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# Certification of Composite-Metal Hybrid Structures

## Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

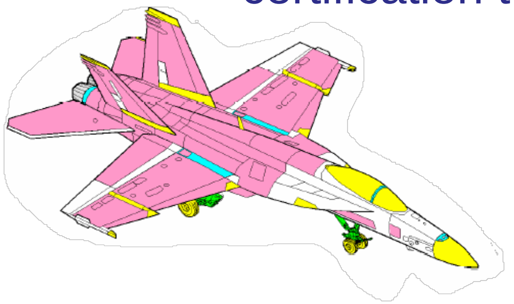
2013 Technical Review


Waruna Seneviratne & John Tomblin

Wichita State University/NIAR

# Certification of Composite-Metal Hybrid Structures

- **Motivation and Key Issues**
  - 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



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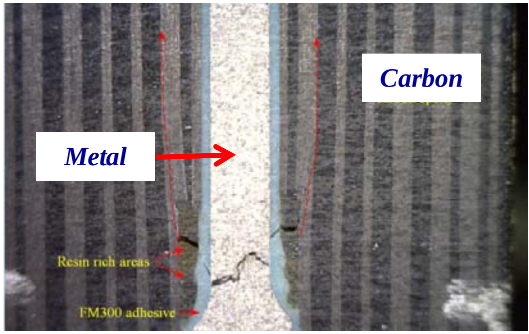
# Certification of Composite-Metal Hybrid Structures

- **Primary Objective**
  - Develop guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.

- **Secondary Objectives**
  - Evaluate the damage mechanics and competing failure modes (origination and propagation)
    - Mechanical & bonded joints
  - Data scatter and reliability analysis, i.e., LEF
  - Modifications to load spectra and application LEF
  - Address mismatched Coefficient of Thermal Expansion (CTE) and ground-air-ground (GAG) effects
  - Impact of environmental effects on hybrid structures
    - Environmental compensation factor (ECF)
    - Test environments

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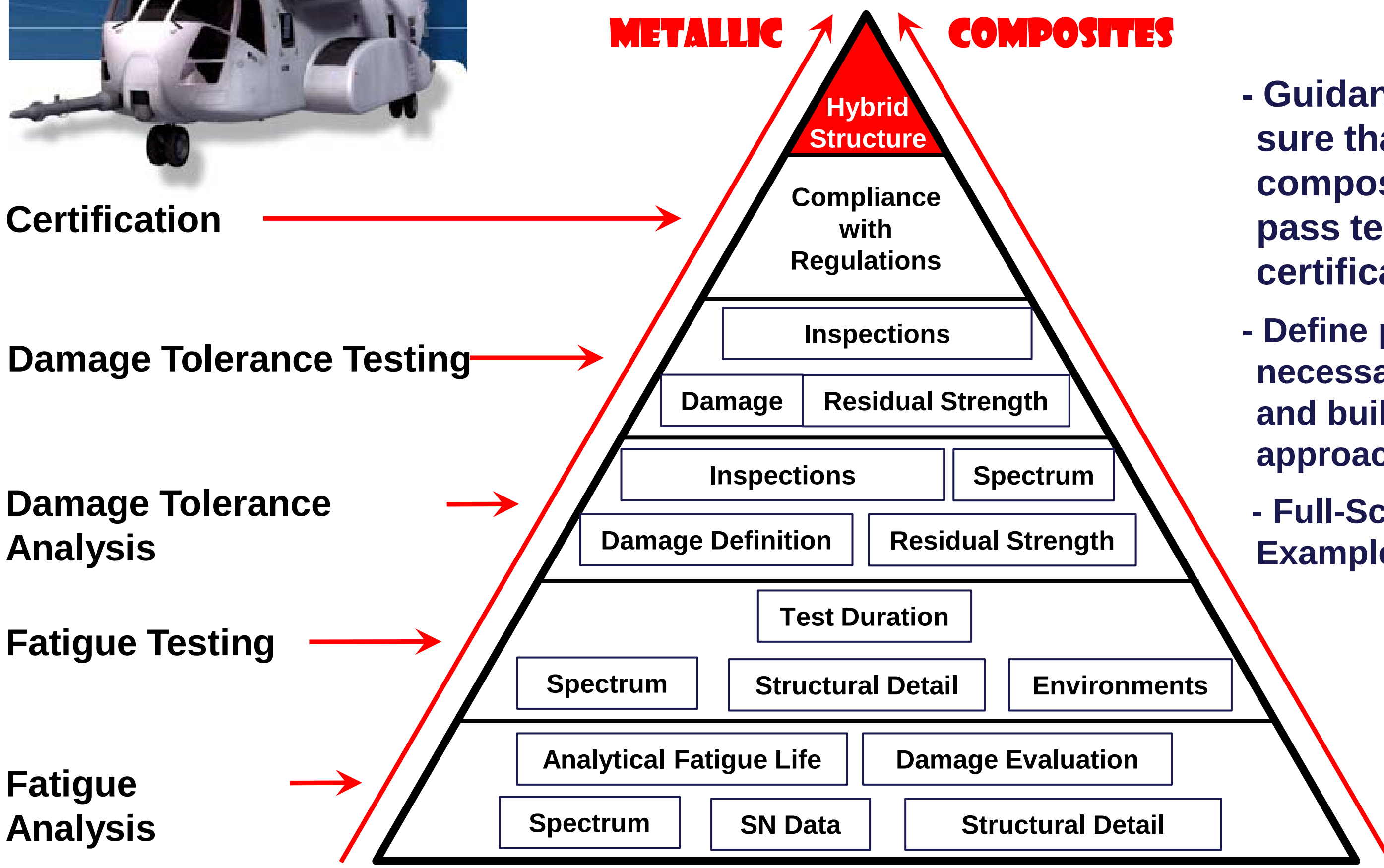
# Approach




- Guidance is need to make sure that both metal and composite are designed to pass testing and certification requirement.
- Define procedures necessary to support testing and building block approaches
- Full-Scale Validation and Examples

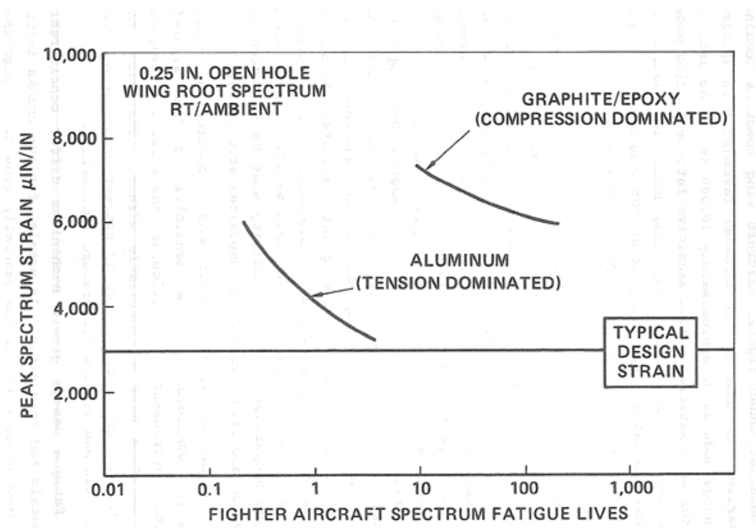
# Certification of Composite-Metal Hybrid Structures

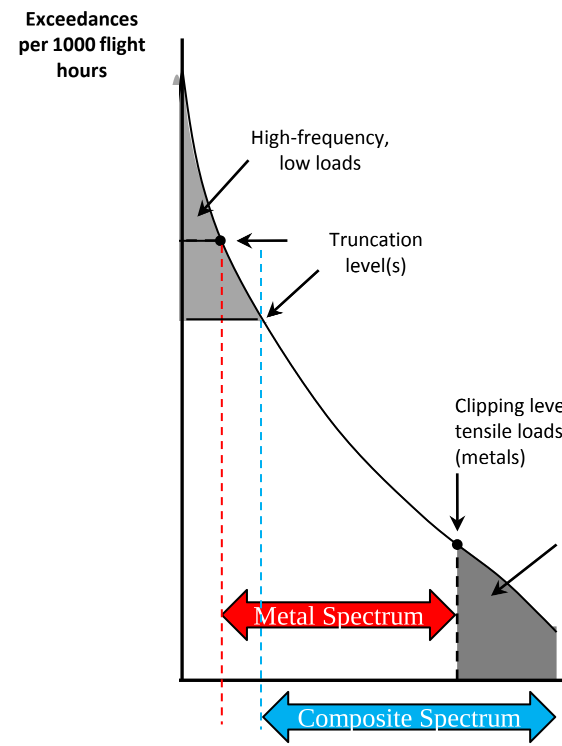
- Principal Investigators & Researchers
  - John Tomblin, *PhD*, and Waruna Seneviratne, *PhD*
  - *Upul Palliyaguru*
- FAA Technical Monitor
  - Curtis Davies and Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz, *PhD*
- Industry Participation
  - Airbus, Boeing, Bombardier, Bell Helicopter, Cessna, Hawker Beechcraft, Honda Aircraft Co., NAVAIR, and Spirit Aerosystems

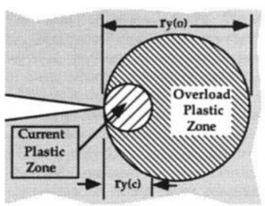
# Spectrum Truncation & Clipping

- 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

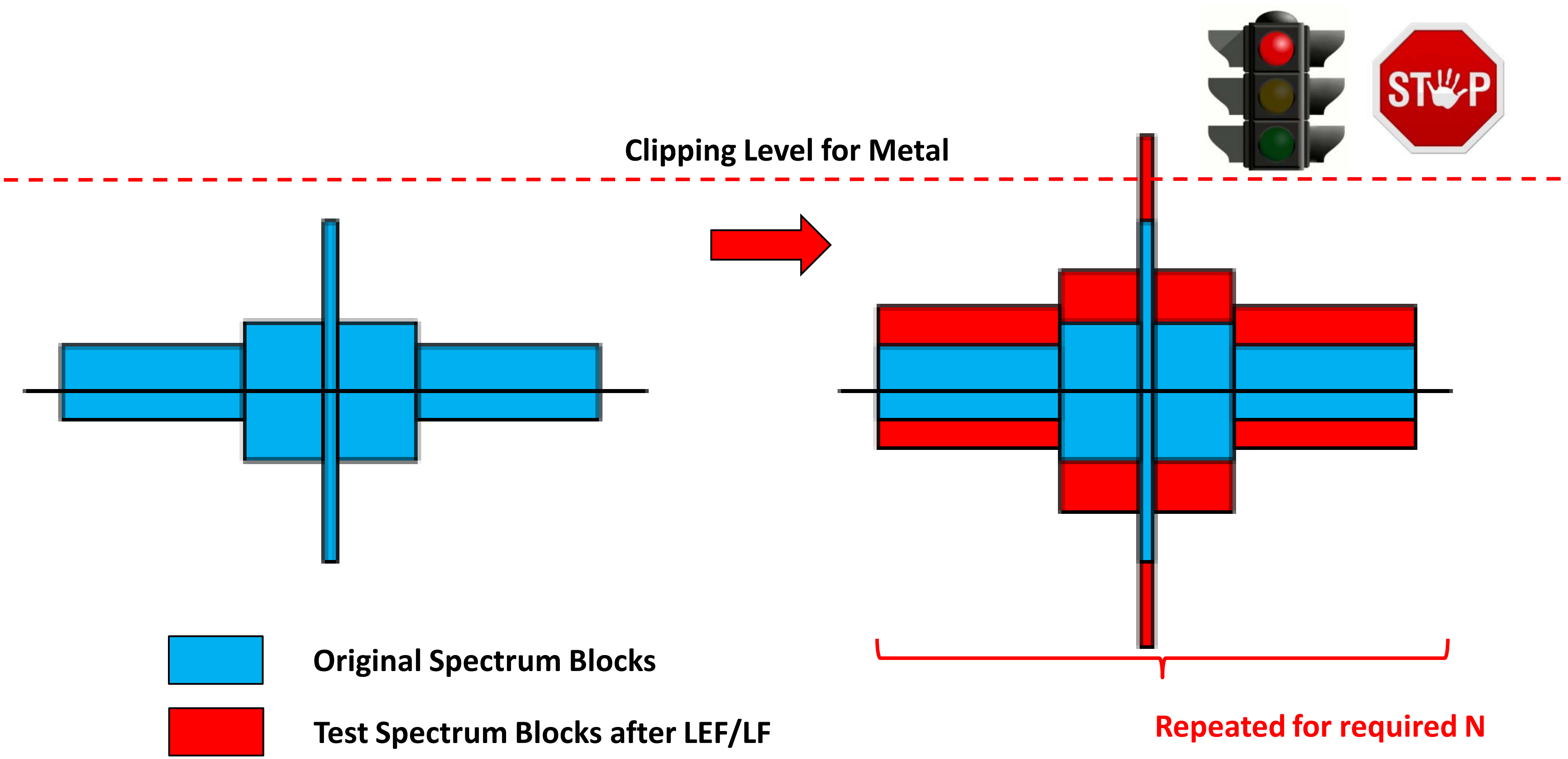
    ➔ Different Truncation Levels



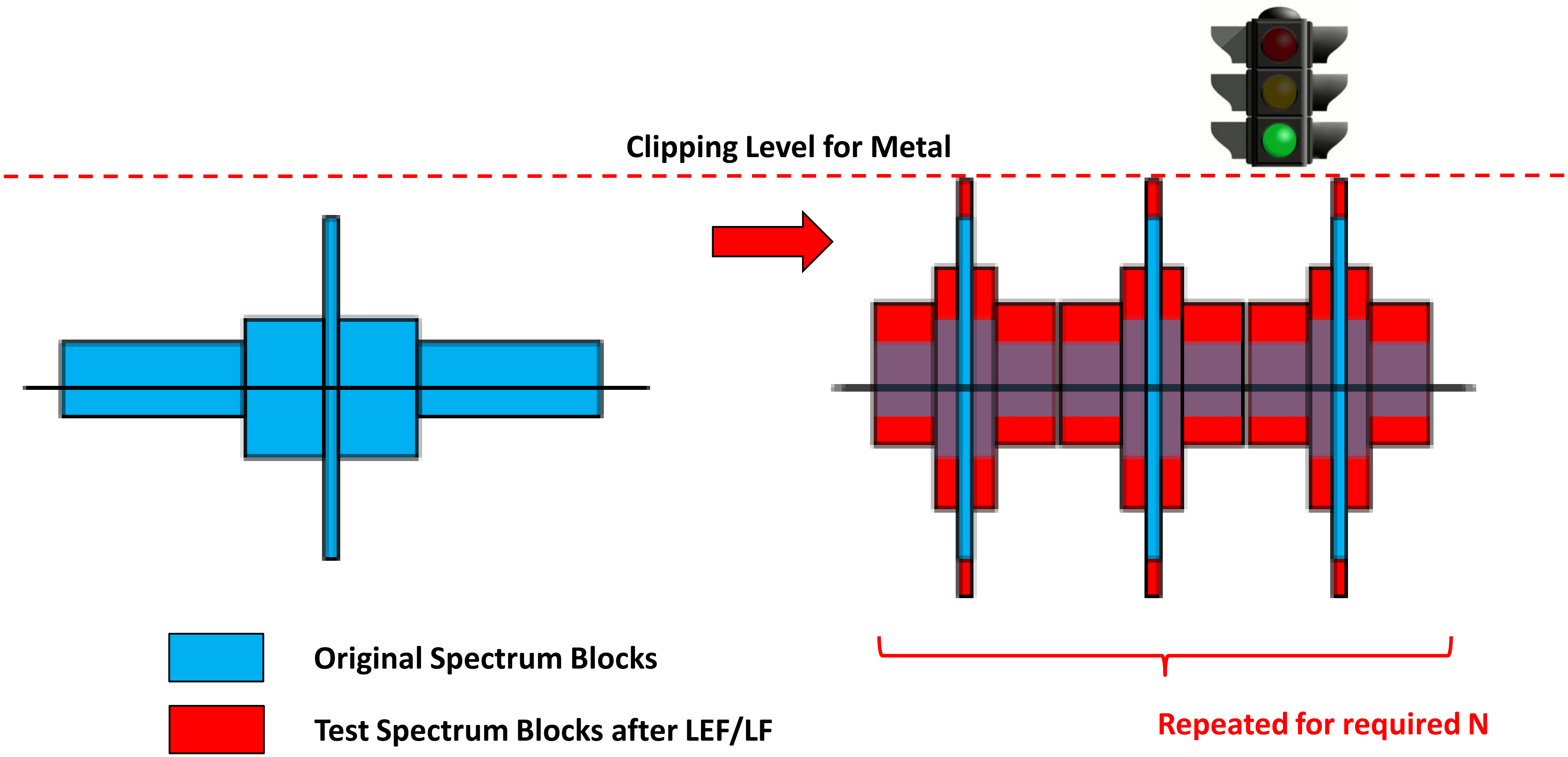



# Load-Life Combined (LEF) Approach

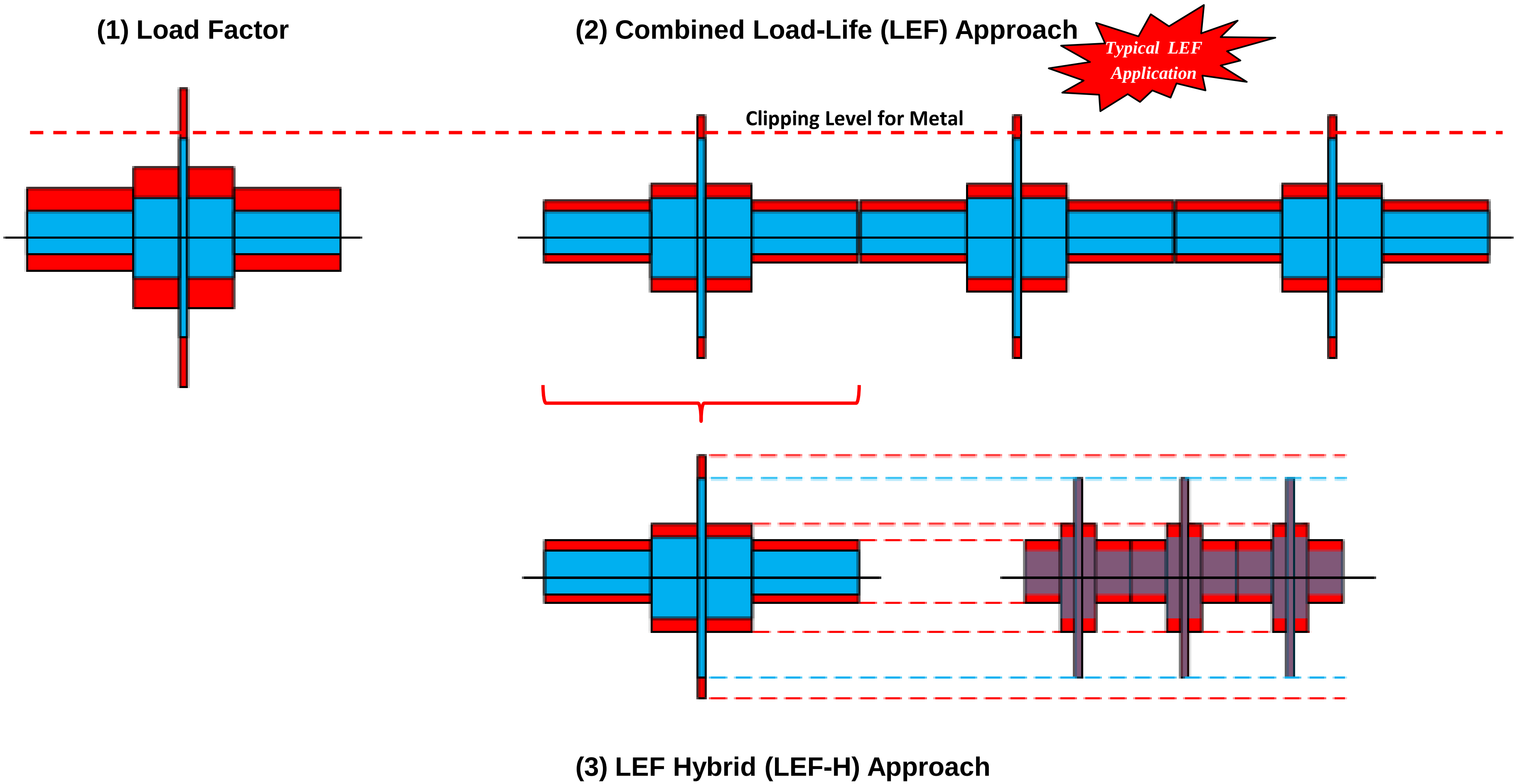


# Load-Life Hybrid (LEF-H) Approach




Spread high load cycles throughout the spectrum (may require additional crack growth analysis for hybrid structures)

# Hybrid (Load-Life) Approach for Hybrid (Composite-Metal) Structures



# Certification of Hybrid Structures

- **Two separate fatigue test articles each focusing metal and composite spectrums**
  - Time consuming and costly
- **Pre-production subcomponent repeated load tests primarily focusing composite structure certification and full-scale test repeated load test focusing metal structure certification**
  - Multiple test articles ➔ time consuming and costly
- **Replace failed metallic part during repeated load test**
  - May not be applicable for metallic driven design
  - Load redistribution due to wide-spread fatigue damage (WFD), i.e., multiple-site damage (MSD) or multiple element damage (MED) scenarios may not be representative
  - Time consuming and costly
  - **Stiffening (reinforce) metal members may cause uncharacteristic load redistribution**
- **Hybrid citification approach using single article initial phase with low or no LEF focusing metallic structure certification and apply LEF for the second phase**
  - Use of ***Load-Life Shift*** to calculate equivalent certified life accounting for the complete test duration for composite
  - Economical and reduce the total required test duration

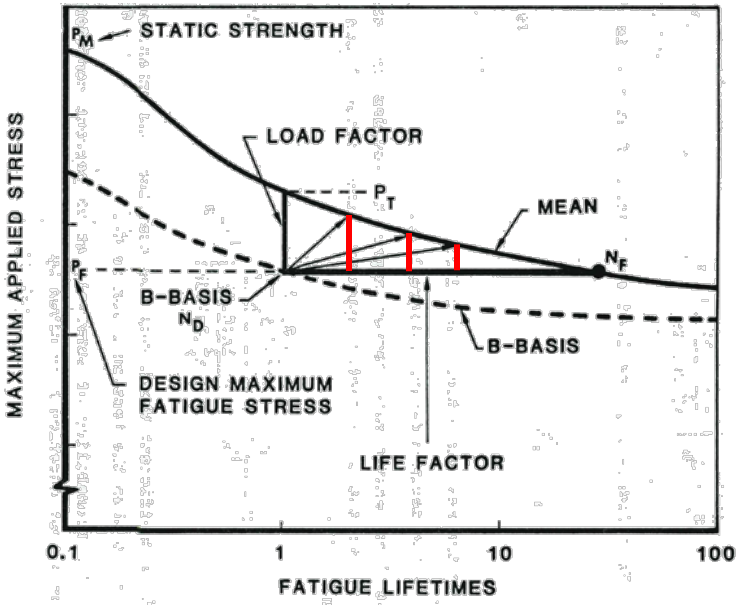
# Load-Life Shift

- Provides a mechanism to obtain credit for the loads applied during first phase (focusing metal) so that the test duration for the composite certification phase can be reduced.

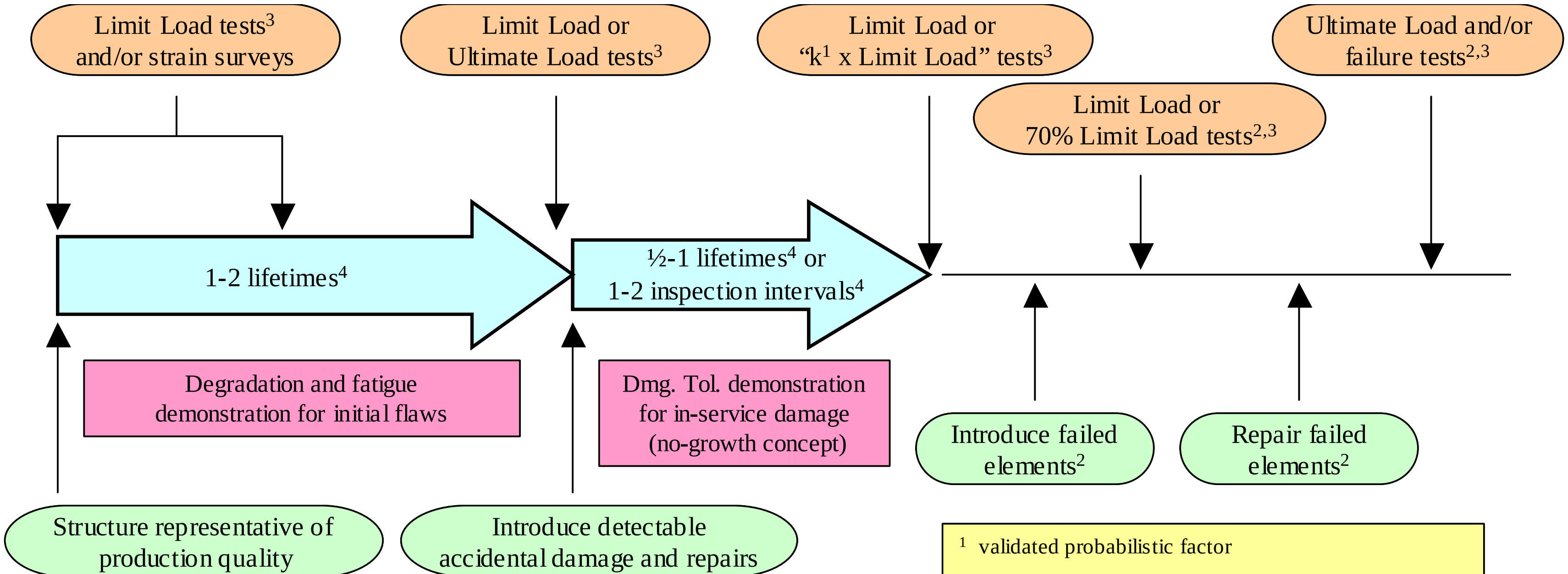
$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

- Simplified version:

$$N_2^T = \left(1 - \frac{N_1^T}{N_1^R}\right) \cdot N_2^R$$



# Full-Scale Test Sequence
# [Typical Transport Aircraft]




[1] validated probabilistic factor

[2] one element at a time, cut, tested to LL or 70% LL, repaired, tested to UL

[3] multiple load cases (including combined), depending on component

[4] with appropriate LEF applied

**Ref: CMH-17**

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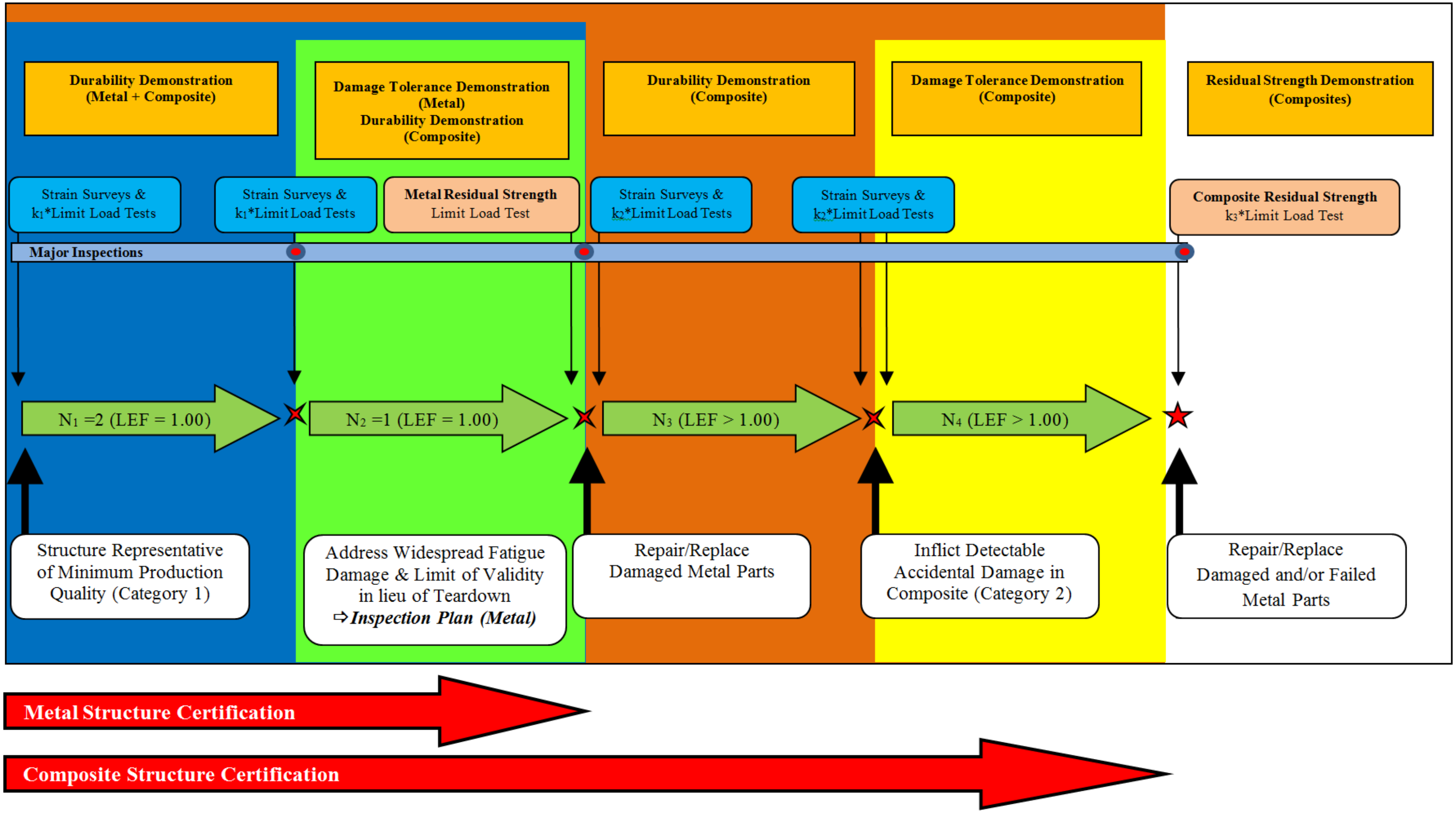
# Test Sequence for Full-Scale Test Substantiation via Load-Life Shift Hybrid Approach




**Load-Life Shift:**

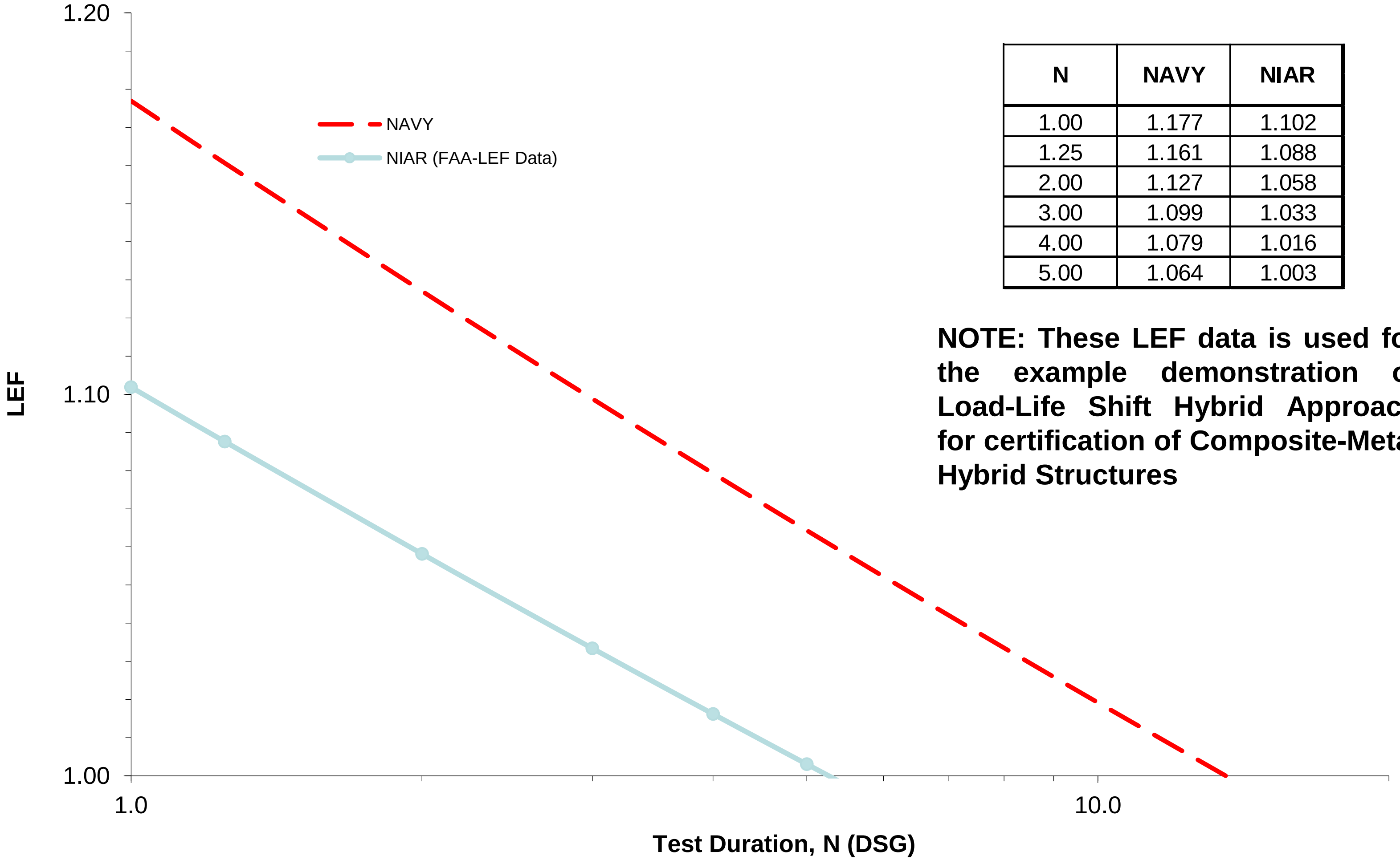
$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

# Load-Life Shift (LLS) Approach

- One durability test article through Load-Life Shift Approach for Hybrid (Composite-Metal) Structures
  - Application of life factor to high loads ensure the reliability for the most critical load levels (for composites)
  - Apply high LEF to reduce the time on low stress cycles
  - Require fatigue analysis of metal structure to alleviate undesirable impacts on metal part
  - 3 DSG for metal substantiation and then composite (credits given to composite cycles during 3 DSGs per Load-life Shift Method)
  - High loads required for composite structure that are above clipping level (prior to applying LEF) can be applied in Phase 2
  - **LLS approach provides a mechanism 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**

**➔ Significant time and cost savings**

# Load-Enhancement Factor Curve
## (Example: NIAR FAA-LEF Data)




| N | NAVY | NIAR |
|---|---|---|
| 1.00 | 1.177 | 1.102 |
| 1.25 | 1.161 | 1.088 |
| 2.00 | 1.127 | 1.058 |
| 3.00 | 1.099 | 1.033 |
| 4.00 | 1.079 | 1.016 |
| 5.00 | 1.064 | 1.003 |

**NOTE: These LEF data is used for the example demonstration of Load-Life Shift Hybrid Approach for certification of Composite-Metal Hybrid Structures**

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# Composite Certification Phase with Load-Life Shift

Example ONLY!

- Load-Life Shift Test Requirements in Composite Phase *(after 3 DLT test with LEF=1 for Metal Certification Phase)*

  - NAVY Data

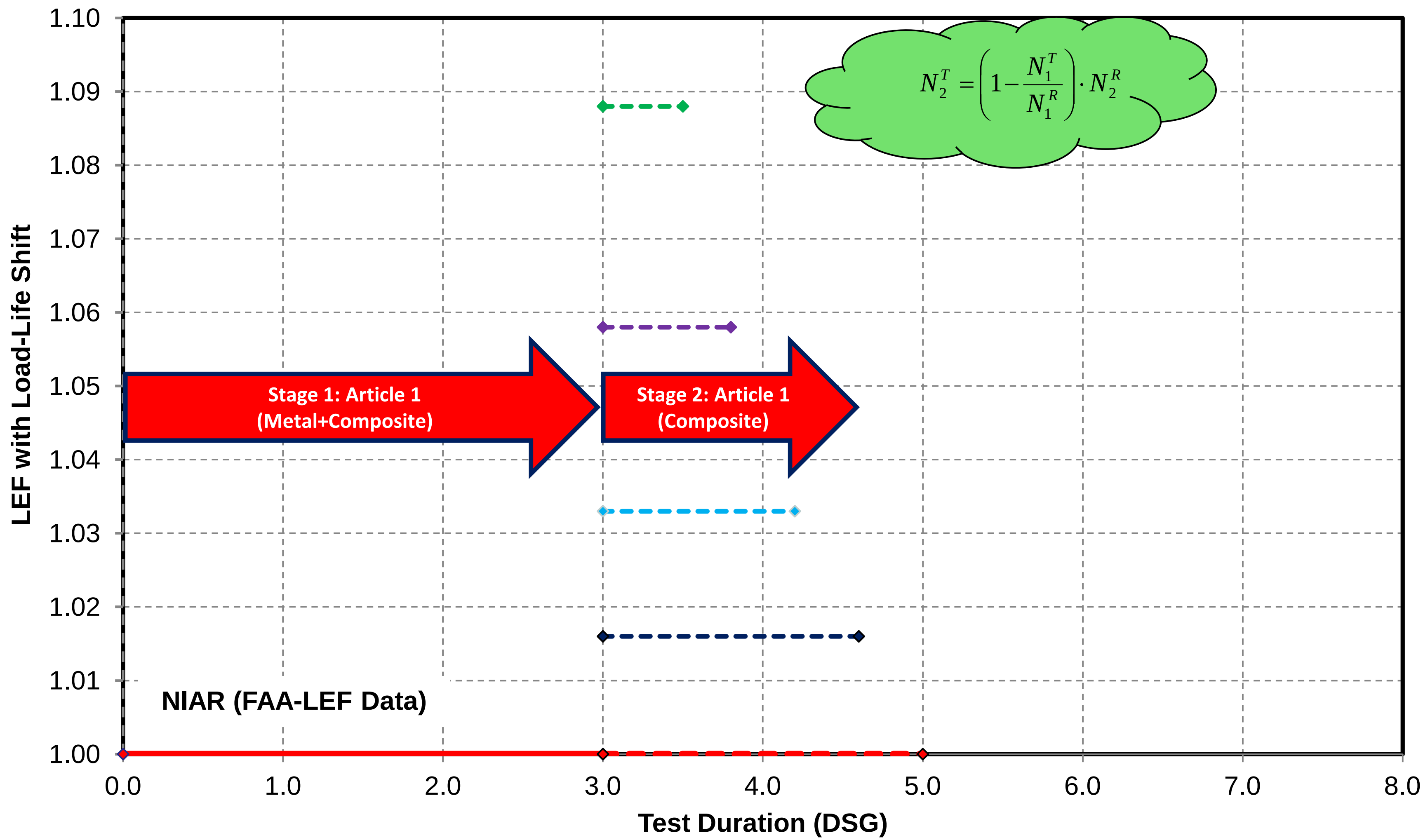
| Option | LEF | Required Test Duration without LLS | Required Test Duration with LLS | Total Test Duration |
|---|---|---|---|---|
| 1 | 1.000 | 14.0 | 11.0 | **14.0** |
| 2 | 1.019 | 10.0 | 4.0 | **7.0** |
| 3 | 1.052 | 6.0 | 2.4 | **5.4** |
| 4 | 1.079 | 4.0 | 1.6 | **4.6** |
| 5 | 1.127 | 2.0 | 0.8 | **3.8** |

  - NIAR Data

| Option | LEF | Required Test Duration without LLS | Required Test Duration with LLS | Total Test Duration |
|---|---|---|---|---|
| 1 | 1.000 | 5.0 | 2.0 | **5.0** |
| 2 | 1.016 | 4.0 | 1.6 | **4.6** |
| 3 | 1.033 | 3.0 | 1.2 | **4.2** |
| 4 | 1.058 | 2.0 | 0.8 | **3.8** |
| 5 | 1.088 | 1.3 | 0.5 | **3.5** |

# LLS Hybrid Certification for Metal-Composite Hybrid Structures

Example ONLY!

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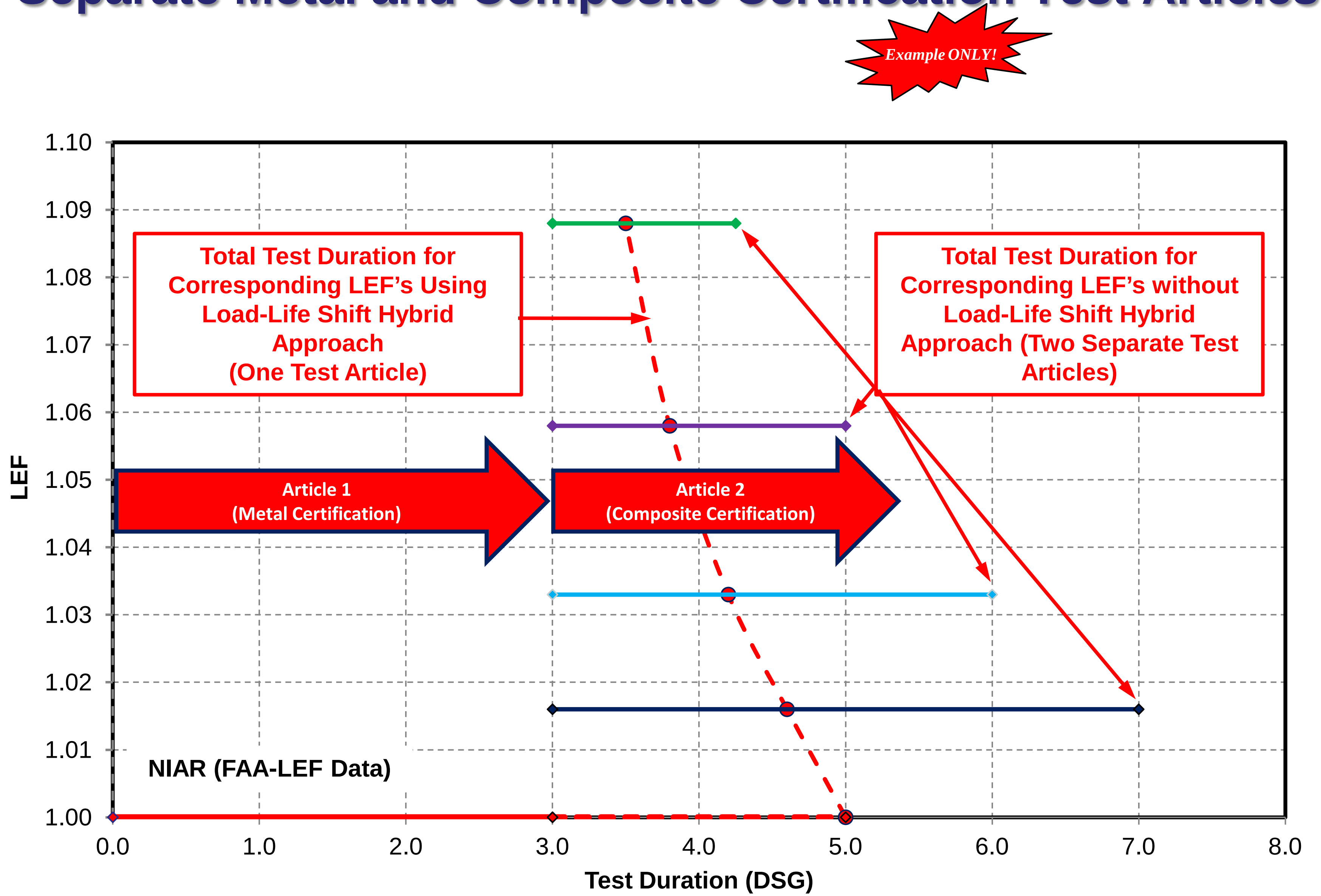
# Separate Metal and Composite Certification Test Articles



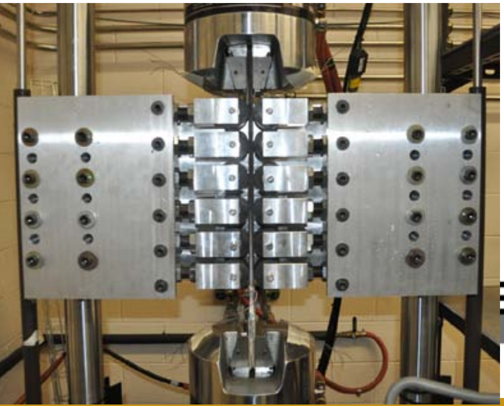
# BUILDING-BLOCK OF TESTING

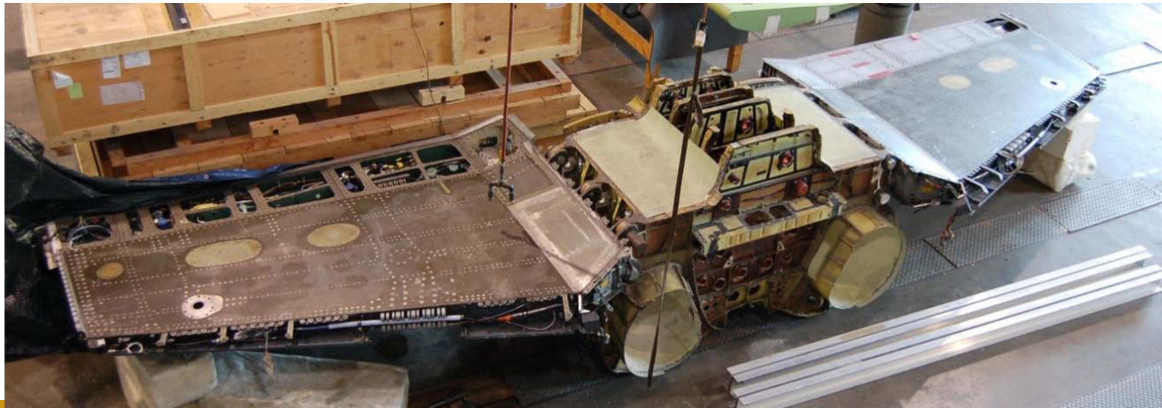
Metal/Composite Specimen Testing

Hybrid Splice joint

F/A-18 Bonded Step-Lap Joint

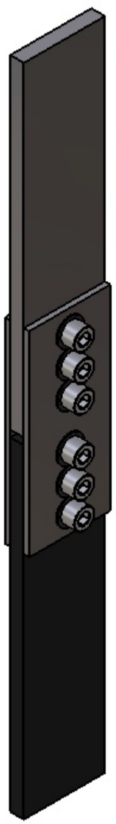
F/A-18 Full-Scale Fatigue Test





# Composite-Metal hybrid Element Testing

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

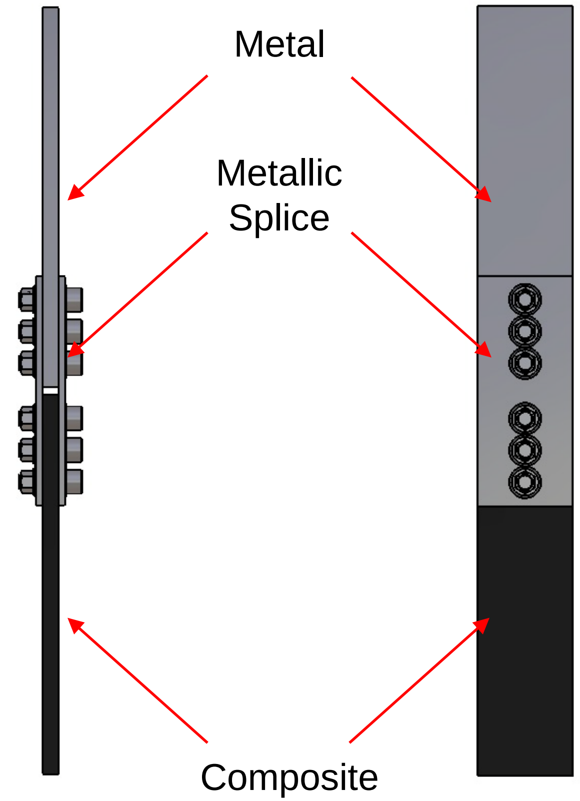


*Damage Growth in Metals* ✓

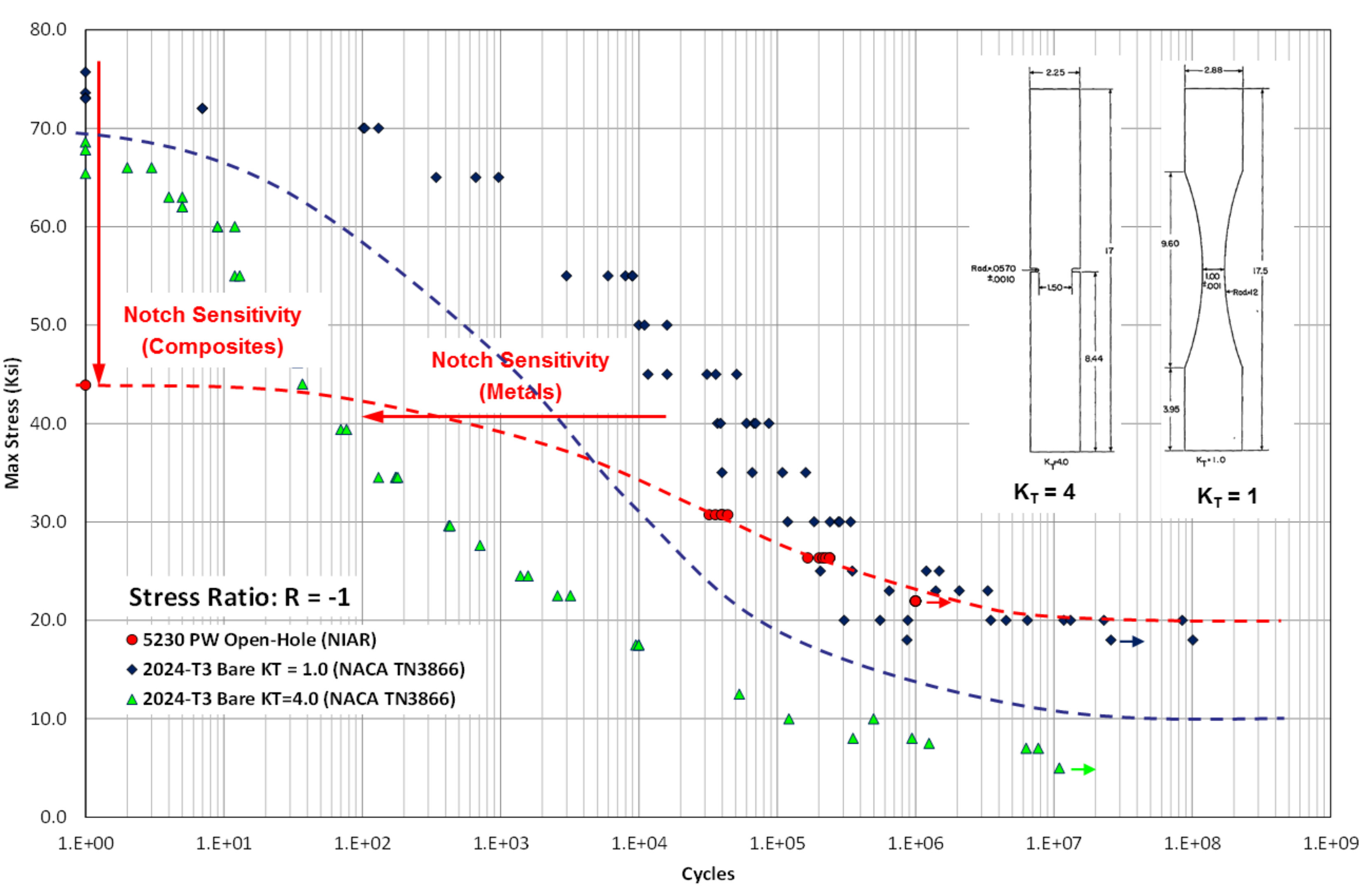
*Damage Growth in Composites* ✓

*Damage Growth in Hybrids* ?

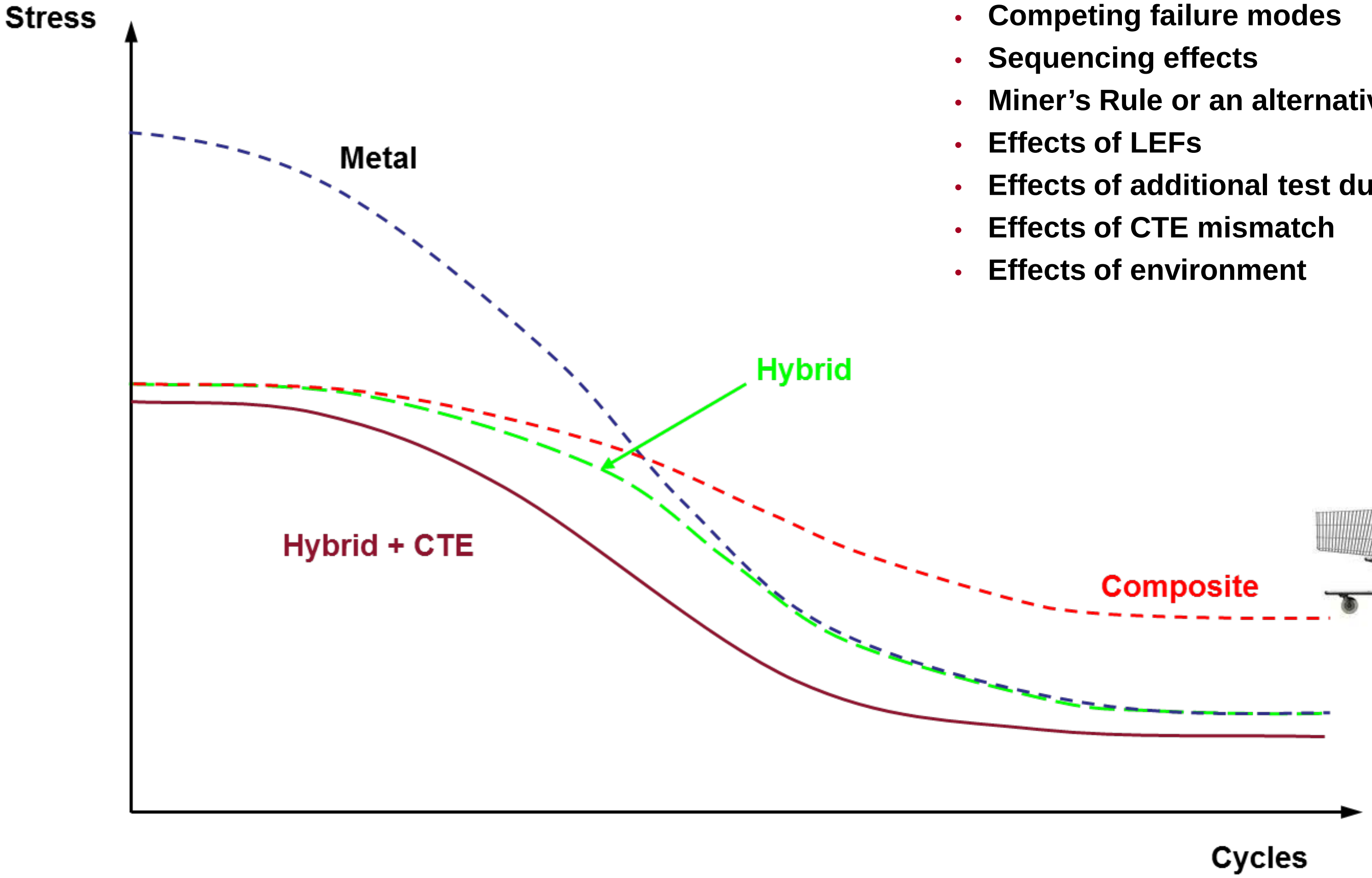
- **Competing failure modes**
- **Sequencing effects**
- **Miner's Rule or an alternative (???)**
- **Effects of LEFs**
- **Effects of additional test duration**
- **Effects of CTE mismatch**
- **Effects of environment**



# Composite-Metal Fatigue Data



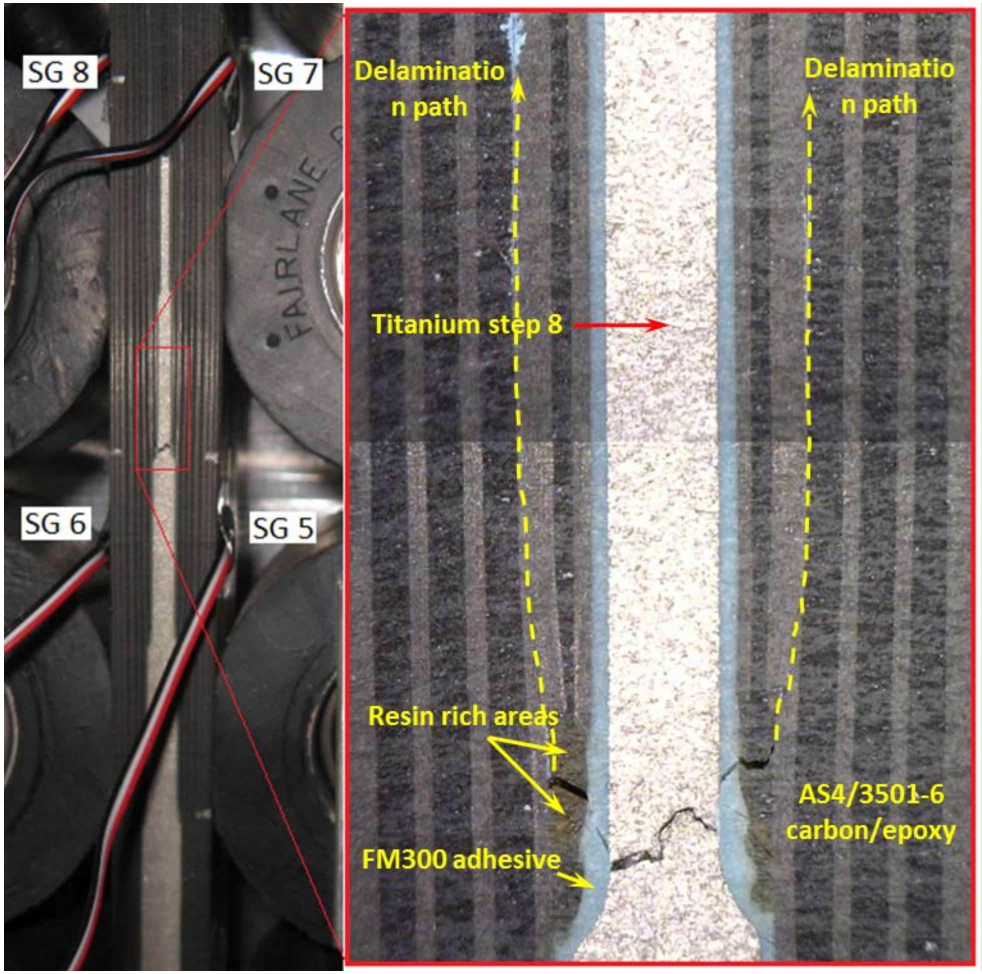
# Composite-Metal Fatigue Data with CTE Effects

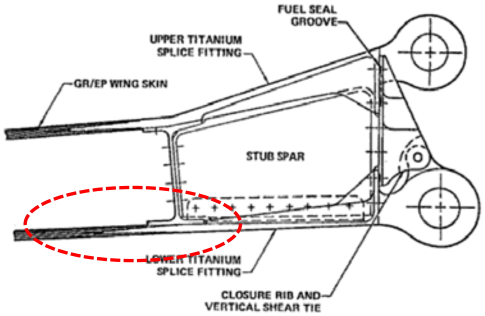



- Competing failure modes
- Sequencing effects
- Miner’s Rule or an alternative (???)
- Effects of LEFs
- Effects of additional test duration
- Effects of CTE mismatch
- Effects of environment

# Progressive Failure on F/A-18 Composite-Titanium Step-Lap Joint

- large delaminations initiated around the areas where titanium fatigue cracks formed
- Presence of microcracks in resin rich areas and adhesive
- Even though the titanium has failed across the step 8 and large delaminations were present, these specimens were able to transfer the fatigue loads across the remainder of the stepped-lap joint for a significant number of fatigue cycles.
  - The load redistribution noticeably overloaded the reminder of the titanium section and caused the final failure.

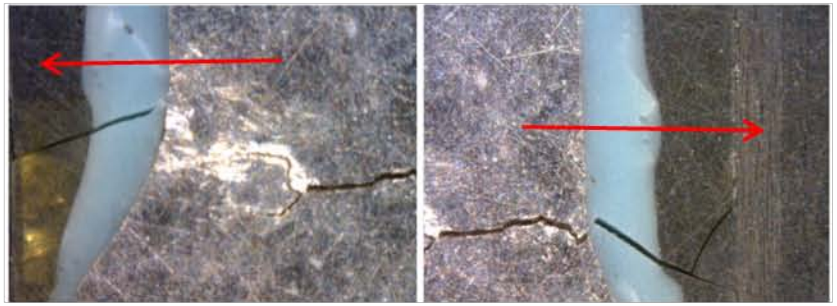



Ref: Seneviratne, *et. al.,* **Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint,** 11th AIAA ATIO Conference, AIAA Centennial of Naval Aviation Forum, Sept., 2011.

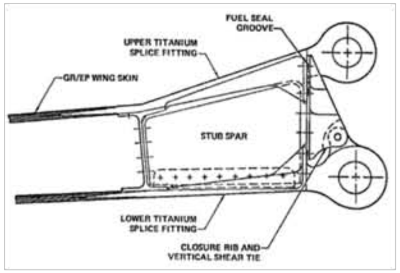
# Progressive Failure on F/A-18 Composite-Titanium Step-Lap Joint

## No-Hole



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

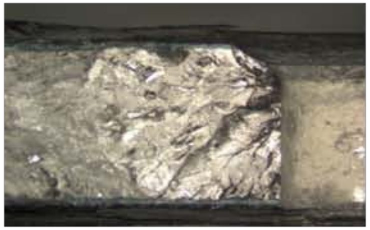
(b) Failure surface –OML side



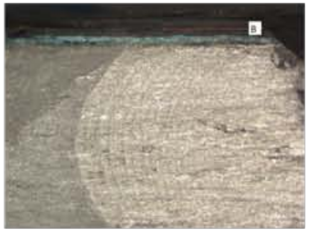

(c) Failure surface –IML side

## Open-Hole

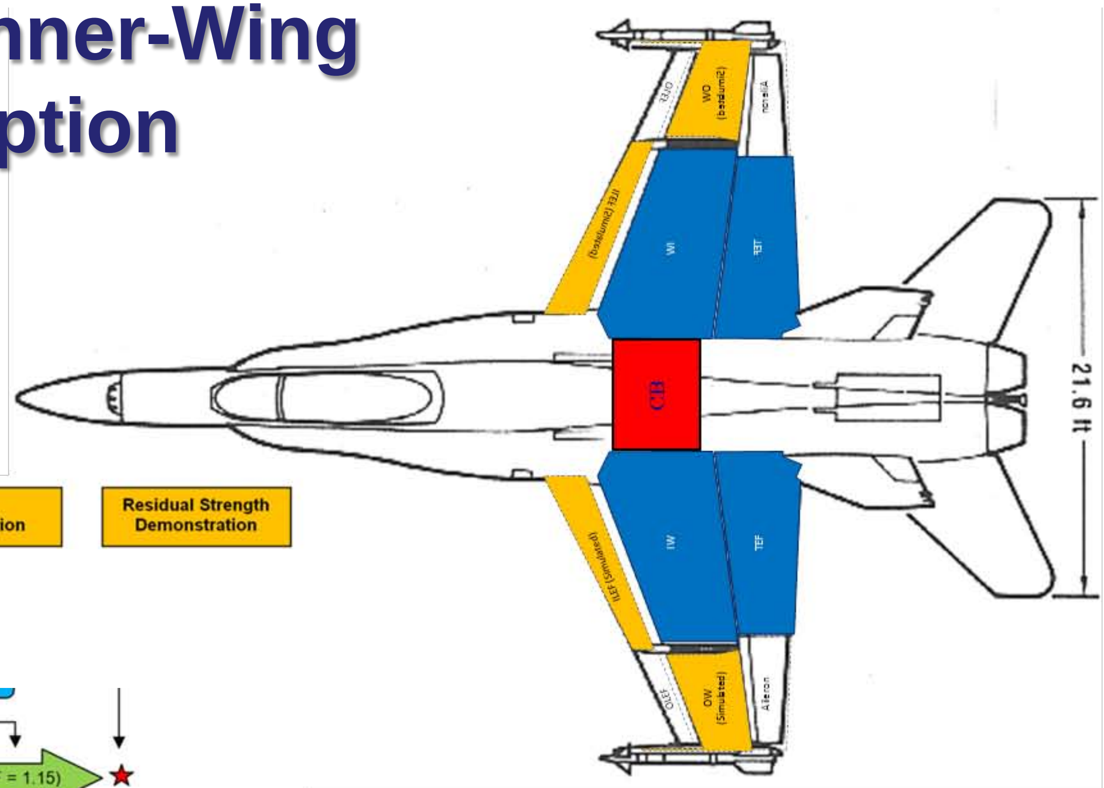
### Unstable Crack Growth

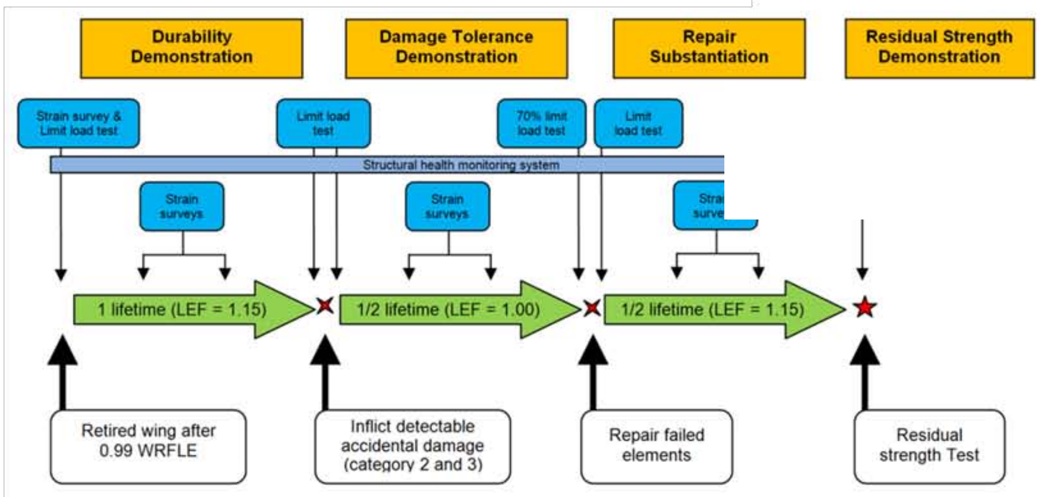



### Stable Crack Growth



# Full-Scale F/A-18 Inner-Wing Test Article Description




# Summary

- **One durability test article for Hybrid (Composite-Metal) Structures**
  - **Load-Life Hybrid (LEF-H) Approach**
    - Application of life factor to high loads ensure the reliability for the most critical load levels (for composites)
    - Apply high LEF to reduce the time on low stress cycles
  - **Load-Life Shift (LLS) Approach**
    - provides a mechanism 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

➔ **Significant time and cost savings**

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# Looking Forward

- **Benefit to Aviation**
  - 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.
    - Guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.
    - Damage mechanics and competing failure modes (origination and propagation)
    - Guidance for hybrid load spectra and application LEF

- **Future needs**
  - Representative test articles
  - Guidance on spectrum development

# Notes

- **Contact (Waruna Seneviratne):**
  - waruna@niar.wichita.edu
  - Ph: 316-978-5221

- **References:**

  - Tomblin, J and Seneviratne, W., **Determining the Fatigue Life of Composite Aircraft Structures Using Life and Load-Enhancement Factors,** DOT/FAA/AR-10/06, Federal Aviation Administration, National Technical Information Service, Springfield, VA, 2010.
  - 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, 2013.
  - Whitehead, R. S., Kan, H. P., Cordero, R., and Seather, E. S., **Certification Testing Methodology for Composite Structures,** Report No. NADC-87042-60, Volumes I and II, October, 1986.

# End of Presentation.

# Thank you.

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