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Analytical Fatigue Life Determination based on Residual Strength Degradation of Composites

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

2017 Technical Review

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

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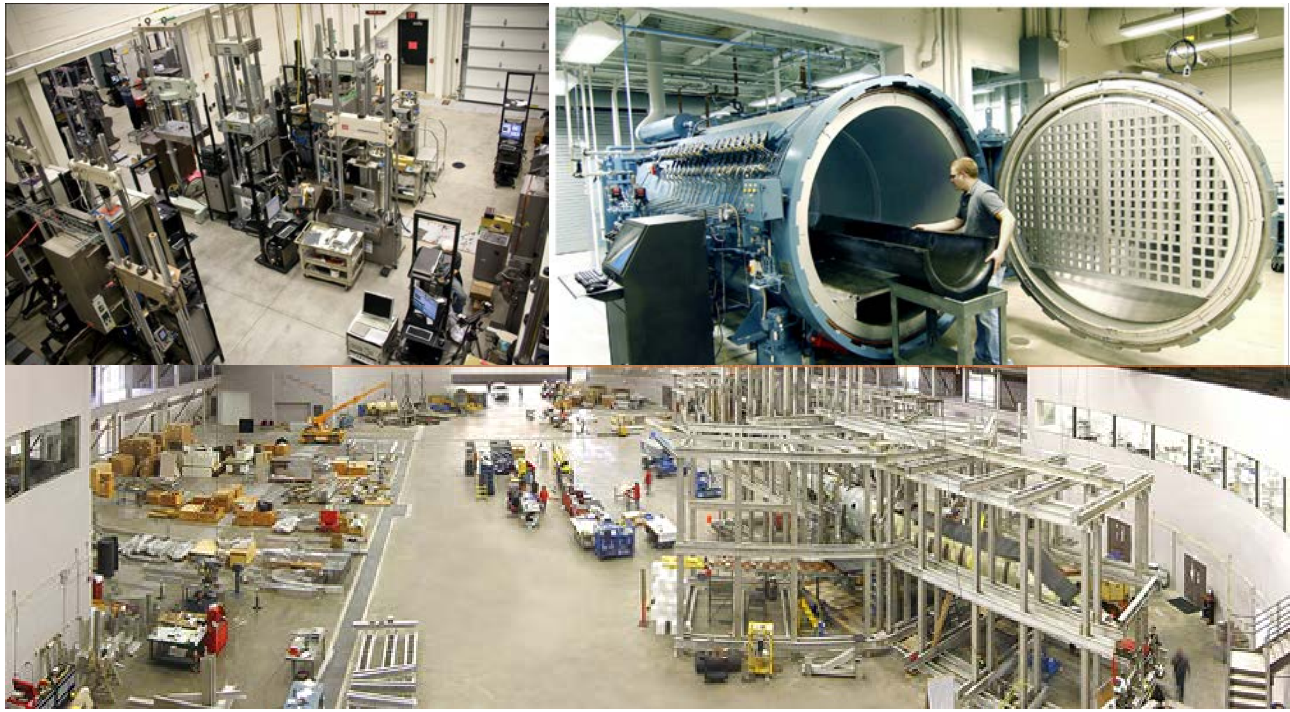
DoD/Industry Participation

Air Force Research Lab (AFRL), Airbus, Boeing, Bombardier, Bell Helicopter, Textron Aviation, Honda Aircraft Co., NAVAIR, and Spirit Aerosystems

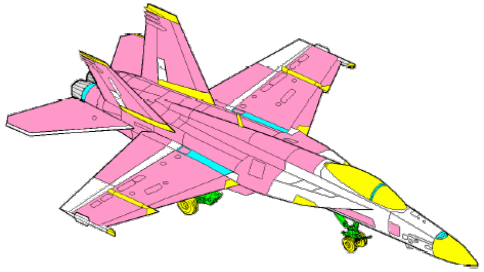
JAMS Joint Advanced Materials & Structures Center of Excellence

CECAM center of excellence for composites and advanced materials



Variable Amplitude Fatigue Damage Growth (Background)

- Due to the anisotropy and heterogeneous nature of composites, fatigue damage growth characteristics of composites are complex and predictive methodologies are at their infant stages.
- Therefore, overly conservative assumptions are made for fatigue life assessment without taking full advantage of fatigue capabilities of composites.
- In order to design efficient composite structures, a greater understanding of fundamentals of fatigue damage initiation and growth characteristics of composite is needed.
- Need to understand the interaction of high-cycle (low stress) and low-cycle (high stress) fatigue on the life assessment of composite.

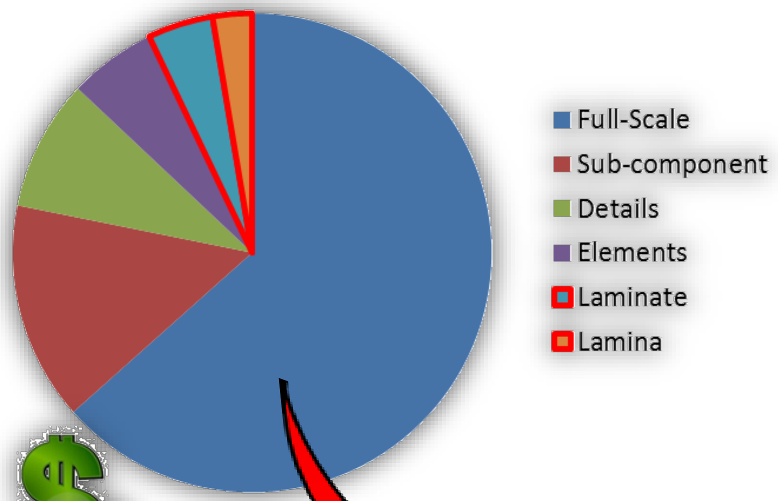


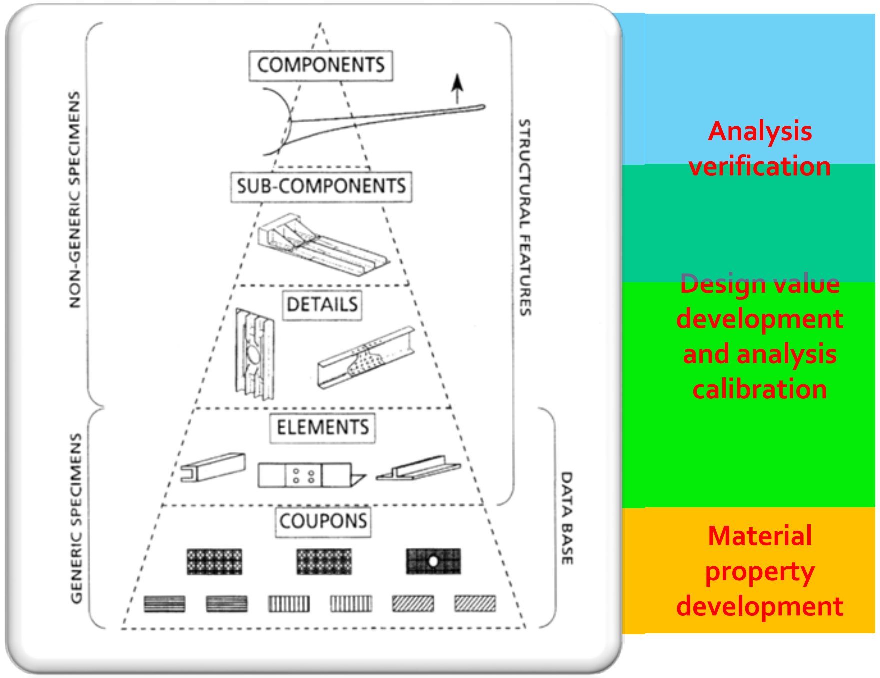
The primary goal of this research is to investigate the fatigue damage growth of composites under variable amplitude fatigue loading.

The secondary goal of the program is to develop tools for determining the residual strength degradation or wearout.

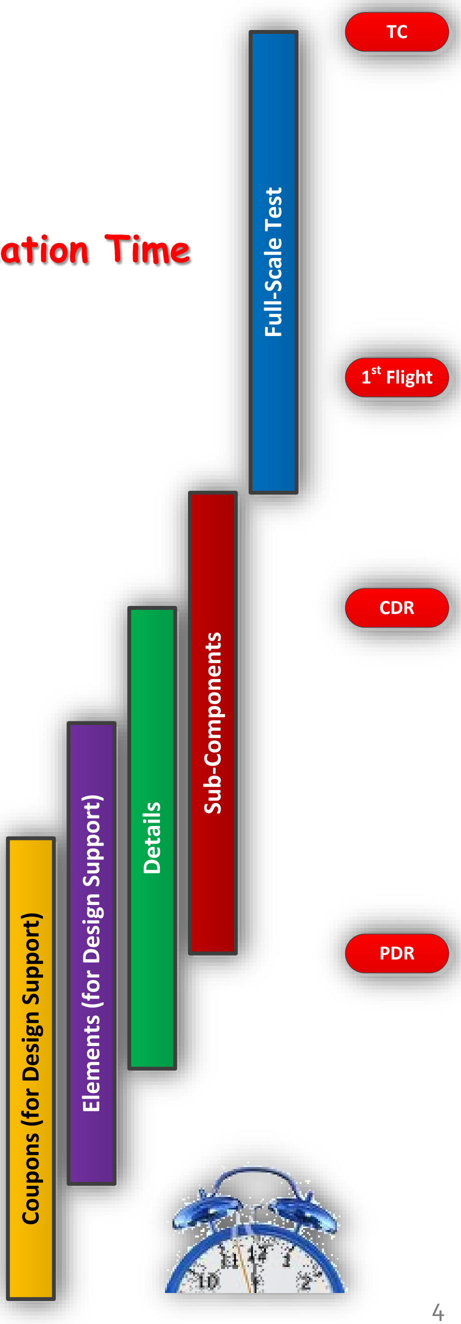
Certification Cost & Time

~ Certification Cost



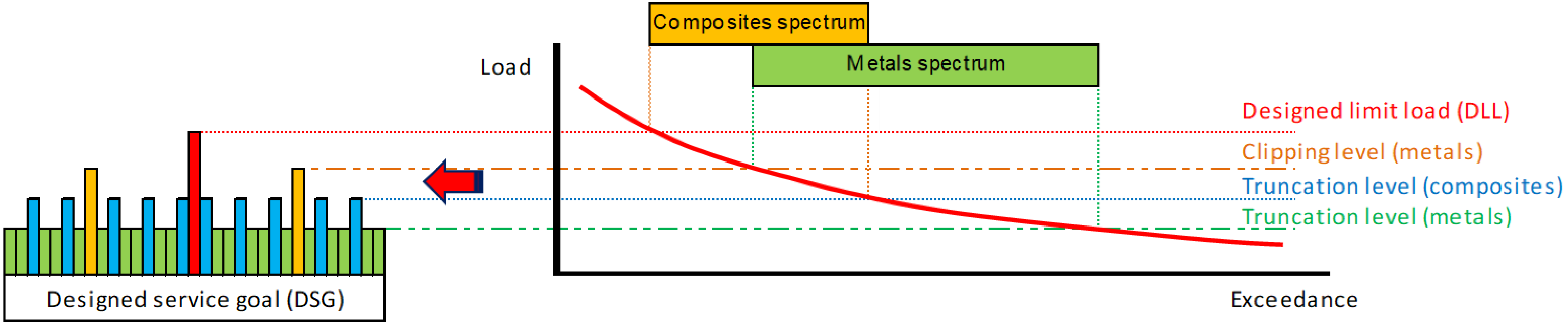


~ Certification Time



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

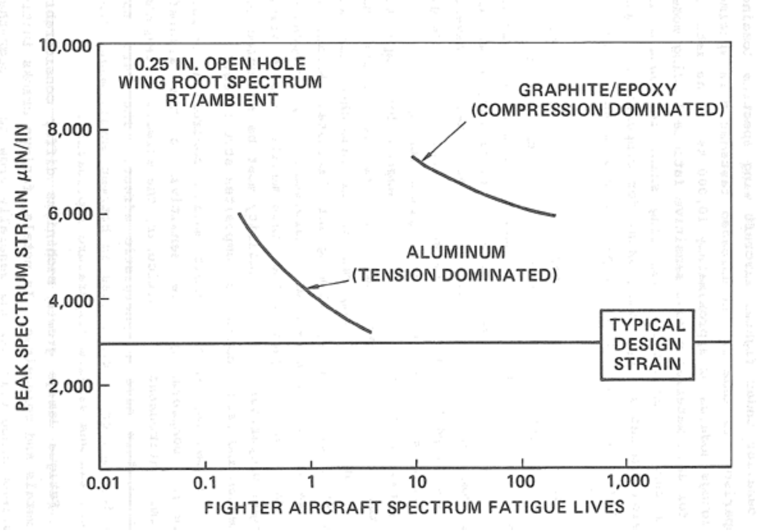
Development of Hybrid Spectrum



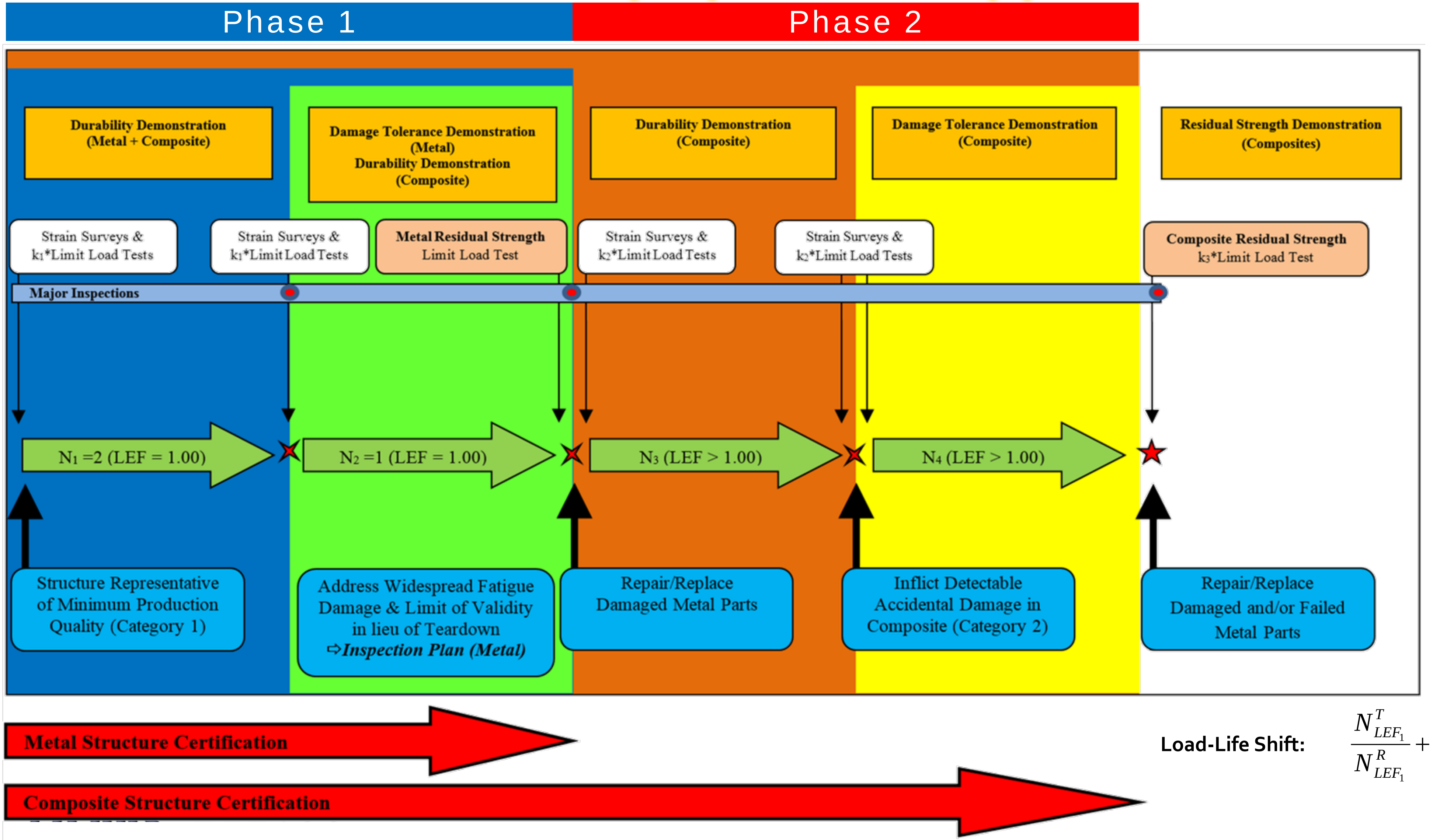
Not to scale

- 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



Deferred Severity Spectrum Approach (Single Full-Scale Test Article)



Phase 1

Phase 2

Durability Demonstration (Metal + Composite)

Strain Surveys & k_1*Limit Load Tests

Major Inspections

$N_1 = 2$ (LEF = 1.00)

Structure Representative of Minimum Production Quality (Category 1)

Damage Tolerance Demonstration (Metal)
Durability Demonstration (Composite)

Strain Surveys & k_1*Limit Load Tests

Metal Residual Strength Limit Load Test

$N_2 = 1$ (LEF = 1.00)

Address Widespread Fatigue Damage & Limit of Validity in lieu of Teardown
➩ ***Inspection Plan (Metal)***

Durability Demonstration (Composite)

Strain Surveys & k_2*Limit Load Tests

N_3 (LEF > 1.00)

Repair/Replace Damaged Metal Parts

Damage Tolerance Demonstration (Composite)

Strain Surveys & k_2*Limit Load Tests

N_4 (LEF > 1.00)

Inflict Detectable Accidental Damage in Composite (Category 2)

Residual Strength Demonstration (Composites)

Composite Residual Strength k_3*Limit Load Test

Repair/Replace Damaged and/or Failed Metal Parts

Metal Structure Certification

Composite Structure Certification

Considerations:

- Limit of Validity (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:

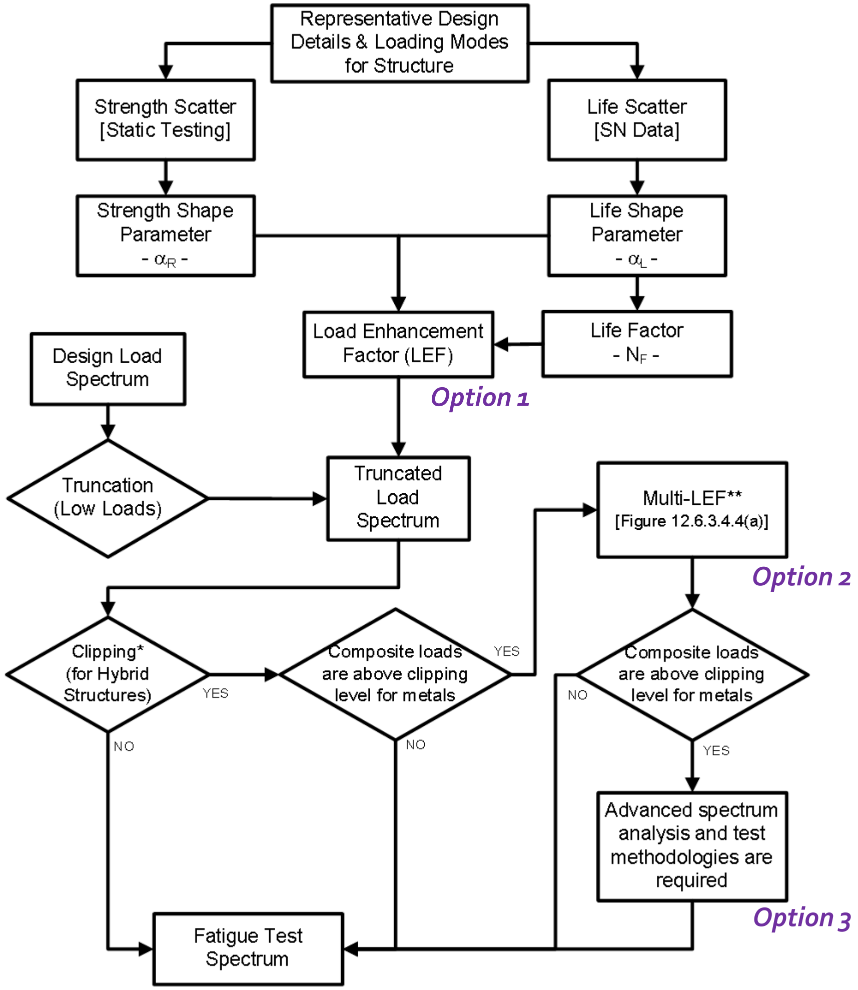
$$\frac{N^T_{LEF_1}}{N^R_{LEF_1}} + \frac{N^T_{LEF_2}}{N^R_{LEF_2}} + \ldots\ldots + \frac{N^T_{LEF_n}}{N^R_{LEF_n}} = \sum_{i=1}^{n} \frac{N^T_{LEF_i}}{N^R_{LEF_i}} \geq 1.0$$

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. (also recent CAMX 2016 paper)

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

Significant modifications to the spectrum are required!



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.

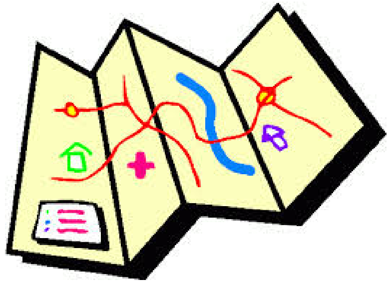
Fatigue Damage Growth of Hybrid Structures (Overview)

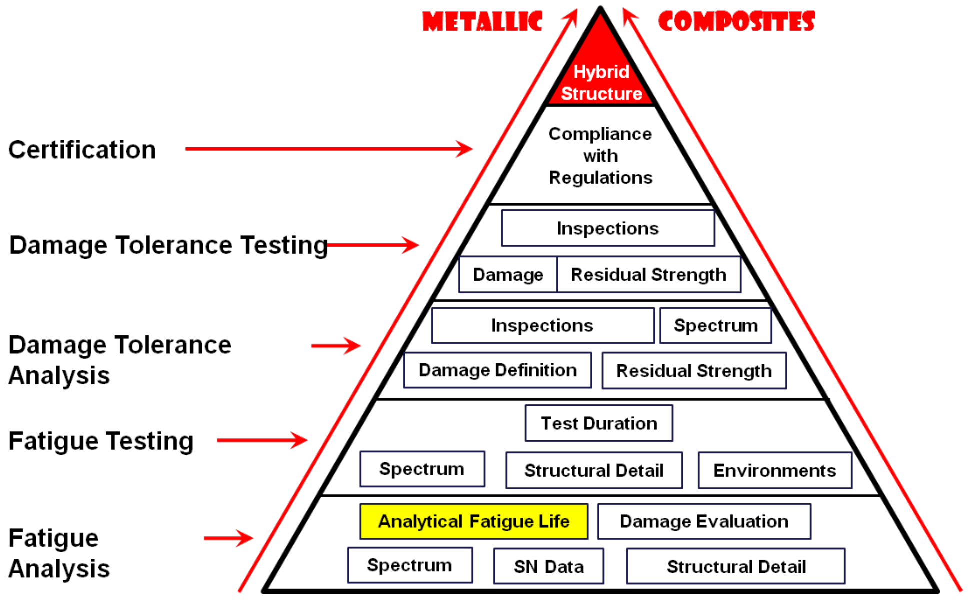
I

- Data Scatter
    - Life factor (N_F) approach
    - Load-enhancement factor (LEF) approach
    - Fatigue scatter analysis techniques
    - Application of LEF and N_F

II

- Certification of hybrid structures
    - Critical loads and different spectrum requirements
    - Notch sensitivity and fatigue sensitivity
    - Hybrid joint testing
    - Certification efficiency
        - Multi-LEF approach
        - Deferred spectrum severity approach
        - *Sequencing effects*





METALLIC
COMPOSITES
Hybrid Structure

Certification → Compliance with Regulations

Damage Tolerance Testing → Inspections; Damage; Residual Strength

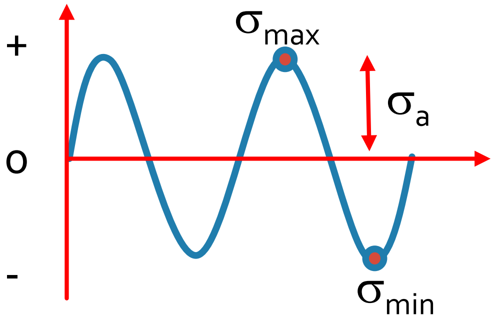
Damage Tolerance Analysis → Inspections; Spectrum; Damage Definition; Residual Strength

Fatigue Testing → Test Duration; Spectrum; Structural Detail; Environments

Fatigue Analysis → Analytical Fatigue Life; Damage Evaluation; Spectrum; SN Data; Structural Detail

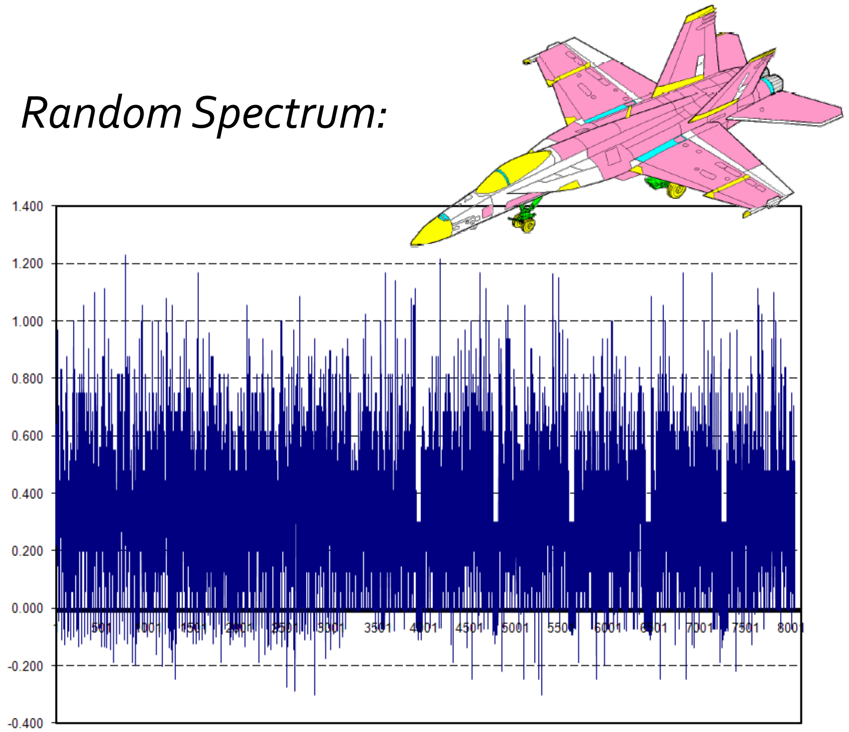
Constant Amplitude vs. Variable Amplitude (Spectrum)

Constant amplitude:



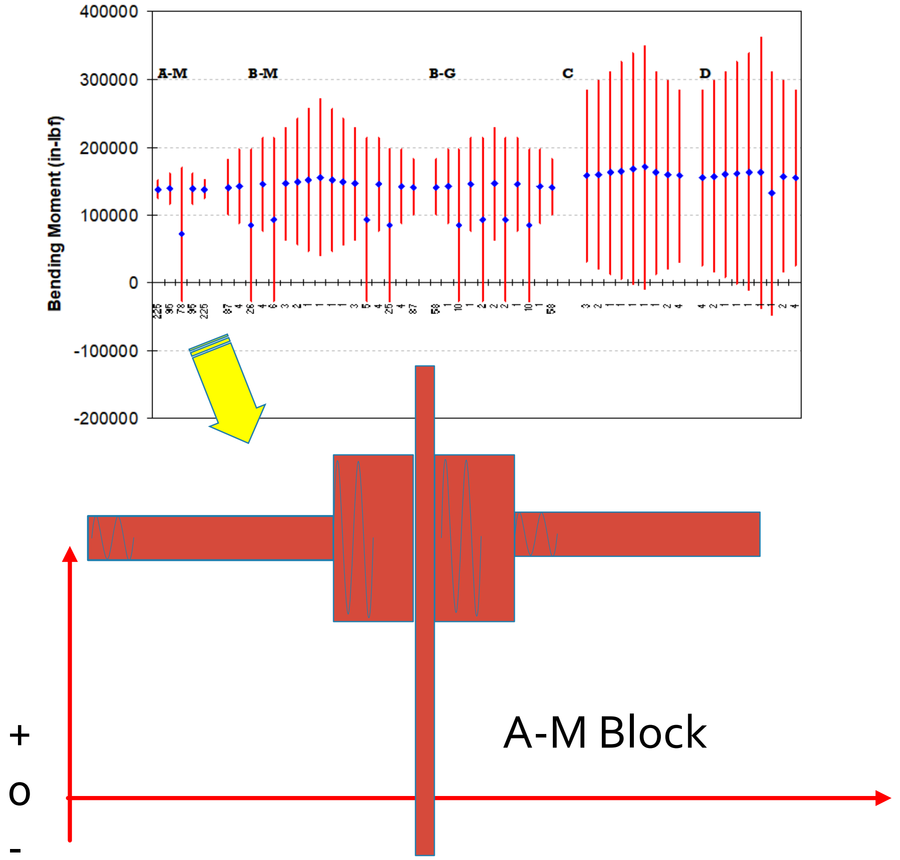
$A = (\sigma_{max} + \sigma_{max})/2$

Random 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.

Block Spectrum:



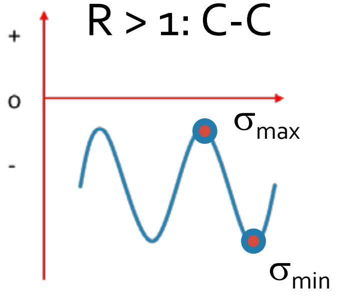
REF: Seneviratne, W. P., "Fatigue Life Determination of a Damage-Tolerant Composite Airframe," Wichita State University, December 2008.

Stress Ratio (R)

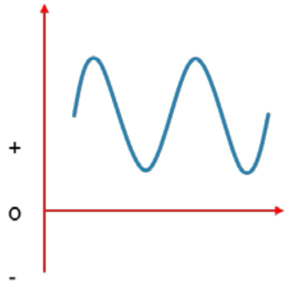
Stress Ratio:

R = min / max stress

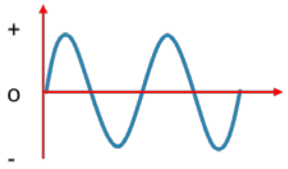
R > 1: C-C

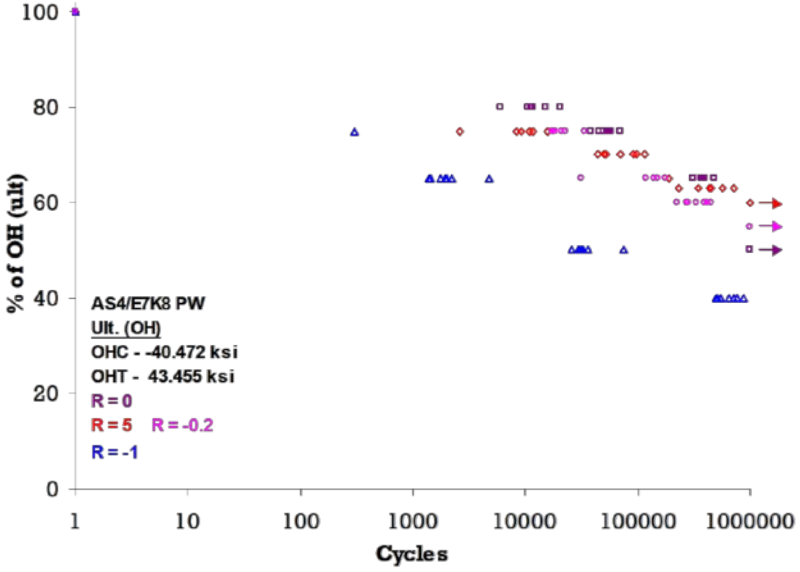


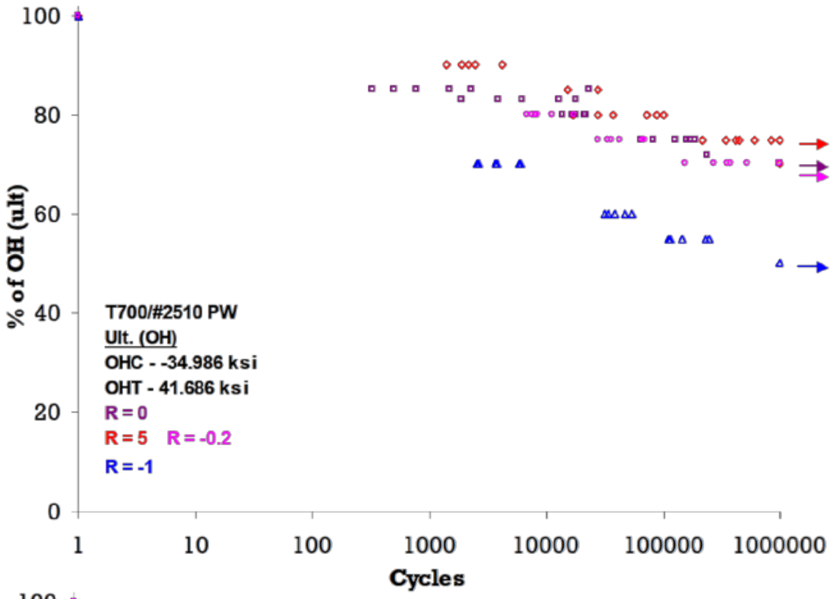
1 > R > 0: T-T

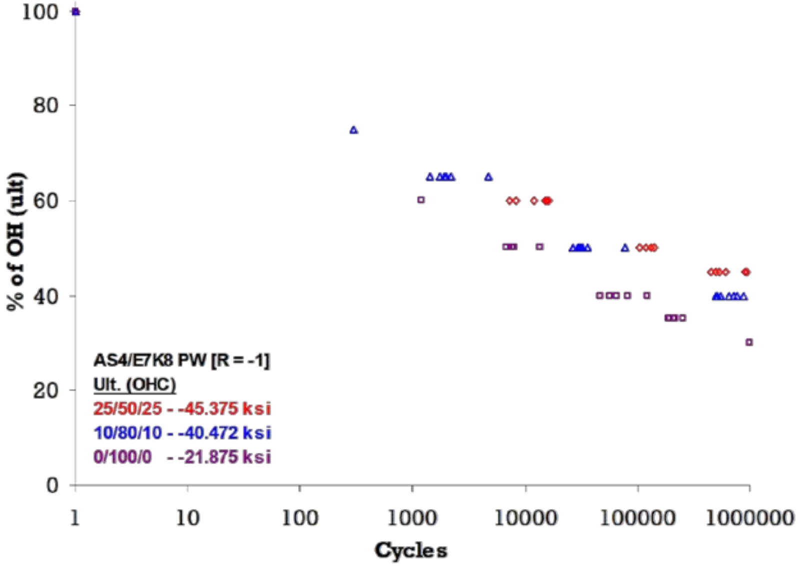


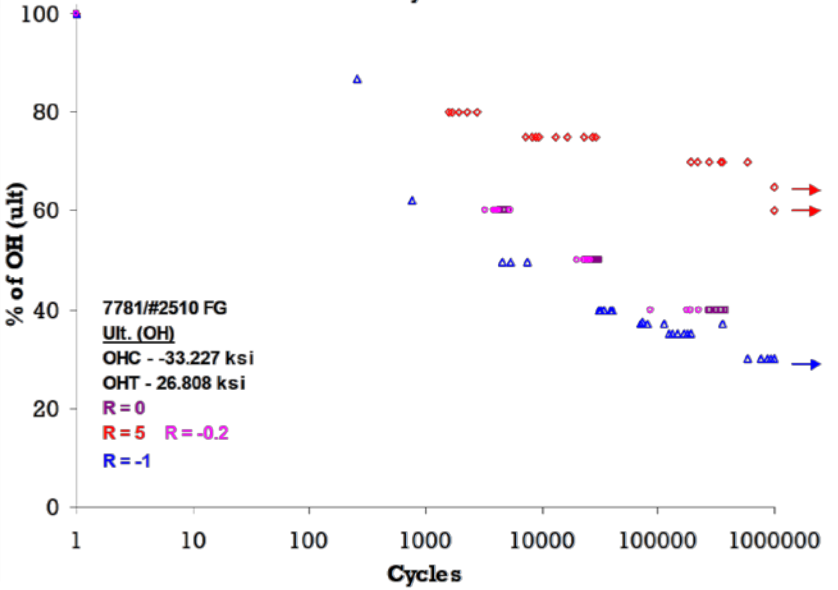
R < 0: C-T



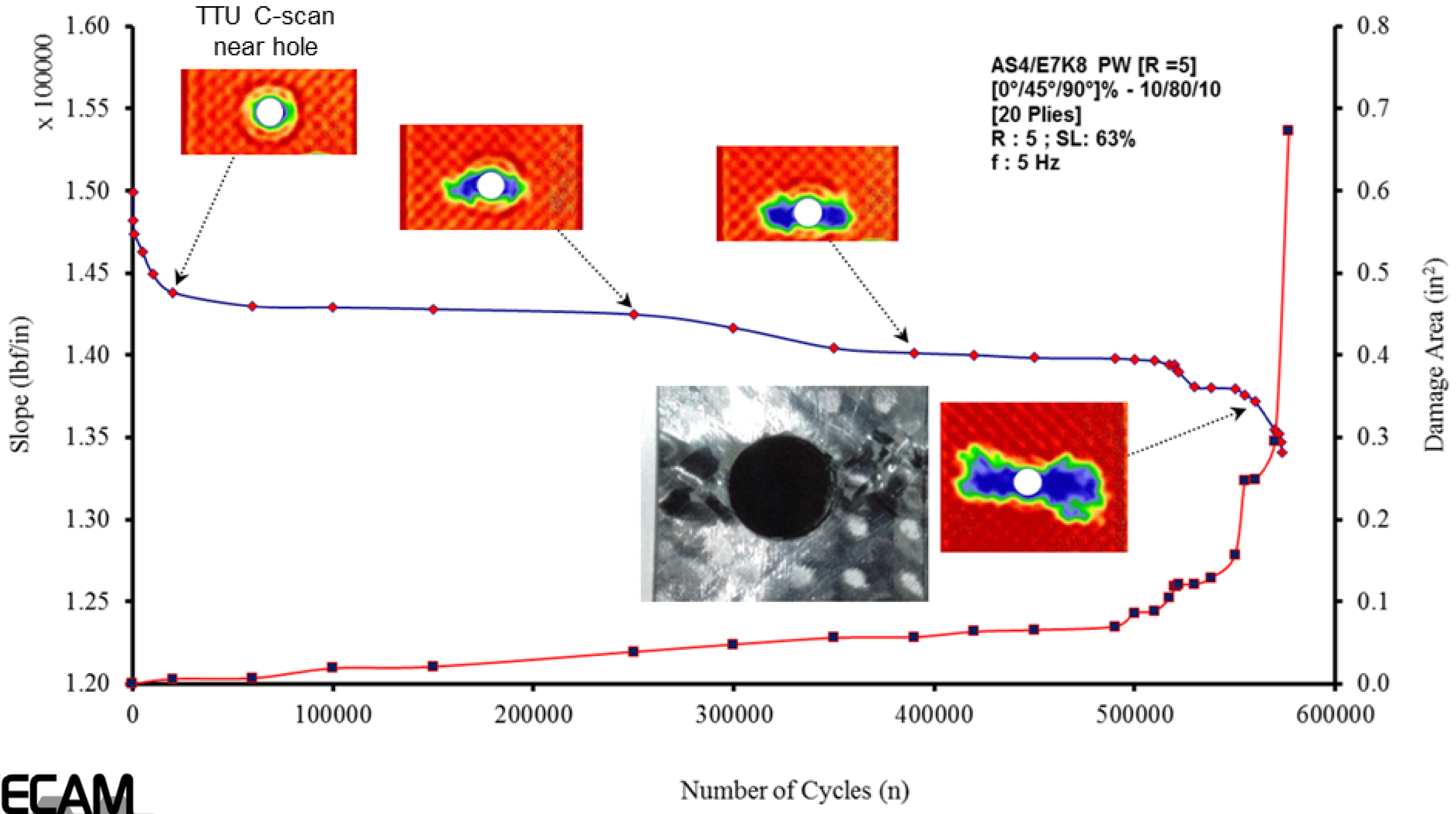






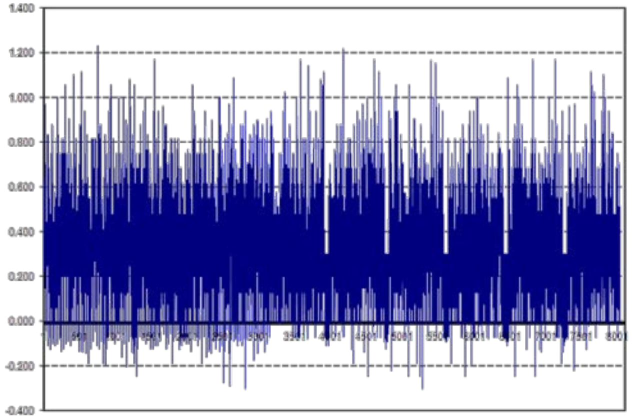


Fatigue Damage Growth for Constant Amplitude Fatigue (OHC)

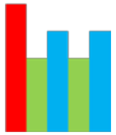


AS4/E7K8 PW [R =5]
[0°/45°/90°]% - 10/80/10
[20 Plies]
R : 5 ; SL: 63%
f : 5 Hz

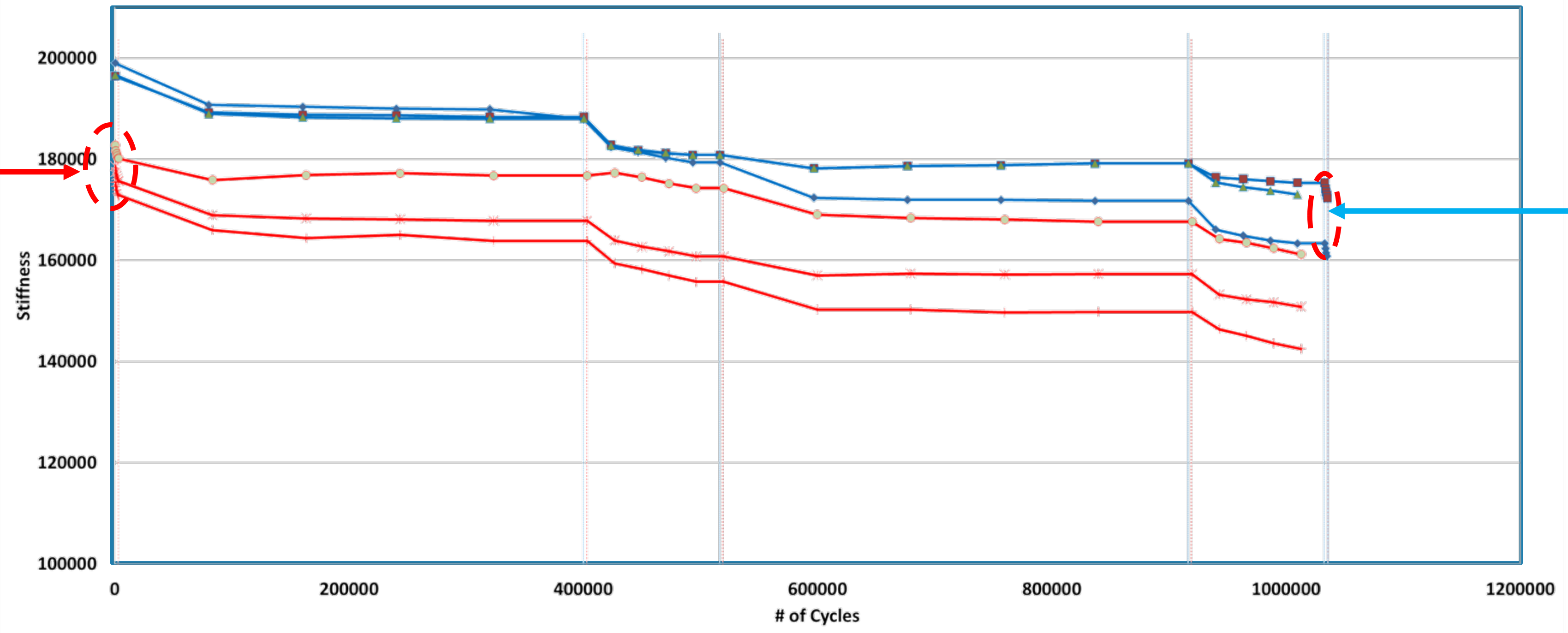
Variable Amplitude Fatigue Testing & Analysis



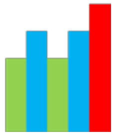
Wearout under Variable Amplitude Fatigue



Fatigue Profile 5	
Stress Level	**# of Cycle**
70	3000
40	400010
55	116330
40	400010
55	116330

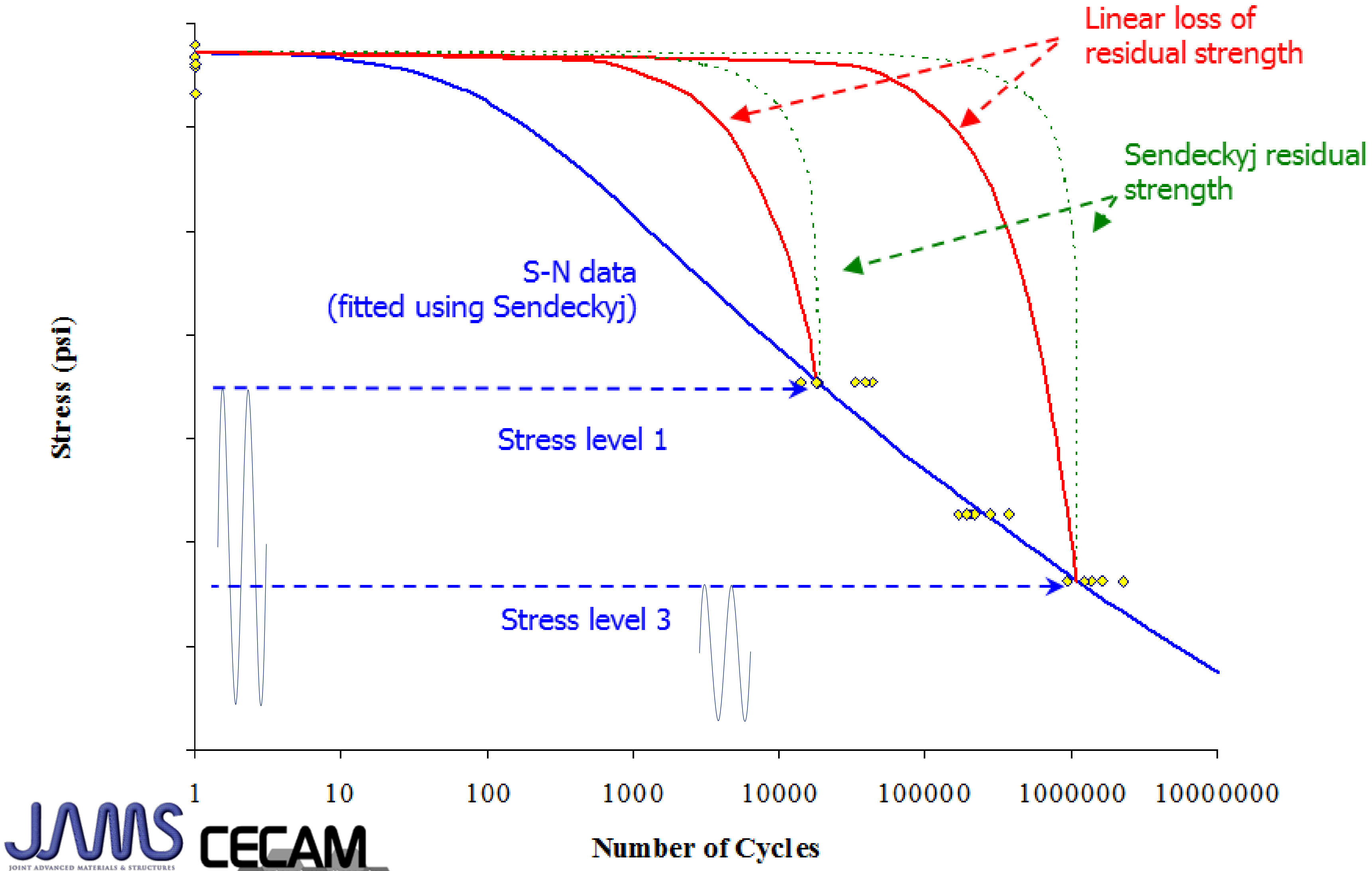


Fatigue Profile 6	
Stress Level	**# of Cycle**
40	400010
55	116330
40	400010
55	116330
70	3000



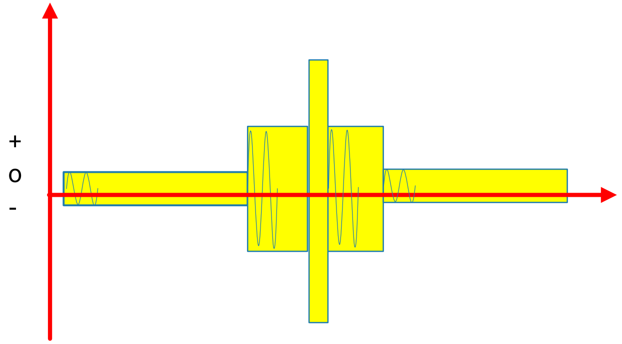
REF: Seneviratne, W., and Tomblin, J., **Load Sequencing Effects and Damage Growth Retardation of Composites**, FAA Joint Advanced Materials & Structures (JAMS), Grapevine, TX, 2016.

Wearout under Constant Amplitude Fatigue

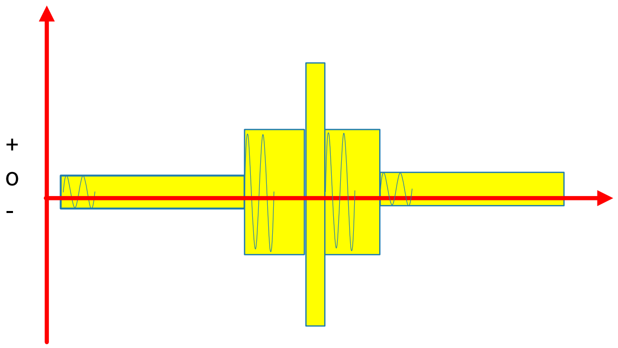


$$\sigma_r = \sigma_e + \left(\frac{\sigma_a - \sigma_e}{N_f(\sigma_a)}\right)\cdot n_f$$

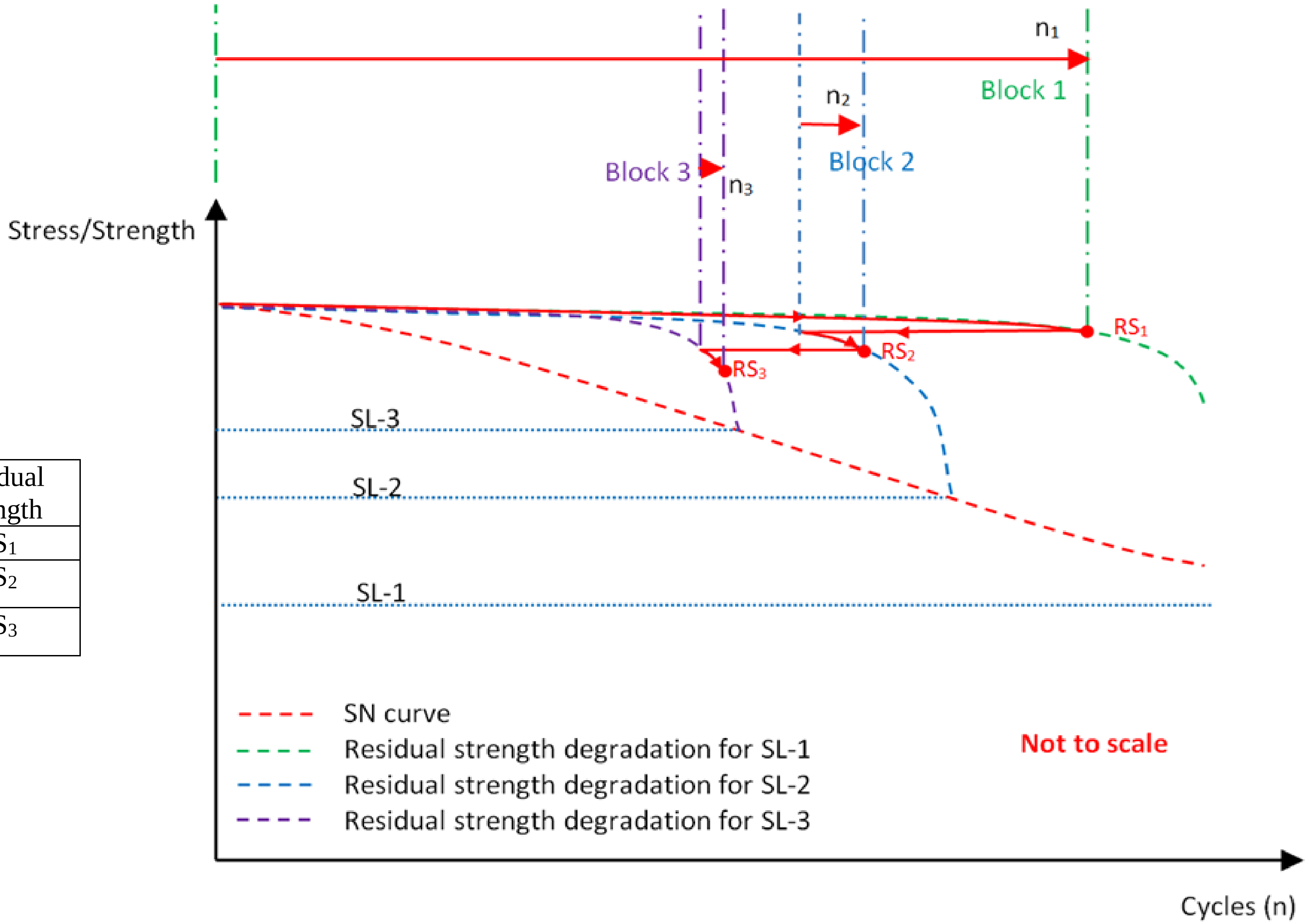
$$\sigma_r = \sigma_a\left[\left(\frac{\sigma_e}{\sigma_a}\right)^{1/S} - C(n_f - 1)\right]^S$$



Residual Strength Degradation



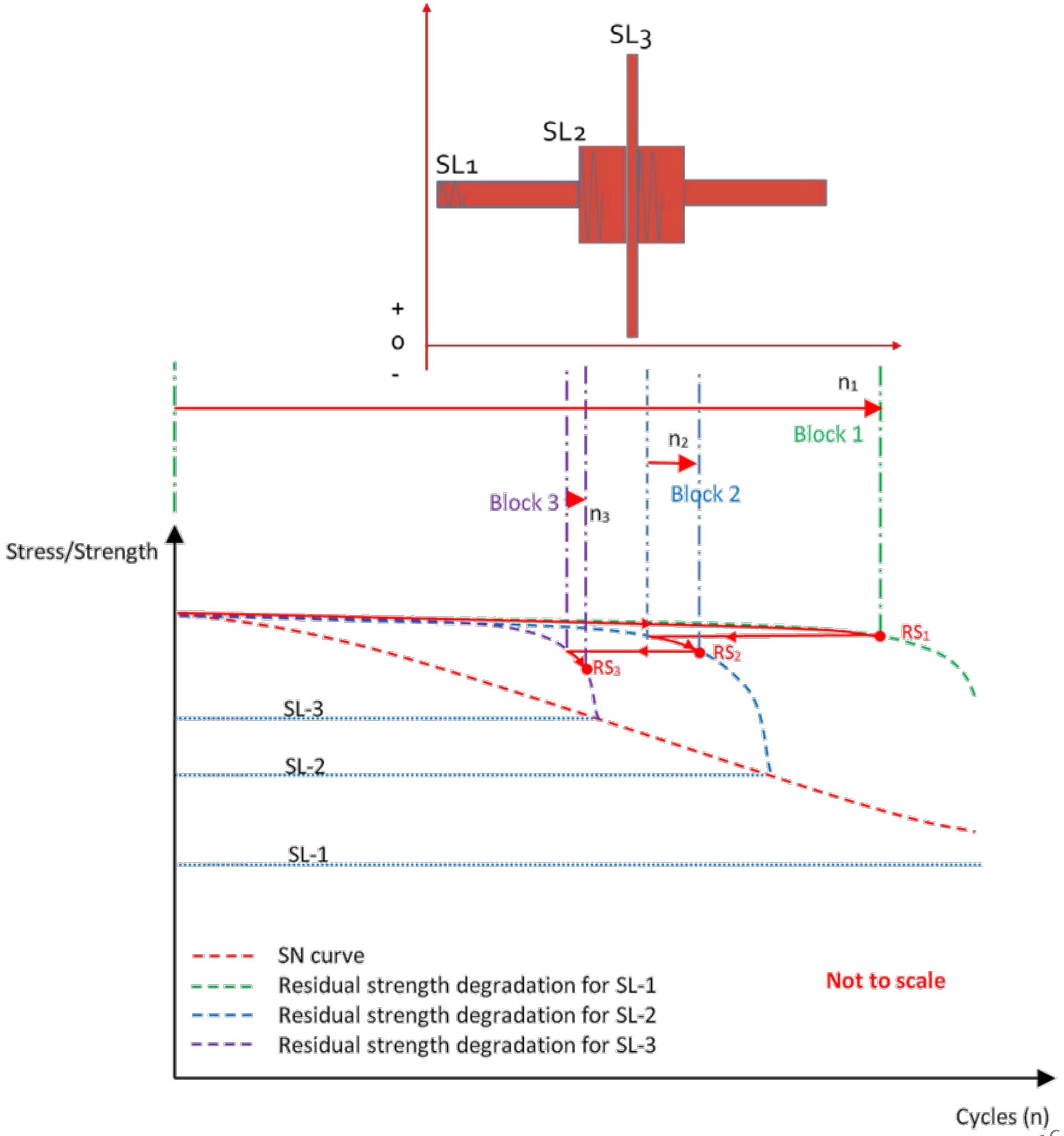
Block No.	Stress Ratio	Stress Level	Number of Cycles in Block	Cumulative Cycles	Residual Strength
1	R = -1	SL-1	n_1	n_1	RS_1
2	R = -1	SL-2	n_2	$n_1 + n_2$	RS_2
3	R = -1	SL-3	n_3	$n_1 + n_2 + n_3$	RS_3



Not to scale

Fatigue Model Based on Residual Strength Degradation (Wearout)

1. Fatigue testing and generate SN data
2. Fatigue data scatter analysis of SN data
    - Generate fitting parameters for Sendeckyj analysis
    - Fatigue data scatter is considered (reliability!)
3. Generate residual strength degradation models
4. Use the residual strength degradation for each block
    - Sequencing effects are considered
5. Predict residual strength degradation or fatigue life
    - Applied stress $\geqslant$ Residual strength → Fatigue failure



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

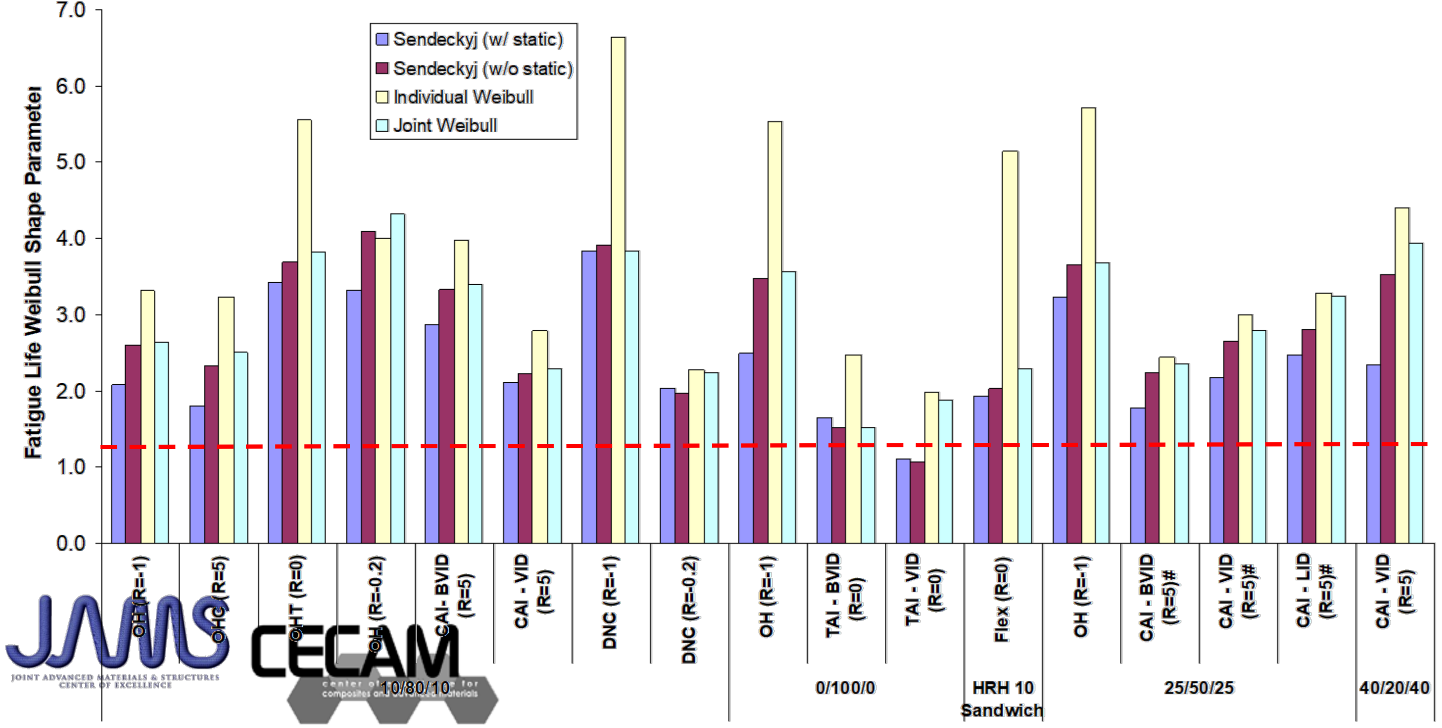
$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

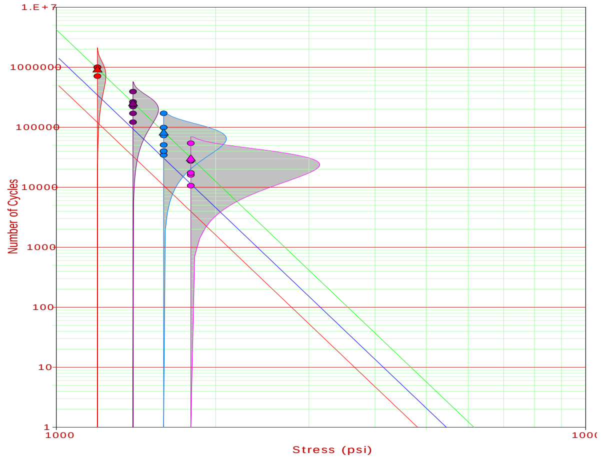
Fatigue Scatter Analysis

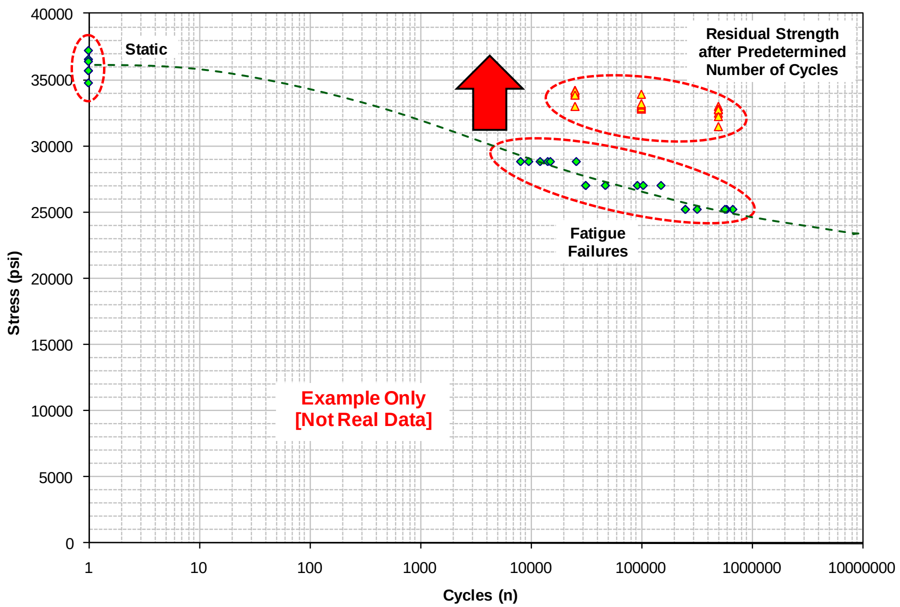
$\alpha_I > \alpha_J > \alpha_S$

WEAROUT MODEL

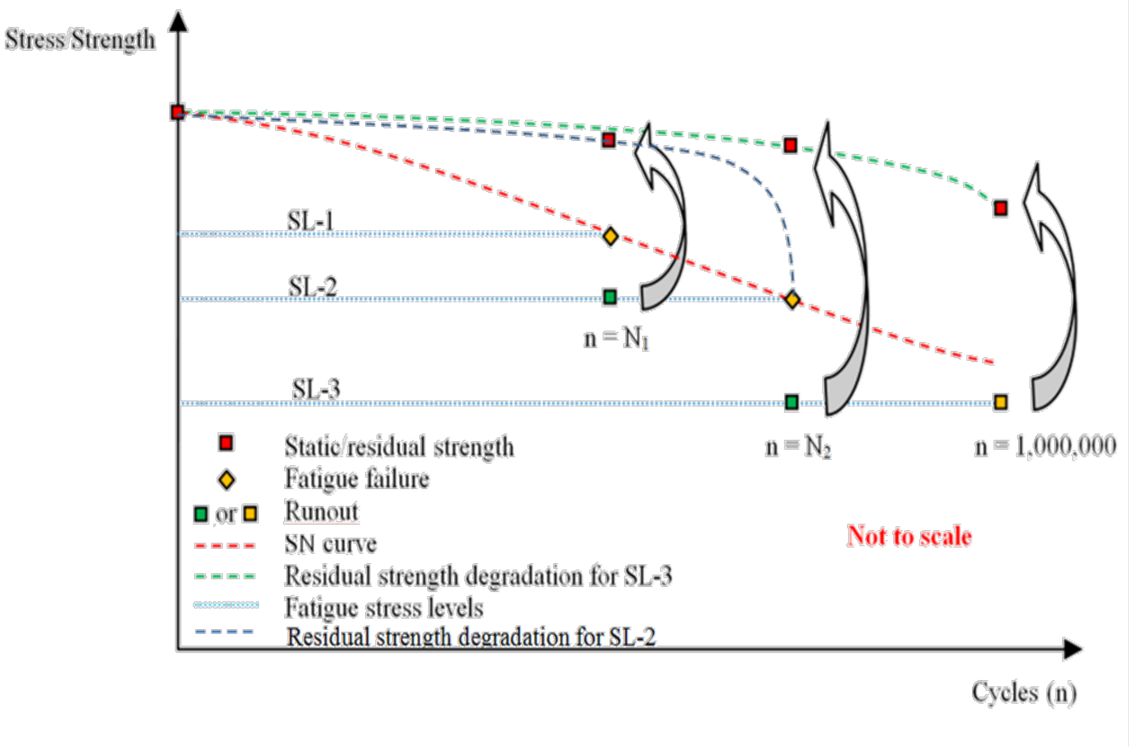
Data Pooling Techniques



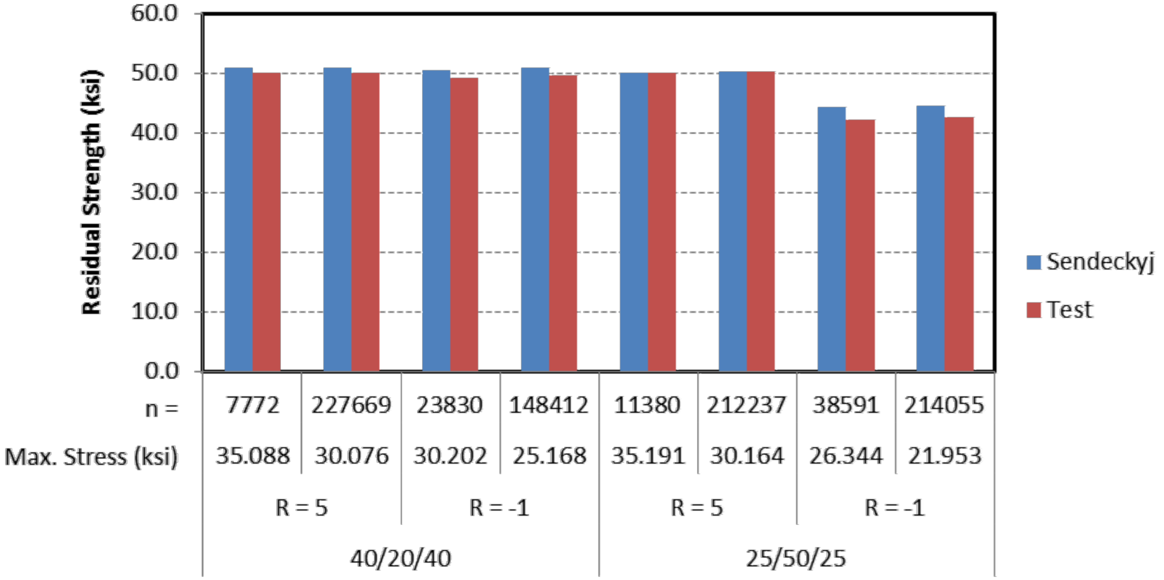




Sendeckyj Residual Strength Model Validation

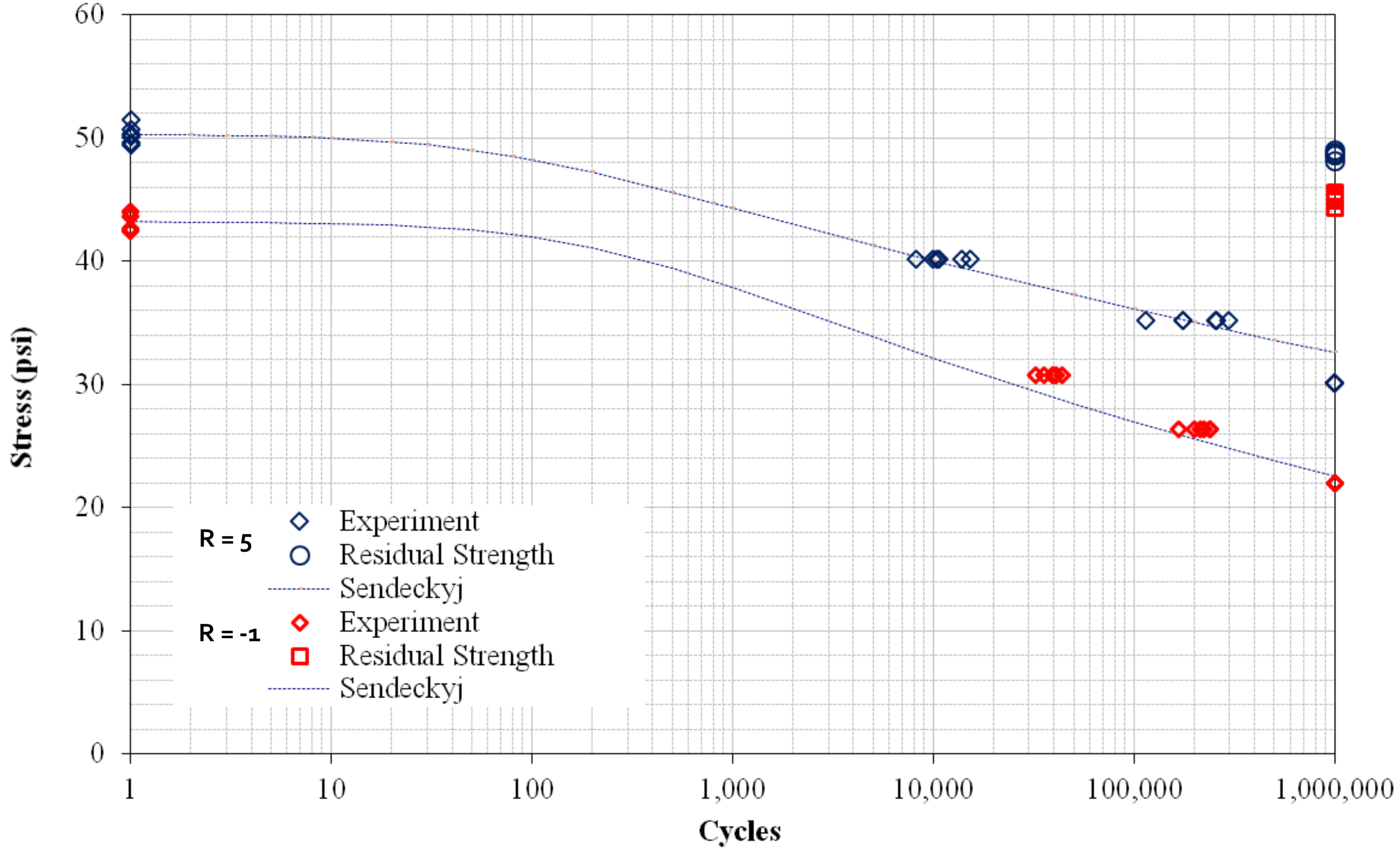


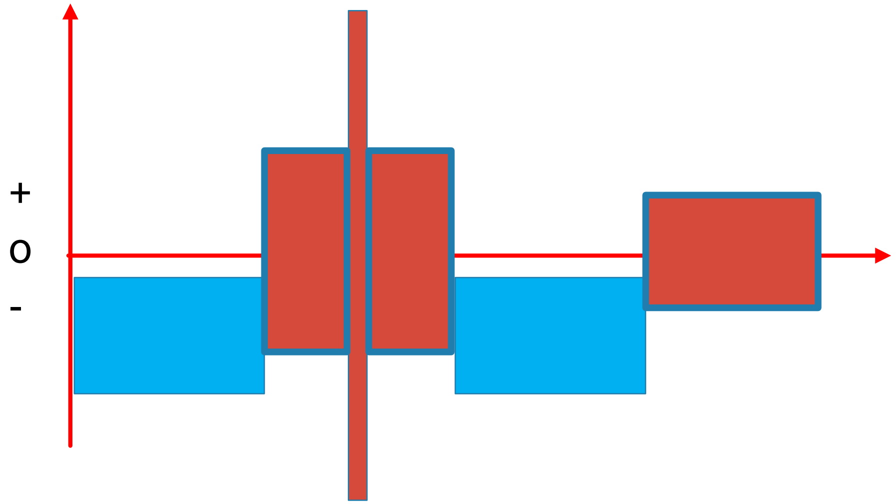
Layup	Stress Ratio	Stress Amplitude [ksi]	n	Residual Strength [ksi]	
				Sendeckyj	Test
40/20/40	R = 5	35.088	7772	50.778	50.023
	R = -1	30.076	227669	50.823	50.091
	R = 5	30.202	23830	50.468	49.274
	R = -1	25.168	148412	50.795	49.700
25/50/25	R = 5	35.191	11380	50.106	50.126
	R = -1	30.164	212237	50.166	50.185
	R = 5	26.344	38591	40.281	42.122
	R = -1	21.953	214055	44.604	42.689



REF: Seneviratne, W. P., Tomblin, J. S., and Palliyaguru, U. **"Fatigue and Residual Strength Analysis of Out-of-Autoclave T650/5320 Plain Weave Fabric Composite Material,"** *CAMX 2014*.

Spectrum with Multiple Stress Ratios

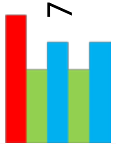




REF: Seneviratne, W. P., Tomblin, J. S., and Palliyaguru, U. **"Fatigue and Residual Strength Analysis of Out-of-Autoclave T650/5320 Plain Weave Fabric Composite Material,"** *CAMX 2014*.

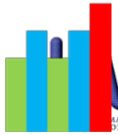
Load Sequencing Effects – Open Hole Tension/Compression (UNI)

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



Fatigue Profile	Specimen Name	Block 1	Block 2	Block 3	Block 4	Block 5	Total # of Cycles	Comments
5	UNI-EX-11	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-13	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-14	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-17	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-19	**3000**	400010	116330	400010	116330	1035680	Survived
5	UNI-EX-21	**3000**	400010	116330	400010	116330	1035680	Survived
6	UNI-EX-12	400010	116330	400010	116330	**2775**	1035455	Failed
6	UNI-EX-15	400010	116330	400010	116330	**3000**	1035680	Survived
6	UNI-EX-16	400010	116330	400010	116330	**472**	1033152	Failed
6	UNI-EX-18	400010	116330	400010	116330	**543**	1033223	Failed
6	UNI-EX-20	400010	116330	400010	116330	**2447**	1035127	Failed
6	UNI-EX-22	400010	116330	400010	116330	**3000**	1035680	Survived

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



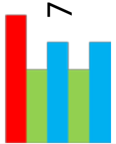
Fatigue Profile 5	
Stress Level	**# of Cycle**
70	3000
40	400010
55	116330
40	400010
55	116330

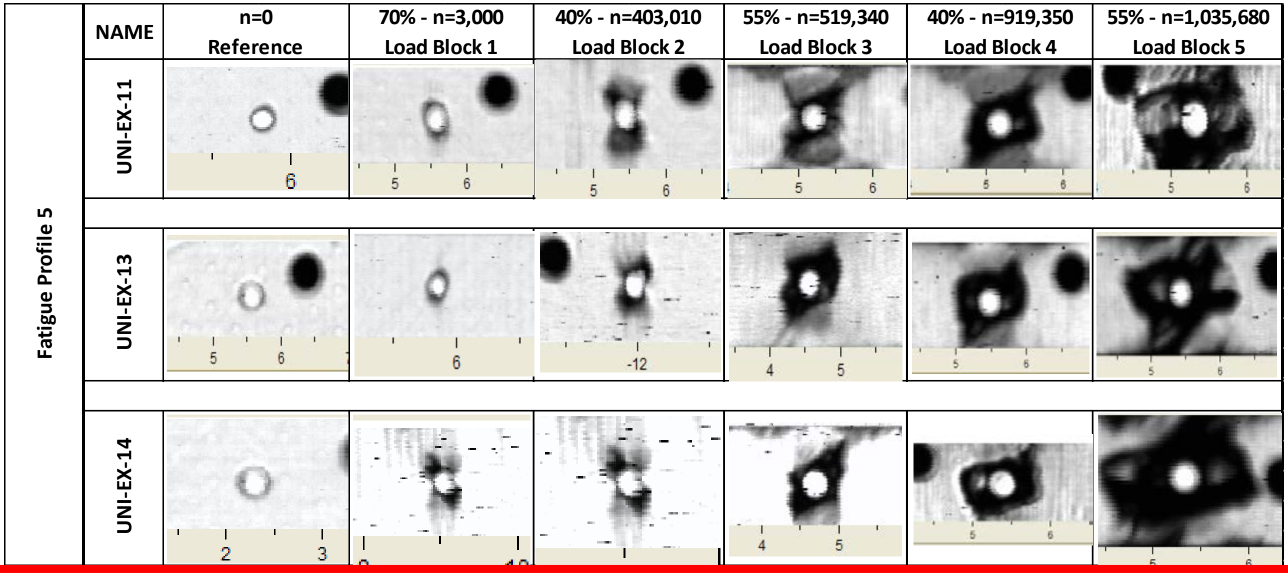
Fatigue Profile 6	
Stress Level	**# of Cycle**
40	400010
55	116330
40	400010
55	116330
70	3000

REF: Waruna Seneviratne and John Tomblin, **"Load Sequencing Effects and Damage Growth Retardation of Composites,"** FAA Joint Advanced Materials & Structures (JAMS), Grapevine, TX, March 2016.

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

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

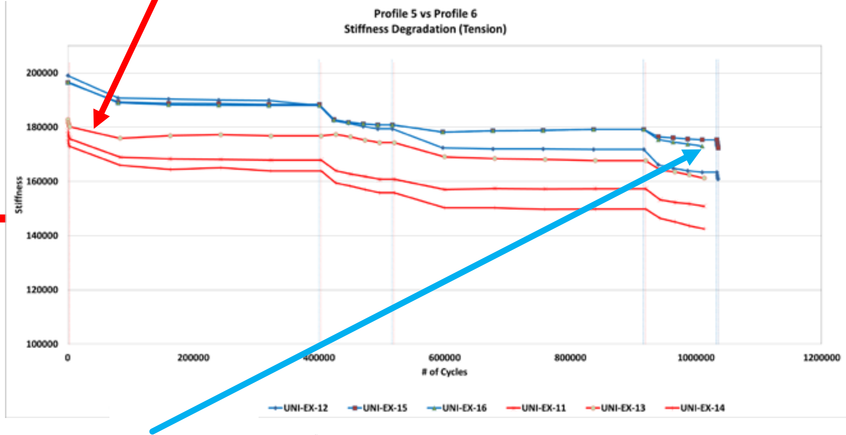




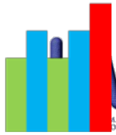
	NAME	n=0 Reference	70% - n=3,000 Load Block 1	40% - n=403,010 Load Block 2	55% - n=519,340 Load Block 3	40% - n=919,350 Load Block 4	55% - n=1,035,680 Load Block 5
Fatigue Profile 5	UNI-EX-11						
	UNI-EX-13						
	UNI-EX-14						

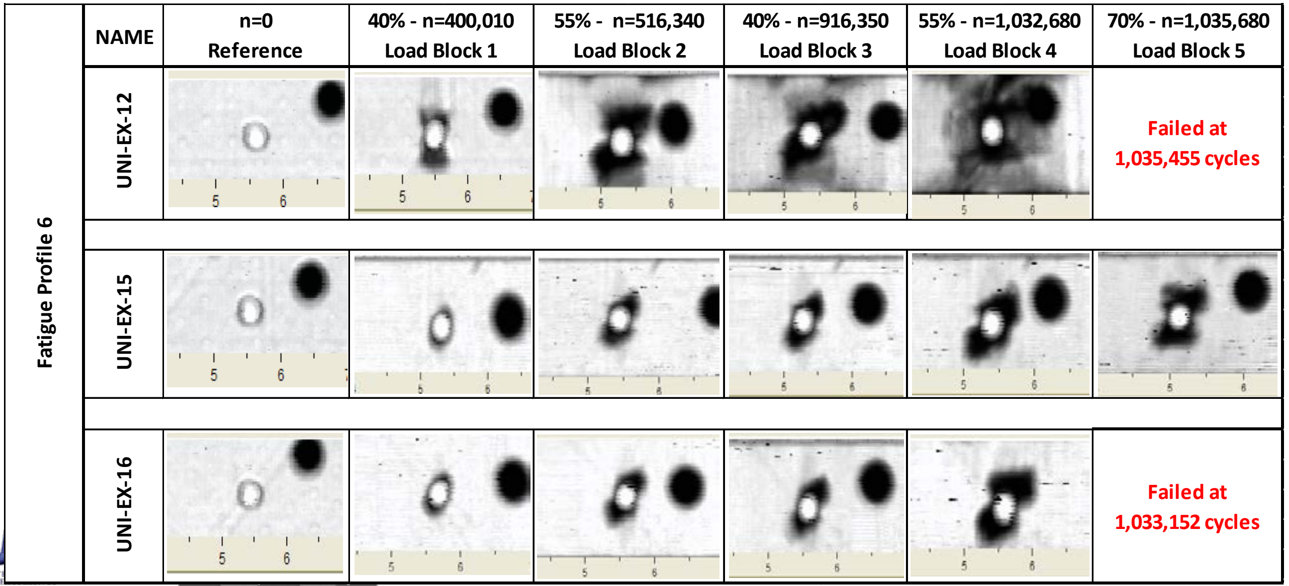
6 spec. survived profile 5

Fatigue Profile 5	
Stress Level	**# of Cycle**
70	3000
40	400010
55	116330
40	400010
55	116330



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





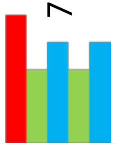
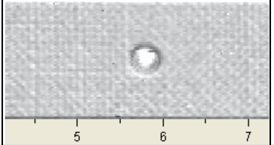
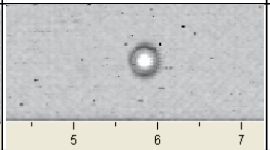
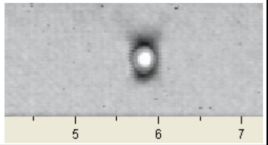
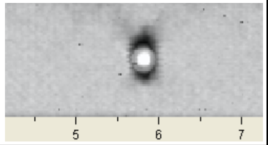
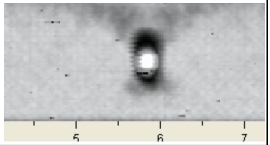
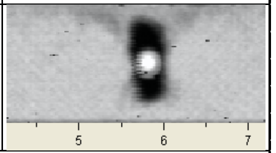
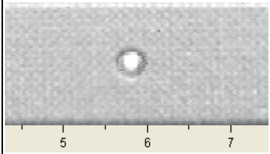
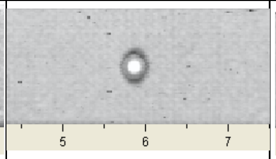
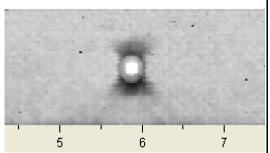
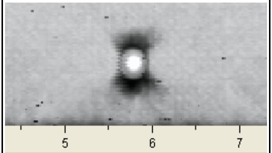
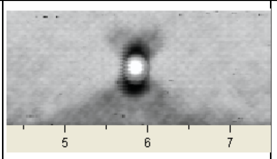
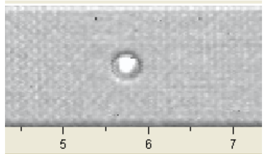
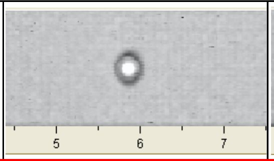
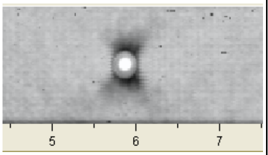
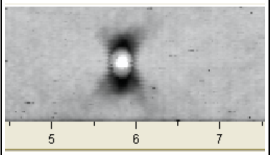
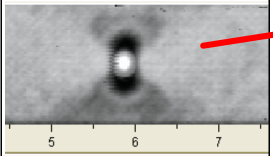
	NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=516,340 Load Block 2	40% - n=916,350 Load Block 3	55% - n=1,032,680 Load Block 4	70% - n=1,035,680 Load Block 5
Fatigue Profile 6	UNI-EX-12						Failed at 1,035,455 cycles
	UNI-EX-15						
	UNI-EX-16						Failed at 1,033,152 cycles

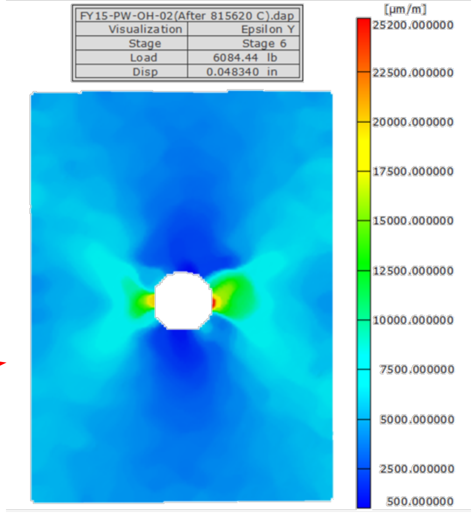
4 spec. failed and 2 spec. survived profile 6

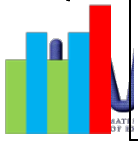
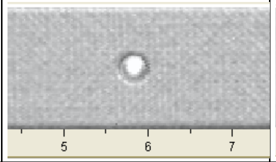
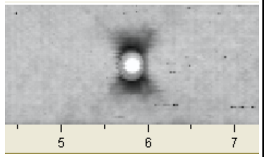
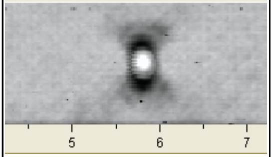
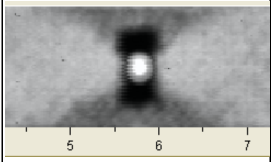
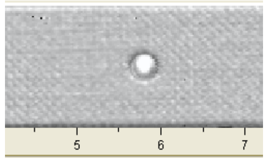
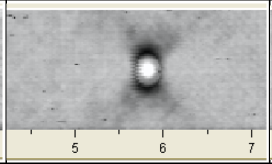
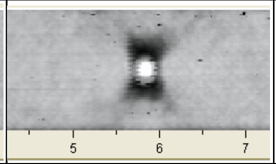
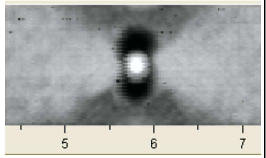
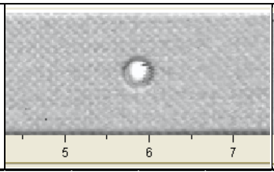
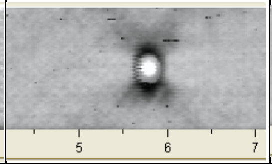
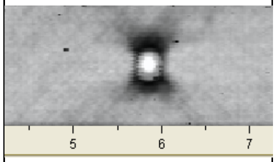
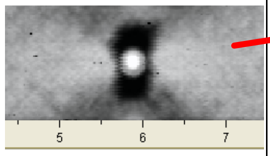
Fatigue Profile 6	
Stress Level	**# of Cycle**
40	400010
55	116330
40	400010
55	116330
70	3000

T650/5320 UNI
R = -1
F = 5 Hz

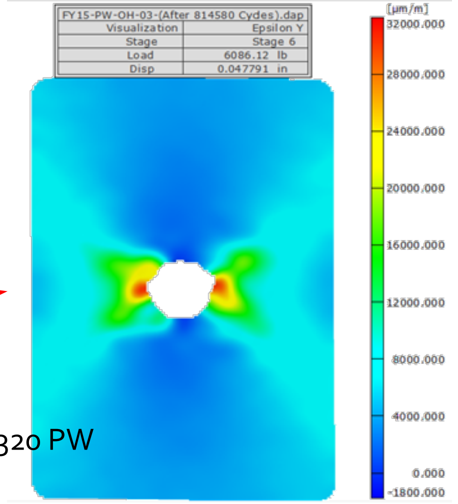
Load Sequencing Effects – Open Hole Tension/Compression (PW)

		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
70-40-55-40-55 (High-Low) 	Fatigue Profile 5	PW-OH-27						
		PW-OH-1						Failed at 823,523 cycles
		PW-OH-2						Failed at 827,830 cycles



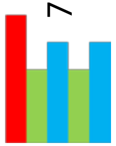
		NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=414,570 Load Block 2	40% - n=814,580 Load Block 3	55% - n=429,140 Load Block 4	70% - n=430180 Load Block 5
40-55-40-55-70 (Low-High) 	Fatigue Profile 6	PW-OH-3					Failed at 815,550 cycles	
		PW-OH-4					Failed at 822,849 cycles	
		PW-OH-6					Failed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

PW Specimens failed before 70% block

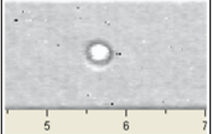
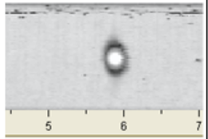
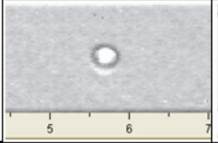
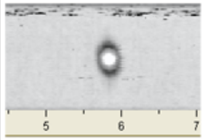
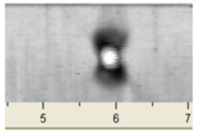
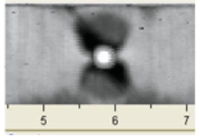
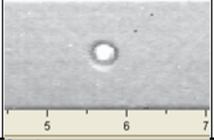
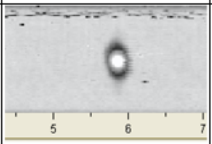
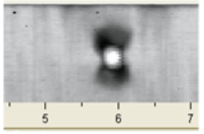
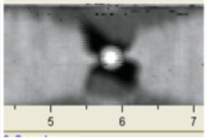
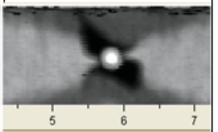
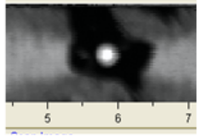


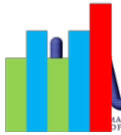
T650/5320 PW
R = -1
F = 5 Hz

Progressive Damage Growth (X-Ray CT)

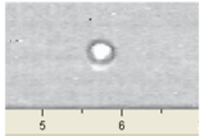
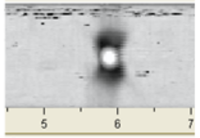
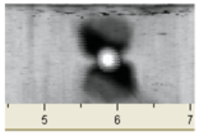
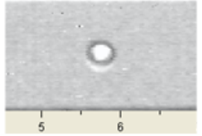
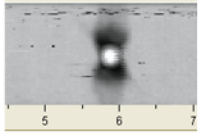
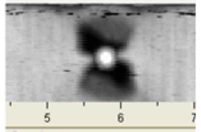
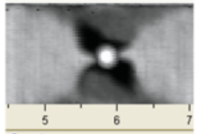
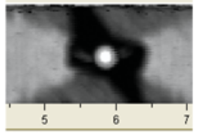
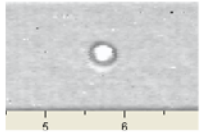
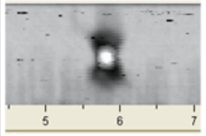
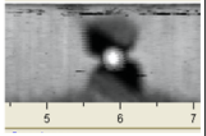
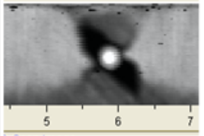
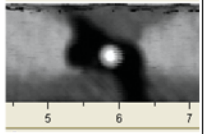
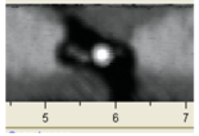


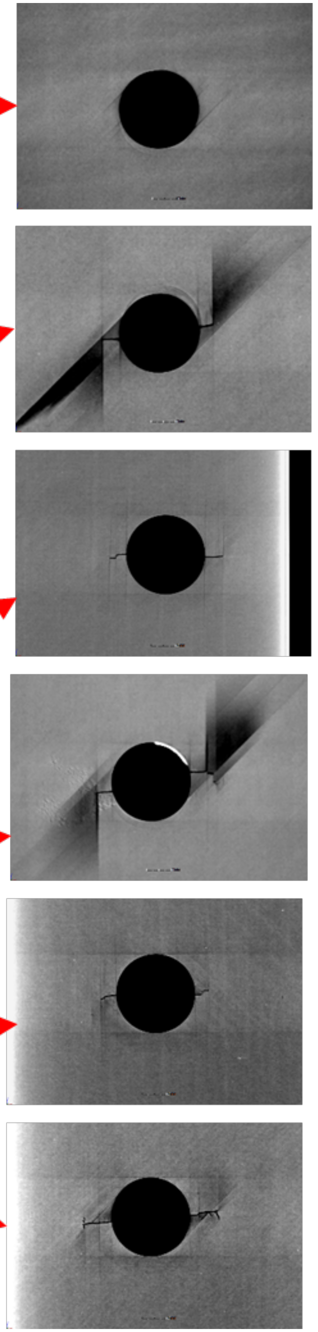
70-40-55-40-55 (High-Low)

		n=0 Reference	70% - n=3,000 Load Block 1	40% - n=403,010 Load Block 2	55% - n=519,340 Load Block 3	40% - n=919,350 Load Block 4	55% - n=1,035,680 Load Block 5
Fatigue Profile - 5	UNI-OH-3						
	UNI-OH-4						
	UNI-OH-9						

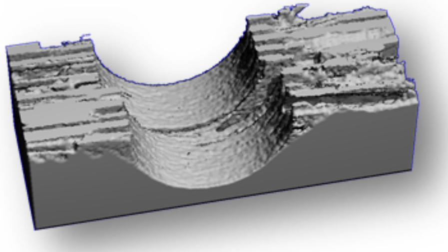


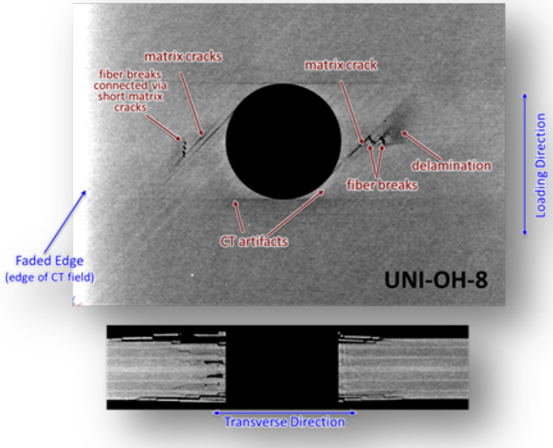
40-55-40-55-70 (Low-High)

		n=0 Reference	40% - n=400,010 Load Block 1	55% - n=516,340 Load Block 2	40% - n=916,350 Load Block 3	55% - n=1,032,680 Load Block 4	70% - n=1,035,680 Load Block 5
Fatigue Profile - 6	UNI-OH-6						
	UNI-OH-7						
	UNI-OH-8						



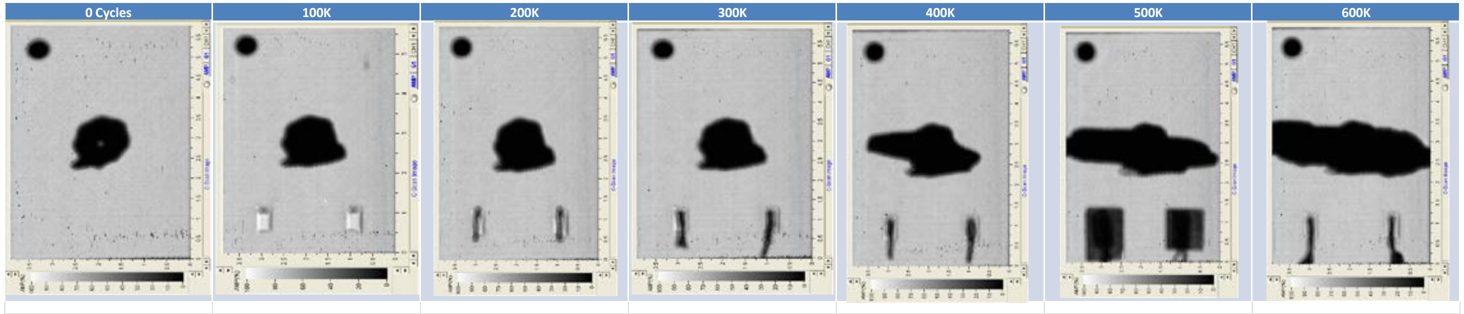
Collaboration with Dr. David Mollenhauer (AFRL)



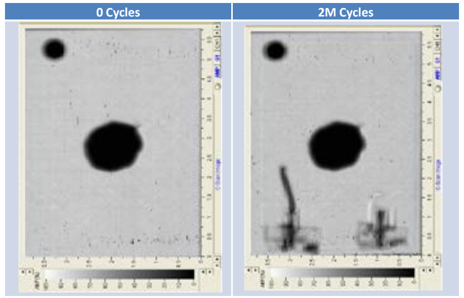


Load Sequencing Effects - Compression After Impact

Constant Amplitude (70% CAI SS)



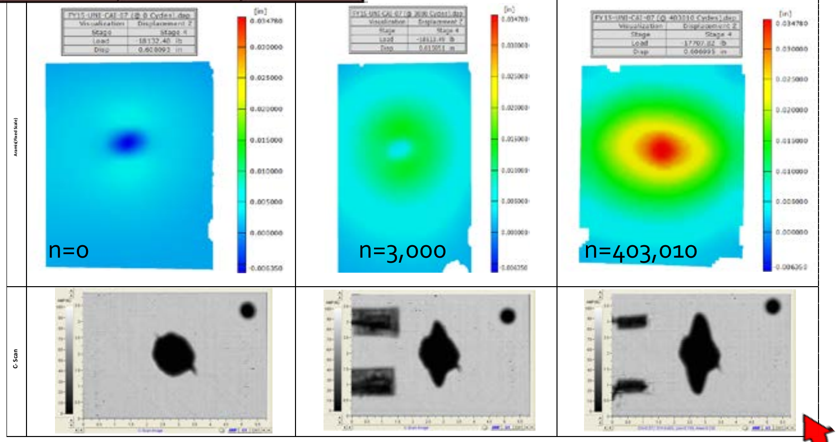
Constant Amplitude (55% CAI SS)



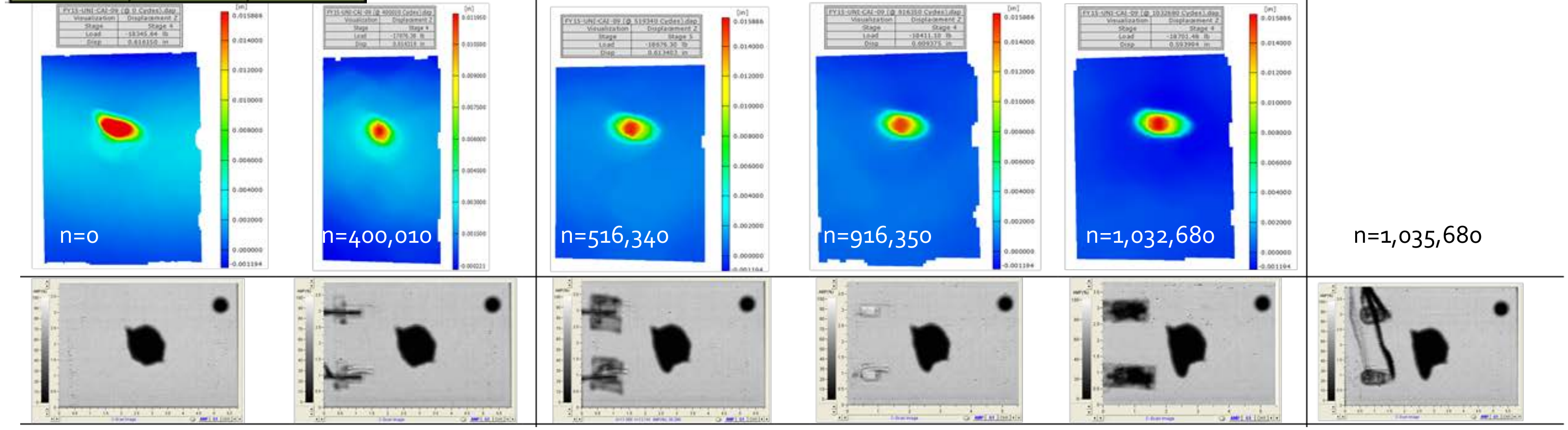
Fatigue Profile 5		
Stress Level	Percentage [%]	# of Cycles
SL1	80	3000
SL2	50	400010
SL3	65	116330
SL4	50	400010
SL5	65	116330

Spectrum Fatigue

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

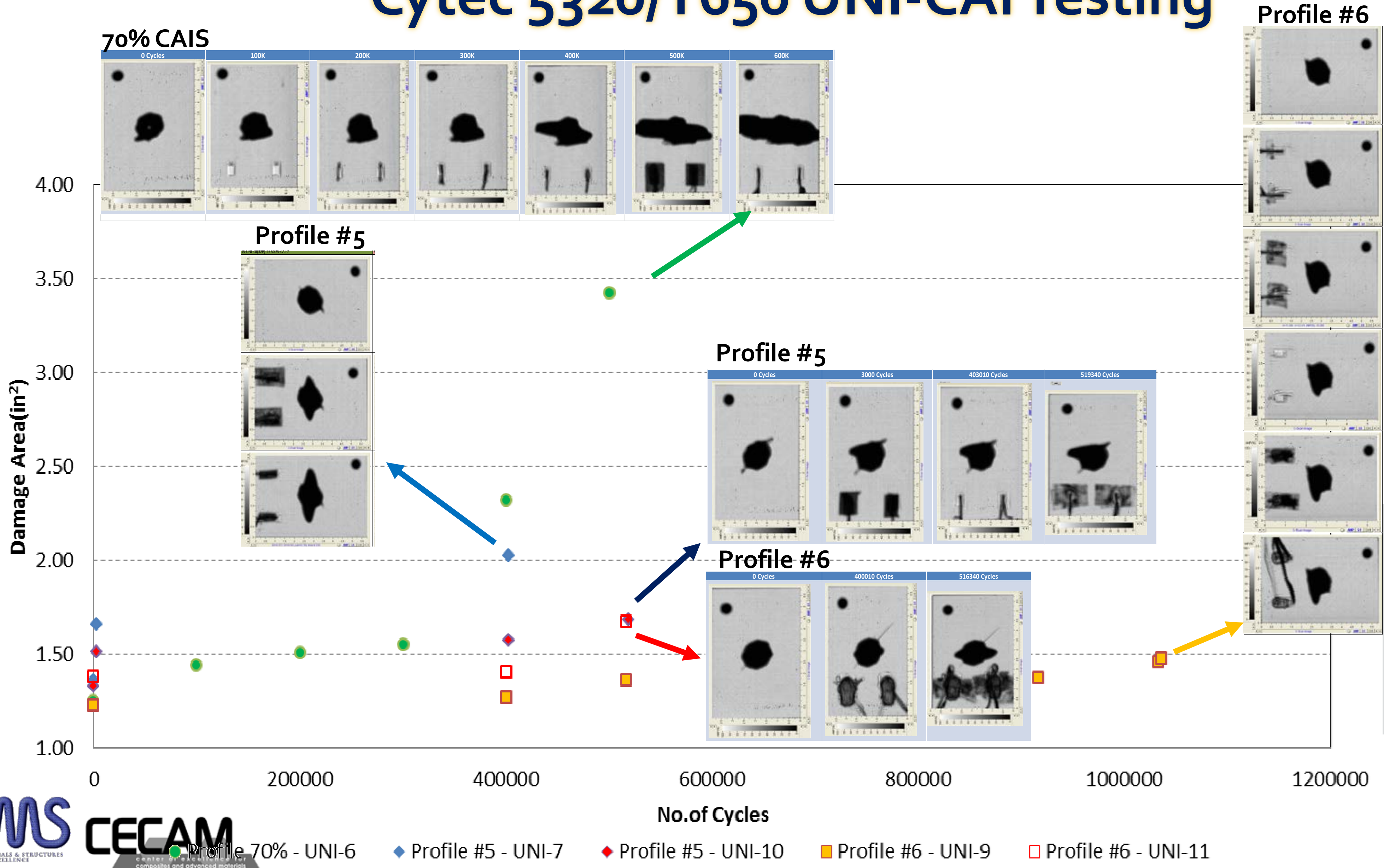


1 spec. failed at n=403,011
1 spec. survived n=1,035,680



3 spec. survived
n=1,035,680

Cytec 5320/T650 UNI-CAI Testing

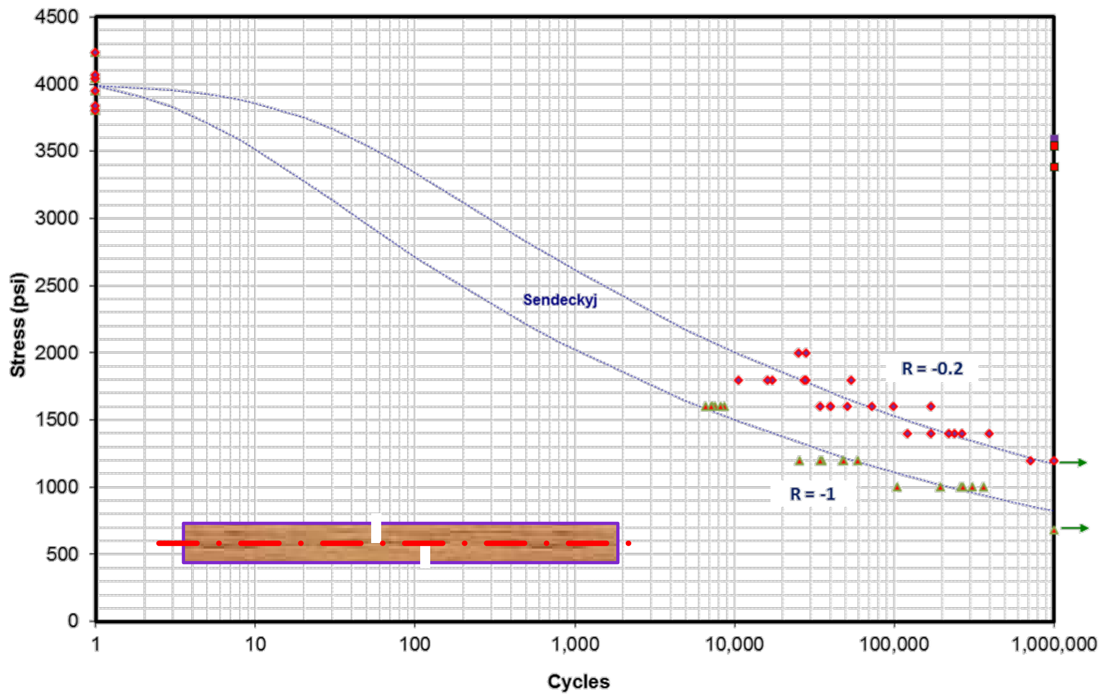


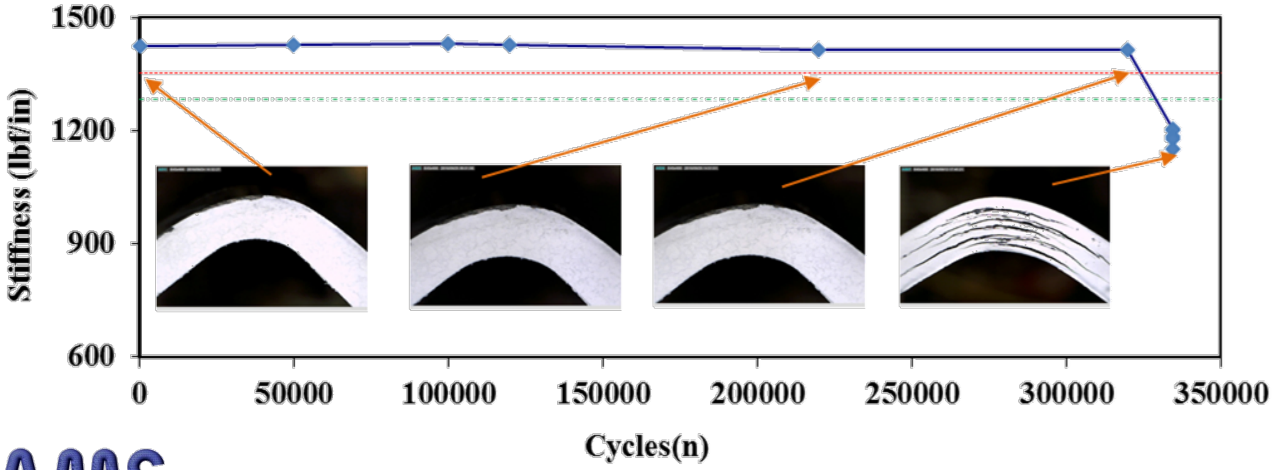
Fatigue Profile 5		
Stress Level	Percentage [%]	# of Cycles
SL1	80	3000
SL2	50	400010
SL3	65	116330
SL4	50	400010
SL5	65	116330

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

Matrix Dominant Failure Modes

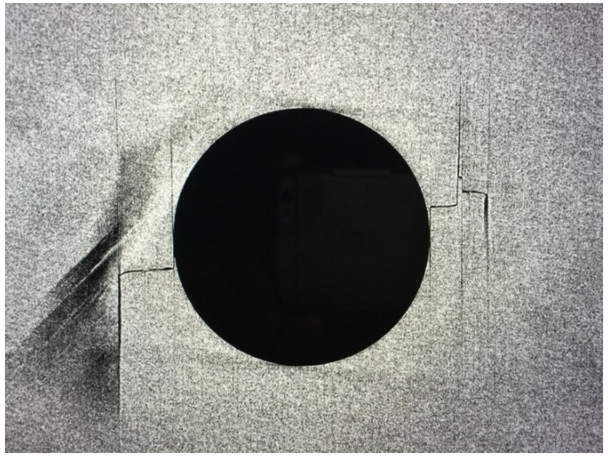
- Significant residual strength degradation
  - Steep SN curves
  - Significant fatigue cracks and stiffness degradation prior to "obvious" fatigue failure
- Multiple crack paths
- High data scatter





Summary

- Need to understand the fatigue damage growth mechanism
  - Interaction of damage growth at various stress levels
    - Multiple failure modes
    - Multiple crack paths
  - High-fidelity inspections for monitoring damage growth
    - Develop innovative ways for monitoring damage growth characteristics
  - Understand influencing factors
    - initial flaw/damage, failure mode, stress ratio, sequencing, frequency, loading mode, etc.
- Various analysis methods are considered
  - Semi-empirical (Wearout Model)
  - Probabilistic
  - Multi-scale modeling
- **Validation of CA models → VA models**



Looking Forward

- **Benefit to Aviation**
  - Investigation of fatigue damage growth of composites under variable amplitude fatigue loading
  - Development of tools for determining the residual strength degradation or wearout and prediction of fatigue life under variable amplitude fatigue cycling (includes sequencing effects)
- **Future needs**
  - Variable amplitude fatigue data for fatigue analysis and validation of wearout models for analytical life predictions
  - Analytical models for predicting residual strength degradation (wearout)