WICHITA STATE UNIVERSITY
NATIONAL INSTITUTE FOR AVIATION RESEARCH

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

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National Institute for Aviation Research (NIAR)
Wichita State University (WSU)

COMPOSITE SAFETY MEETINGS
Civil Aviation Authority of New Zealand
Wellington, New Zealand
March 02-03, 2016

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

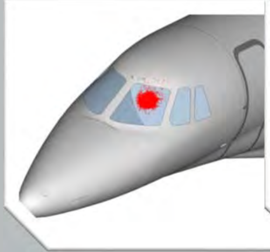
- Aging Aircraft, Composites & Mechanical Test, Full-Scale Structural Test, Ballistic & Impact Dynamics

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

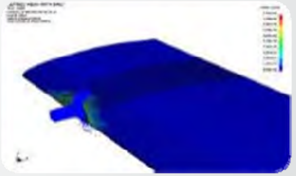
Ballistics/ Impact

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

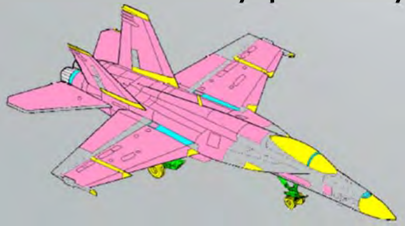
Reverse Engineering

Virtual Reality

Beech Wind Tunnel

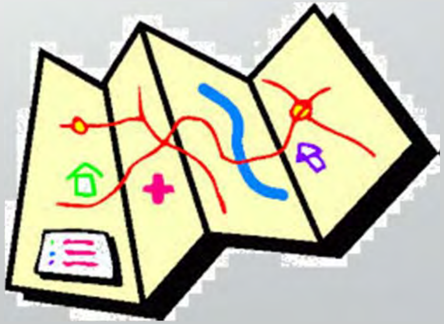
Certification Challenges for Hybrid Structures

- 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



CMH-17 Rev. G

12.6 Durability and Damage Growth Under Cyclic Loading

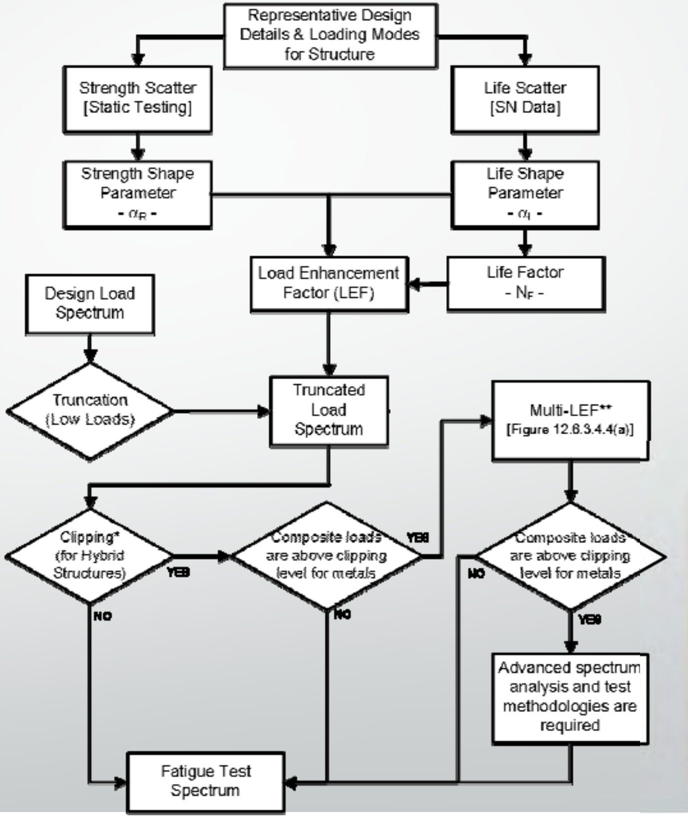
12.6.1 Influencing factors

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

CMH-17 COMPOSITE MATERIALS HANDBOOK



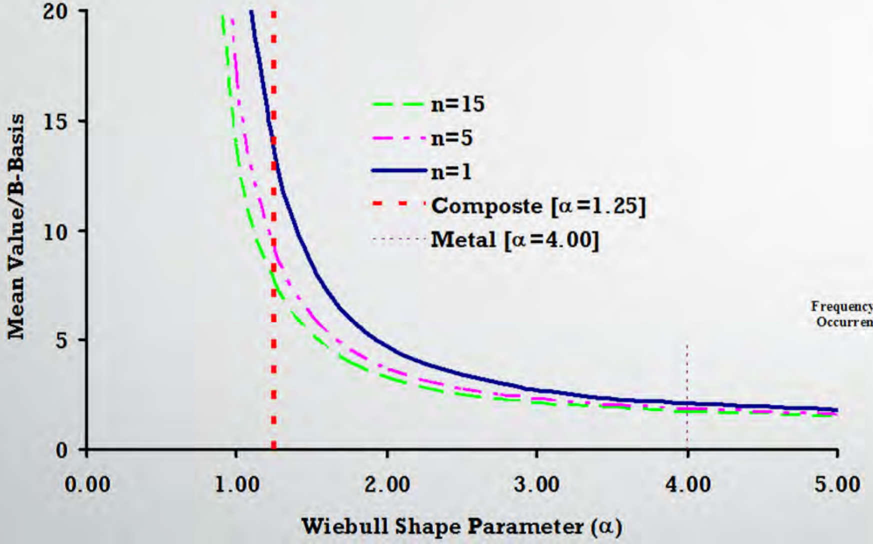
NOTES:
* Clipping of high loads are only required for metals; composite loads should not be clipped.
** Further analysis and supporting experiments are required prior to applying these methods.

Life Factor Approach

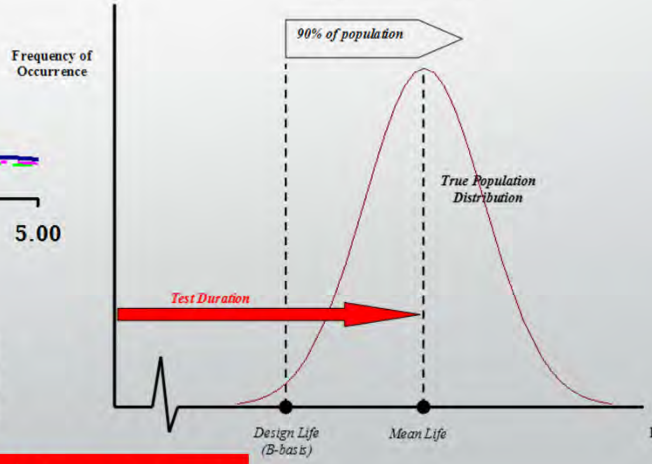
Structure is tested for additional fatigue life to achieve the desired level of reliability

- Life Scatter Factor (LSF)

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



	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



Newer composite materials/processes indicates significantly lower life factors

NIAR Wichita State University National Institute for Aviation Research

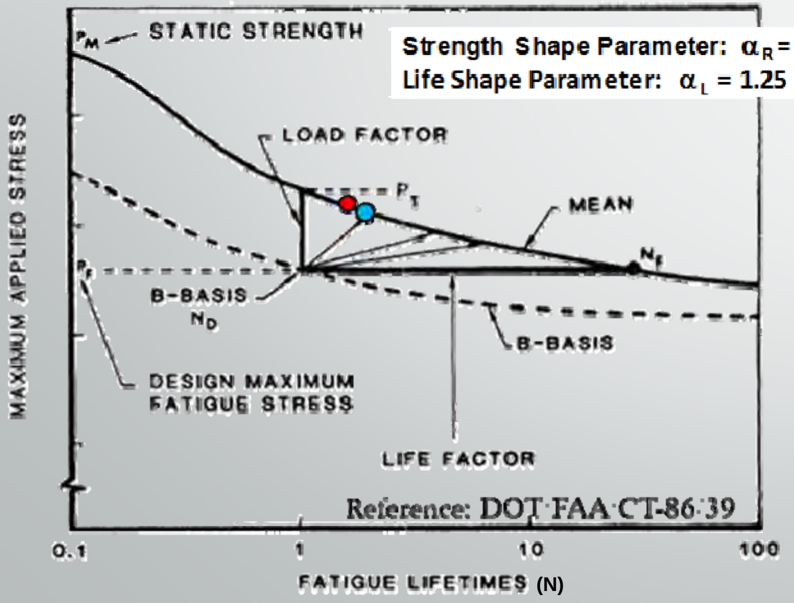
Load-Enhancement Factor (LEF) Approach

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) Report No. NADC-87042-60, Volumes I and II, October, 1986

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

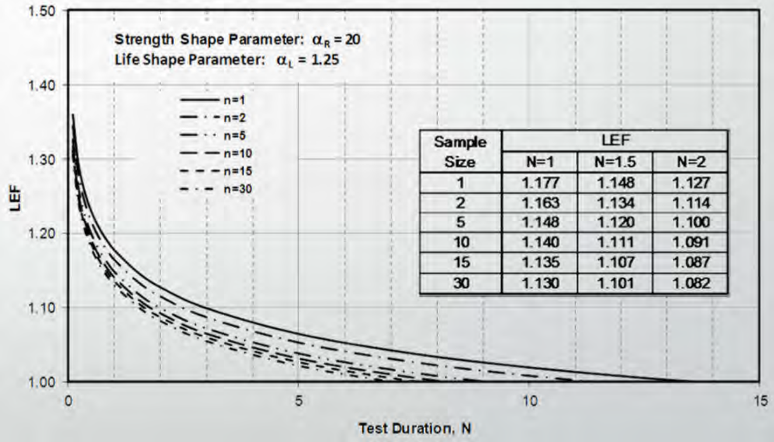


$$LEF(N) = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)^{\alpha_L/\alpha_R}}{\left\{\frac{-\ln(R)\cdot N^{\alpha_L}}{\left[\chi_\gamma^2(2n)/2n\right]}\right\}^{1/\alpha_R}}$$

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

For N = 1.5 ➔ ● LEF = 1.15 (B-basis)

For N = 2.0 ➔ ● LEF = 1.13 (B-basis)



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

- 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

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

- Sendeckyj Equivalent Strength Model

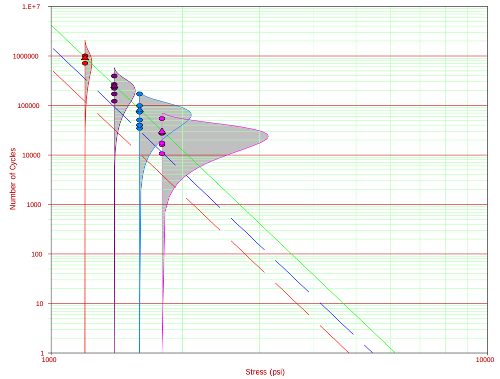
$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

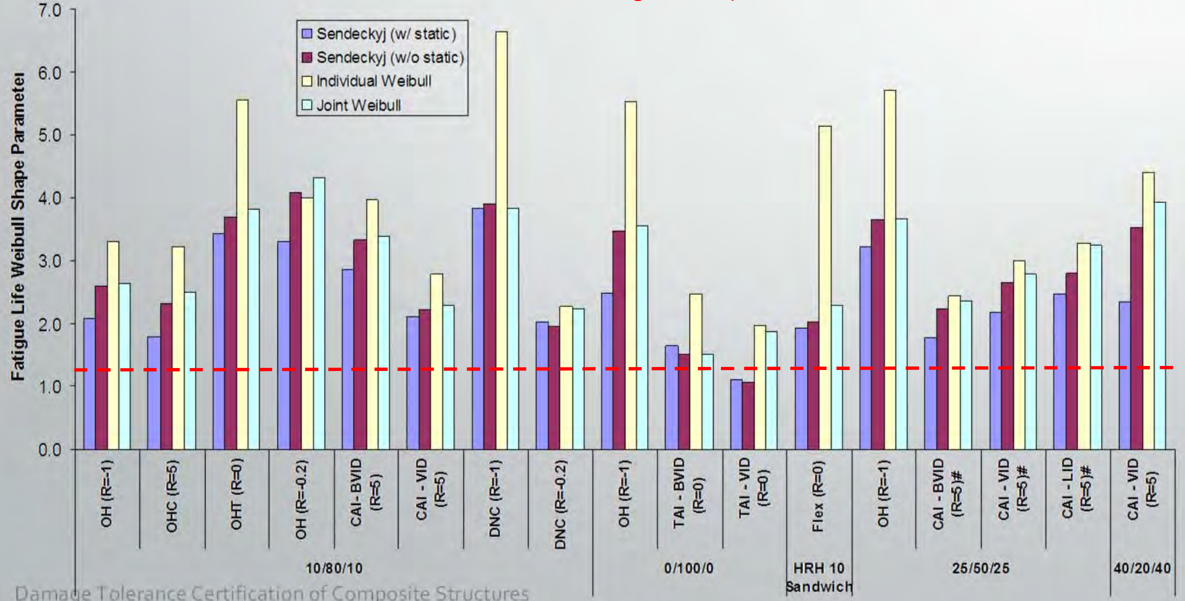
Data Pooling Techniques

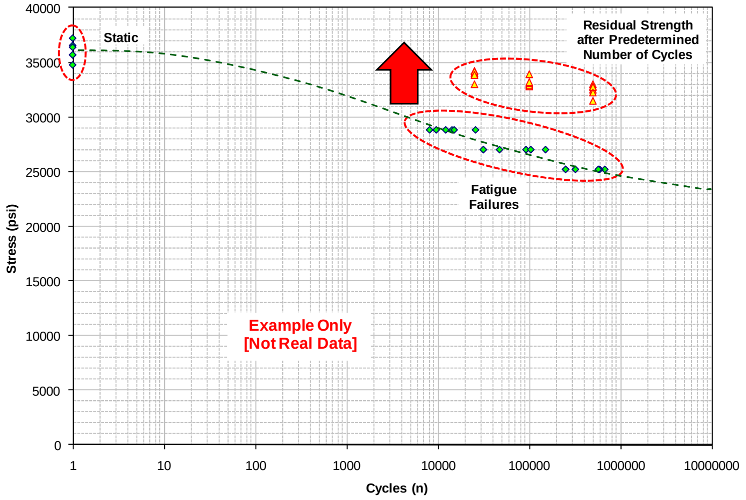
<u>NADC Fatigue Scatter Analysis</u>

$\alpha_I > \alpha_J > \alpha_S$

NAVY LEF APPROACH IS NOT RESTRICTED TO THESE SCATTER ANALYSIS METHODS

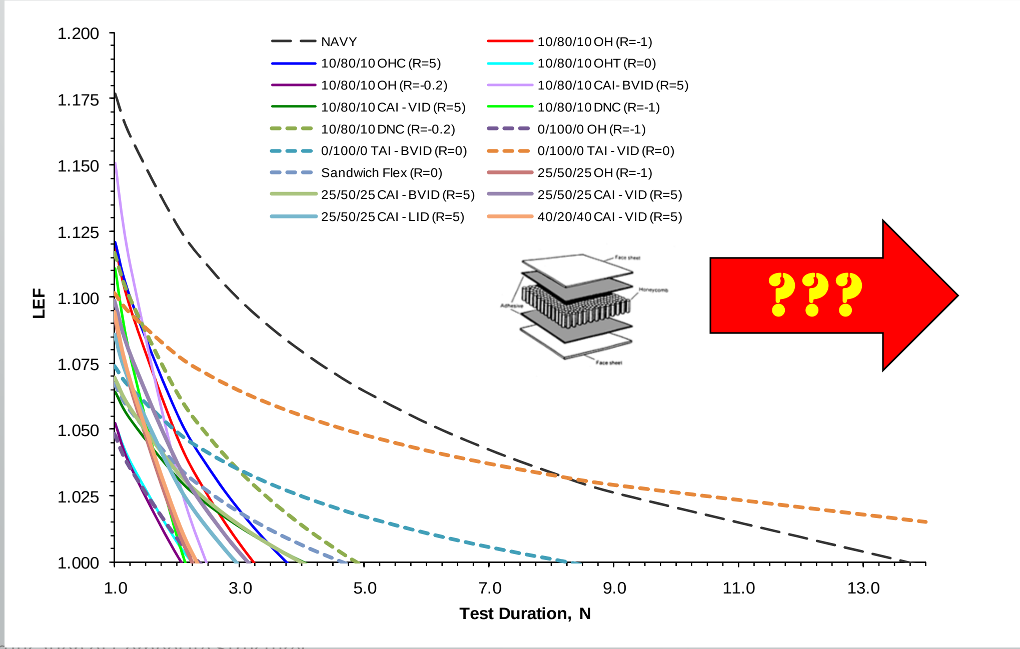






Selection of Shape Parameters

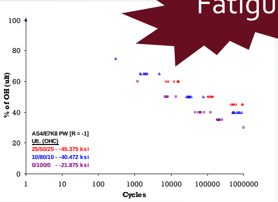
- Selection of shape parameters from a single SN curve is not a practical method of deriving LEFs and/or N_F for a particular structure.
  - *LEF (NAVY-Whitehead) approach links strength and life scatter and provides a LEF as a function of test duration*
  - *Engineering judgment is subjective*



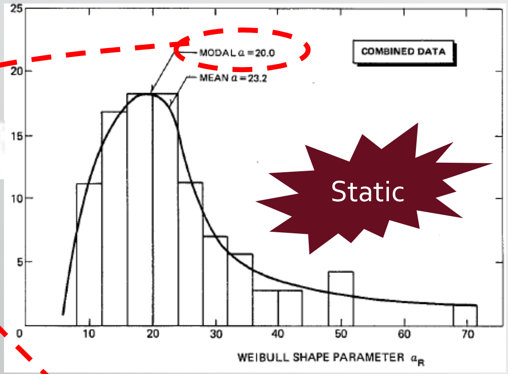
Generation of LEF Curve

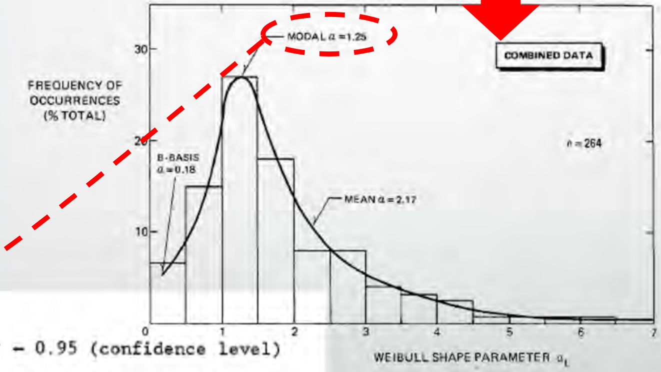
Fatigue

Fatigue Data Fitting Models



Static



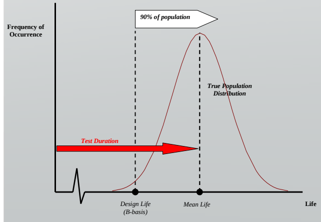


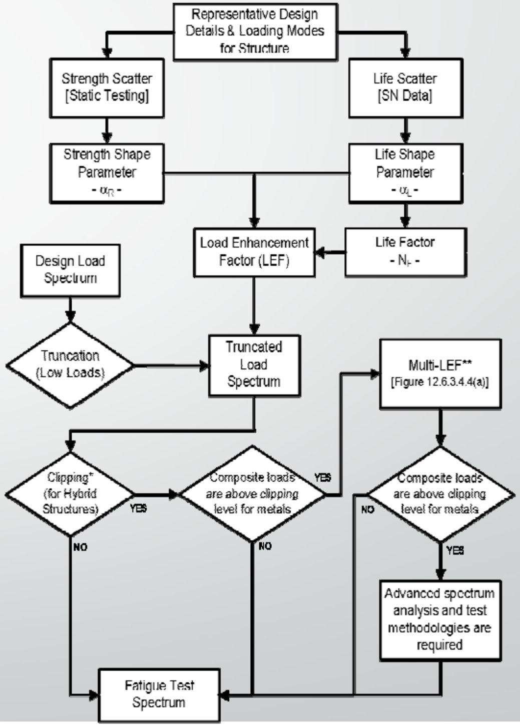
$\alpha_L = 1.25$ n = 1 (one test article)

$\alpha_R = 20.0$ p = 0.9 (B-Basis) $\gamma = 0.95$ (confidence level)

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

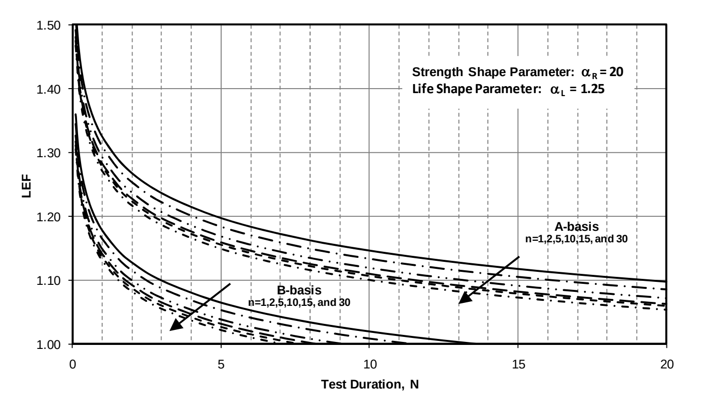
test duration	load enhancement factor	
1.0	1.177	Load Factor
1.5	1.148	LEF
2.0	1.127	
3.0	1.099	
13.3	1.0	Life Factor



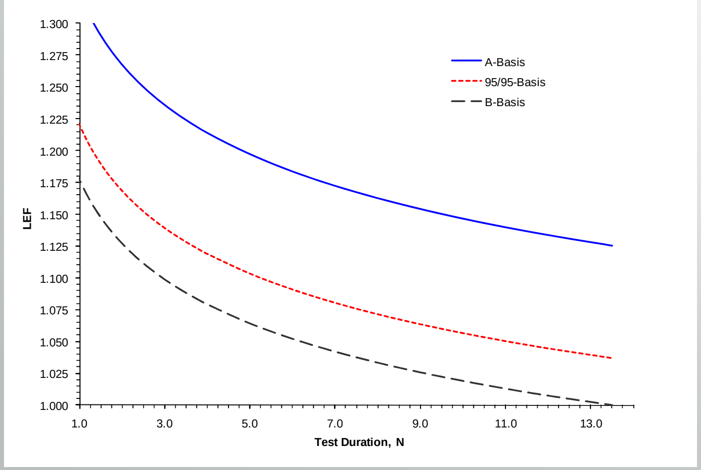


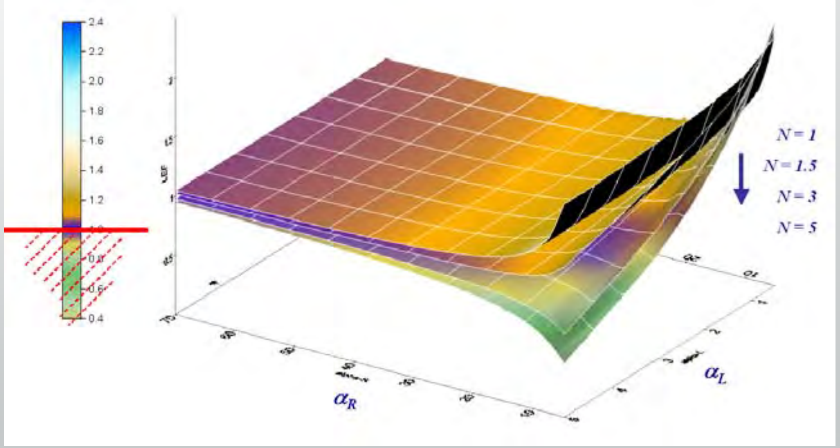
NOTES:
* Clipping of high loads are only required for metals; composite loads should not be clipped.
** Further analysis and supporting experiments are required prior to applying these methods.

Variables Associated with LEF



Sample Size	One Lifetime Test		1.5 Lifetime Test		Two Lifetime Test	
	A-Basis	B-Basis	A-Basis	B-Basis	A-Basis	B-Basis
1	1.324	1.177	1.291	1.148	1.268	1.127
2	1.308	1.163	1.276	1.134	1.253	1.114
5	1.291	1.148	1.259	1.120	1.237	1.100
10	1.282	1.140	1.250	1.111	1.227	1.091
15	1.277	1.135	1.245	1.107	1.223	1.087
30	1.270	1.130	1.239	1.101	1.217	1.082





Key Characteristics of LEF/N_F

- LEF = f(N)

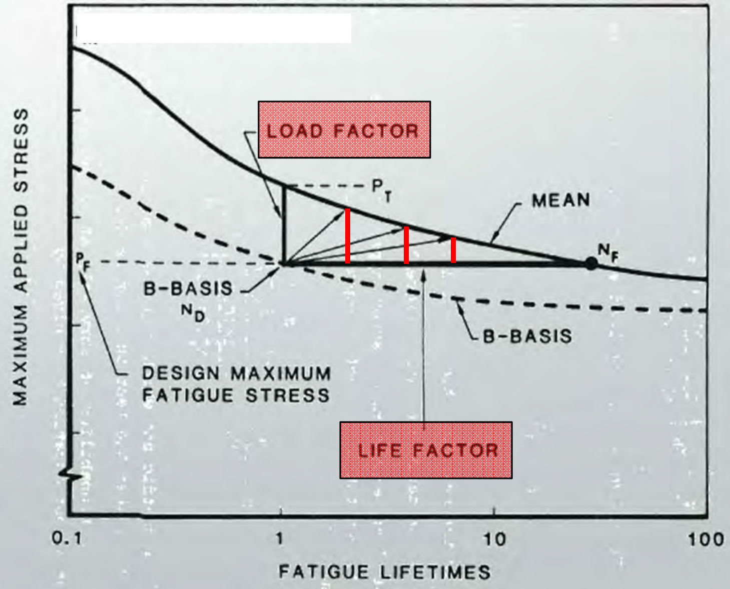
$$LEF(N) = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)^{\alpha_L/\alpha_R}}{\left\{\frac{-\ln(R)\cdot N^{\alpha_L}}{\left[\chi_\gamma^2(2n)/2n\right]}\right\}^{1/\alpha_R}}$$

  - LEF requirement decreases with higher test duration

- N_F is a constant

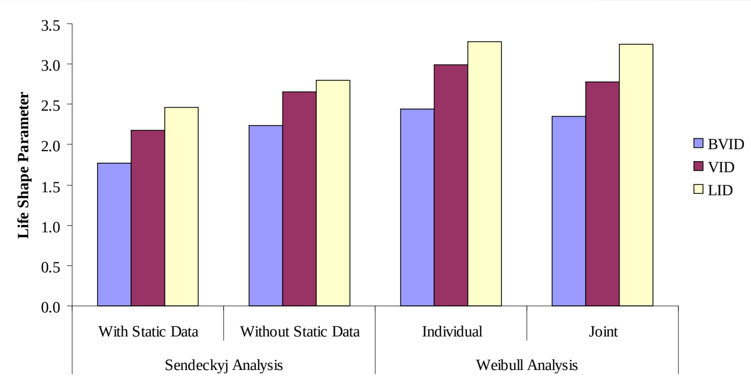
$$N_F = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left[\frac{-\ln(p)}{\left[\frac{\chi_\gamma^2(2\cdot n)}{2\cdot n}\right]}\right]^{\frac{1}{\alpha_L}}}$$

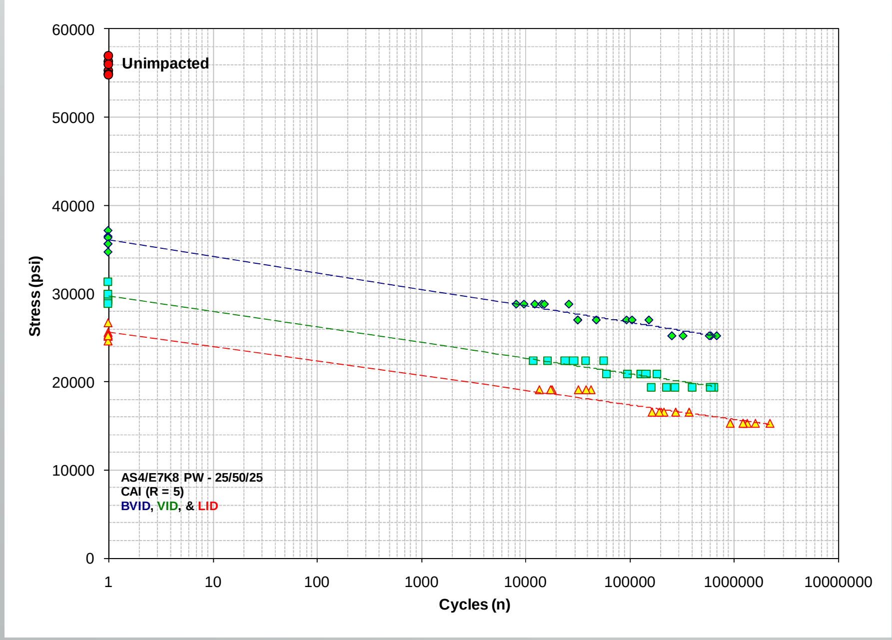
- LEF curve is NOT a SN curve

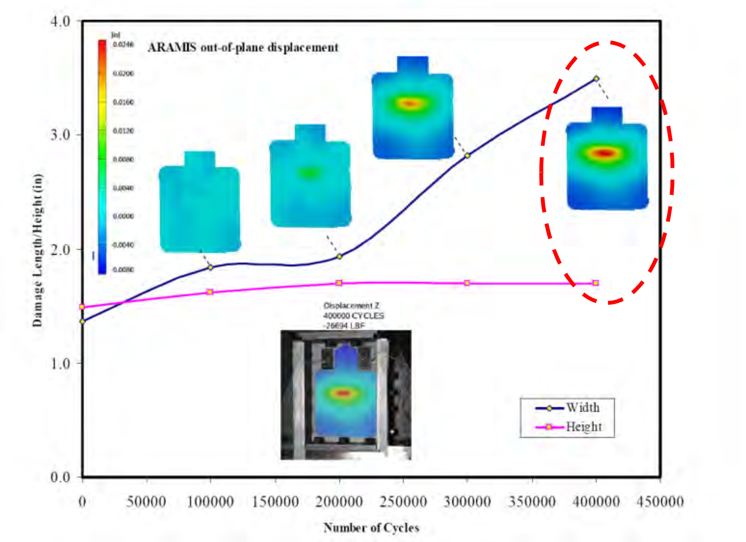


Effects of Damage on α

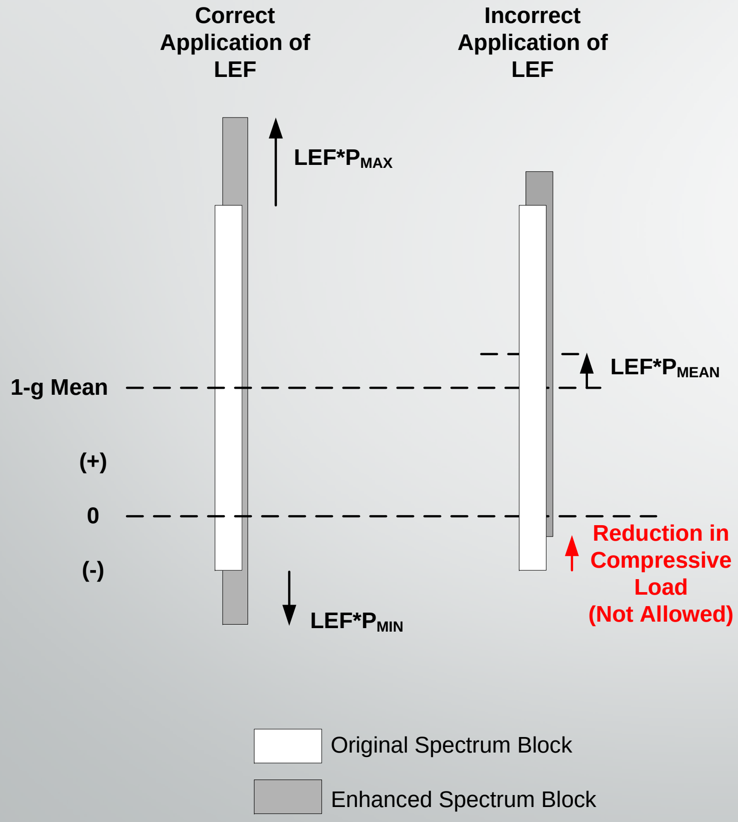
- Damage Tolerance Element Tests
  - Data scatter associated with final failure is conservative or representative of scatter at onset of damage propagation







Application LEF

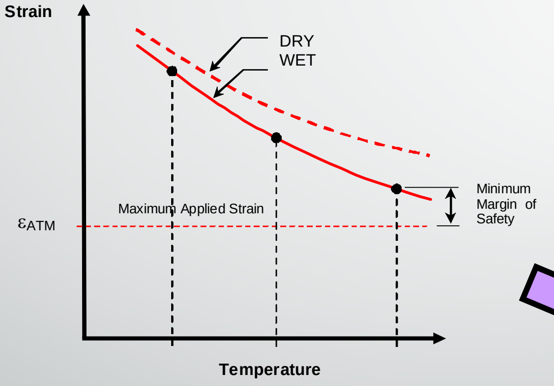


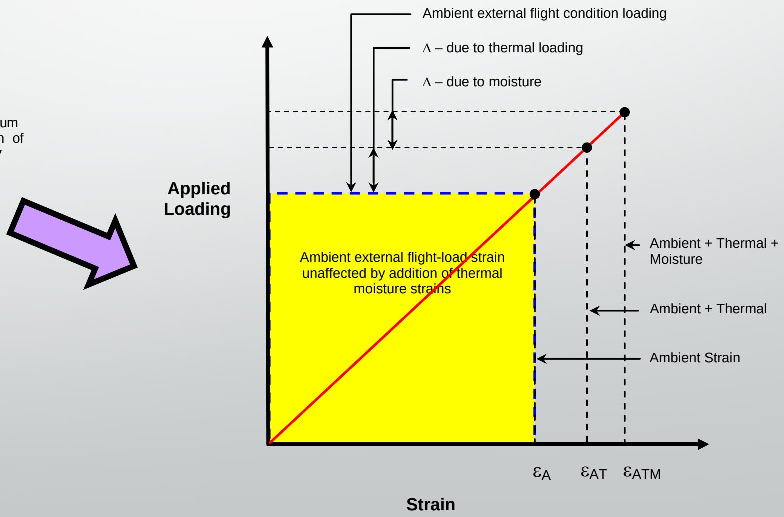
- The application of load enhancements **must preserve the stress ratio of each load cycle throughout the spectrum** so that the fatigue damage mechanism and the life are not artificially influenced. The LEF must be applied to the minimum/maximum load in the fatigue spectrum

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

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

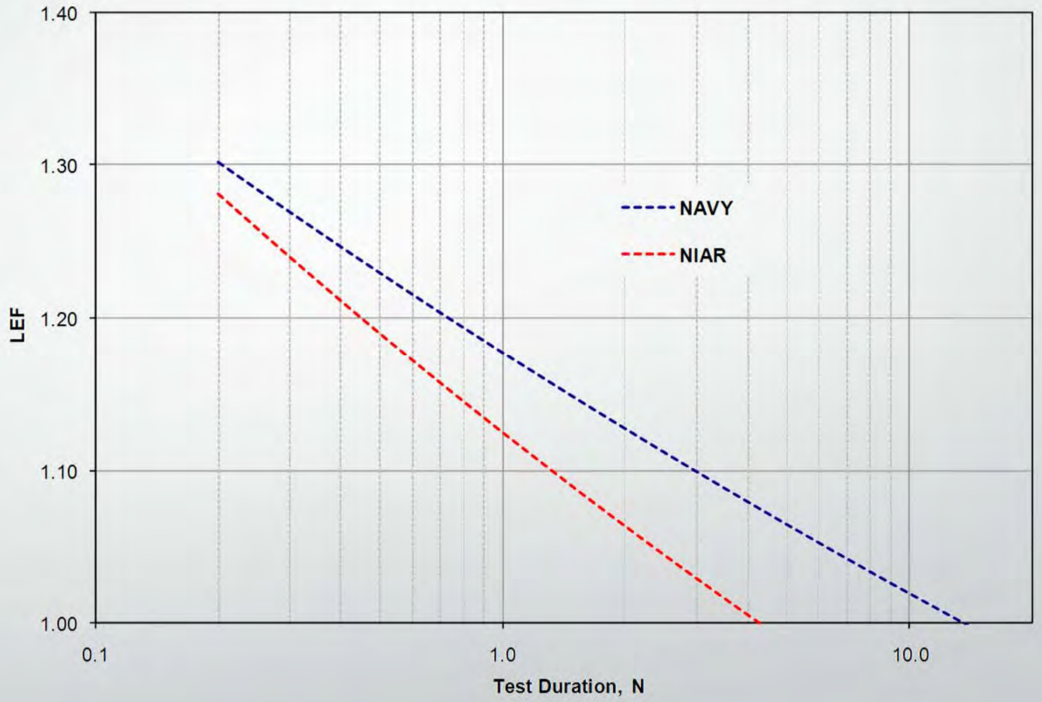




DOT/FAA/AR-10/06

Static Scatter Factor	**20.000**	**26.310**
Fatigue Scatter Factor	**1.250**	**2.131**
NF	**13.558**	**4.259**

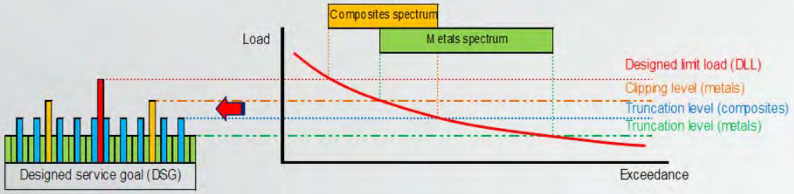
# of Lives (N)	NAVY	NIAR
1.00	**1.177**	**1.125**
1.50	**1.148**	**1.088**
2.00	1.127	1.063
2.50	1.111	1.044
3.00	**1.099**	**1.029**
3.50	1.088	1.016
4.00	1.079	1.005
4.25	1.075	1.000
4.50	1.071	0.996
5.00	1.064	0.987
6.00	1.052	0.973
7.00	1.042	0.961
8.00	1.034	0.950
9.00	1.026	0.941
13.60	1.000	0.908



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



Design Feature/Failure Mode*	Test Method	Environmental Condition	Static	Fatigue - Cyclic Test R ratio# (3 Stress Levels)			
				R1	R2	R3	R4
1	1	1	B x 6	B x 3 x F			
..	..	..	**		B x 3 x F		
..	..	..	B x 6			B x 3 x F	
..	..	..	B x 6				B x 3 x F
..	..	..					
..	..	..	B x 6			B x 3 x F	
i	*j*	*k*	B x 6		**		
			α_R	α_L			

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.

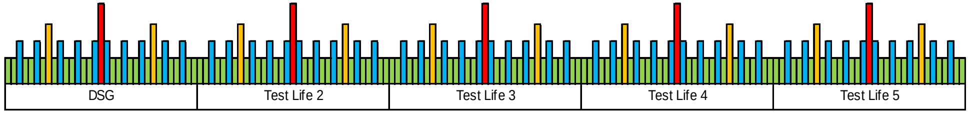
** Since static and fatigue modal analyses are conducted seperately, for a given feature, it is not required to have both static and fatigue data for a given design feature.

For a given design, more than four critical stress ratios are possible.

Method 1: Life Factor Approach

$N_1 = N_2 = N_3 = ... = N_i = N_F$

➔ $LEF_1 = LEF_2 = LEF_3 = ... = LEF_i = 1.0$

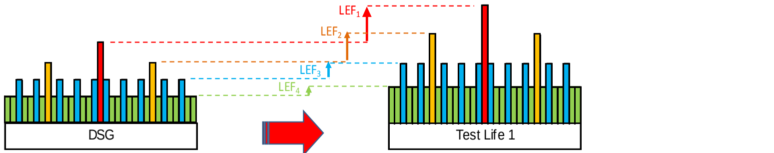


Original spectrum is repeated for Life factor; example (N_F) = 5

Method 2: Load Factor Approach

$N_1 = N_2 = N_3 = ... = N_i = 1$

➔ $LEF_1 = LEF_2 = LEF_3 = ... = LEF_i = LEF_{@N=1}$

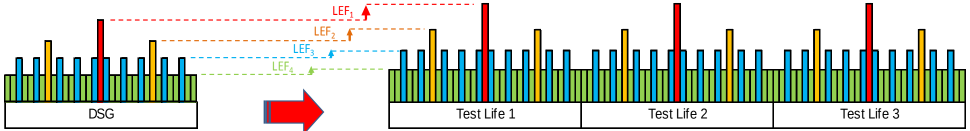


Original Spectrum is multiplied by LEF for N = 1 with Load Factor (N = 1 for $LEF_1 = LEF_2 = LEF_3 = LEF_4 = LEF_{@ N=1}$)

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

$N_1 = N_2 = N_3 = ... = N_i$

➔ $LEF_1 = LEF_2 = LEF_3 = ... = LEF_i$

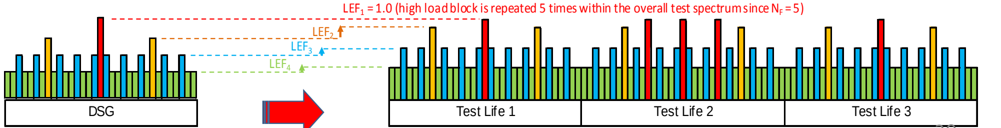


Original Spectrum is multiplied by appropriate LEF with combined load-life factor (example: $N = 3 < N_F$ for $LEF_1 = LEF_2 = LEF_3 = LEF_4$)

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

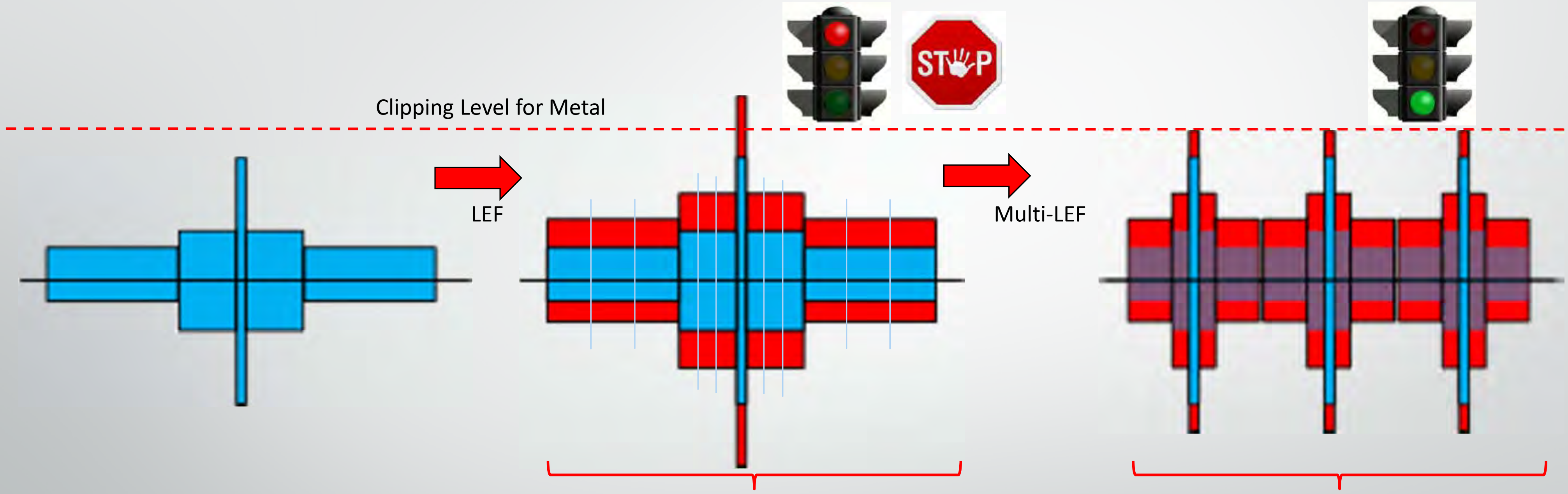
$N_1 \neq N_2 \neq N_3 \neq .... \neq N_i$

➔ $LEF_1 \neq LEF_2 \neq LEF_3 \neq .... = LEF_i$



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

Multi-LEF Approach for Hybrid Structures

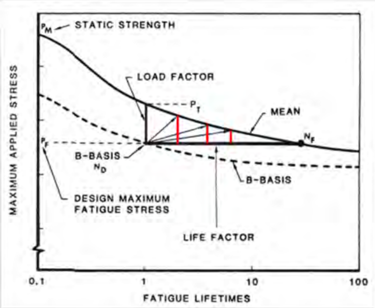


Repeated for required N

Repeated for required N

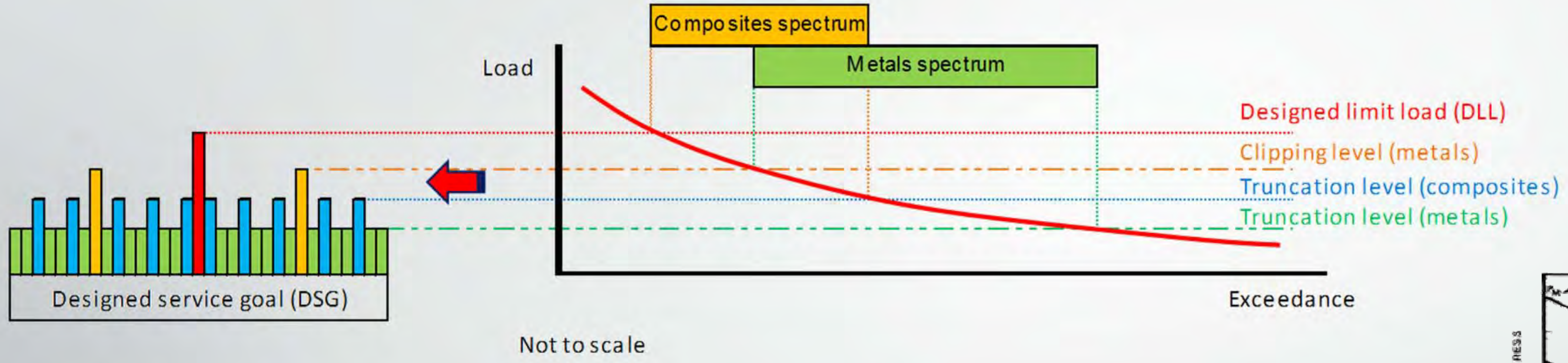
Original Spectrum Blocks

Test Spectrum Blocks after LEF



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

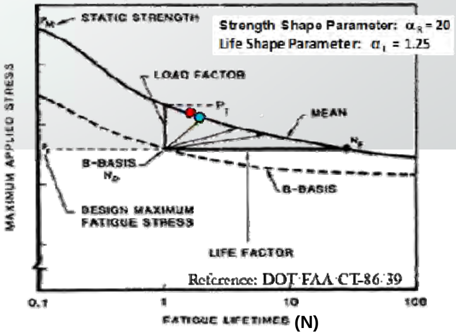
Multi-LEF Approach for Hybrid Structures

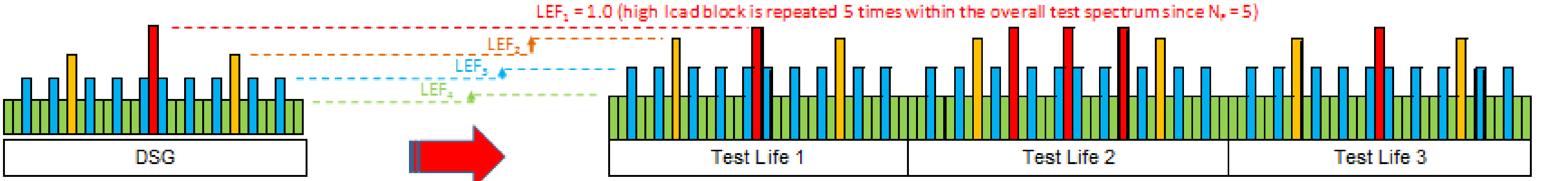


Method 4: Multi Load-Life Factor (multi-LEF) Approach

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

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



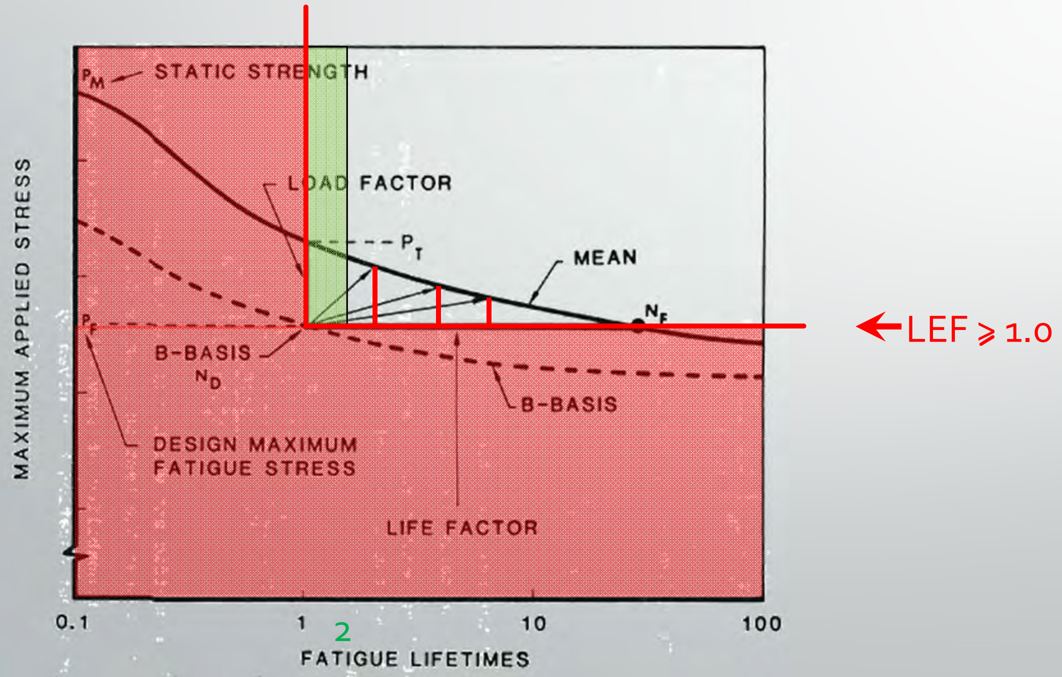


Original Spectrum is multiplied by appropriate LEF

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

Boundaries of LEF Curve & Related Regulations

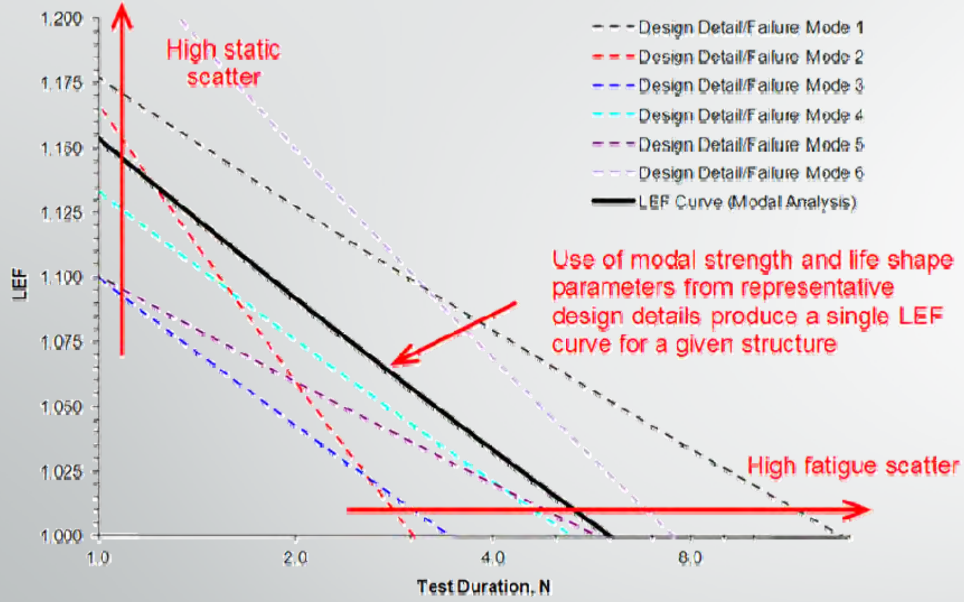
- Test duration must be greater than 2 DSG (with appropriate LEF for composites)
  - Hybrid (metal-composites) structures: minimum 3 DSG ➔ **LOV for Metals (LOV for Composites?)**
- LEF must be greater than 1.0

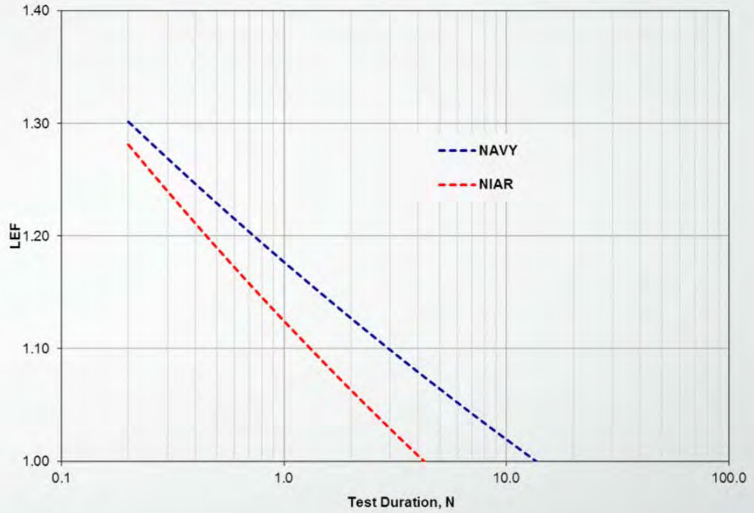


The LEF relationship can provide a wide spectrum of load and life combinations to achieve the desired reliability. However, practical considerations result in limits on these values.

- 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



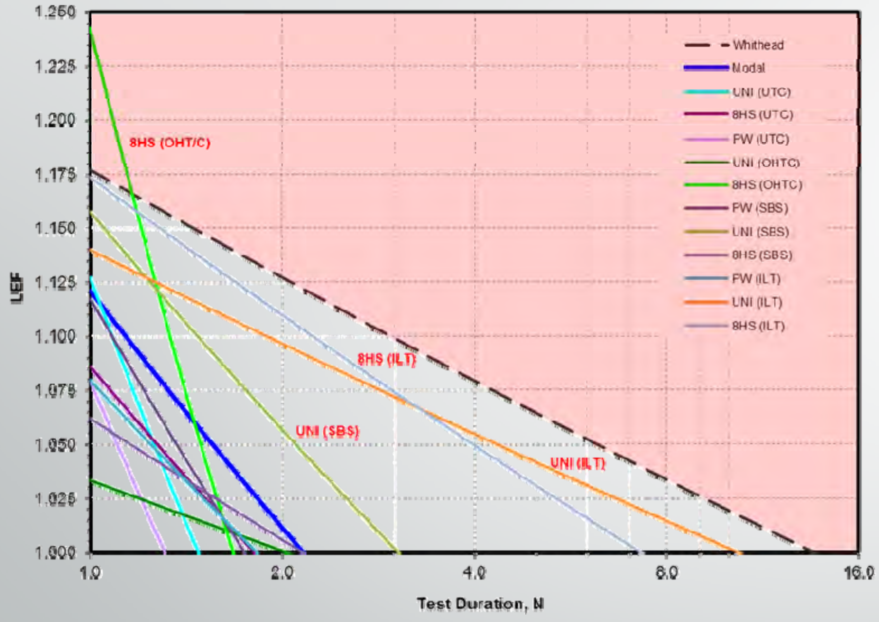


Failure modes with large scatter shall be interrogated at element/sub-component level(s)

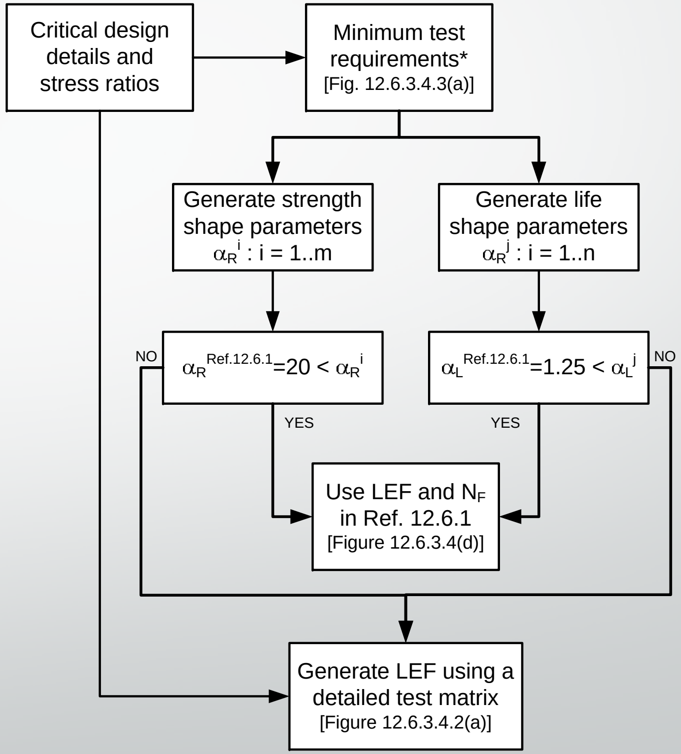
Composite data analyzed in DOT/FAA/AR-10/6 suggest that NADC (DOT/FAA/CT-86-39) LEFs are conservative for modern composites as a result of the improvements in materials and process techniques, and test methods (i.e., less scatter in test data). Therefore, in the absence of sufficient test data, the NADC 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:
1. Whitehead, R.S., Kan, H. P., Cordero, R., and Saether, E. S., "Certification Testing Methodology for Composite Structures," Volumes I and II, Report No. NADC-87042-60 (DOT/FAA/CT-86-39), October 1986.
2. Tomblin, J. and Seneviratne, W., "Determining the Fatigue Life of Composite Aircraft Structures Using Life and Load-Enhancement Factors," DOT/FAA/AR-10/6, June 2011.

Substantiation of Using NADC LEF



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

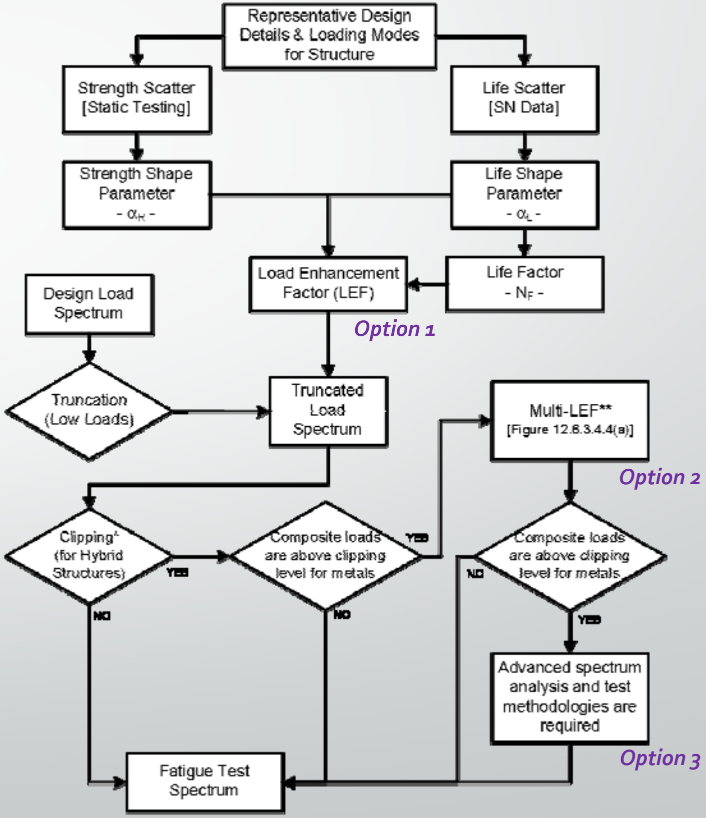


NOTES:
* Number of static data sets and fatigue SN curves are m and n, respectively.

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

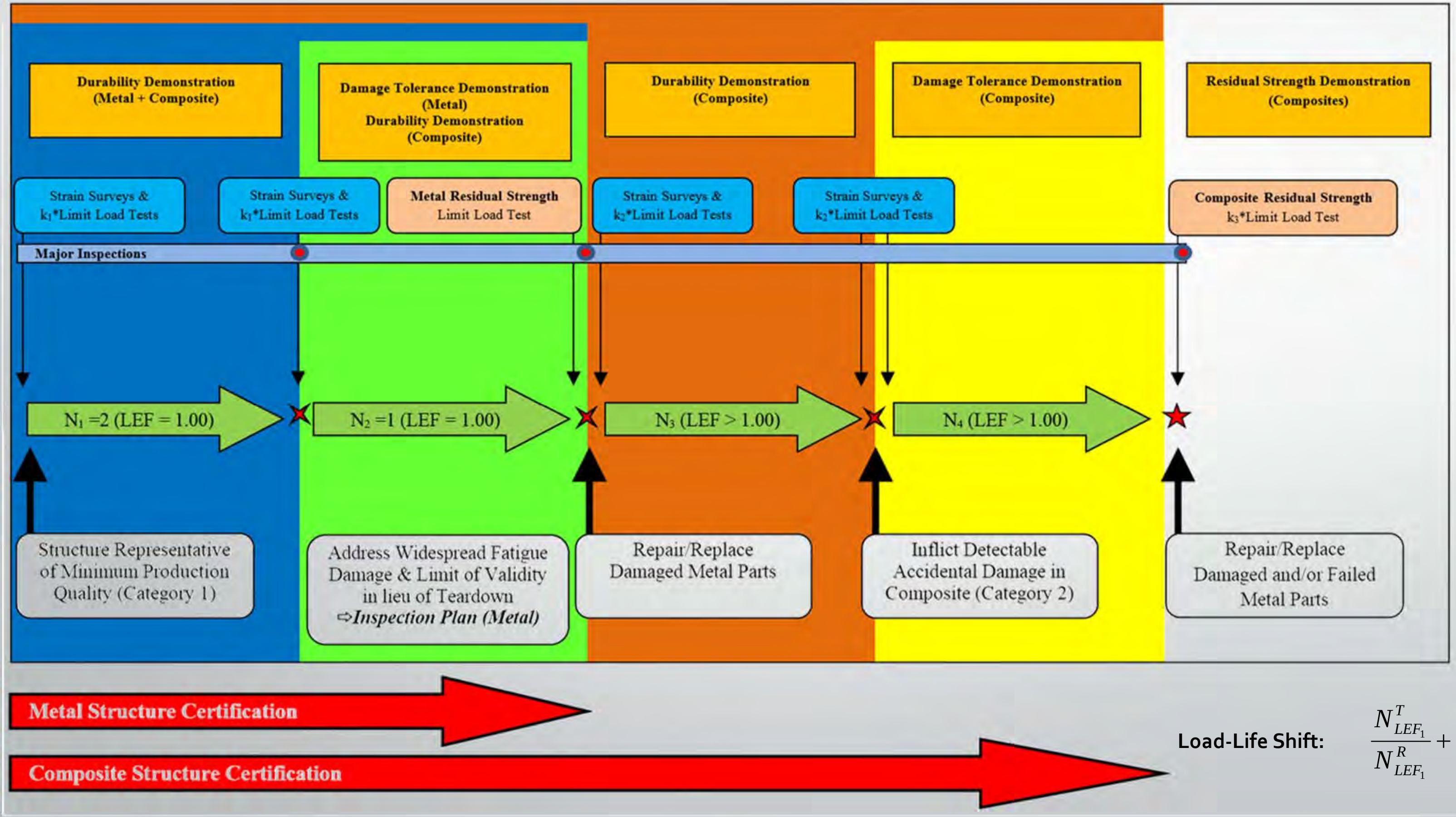
These options can be combined



NOTES:
* Clipping of high loads are only required for metals; composite loads should not be clipped.
** Further analysis and supporting experiments are required prior to applying these methods.

NIAR Wichita State University National Institute for Aviation Research

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.

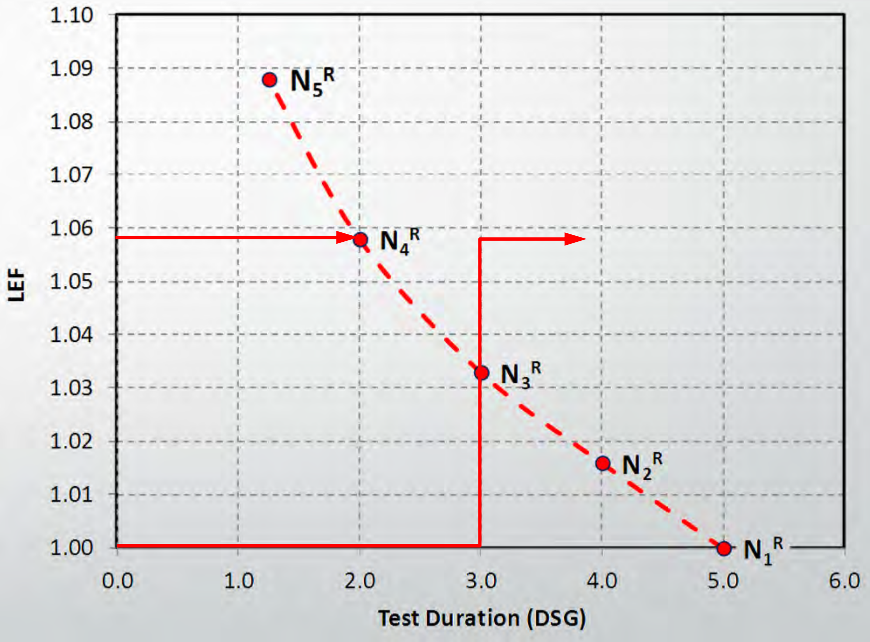
Load-Life Shift

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

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

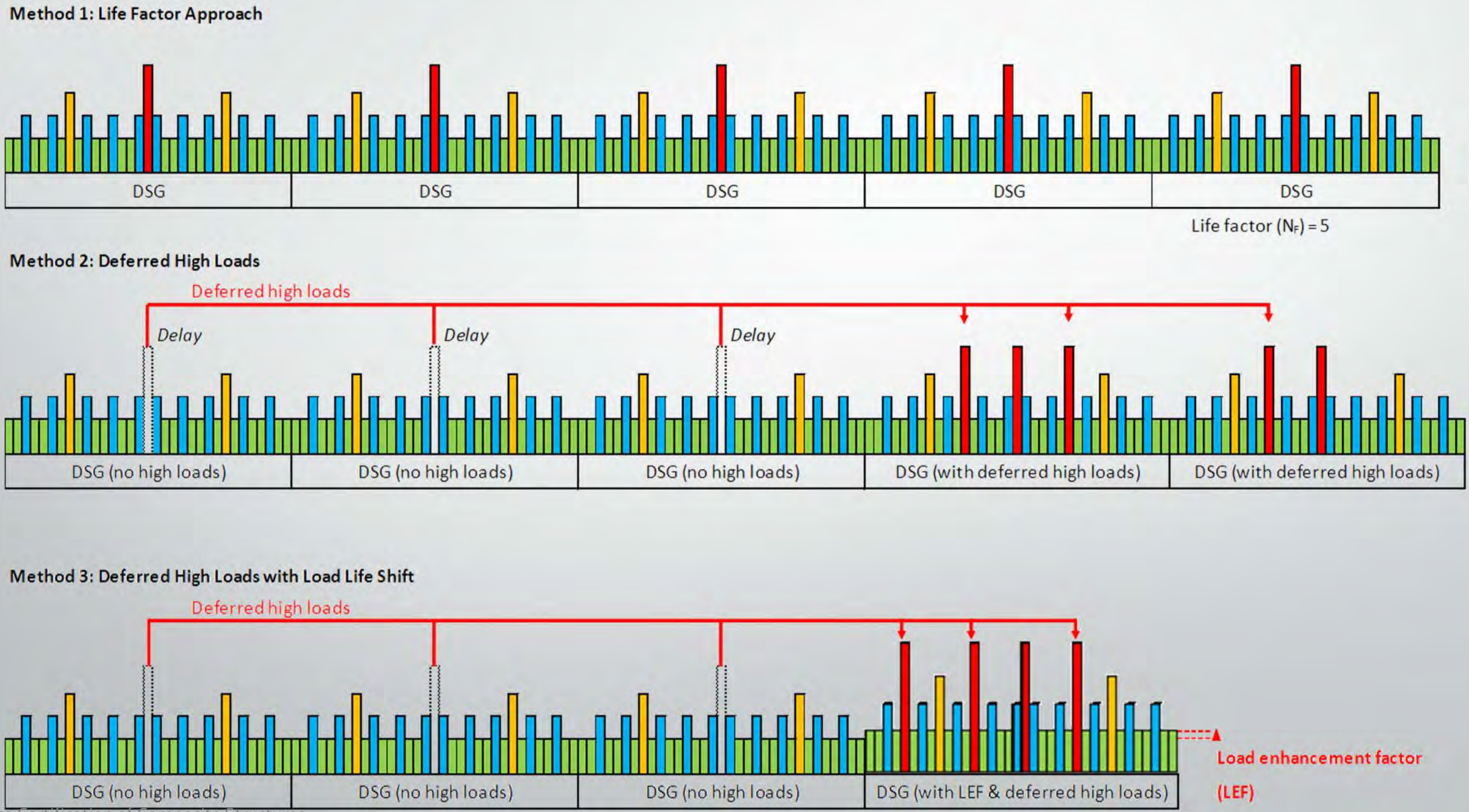
- Simplified (two-step) version:

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

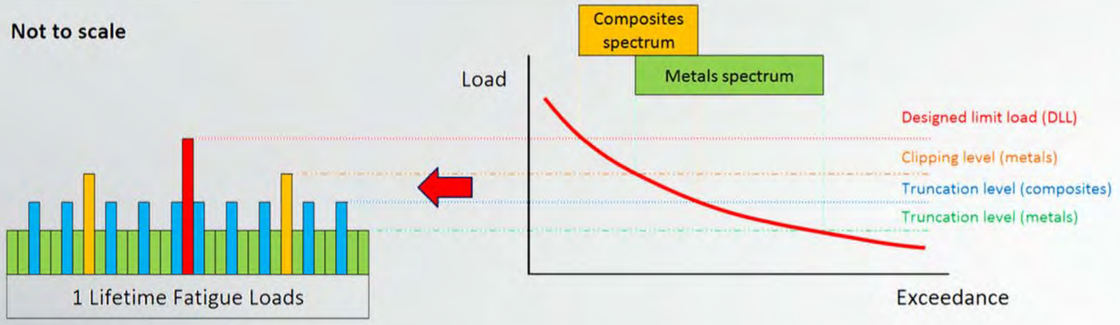


REF: Seneviratne, W. P., and Tomblin, J. S., **"Certification of Composite-Metal Hybrid Structures using Load-Enhancement Factors,"** *FAA Joint Advanced Materials and Structures (JAMS)/Aircraft Airworthiness and Sustainment (AA&S),* Baltimore, MD, 2012.

Deferred Spectrum for Hybrid FSFT



Deferred Spectrum for Hybrid FSFT (contd.)

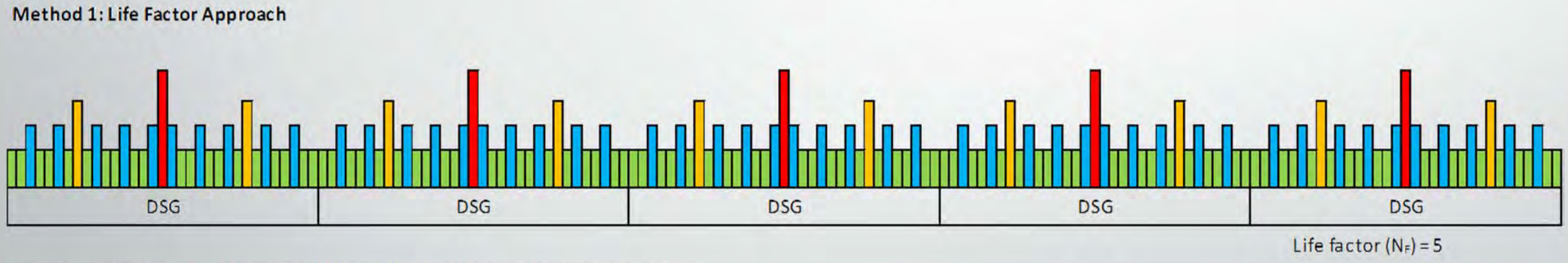


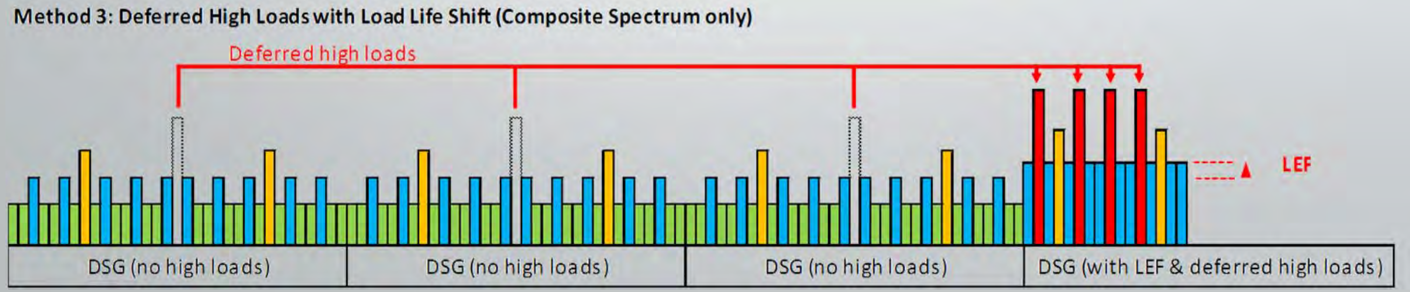
Metals:

severe flight loads result in crack-growth retardation

Composites:

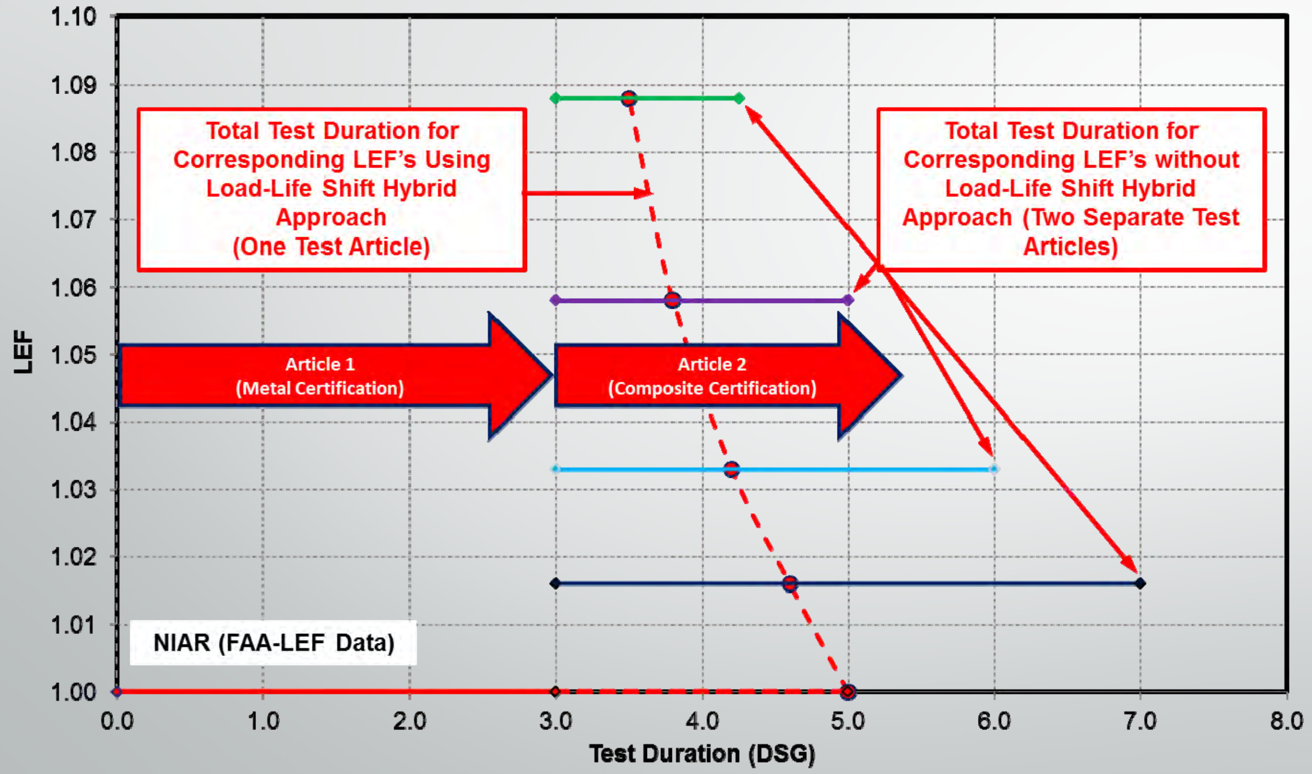
severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life



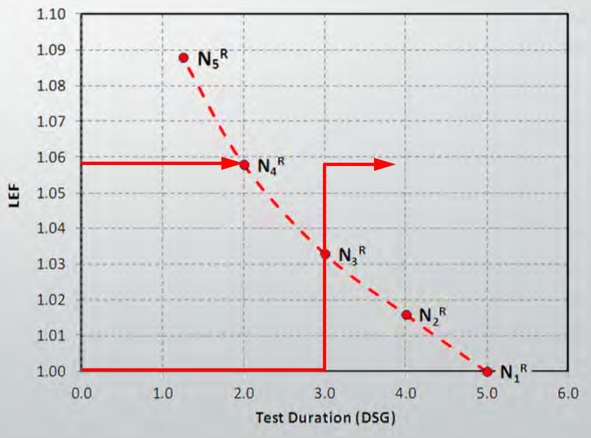


Cycles below composites truncation level (green) are eliminated after 3 DSG

Separate Metal and Composite Certification Test Articles



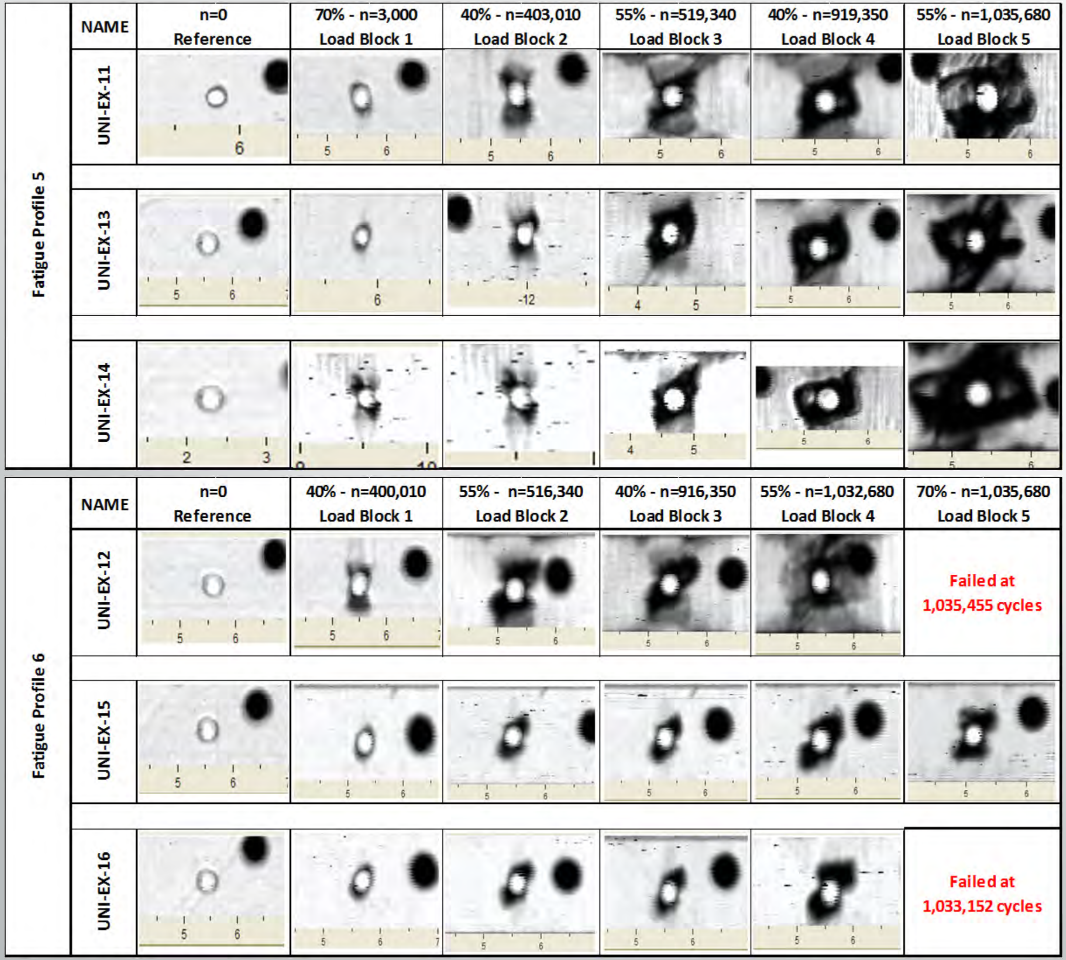
Option	LEF	Required Test Duration without LLS	Required Test Duration with LLS	Total Test Duration
1	1.000	5.0	2.0	**5.0**
2	1.016	4.0	1.6	**4.6**
3	1.033	3.0	1.2	**4.2**
4	1.058	2.0	0.8	**3.8**
5	1.088	1.3	0.5	**3.5**



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)

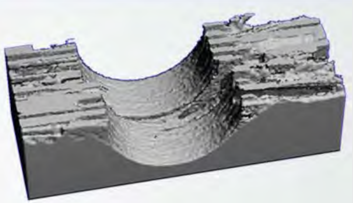
70-40-55-40-55 (High-Low)



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

6 spec. survived profile 5

4 spec. failed and 2 spec. survived profile 6



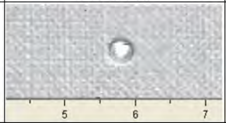
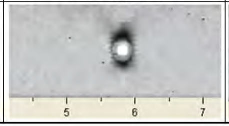
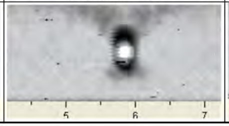
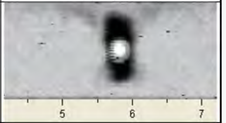
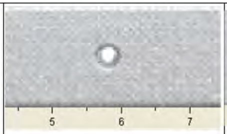
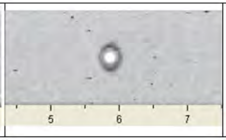
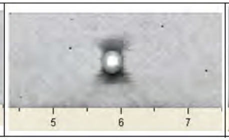
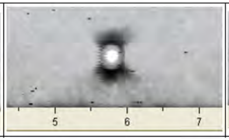
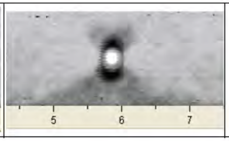
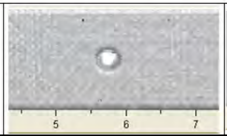
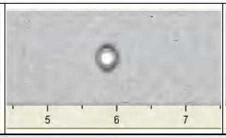
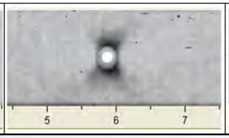
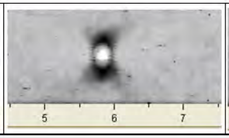
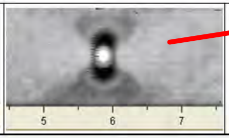
High-Low			Low-High		
Spectrum Block	% of Ultimate	Number of Cycles in Block	Spectrum Block	% of Ultimate	Number of Cycles in Block
1	70	3000	1	40	400010
2	40	400010	2	55	116330
3	55	116330	3	40	400010
4	40	400010	4	55	116330
5	55	116330	5	70	3000

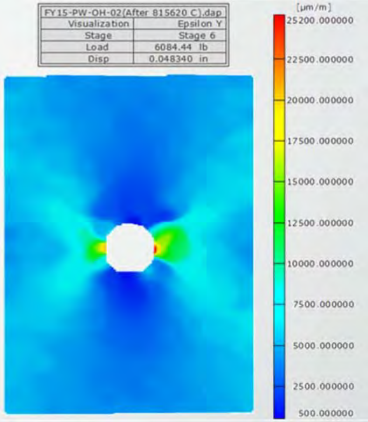
Lower level building-blocks of testing:

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)

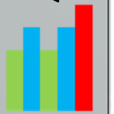
Load Sequencing Effects – Open Hole Tension/Compression (PW)

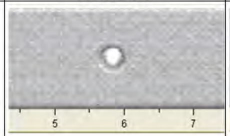
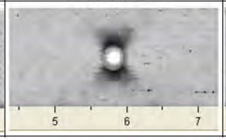
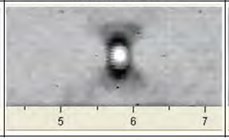
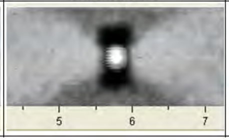
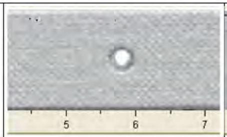
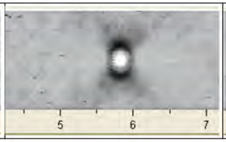
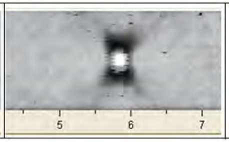
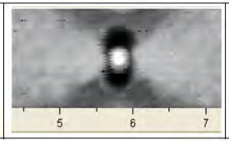
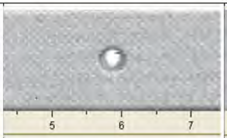
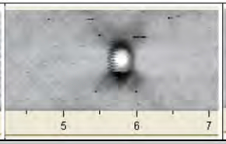
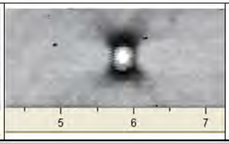
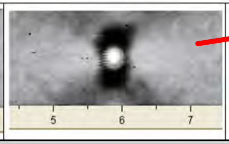
70-40-55-40-55 (High-Low)

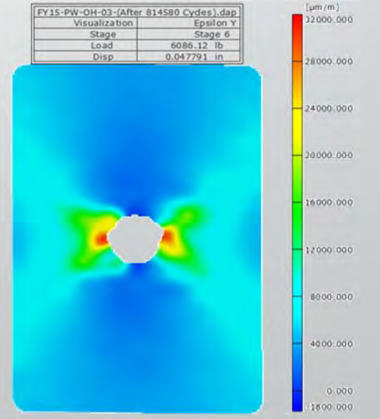
Fatigue Profile 5	NAME	n=0 Reference	70% - n=1,040 Load Block 1	40% - n=401,050 Load Block 2	55% - n=415,610 Load Block 3	40% - n=815,620 Load Block 4	55% - n=830,180 Load Block 5
	PW-OH-27						
	PW-OH-1						Failed at 823,523 cycles
	PW-OH-2						Failed at 827,830 cycles



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

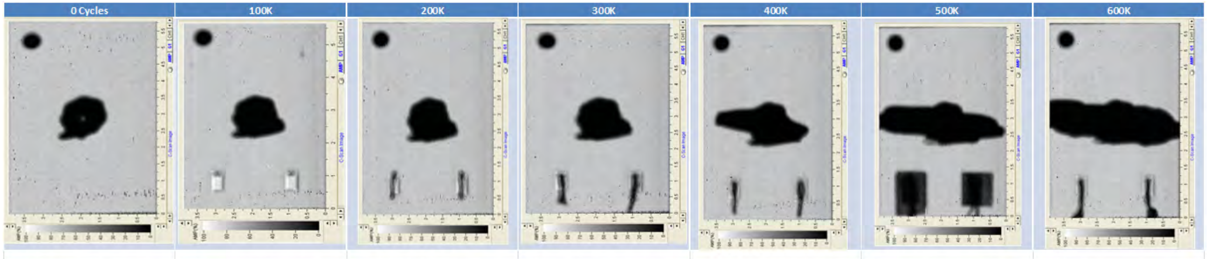


Fatigue Profile 6	NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=414,570 Load Block 2	40% - n=814,580 Load Block 3	55% - n=429,140 Load Block 4	70% - n=430180 Load Block 5
	PW-OH-3					Failed at 815,550 cycles	
	PW-OH-4					Failed at 822,849 cycles	
	PW-OH-6					Failed at 816,002 cycles	

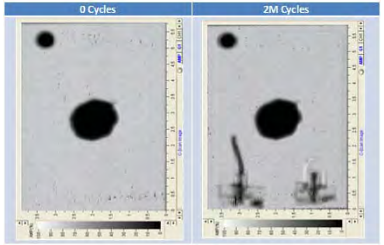


Load Sequencing Effects - Compression After Impact

Constant Amplitude (70% CAI SS)

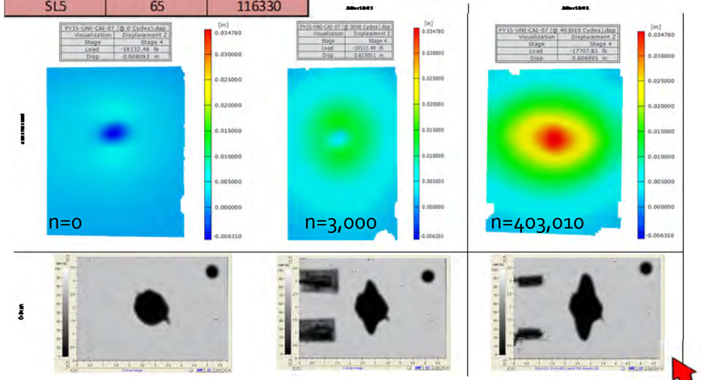


Constant Amplitude (55% CAI SS)



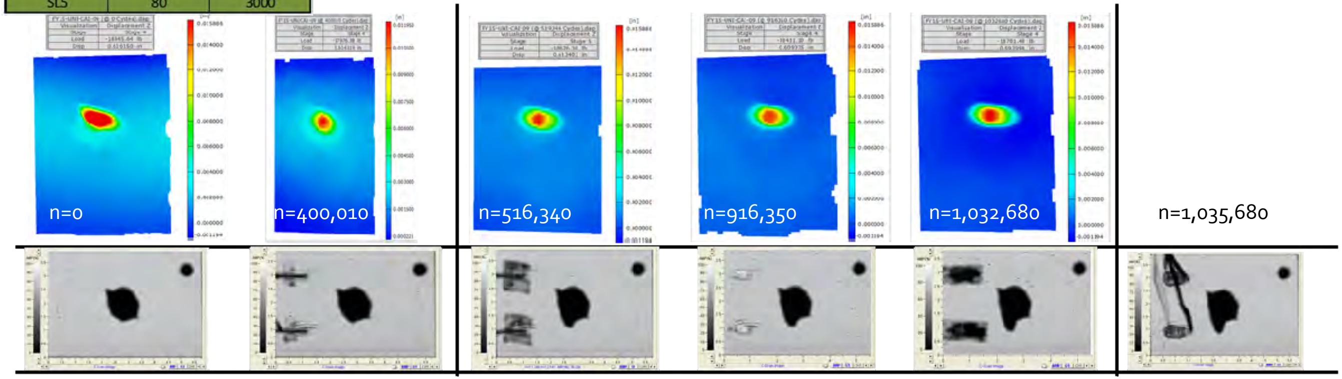
Spectrum Fatigue

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



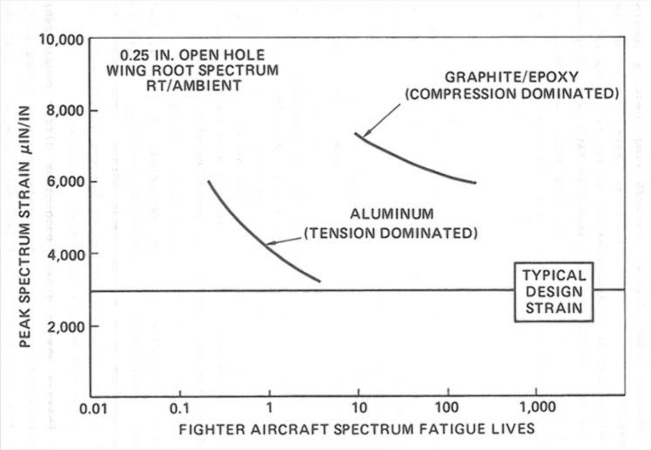
1 spec. failed at n=403,011
1 spec. survived n=1,035,680

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



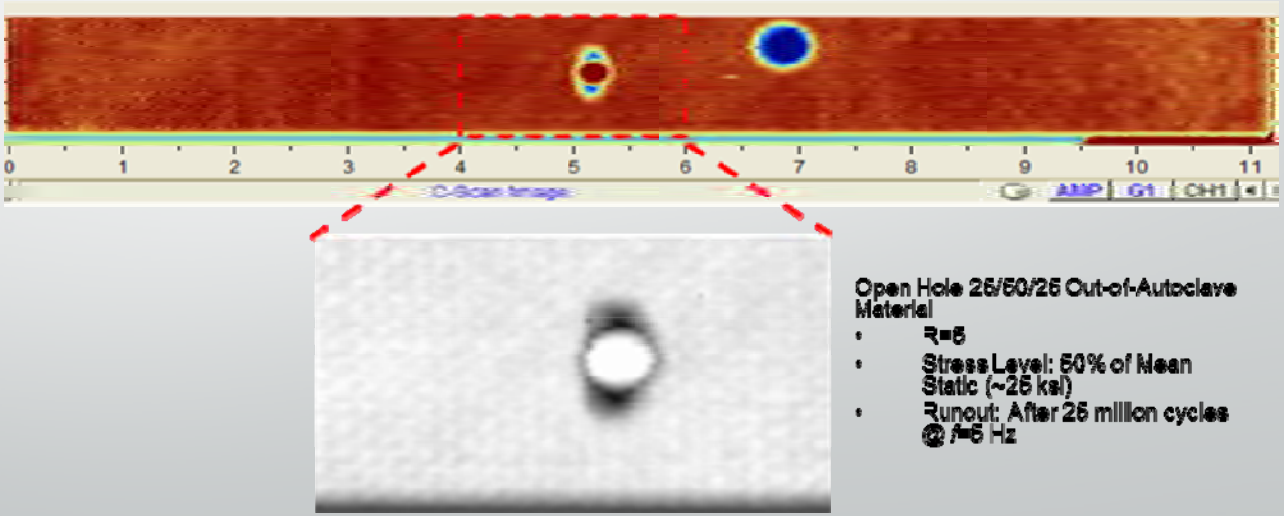
3 spec. survived
n=1,035,680

Operating Stress/Strain Levels



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

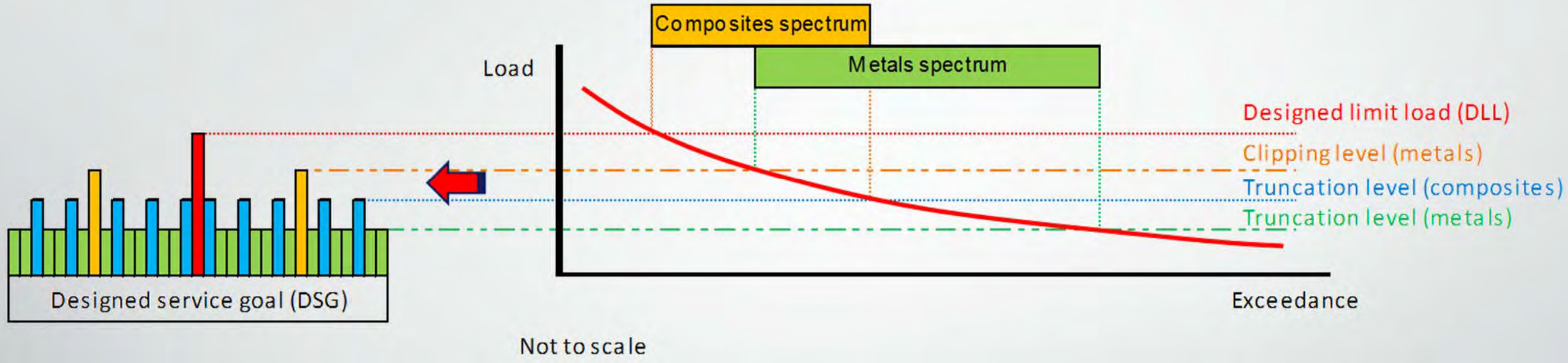
Operating levels for composites are significantly low
➔ No sequencing effects



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

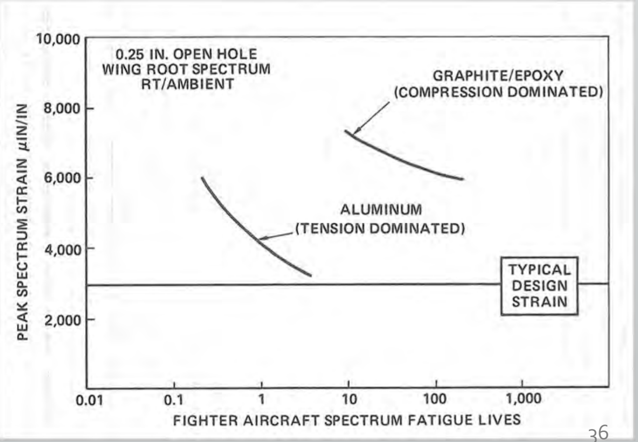
- R=5
- Stress Level: 50% of Mean Static (~25 ksi)
- Runout: After 25 million cycles @ f=5 Hz

Development of Hybrid Spectrum

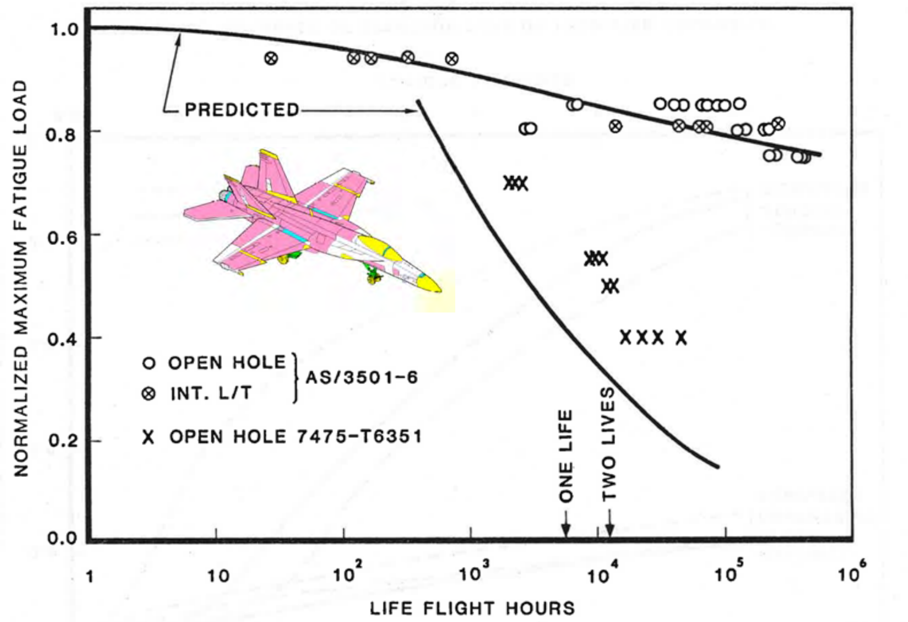


- Differences between composite and metallic spectrums
  - Metals: severe flight loads result in crack-growth retardation → Clipping
  - Composites: severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life
  - Flaw growth threshold for metals may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

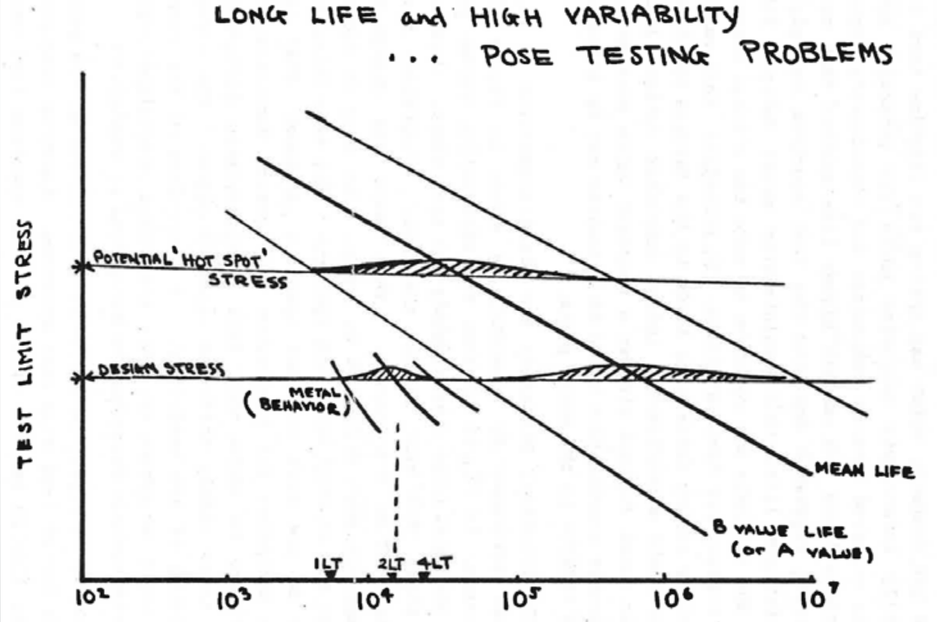
  → Different Truncation Levels



Composite vs. Metal Fatigue Sensitivity

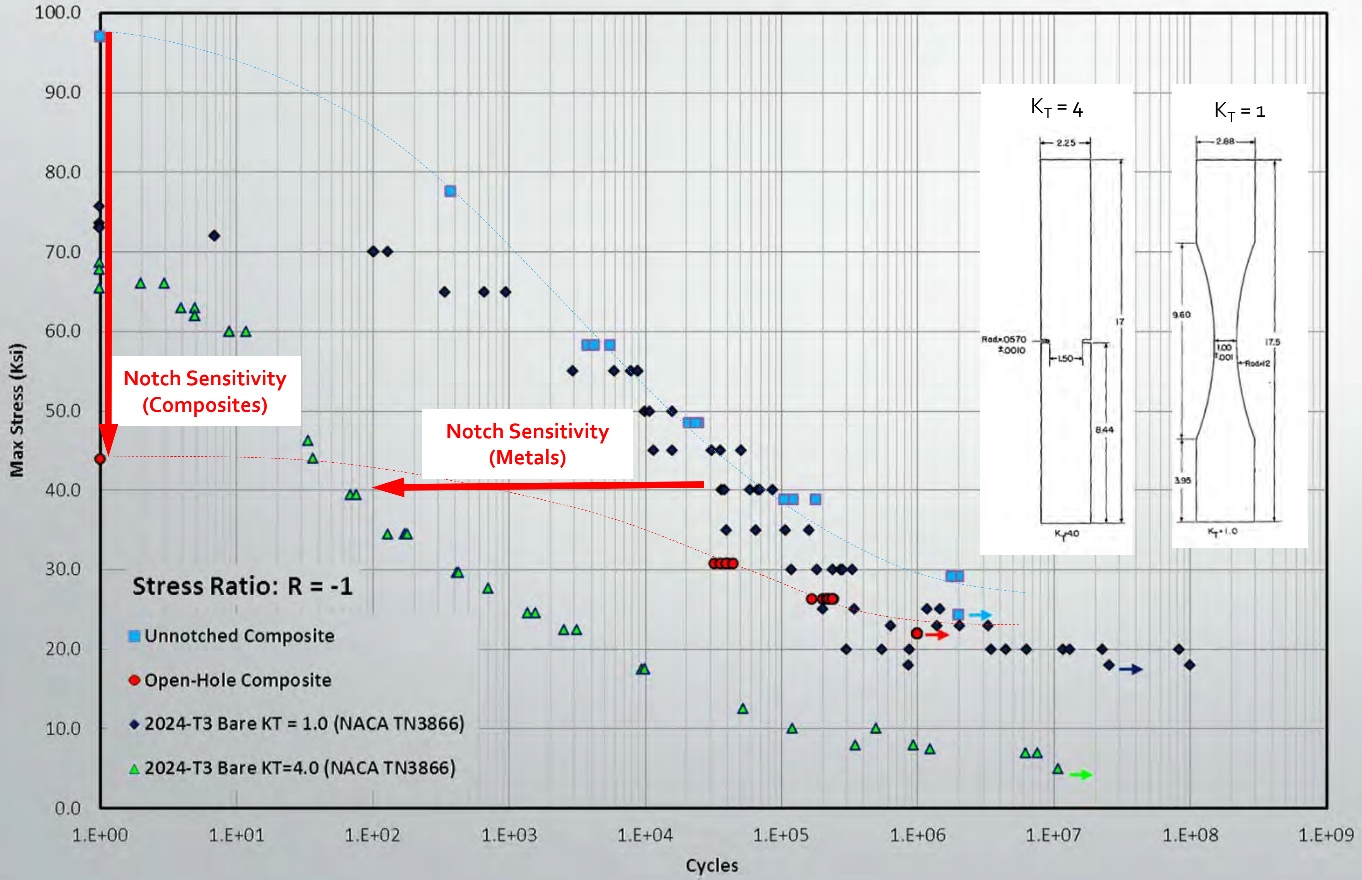


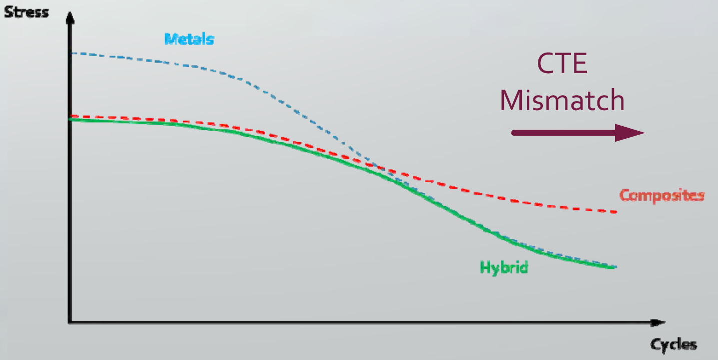
Comparison of composite and metallic fatigue behavior for a wing spectrum
Ref: Whitehead, *et. al.* (1986), NADC-87042-60



Ref: Dr. A. Someroff (1981), NAVAIR
(extracted from NADC-87042-60)

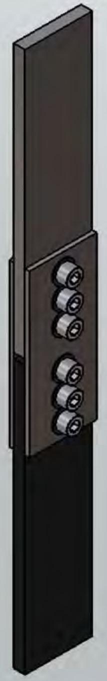
Composite vs. Metal - Sensitivity





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



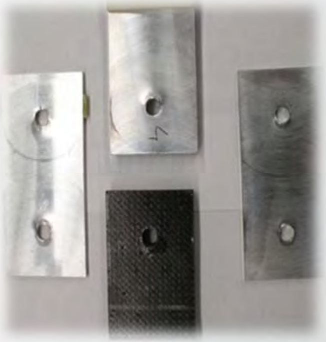
Damage Growth in Metals ✓

Damage Growth in Composites ✓

Damage Growth in Hybrids ?

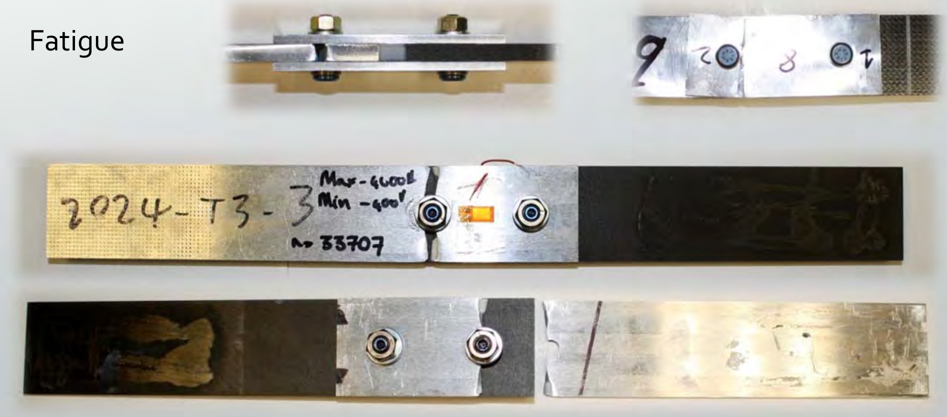
- Competing failure modes
- Sequencing effects
- Miner's Rule or an alternative (???)
- Effects of LEFs
- Effects of additional test duration
- Effects of CTE mismatch
- Effects of environment

Static - Tension



Static - Compression

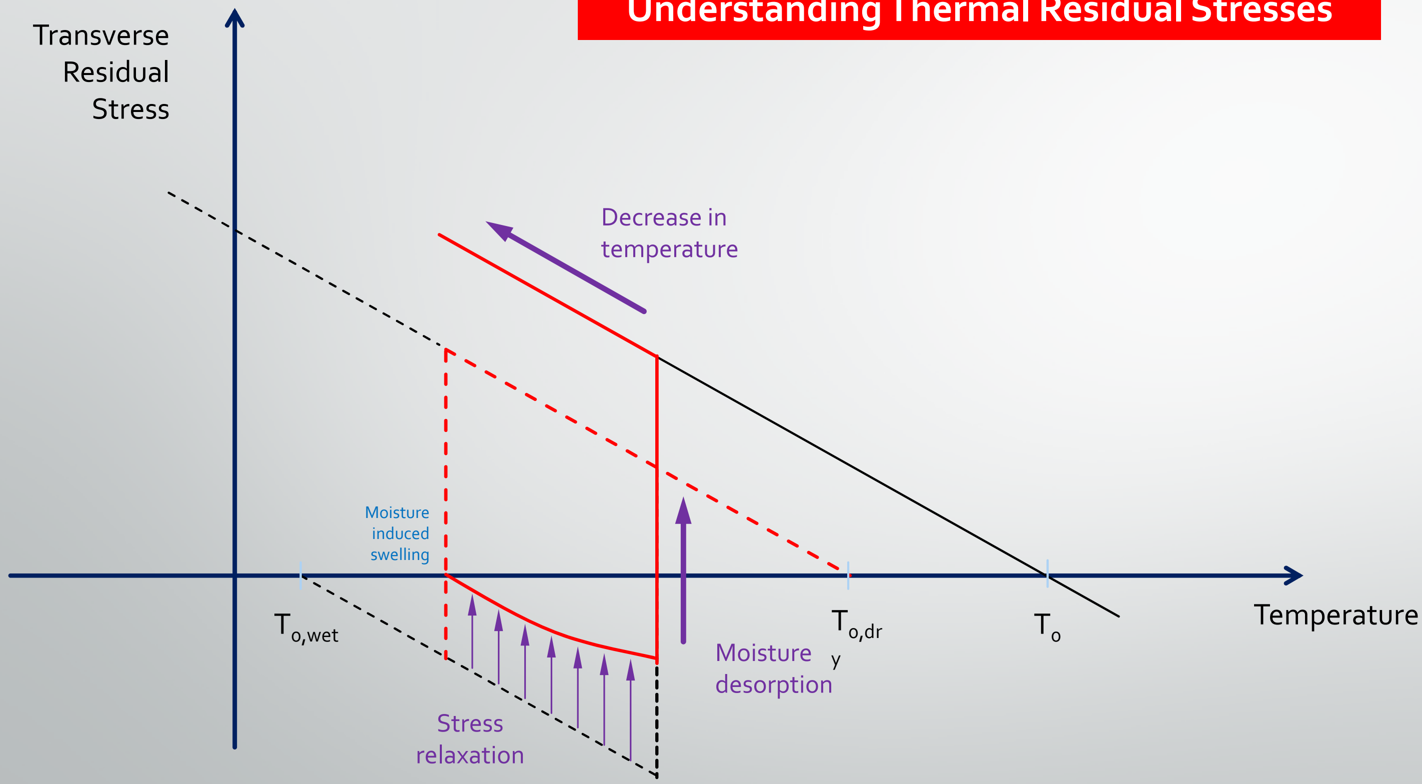
Fatigue

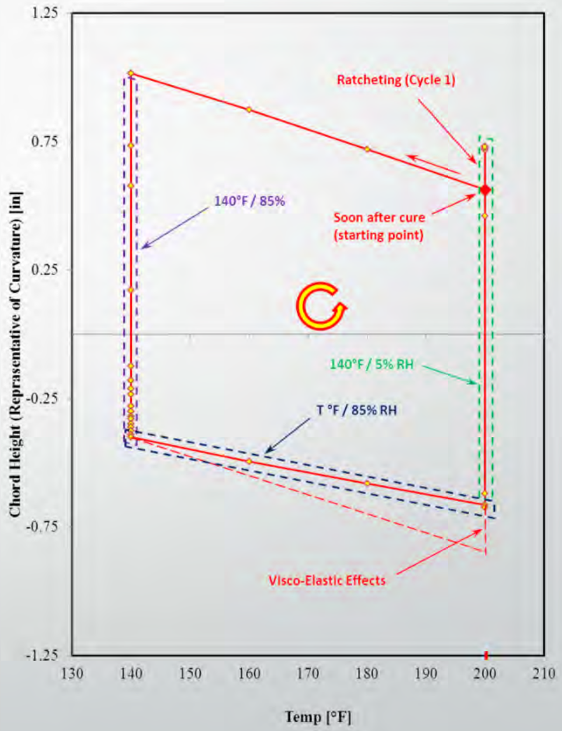


Other Research Topics

Viscoelastic Behavior of TRS due to Hygrothermal History

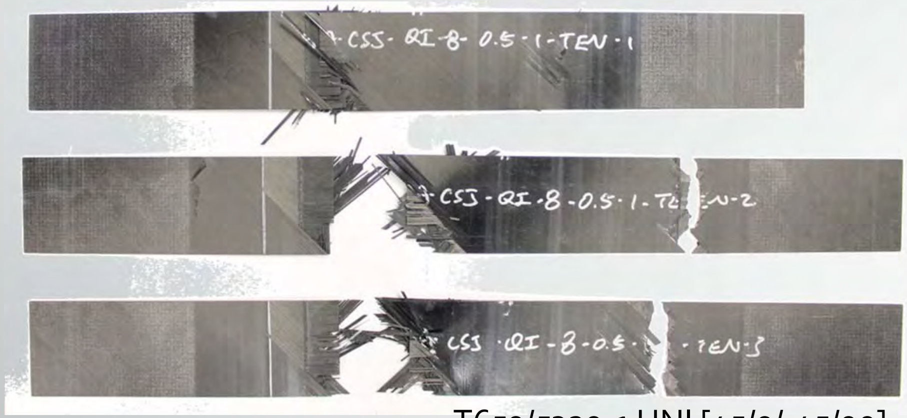
Understanding Thermal Residual Stresses



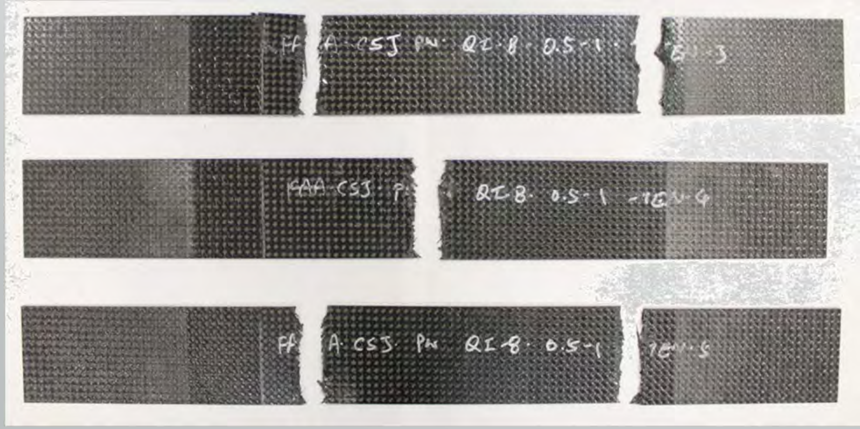


REF: Rothschilds, R. J., Ilcewicz, L. B., Nordin, P., and Applegate, S. H., "The Effect of Hygrothermal Histories on Matrix Cracking in Fiber Reinforced Laminates," *Journal of Engineering Materials and Technology*, Vol. 110, pp. 158-168, 1988.

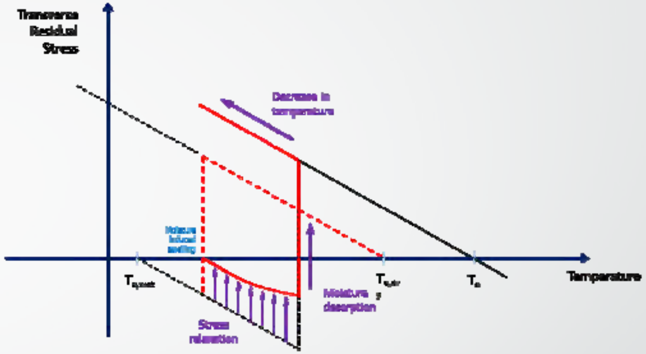
8-Ply Spliced Tensile Specimens

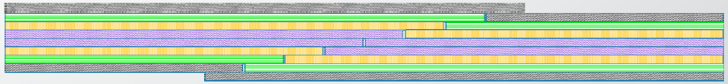


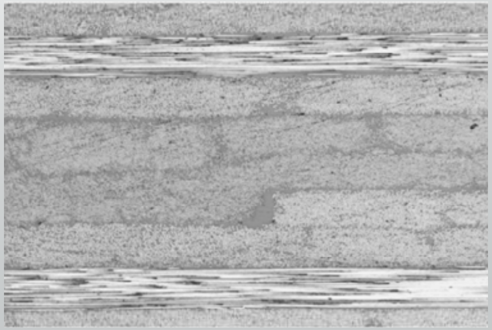
T650/5320-1 UNI [45/0/-45/90]$_s$



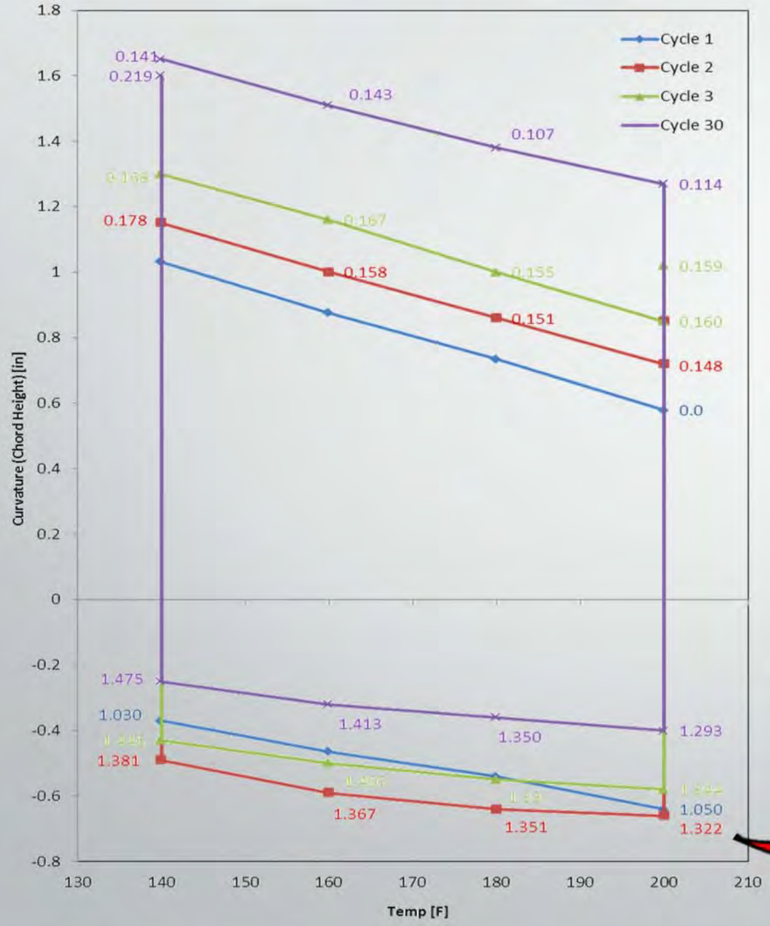
T650/5320-1 PW [45/0/-45/90]$_s$

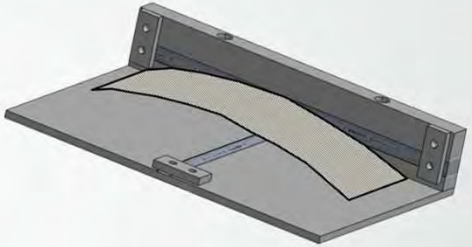


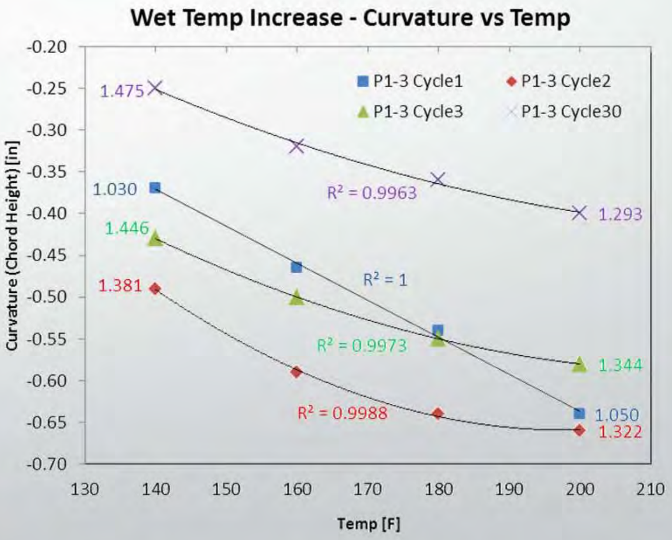




Ratcheting Effects – 4-Ply Specimens



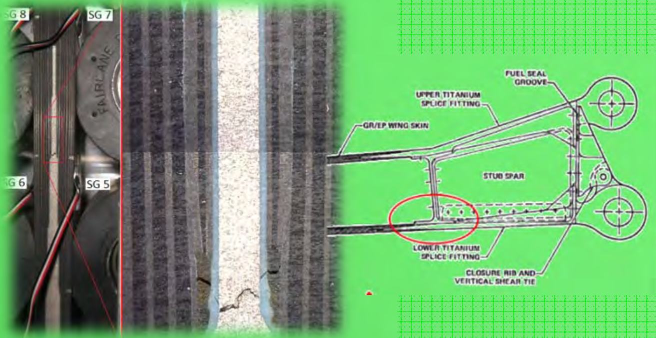


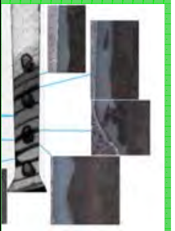


Life Extension of F/A-18 Composite Structure

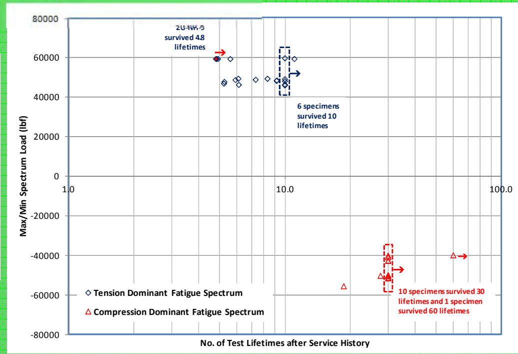
Hybrid – Repair – Aging

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

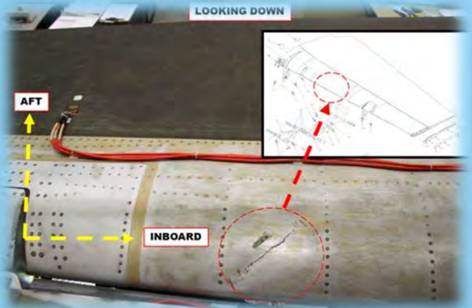


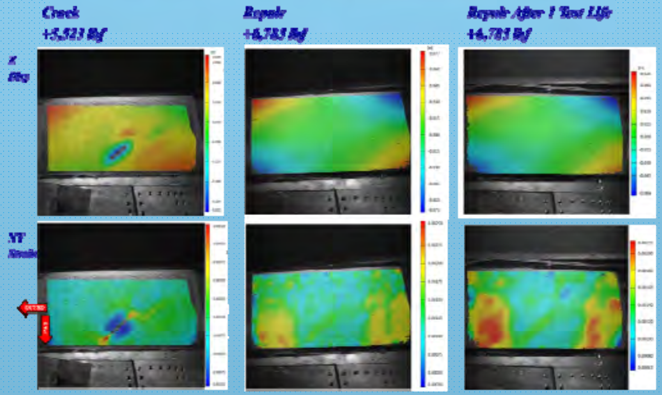


Inspections after 10 lifetimes

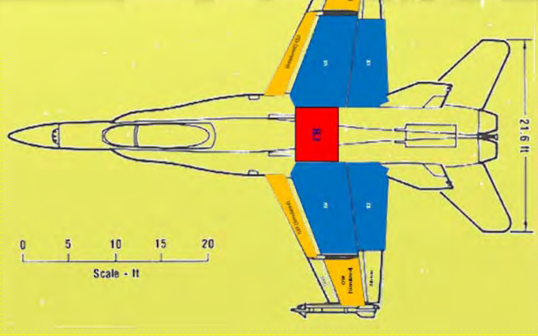


ASIP 2012
Durability of Composite Wet Layup Repair on Metallic Leading Edge of F/A-18 Trailing-Edge Flap

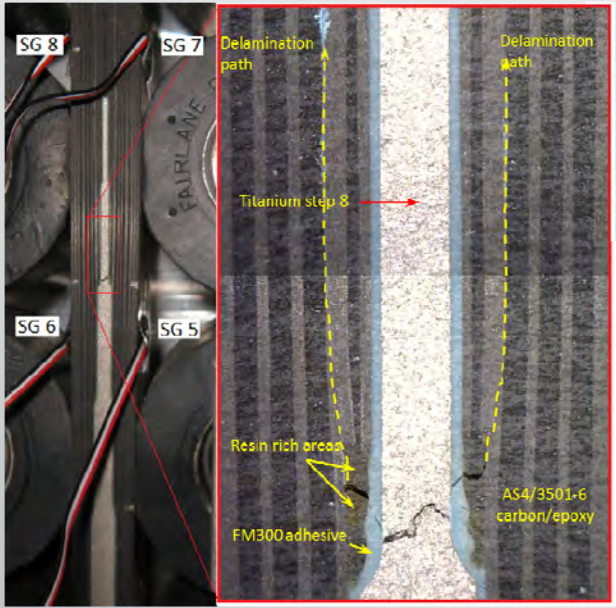


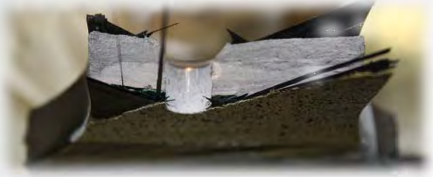


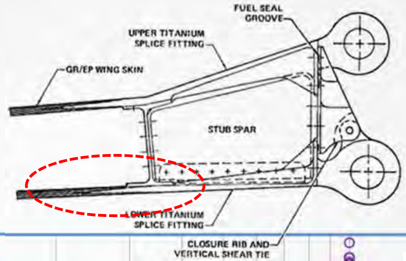
ASIP 2013-14
Full-Scale Fatigue Testing of F/A-18 A-D Inner Wing



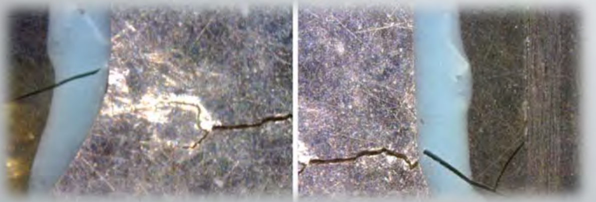
F/A-18 Wing-Root Stepped-Lap Hybrid Bonded Joint

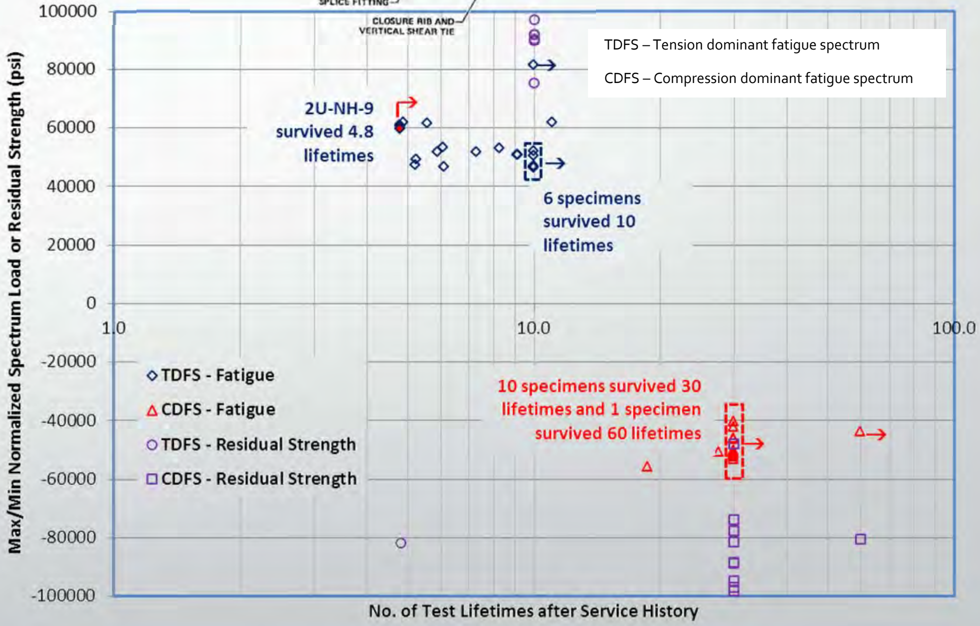






Intensified spectrum

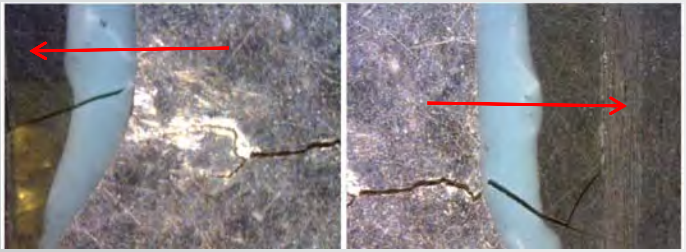




Ref: Seneviratne, W., *et.al.*, "Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and the Centennial of Naval Aviation Forum, September 2011.

Progressive Damage Growth of Titanium (TDFS)

No-Hole



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

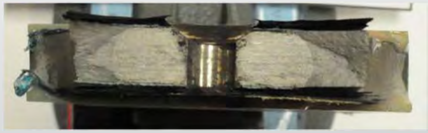
(b) Failure surface –OML side

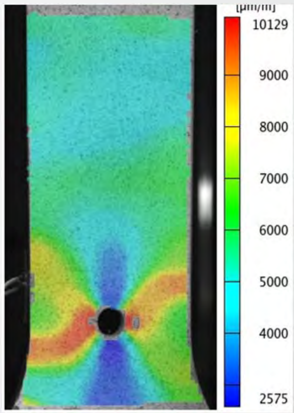
(c) Failure surface –IML side

Open-Hole

Unstable Crack Growth

Stable Crack Growth





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

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

CMH-17 COMPOSITE MATERIALS HANDBOOK

JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

References

- **Contact (Waruna Seneviratne):**
  - waruna@niar.wichita.edu
- **References:**

  - 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.
  - Seneviratne, W., **Fatigue Life Determination of a Damage-Tolerant Composite Airframe,** Wichita State University, December 2008.
  - 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.
  - 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.