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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

2014 Technical Review

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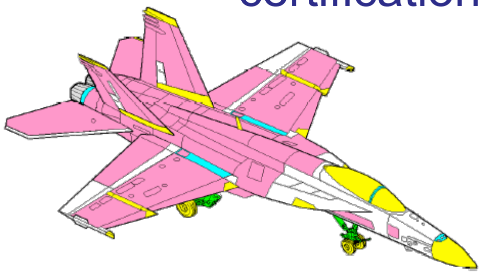
Wichita State University/NIAR

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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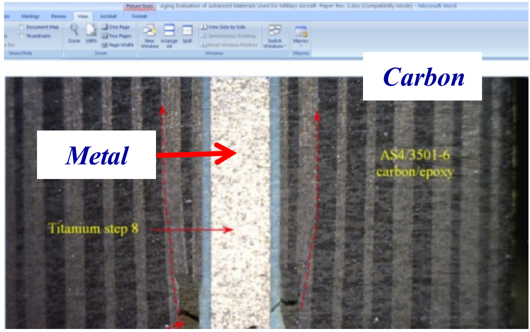
Certification of Composite-Metal Hybrid Structures

- **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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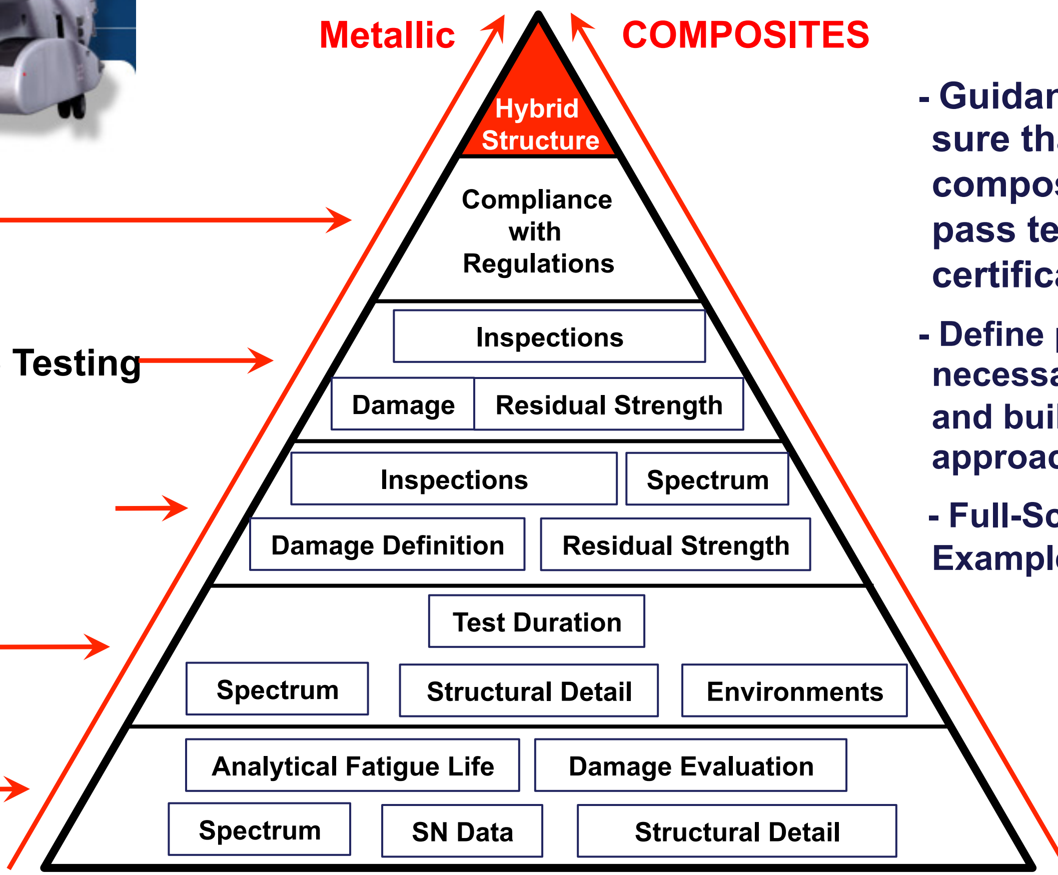
Approach



Certification

Damage Tolerance Testing

Damage Tolerance Analysis

Fatigue Testing

Fatigue Analysis

- 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

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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

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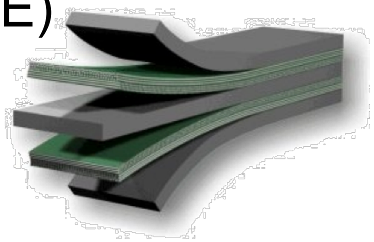
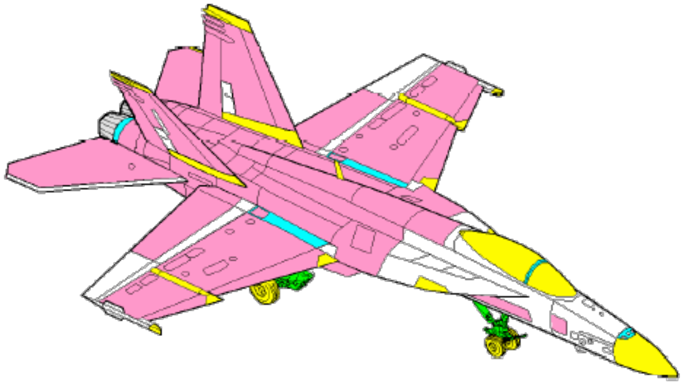
Definitions

- Hybrid Materials – Composite-Metal Laminates
    - Glass Laminate Aluminum Reinforced Epoxy (GLARE)
    - Aramid aluminum laminate (ARALL)
    - Titanium graphite composite (TIGR)



- Hybrid Laminates – fabric/tape, glass/carbon, etc.
- Hybrid Structures – carbon skins bolted to metal substructure; glass skins bonded to carbon spars, etc.



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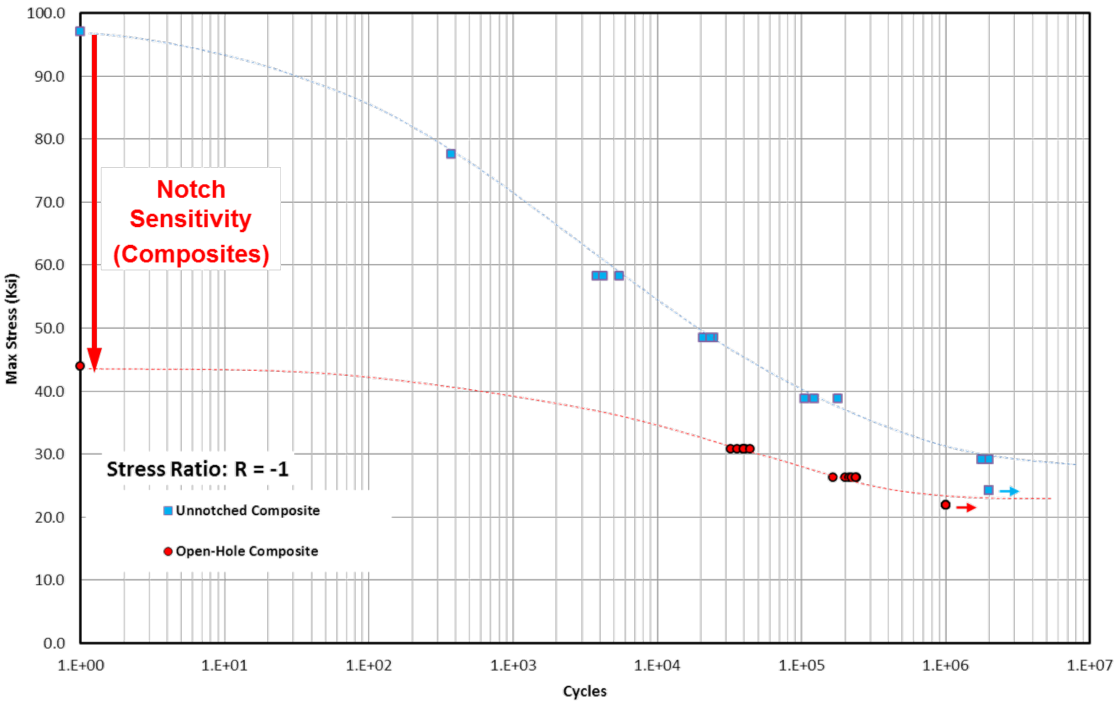
Composite Notch Sensitivity & Fatigue Threshold



- High notch sensitivity at lower cycles
- Insensitive notch sensitivity at high cycles
- Fatigue threshold is unaffected

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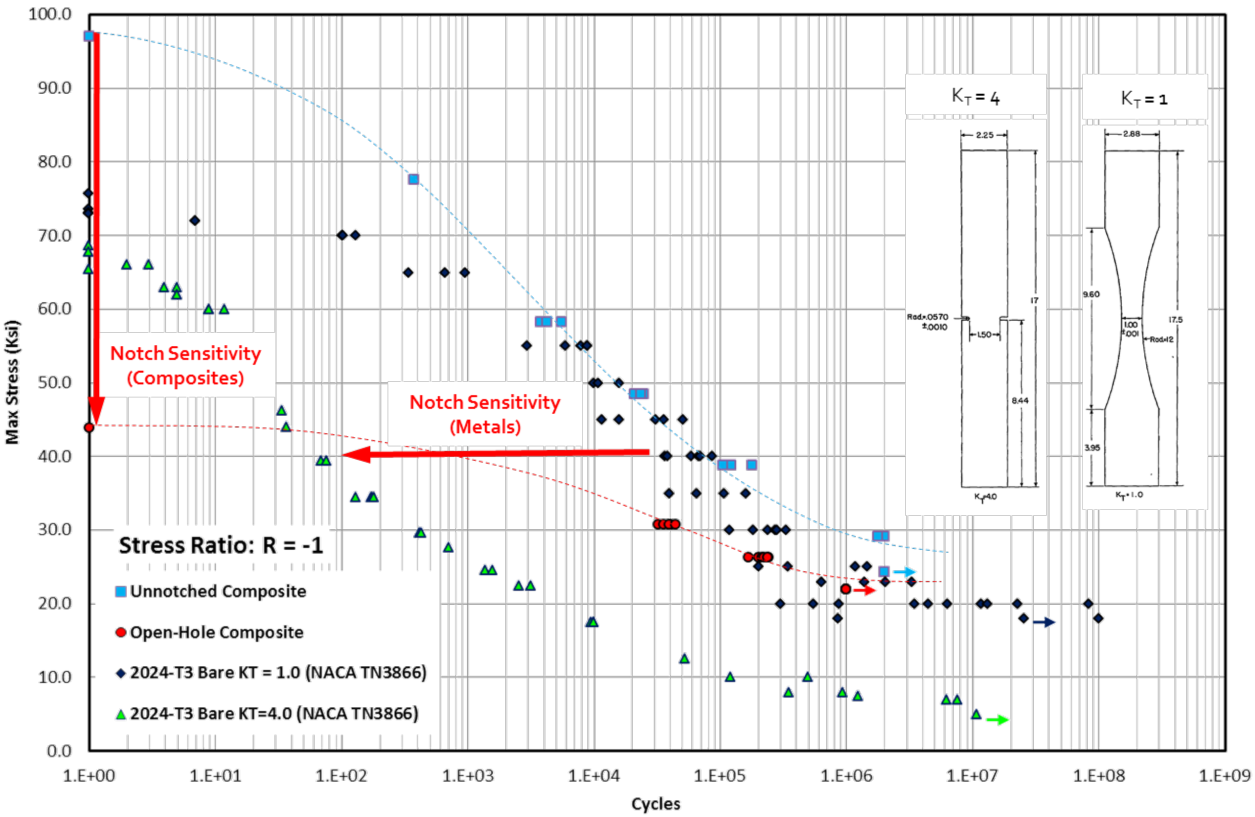
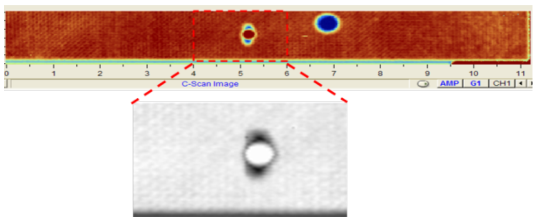
Composite vs. Metal - Sensitivity



Open Hole 25/50/25 Out-of-Autoclave Material

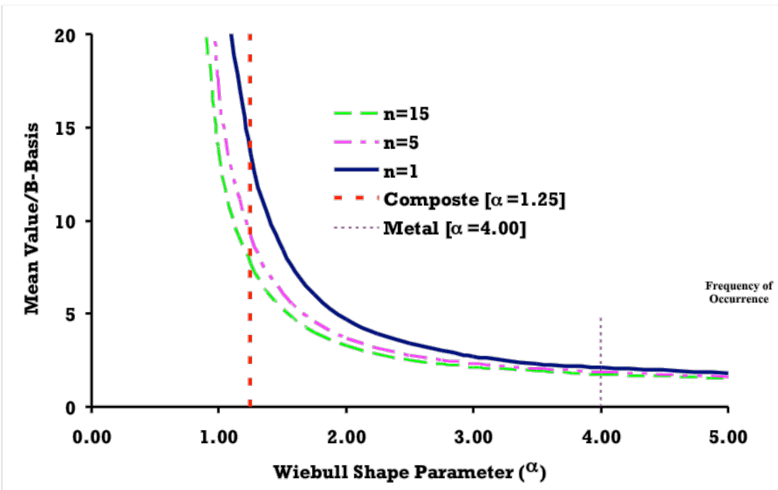
- R=5
- Stress Level: 50% of Mean Static (~25 ksi)
- Runout: After 25 million cycles @ *f*=5 Hz



Life Factor Approach

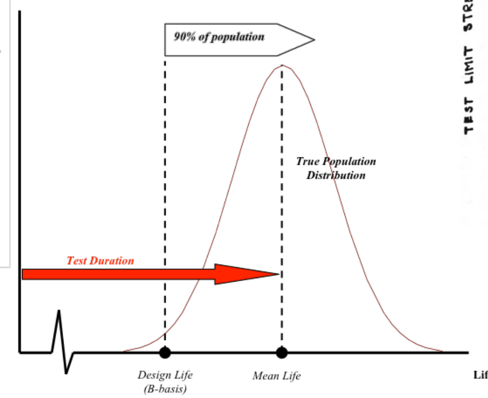
Structure is tested for additional fatigue life to achieve the desired level of reliability

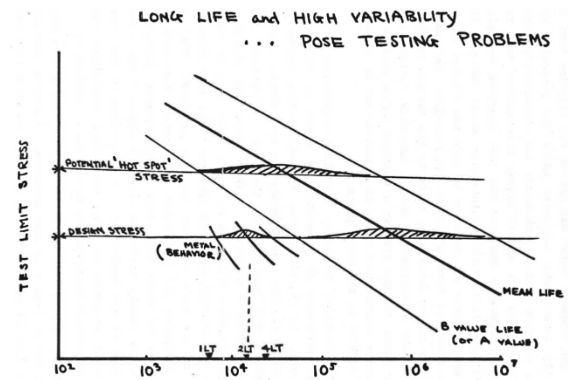
- Life Scatter Factor (LSF)



	n = 1	n = 5	n = 15
Composites Alpha = 1.25	13.558	9.143	7.625
Metals Alpha = 4.0	2.093	1.851	1.749

$$N_F = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left[\frac{-\ln(R)}{\left[\chi^2_\gamma(2n)/2n\right]}\right]^{1/\alpha_L}}$$





Ref: Dr. A. Someroff (1981), NAVAIR

Successful repeated load test to mean fatigue life (established by the scatter factor) demonstrates B-basis reliability on design lifetime

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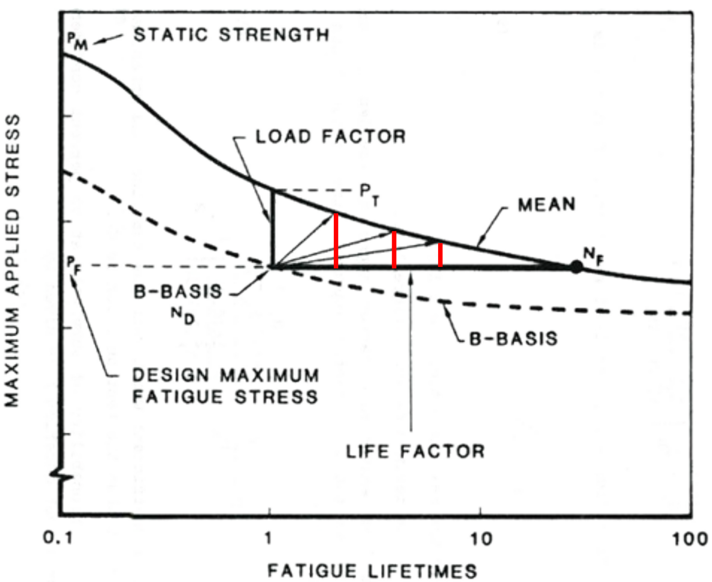
Load-Enhancement Factor (LEF) Approach

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**

Whitehead, et. al (NAVY/FAA research for F-18 certification)

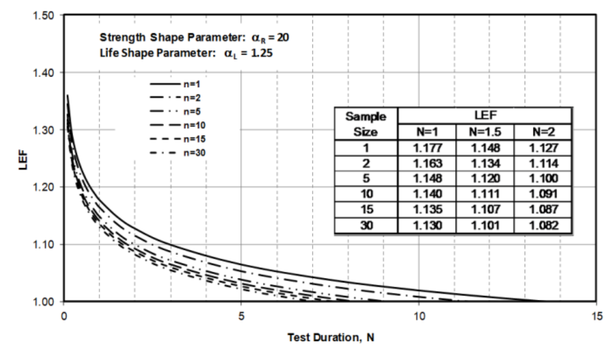


- Load Enhancement Factor (LEF)

$$LEF(N) = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)^{\alpha_L/\alpha_R}}{\left\{\frac{-\ln(R)\cdot N^{\alpha_L}}{\left[\chi_\gamma^2(2n)/2n\right]}\right\}^{1/\alpha_R}}$$

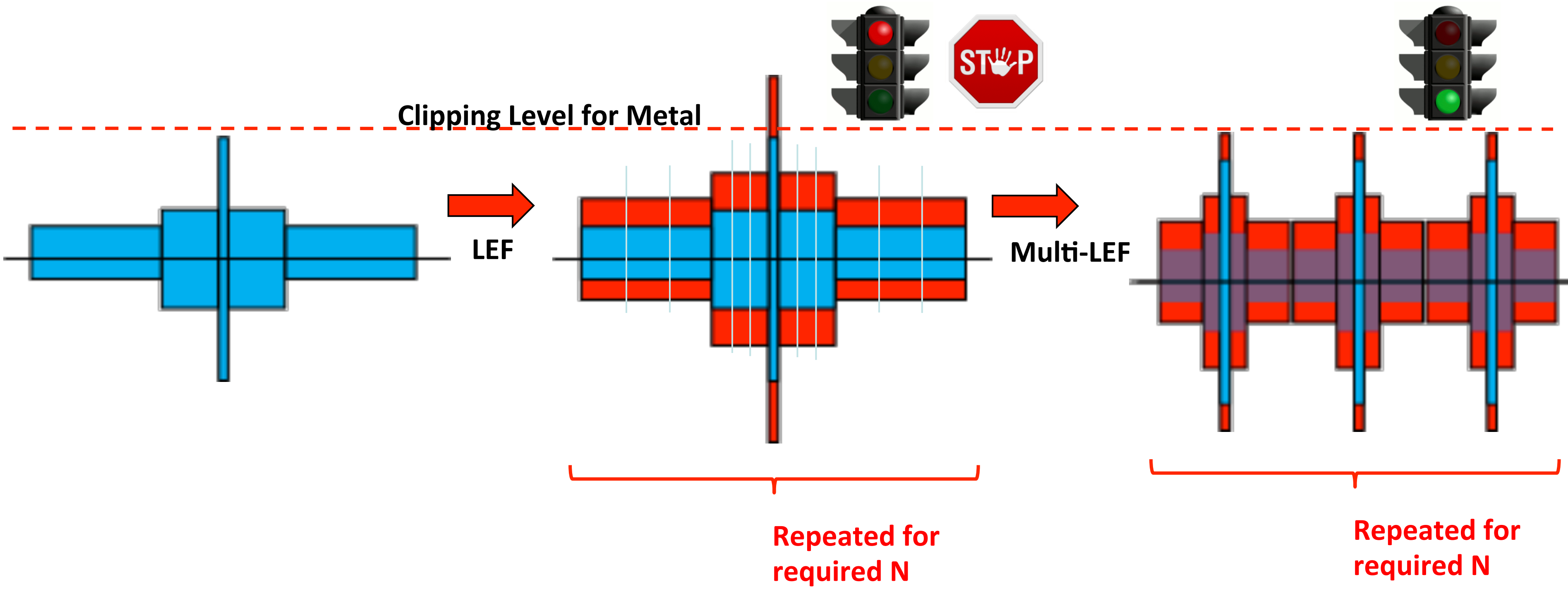
$$LEF(N) = \left(\frac{N_F}{N}\right)^{\frac{\alpha_L}{\alpha_R}}$$

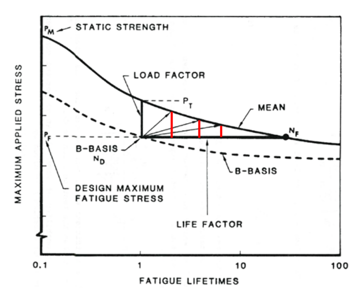
LEF is a function of the test duration



Sample Size	LEF		
	N=1	N=1.5	N=2
1	1.177	1.148	1.127
2	1.163	1.134	1.114
5	1.148	1.120	1.100
10	1.140	1.111	1.091
15	1.135	1.107	1.087
30	1.130	1.101	1.082

Multi-LEF Approach for Hybrid Structures





Original Spectrum Blocks

Test Spectrum Blocks after LEF

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

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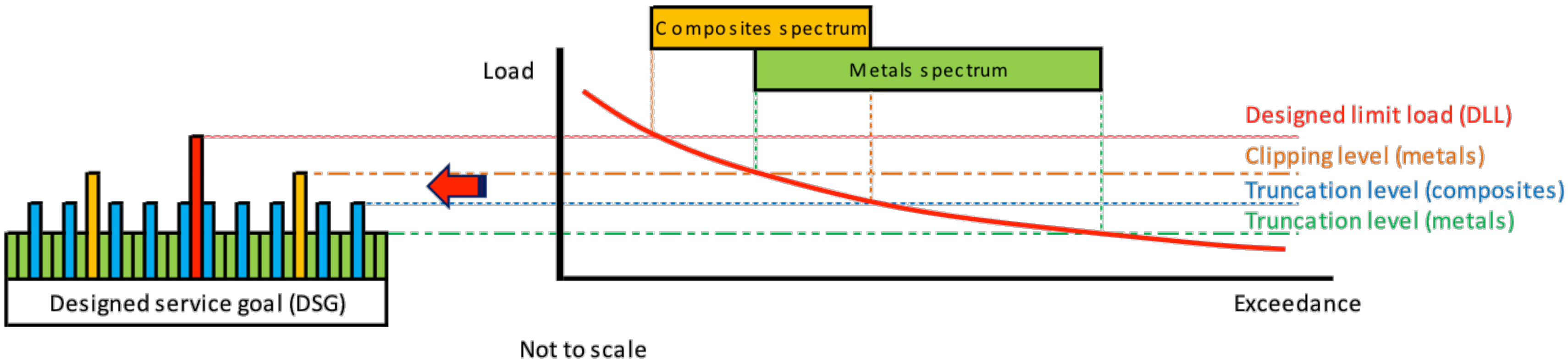
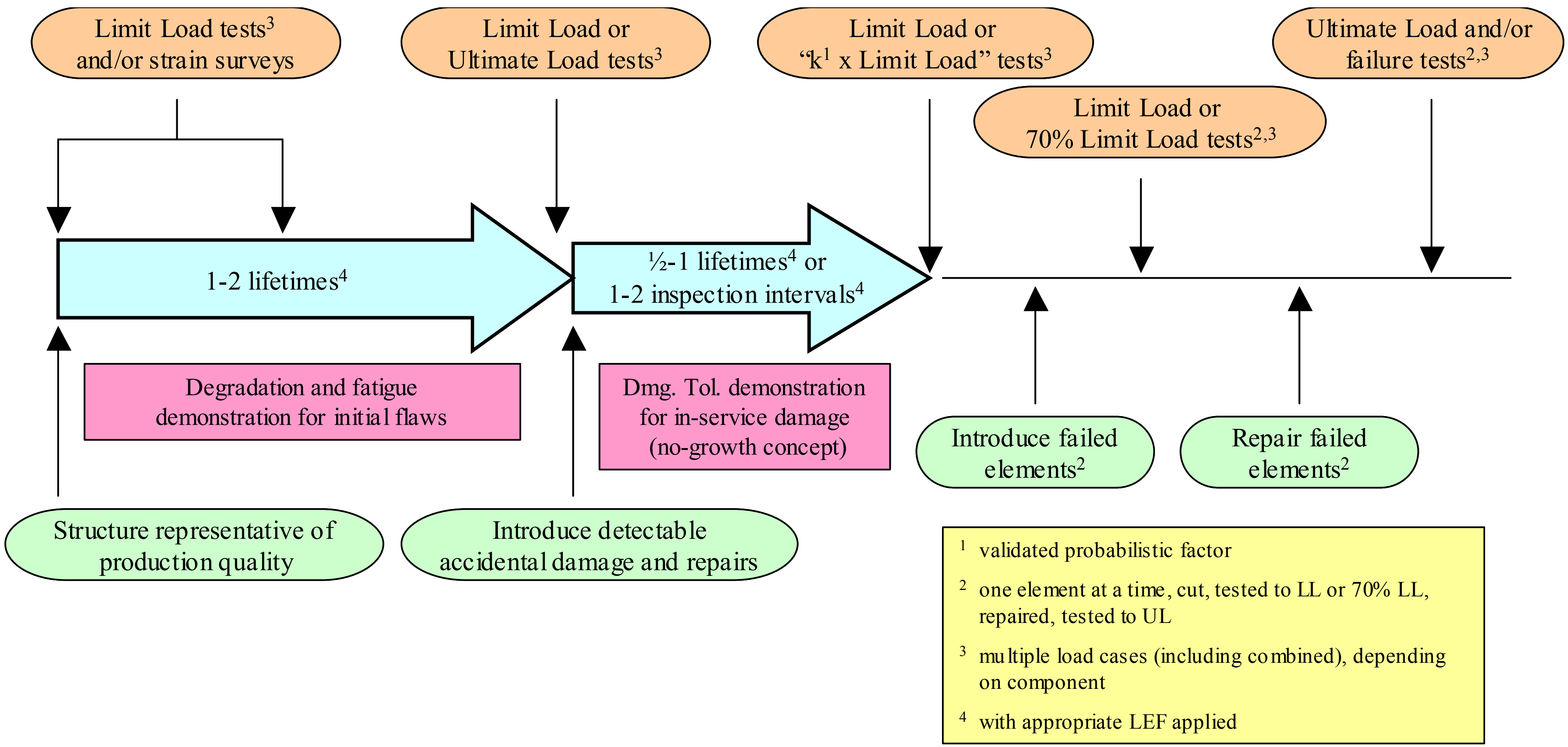
Development of Hybrid Spectrum



- Differences between composite and metallic spectrums
  - Metals (tension): severe flight loads result in crack-growth retardation ➔ Clipping
  - Composites (compression): 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

Full-Scale Test Sequence



Composite Materials Handbook (CMH-17)

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

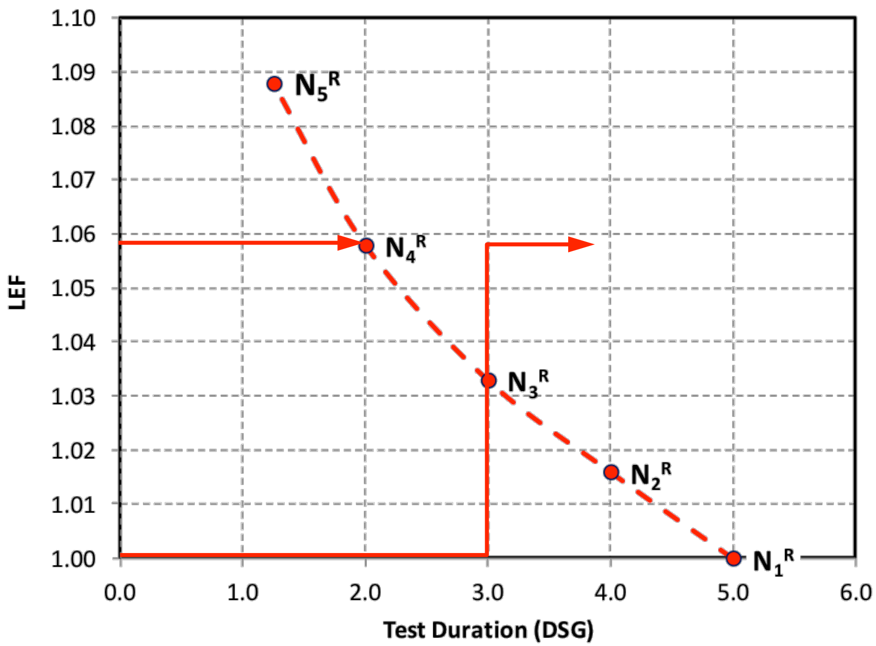
Load-Life Shift

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

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

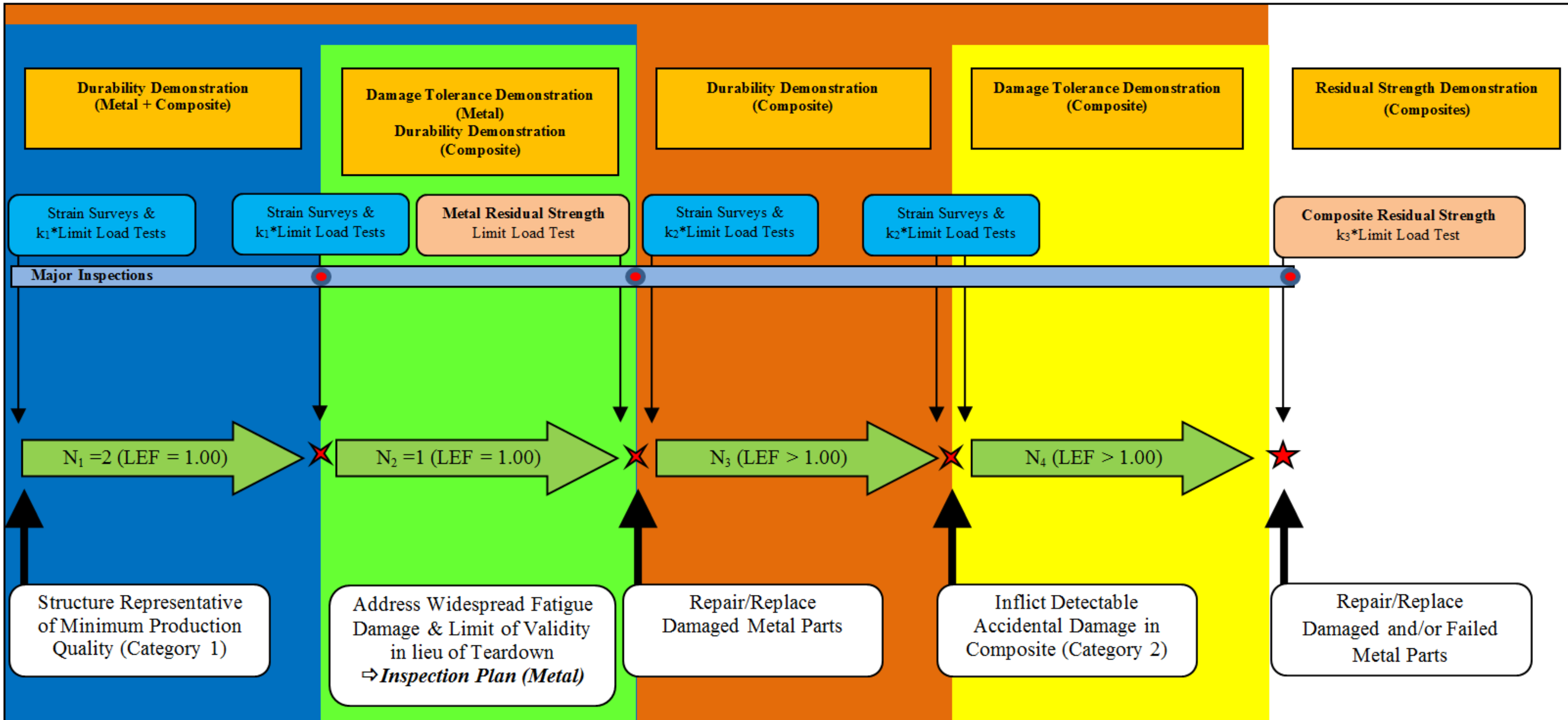
- Simplified (two-step) version:

$$N^T_2 = \left(1 - \frac{N^T_1}{N^R_1}\right) \cdot N^R_2$$



REF: Seneviratne, W. P., and Tomblin, J. S., "Certification of Composite-Metal Hybrid Structures using Load-Enhancement Factors," *FAA Joint Advanced Materials and Structures (JAMS)/Aircraft Airworthiness and Sustainment (AA&S),* Baltimore, MD, 2012.

Test Sequence for Hybrid Full-Scale Test Substantiation



Metal Structure Certification

Load-Life Shift:

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

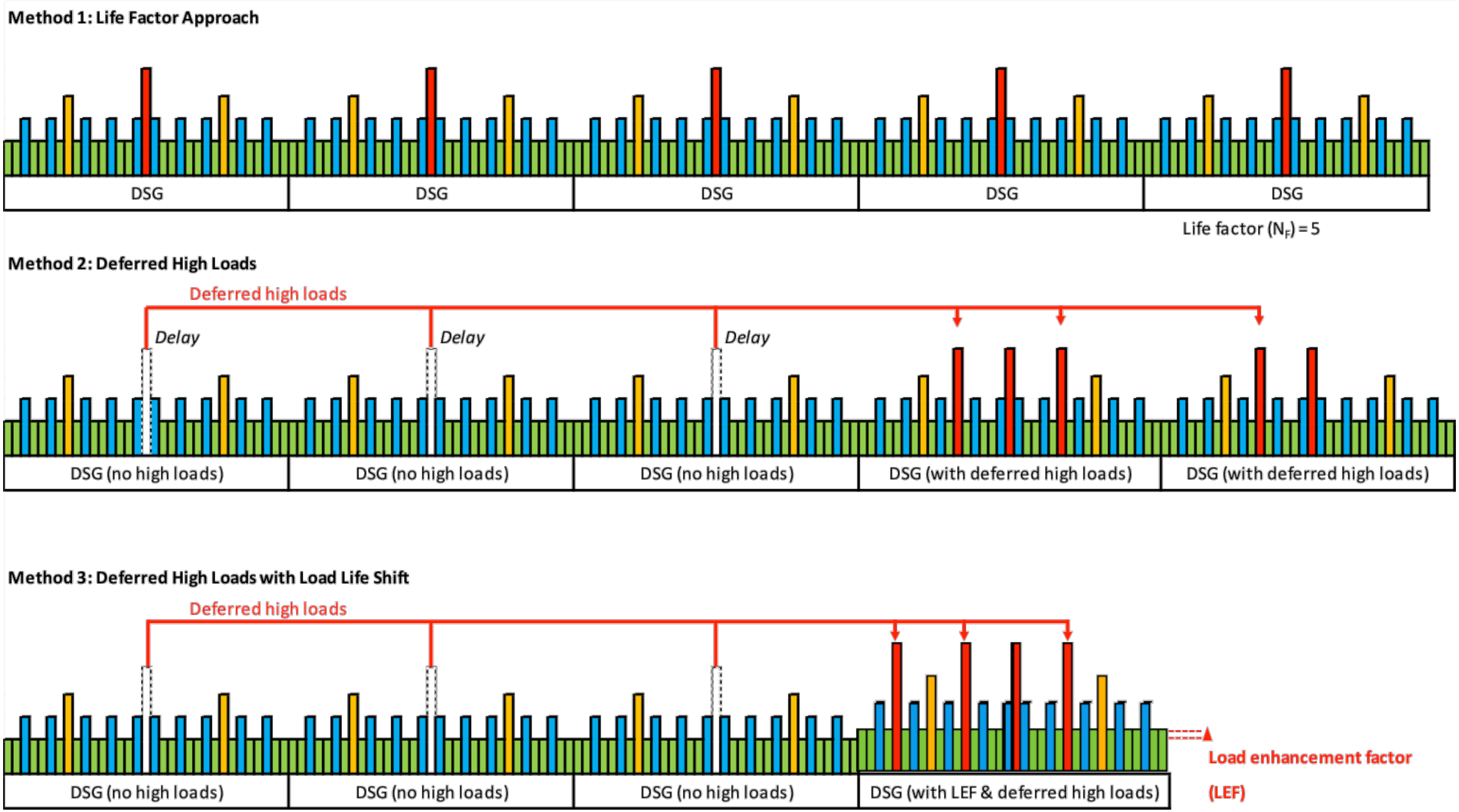
Composite Structure Certification

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

Application of Hybrid Spectrum



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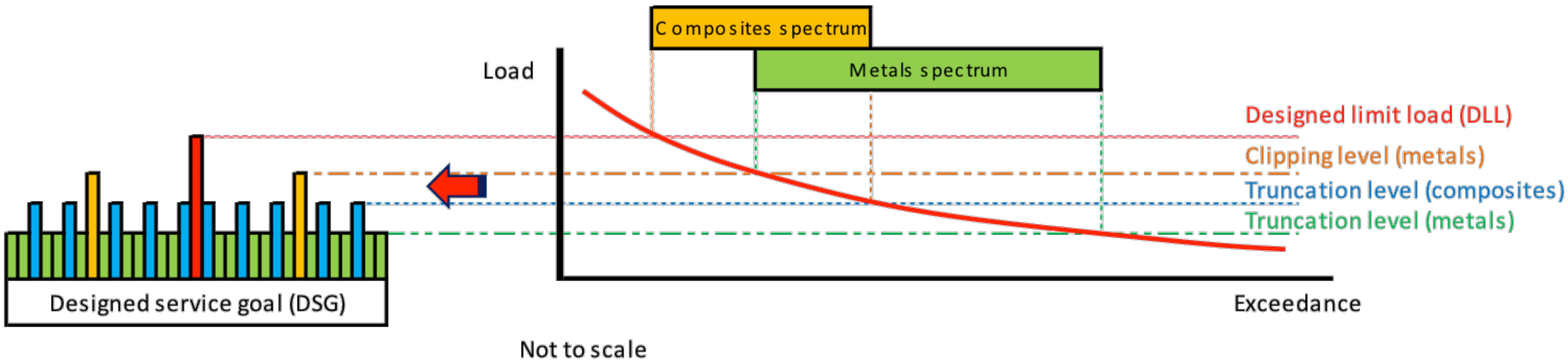
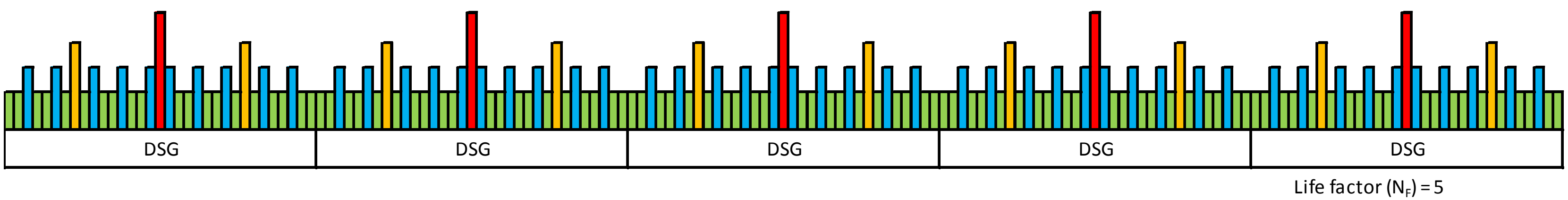
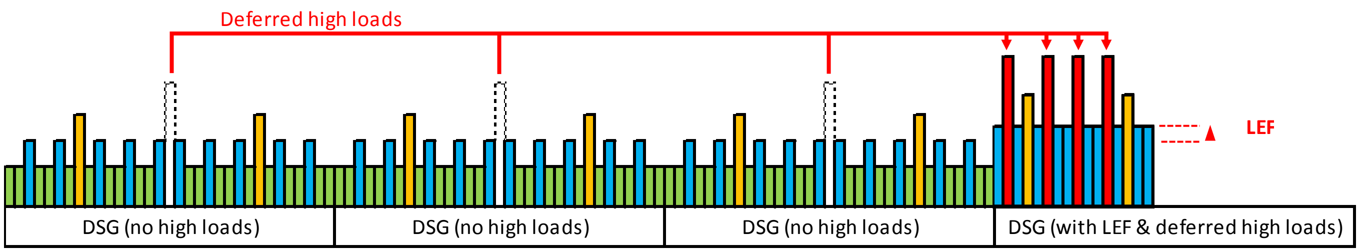
Application of Hybrid Spectrum



Method 1: Life Factor Approach



Method 3: Deferred High Loads with Load Life Shift (Composite Spectrum only)



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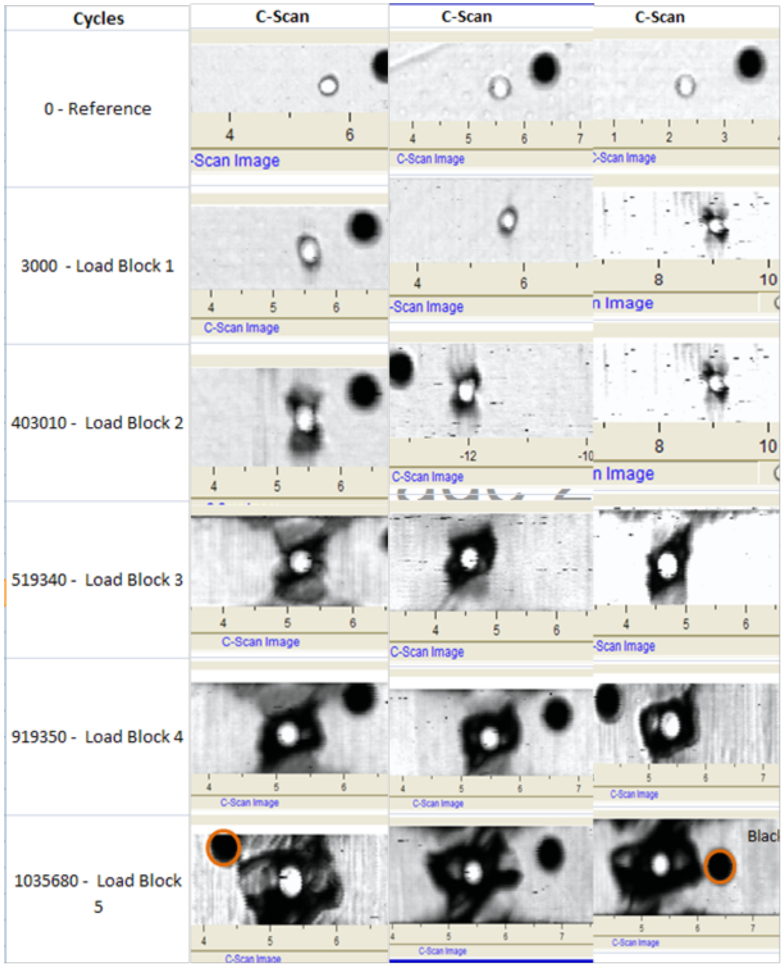
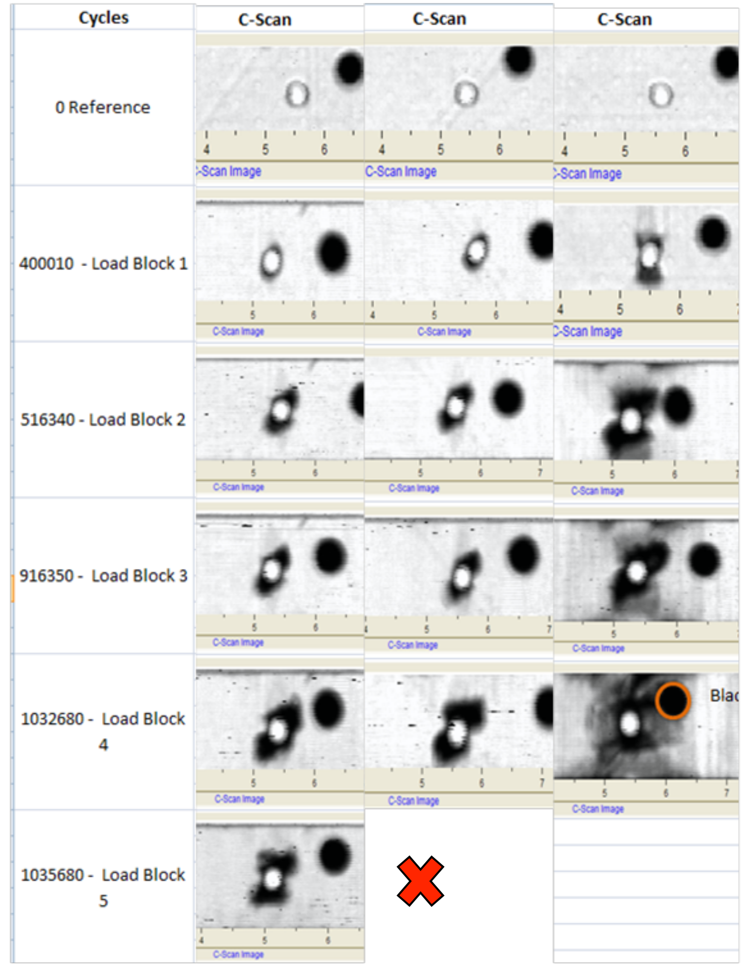
Load Sequencing Effects

70-40-55-40-55 (High-Low)



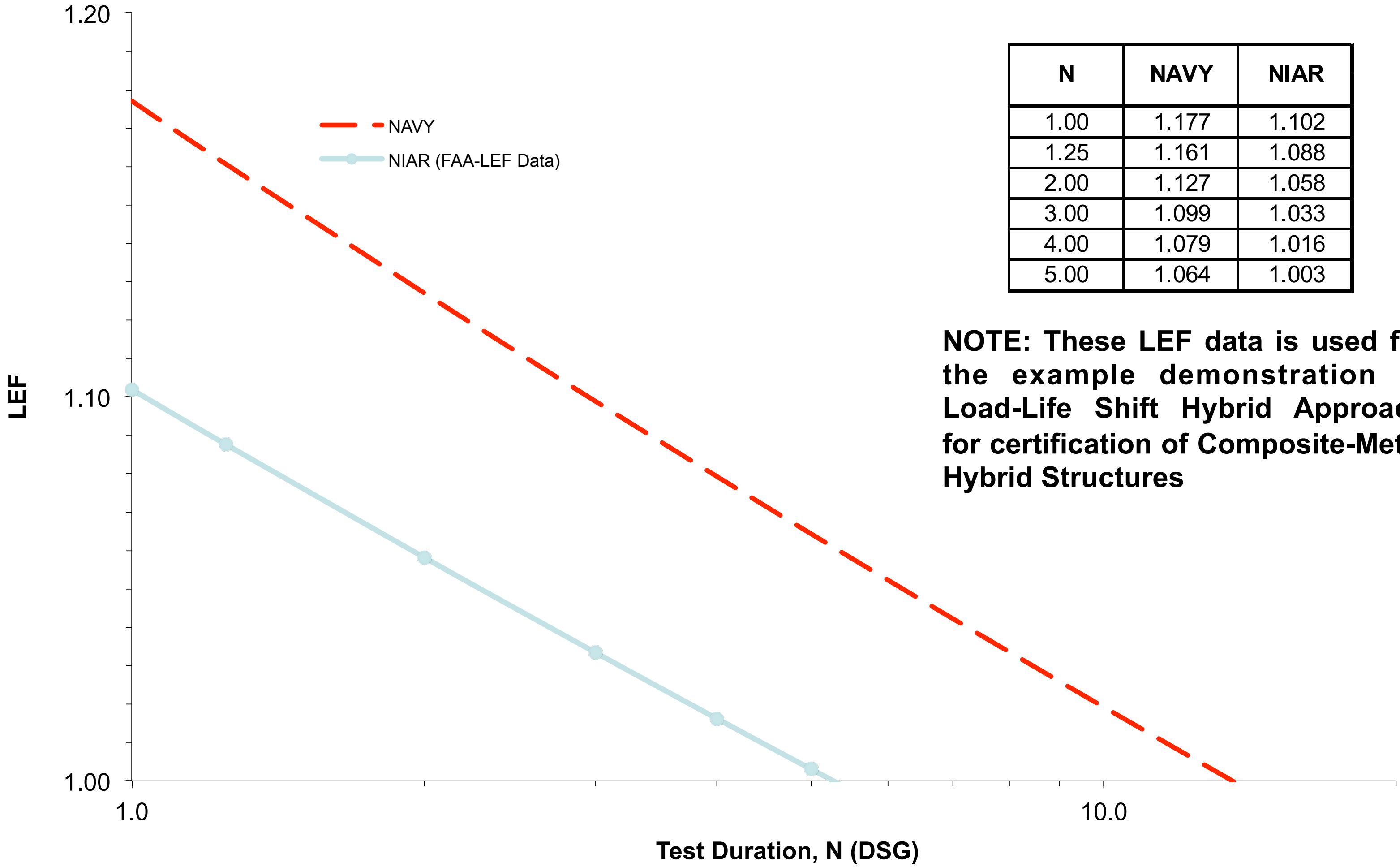
40-55-40-55-70 (Low-High)



All survived 1,035,680 cycles | **1,035,680** | **1,033,152** | **1,035,455 cycles**

runouts | **Fatigue Failures**

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

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

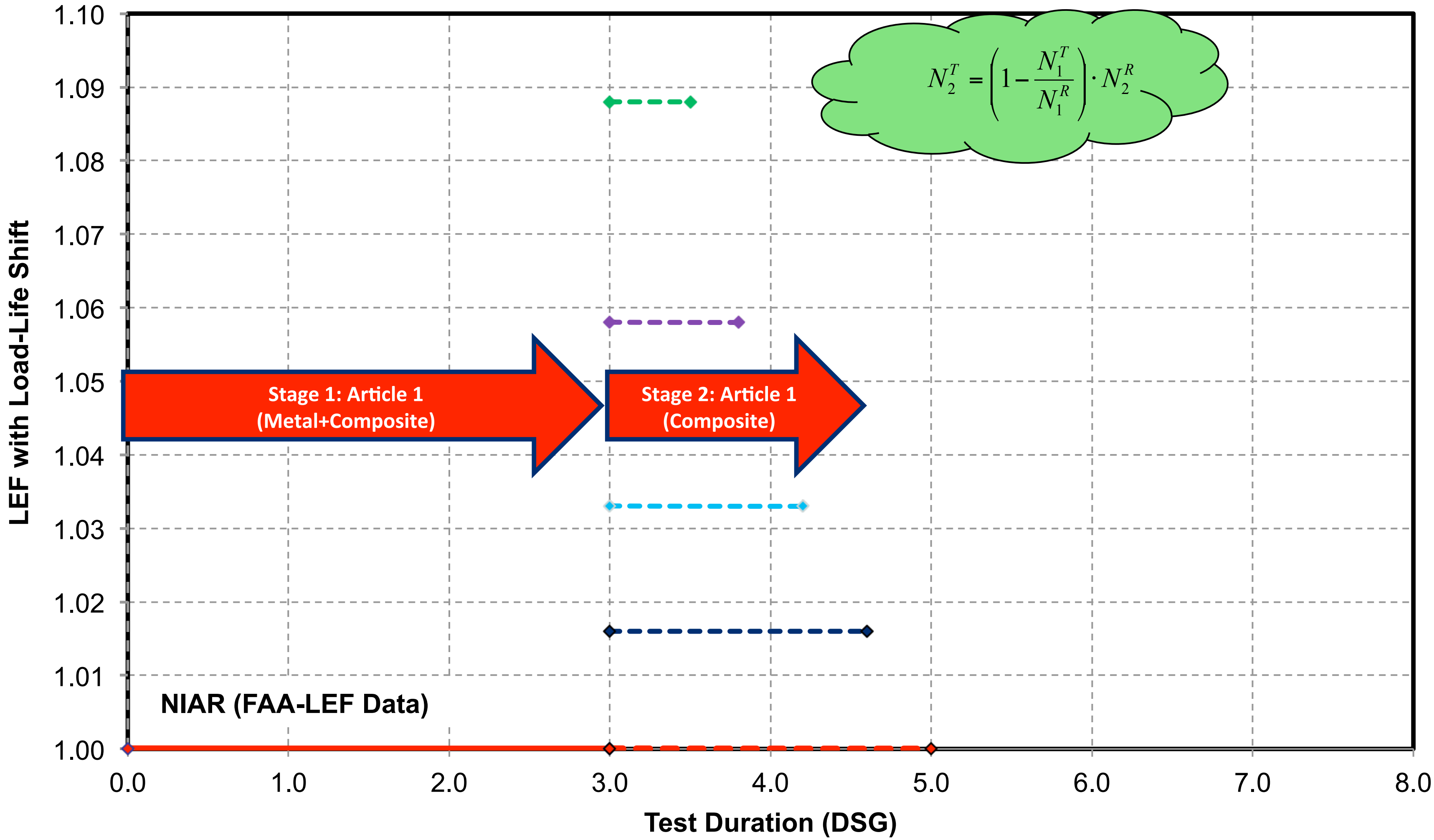
Option	LEF	Required Test Duration without LLS	Required Test Duration with LLS	Total Test Duration
1	1.000	14.0	11.0	**14.0**
2	1.019	10.0	4.0	**7.0**
3	1.052	6.0	2.4	**5.4**
4	1.079	4.0	1.6	**4.6**
5	1.127	2.0	0.8	**3.8**

  - 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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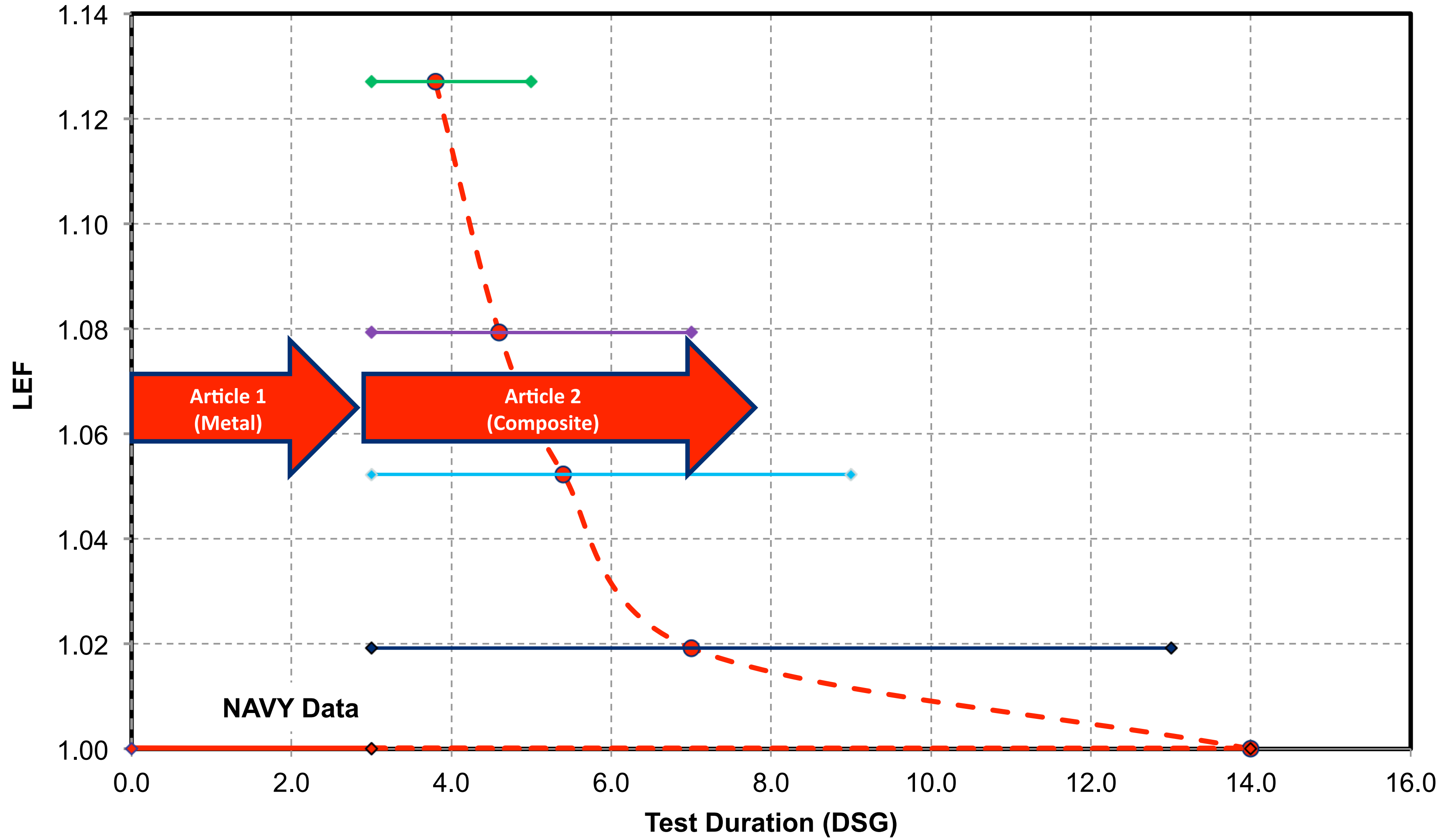
NAVY Data
LLS & 2T Comparison



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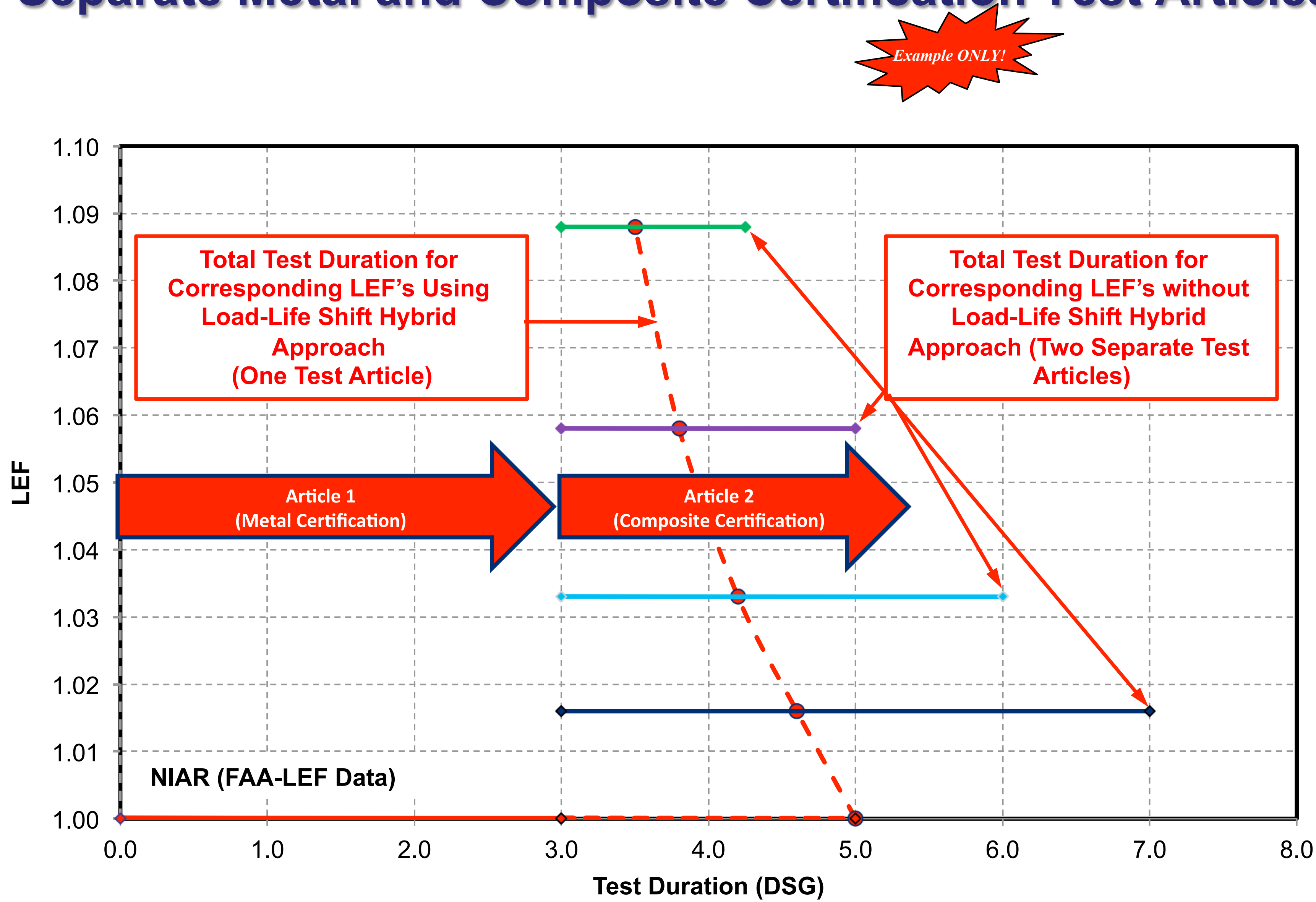
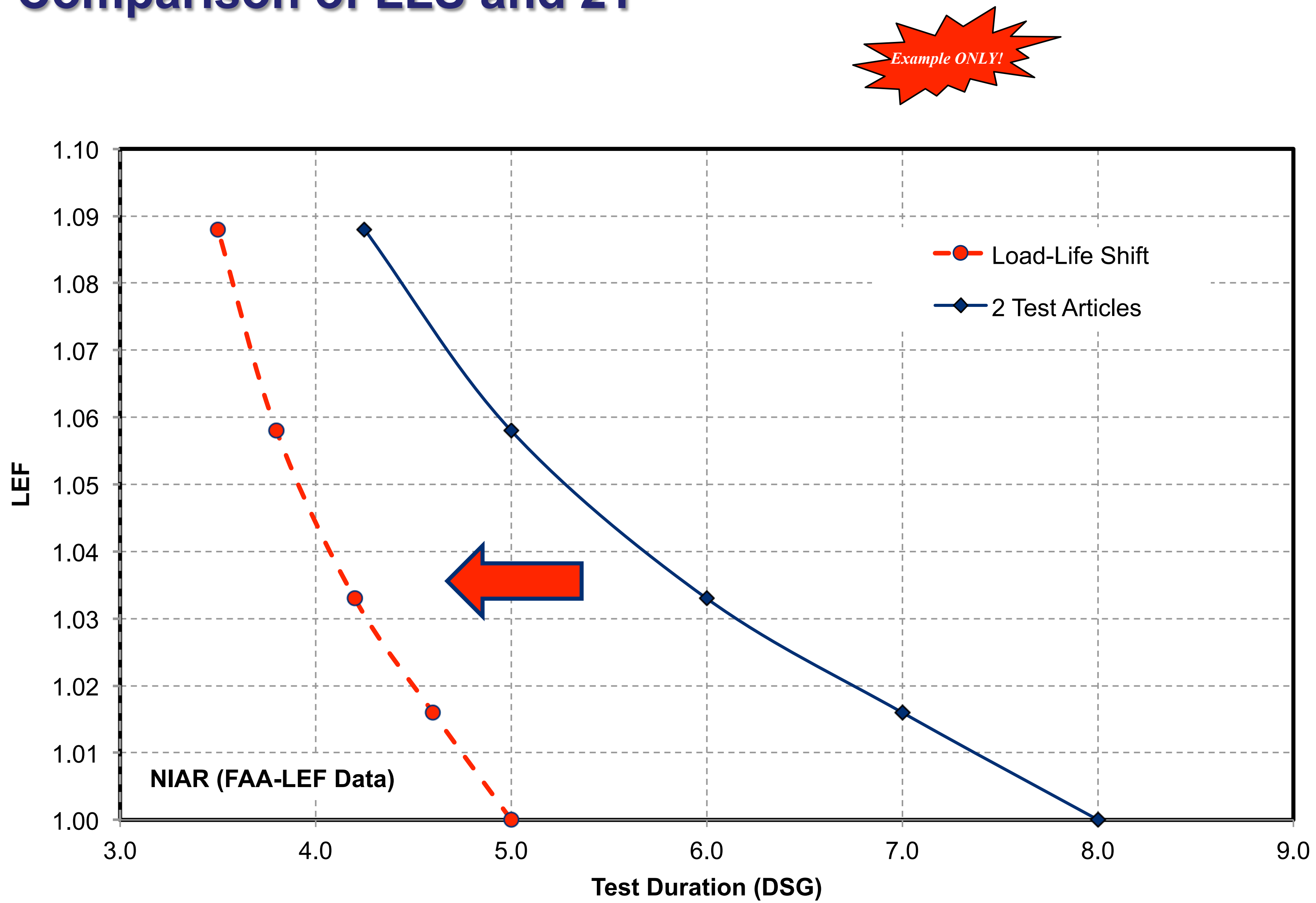
Separate Metal and Composite Certification Test Articles



Comparison of LLS and 2T



Summary

- 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

- Composite structures are operating at much lower stress levels than their maximum strength and most of the loads are below fatigue threshold
  - Sequencing effects will not have any impact on the damage growth behavior at these levels. However, sequencing effects must be studied at lower levels of building blocks of testing to understand the failure mechanism(s)
  - Must consider occasional high loads and their impact on modified hybrid spectrums
- Critical damage threats are identified including their PoO (frequency) and detectability

  ➔ identify which threats require detailed analysis and supporting tests

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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