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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

2012 Technical Review

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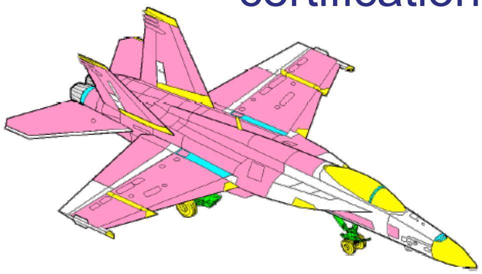
Wichita State University/NIAR

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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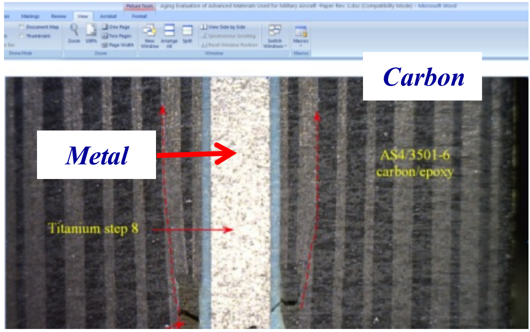
Certification of Composite-Metal Hybrid Structures

- **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

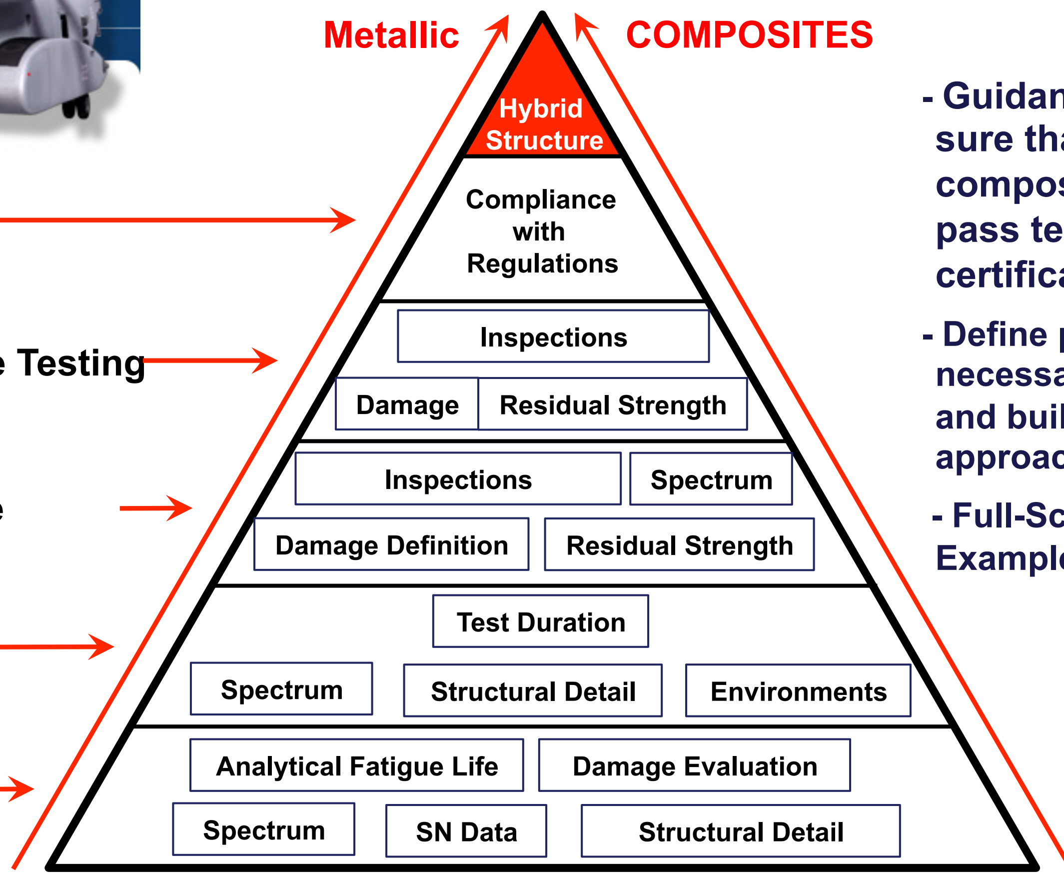
Certification

Damage Tolerance Testing

Damage Tolerance Analysis

Fatigue Testing

Fatigue Analysis



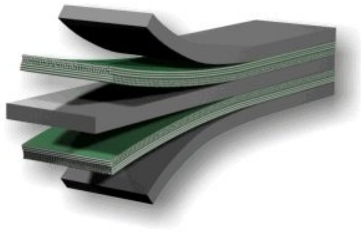
- Guidance is need to make sure that both metal and composite are designed to pass testing and certification requirement.
- Define procedures necessary to support testing and building block approaches
- Full-Scale Validation and Examples

Certification of Composite-Metal Hybrid Structures

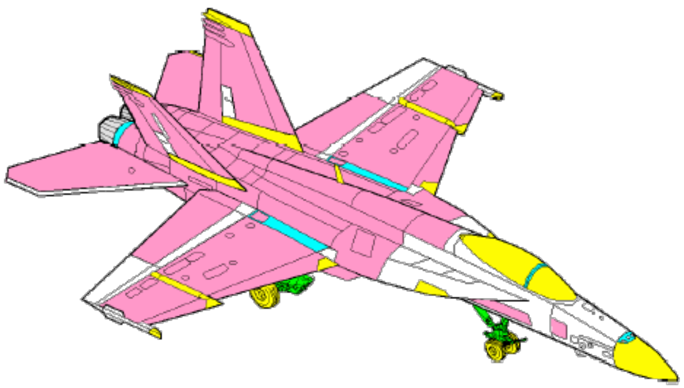
- Principal Investigators & Researchers
  - John Tomblin, *PhD*, and Waruna Seneviratne, *PhD*
- FAA Technical Monitor
  - Curtis Davies and David Westlund
- Other FAA Personnel Involved
  - Larry Ilcewicz, *PhD*
- Industry Participation
  - Airbus, Boeing, Cessna, Bombardier, Hawker Beechcraft, Honda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

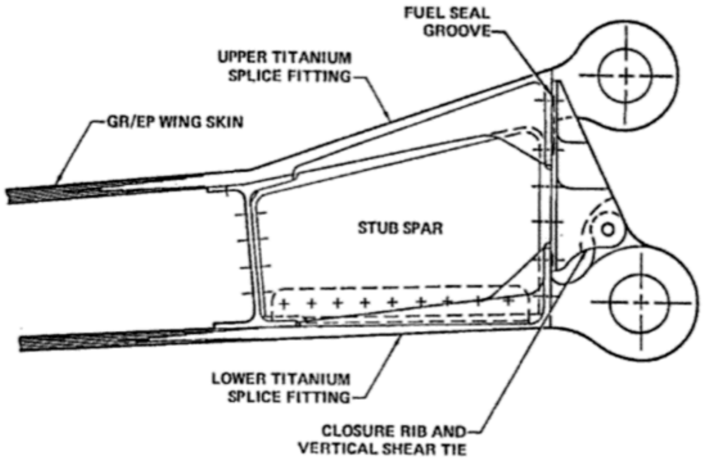
Definitions

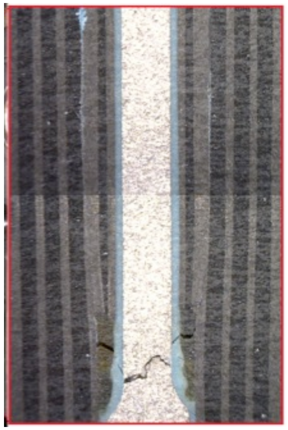
- Hybrid Materials – Composite-Metal Laminates (GLARE, ARALL, TIGR)



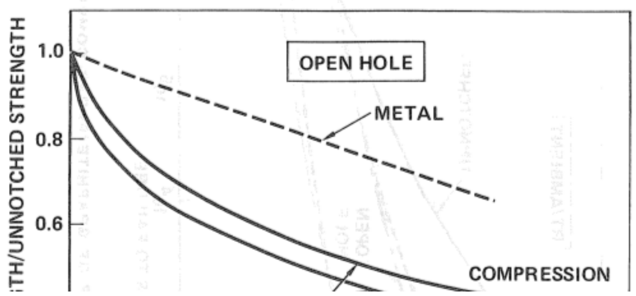
- Hybrid Laminates – fabric/tape, glass/carbon, etc.
- Hybrid Structures – carbon skins bolted to metal substructure; glass skins bonded to carbon spars, etc.





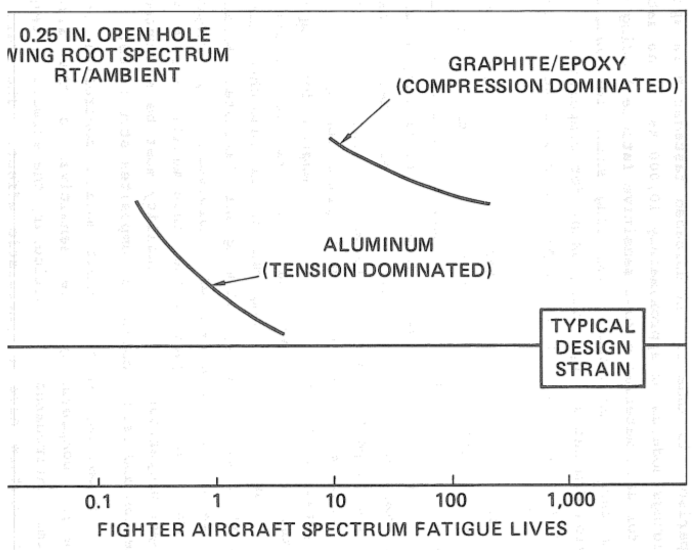


Composites-Metal Comparison



Notch sensitivity (static)

Fatigue sensitivity



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

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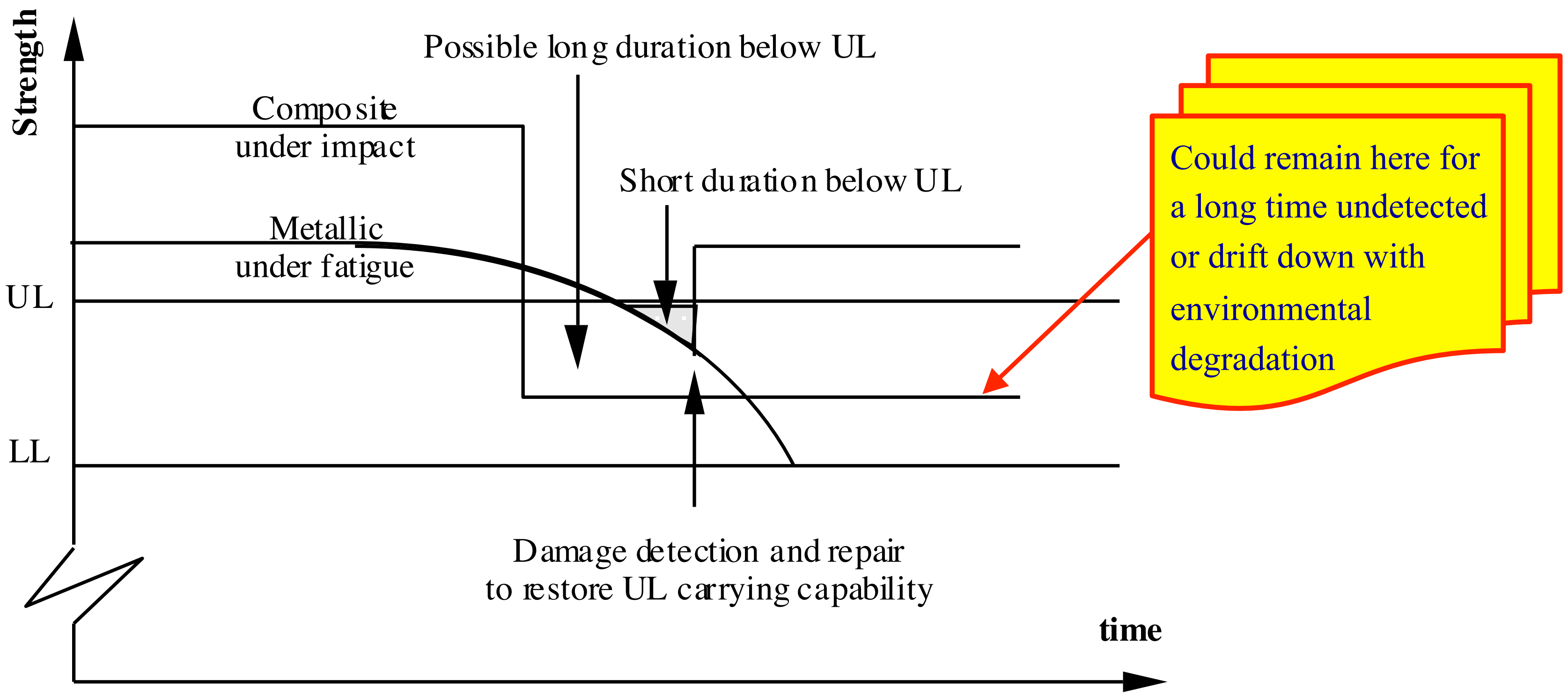
Composite and Metal Damage Tolerance

- “This sketch shows the difference that can be found between non-growing impact damage in a composite structure and a prone-to-grow fatigue crack in a metallic one. As shown with the metal curve, *an inspection interval can be rationally derived such that fatigue damage in metallic structure is safely detected and repaired before the strength drops below Limit Loads*. Metal crack growth analyses and tests have matured to support such an assessment.” – [CMH-17 Volume 3 Chapter 12]



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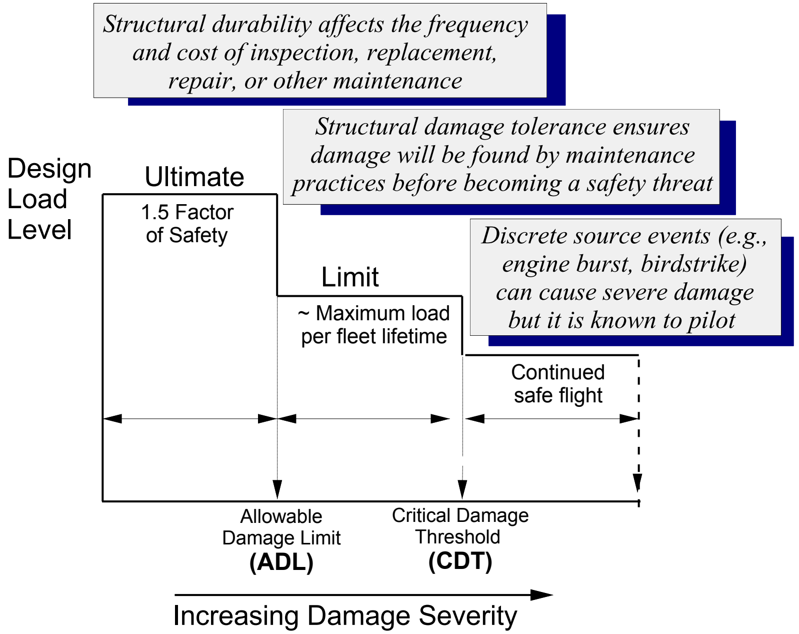
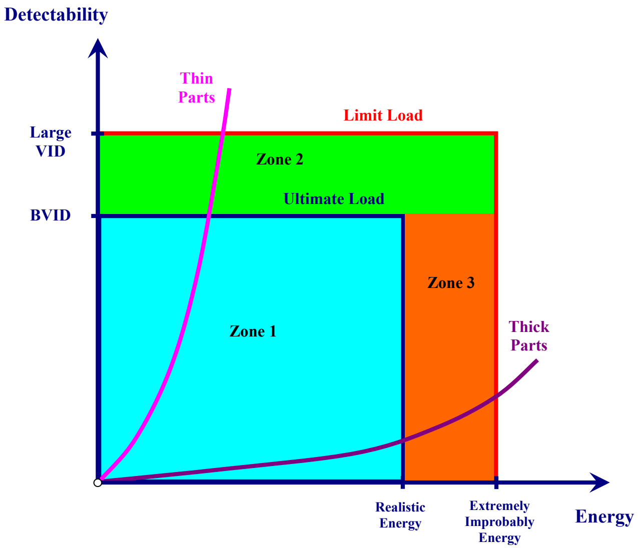
Damage Tolerance Test Substantiation

Safety-of-Flight composite aircraft structure should be designed damage tolerant

The damage tolerance evaluation should:

- **Include anticipated manufacturing and service related defects/damage**
- **Demonstrate a "B" - Basis (or "A" - Basis, as appropriate) repeated-load life, inspection interval, etc.**
- **Include the considerations contained in FAA Advisory Circulars (AC) 20-107B, Composite Aircraft Structure, and 25.571-1C, Damage-Tolerance and Fatigue Evaluation of Structure**





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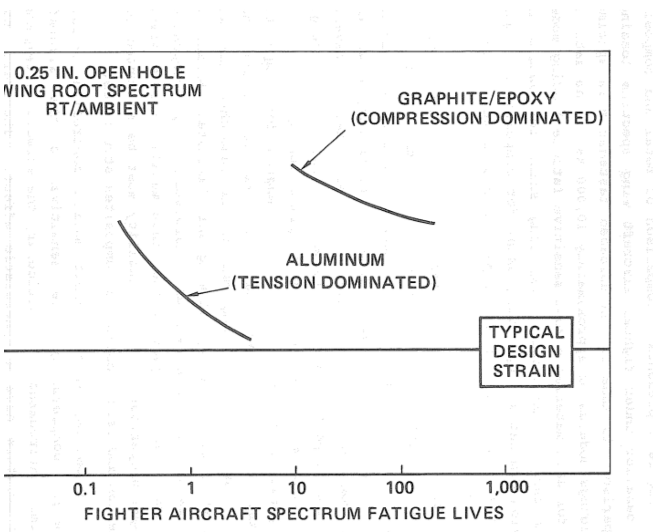
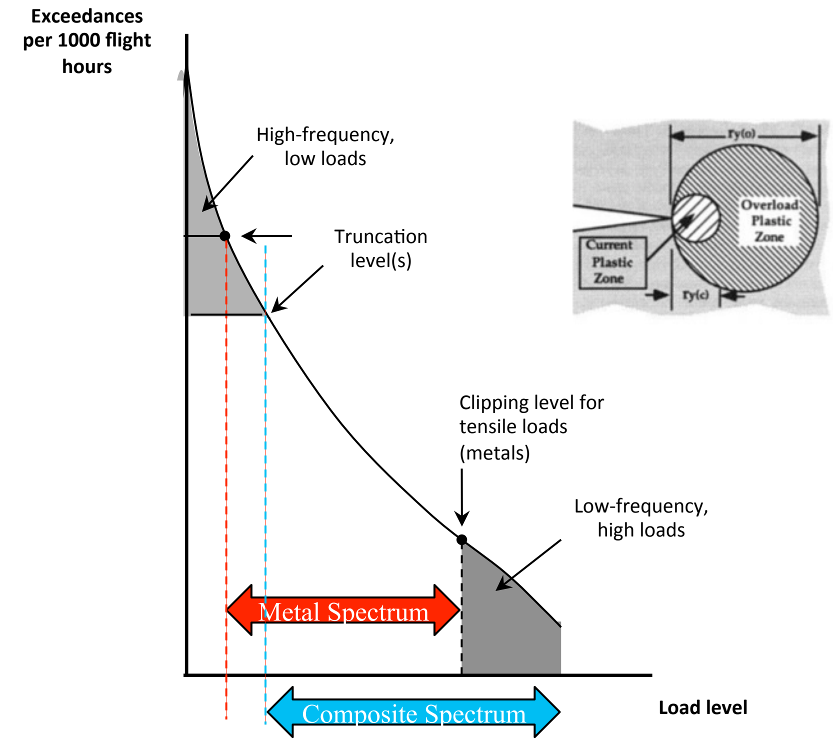
Spectrum Truncation & Clipping

- 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





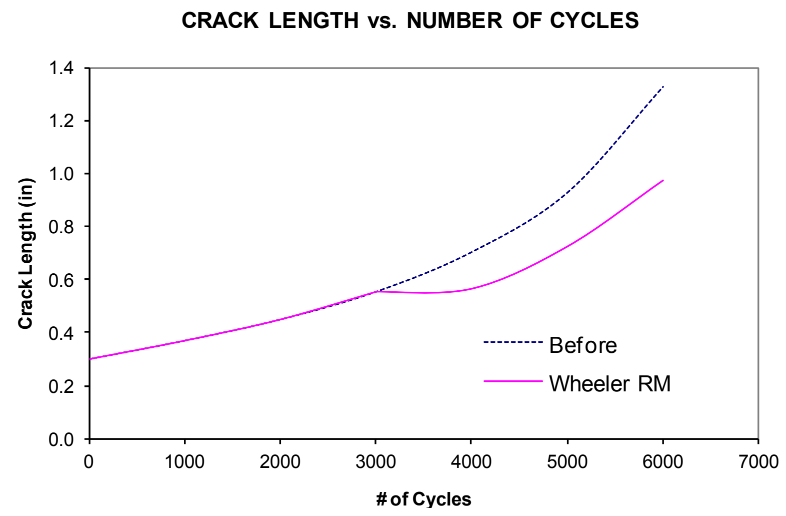
Overload Effects on Metals

Wheeler Retardation Model (Example)

(a) Without the overload effects.

a	Cumulative Cycles	σ_{max} (ksi)	σ_{min} (ksi)	R	Kmax ($ksi{*}in^{.5}$)	d2a/dN	da/dN	ΔN	(da/dN)*ΔN
0.300	0	18	3.6	0.2	19.6	0.00014	0.00007	1000	0.0700
0.370	1000	18	3.6	0.2	21.7	0.00016	0.00008	1000	0.0800
0.450	2000	18	3.6	0.2	24.0	0.00021	0.00011	1000	0.1050
0.555	3000	18	3.6	0.2	26.6	0.00030	0.00015	1000	0.1500
0.705	4000	18	3.6	0.2	30.0	0.00045	0.00023	1000	0.2250
0.930	5000	18	3.6	0.2	34.5	0.00080	0.00040	1000	0.4000
1.330	6000								

$Kmax = \sigma max{*}(\pi a)^{.5}1.12$



(b) With the overload effects on crack growth [Wheeler Retadation model].

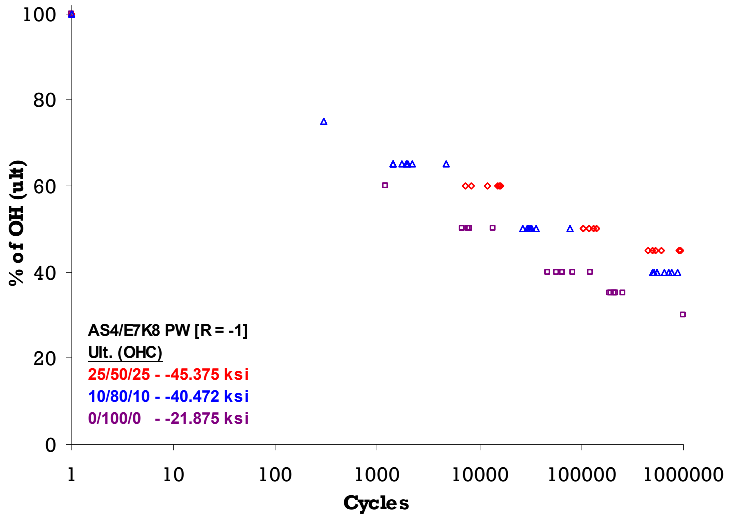
a	Cumulative Cycles	σ_{max} (ksi)	σ_{min} (ksi)	R	Kmax ($ksi{*}in^{.5}$)	r_p (inch)	$a_{OL}+r_{pOL}$ (inch)	a_i+r_{pi} (inch)	Φ	d2a/dN	da/dN	ΔN	Φ (da/dN)*ΔN
0.3000	0	18	3.6	0.2	19.6				1	0.00014	0.00007	1000	0.0700
0.3700	1000	18	3.6	0.2	21.7				1	0.00016	0.00008	1000	0.0800
0.4500	2000	18	3.6	0.2	24.0				1	0.00021	0.00011	1000	0.1050
0.5550	3000	27	5.4	0.2	39.9	0.0549			1	0.00031	0.00016	1	0.0002
0.5552	3001	18	3.6	0.2	26.6	0.0244	0.610	0.580	0.0754	0.00030	0.00015	1000	0.0113
0.5665	4001	18	3.6	0.2	26.9	0.0249	0.610	0.591	1	0.00032	0.00016	1000	0.1600
0.7265	5001	18	3.6	0.2	30.5	0.0319	0.610	0.758	1	0.00050	0.00025	1000	0.2500
0.9765	6001												

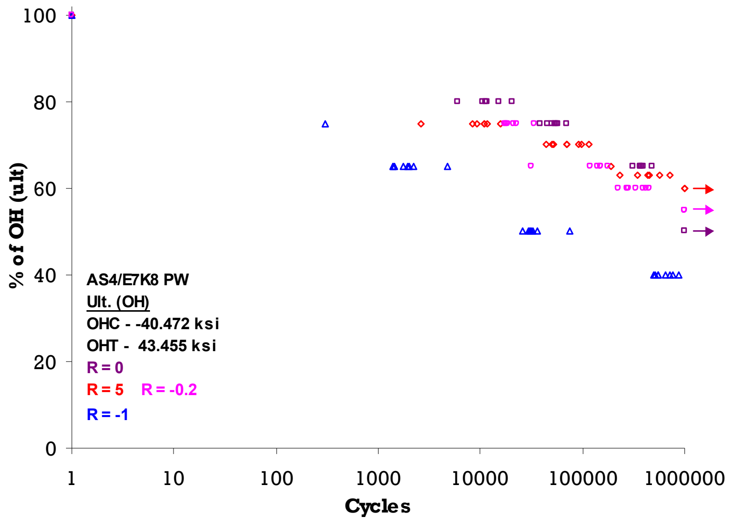
$r_p = Kmax^2 / (2\pi\sigma_{ys}^2)$

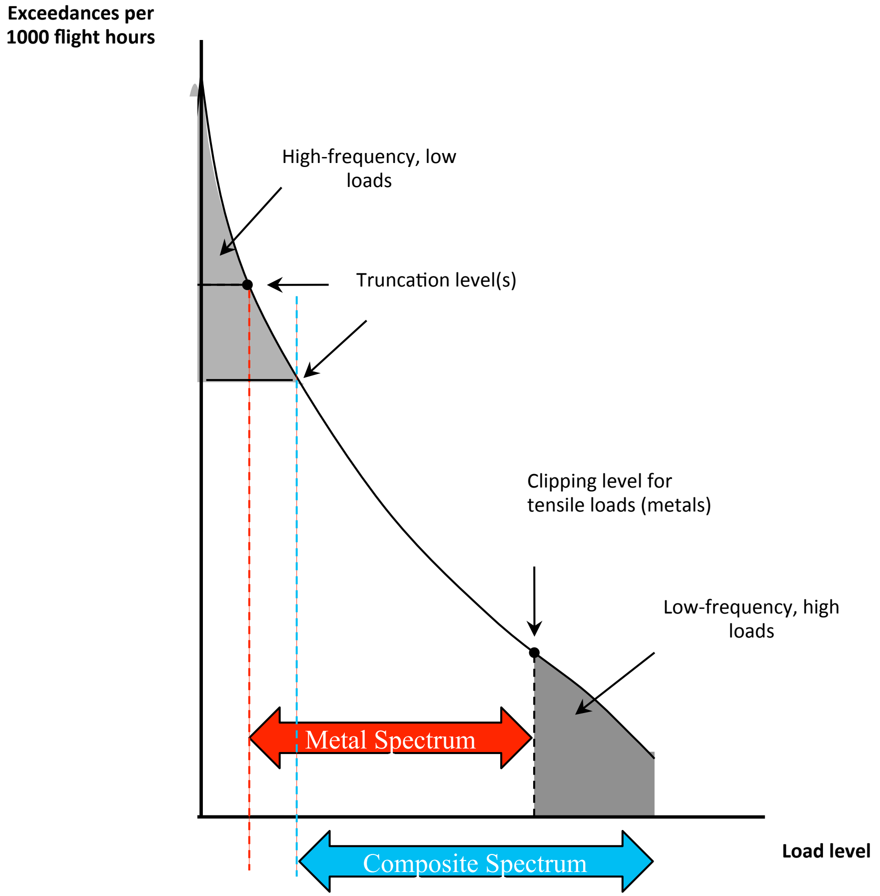
$\Phi = (r_{pi}/(r_{pOL}+a_{OL}-a_i))^m$

m = 3.2

Truncation - Endurance limit



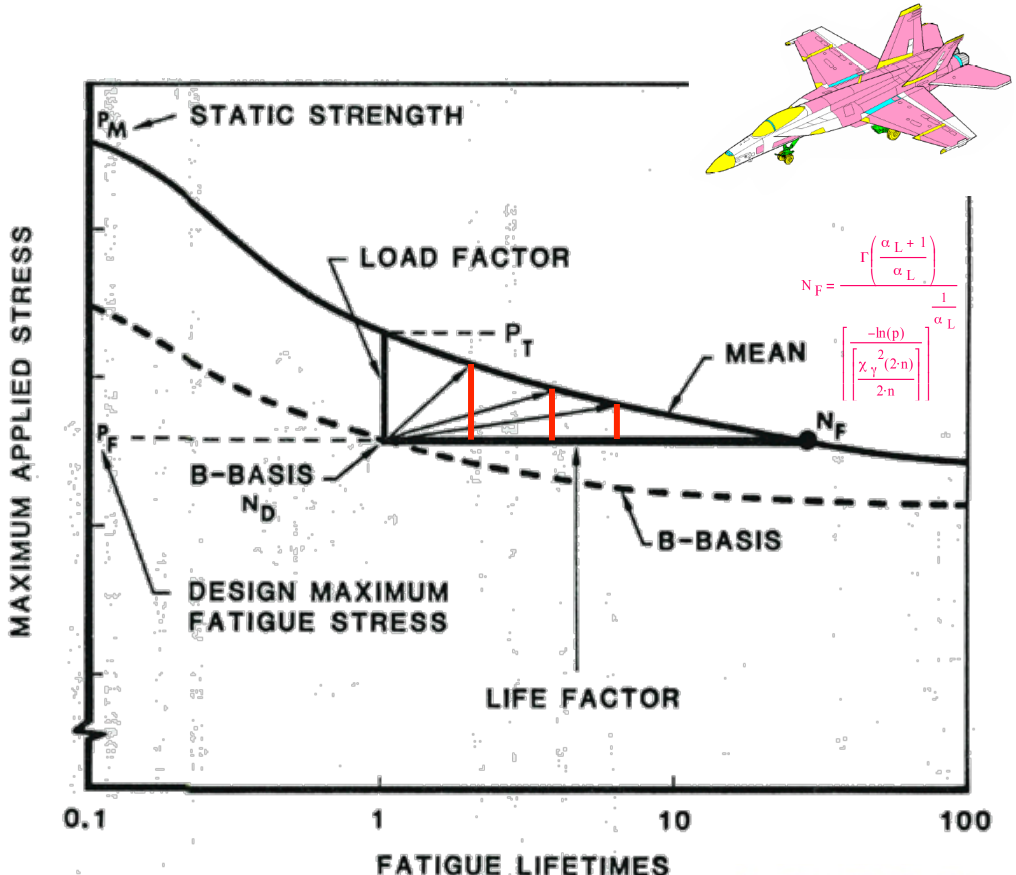




Load-Life Enahncment Factor Approach

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

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



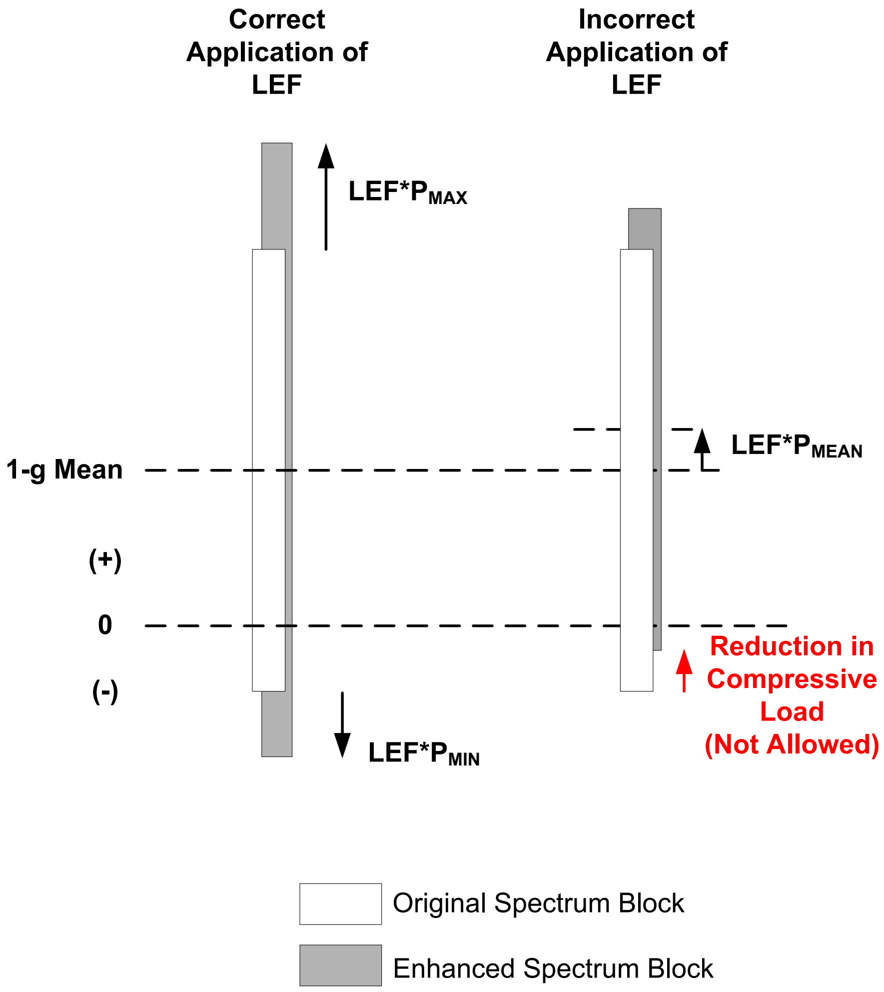
- Load (Scatter) Factor

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

- Load Enhancement Factor (LEF)

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

Application of LEF



- 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

$$P_{Min/Max} = \left[\left(Load_{1-g}\right) + \left(\frac{\Delta Load}{\Delta g}\right) \cdot \Delta g\right] \cdot LEF$$

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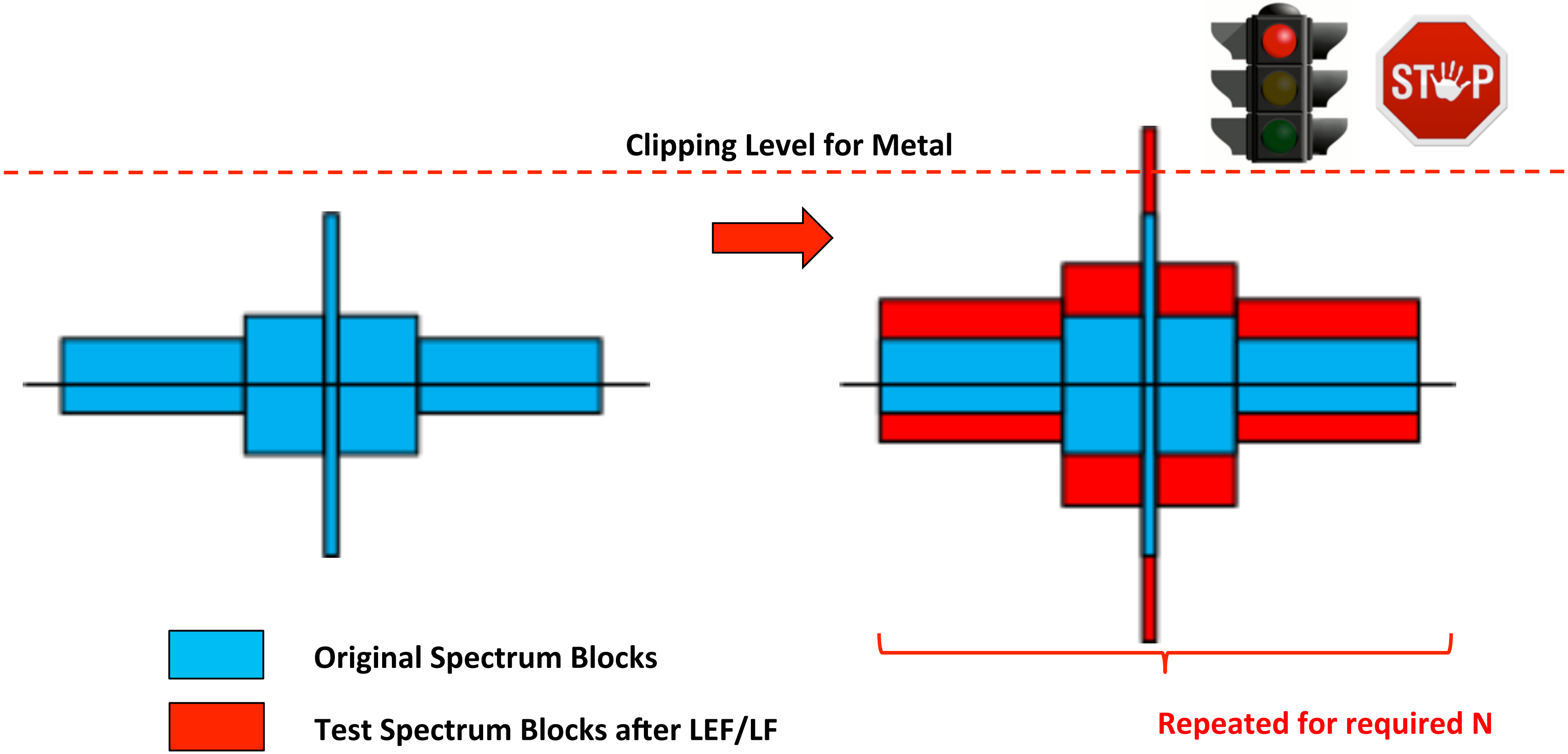
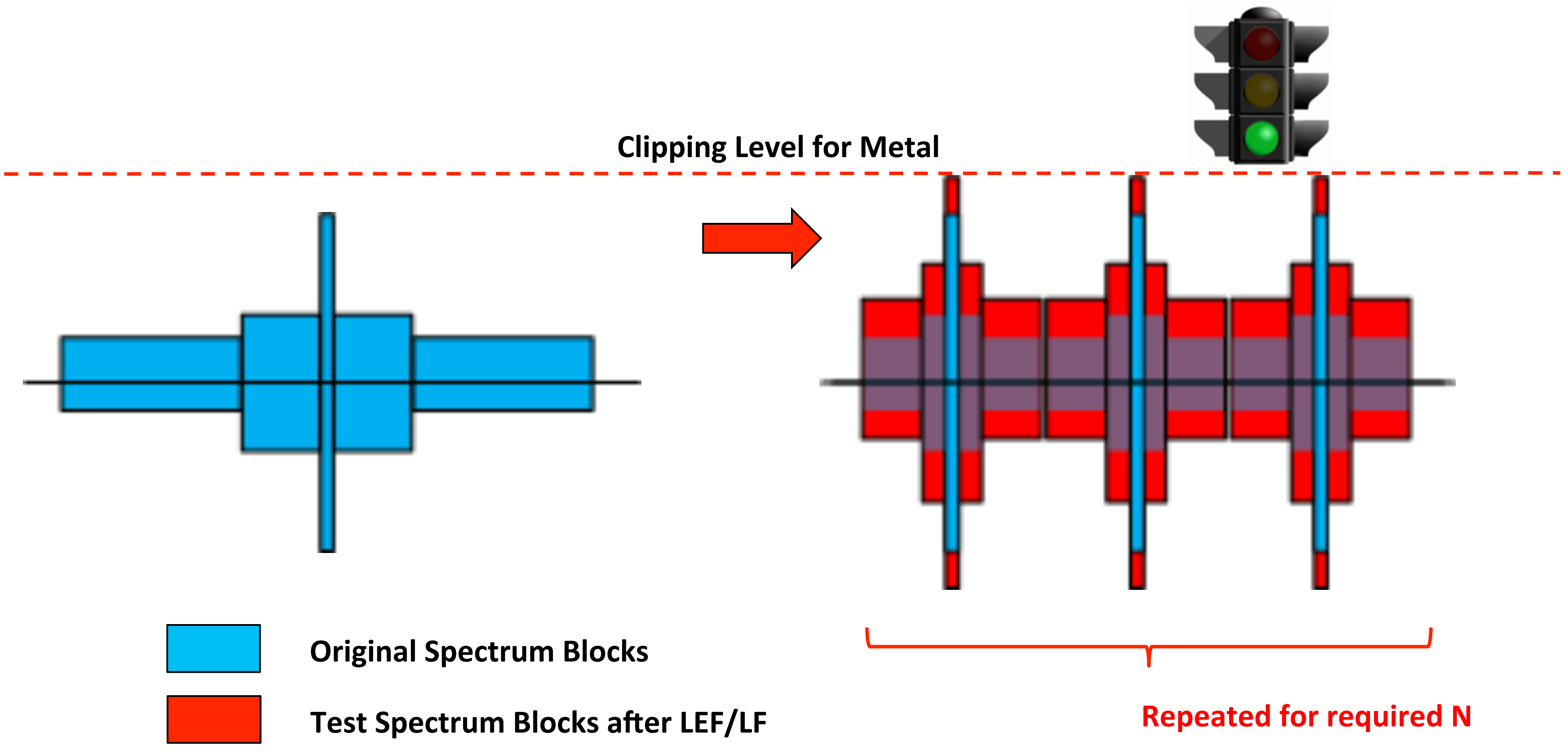
Load-Life Combined (LEF) Approach



Load-Life Hybrid (LEF-H) Approach



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

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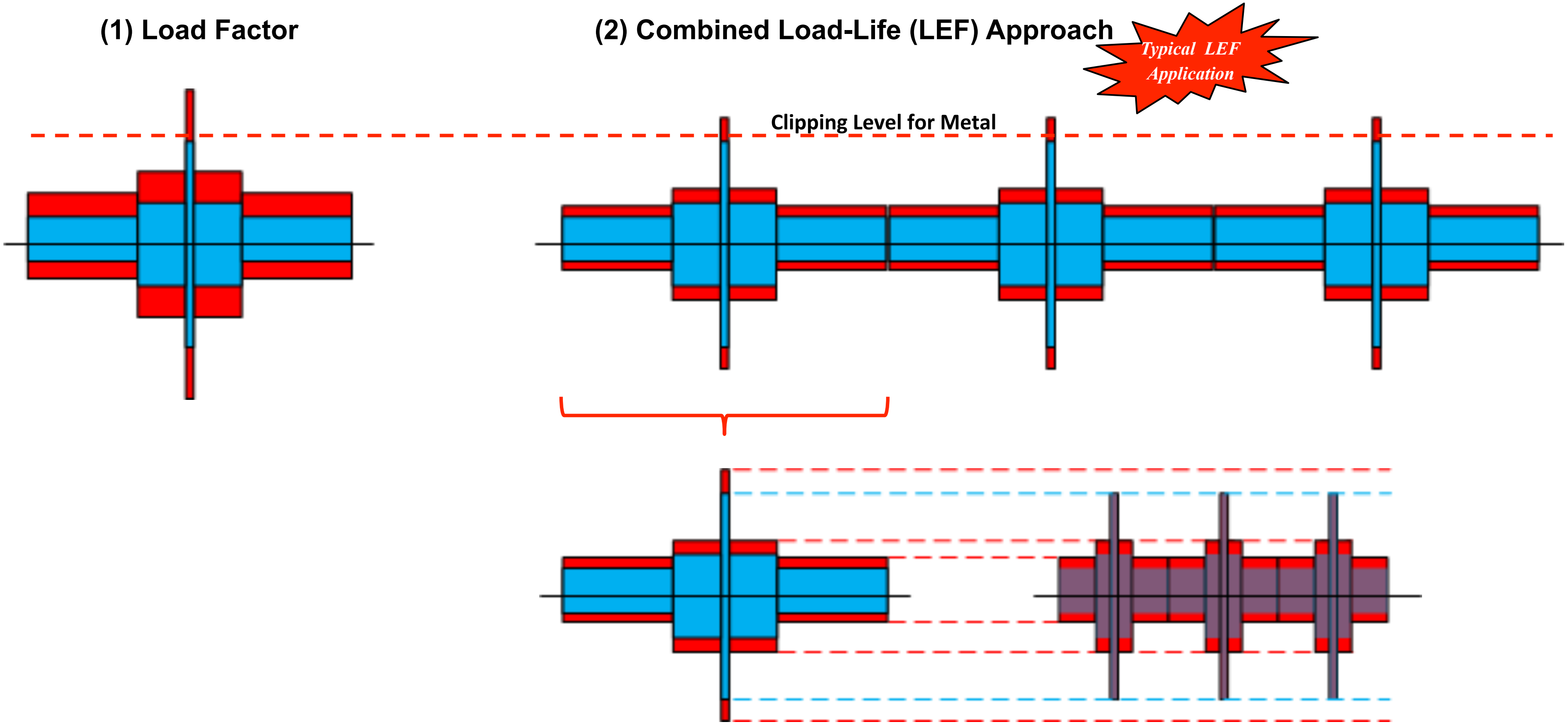
Hybrid (Load-Life) Approach for Hybrid (Composite-Metal) Structures

(1) Load Factor

(2) Combined Load-Life (LEF) Approach



(3) LEF Hybrid (LEF-H) Approach

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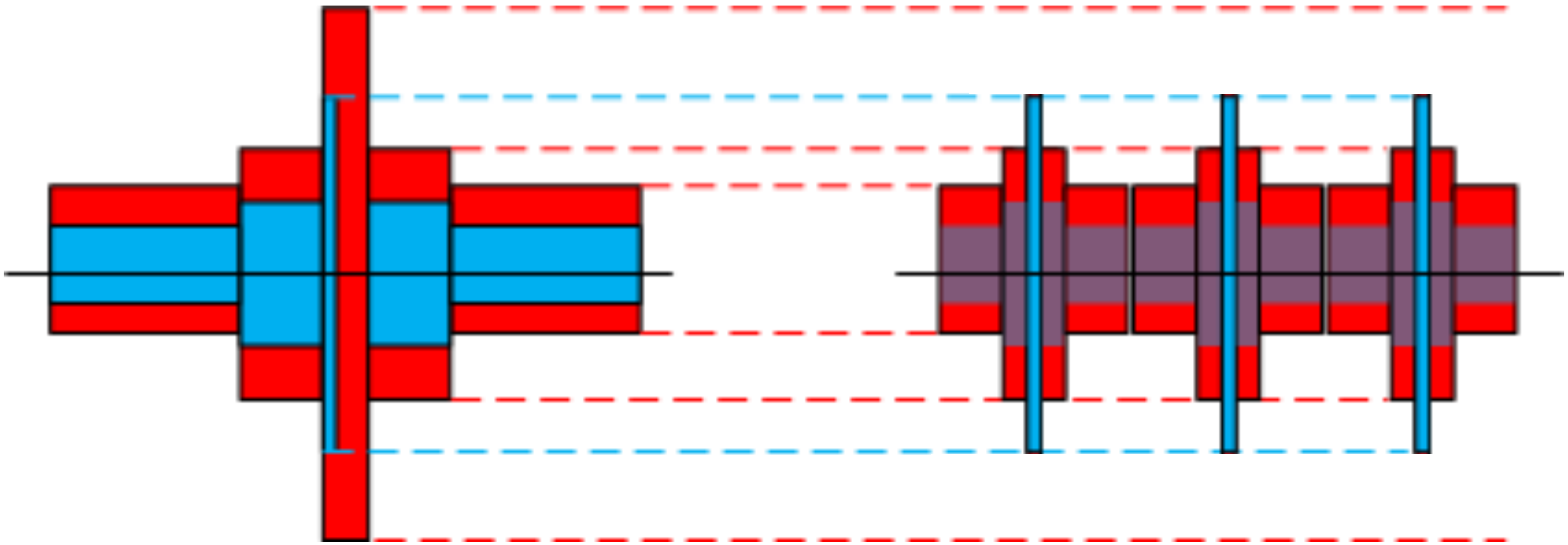
LEF Hybrid (LEF-H) Approach



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 should not be allowed due to 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

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

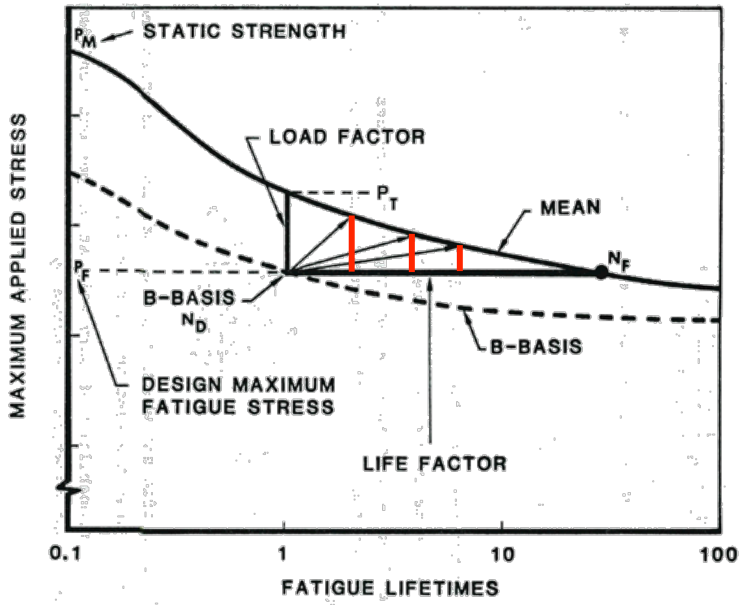
Load-Life Shift

- 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:

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



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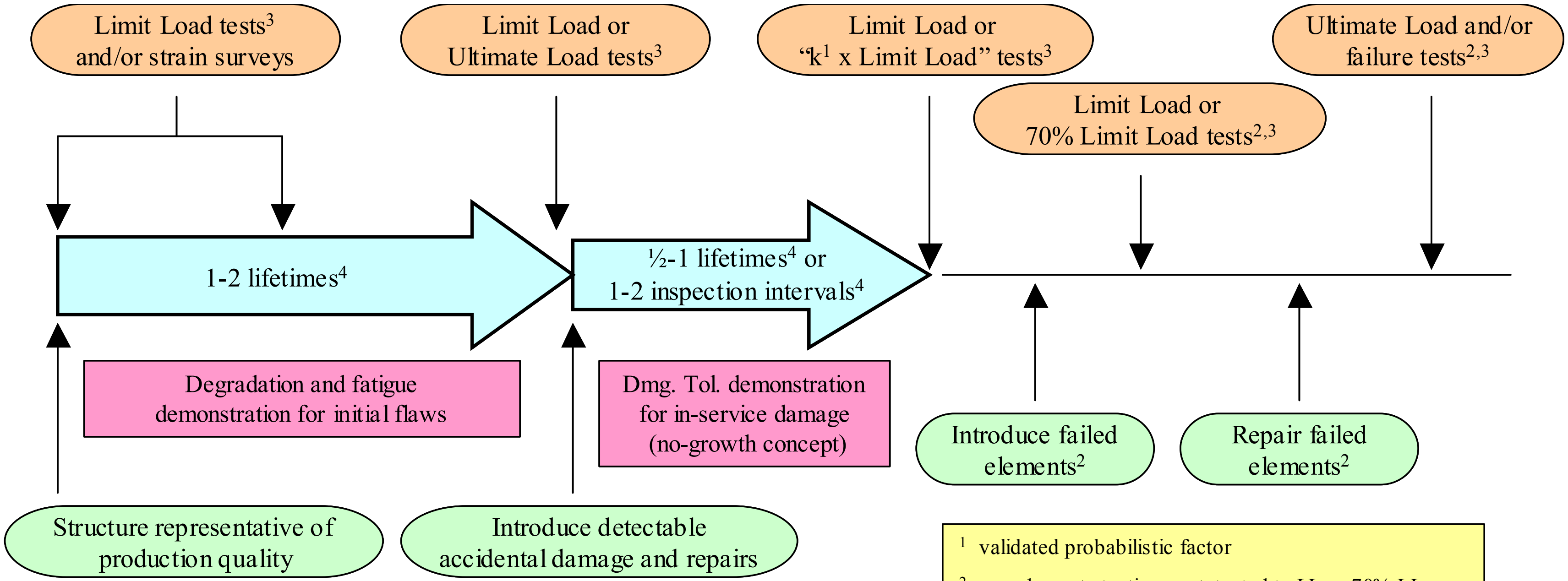
Full-Scale Test Sequence [Typical Transport Aircraft]



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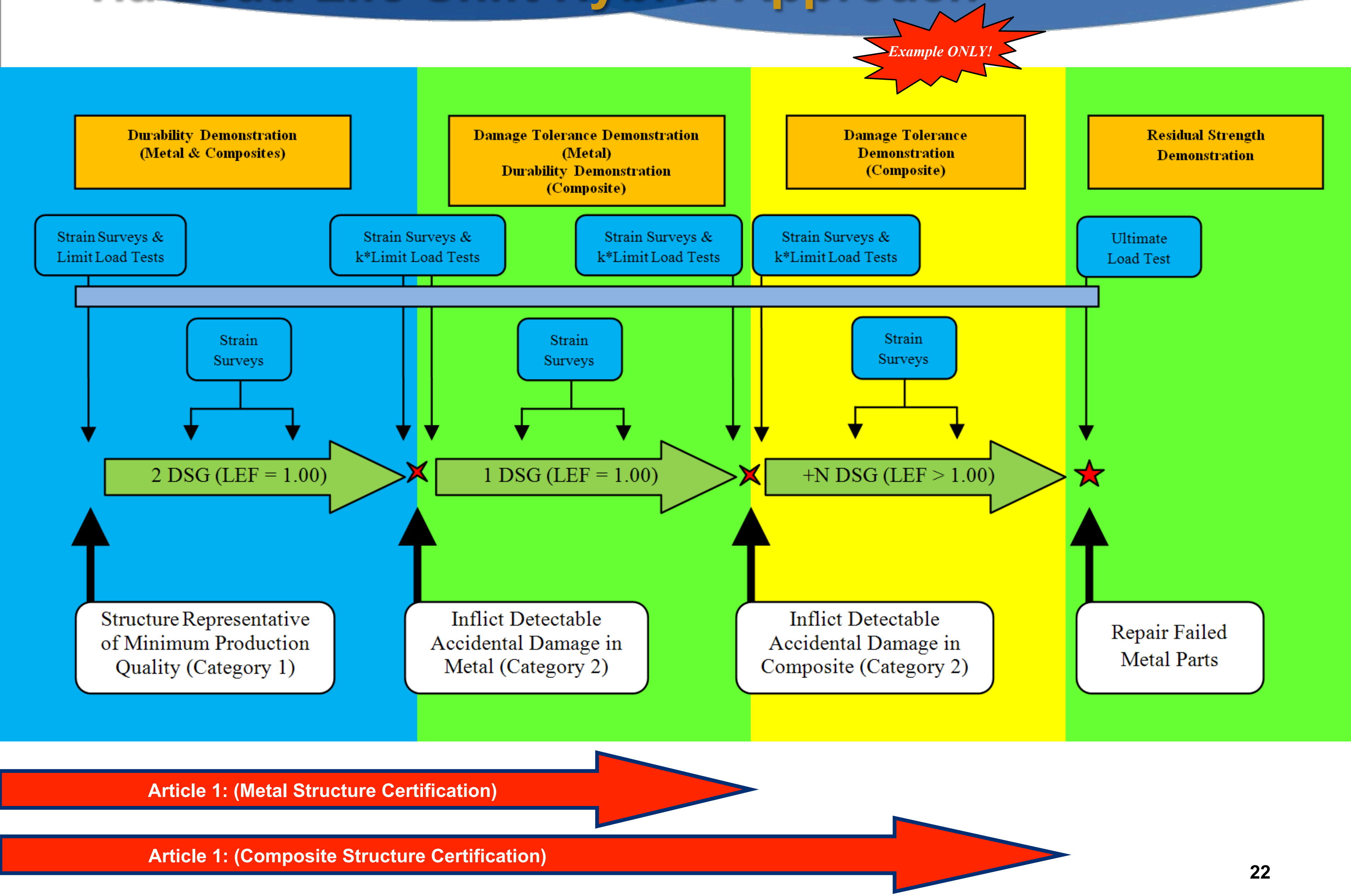
Test Sequence for Full-Scale Test Substantiation via Load-Life Shift Hybrid Approach



Load-Life Shift (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

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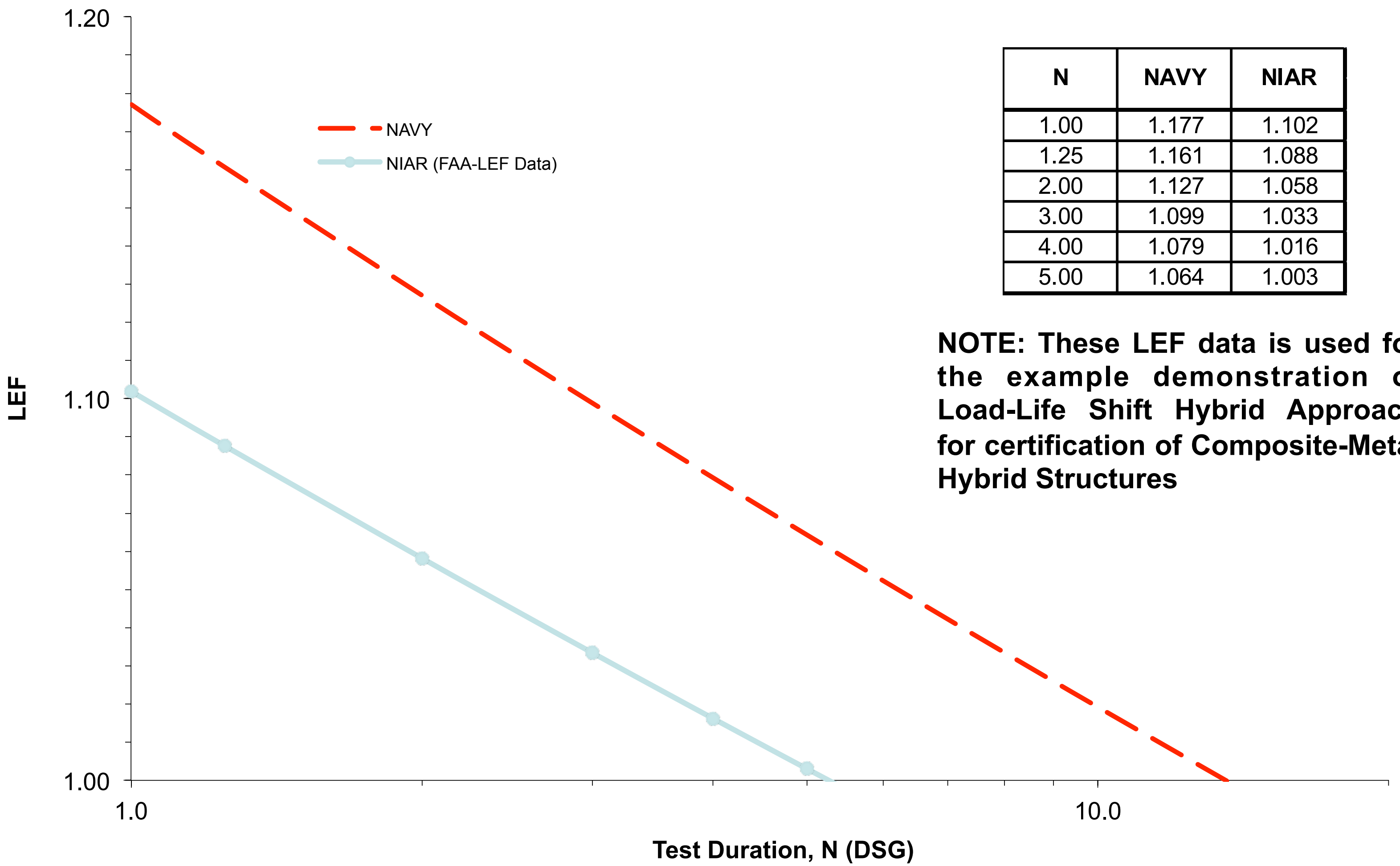
Load-Enhancement Factor Curve (Example: NIAR FAA-LEF Data)



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!

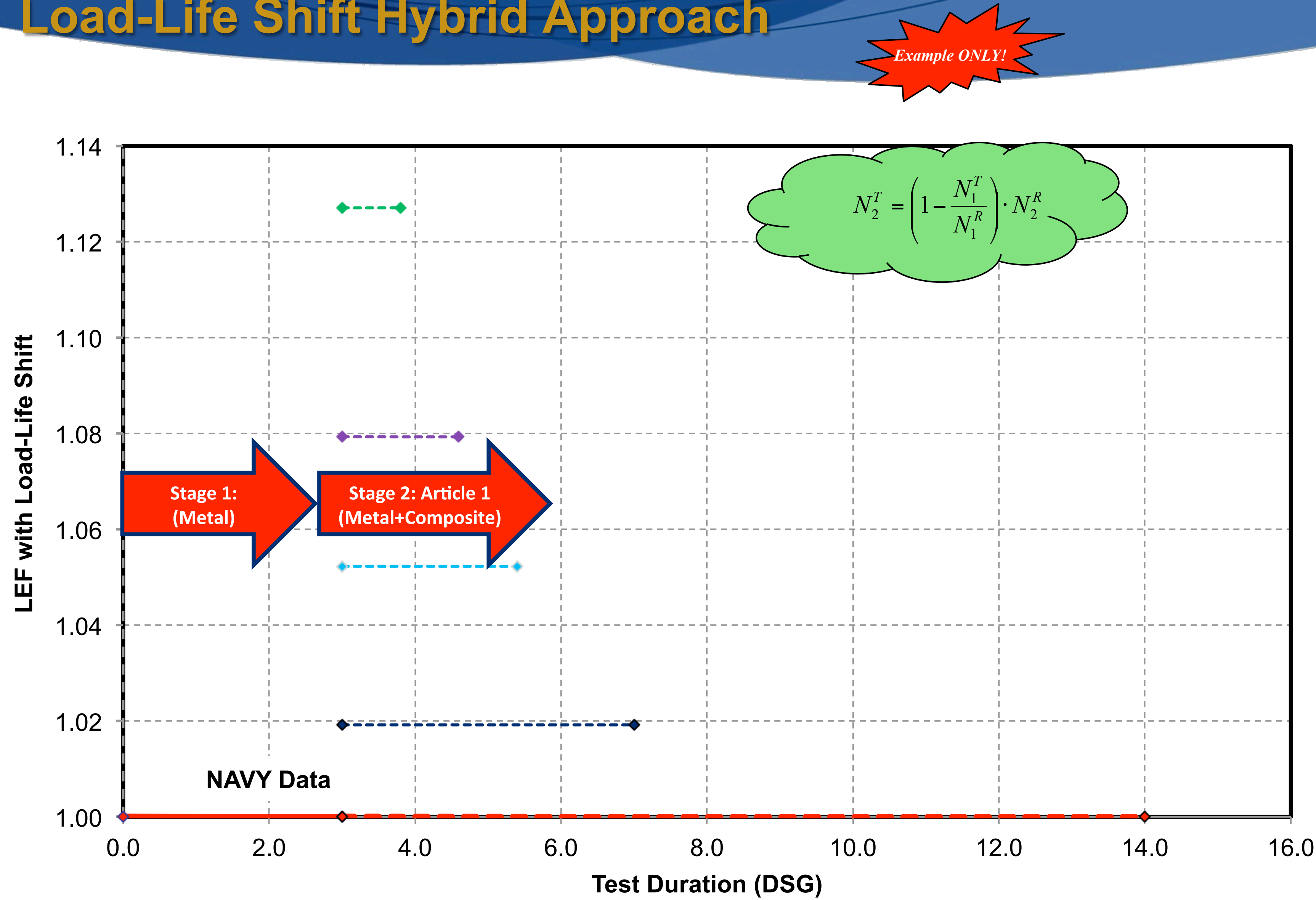
- Load-Life Shift Test Requirements in Composite Phase *(after 3 DLT test with LEF=1 for Metal Certification Phase)*
  - NAVY Data

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**

NAVY Data
Load-Life Shift Hybrid Approach



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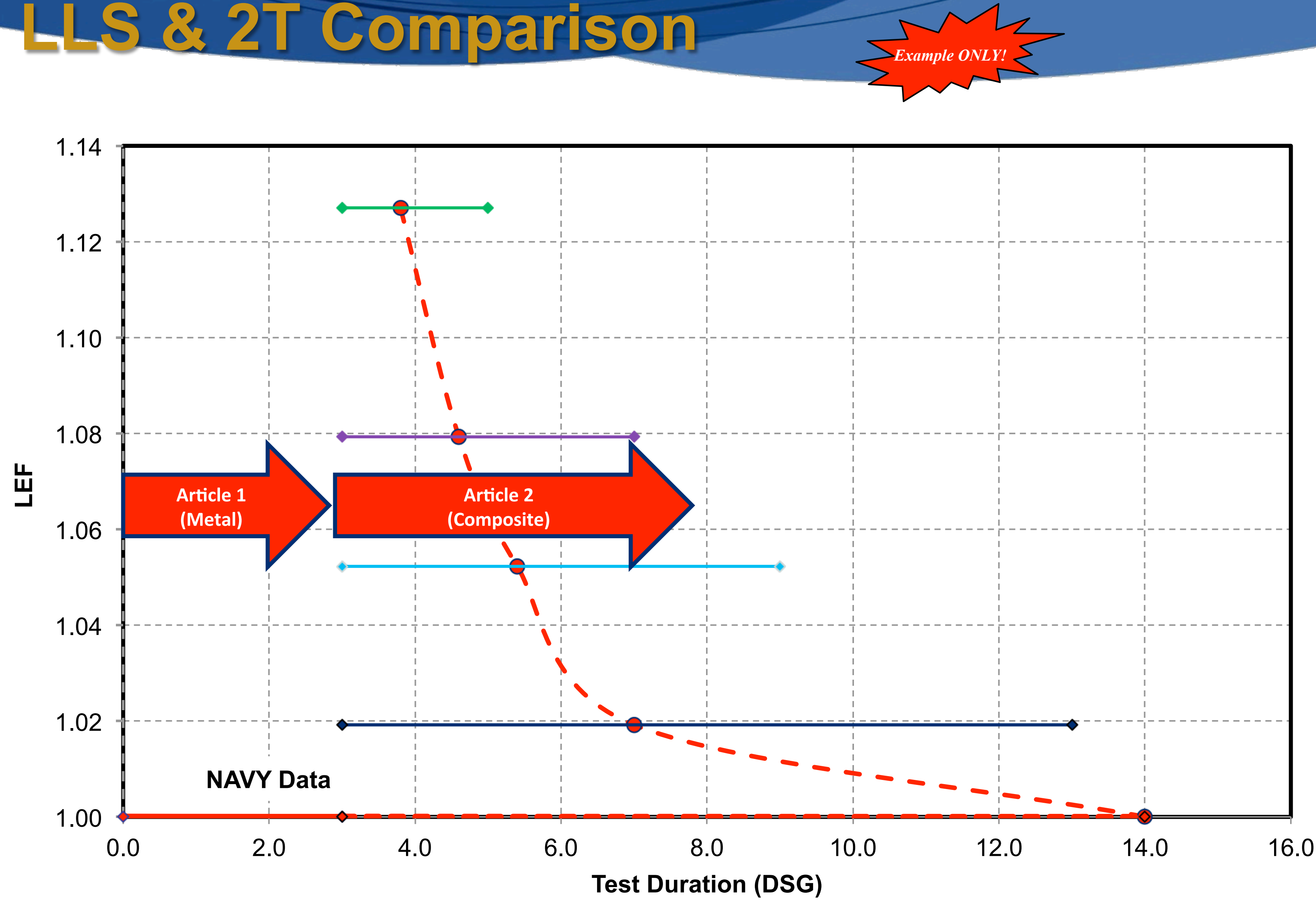
NAVY Data
LLS & 2T Comparison



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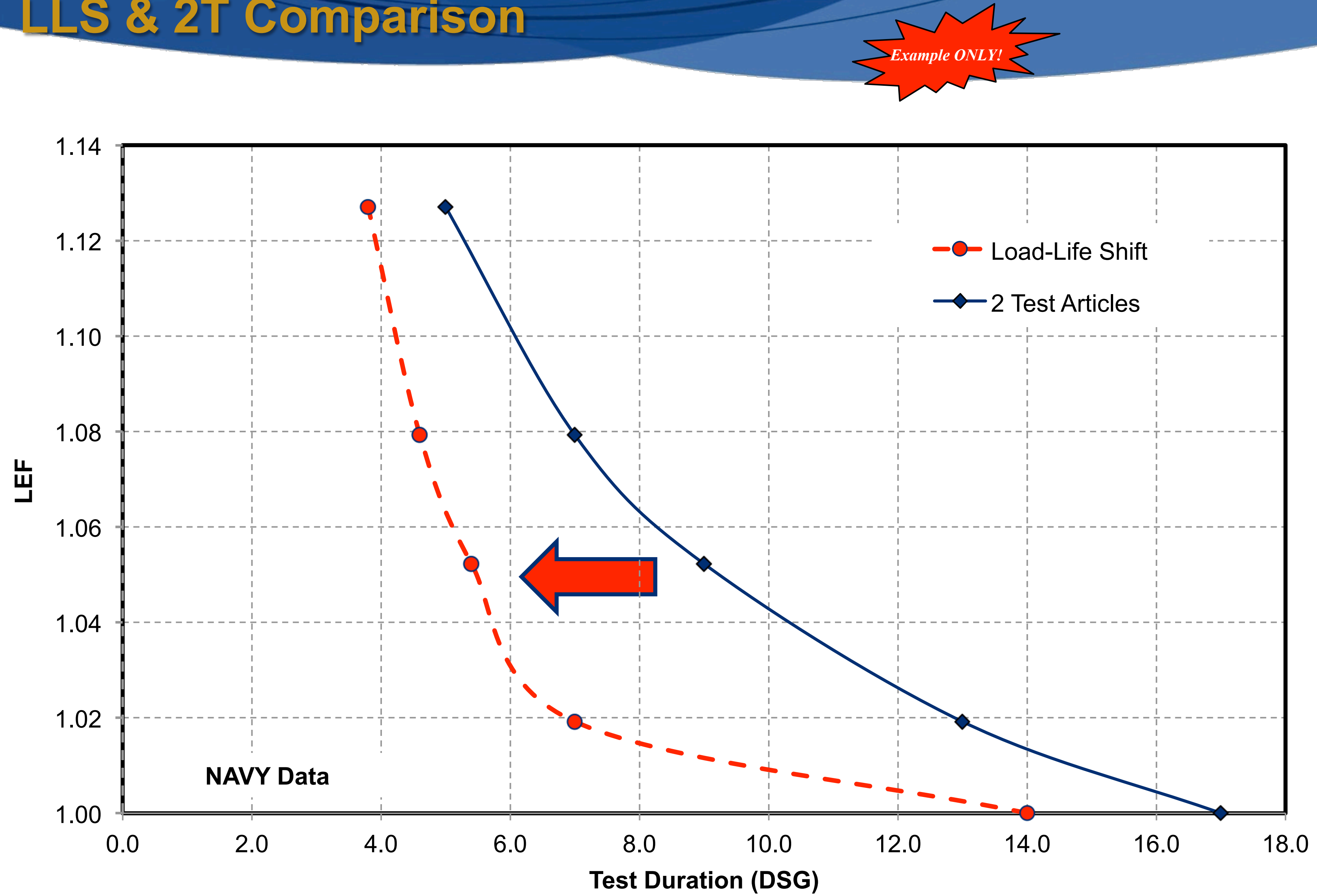
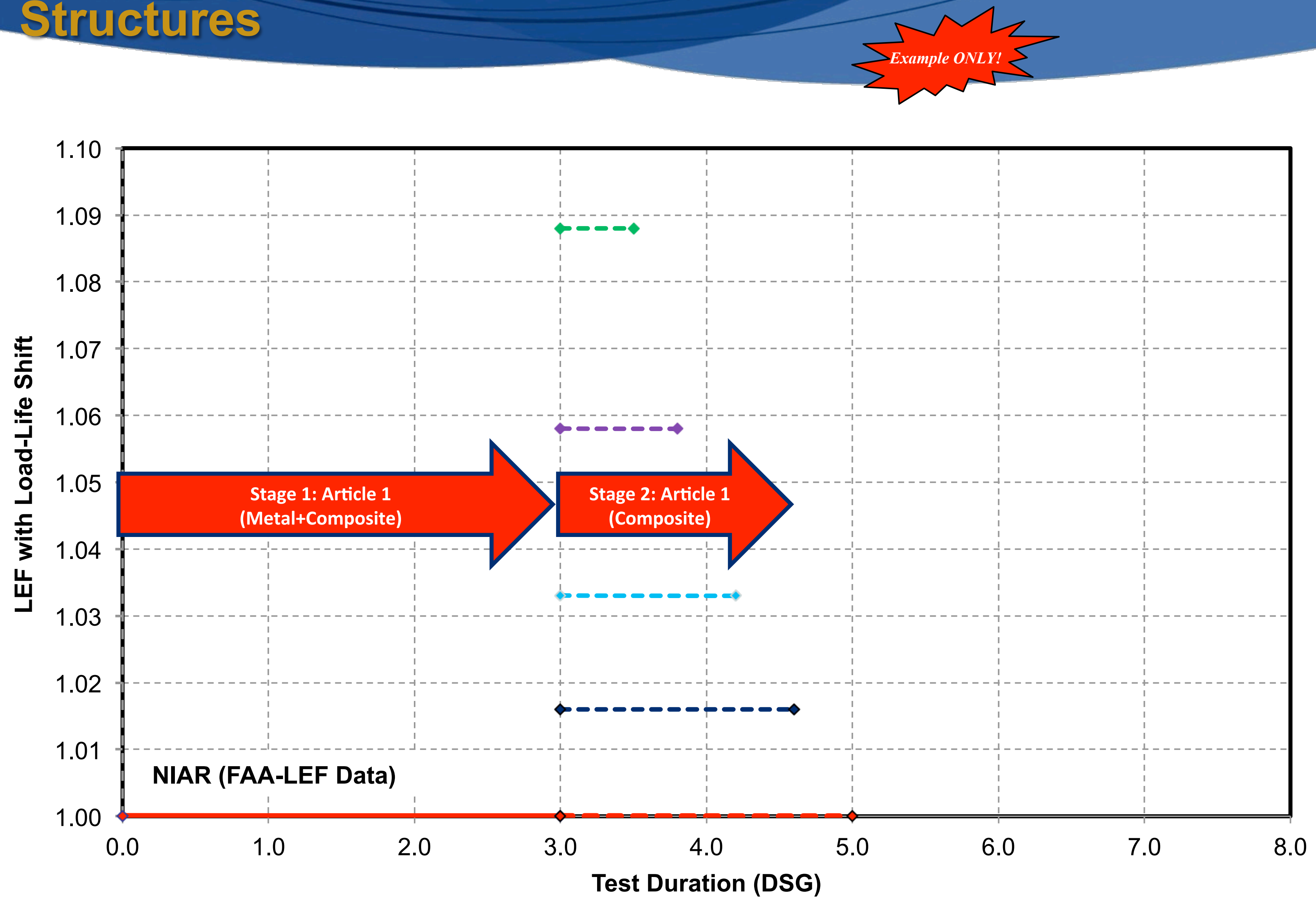
NAVY Data
LLS & 2T Comparison

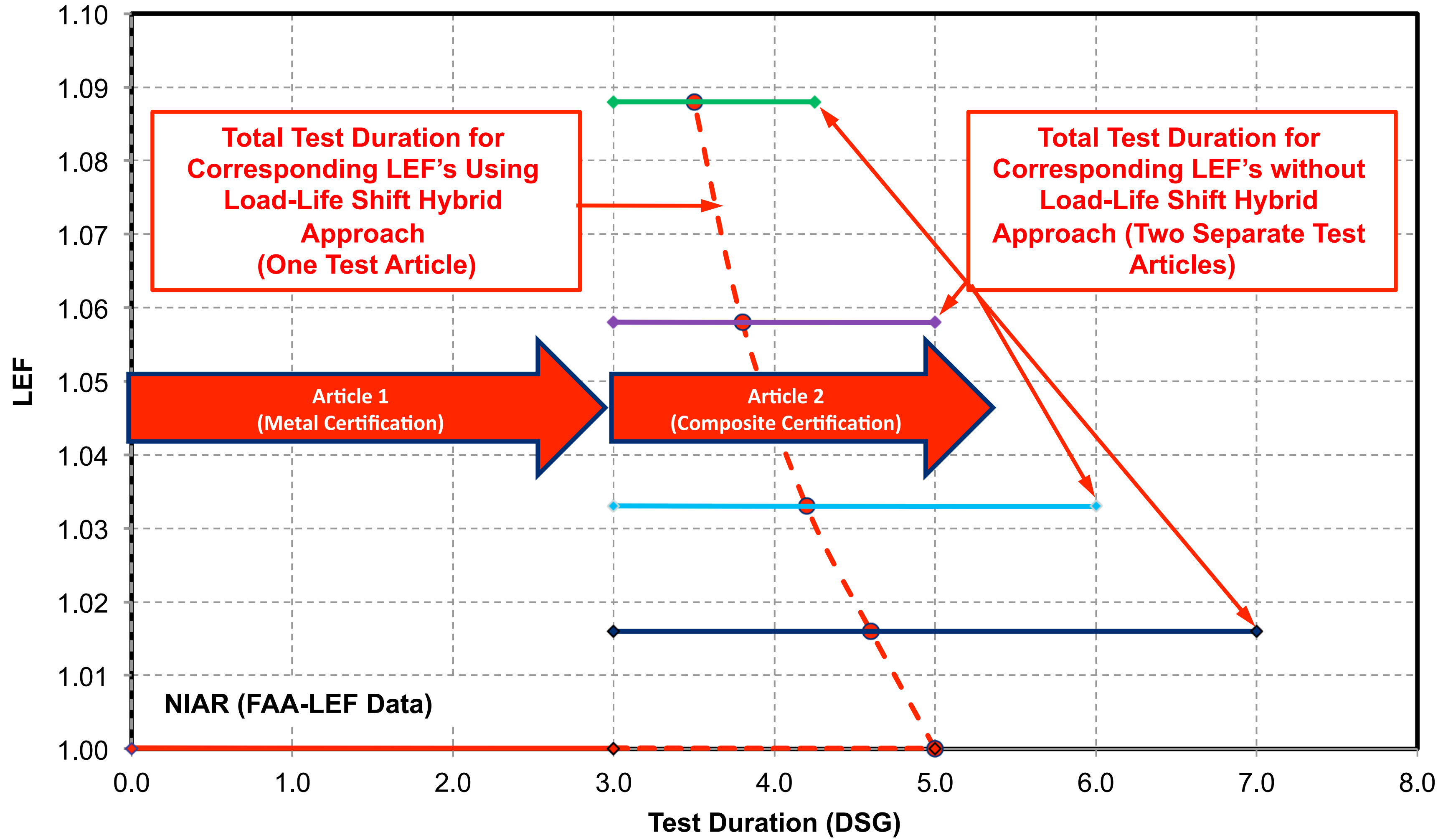


LLS Hybrid Certification for Metal-Composite Hybrid Structures



Separate Metal and Composite Certification Test Articles

Example ONLY!



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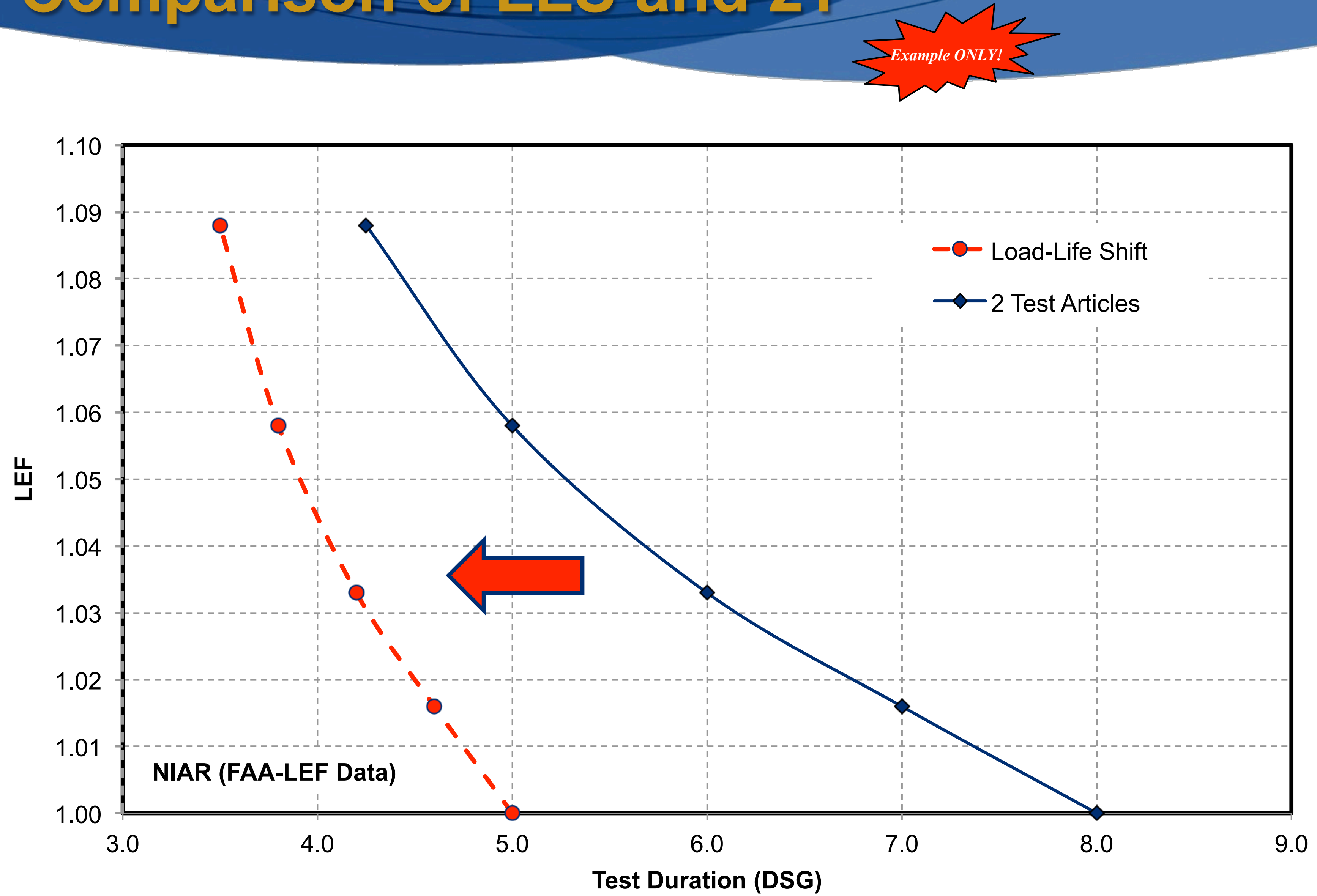
Comparison of LLS and 2T



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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, 2012.
  - 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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