NIAR Research on Certification of Composite-Metal Hybrid Structures

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FAA/Bombardier/TCCA/EASA
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Federal Aviation Administration
JAMS Joint Advanced Materials & Structures Center of Excellence
CMH-17 Composite Materials Handbook

EASA
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NAVAIR
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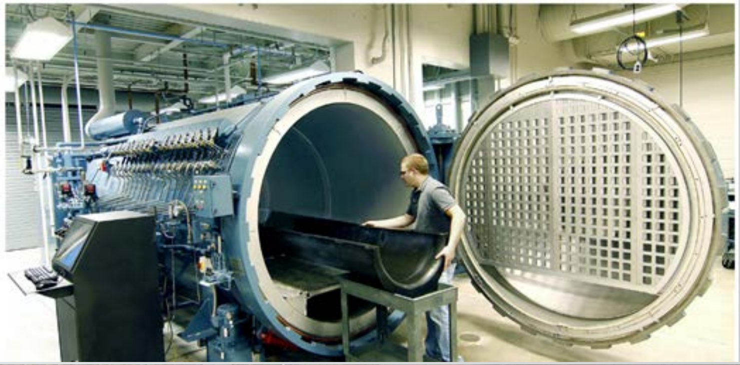
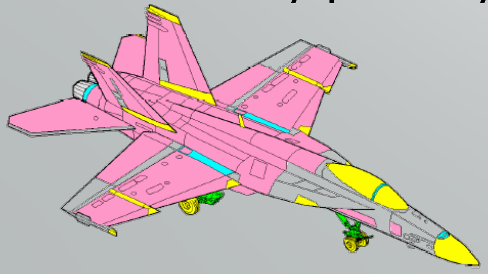


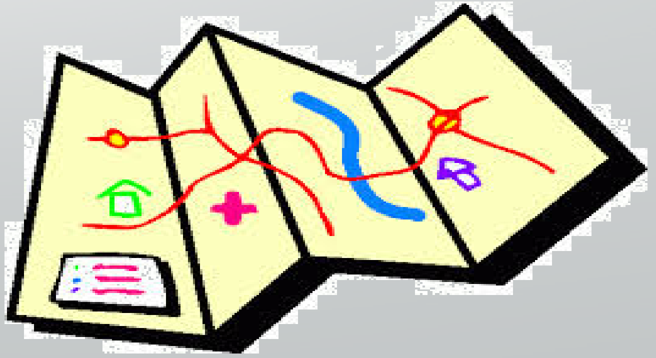
Motivation & Key Issues

- 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



Outline of the Presentation

- CMH-17 Rev. G
  - Overview of updated contents in Chapter 12 **(Damage Tolerance Chapter)**
- CMH-17 Rev. H
  - New Topics in Chapter 12 **(Damage Tolerance Chapter)**
- Overview of Hybrid Studies
  - Multi-LEF
  - Deferred Severity Spectrum
  - Sequencing Effects



CMH-17 Rev. G

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

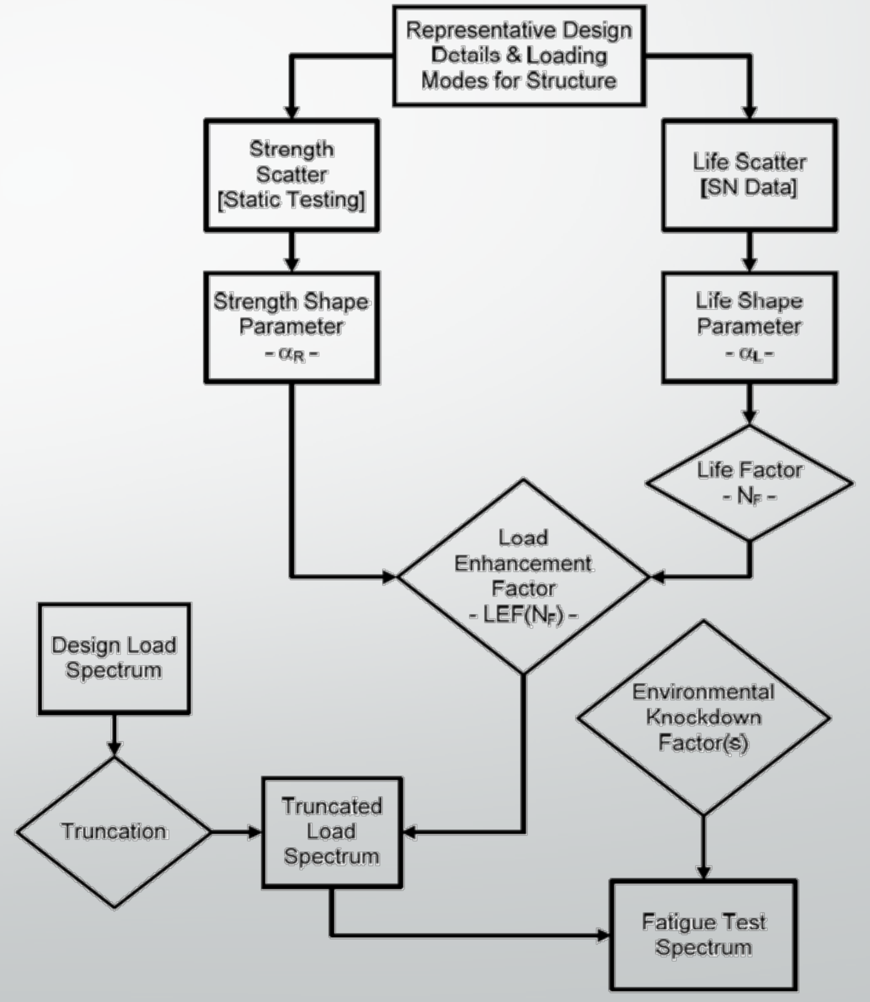


FIGURE 12.6.3 *Derivation and application of life and load-enhancement factors through scatter analysis of composite test data.*

Fatigue Scatter Analysis Techniques

- Individual Weibull
- Joint Weibull

$$\sum_{i=1}^{M}\left\{n_{fi}\cdot\left[\frac{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}\cdot\ln(x_{ij})}{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}}-\frac{1}{\hat{\alpha}}-\frac{\sum_{j=1}^{n_{fi}}\ln(x_{ij})}{n_{fi}}\right]\right\}=0$$

- Sendeckyj Equivalent Strength Model

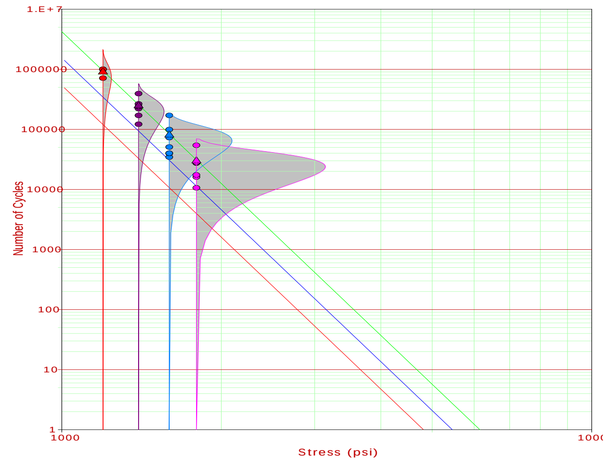
$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

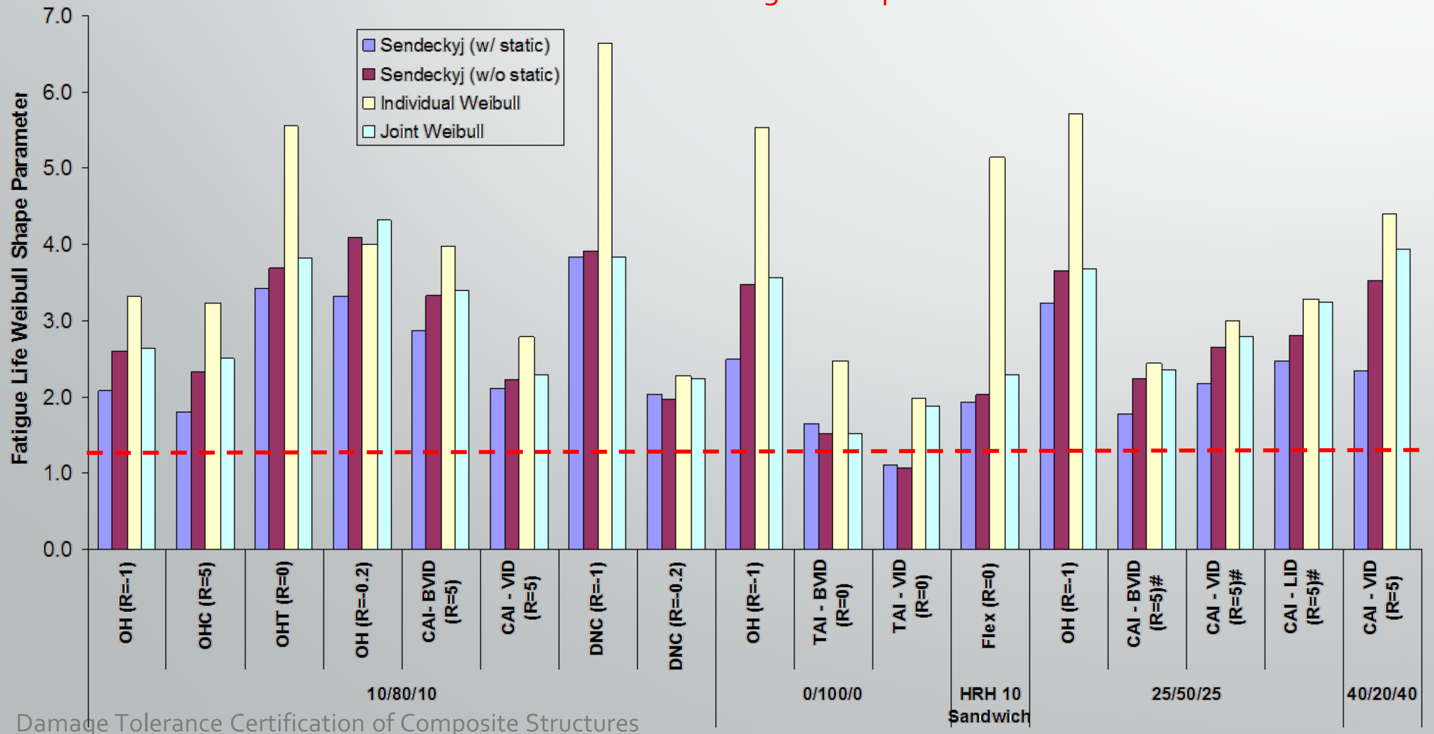
Data Pooling Techniques

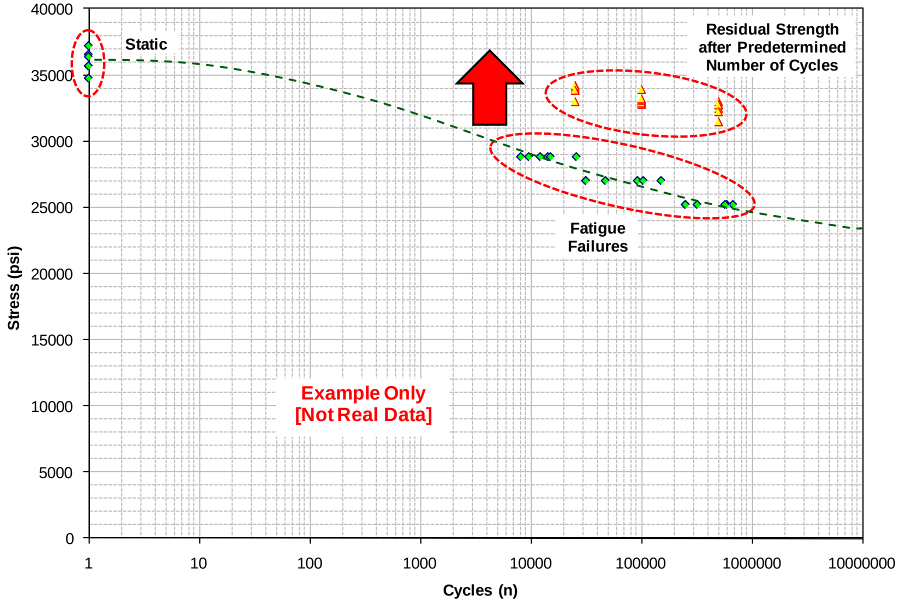
NADC Fatigue Scatter Analysis

$\alpha_I > \alpha_J > \alpha_S$

NAVY LEF APPROACH IS NOT RESTRICTED TO THESE SCATTER ANALYSIS METHODS

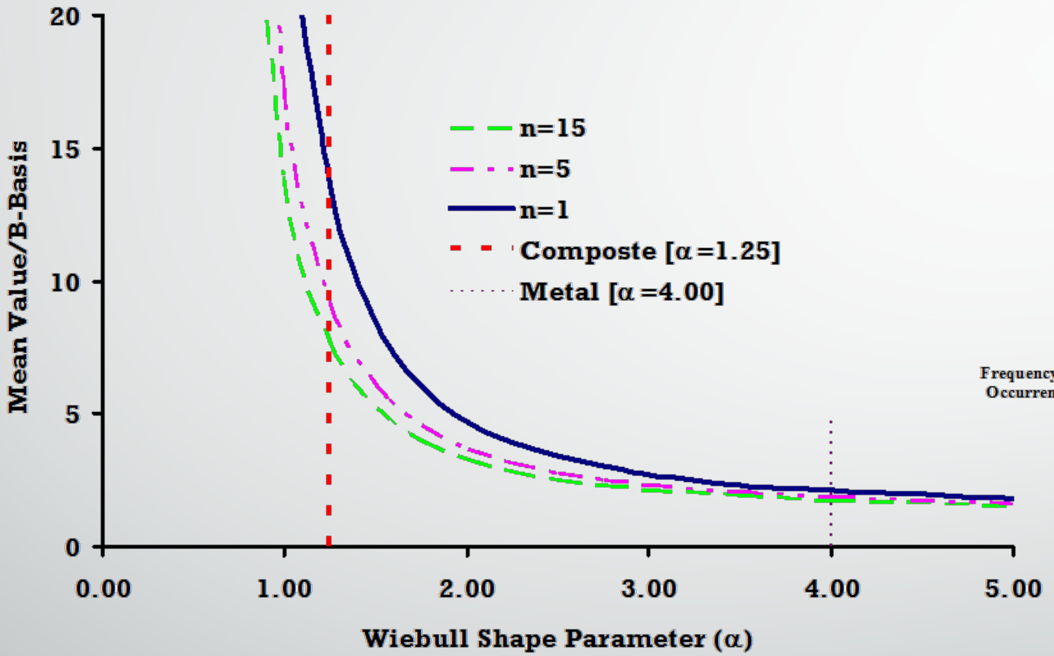






Life Factor Approach

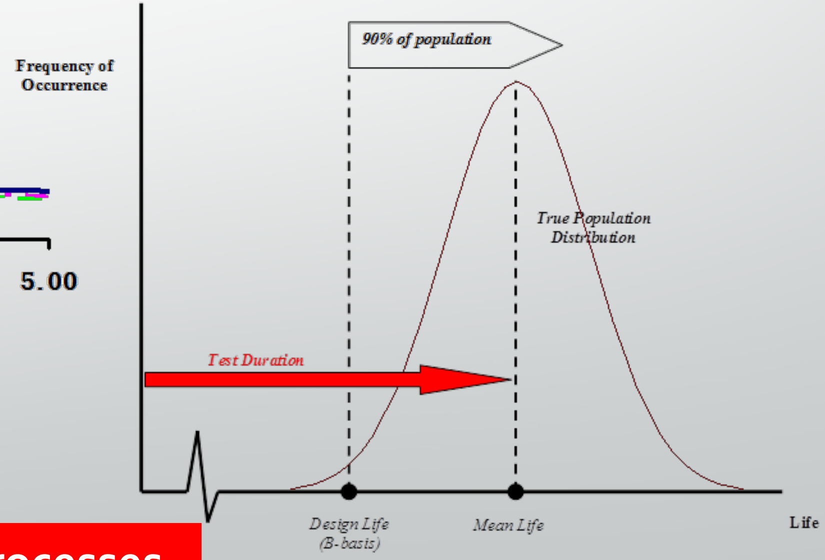
Structure is tested for additional fatigue life to achieve the desired level of reliability



	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

- Life Scatter Factor (LSF)

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



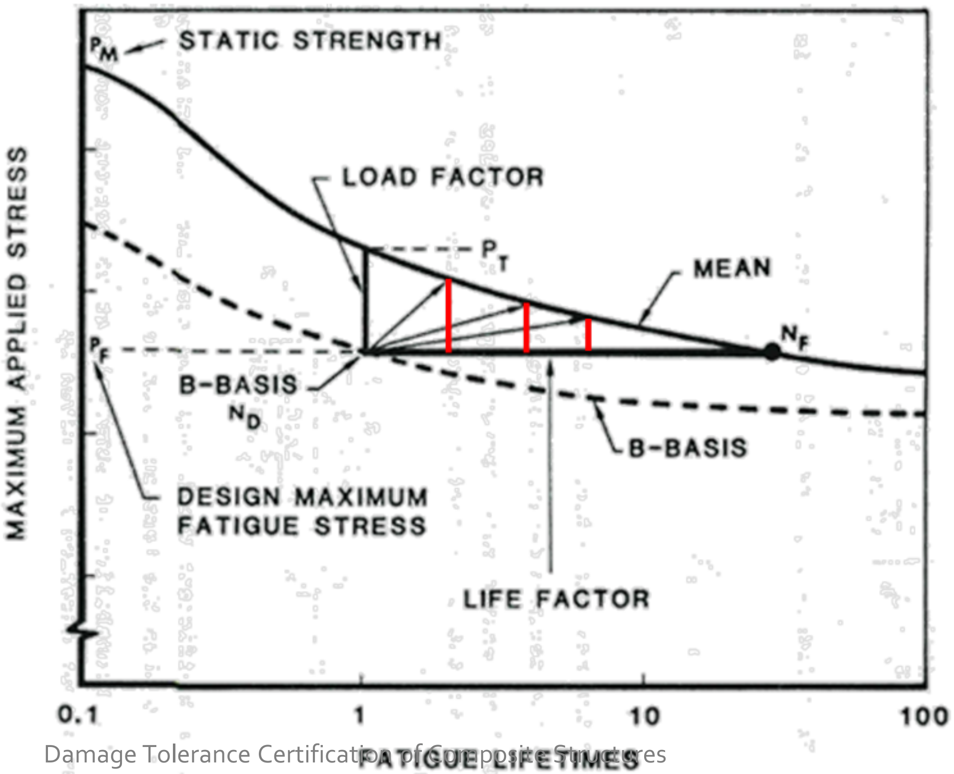
Newer composite materials/processes indicates significantly lower life factors

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

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



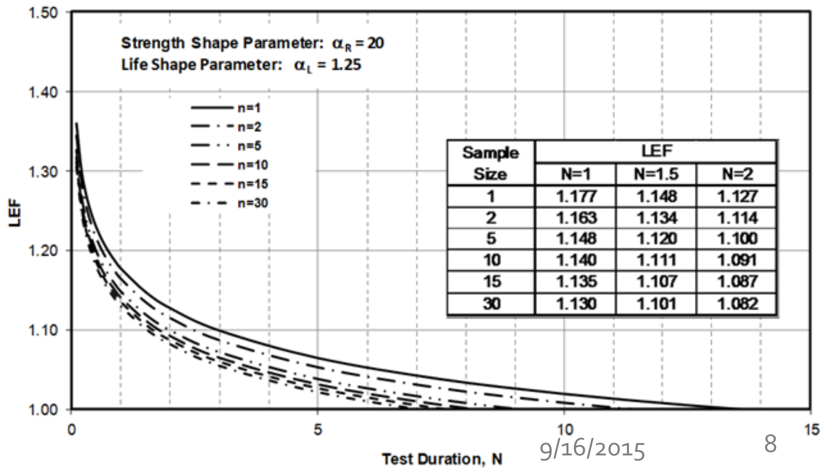
- Load Enhancement Factor (LEF)

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

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

LEF is a function of the test duration

- LEF Is a function of test duration (for various confidance levels)
- New materilas/processes
- Not an SN curve

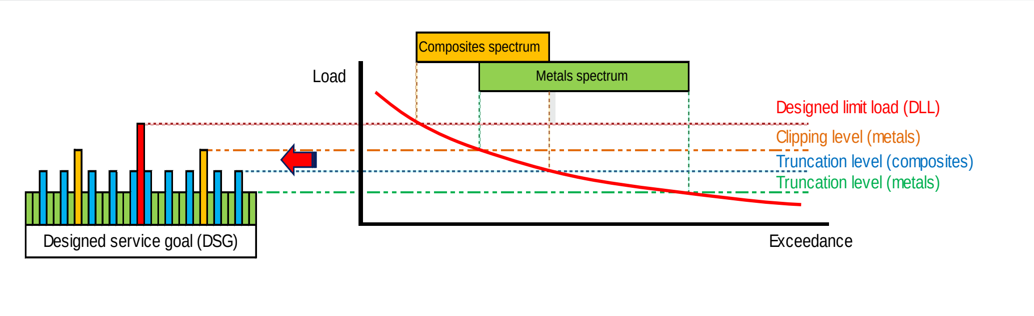


Sample Size	LEF N=1	LEF N=1.5	LEF N=2
1	1.177	1.148	1.127
2	1.163	1.134	1.114
5	1.148	1.120	1.100
10	1.140	1.111	1.091
15	1.135	1.107	1.087
30	1.130	1.101	1.082

12.6.3.4.2 LEFs for complex structure

- Modal analysis
- 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
  - Validation for failure modes with LEFs higher than that selected via modal analysis performed at element or subcomponent tests.

Guidance on Development & Application of LEF



Design Detail	Test Method	Loading Condition	Environmental Condition	Static	Fatigue - Cyclic Test R ratio (3 Stress Levels)			
					R1	R2	R3	R4
1	Method 1	1	1	B x 6				B x 3 x F
2	Method 2	2	1	B x 6				B x 3 x F
3	Method 3	3	1	B x 6	B x 3 x F			
4	Method 4	4	1	B x 6			B x 3 x F	
5	Method 5	5	1	B x 6		B x 3 x F		
5	Method 5	5	2	B x 6		B x 3 x F		

α_R (Static) α_L (Fatigue)

Notes: Minimum Requirments

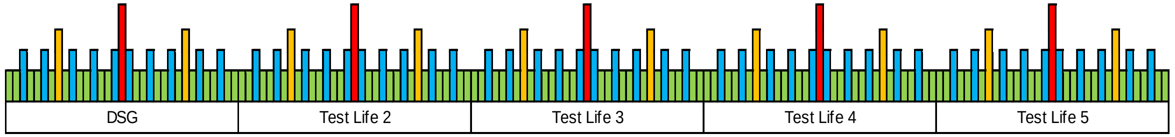
Static - B x (# of test specimens); B =
- 1, if no significant batch variability exists in lamina level
- 3, if significant batch variability exists in lamina level

Fatigue - B x (# of stress levels) x F; F =
- 6 for pooled fatigue analysis techniques, when **B = 1**
- 2 for pooled fatigue analysis techniques, when B = 3
- 2 for individual fatigue analysis techniques, when B = 3
- 6 for individual fatigue analysis techniques, when B = 1

Method 1: Life Factor Approach

$N_1 = N_2 = N_3 = \ldots\ldots = N_i = N_F$

$\rightarrow LEF_1 = LEF_2 = LEF_3 = \ldots\ldots = LEF_i = 1.0$

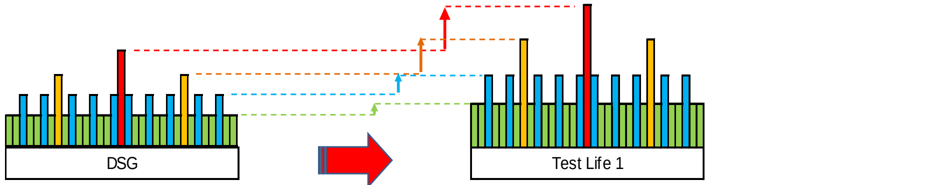


Original spectrum is repeated for Life factor; example (N_F) = 5

Method 2: Load Factor Approach

$N_1 = N_2 = N_3 = \ldots\ldots = N_i = 1$

$\rightarrow LEF_1 = LEF_2 = LEF_3 = \ldots\ldots = LEF_i = LEF_{@N=1}$



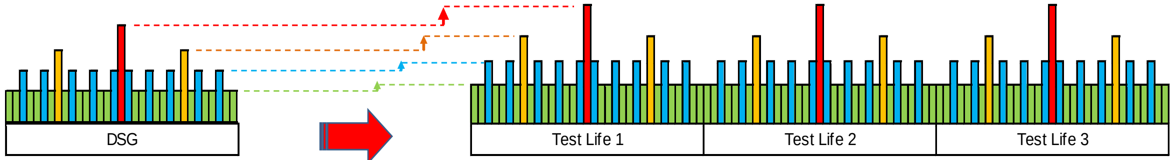
Original Spectrum is multiplied by LEF for N = 1

with Load Factor (N = 1 for $LEF_1 = LEF_2 = LEF_3 = LEF_4 = LEF_{@ N=1}$)

Method 3: Combined Load-Life Factor (LEF) Approach

$N_1 = N_2 = N_3 = \ldots\ldots = N_i$

$\rightarrow LEF_1 = LEF_2 = LEF_3 = \ldots\ldots = LEF_i$



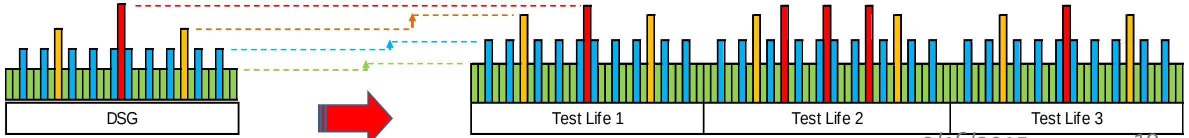
Original Spectrum is multiplied by appropriate LEF

with combined load-life factor (example: N = 3 < N_F for $LEF_1 = LEF_2 = LEF_3 = LEF_4$)

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

$N_1 \neq N_2 \neq N_3 \neq \ldots\ldots \neq N_i$

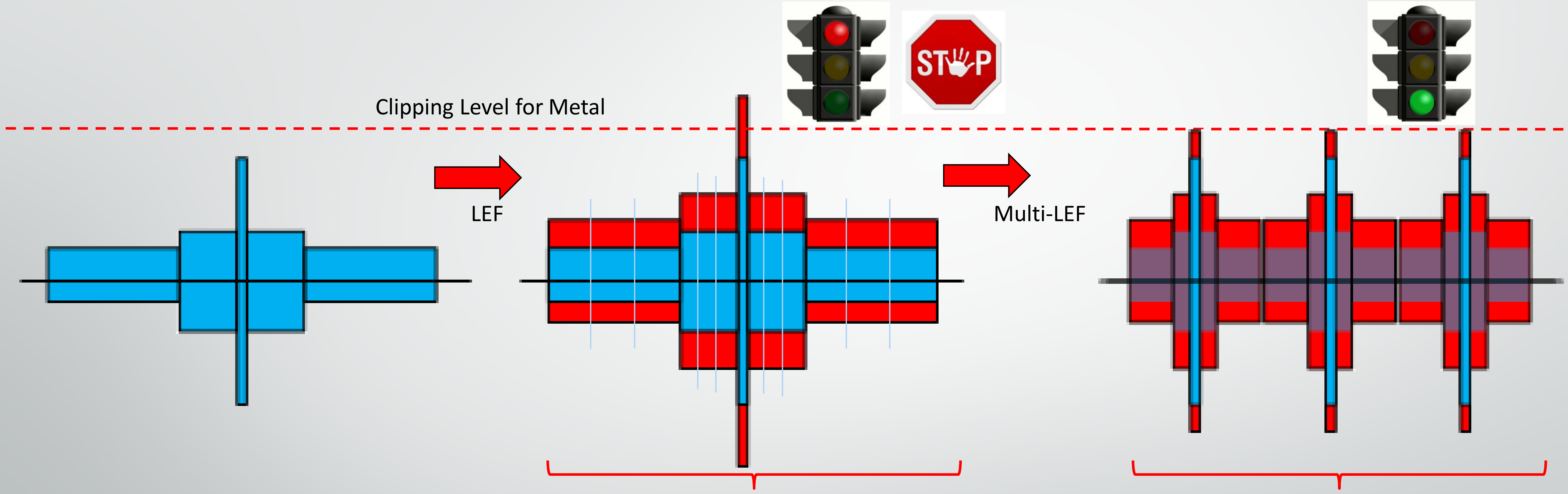
$\rightarrow LEF_1 \neq LEF_2 \neq LEF_3 \neq \ldots\ldots = LEF_i$



Original Spectrum is multiplied by appropriate LEF

with multiple combined load-life factors (example: N = 3 < N_F for $LEF_2 = LEF_3 = LEF_4 \neq LEF_1 = 1.0$ with N = N_F

Multi-LEF Approach for Hybrid Structures

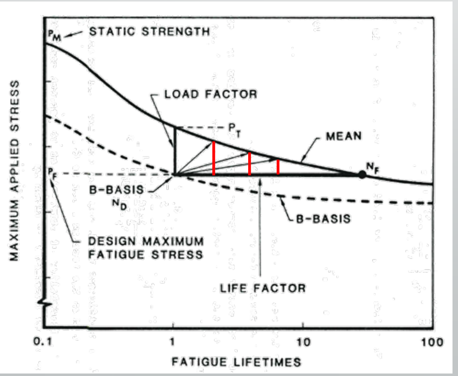


Repeated for required N

Repeated for required N

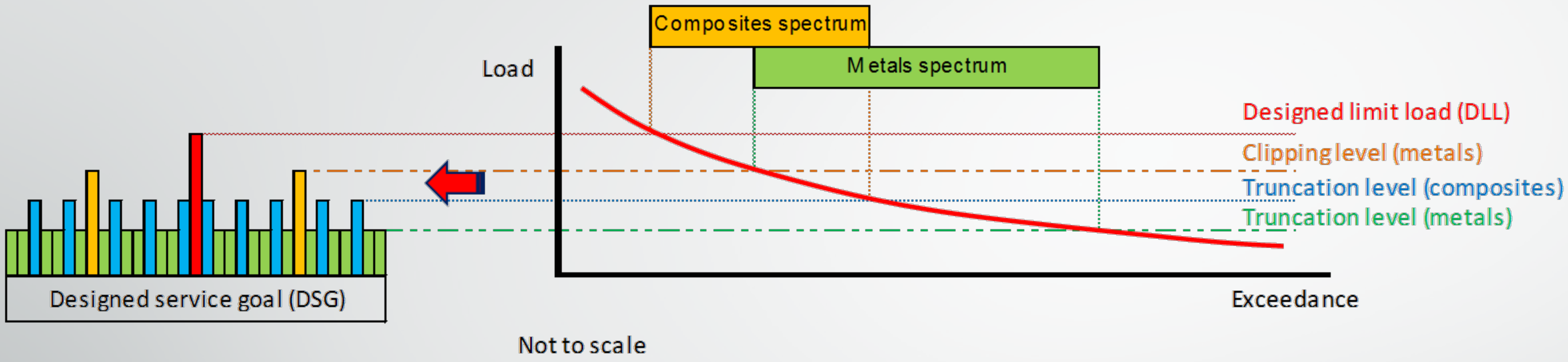
Original Spectrum Blocks

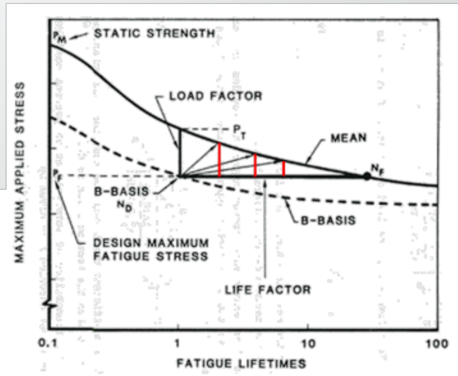
Test Spectrum Blocks after LEF



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

Multi-LEF Approach for Hybrid Structures

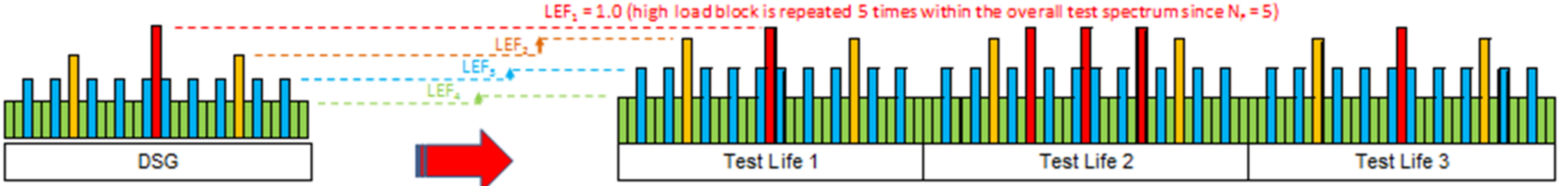




Method 4: Multi Load-Life Factor (multi-LEF) Approach

$N_1 \neq N_2 \neq N_3 \neq \ldots\ldots\ldots \neq N_i$

$\rightarrow LEF_1 \neq LEF_2 \neq LEF_3 \neq \ldots\ldots\ldots = LEF_i$



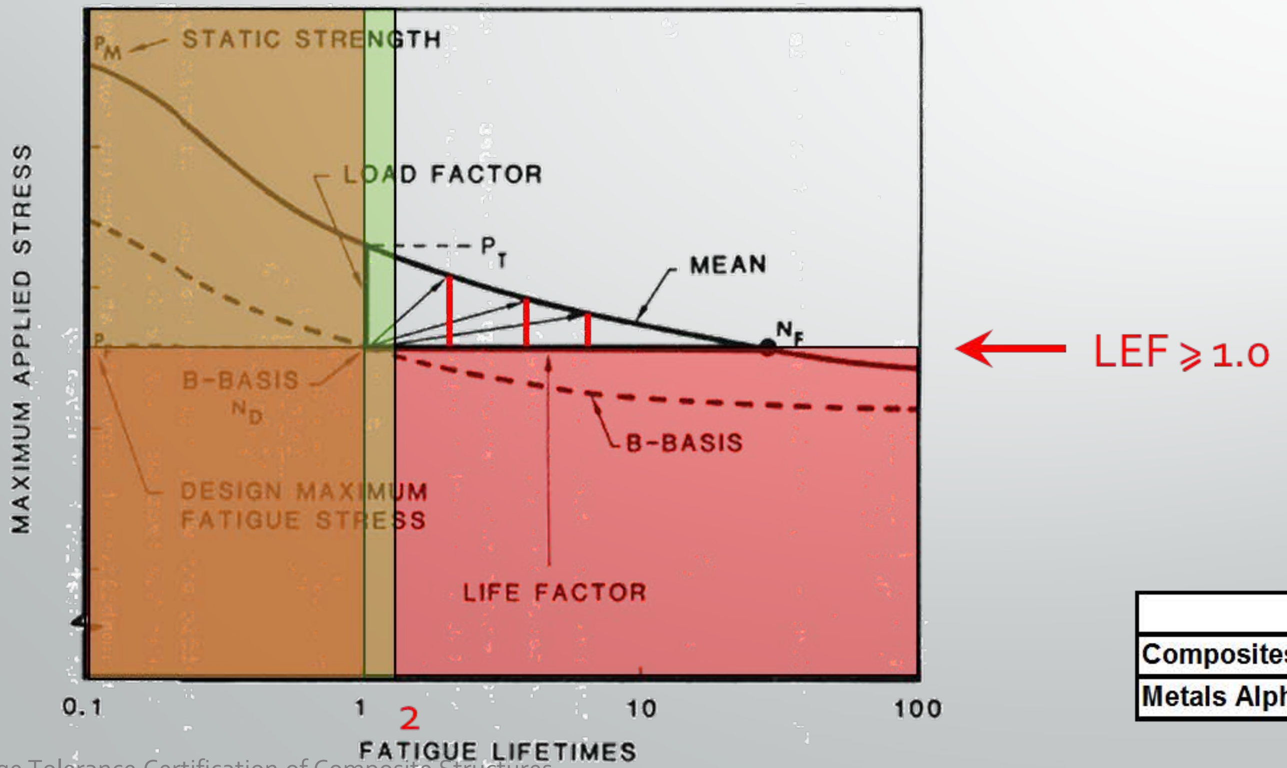
Original Spectrum is multiplied by appropriate LEF

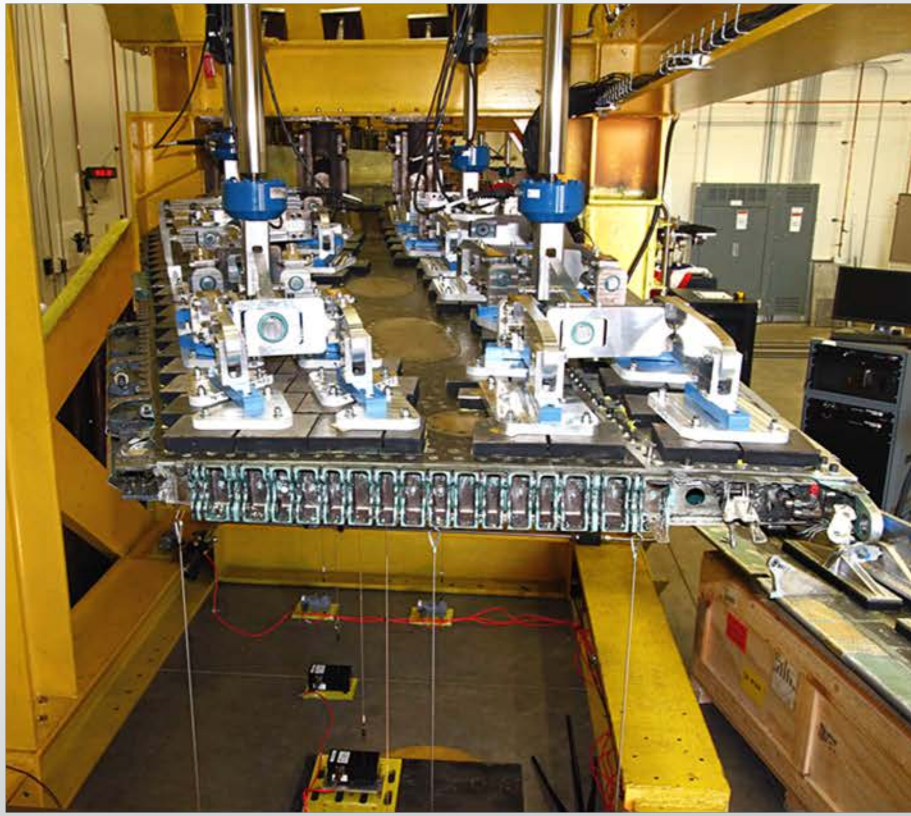
with multiple combined load-life factors (example: $N = 3 < N_F$ for $LEF_2 = LEF_3 = LEF_4 \neq LEF_1 = 1.0$ with N = N

CMH-17 Rev. H

New Topics in Chapter 12 (Damage Tolerance Chapter)

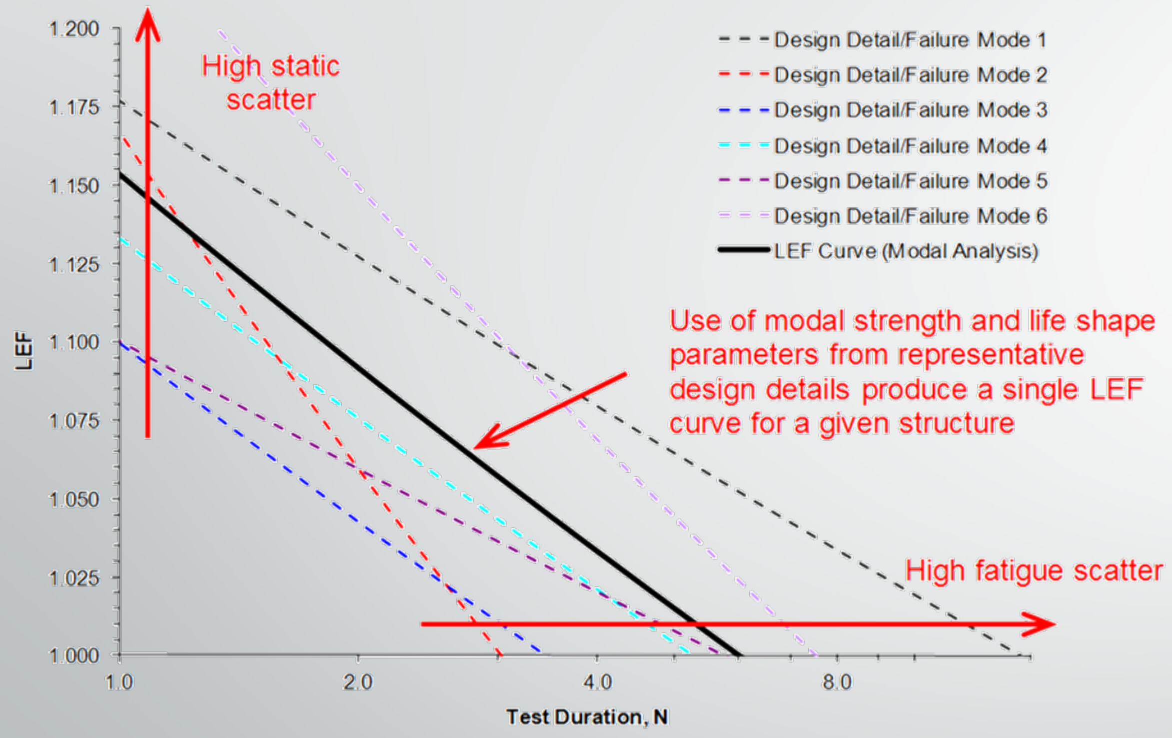
- **Boundaries of LEF Curve**
  - Test duration must be greater than 1 DSG
    - Hybrid (metal-composites) structures: minimum 2 DSG → LOV for Metals (LOV for Composites?)
  - LEF must be greater than 1.0

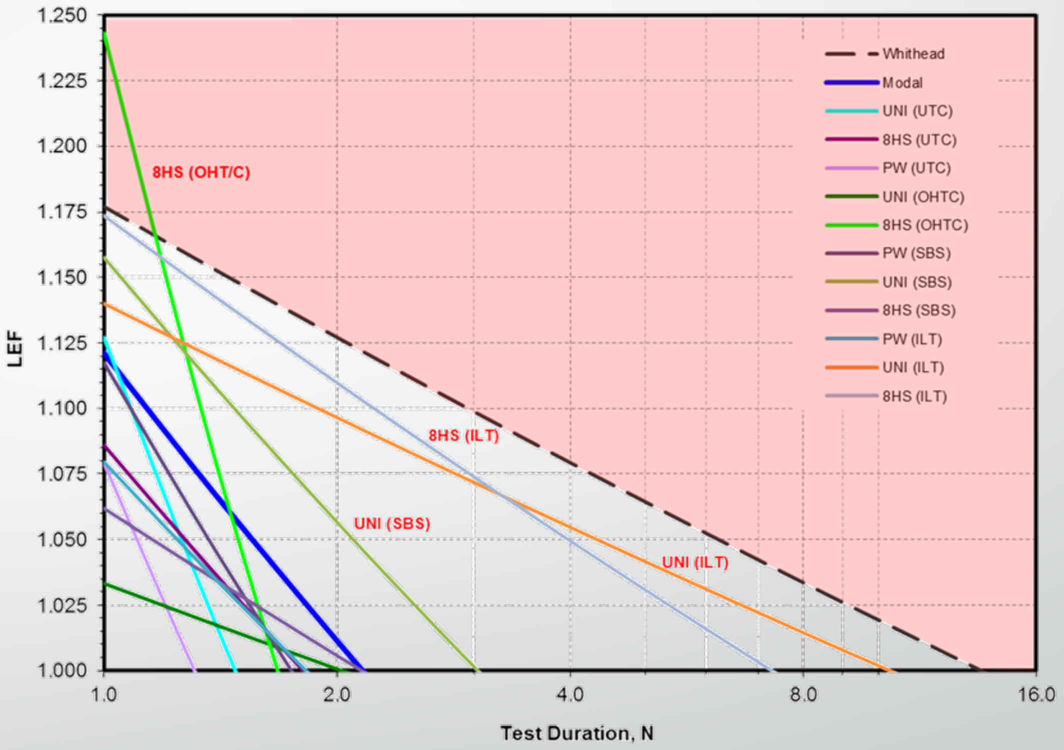




	n = 1	n = 5	n = 15
Composites Alpha = 1.25	13.558	9.143	7.625
Metals Alpha = 4.0	2.093	1.851	1.749

Fidelity of Modal Analysis & Substantiation of Using NADC LEF



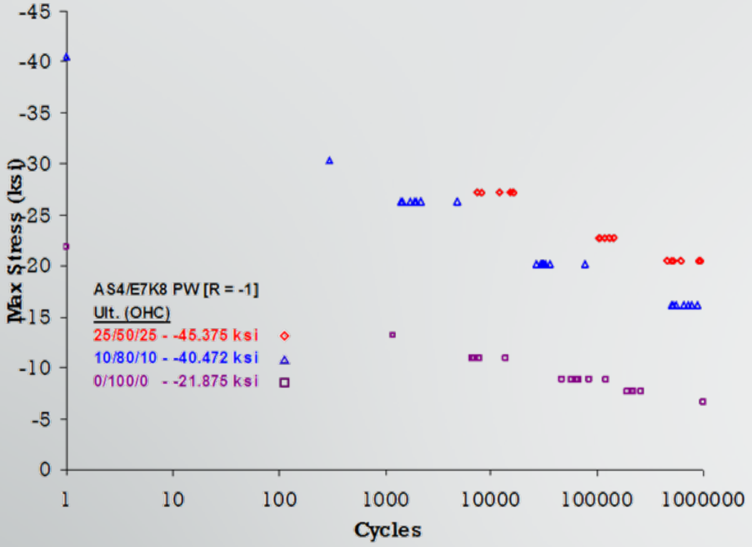


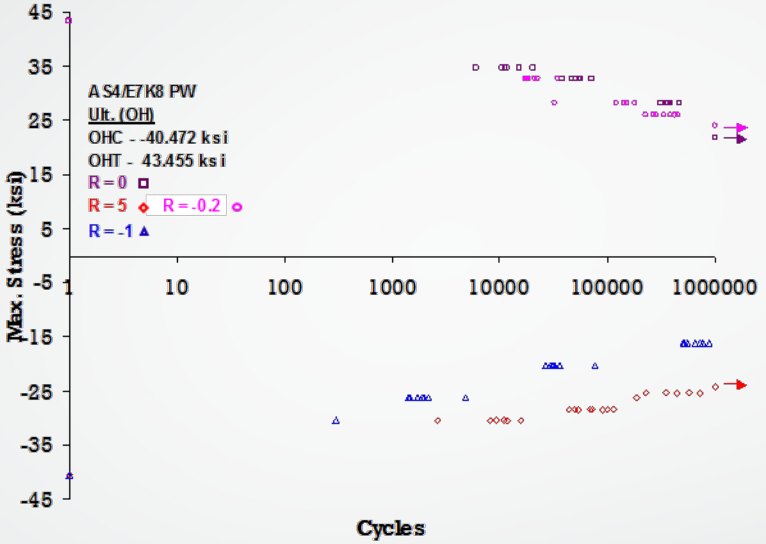
Failure modes with large scatter shall be interogated at element/sub-component level(s)

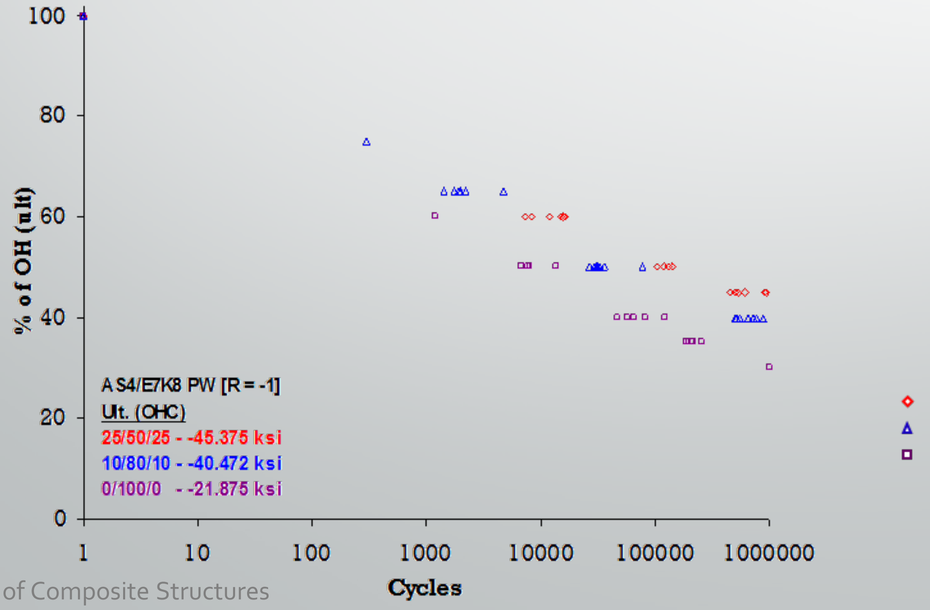
Use of historic Navy LEF curve must be substantiated with a reduced LEF test matrix

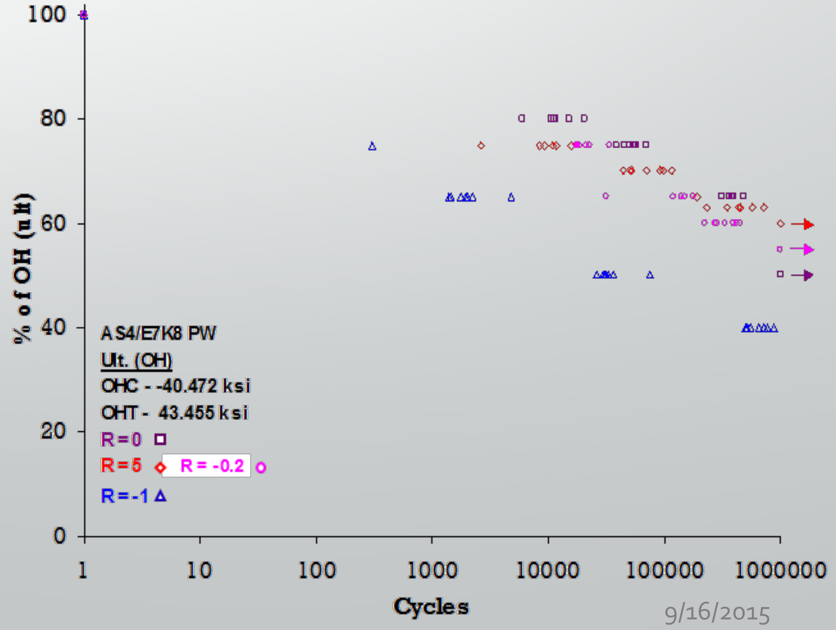
NIAR Wichita State University National Institute for Aviation Research

Effects of Layup Sequence and R-Ratios

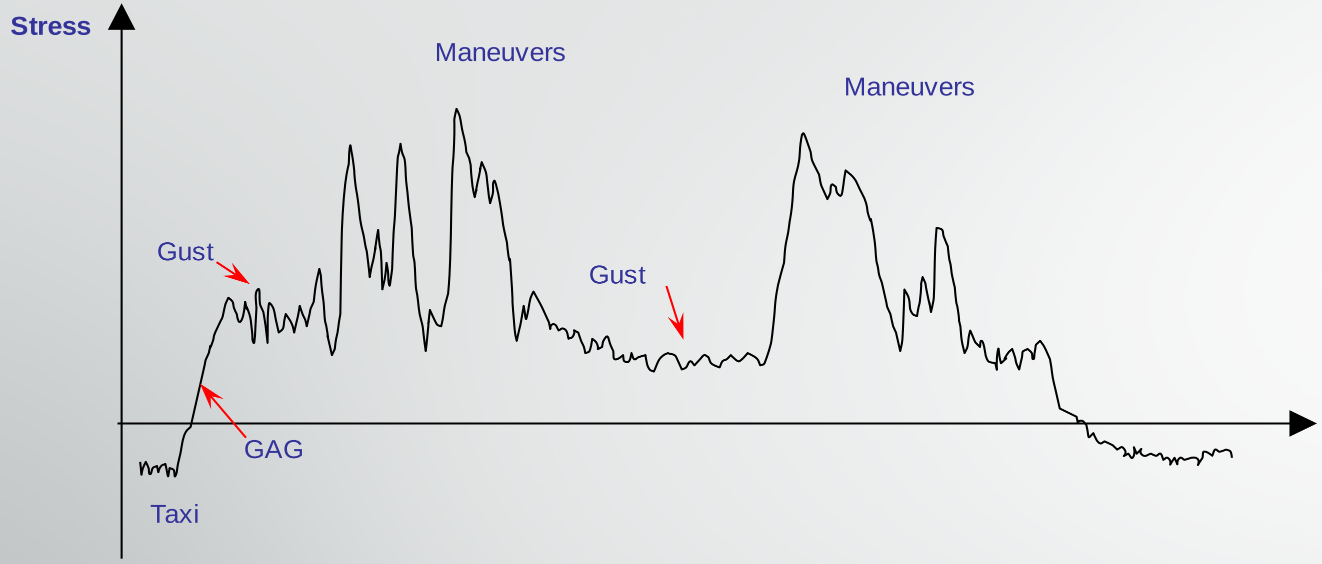




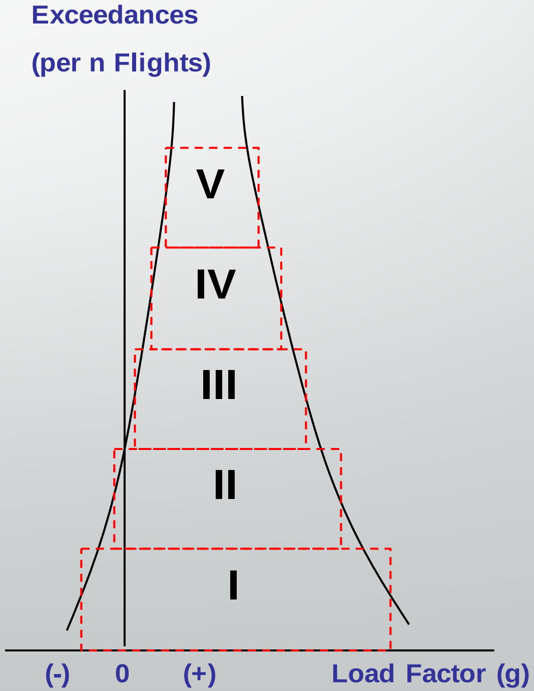




Exceedance Curves & Test Spectrum Development



Industry support is needed.



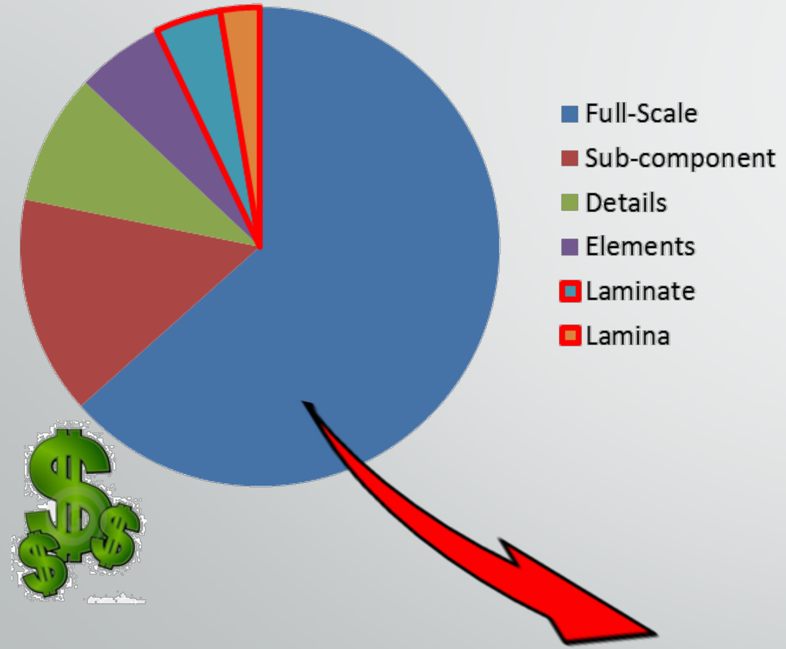
- Flight/taxi test data are converted to a exceedance curves for different events
- Exceedance curves are then converted into load spectra
- Spectrum (sequence) is developed
- Analysis spectrum is then modified for cyclic test
  - Truncation & clipping high loads to avoid retardation/plasticity)
  - Life factor to account for uncertainties in usage
  - Load-enhancement factor to reduce test duration for composites

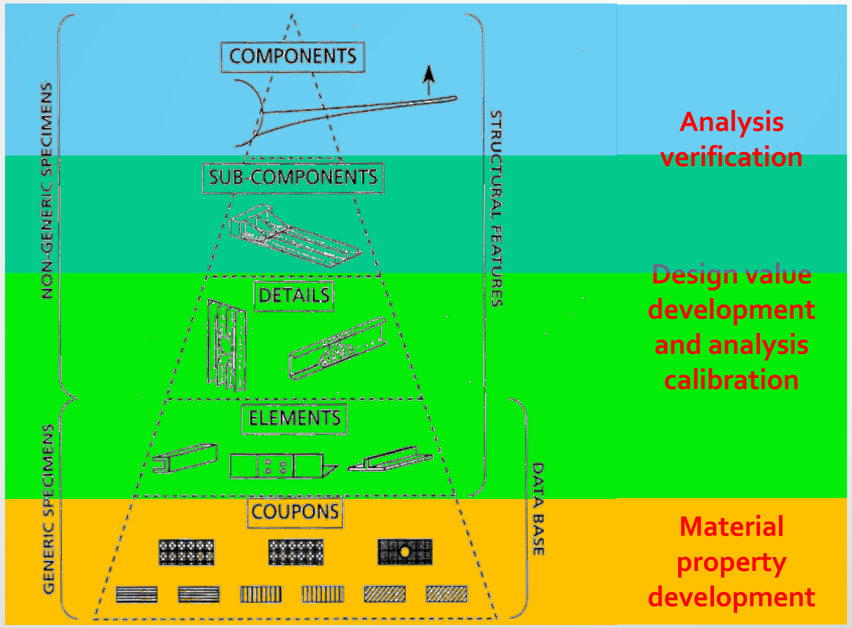
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

- 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)
  - 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
  - Multi-LEF Approach
  - Deferred Spectrum Approach

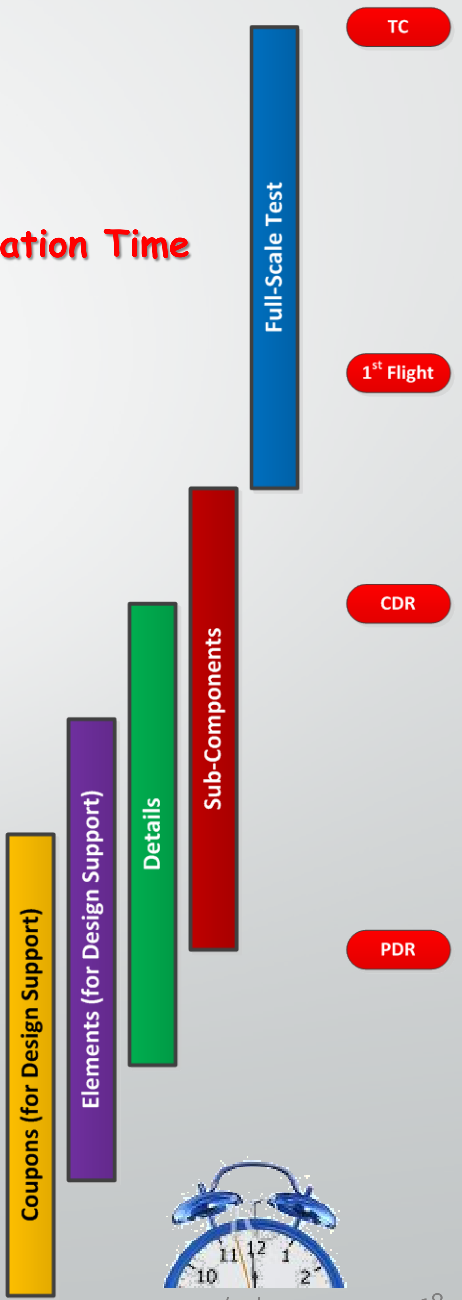
Certification Cost & Time

~ Certification Cost



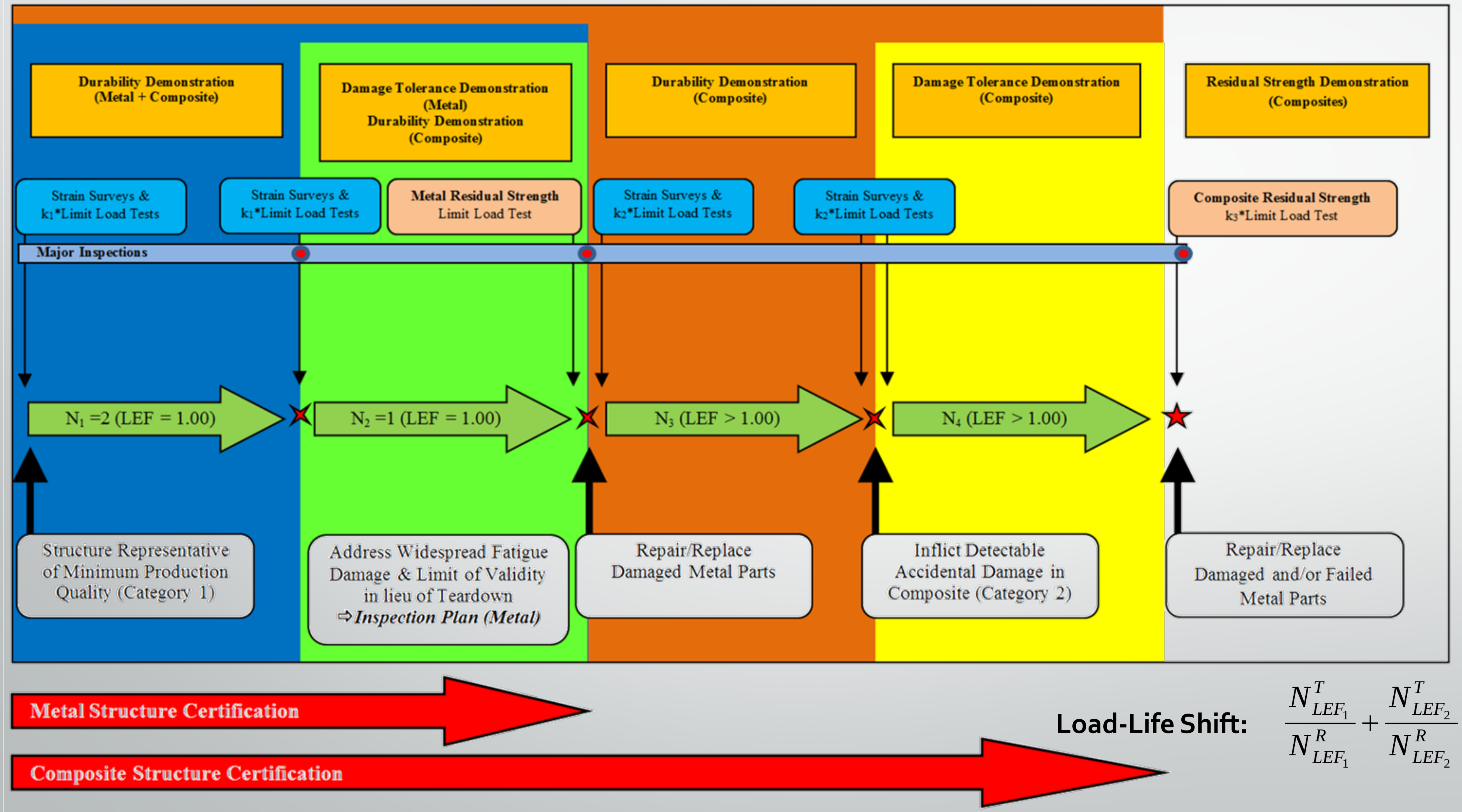


~ Certification Time



Full-scale test is a significant portion of the overall budget
Improvements to full-scale test duration → Reduction to overall test timeline

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

Load-Life Shift:

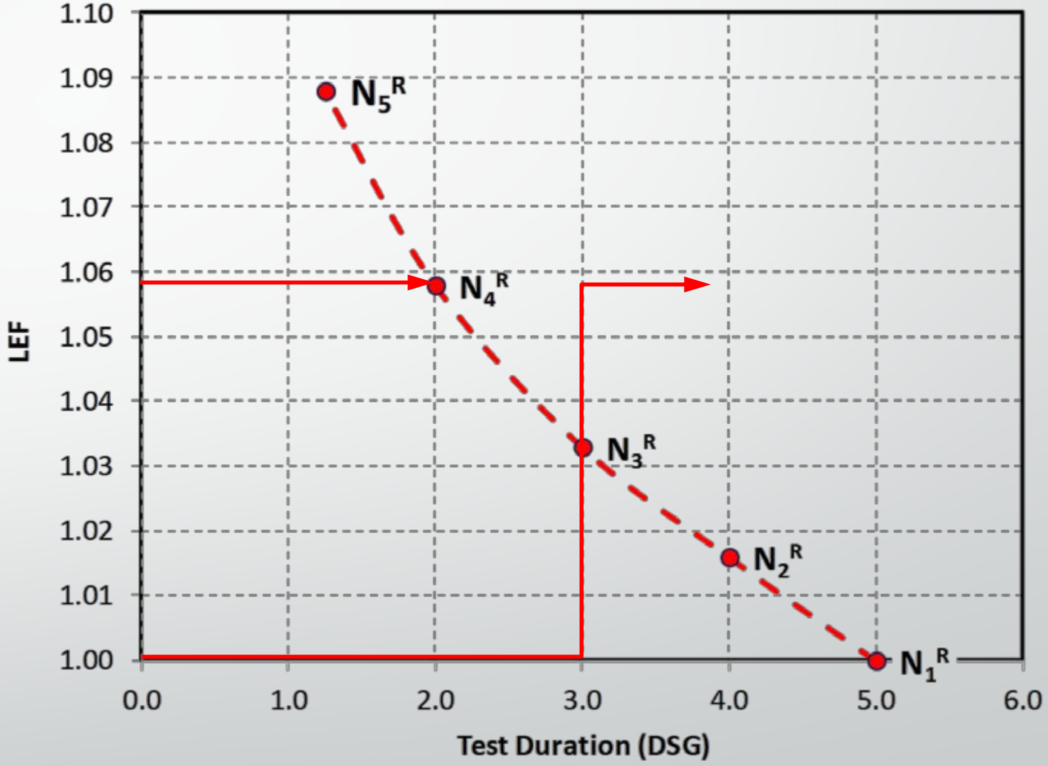
$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

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.

Load-Life Shift

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

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



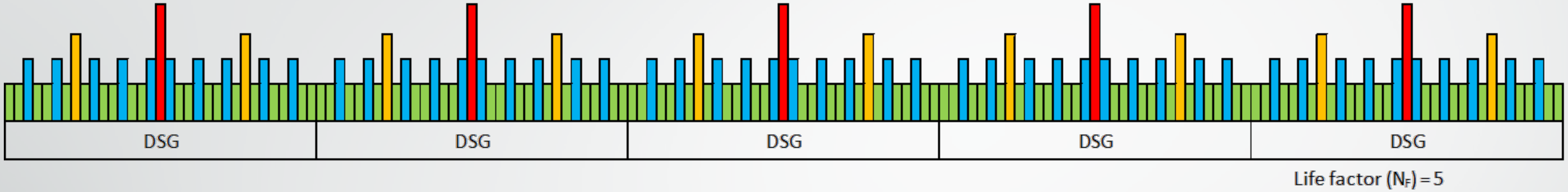
- Simplified (two-step) version:

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

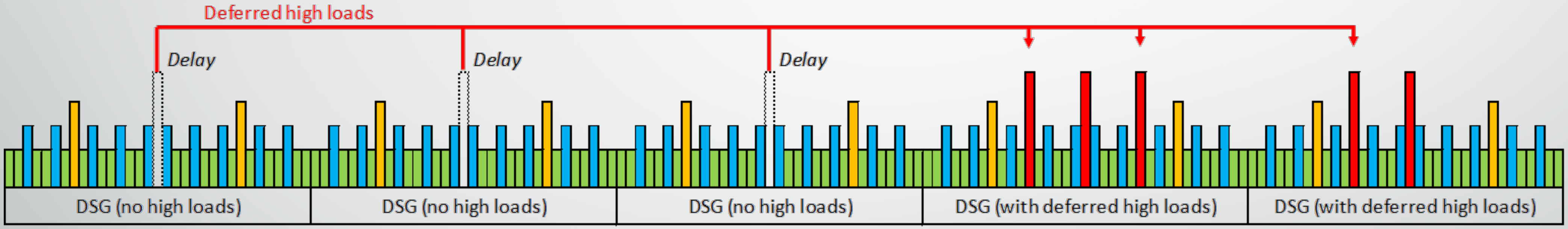
REF: Seneviratne, W. P., and Tomblin, J. S., **“Certification of Composite-Metal Hybrid Structures using Load-Enhancement Factors,”** *FAA Joint Advanced Materials and Structures (JAMS)/Aircraft Airworthiness and Sustainment (AA&S),* Baltimore, MD, 2012.

Deferred Spectrum for Hybrid FSFT

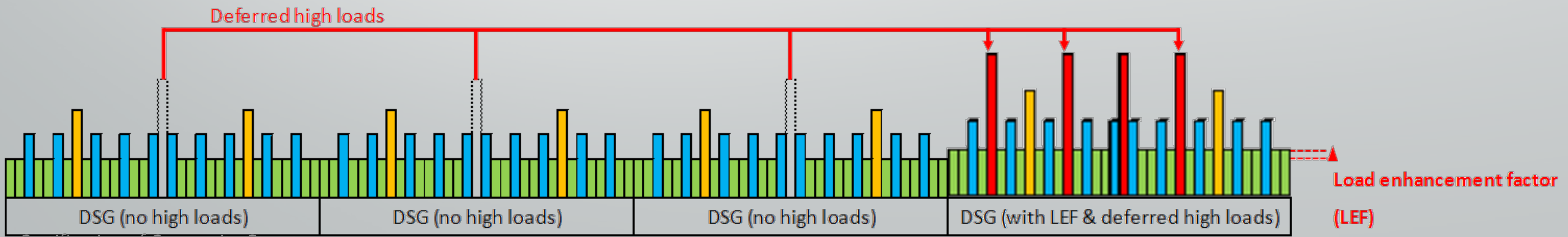
Method 1: Life Factor Approach



Method 2: Deferred High Loads

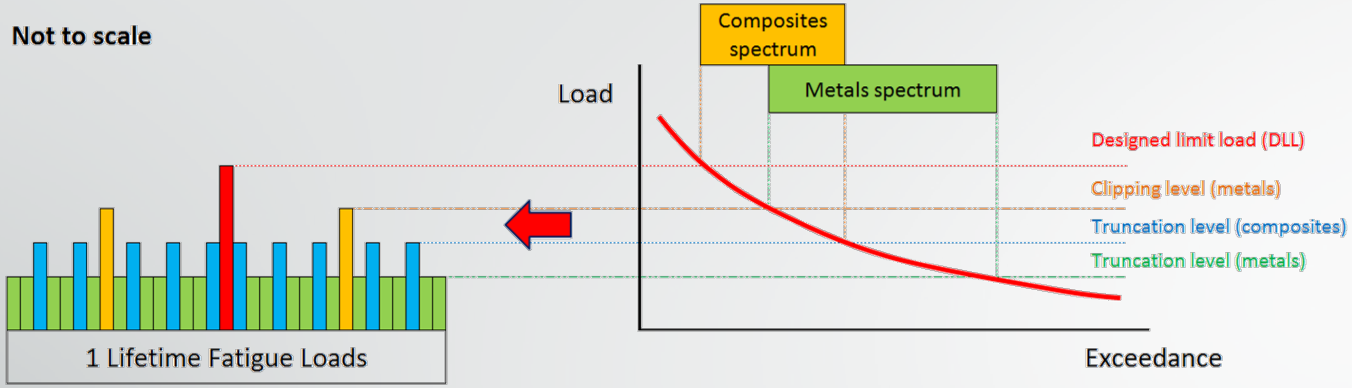


Method 3: Deferred High Loads with Load Life Shift



Deferred Spectrum for Hybrid FSFT (contd.)

Not to scale



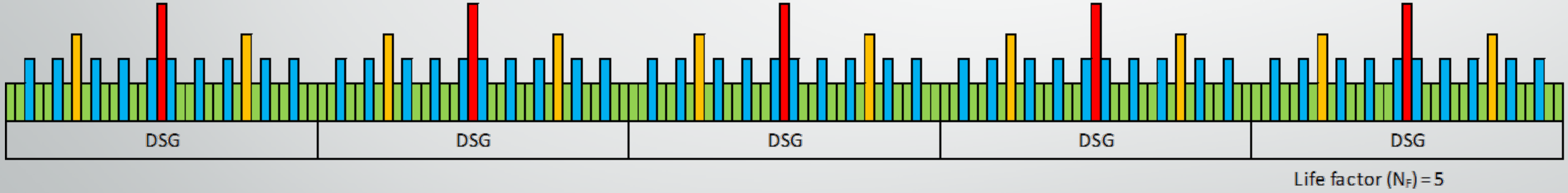
Metals:

severe flight loads result in crack-growth retardation

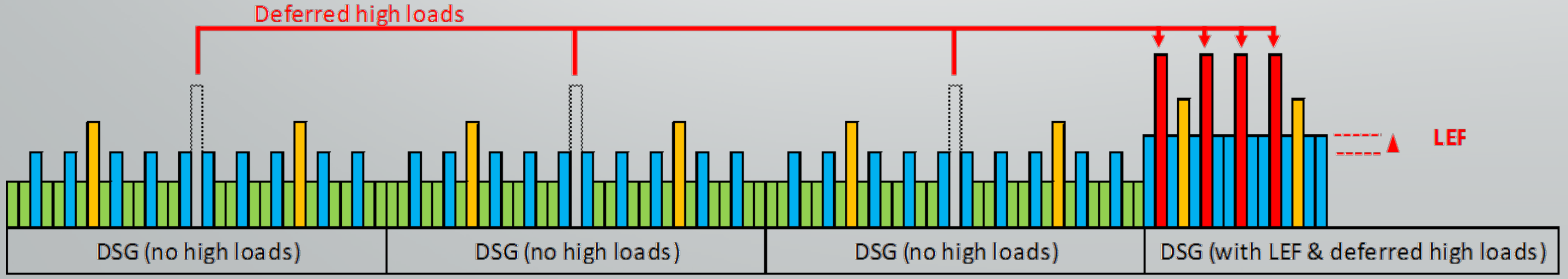
Composites:

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

Method 1: Life Factor Approach

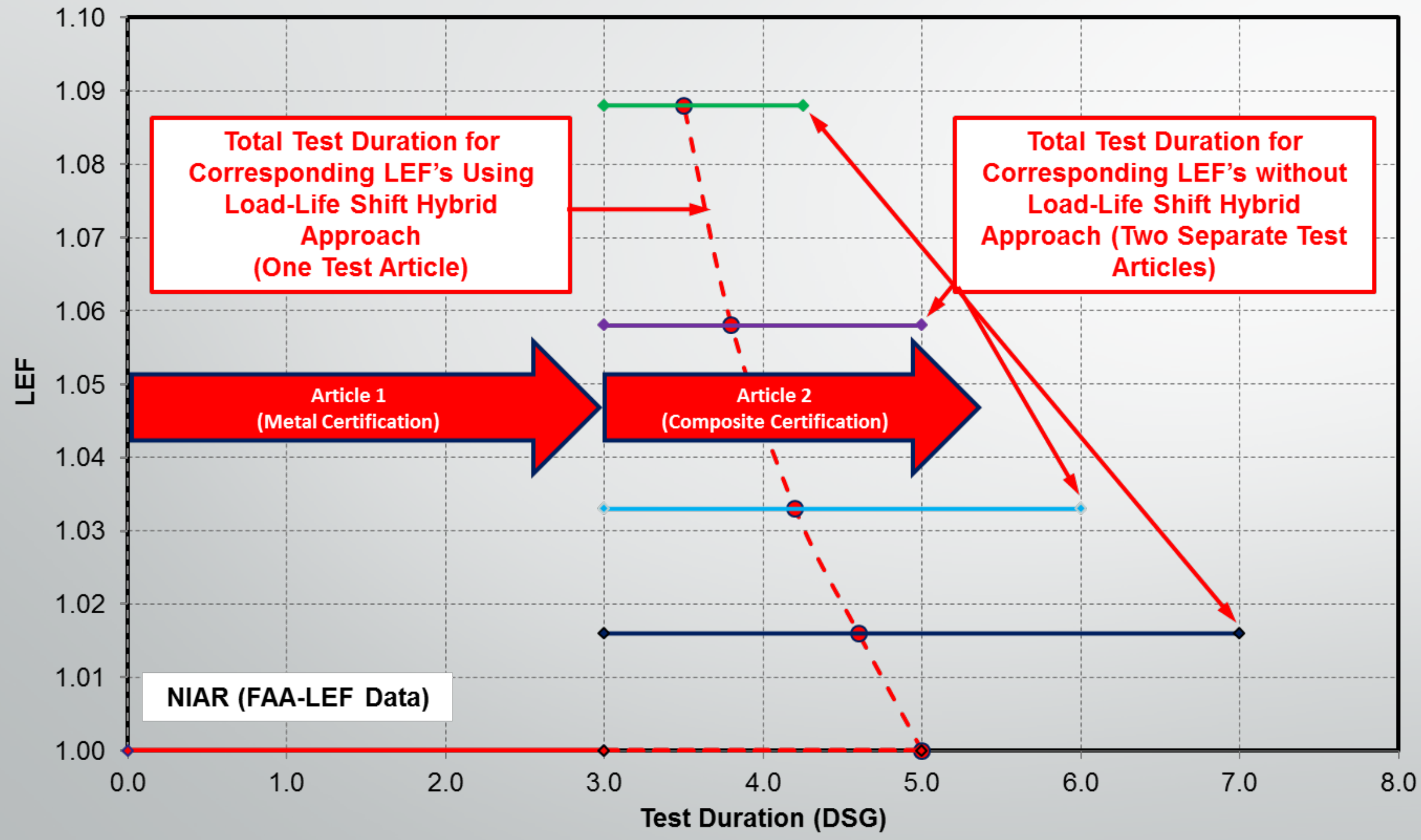


Method 3: Deferred High Loads with Load Life Shift (Composite Spectrum only)

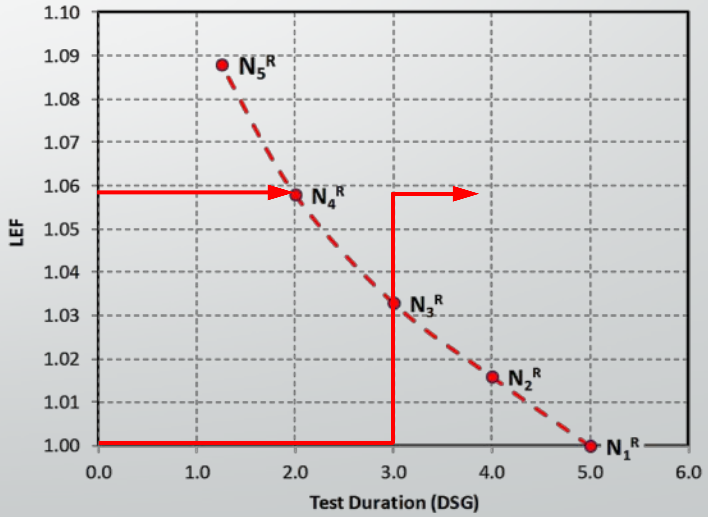


Cycles below composites truncation level (green) are eliminated after 3 DSG

Separate Metal and Composite Certification Test Articles



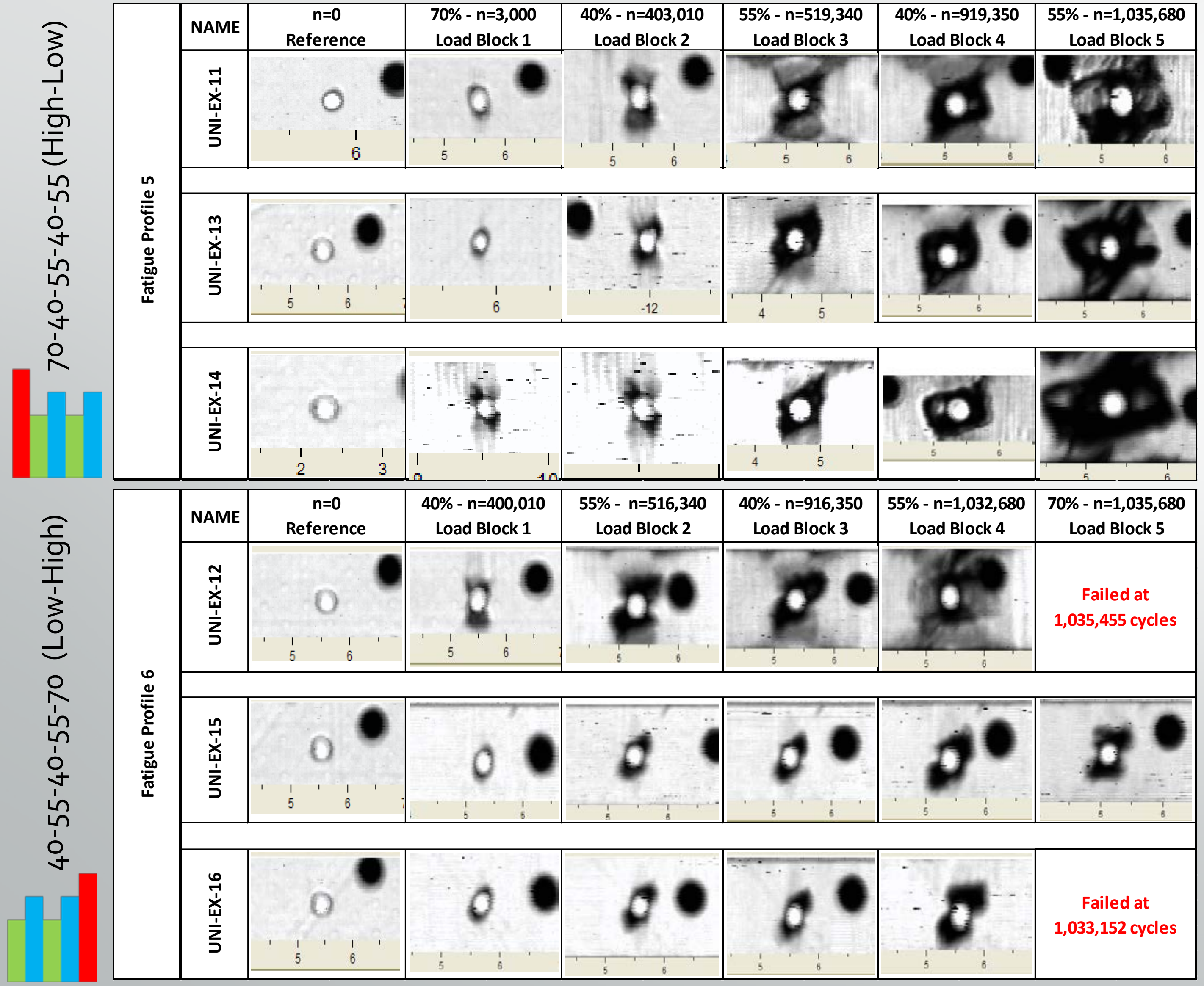
Option	LEF	Required Test Duration without LLS	Required Test Duration with LLS	Total Test Duration
1	1.000	5.0	2.0	**5.0**
2	1.016	4.0	1.6	**4.6**
3	1.033	3.0	1.2	**4.2**
4	1.058	2.0	0.8	**3.8**
5	1.088	1.3	0.5	**3.5**



Load-Life Shift:

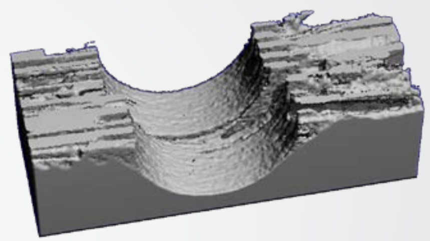
$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

Load Sequencing Effects – Open Hole Tension/Compression (UNI)



6 spec. survived profile 5

4 spec. failed and 2 spec. survived profile 6



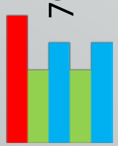
High-Low			Low-High		
Spectrum Block	% of Ultimate	Number of Cycles in Block	Spectrum Block	% of Ultimate	Number of Cycles in Block
1	70	3000	1	40	400010
2	40	400010	2	55	116330
3	55	116330	3	40	400010
4	40	400010	4	55	116330
5	55	116330	5	70	3000

Lower level building-blocks of testing:

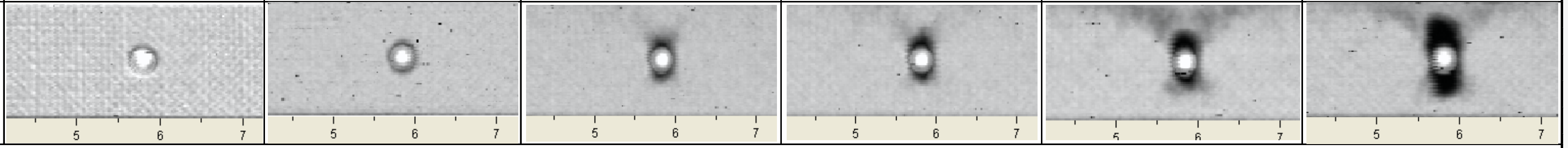
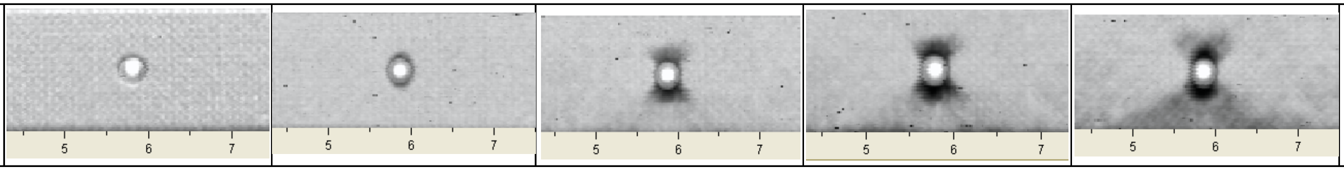
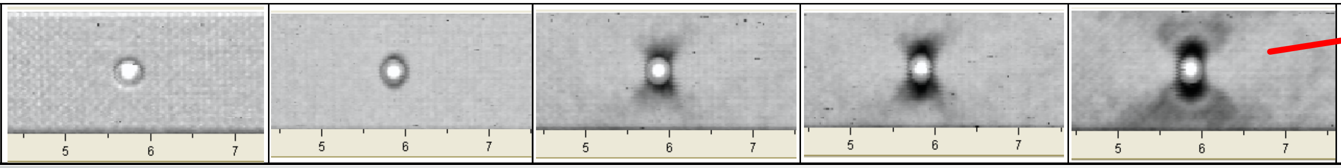
1. Sequencing effects for validation of deferred spectrum
2. Mismatch of CTE's
3. Environmental issues for composite (ex., hot-wet)
4. Hot spots (ex., ILS/ILT for composites)

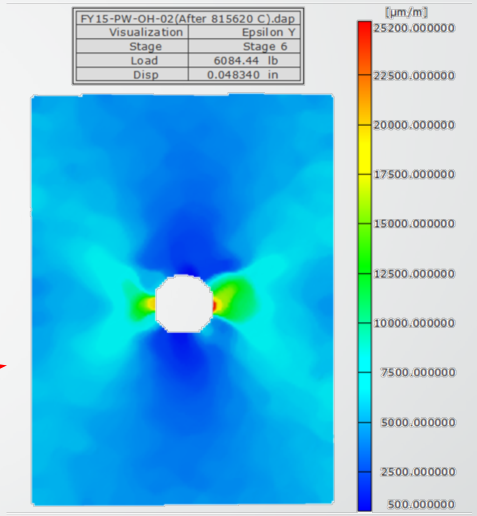
Load Sequencing Effects – Open Hole Tension/Compression (PW)

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

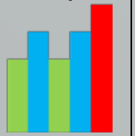


Fatigue Profile 5

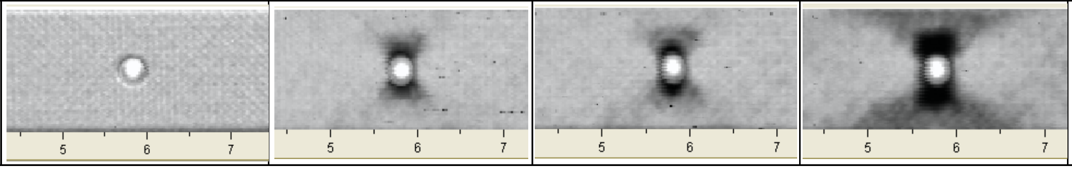
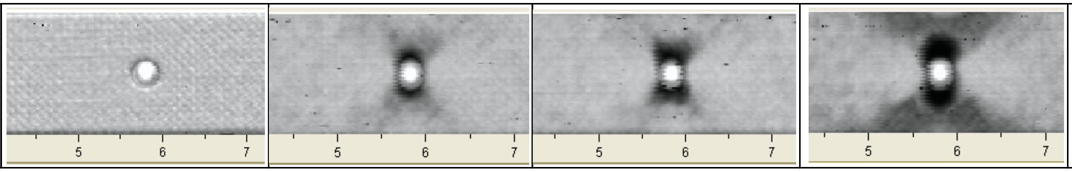
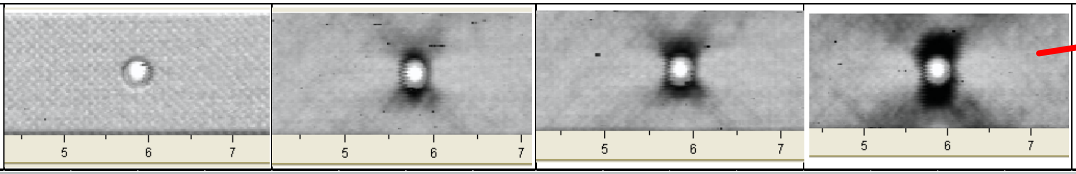
NAME	n=0 Reference	70% - n=1,040 Load Block 1	40% - n=401,050 Load Block 2	55% - n=415,610 Load Block 3	40% - n=815,620 Load Block 4	55% - n=830,180 Load Block 5
PW-OH-27						
PW-OH-1						Failed at 823,523 cycles
PW-OH-2						Failed at 827,830 cycles

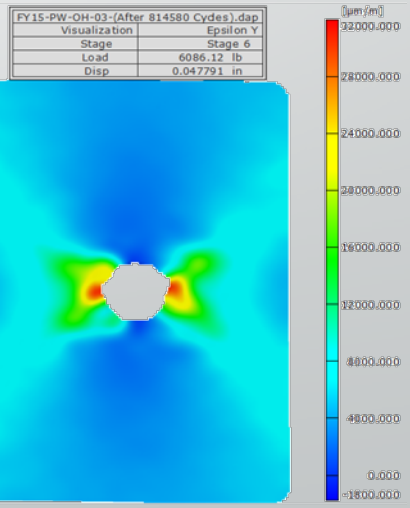


40-55-40-55-70 (Low-High)



Fatigue Profile 6

NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=414,570 Load Block 2	40% - n=814,580 Load Block 3	55% - n=429,140 Load Block 4	70% - n=430180 Load Block 5
PW-OH-3					Failed at 815,550 cycles	
PW-OH-4					Failed at 822,849 cycles	
PW-OH-6					Failed at 816,002 cycles	



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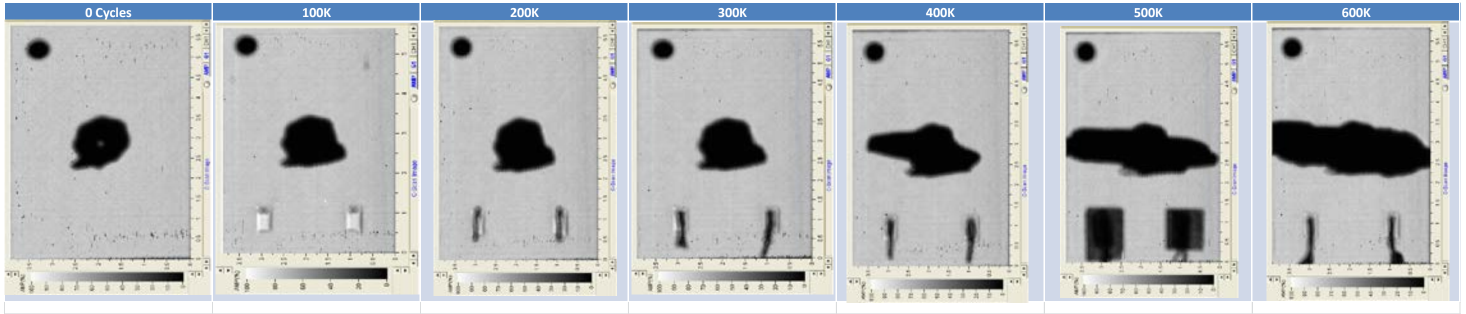
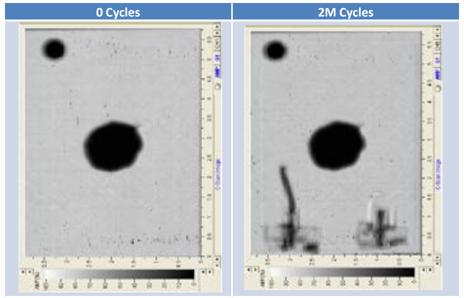
Load Sequencing Effects - Compression After Impact

Constant Amplitude (70% CAI SS)

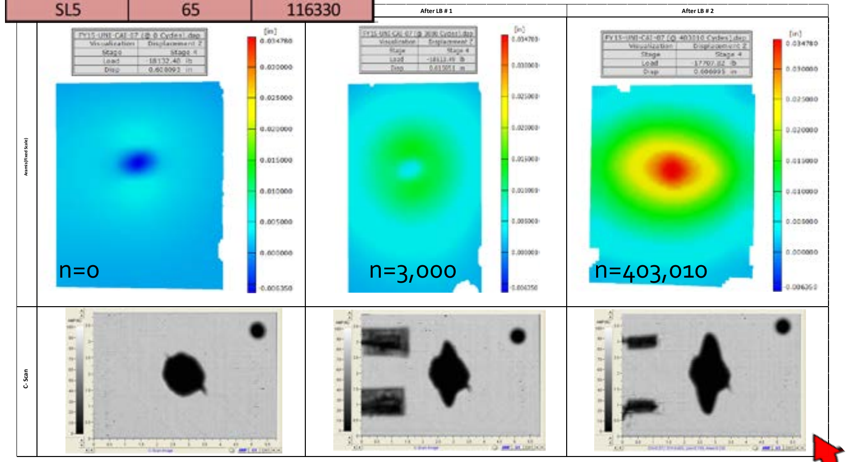


Constant Amplitude (55% CAI SS)



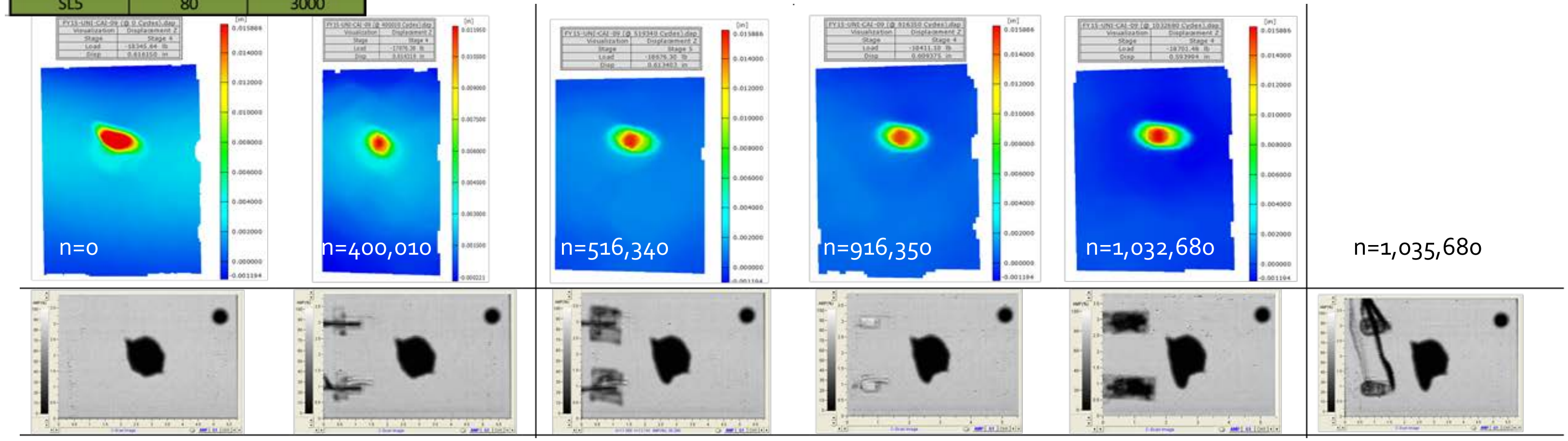
Spectrum Fatigue

Fatigue Profile 5		
Stress Level	Percentage [%]	# of Cycles
SL1	80	3000
SL2	50	400010
SL3	65	116330
SL4	50	400010
SL5	65	116330



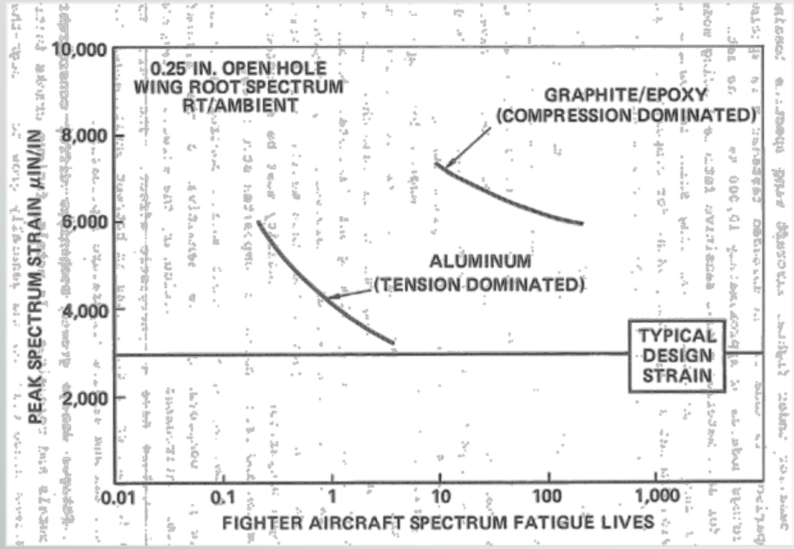
1 spec. failed at n=403,011
1 spec. survived n=1,035,680

Fatigue Profile 6		
Stress Level	Percentage [%]	# of Cycles
SL1	50	**400010**
SL2	65	116330
SL3	50	400010
SL4	65	116330
SL5	80	3000



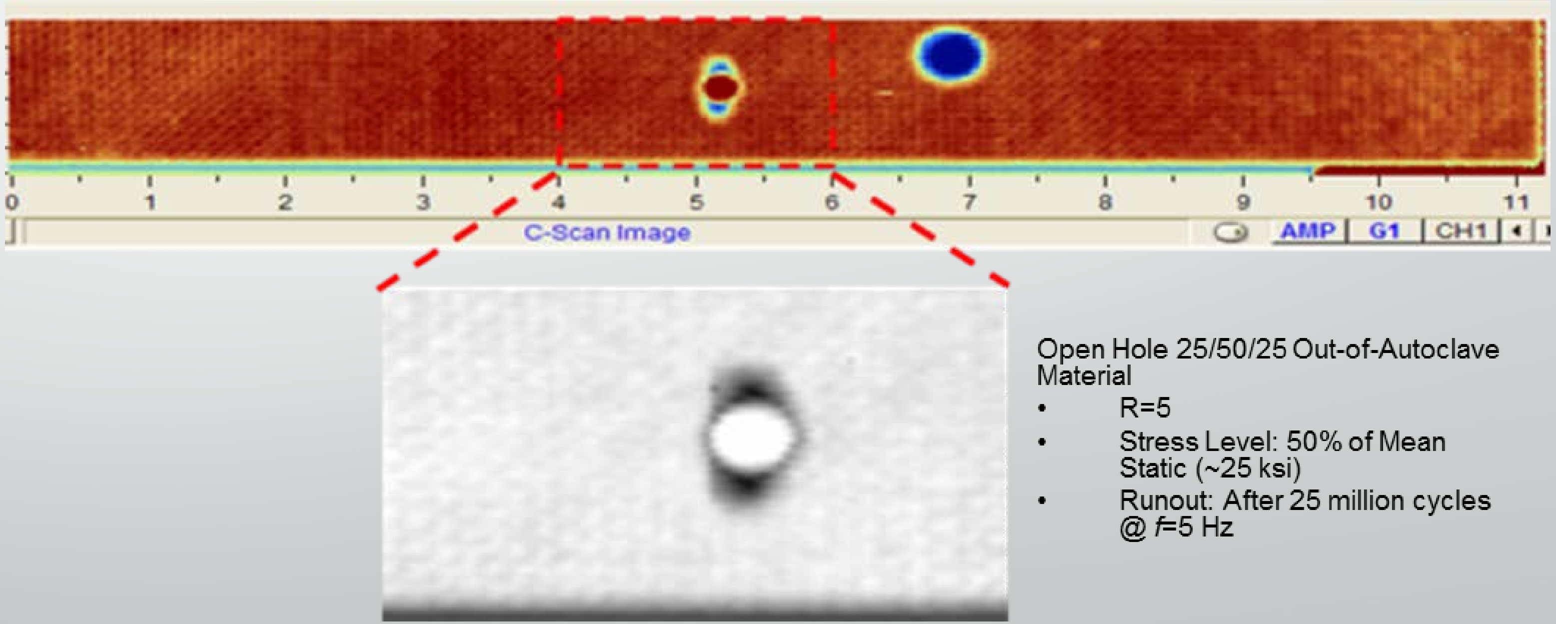
3 spec. survived
n=1,035,680

Operating Stress/Strain Levels



Ref: Whitehead, *et. al.* (1986), NADC-87042-60

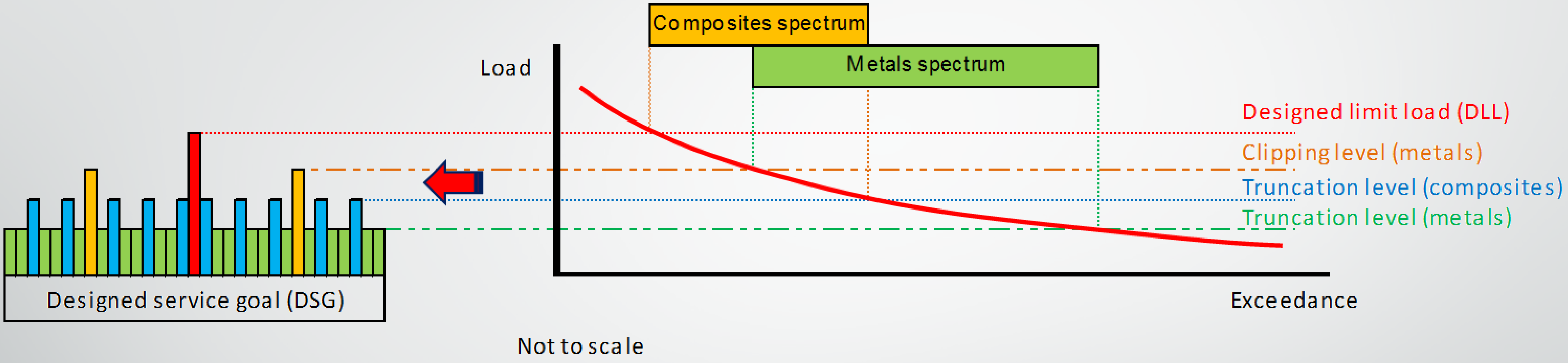
Operating levels for composites are significantly low
➔ No sequencing effects



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

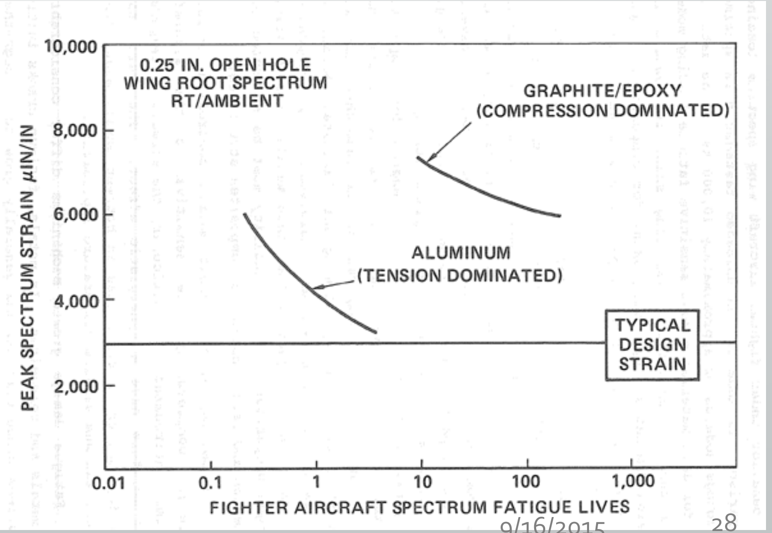
- R=5
- Stress Level: 50% of Mean Static (~25 ksi)
- Runout: After 25 million cycles @ *f*=5 Hz

Development of Hybrid Spectrum



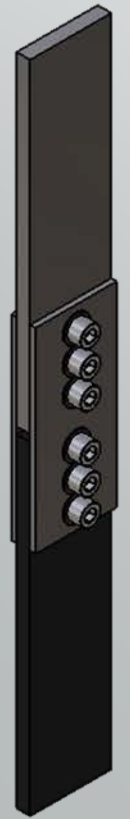
- Differences between composite and metallic spectrums
  - Metals: severe flight loads result in crack-growth retardation ➔ Clipping
  - Composites: severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life
  - Flaw growth threshold for metals may be lower load level than that for composites

  ➔ Different Truncation Levels



Composite-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 ☑

↓

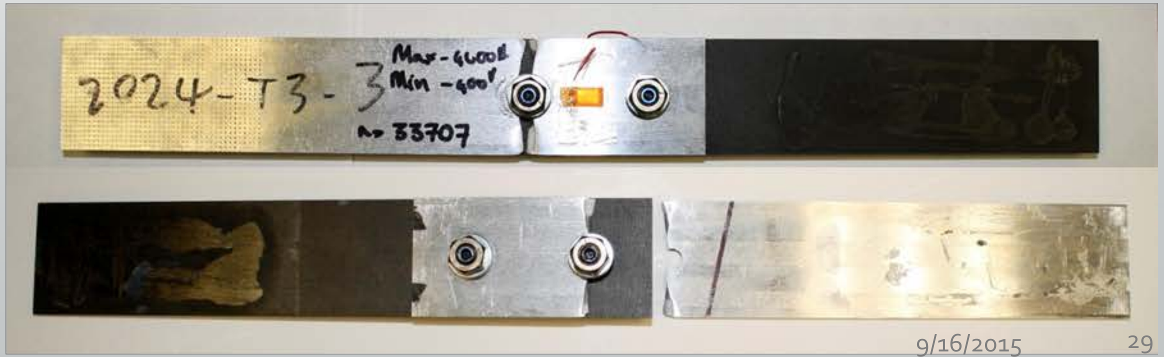
Damage Growth in Hybrids ?

- 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



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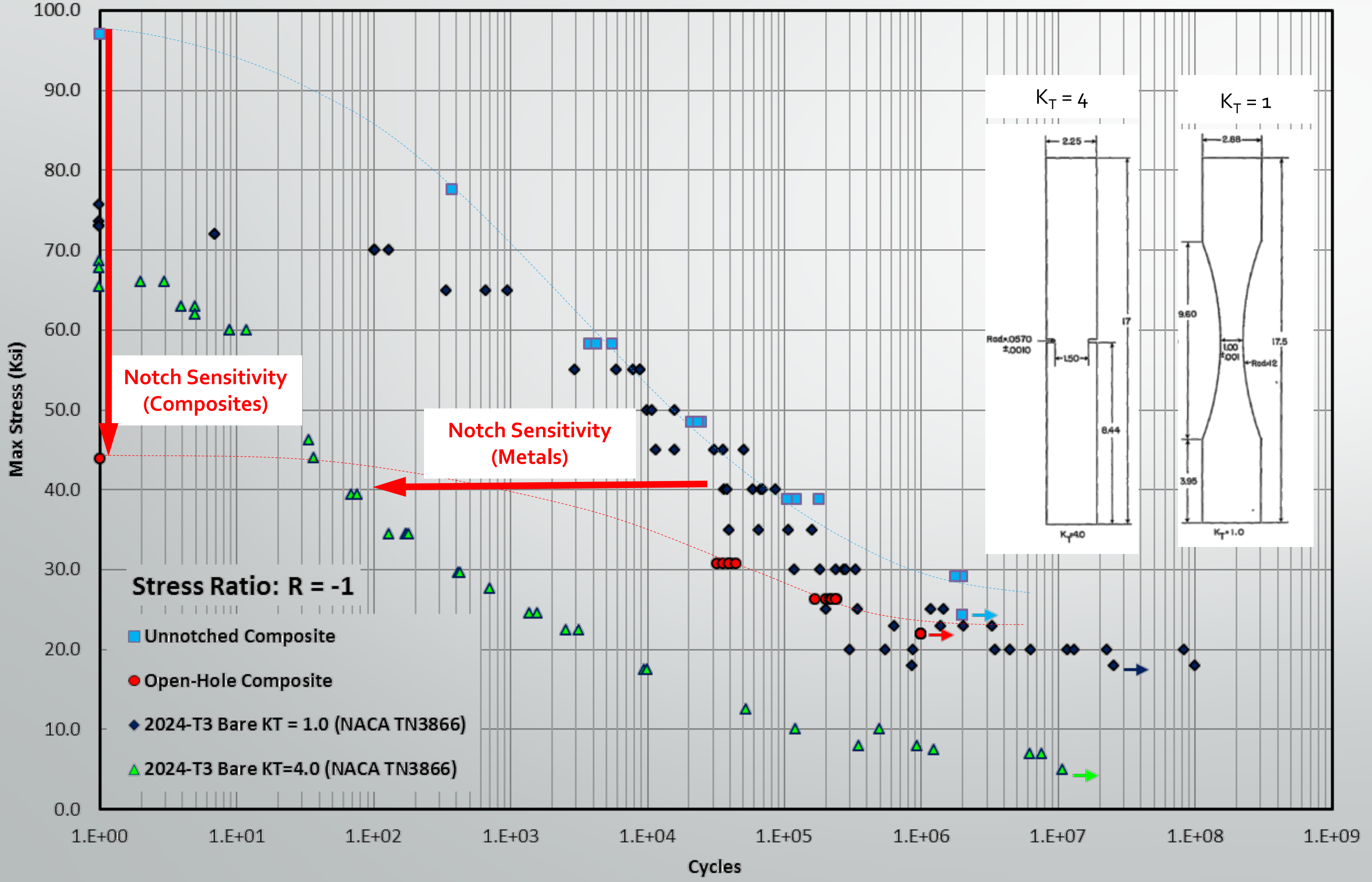
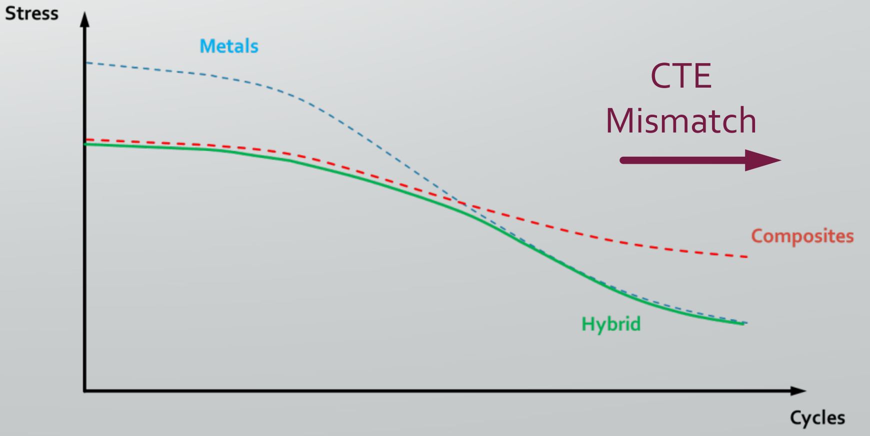
Composite vs. Metal - Sensitivity



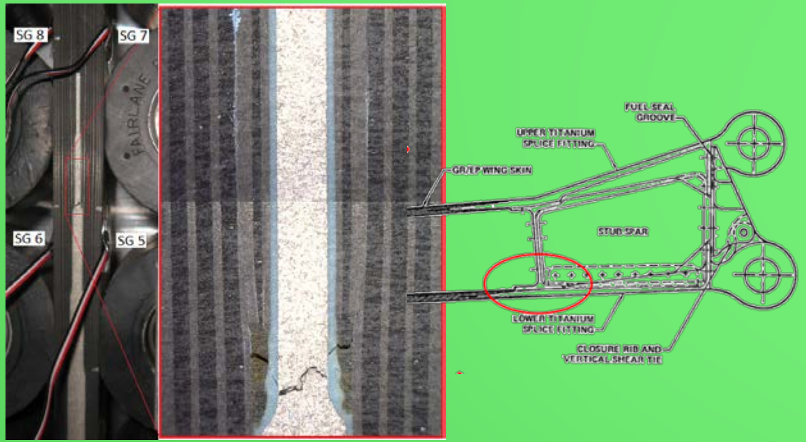


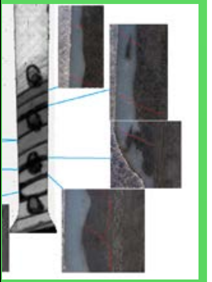
~~Aging of~~ F/A-18 Composite Structure

Hybrid – Repair – Aging

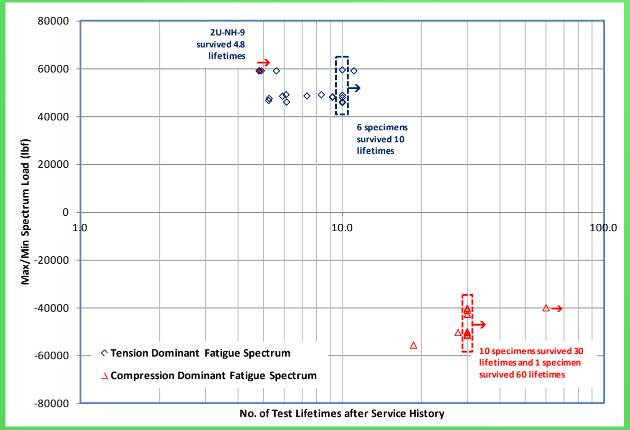
ASIP 2010-11

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



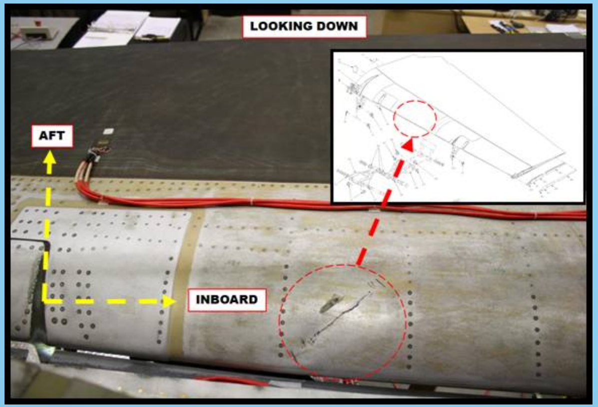


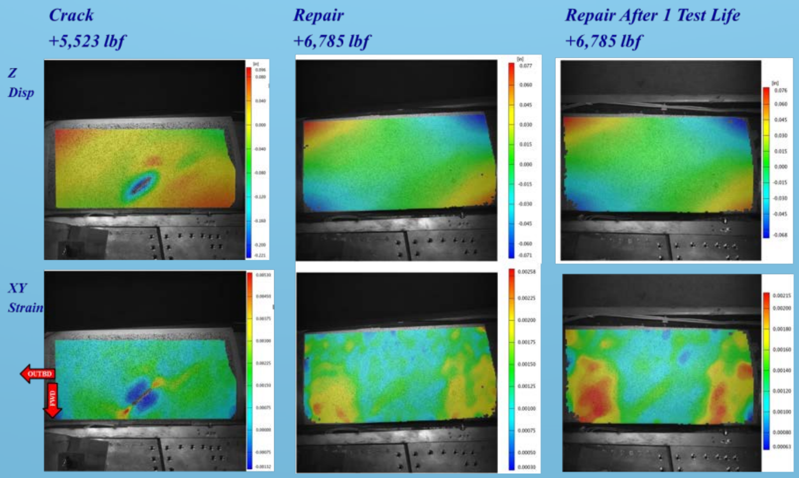
Inspections after 10 lifetimes



ASIP 2012

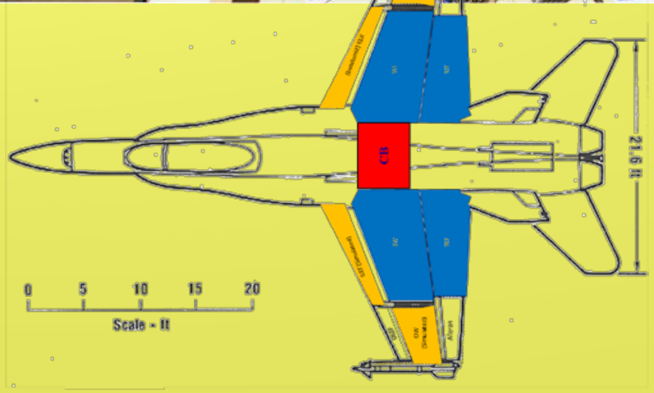
Durability of Composite Wet Layup Repair on Metallic Leading Edge of F/A-18 Trailing-Edge Flap



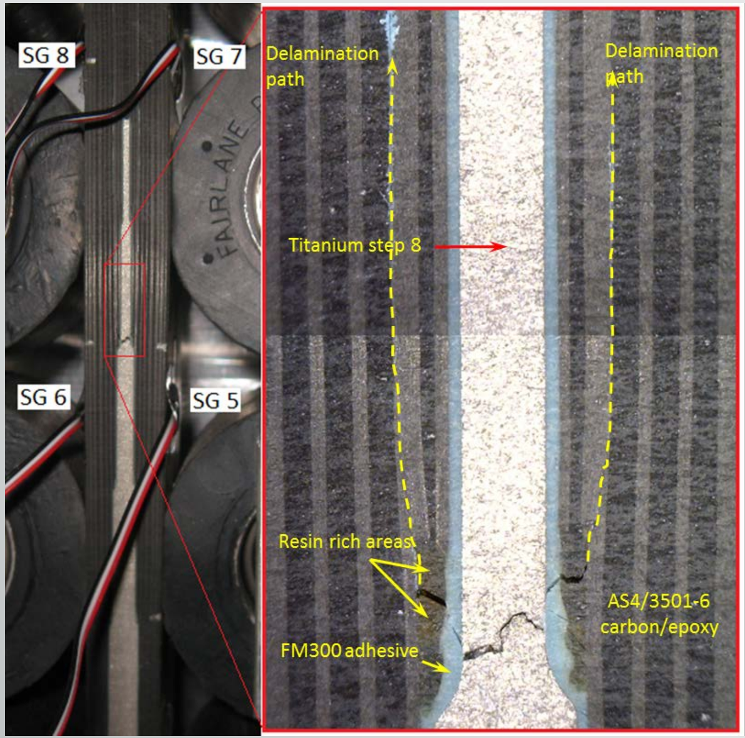


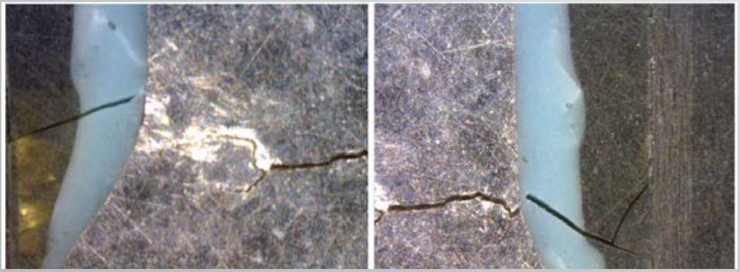
ASIP 2013-14

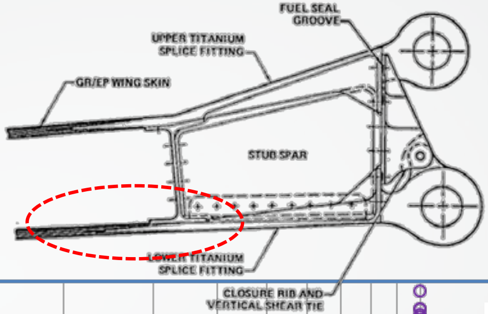
Full-Scale Fatigue Testing of F/A-18 A-D Inner Wing

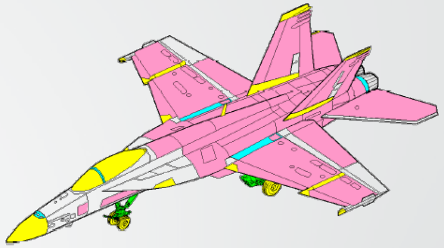


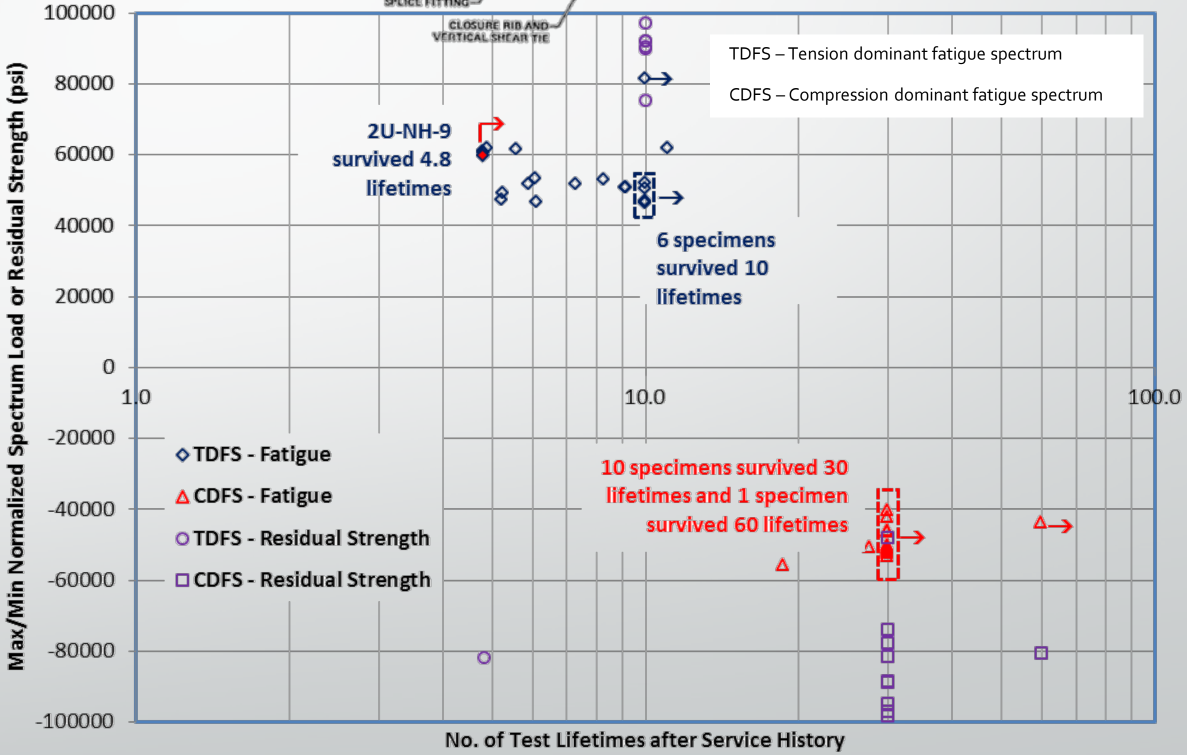
F/A-18 Wing-Root Stepped-Lap Hybrid Bonded Joint





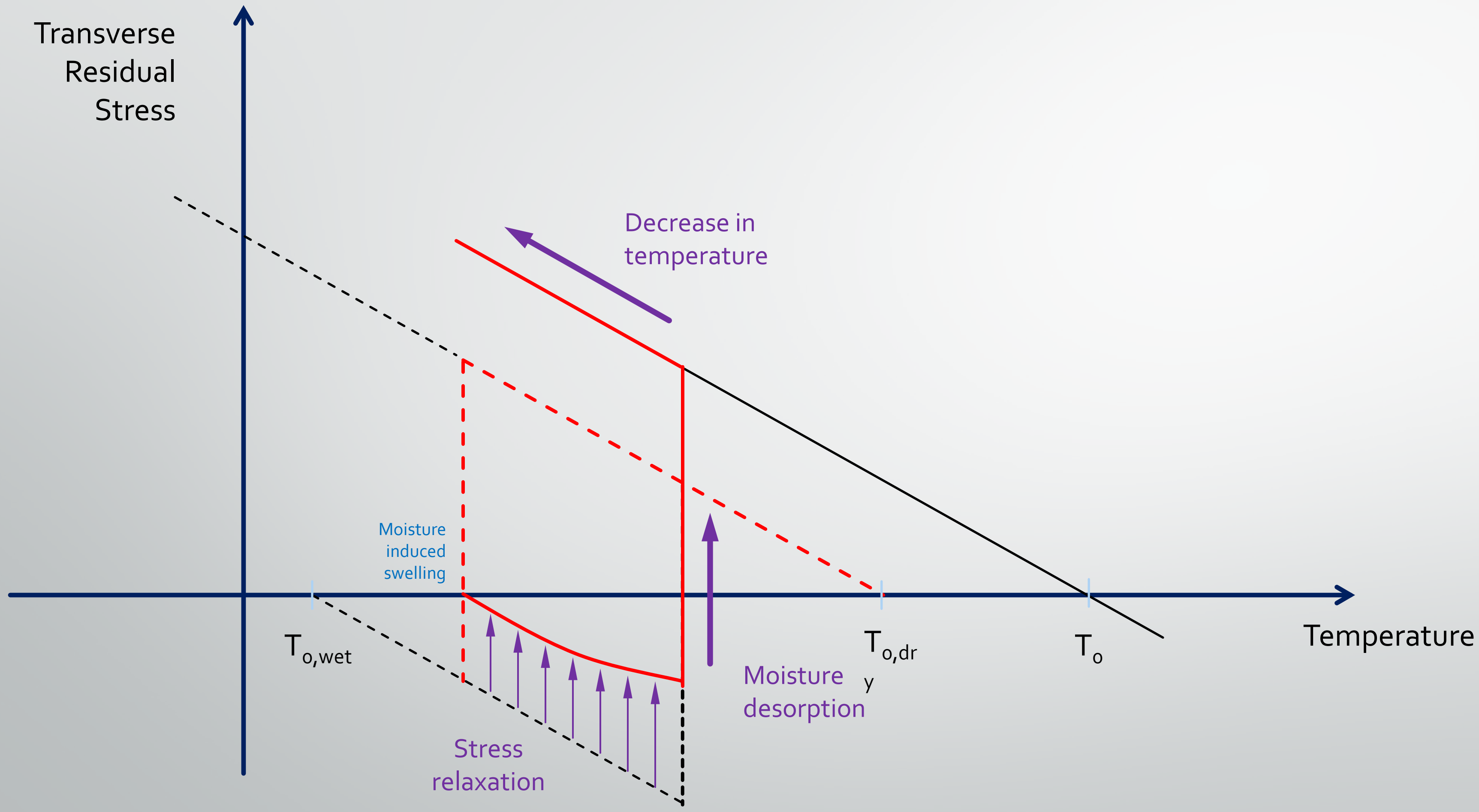


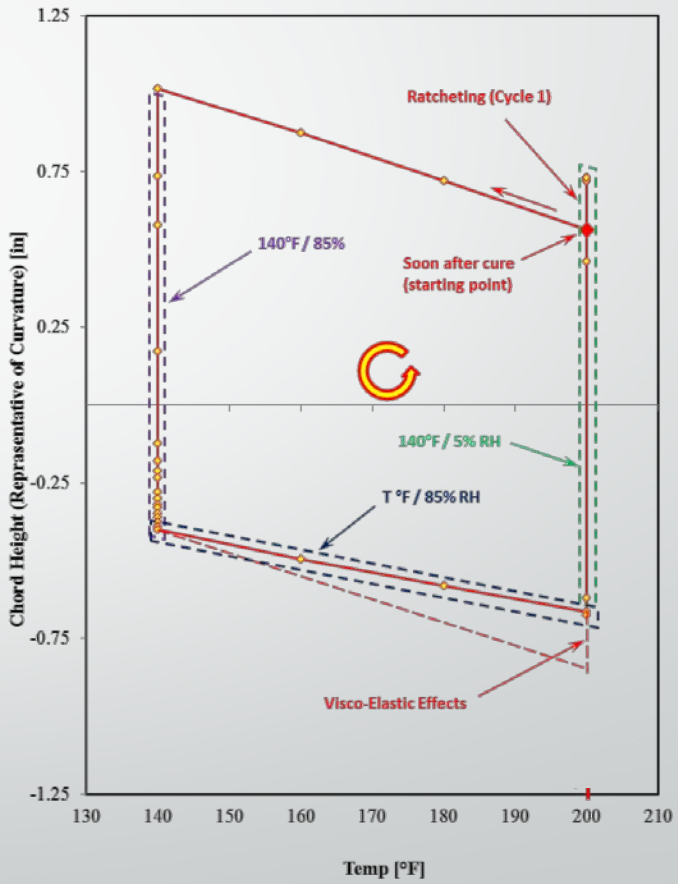




Ref: Seneviratne, W., *et.al.*, "Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and the Centennial of Naval Aviation Forum, September 2011.

Viscoelastic Behavior of TRS due to Hygrothermal History





REF: Rothschilds, R. J., Ilcewicz, L. B., Nordin, P., and Applegate, S. H., "The Effect of Hygrothermal Histories on Matrix Cracking in Fiber Reinforced Laminates," *Journal of Engineering Materials and Technology*, Vol. 110, pp. 158-168, 1988.

Summary

- CMH-17 Rev. H contents will be discussed during meeting in Wichita (October)
- Research findings will be presented at next FAA Joint Advanced Materials & Structures (JAMS) workshop
  - Hybrid fatigue study with thermal effects
  - Load sequencing studies
  - Hygrothermal history
- Multi-LEF Approach can be applied to hybrid structures to prevent metal overloads
  - Case studies
- Deferred spectrum
  - Composite-dominant design
  - Need analysis/tests to justify spectrum modifications
  - Case studies

Questions

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