Transport Aircraft Composite Aging

AIAA SciTech Forum and Exposition

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Outline

- **Transport Aircraft Composite Structures**
- Aging
- Substantiation
- Early Experiences
- Industry Best Practices
- In-Service Experience
- Summary
- Recommendations

Historical Perspective

Over the past four decades, the use of composite materials in commercial aircraft structures has been continuously increasing.

- Initial use of composite materials in secondary structure accounted for about 5% of the structural weight and, with the addition of empennage structure, 10% of the structural weight.
- Introduction into both wing and fuselage structure has resulted in composite materials accounting for a structural weight percentage approaching 55%.

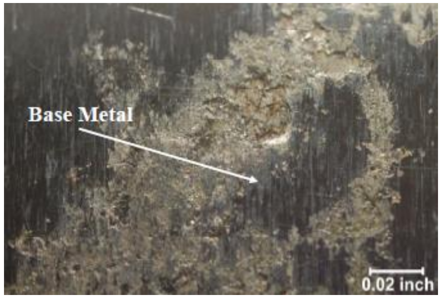
Why Composite Structures?

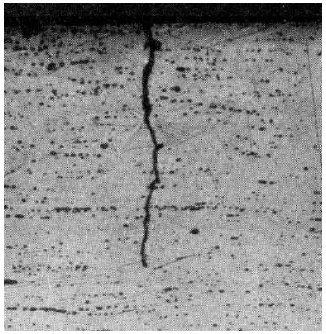
Passenger Benefits

- More comfort features

Airline Benefits

- Reduced weight
- Longer life
- Reduced maintenance burden
  - Corrosion
  - Fatigue





Airplane Performance Benefits

- Improved aerodynamic efficiency

Design Benefits

- Ability to tailor stiffness
- Conducive to integral designs

Production Benefits

- Fewer parts, reduced assembly time, more consistent assembly, less hazardous chemicals & waste

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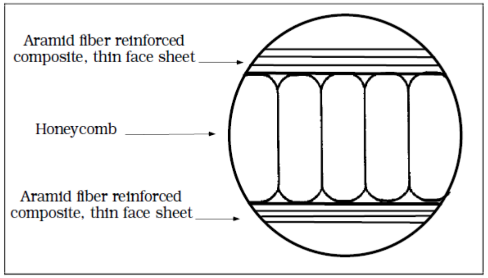
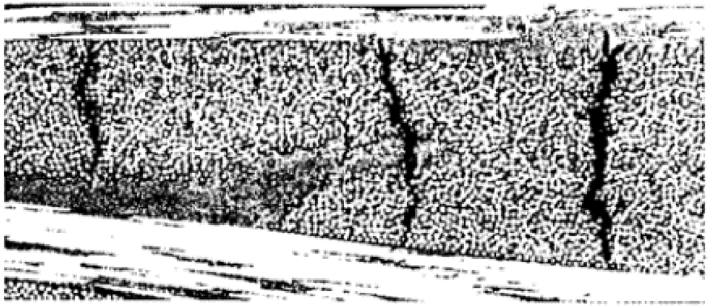
What do we Mean by Aging?

Composite Aging Definition

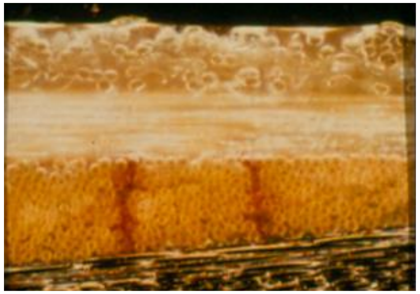
- Response of an aircraft structures material system in service to long-term exposure environments. A fundamental understanding of the physical or chemical phenomena that can cause changes in the molecular structure of resins and epoxy-based materials to occur.

- This can result in mechanical, and physical properties affected in ways that can compromise the reliability of resin-based engineering components and structures.





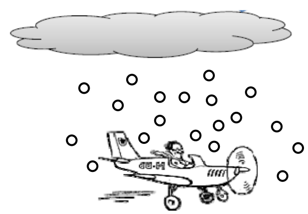
ELECTRON MICROGRAPH OF TVM IN FABRIC

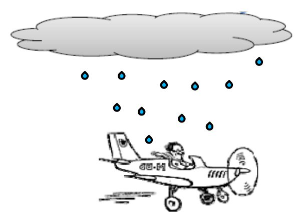


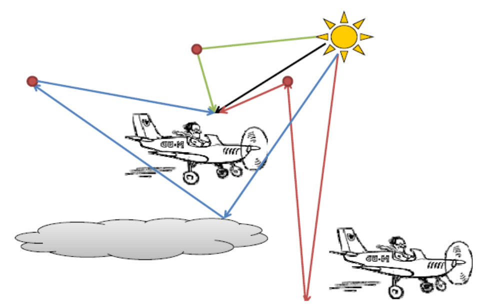
Aging Threats

Aging threats can be classified in two major categories

- Environmental degradation
  - Erosion
  - Aggressive fluids
  - Ultra-violet
  - Lightning strike
    - Direct effect
    - Indirect effect
  - Temperature
    - Including thermal aging
  - Humidity
  - Mechanical impact (in production and/or in-service)
- Load-induced degradation
  - Mechanical loading (including cycling and creep)







<u>All these parameters are addressed in the aircraft design</u>

Addressing Aging Threats

- Erosion → Anti-erosion coating
- Aggressive fluids → More benign than moisture
- Ultra-violet → Anti-UV coating
- Lightning strike → Woven metallic fibers or metallic foil protection, and design practices
  - Direct effect
  - Indirect effect
- Temperature
  - Including thermal aging
- Humidity
- Mechanical impact (in production and/or in-service)
- Mechanical loading (including cycling and creep)

(Temperature, Humidity, Mechanical impact, Mechanical loading) → Testing and design practices

Robust approach, demonstrated very reliable designs with over 1 billion flight hours (>100,000 years)

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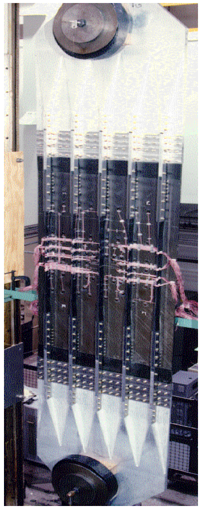
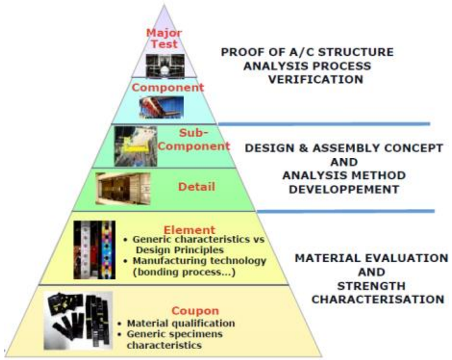
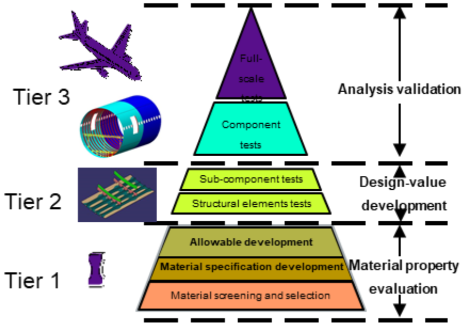
Aging Evaluations







- The effect of mechanical fatigue and temperature/humidity on the material system is evaluated at the coupon level.
- The effects of accidental damage and joint fatigue are evaluated at higher testing levels.
- Design allowables are developed for the appropriate expected service conditions.

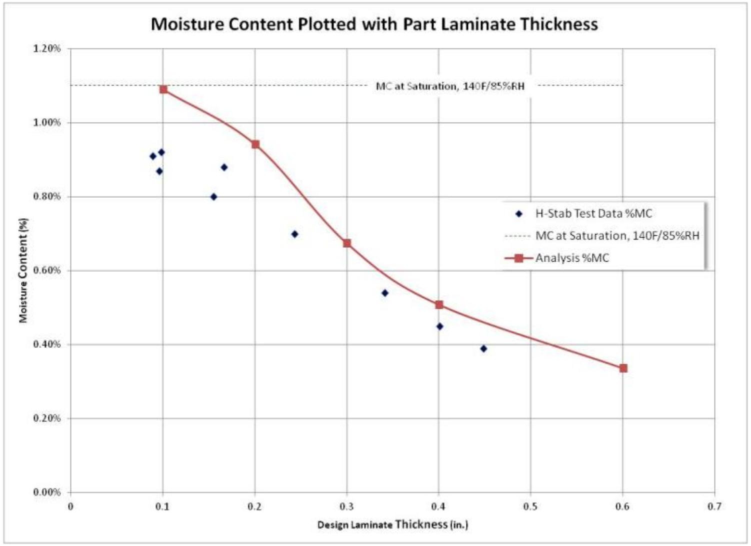
<u>Mechanical performance assessment largely based on empirical testing</u>

Material Dev/Qual: Moisture Approach

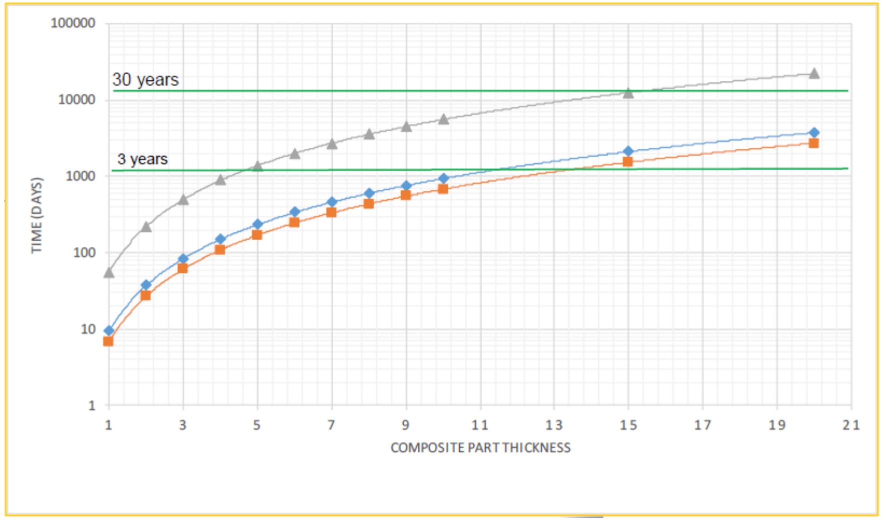
Qualification/Testing time depends on aging of the thickest specimen

- Reduction of «matrix» dominated properties (compression, ILSS ,bearing) which are amplified when in- service temperature increase
- Reduction of Glass Transition (T_g) temperature
- No real effect on stiffness behavior.

Chart shows moisture uptake for different thicknesses with a typical flight profile over the life of the airframe



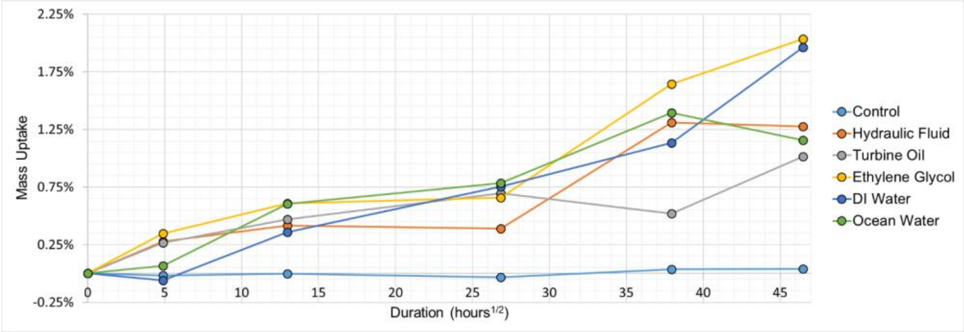
Extrapolation for necessary time (30 years) to achieve 99,9% at equilibrium level (here 1%) for a defined humidity level (here 85% RH) at several service temperatures (23°C, 70°C, 80°C)

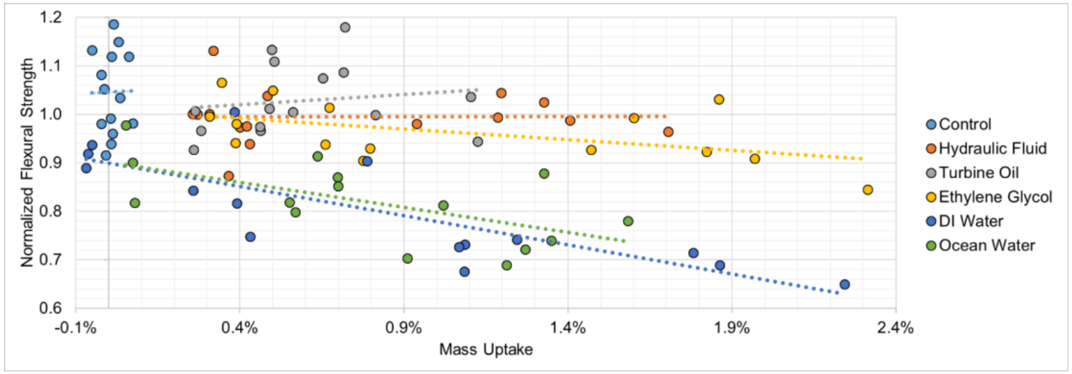


Material Dev/Qual: Fluid Sensitivity

Composite structures are exposed to a number of fluids and solvents both during manufacturing and in service

- Examples include skydrol, jet fuel, deicing fluid, and MEK.
- Test data demonstrates effect is usually lower than humidity for typical carbon/epoxy materials.



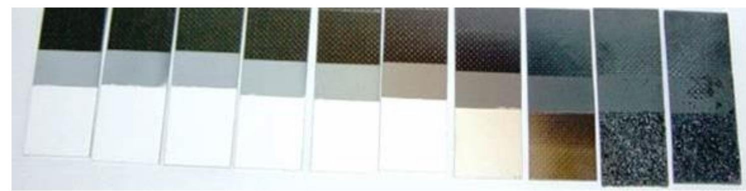


Additional Material Aging Considerations

Non-routine thermal events

- Lightning Strike
- Electrical Arcing
- Fires
- Exhaust Impingement

Thermal Envelope for reference standard fabrication:
- Temperature Range: 325 - 700 ºF
- Exposure Duration: 5 minutes to 1 hour



Erosion

Environmental cycling

Thick Filler Cracking due to thermal cycling

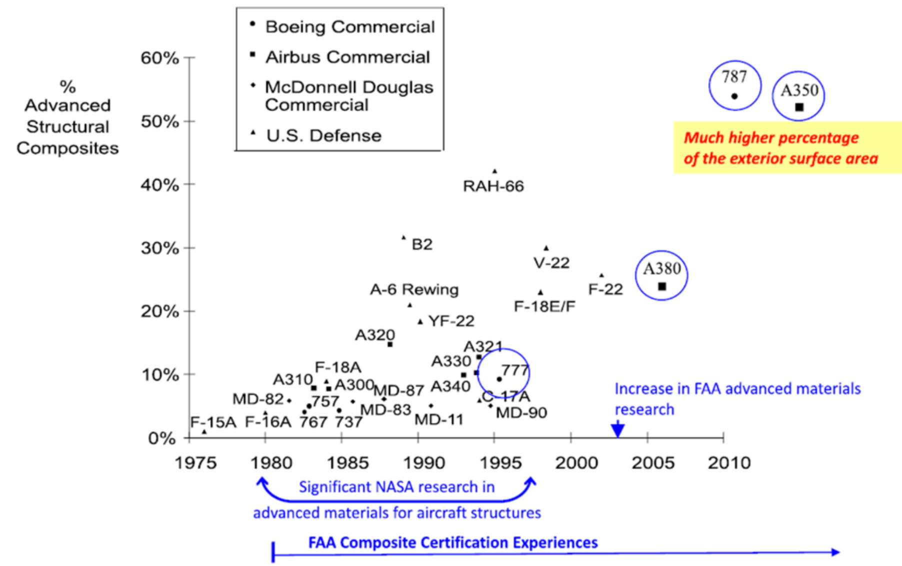
Fatigue Sensitivity

Current composite designs exhibit low sensitivity to fatigue as demonstrated by service history.

- Over 1 billion accumulated flight hours.
- Over 50 years of experience in design, analysis and validation.
- Hundreds of large sub-components to full-scale components tested.

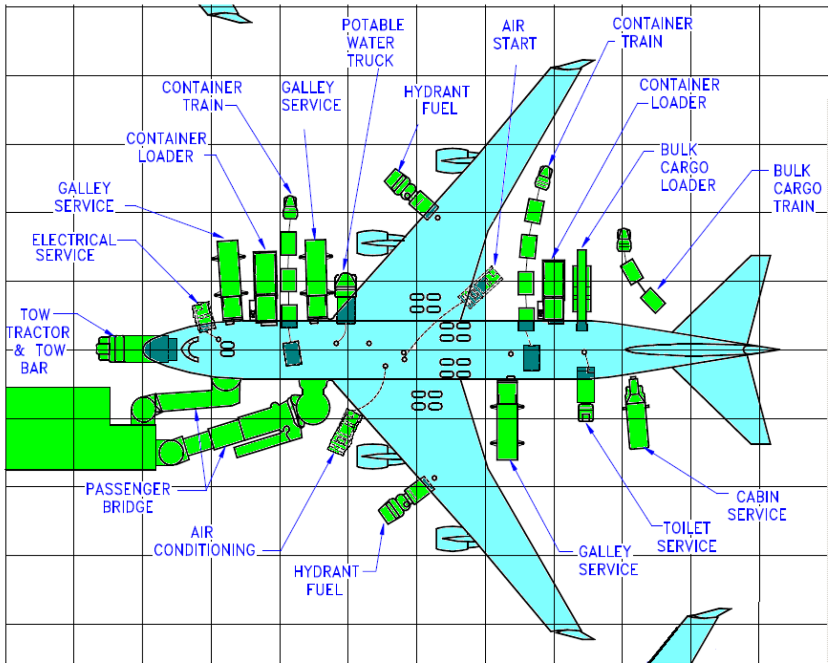
Considerations

- Material and failure mode.
- Damage onset.
- Scatter characteristics.
- Environmental effects.
- Residual strength.



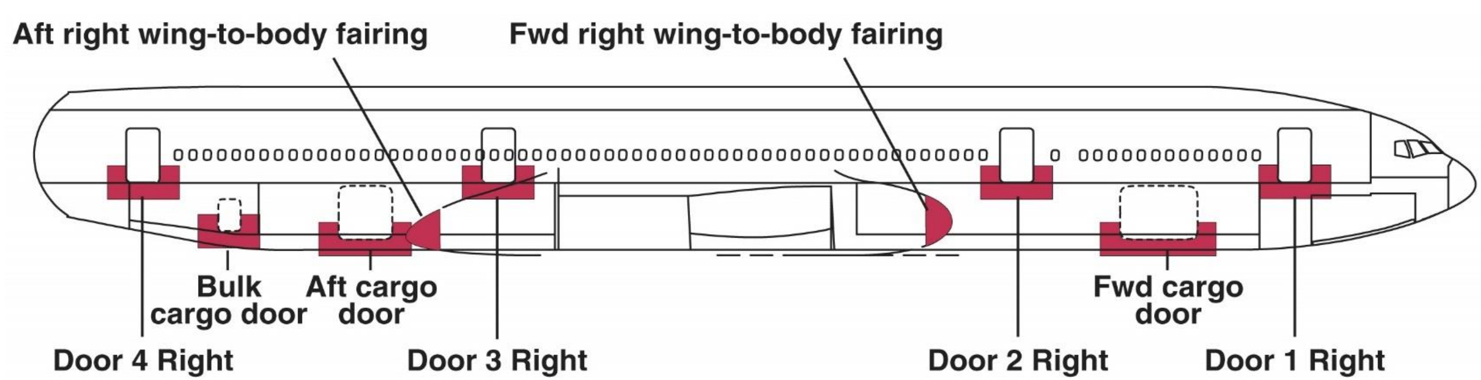
<u>Low sensitivity to fatigue as demonstrated by service history</u>

Accidental Damage – In-Service Experience



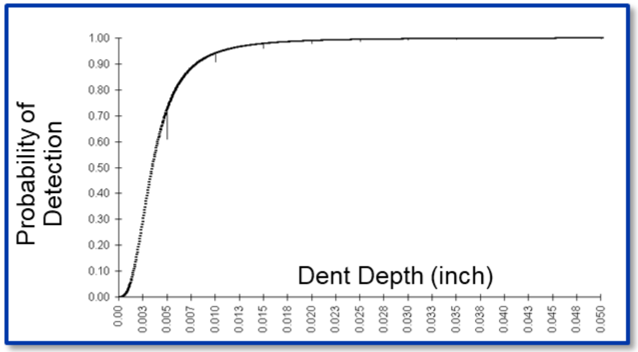
Accidental damage assessment

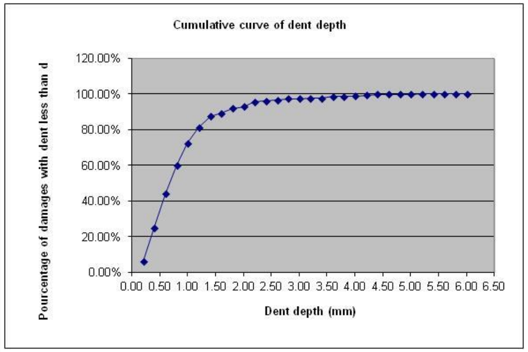
- Data sources:
  - Maintenance logbooks
  - Airline telexes
  - Aircraft on ground experience
  - Service Bulletins, Service Letters, SRPs
  - Customer Technical Forums



Accidental Damage – Criteria

Threat	Criteria		Requirement
	Deterministic	Probabilistic	
Minimum energy for robustness	48 in-lbs normal to surface	Zoning by threat	No repair required No non-visible damage growth under cyclic loading Accounted for in ultimate design allowables
BVID - general acreage	≤ 1,200 in-lbs, or ≤ 0.040" dent depth but not < 0.010" dent depth w/ relaxation	35-140 Joules (310-1,240 in-lbs) Energy levels cut-offs derived from in-service data	Barely visible damage assumed not found during scheduled maintenance No detrimental damage growth under cyclic loading Capable of ultimate strength
BVID - damage prone areas	Consider: • 1,200-2,400 in-lbs • multiple, superimposed impacts • clustered impacts	140-250 Joules (1,240-2,210 in-lbs)	Barely visible damage assumed not found during scheduled maintenance No detrimental damage growth under cyclic loading Capable of ultimate strength and/or strength level based on Composite Probabilistic Analysis

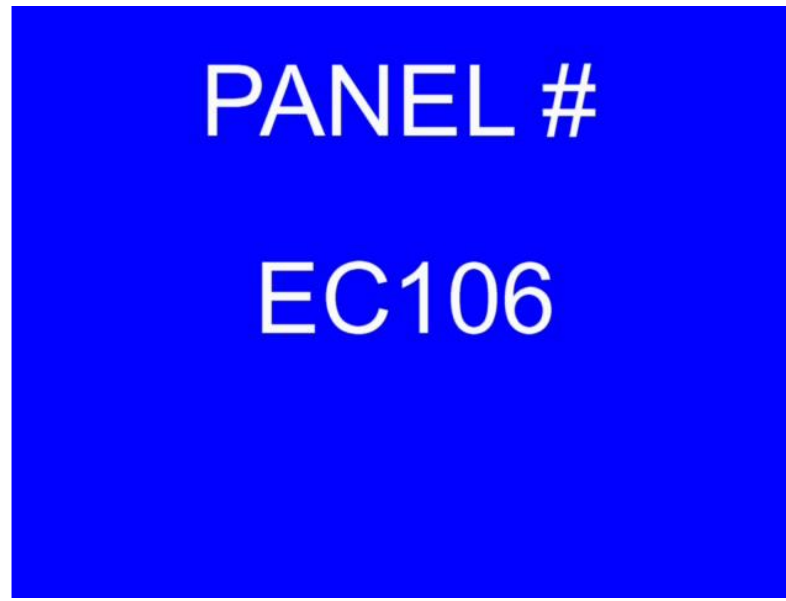




Accidental Damage – Assessment

The effects of accidental damage are evaluated at higher testing levels.

- Most of the emphasis in composite structural impact and residual strength testing to date has focused on impact criteria established for design purposes.
- The most structurally efficient approach derived from such efforts is semi-empirical, starting at the subcomponent test level.



<u>Mechanical performance assessment largely based on empirical testing</u>

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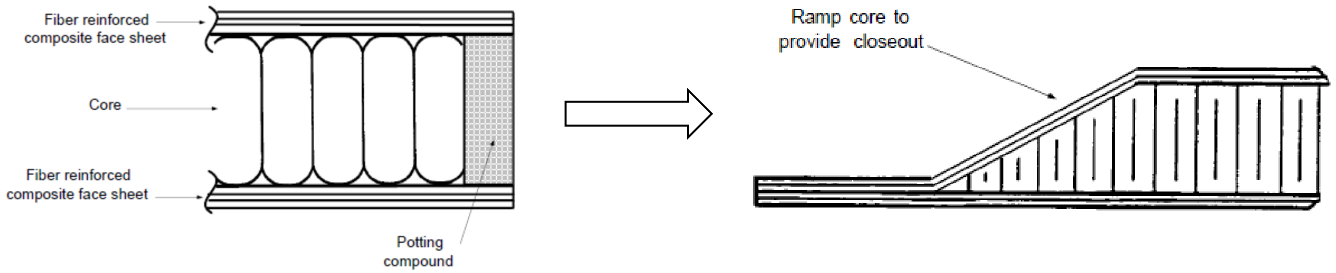
Early Experiences

Service experience of composite aircraft structure has generally been very good

Most service aging problems for composite aircraft structures have been related to specific design or processing details and a combination of environmental effects and mechanical loading considerations.

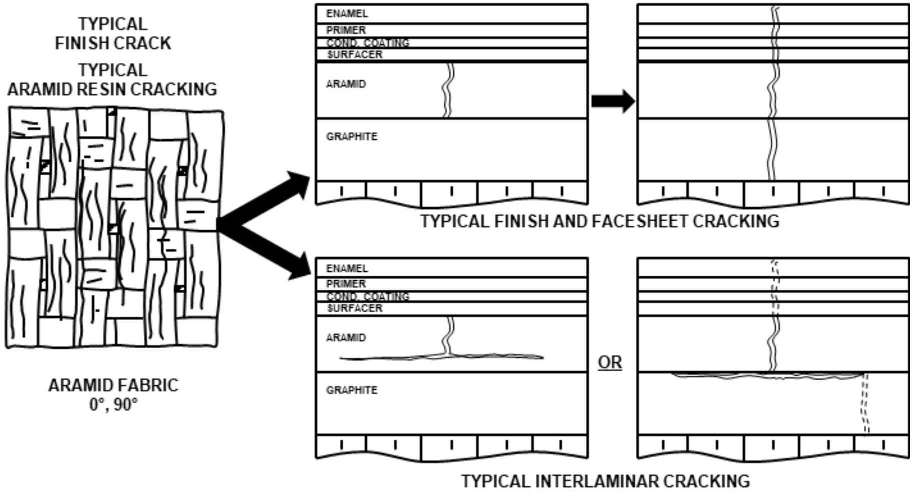
- Based on surveys of aircraft structure, aging related degradation has been found mainly on:
  - Movable surfaces (e.g., spoilers, elevator)
  - Secondary structure (e.g. landing gear doors and aerodynamic fairings)
- Design improvements were used to correct these behaviors.



Aramid Fiber/Epoxy

Panels fabricated with aramid fiber composites result in high thermal residual stresses which can lead to systematic matrix cracking caused by GAG environmental cycling and a number of other contributing factors.

- Micro-cracking by itself resulted in little reduction in residual strength.
- Matrix cracks linked up providing a path for fluid ingression through the thin facesheets and into honeycomb core.
- Fluid ingression caused problems with control surface weight and balance.
  - Leading to honeycomb core degradation.
  - Pieces of the sandwich panel would depart the aircraft due to freeze/thaw.



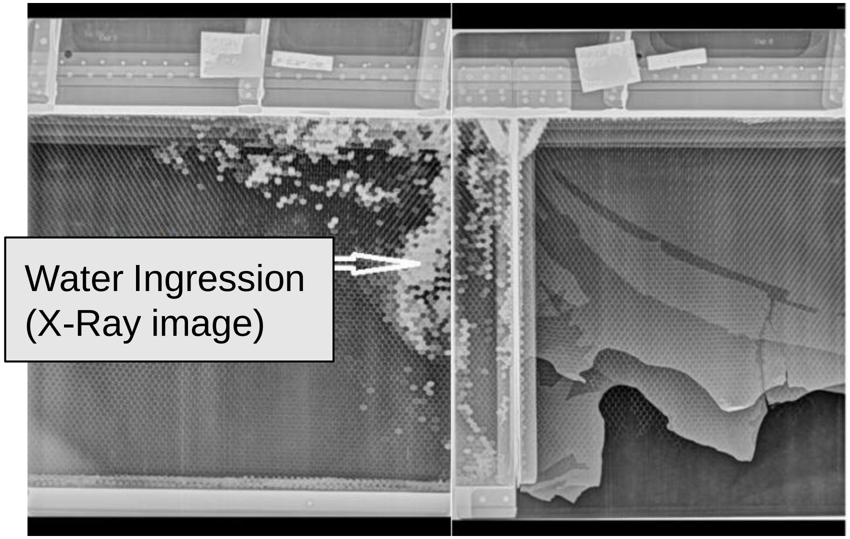
<u>No longer used in thin facesheet sandwich structure</u>

Water Ingression

Undesirable service experience associated with sandwich honeycomb construction

- The root cause of the problems incurred were related to water ingress susceptibility due to thin-walled sandwich construction, poor design details and insufficient robustness against low energy accidental impacts.

- Design experience applied on sandwich technologies used on landing gear door and movable surfaces (spoiler, rudder) show an improved resistance to water ingression.



<u>Improved resistance to water ingression through design modifications</u>

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Industry Best Practices

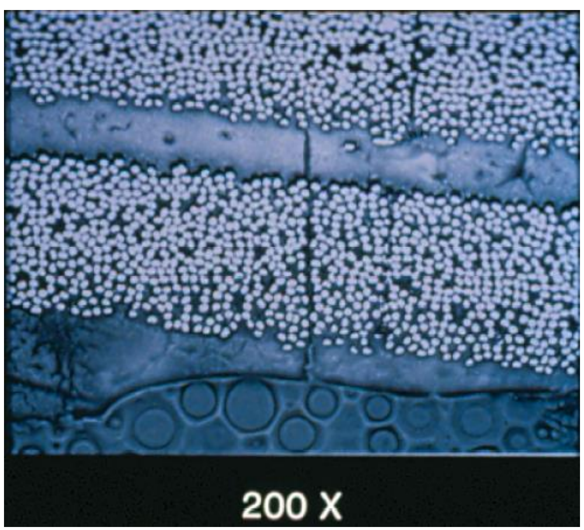
Current industry practices enable composite structures to avoid safety related aging mechanisms

- Design Practice
- Fatigue Loading
- Design Details
- In-Service & Repair Considerations
- Compensation Factors
- Repetitive Impact Damage & Damage Accumulation
- Substantiation
- Service History and Lessons Learned

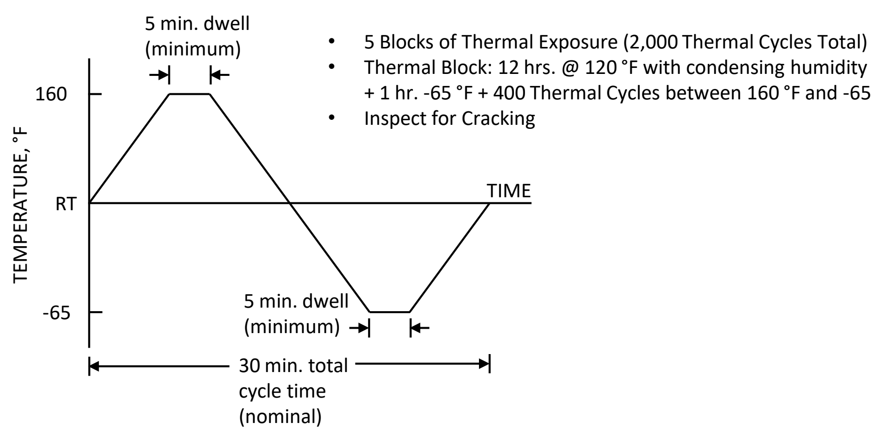
Industry Best Practices

Design Practice

- Understand aging mechanisms and generally avoid them by design.
- Use material screening to avoid materials and fiber architectures (types and forms) that are susceptible to aging.
- Carefully evaluate aging for new and novel designs and material forms.
- Conservative evaluation of potential combination of loading and environmental degradation that may occur during the life of the aircraft.



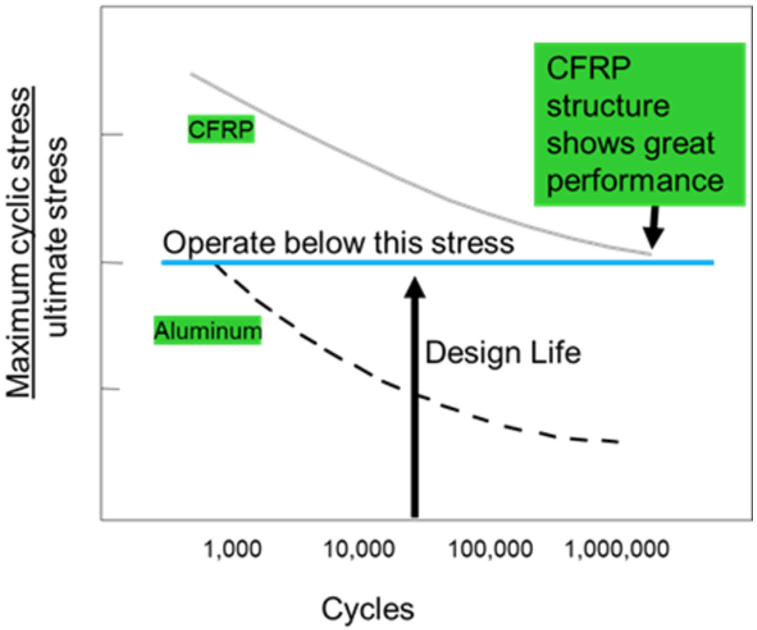
Environmental Cycling Example
(Kevlar Cycle)



Industry Best Practices

Fatigue Loading

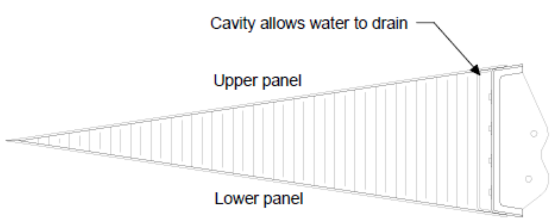
- Understand cyclic strain levels and keep operating strain levels low enough to maintain “no detrimental growth” of impacts and defects.
  - Pay careful attention to resin dominated failure modes and sustained out of plane stresses.
- Keep static strains below levels that would make composites fatigue sensitive.
- Keep strains low enough and substructure durable enough that multiple impacts are not likely to coalesce (and reduce strength).

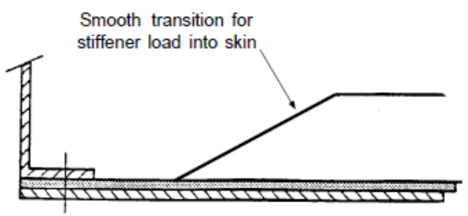


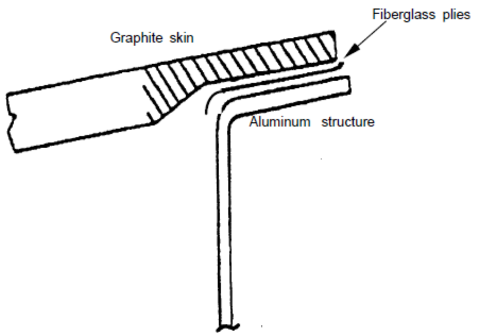
Industry Best Practices

Design Details

- Pay careful attention to primary load paths through bonded joints/matrix.
- Carefully evaluate fatigue-sensitive design details.
  - In particular for details with out-of-plane loading in the presence of impacts or interlaminar/bondline defects.
- Carefully design sandwich structures and associated design details.
  - Evaluate design details for potential water ingress.
  - Consider facesheet disbond growth and arrestment.
  - Establish design guidelines (e.g., minimum core densities, minimum facesheet thicknesses).







Industry Best Practices

In-Service and Repair Considerations

- Consider reparability of structural details that are prone to in-service damage accumulation and/or are susceptible to erosion.
- Consider multiple repairs over lifetime interacting.
- Design repairs that result in the repaired structure being as robust as the original structure.

Evaluation of repairs developed for potential high threat areas

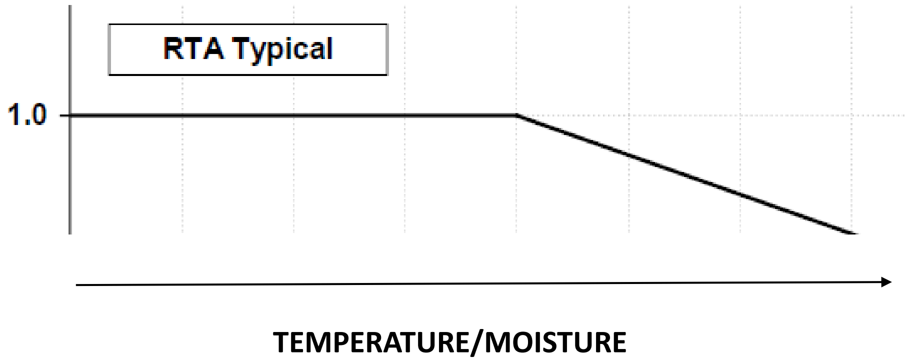
Component test article with SRM-type repairs

Approach Validated by Full-Scale Demonstration

Industry Best Practices

Compensation Factors

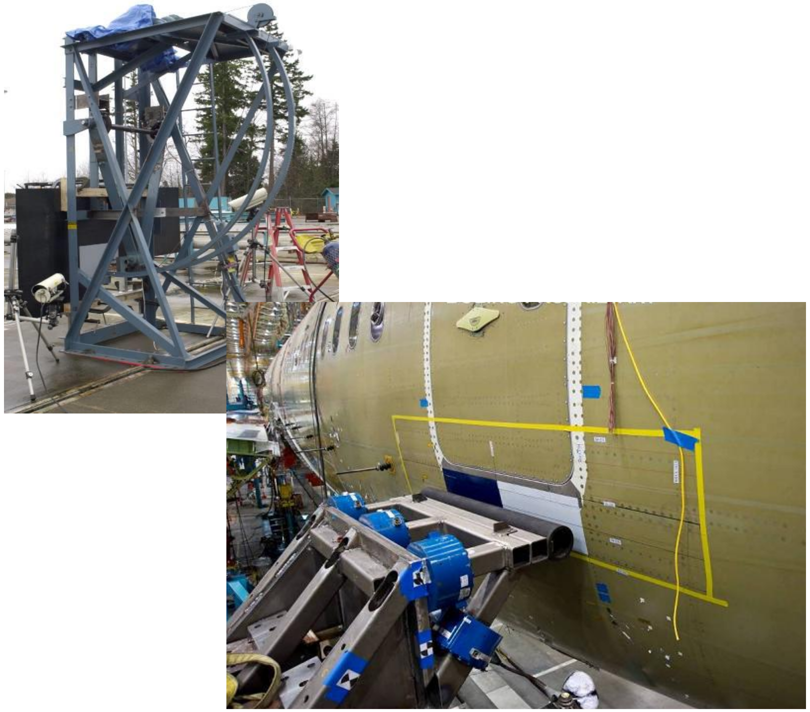
- Compensation factors are used to address environmental deterioration effects (e.g. moisture absorption) and are considered in the basic design and certification.
- Similar compensation factors may also be used during testing to understand required loading.
- Note that these factors are based on the service environment of the application.



Industry Best Practices

Repetitive Impact Damage & Damage Accumulation

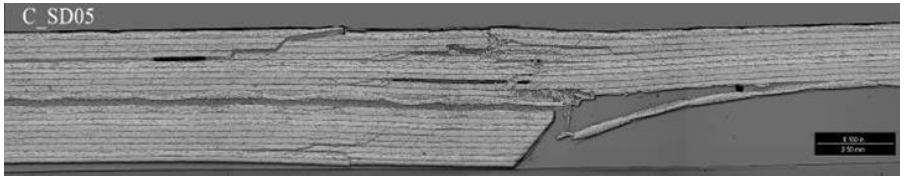
- Evaluate the effect of damage accumulation and possible interactions between damage threats that could lead to widespread degradation.
- Identify high risk impact areas and demonstrate no growth in test program with multiple BVID impacts. Address multiple impacts in inspection tasks.
- Damage in general structure is NOT widespread and is randomly distributed. High risk areas covered by test program and design philosophy.
- Door surround structure evaluated with simulated ground handling equipment.



Industry Best Practices

Substantiation

- Perform large-scale "no detrimental growth" fatigue testing with a wide range of impacts, including a residual strength test to show no degradation. Load Enhancement Factors (LEFs) are used in fatigue testing.
- Impact evaluation using representative energy levels.
- Limits of Validity (LOV) are generally controlled by metal structure but environmental degradation and damage accumulation on composite structure must be considered.



Industry Best Practices

Service History and Lessons Learned

- Accelerated testing can't cover all aspects of in-service environment, aging, or multi-site accidental damage over life of the aircraft.
- Perform early inspection of critical locations (especially for new materials/construction) to validate the engineering assumptions (Engineering Evaluation programs).

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  - **Teardowns**
    - Boeing
    - Airbus
    - FAA
  - Engineering Evaluation Programs
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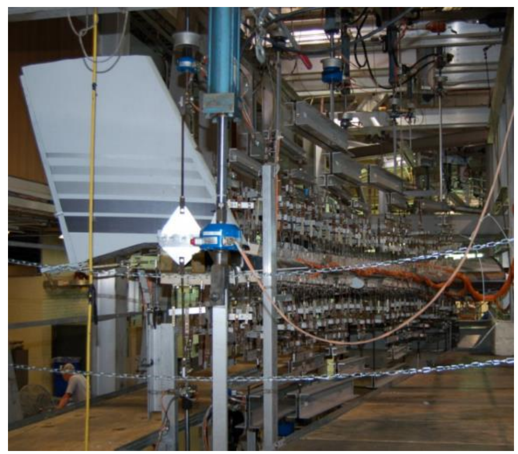
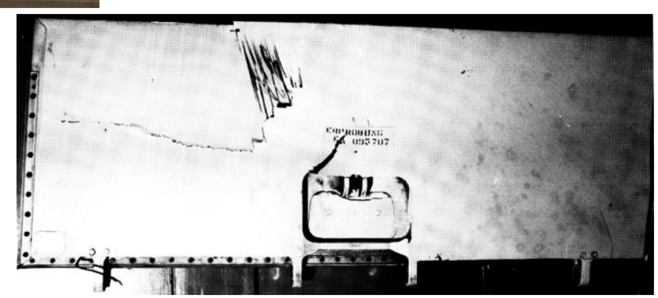
Teardowns

A number of investigations have been performed on aircraft retired from service.

- Tear down and mechanical testing results have shown no degradation in performance compared to baseline capability established at time of certification.

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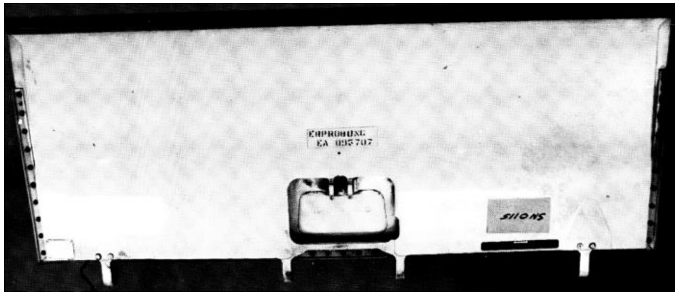
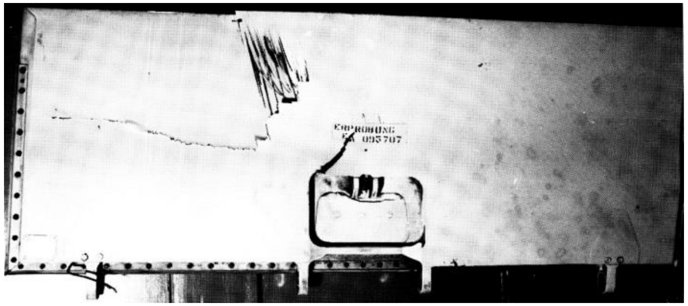
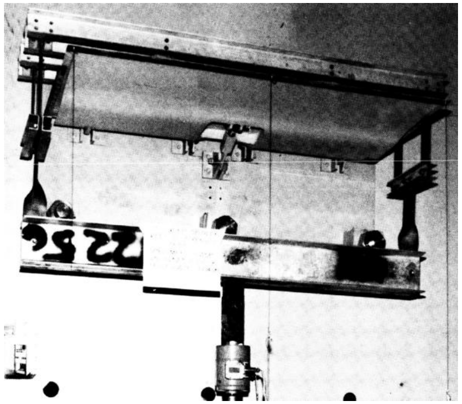
Boeing 737 Spoilers

15 years of service – 37,000 Flight Hours

- Sandwich structure
- 108 Spoilers – cumulative over 2 million flight hours and 3 million landings.
- Moisture content less than 1.1%
- No appreciable strength loss.

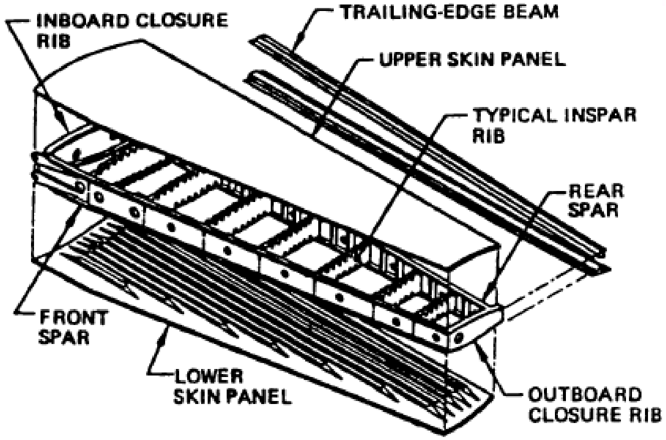




Boeing 737 Horizontal Stabilizers

6 – 18 years of service (3 articles)

Up to 55,000 flight hours and up to 52,000 flight cycles

- Solid laminate panels and spars, sandwich ribs.
- No noticeable or measurable degradation in material characteristics of interest.

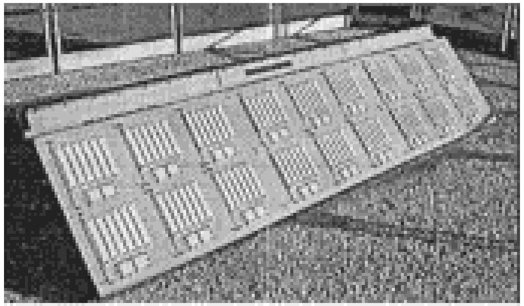


Boeing 777 Horizontal Stabilizer

21,000 Flight Hours

3,000 Flight Cycles

- Solid laminate.
- Confirmed conservatism of engineering assumptions (moisture content less than 1%).
- Additionally, panels attached to racks in several locations around the world were subjected to long term exposure and tested to confirm engineering assumptions.



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Airbus A300B Airbrakes

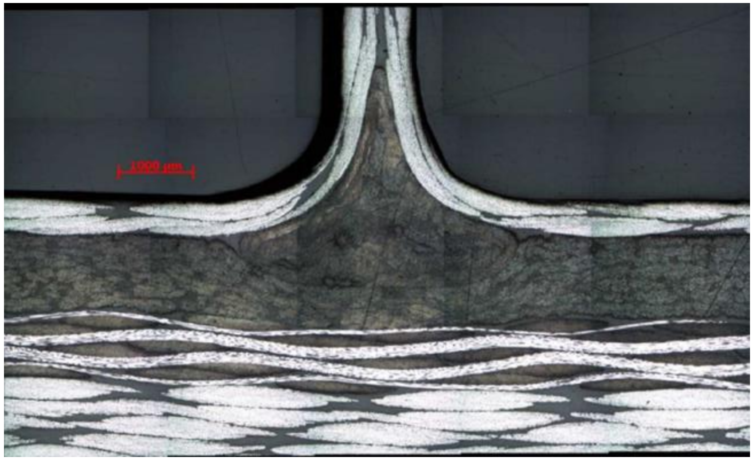
5-17 years of service

- Sandwich structure
- Five Airbrakes tested to rupture showing no appreciable change compared to the strength level demonstrated initially after 5 to 17 years of real flight.
- No noticeable degradation in material characteristics. Max moisture content of 0.9% was below values using accelerated aging (85%RH, 70°C).
- No growth of damage was found during this campaign.

Airbus A320 Horizontal Stabilizers

20 years of service – 60,000 Flight Cycles

- Solid laminate (integral co-cured skin/stringer and rib feet)
- Moisture content below certification baseline (less than 1.3%).
- No noticeable degradation in material characteristics.

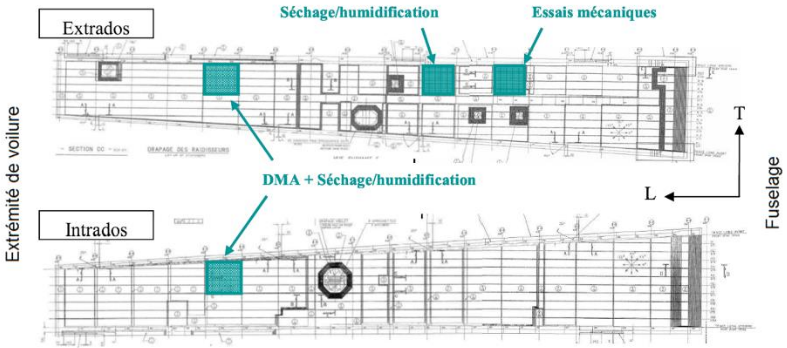


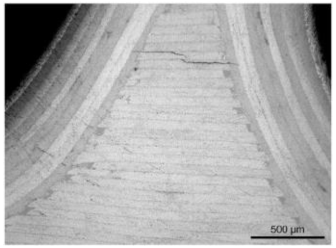
V10F and ATR 72 Wings

V10F 10,000 Flight Hours

ATR 72 1,000 Flight Cycles

- Solid laminate
- Normal evolution of the T_g as a function of humidity.
- Maximum moisture content below the amount used for accelerated aging in certifying the airplane (1.0% vs. 1.3%).
- No detrimental effects from any damage accumulated on the aircraft.

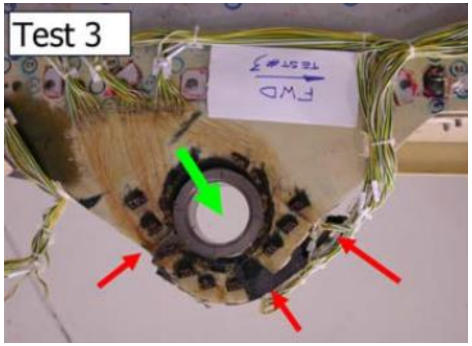


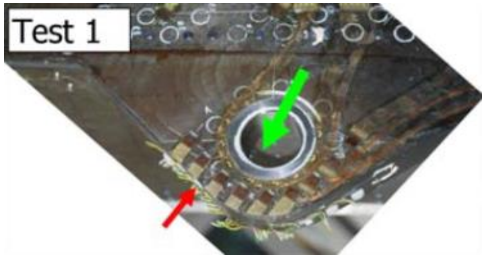


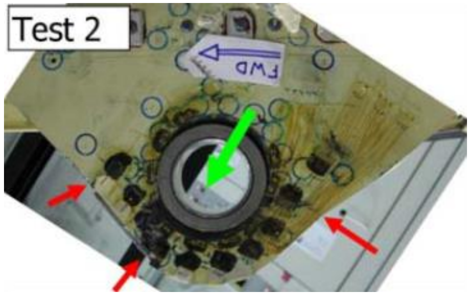
Airbus A300-600 Vertical Stabilizer

Extracted from the fleet with more than 15 years of service

- Solid laminate
- No strength deterioration in high loaded introduction area (lug test) after aging, repetitive loading and high peak loads.
- Demonstrated same strength level achieved at Type Certification.







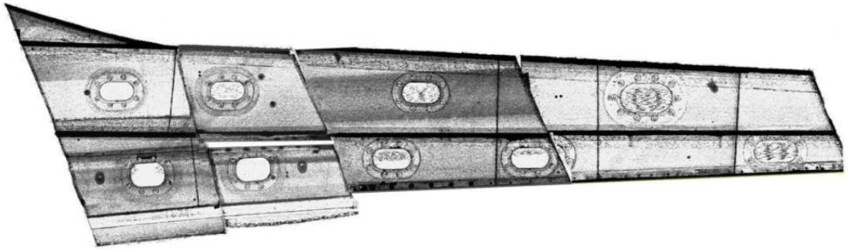
Outline

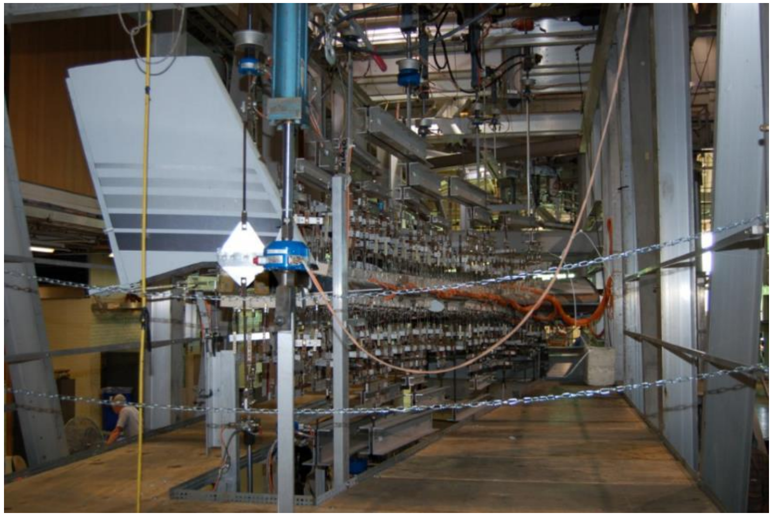
- Transport Aircraft Composite Structures
- Aging
- Substantiation
- Early Experiences
- Industry Best Practices
- In-Service Experience
  - Teardowns
    - Boeing
    - Airbus
    - **<u>FAA</u>**
  - Engineering Evaluation Programs
  - Conclusions
- Summary
- Recommendations

Beechcraft Starship Wing

12 years – 1,800 flight hours

- Structure showed no detrimental signs of aging to the naked eye.
- No evidence of degradation in the thermal properties and fully cured/cross-linked.
- Structure had reached moisture equilibrium (Max 1.1-1.3%).
- Porosity levels correlate with OEM production information.
- Full-scale test results of the aged wing correlated well with the results obtained for the certification article.

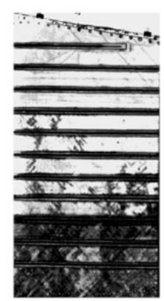


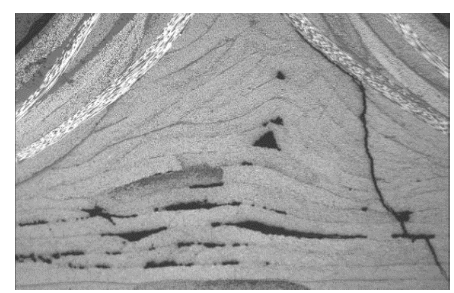


Boeing 737 Horizontal Stabilizer

18 years of service – 52,000 flight hours and 48,000 flight cycles

- Solid laminate panels and spars, sandwich ribs.
- No obvious signs of aging to the naked eye.
- Moisture levels in the structure as predicted during the design phase.
- No evidence of degradation in properties and 95% cured/cross-linked.
- Residual strengths met or exceeded the baseline values.





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Engineering Evaluation Programs

Engineering evaluation programs are NOT a safety or certification program

Confirm aircraft design engineering assumptions

- Evaluate response to service environment.
- Evaluate scheduled maintenance intervals.
- Improve MPD structural tasks and intervals, Structural Repair Manuals and Airplane Maintenance Manuals.
  - Improve related Customer Support documents.

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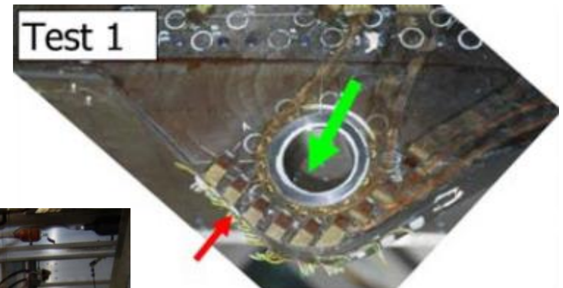
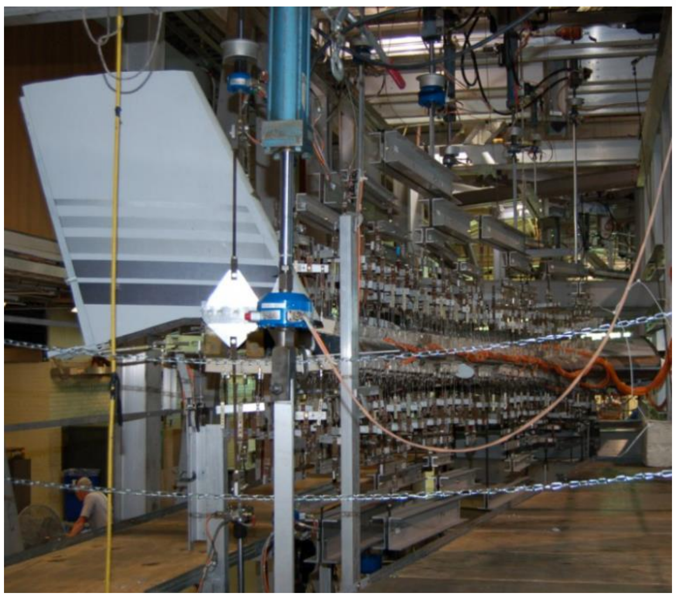
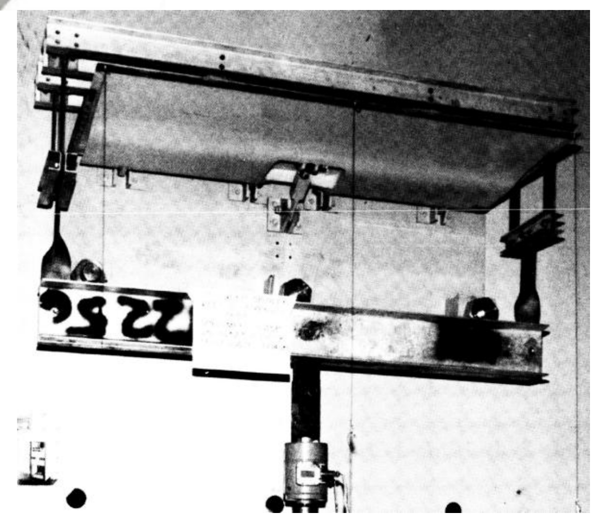
Aging – Environmental Conditions

Assessment performed on parts extracted from aged aircraft

- Mechanical strength
- Physical properties
- Chemical properties





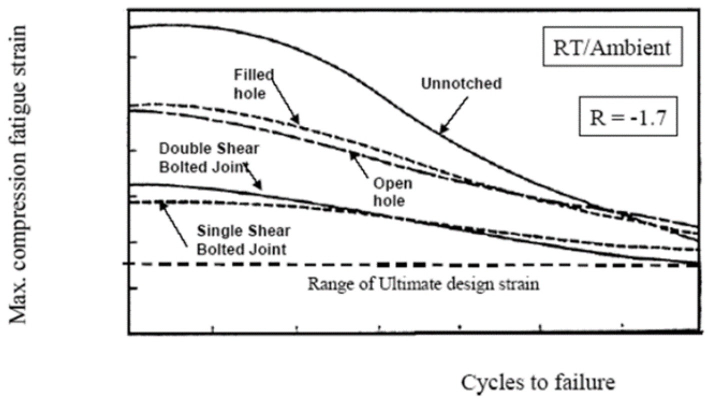


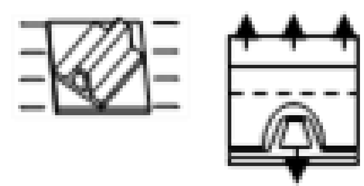
<u>Demonstrated conservative and robust engineering assumptions used in design</u>

Aging – Loading Conditions

When sizing to static loads and considering joints, repairs and damage threats, fatigue concerns from in-plane loads are not typically a concern.

Resin dominated failure modes and sustained out of plane stresses are properly addressed in the airplane design





Demonstrated suitability of engineering approach for cyclic loading

787/A350 Fleet Summary – December 2019

- Since entry into service:
  - ~ 2,500,000 departures
  - ~ 15,000,000 flight hours
  - > 50 billion lbs of fuel saved

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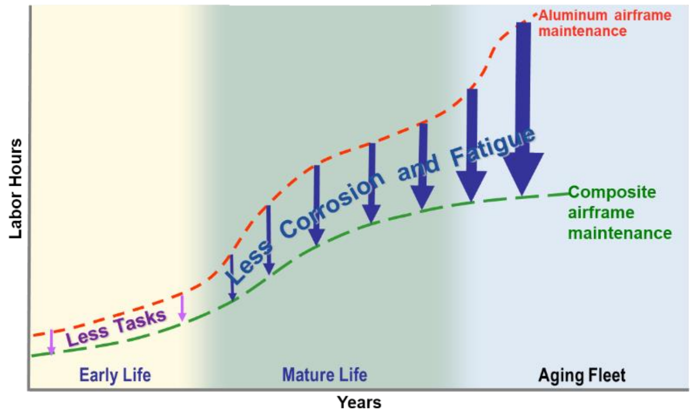
Summary

Main aging related phenomenon in metal structure not a key concern in composite structure

- The majority of metallic structures inspections are driven by corrosion and fatigue.



Service experience of composite aircraft structure has generally been very good

- Early aging related behavior was corrected by design improvements and material screening.

Summary

Current industry practice

- The structure's response to aging threat, individually and in combination, is characterized and addressed in the design of the composite structure.

Results from teardown of in-service aircraft

- Teardowns performed on aircraft retired from operations after long service histories.
  - Airbus: A300B Airbrakes, A320 HTP, ATR 72 wing and A300-600 VTP.
  - Boeing: 737 spoilers and HTP, and 777 HTP.
  - FAA/NIAR: Beechcraft Starship wing and Boeing 737 HTP.
- No appreciable loss of strength reported.
- No measurable degradation in material characteristics.

In-service experience validates engineering assumptions

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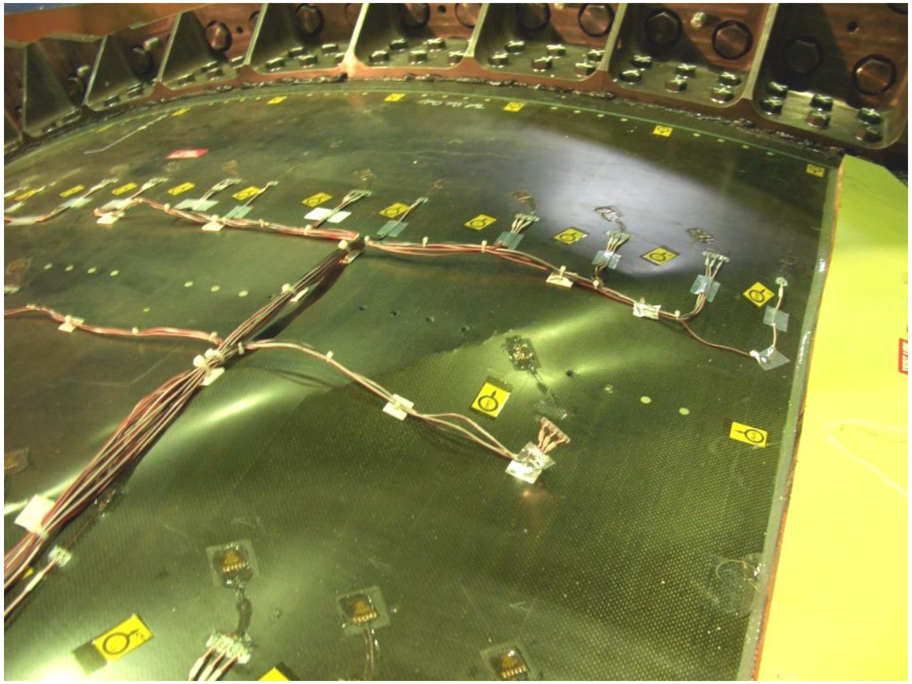
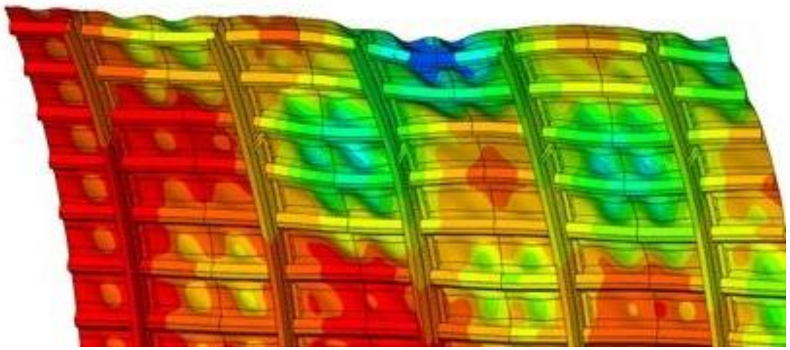
Recommendations – Accidental Damage

Development of accidental damage modelling principles for residual strength

- Largely established by test up to large scale level.
- Complex phenomenon (geometry/scale effect) on top of interactions with loading conditions including buckling.





Recommendations – Accelerated Aging

Development of an accelerated aging test protocol that mimics real in-service conditions

- The Kevlar Cycle is a mixed environmental cycle that combines hot and cold thermal cycling, and some moisture to try and discern the durability of a materials system – mostly uncovering issues at the surface, such as micro-cracking.
- The test gives us a common method that informs us of a propensity of a material to degrade under key conditions, by itself, is insufficient to give us all of the information we need about environmental durability.
- Any new test method that we develop should combine targeted testing with actual in-service experience along with some structural/molecular modeling to fill in the blanks.
- Formulate accelerated tests must be predictive of actual in-service environments.

THANK YOU!