NIAR Research on Certification of Composite-Metal Hybrid Structures & Joints

Waruna Seneviratne
National Institute for Aviation Research (NIAR)
Wichita State University (WSU)
NIAR Services & Representative Clients

- Research & Development
- Design
- Certification Testing
- Technology Transfer
- Training

More than 100 aviation customers
NIAR Locations

NIAR Headquarters @ Wichita State University
- Composites & Mechanical Test, Computational Mechanics, Crash Dynamics, Environmental Test, Human Factors, Mechanical Test, Research Machine Shop, Walter H. Beech Wind Tunnel

Aircraft Structural Test & Evaluation Center @ Kansas Coliseum
- Aging Aircraft, Composites & Mechanical Test, Full-Scale Structural Test, Ballistic & Impact Dynamics

National Center for Aviation Training
- Advanced Coatings, CAD/CAM, Composites & Advanced Materials, Nondestructive Testing, Virtual Reality, Reverse Engineering

Environmental Test Labs @ Beechcraft (former Boeing Wichita Facility)
- Environmental Test, Full-Scale Structural Test, Metrology
Capabilities that provide unique capacity to conduct R&D from bench top to full scale...

- Advanced Coatings
- Aging Aircraft
- Ballistics/Impact
- CAD/CAM
- CIBOR
- Composites
- Computational Mechanics
- Crash Dynamics
- Electromagnetic Effects
- Environmental Test
- Full-scale Structural Test
- Human Factors
- Mechanical Test
- Metrology
- NDT
- Oil Analysis
- Research Machine Shop
- Reverse Engineering
- Virtual Reality
- Beech Wind Tunnel
Certification Challenges for Hybrid Structures

• Damage growth mechanics, critical loading modes and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming.

• Data scatter in composites compared to metal data is significantly higher requiring large test duration to achieve a particular reliability that a metal structure would demonstrate with significantly low test duration.

• Metal and composites have significantly different coefficient of thermal expansion (CTE)

• Mechanical and thermal characteristics of composites are sensitive to temperature and moisture

• Need for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority
Outline of Presentation

• CMH-17 activities

• Load-Enhancement Factor (LEF)
  • Development
  • Application to Complex Structure
    • Multi-LEF
    • Deferred Severity Spectrum

• Hybrid Structures

• Viscoelastic Behavior of TRS due to Hygrothermal History

• Adhesive Joint Research
  • F/A-18 wing-root hybrid joint
12.6 Durability and Damage Growth Under Cyclic Loading

12.6.1 Influencing factors
12.6.2 Design issues and guidelines
12.6.3 Test issues
  12.6.3.1 Scatter analysis of composites
    12.6.3.1.1 Individual Weibull method
    12.6.3.1.2 Joint Weibull method
    12.6.3.1.3 Sendeckyj equivalent static strength model
  12.6.3.2 Life Factor approach
  12.6.3.3 Load Factor approach
  12.6.3.4 Load Enhancement Factor approach
    12.6.3.4.1 Description
    12.6.3.4.2 LEFs for complex structure
    12.6.3.4.3 Testing Requirements
    12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure
  12.6.3.5 Ultimate strength approach
  12.6.3.6 Test spectrum development
  12.6.3.7 Test environment
  12.6.3.8 Damage growth
Life Factor Approach

Structure is tested for additional fatigue life to achieve the desired level of reliability

- Life Scatter Factor (LSF)

\[ N_f = \frac{\Gamma\left(\frac{\alpha_i + 1}{\alpha_i}\right)}{-\ln(R)} \left(\frac{\chi^2(2n)}{2n}\right) \]

Newer composite materials/processes indicates significantly lower life factors
Load-Enhancement Factor (LEF) Approach

Increase applied loads in fatigue tests so that the same level of reliability can be achieved with a shorter test duration

– Combined load-life approach


FAA – NIAR Follow-on Investigation: DOT/FAA/AR-10/6, June, 2011

For $N = 1.5$ ➔ $\text{LEF} = 1.15$ (B-basis)
For $N = 2.0$ ➔ $\text{LEF} = 1.13$ (B-basis)

LEF Is a function of test duration (for various confidence levels)
• New materials/processes
• Not an SN curve
Fatigue Scatter Analysis Techniques

- Individual Weibull
- Joint Weibull
- Sendeckyj Equivalent Strength Model

\[
\alpha_i > \alpha_j > \alpha_S
\]

NADC Fatigue Scatter Analysis

NAVY LEF APPROACH IS NOT RESTRICTED TO THESE SCATTER ANALYSIS METHODS

Data Pooling Techniques

Stress (psi)
Number of Cycles

Fatigue Failures
Residual Strength after Predetermined Number of Cycles

Example Only
[Not Real Data]
Selection of Shape Parameters

• Selection of shape parameters from a single SN curve is not a practical method of deriving LEFs and/or \( N_F \) for a particular structure.
  
  • LEF (NAVY-Whitehead) approach links strength and life scatter and provides a LEF as a function of test duration
  
  • Engineering judgment is subjective

[Graph showing LEF as a function of test duration]
Generation of LEF Curve

Fatigue Data Fitting Models

Fatigue

<table>
<thead>
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<th>Test Duration</th>
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<tr>
<td>13.3</td>
<td>1.0 Life Factor</td>
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LEF = \left( \frac{\sigma_L}{\sigma_R} \right) \left( \frac{1}{\alpha_L} \right) \left( \frac{1}{\alpha_R} \right) \left( -\ln(p) \right)^{\frac{1}{2n}}

\sigma_L = 1.25
\sigma_R = 20.0
p = 0.9 (B-Basis)
\gamma = 0.95 (confidence level)

Life Factor

Life

Test Duration

Load Factor

Damage Tolerance Certification of Composite Structures

3/2/2016
Variables Associated with LEF

Strength Shape Parameter: $\alpha = 30$

Life Shape Parameter: $\beta = 1.25$

Damage Tolerance Certification of Composite Structures

<table>
<thead>
<tr>
<th>Sample Size</th>
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<th>1.5 Lifetime Test</th>
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<td>30</td>
<td>1.270</td>
<td>1.130</td>
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</table>
Key Characteristics of LEF/NF

- LEF = $f(N)$

$$LEF(N) = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)^{\alpha_L/\alpha_s}}{\left\{-\ln(R) \cdot N^{\alpha_s}ight\}^{\frac{\alpha_L}{\alpha_s}} \left\{\chi^2(2n)\right\}^{\frac{2n}{2n}}.}$$

- LEF requirement decreases with higher test duration

- $N_F$ is a constant

- LEF curve is NOT a SN curve
Effects of Damage on $\alpha$

- Damage Tolerance Element Tests
  - Data scatter associated with final failure is conservative or representative of scatter at onset of damage propagation
The application of load enhancements must preserve the stress ratio of each load cycle throughout the spectrum so that the fatigue damage mechanism and the life are not artificially influenced. The LEF must be applied to the minimum/maximum load in the fatigue spectrum.

\[
P_{\text{Min/Max}} = \left( \text{Load}_{1-g} \right) + \left( \frac{\Delta \text{Load}}{\Delta g} \right) \cdot \Delta g \cdot \text{LEF}
\]
Environmental Compensation Factor (ECF)

- Some applications may require other factors such as spectrum severity factors and environmental compensation factors (ECF) in addition to LEF.
- Typically, durability test is carried out with no ECF for fatigue spectrum and intermittent k*LL static test/strain surveys with ECF.

![Graph showing the relationship between strain and temperature with ECF](image)

Ambient Strain

Ambient + Thermal + Moisture

Δ - due to thermal loading

Δ - due to moisture

Ambient external flight condition loading

Minimum Margin of Safety

Maximum Applied Strain

Ambient external flight condition strain unaffected by addition of thermal moisture strains

DRY

WET

Damage Tolerance Certification of Composite Structures
<table>
<thead>
<tr>
<th>Static Scatter Factor</th>
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<td>NIAR</td>
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12.6.3.4.2 LEFs for Complex Structure

- Modal analysis
  - Use of modal value from the statistical analysis of shape parameters from various design details/failure modes

- Current industry practice
  - Use of “traditional” LEF values (1.15) unless substantial test databases are developed to support use of lower LEFs
    - Less data required to verify that traditional values are conservative
  - Use a single LEF for the complete test duration
  - Use a single LEF for the complete test spectrum
    - Possibly not apply LEF to fatigue loads in cases where resulting load would be at or above Limit Load
  - Select LEFs based on modal analysis

- Recommended best practices
  - Develop LEF applicable to materials and structural details/failure modes applicable to a specific structure
    - Use of historic Navy LEF curve must be substantiated with a reduced LEF test matrix
  - Investigate fidelity of modal analysis
    - Failure modes with large scatter shall be interrogated at element/sub-component level(s)
  - Immerging methods (Multi-LEF and Deferred Severity Spectrum)
Guidance on Development & Application of LEF

**Notes:**
- Design features includes monolithic and/or sandwich structure with different materials, layup sequences, bolted and/or bolted joints, etc. Note that multiple design features can have the same failure mode.
- Since static and fatigue modal analyses are conducted separately, for a given feature, it is not required to have both static and fatigue data for a given design feature.
- For a given design, more than four critical stress ratios are possible.
Multi-LEF Approach for Hybrid Structures

Clipping Level for Metal

LEF

Multi-LEF

Repeated for required N

Original Spectrum Blocks

Test Spectrum Blocks after LEF

Spread high load cycles throughout the spectrum (may require additional crack growth analysis for hybrid structures)
12.6.3.3 Load Enhancement Factor using Scatter Analysis

Multi-LEF Approach for Hybrid Structures

Method 4: Multi Load-Life Factor (multi-LEF) Approach

\[ N_1 \neq N_2 \neq N_3 \neq \ldots \neq N_i \]
\[ \Rightarrow \text{LEF}_1 \neq \text{LEF}_2 \neq \text{LEF}_3 \neq \ldots \neq \text{LEF}_i \]

\[ \text{LEF}_1 = 1.0 \text{ (high load block is repeated 5 times within the overall test spectrum since } N_5 = 5) \]

Original Spectrum is multiplied by appropriate LEF

with multiple combined load-life factors (example: \( N = 3 < N_f \) for \( \text{LEF}_2 = \text{LEF}_3 = \text{LEF}_4 \neq \text{LEF}_1 = 1.0 \) with \( N = N_f \))
12.6.3.3 Load Enhancement Factor using Scatter Analysis

**Boundaries of LEF Curve & Related Regulations**

- Test duration must be greater than 2 DSG (with appropriate LEF for composites)
  - Hybrid (metal-composites) structures: minimum 3 DSG ➞ **LOV for Metals (LOV for Composites?)**

- LEF must be greater than 1.0

The LEF relationship can provide a wide spectrum of load and life combinations to achieve the desired reliability. However, practical considerations result in limits on these values.

- The fatigue test spectrum loading should always be at least as large as the actual loading on the structure. This has the effect of limiting the LEF to being greater than or equal to 1.0, even if the test is conducted beyond the life factor.
- In addition, for the metallic structure, the test duration should be sufficient to demonstrate that the structure is free from wide-spread fatigue damage (WFD) prior to limit of validity (LOV).
- **AC 25-571 D:** Test article must be cycled to 3 DSGs in order to avoid maintenance actions associated with WFD.
Fidelity of Modal Analysis

Failure modes with large scatter shall be interrogated at element/sub-component level(s)

Composite data analyzed in DOT/FAA/AR-10/6 suggest that NADC (DOT/FAA/CT-86-39) LEFs are conservative for modern composites as a result of the improvements in materials and process techniques, and test methods (i.e., less scatter in test data). Therefore, in the absence of sufficient test data, the NADC values can likely be used during large-scale test substantiation. However, new or novel materials, material forms, or design details will likely require validation of the strength and life shape parameters, to ensure they are equivalent or better than the NADC values.

REF:
**Substantiation of Using NADC LEF**

12.6.3.3 Load Enhancement Factor using Scatter Analysis

Use of historic Navy LEF curve must be substantiated with a reduced LEF test matrix

**Critical design details and stress ratios**

- Minimum test requirements* [Fig. 12.6.3.4.3(a)]
- Generate strength shape parameters $\alpha_s^i$, $i = 1..m$
- Generate life shape parameters $\alpha_L^j$, $i = 1..n$

**NOTES:**
- Number of static data sets and fatigue SN curves are $m$ and $n$, respectively.

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Certification of Composite-Metal Hybrid Structures
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

- Current industry practice generally avoids addressing metallic and composite fatigue with the same article.
- Emerging approaches that may enable addressing metallic and composite fatigue with the same article (for composite-dominant designs):
  - **Option 1**: Drive LEFs low enough (either via increasing the test duration and/or via thorough testing to substantiate lower values) to avoid overload concerns in metal.
  - **Option 2**: Multi-LEF Approach.
  - **Option 3**: Deferred Spectrum Approach.

These options can be combined.
Considerations for Metal/Composite Hybrid Structure

**Single Article for Composite-Metal Hybrid FSFT**

**Considerations:**
- LOV
- Type certificate (FTA remain ahead of fleet)
- Effects of LEFs (crack growth retardation in metals)
- Sequencing effects
- Effects of additional test duration on metals
- Invalidation of metal test when high loads are applied (life extension)
- Competing failure modes
- Effects of CTE mismatch
- Effects of environment

![Diagram](image)

**Load-Life Shift:**
\[
\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0
\]

**References:**
- Damage Tolerance Certification of Composite Structures
Load-Life Shift

- A mechanism to apply different LEFs for multi-phase test programs for a given reliability level to substantiate design lifetime.

\[
\frac{N_{T_{LEF_1}}^{R}}{N_{LEF_1}^{R}} + \frac{N_{T_{LEF_2}}^{R}}{N_{LEF_2}^{R}} + \ldots + \frac{N_{T_{LEF_n}}^{R}}{N_{LEF_n}^{R}} = \sum_{i=1}^{n} \frac{N_{T_{LEF_i}}^{R}}{N_{LEF_i}^{R}} \geq 1.0
\]

- Simplified (two-step) version:

\[
N_{T_2}^{R} = \left(1 - \frac{N_{T_1}^{R}}{N_{1}^{R}} \right) \cdot N_{2}^{R}
\]

12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Deferred Spectrum for Hybrid FSFT

Method 1: Life Factor Approach

Method 2: Deferred High Loads

Method 3: Deferred High Loads with Load Life Shift

Damage Tolerance Certification of Composite Structures
Deferred Spectrum for Hybrid FSFT (contd.)

**Metals:**
severe flight loads result in crack-growth retardation

**Composites:**
severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life

Cycles below composites truncation level (green) are eliminated after 3 DSG
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Separate Metal and Composite Certification Test Articles

<table>
<thead>
<tr>
<th>Option</th>
<th>LEF</th>
<th>Required Test Duration without LLS</th>
<th>Required Test Duration with LLS</th>
<th>Total Test Duration</th>
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<td>1.088</td>
<td>1.3</td>
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Load-Life Shift:

\[ \frac{N_{LEF_1}^T}{N_{LEF_1}^R} + \frac{N_{LEF_2}^T}{N_{LEF_2}^R} + \ldots + \frac{N_{LEF_n}^T}{N_{LEF_n}^R} = \sum_{i=1}^{n} \frac{N_{LEF_i}^T}{N_{LEF_i}^R} \geq 1.0 \]
Load Sequencing Effects – Open Hole Tension/Compression (UNI)

12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects / 12.6.3.8 Damage growth

Lower level building-blocks of testing:
1. Sequencing effects for validation of deferred spectrum
2. Mismatch of CTE’s
3. Environmental issues for composite (ex., hot-wet)
4. Hot spots (ex., ILS/ILT for composites)
### Load Sequencing Effects – Open Hole Tension/Compression (PW)

#### 12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects / 12.6.3.8 Damage growth

<table>
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<th>n=0 Reference</th>
<th>70% - n=1,040 Load Block 1</th>
<th>40% - n=401,005 Load Block 2</th>
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**Fatigue Profile 5**

- Failed at 823,523 cycles
- Failed at 827,830 cycles

<table>
<thead>
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<th>NAME</th>
<th>n=0 Reference</th>
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<th>55% - n=414,570 Load Block 2</th>
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**Fatigue Profile 6**

- Failed at 815,550 cycles
- Failed at 822,849 cycles
- Failed at 816,002 cycles

**Certification of Composite-Metal Hybrid Structures**

33
Load Sequencing Effects - Compression After Impact

12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects / 12.6.3.8 Damage growth

**Constant Amplitude (70% CAI SS)**

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**Spectrum Fatigue**

1 spec. failed at n=403,011
1 spec. survived n=1,035,680

**Constant Amplitude (55% CAI SS)**

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3 spec. survived n=1,035,680

Certification of Composite-Metal Hybrid Structures
Operating Stress/Strain Levels

Operating levels for composites are significantly low
⇒ No sequencing effects

Ref: Whitehead, et. al. (1986), NADC-87042-60
Differences between composite and metallic spectrums

- Metals: severe flight loads result in crack-growth retardation ➜ Clipping
- Composites: severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life
- Flaw growth threshold for metals may be lower load level than that for composites ➜ Different Truncation Levels
Composite vs. Metal Fatigue Sensitivity

Comparison of composite and metallic fatigue behavior for a wing spectrum
Ref: Whitehead, et. al. (1986), NADC-87042-60

Ref: Dr. A. Someroff (1981), NAVAIR (extracted from NADC-87042-60)
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Composite vs. Metal - Sensitivity

- Notch Sensitivity (Composites)
- Notch Sensitivity (Metals)

Damage Tolerance Certification of Composite Structures
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Composite-Metal Bolted Joints

- 2 x 3 0.25-inch fasteners with 0.5-inch pitch
- 2 metallic splice plates
- Anti-buckling fixture for compression loading

Damage Growth in Metals

Damage Growth in Composites

Damage Growth in Hybrids

- Competing failure modes
- Sequencing effects
- Miner’s Rule or an alternative (???)
- Effects of LEFs
- Effects of additional test duration
- Effects of CTE mismatch
- Effects of environment

Static - Tension

Static - Compression

Fatigue

Damage Tolerance Certification of Composite Structures
Other Research Topics
Viscoelastic Behavior of TRS due to Hygrothermal History

Understanding Thermal Residual Stresses

Transverse Residual Stress

Temperature

T_{0,wet} T_{0,dr} T_{0}

Decrease in temperature

Moisture induced swelling

Stress relaxation

Moisture desorption


Damage Tolerance Certification of Composite Structures

9/16/2015
8-Ply Spliced Tensile Specimens

T650/5320-1 UNI [45/0/-45/90]s

T650/5320-1 PW [45/0/-45/90]s
Ratcheting Effects – 4-Ply Specimens
Life Extension of F/A-18 Composite Structure

ASIP 2010-11
Fatigue Life Assessment of F/A-18 A-D Wing-Root Composite-Titanium Stepped-Lap Bonded Joint

ASIP 2012
Durability of Composite Wet Layup Repair on Metallic Leading Edge of F/A-18 Trailing-Edge Flap

ASIP 2013-14
Full-Scale Fatigue Testing of F/A-18 A-D Inner Wing

12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Fatigue Life Assessment of F/A-18 A-D Wing-Root Composite-Titanium Stepped-Lap Bonded Joint

Inspections after 10 lifetimes

Tensile Dominant Fatigue Spectrum
Compression Dominant Fatigue Spectrum

Check 155,513 lbf
Repair 16,783 lbf
Repair After 1 Test Life 16,783 lbf

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12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

F/A-18 Wing-Root Stepped-Lap Hybrid Bonded Joint

Progressive Damage Growth of Titanium (TDFS)

(a) Fatigue crack propagation from titanium to composite through adhesive layer.

(b) Failure surface – OML side

(c) Failure surface – IML side

No-Hole

Open-Hole

Unstable Crack Growth

Stable Crack Growth

3L-FH-7 fatigue damage (inspected after residual strength test)

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Summary

- Multi-LEF Approach can be applied to hybrid structures to prevent metal overloads
- Deferred severity spectrum
  - Smart Testing ➔ Significantly reduce the total test duration and cost of FSFT
  - Applicable for composite-dominant designs
  - Need analysis/tests to justify spectrum modifications
    - Sequencing effects
  - Effects of additional test duration on metals
    - Invalidation of metal test when high loads are applied (life extension)
- Additional considerations
  - Competing failure modes
  - Effects of CTE mismatch
  - Effects of environment
References

• Contact (Waruna Seneviratne):
  • waruna@niar.wichita.edu

• References:
  • Seneviratne, W., Fatigue Life Determination of a Damage-Tolerant Composite Airframe, Wichita State University, December 2008.
  • Tomblin, J and Seneviratne, W., Durability and Damage Tolerance Testing of Starship Forward Wing with Large Damages, DOT/FAA/AR-11/XX, Federal Aviation Administration, National Technical Information Service, Springfield, VA, 2012.