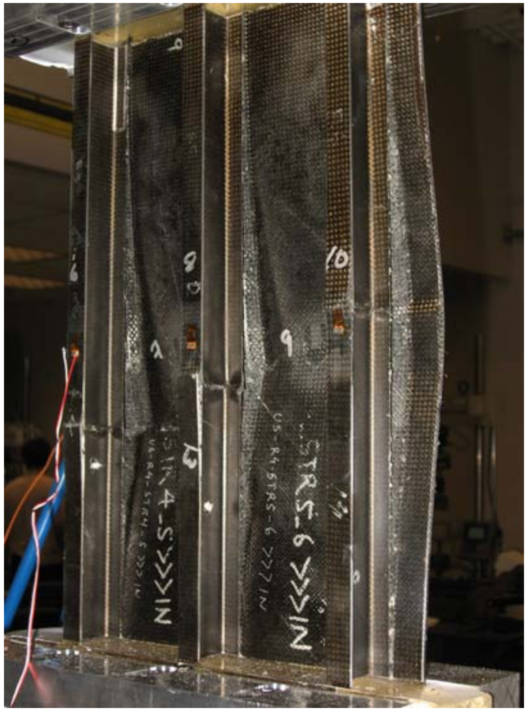
Mechanical Tests Results



Element Testing-Crippling

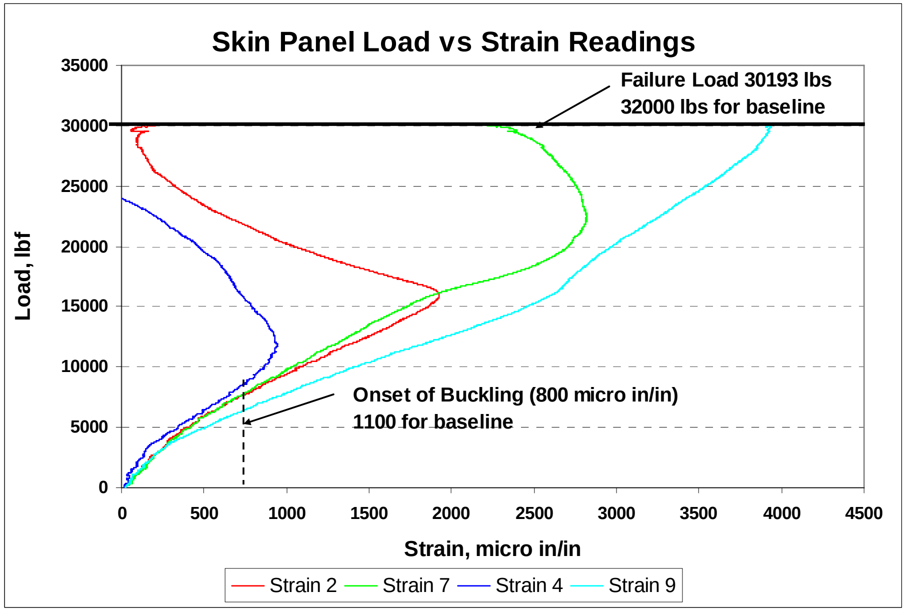


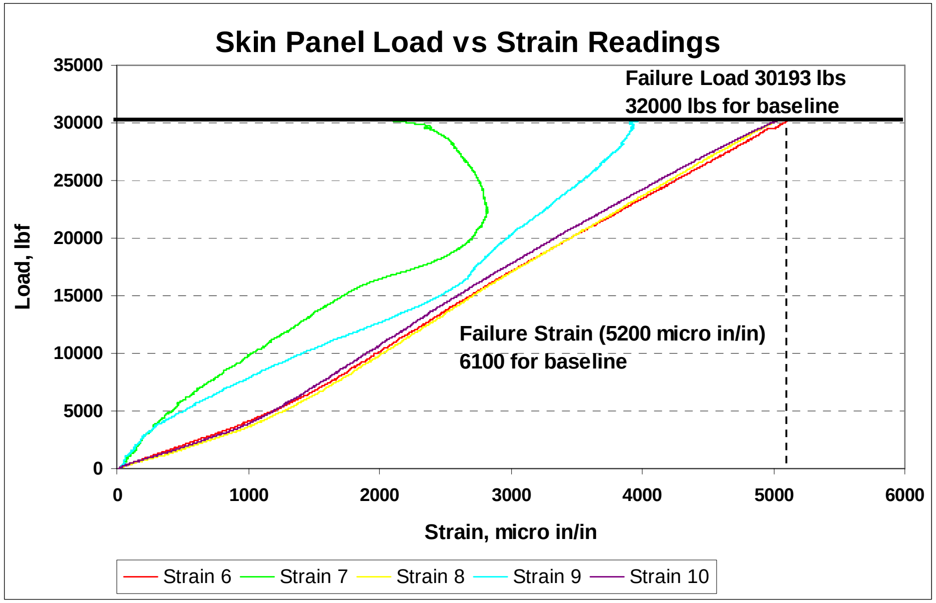
Crippling Test Set-Up



Failed Specimen

Element Testing-Crippling





Conclusions
Value of the results

- Structure held extremely well after 18 years of service: no obvious signs of aging to the naked eye such as pitting and corrosion as would a metal structure with a similar service history exhibit
- Physical tests showed moisture levels in the structure after 18 years of service as predicted during the design phase
- Thermal analysis results very consistent with those obtained for the left hand stabilizer
- Significant improvements in composite manufacturing processes and NDI methods
- Teardown provides closure to a very successful NASA program and affirms the viability of composite materials for use in structural components

A Look Forward
Benefits to Aviation

- **Understand the aging mechanism of composite structures (current aging studies focused on metal structures)**

<u>Producibility</u> large co-cured assemblies reduce part and assembly cost, however other costs should be taken into account, for example, when disposing of non-conforming assemblies

<u>Supportability</u> needs to be addressed in design. Composite structures must be designed to be inspectable, maintainable and repairable

- **most damage to composite structures occurs during assembly or routine aircraft maintenance**
- **SRM's, engineering information needed for in-service maintenance and repair**

And Finally

Thanks to:

- **Dr. Matthew Miller, Dan Hoffman, Jeff Kollgaard, Karl Nelson, The Boeing Company**

- **John Fitzpatrick, Michael Montgomery, NIAR Aging Aircraft Laboratory**
- **Abhijit Sonambekar, NIAR Fatigue and Fracture Laboratory**
- **Matt Oplinger, NIAR Composites Laboratory**