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Fatigue and Residual Strength Analysis of Composite Material

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

2015 Technical Review

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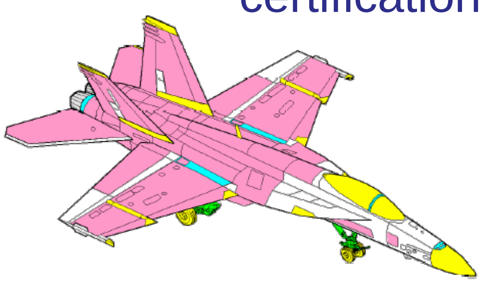
Certification of Composite-Metal Hybrid Structures

- **Motivation and Key Issues**
  - Damage growth mechanics, critical loading modes and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming.
  - Data scatter in composites compared to metal data is significantly higher requiring large test duration to achieve a particular reliability that a metal structure would demonstrate with significantly low test duration.
  - Metal and composites have significantly different coefficient of thermal expansion (CTE)
  - Mechanical and thermal characteristics of composites are sensitive to temperature and moisture
  - Need for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority



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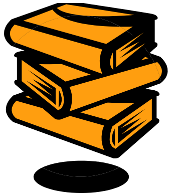
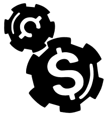
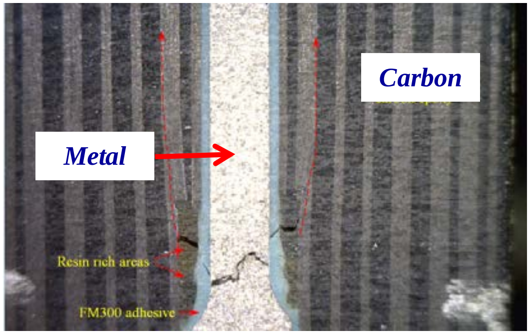
Certification of Composite-Metal Hybrid Structures

- **Primary Objective**
  - Develop guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.





- **Secondary Objectives**
  - Evaluate the damage mechanics and competing failure modes (origination and propagation)
    - Mechanical & bonded joints
  - Data scatter and reliability analysis, i.e., LEF
  - Modifications to load spectra and application LEF
  - Address mismatched Coefficient of Thermal Expansion (CTE) and ground-air-ground (GAG) effects
  - Impact of environmental effects on hybrid structures
    - Environmental compensation factor (ECF)
    - Test environments



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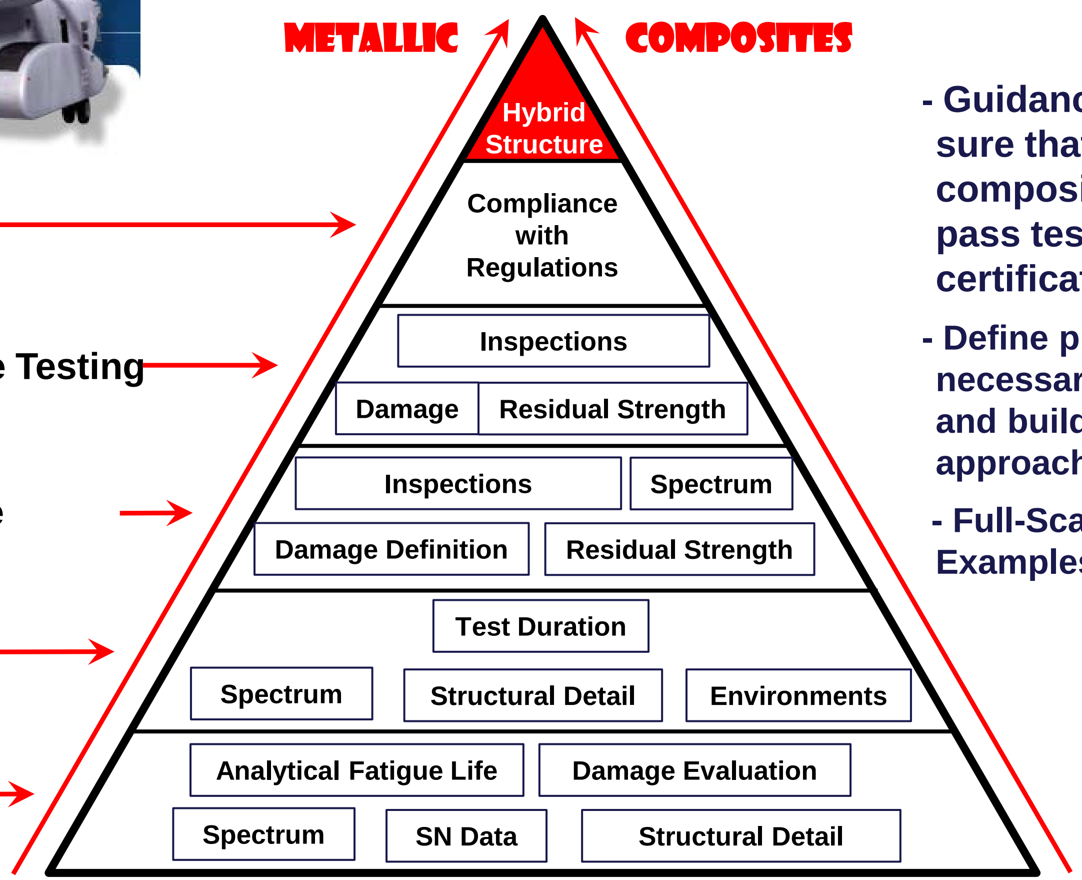
Certification of Composite-Metal Hybrid Structures

- Principal Investigators & Researchers
  - John Tomblin, *PhD*, and Waruna Seneviratne, *PhD*
  - *Upul Palliyaguru*
- FAA Technical Monitor
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz, *PhD* and Curtis Davies
- Industry Participation
  - Airbus, Boeing, Bombardier, Bell Helicopter, Cessna, Honda Aircraft Co., NAVAIR, and Spirit Aerosystems

Approach



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

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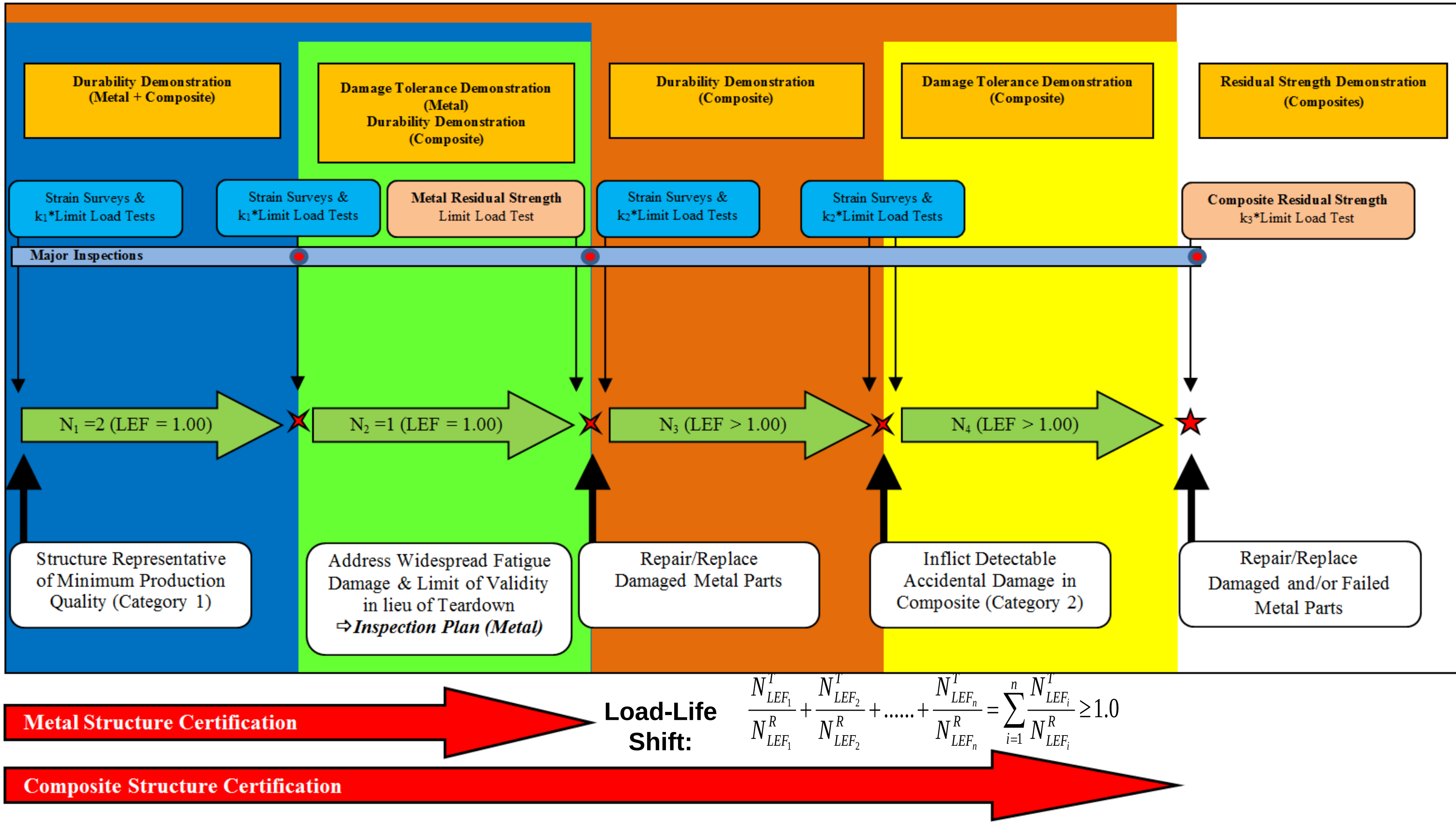
Test Sequence for Hybrid Full-Scale Test Substantiation



Load-Life Shift:

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

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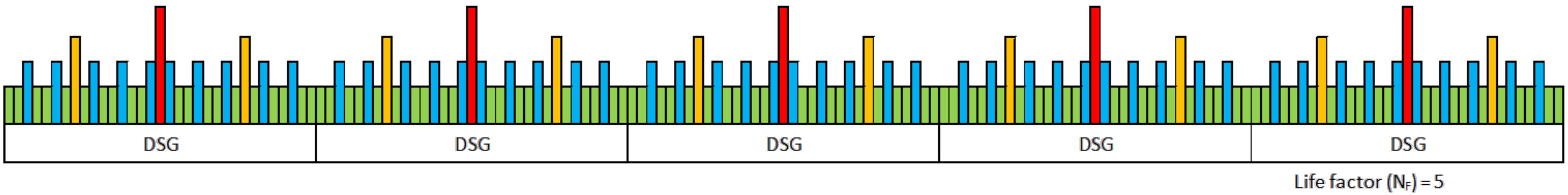
Load-Life Shift (LLS) Approach

- One durability test article through Load-Life Shift Approach for Hybrid (Composite-Metal) Structures
  - Application of life factor to high loads ensure the reliability for the most critical load levels (for composites)
  - Apply high LEF to reduce the time on low stress cycles
  - Require fatigue analysis of metal structure to alleviate undesirable impacts on metal part
  - 3 DSG for metal substantiation and then composite (credits given to composite cycles during 3 DSGs per Load-life Shift Method)
  - High loads required for composite structure that are above clipping level (prior to applying LEF) can be applied in Phase 2
  - **LLS approach provides a mechanism for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority**

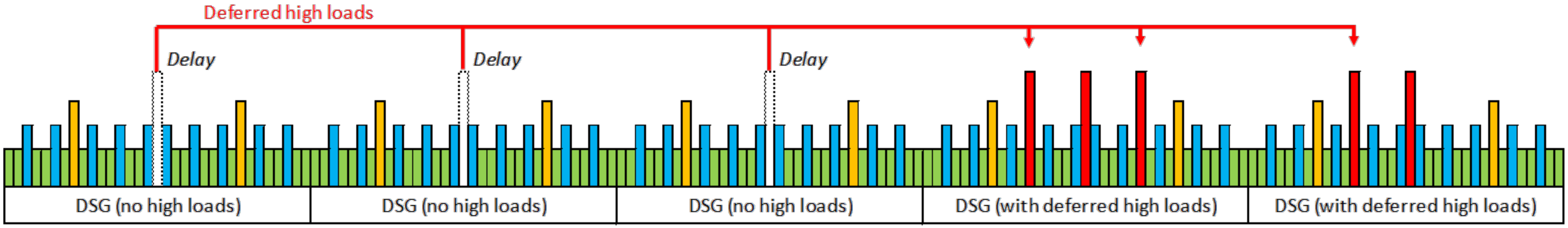
  ➔ Significant time and cost savings

Application of Hybrid Spectrum

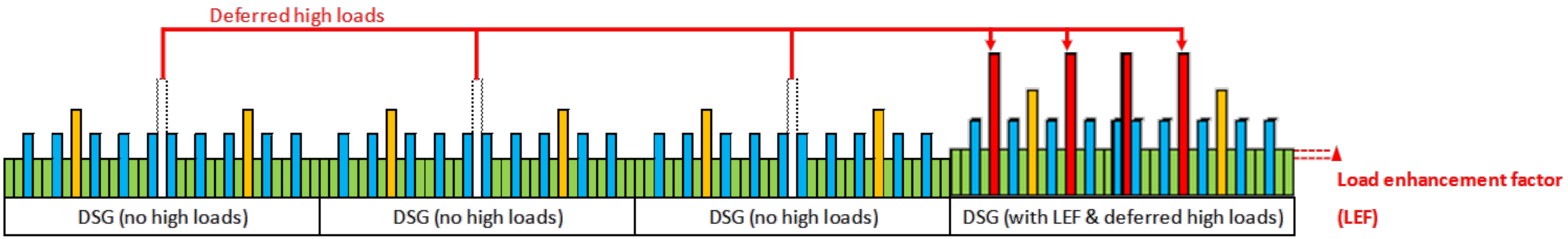
Method 1: Life Factor Approach



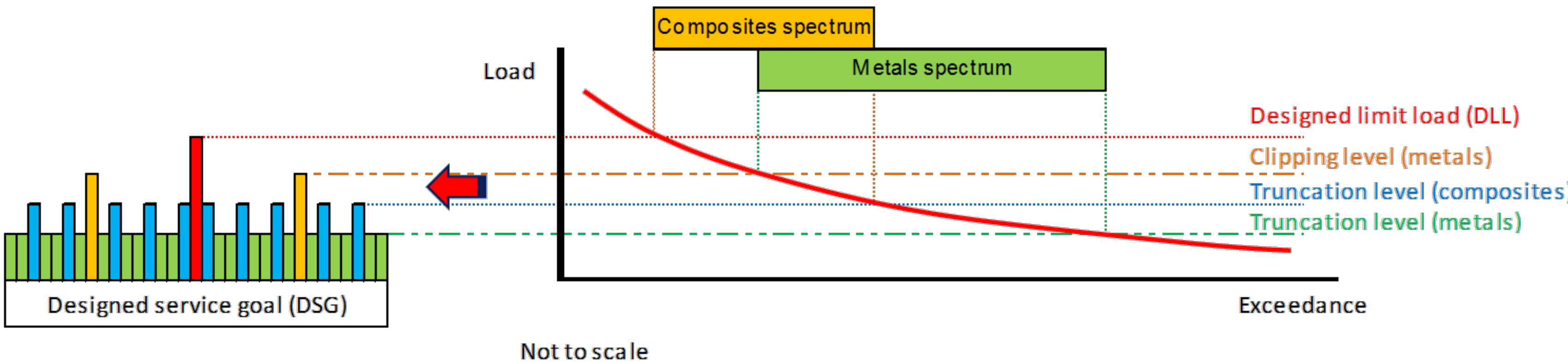
Method 2: Deferred High Loads



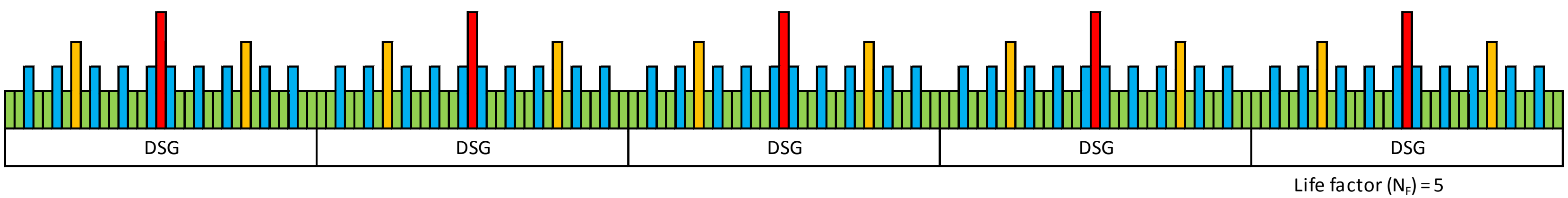
Method 3: Deferred High Loads with Load Life Shift



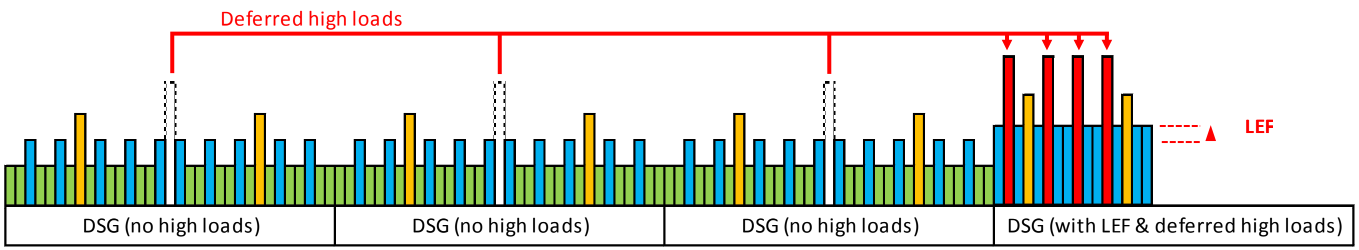
Deferred Spectrum for Hybrid Structures



Method 1: Life Factor Approach



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



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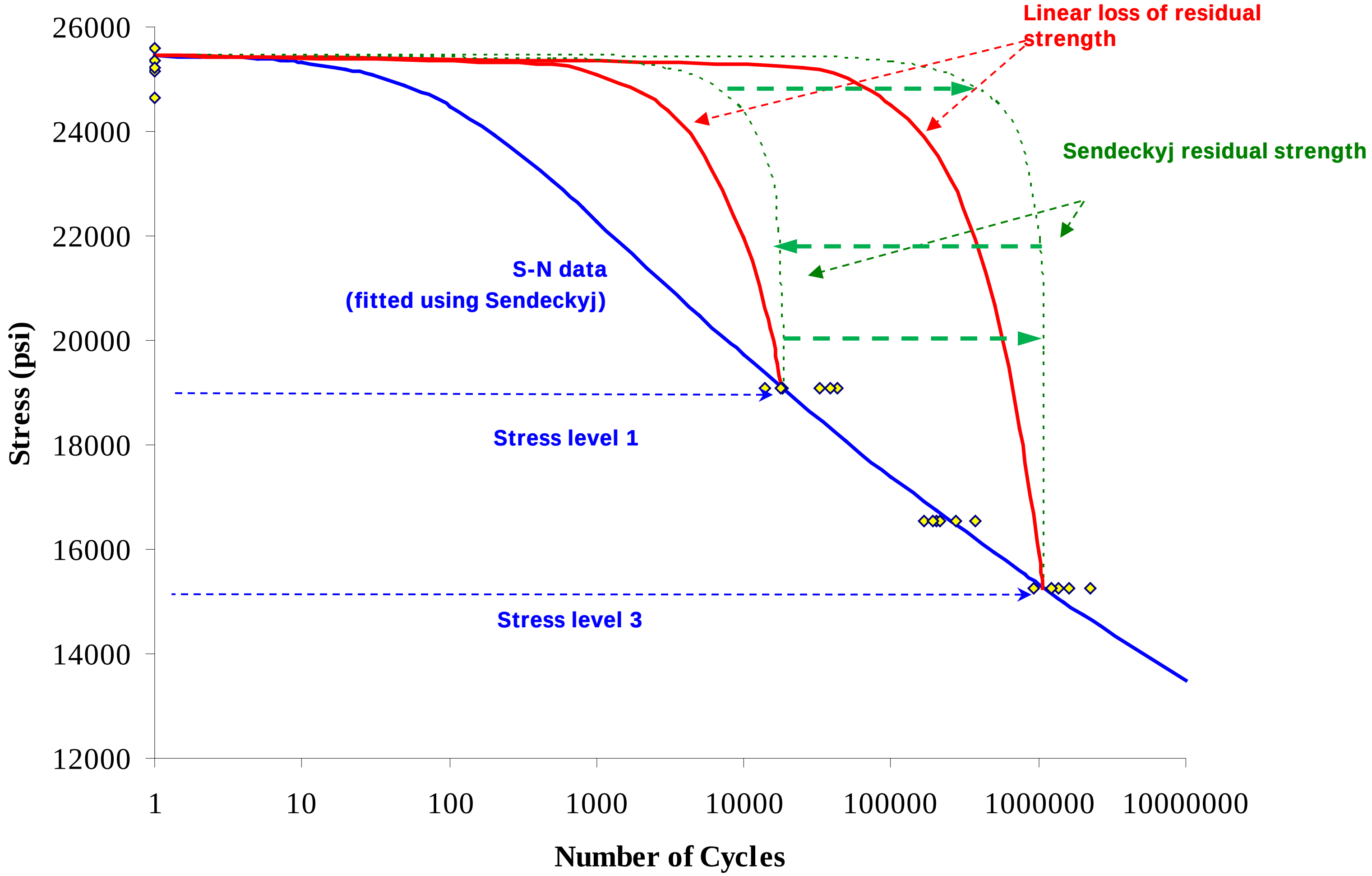
Residual Strength Analysis



Overview Current Study

- Open-hole compression specimens with two different layup sequences (hard and quasi-isotropic) were fabricated and tested with two different stress ratios (R = -1 and 5).
- Upon completion of the initial SN curves, an analysis was conducted using individual Weibull, joint Weibull, and Sendeckyj fatigue analyses techniques to compare the fatigue data scatter of T650/5320 plain weave fabric material.
- Sendeckyj analysis was further extended to evaluate the residual strength degradation and compared against residual strength determined after constant amplitude fatigue testing at two different stress levels.
- Spectrum Testing
  - A detail fatigue damage growth investigation was conducted using two different test spectra (focusing on arrangement of high loads) to investigate the load sequencing effects for the OoA material system.

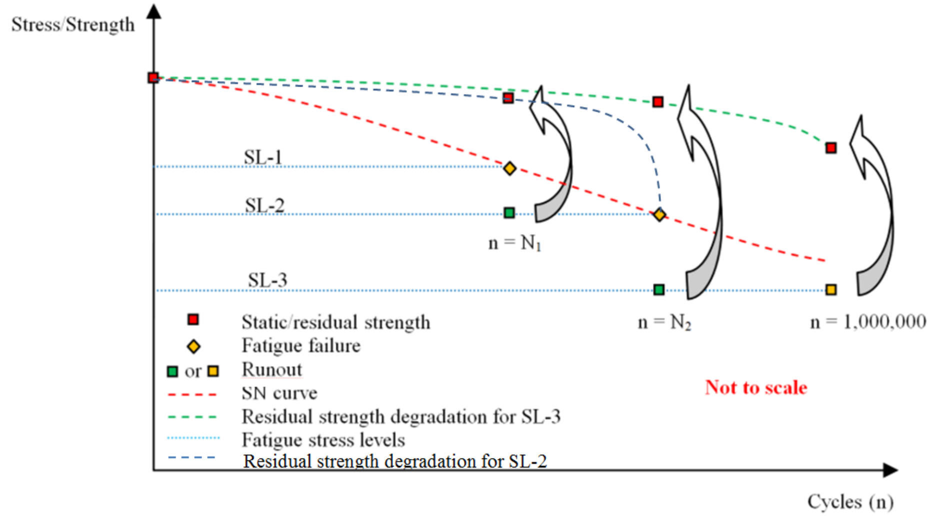
Material

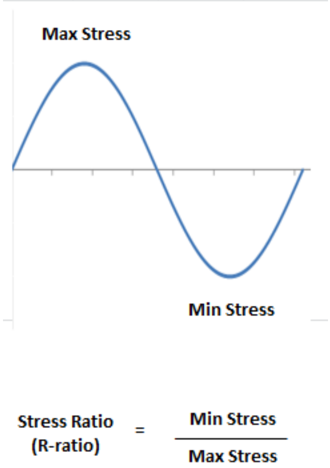
- Material: T650/5320 plain weave
- Out-of-autoclave cure: 290°F for 120-180 min
- Stacking sequences:
  – Hard laminate: 40/20/40
  $[(0/90)_2/0/45/-45/(90/0)_2]_s$
  – Quasi-isotropic laminate: 25/50/25
  $[45/0/-45/90]_{3S}$

Test Matrix 1

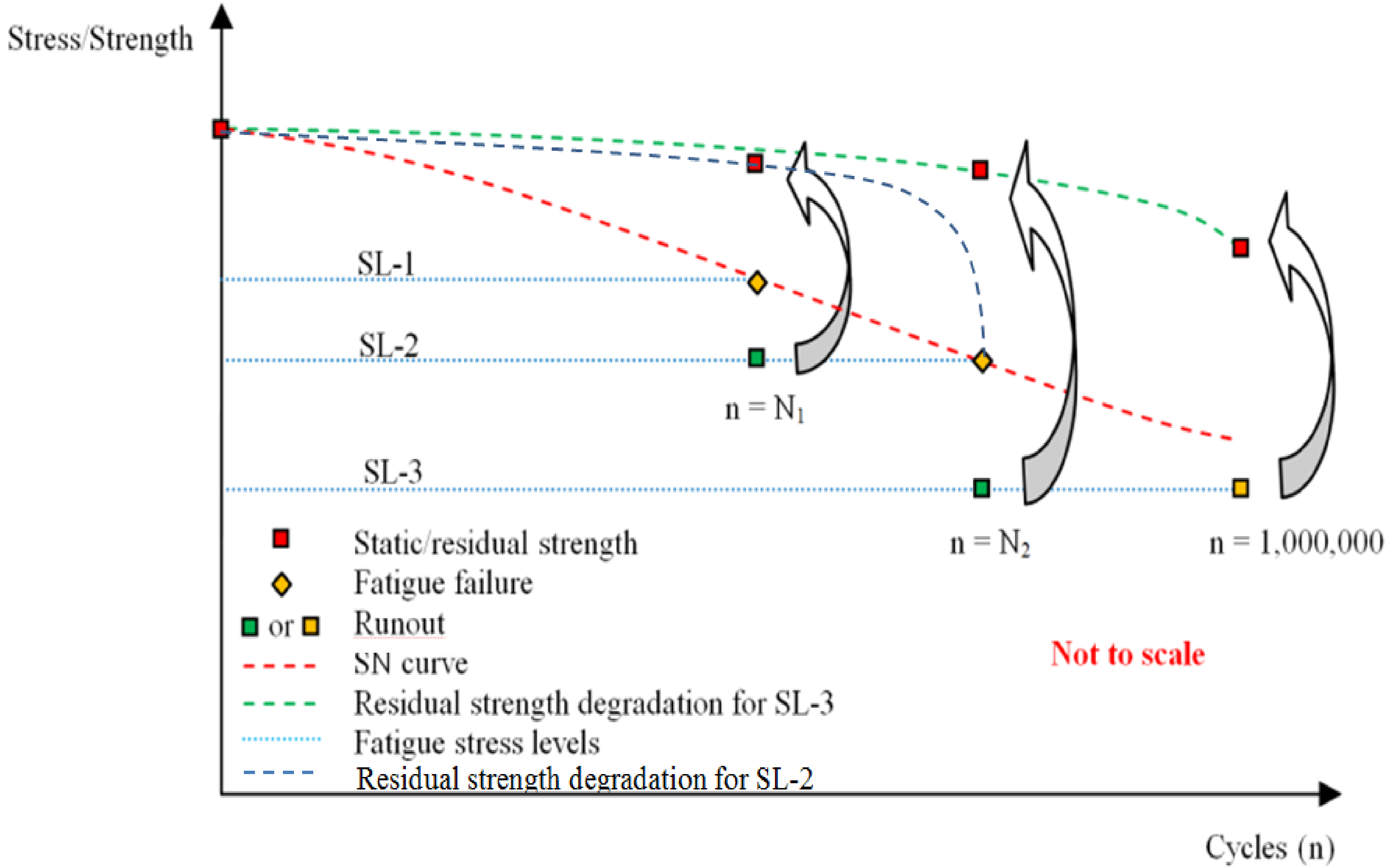
- Constant-amplitude fatigue testing
  - Modified open-hole compression test setup

Layup sequence	Stress ratio	Static (%)	Fatigue stress level (%)			Residual strength stress level (%)	
25/50/25	R = 5	100	80	70	60	70	60
	R = -1	100	70	60	50	60	50
40/20/40	R = 5	100	80	70	60	70	60
	R = -1	100	70	60	50	60	50





Test Matrix 1 – cont.

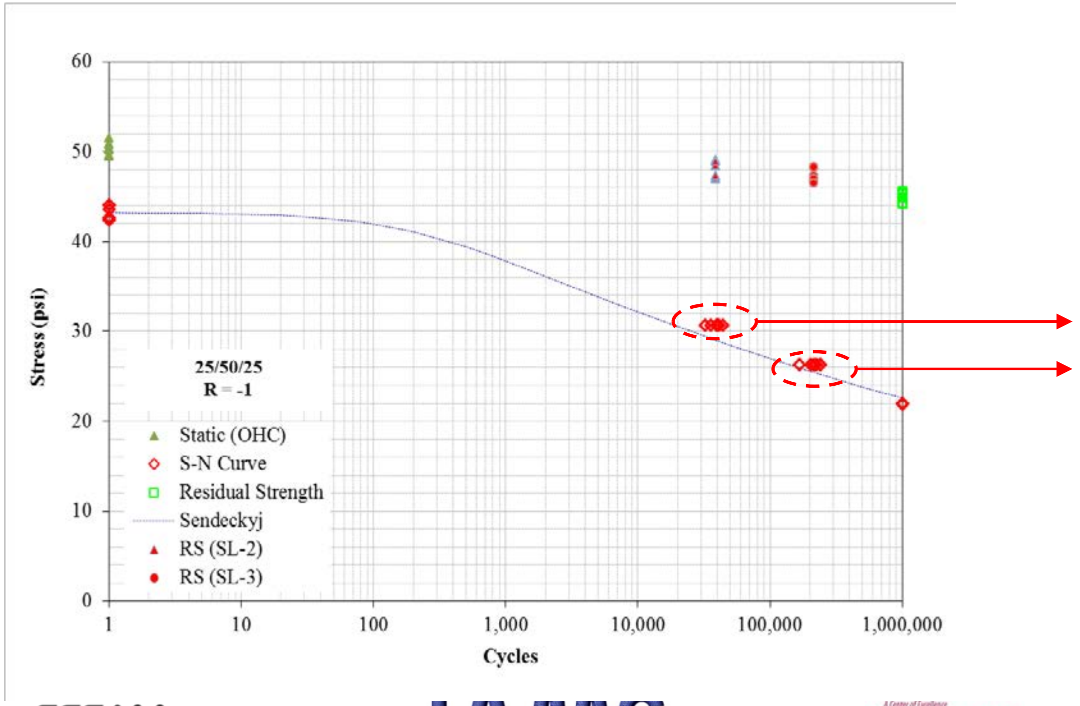


Fatigue Data Scatter Analysis

- Individual Weibull
  - Shape parameter
- Joint Weibull
  - Shape parameter
- Sendeckyj Wearout
  - Shape parameter
  - Curve fit for S-N data
  - Residual strength degradation (wearout)

Individual Weibull Analysis

- Fatigue failures in each stress level with more than 5 samples is analyzed using Weibull analysis and all shape parameters are arithmetically average to define data scatter in S-N curve



Joint Weibull Analysis

- In the joint Weibull (JW) analysis, *M* groups of data having a common shape parameter, but different scale parameters, are pooled.
- The common shape and scale parameters are obtained using the joint maximum likelihood estimate method.

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

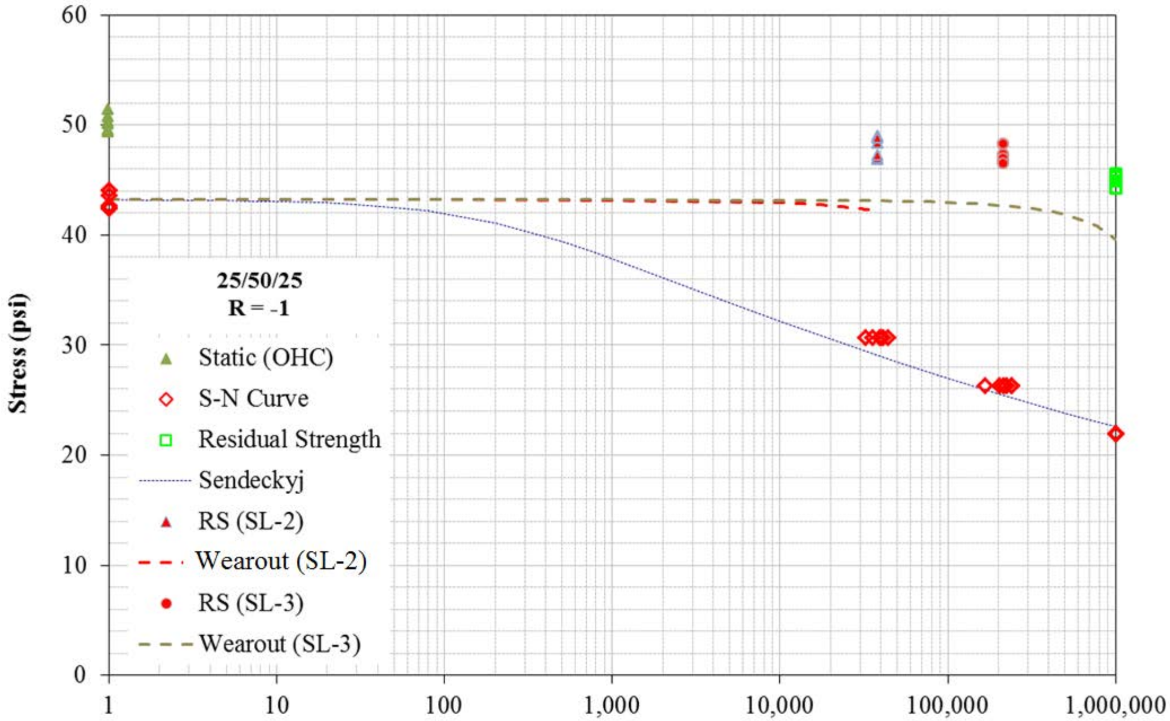
$$\beta_i=\left(\frac{1}{n_{fi}}\cdot\sum_{j=1}^{n_i} x_{ij}^{\alpha}\right)^{1/\alpha}$$

n_i – number of data points in the i^{th} group of data (i=1,2,….,*M*)

n_{fi} – number of failures in the i^{th} group of data (i=1,2,….,*M*)

Sendeckyj Analysis

- Uniquely relates the static strength and residual strength to fatigue life.
- Analysis pools static strength, fatigue life, and residual static strength data and converts it into equivalent static strength data.



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

σ_e – equivalent static strength

σ_a – maximum applied cyclic stress

σ_r – residual strength

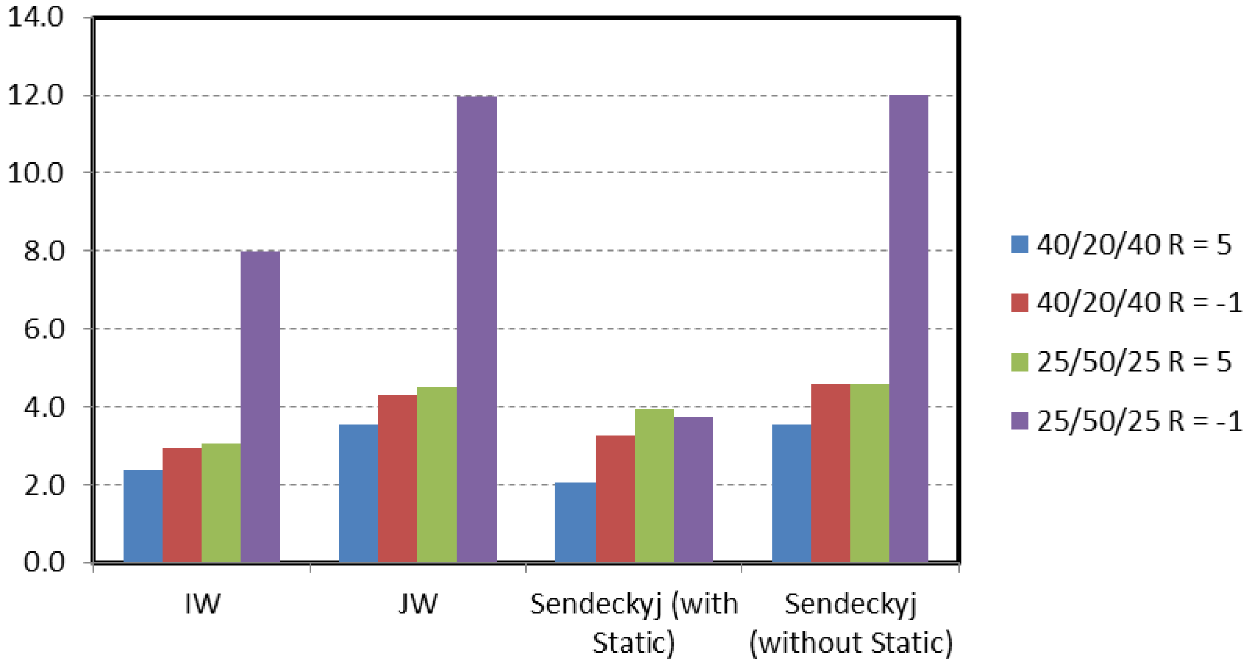
N_f – number of fatigue cycles

S and C are fitting parameters

Scatter Analysis

Layup sequence	Stress ratio	Static (IW)	Weibull analysis		Sendeckyj analysis	
			IW	JW	With static data	without static data
40/20/40	R = 5	39.851*	2.382	3.528	2.066	3.525
	R = -1	26.050**	2.944	4.288	3.271	4.593
25/50/25	R = 5	73.011*	3.042	4.521	3.963	4.567
	R = -1	69.192**	7.977	11.970	3.733	11.996

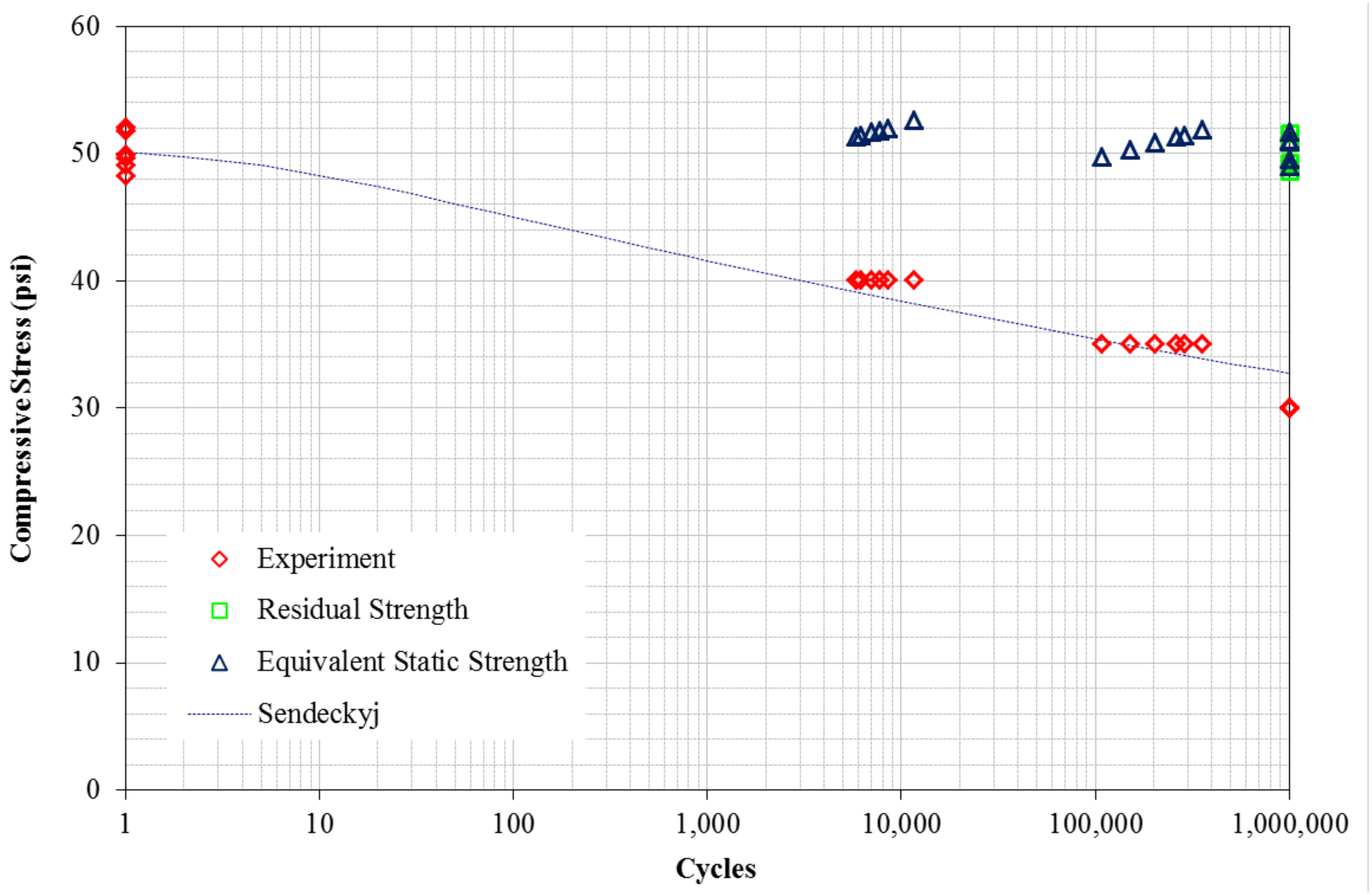
*** Compression data analysis; ** Tension data analysis**



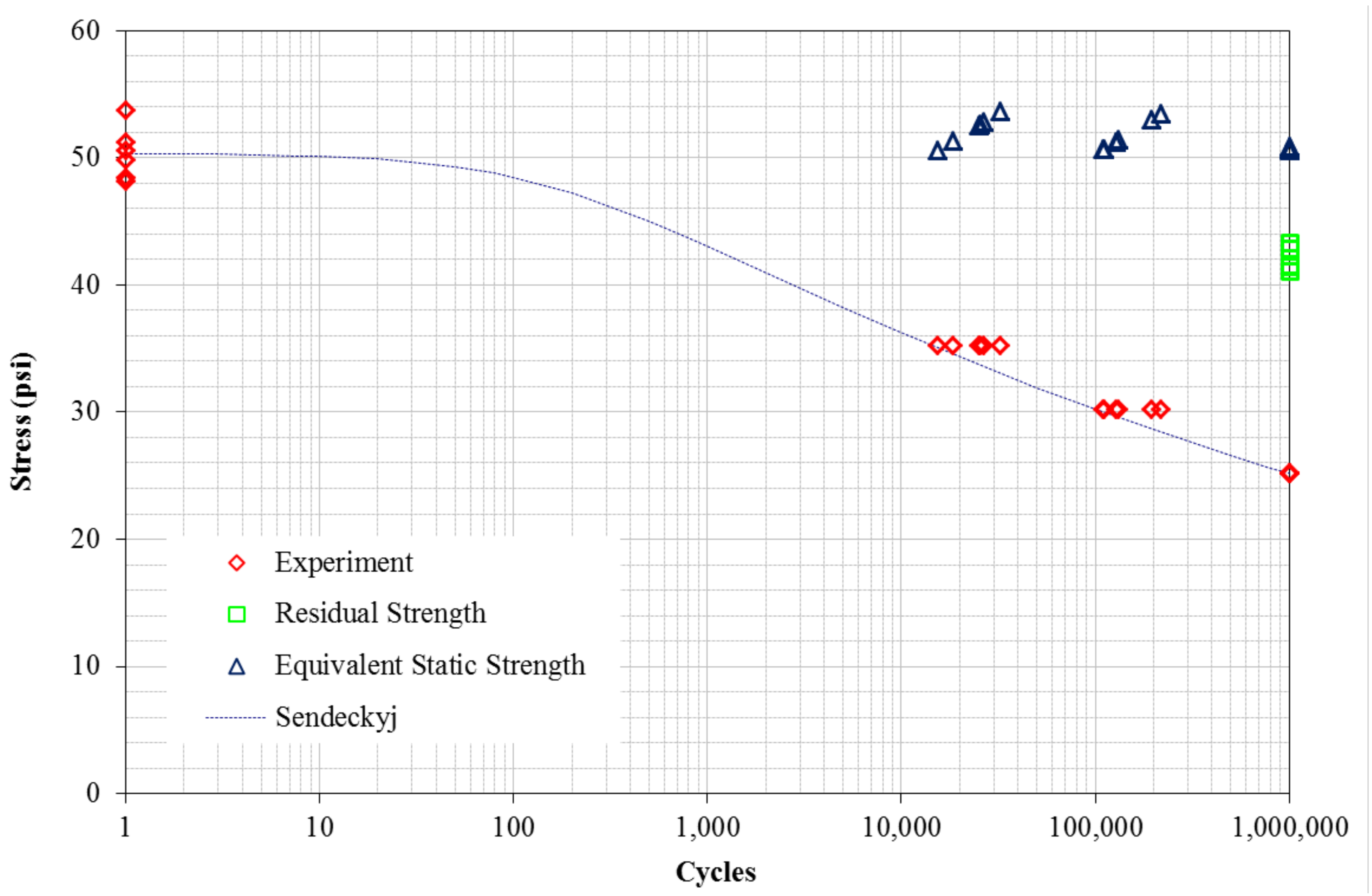
Initial Sendeckyj Analysis

- Initial Sendeckyj Analysis: Static, fatigue failure data from two stress levels (SL-1 and SL-2), and residual strength of runout at 1,000,000 cycles data are used for obtaining Sendeckyj fitting parameters S and C.
  - Initial Sendeckyj fit
  - Residual strength at n=N1 (average # of cycles for fatigue failures at SL-1) for SL-2 is calculated
  - Residual Strength at n=N2 (average # of cycles for fatigue failures at SL-2) for SL-3 is calculated

40/20/40 - R = 5


Compressive Stress (psi)
60
50
40
30
20
10
0
1
10
100
1,000
10,000
100,000
1,000,000
Cycles
Experiment
Residual Strength
Equivalent Static Strength
Sendeckyj

40/20/40 - R = -1



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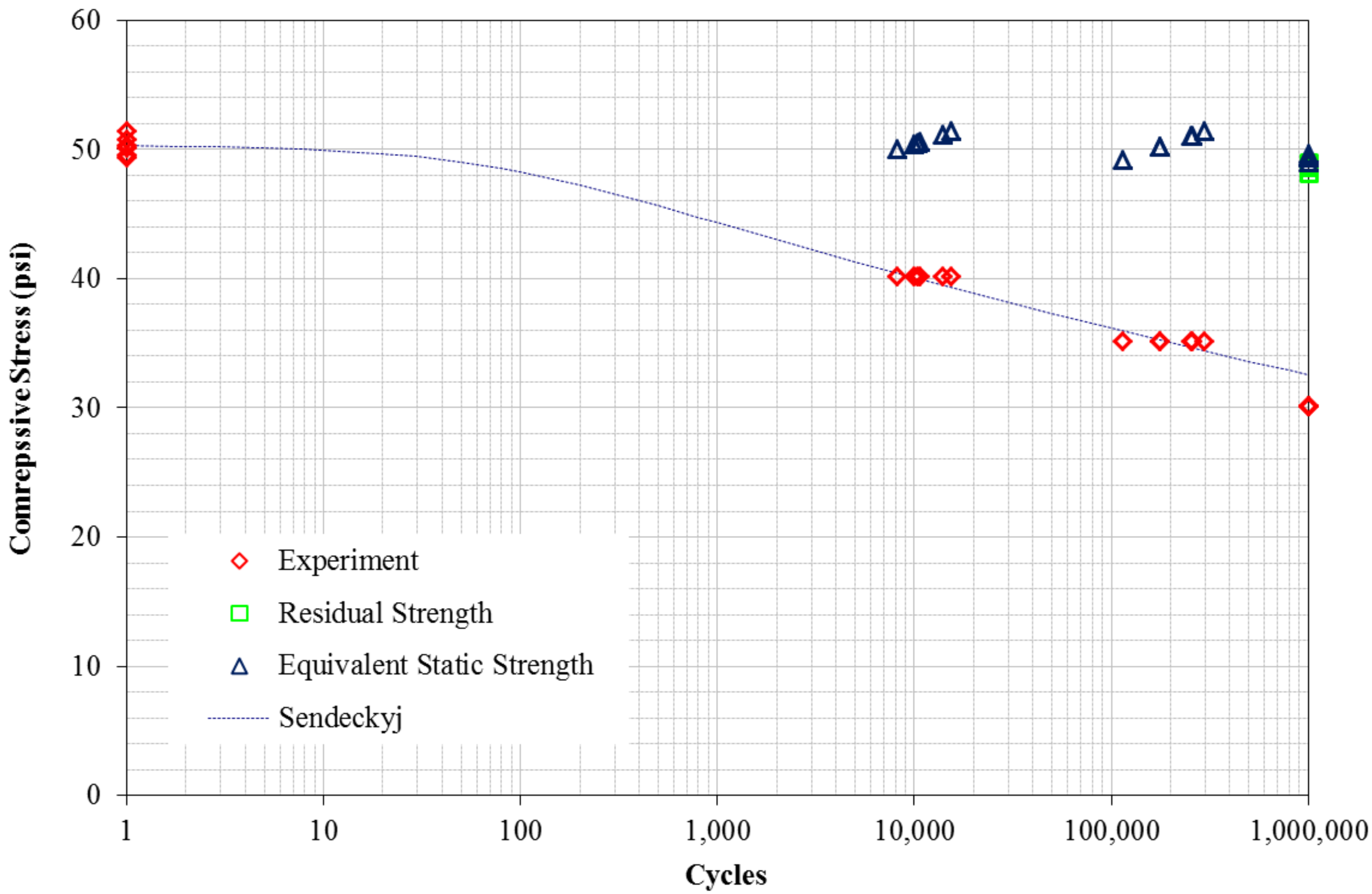
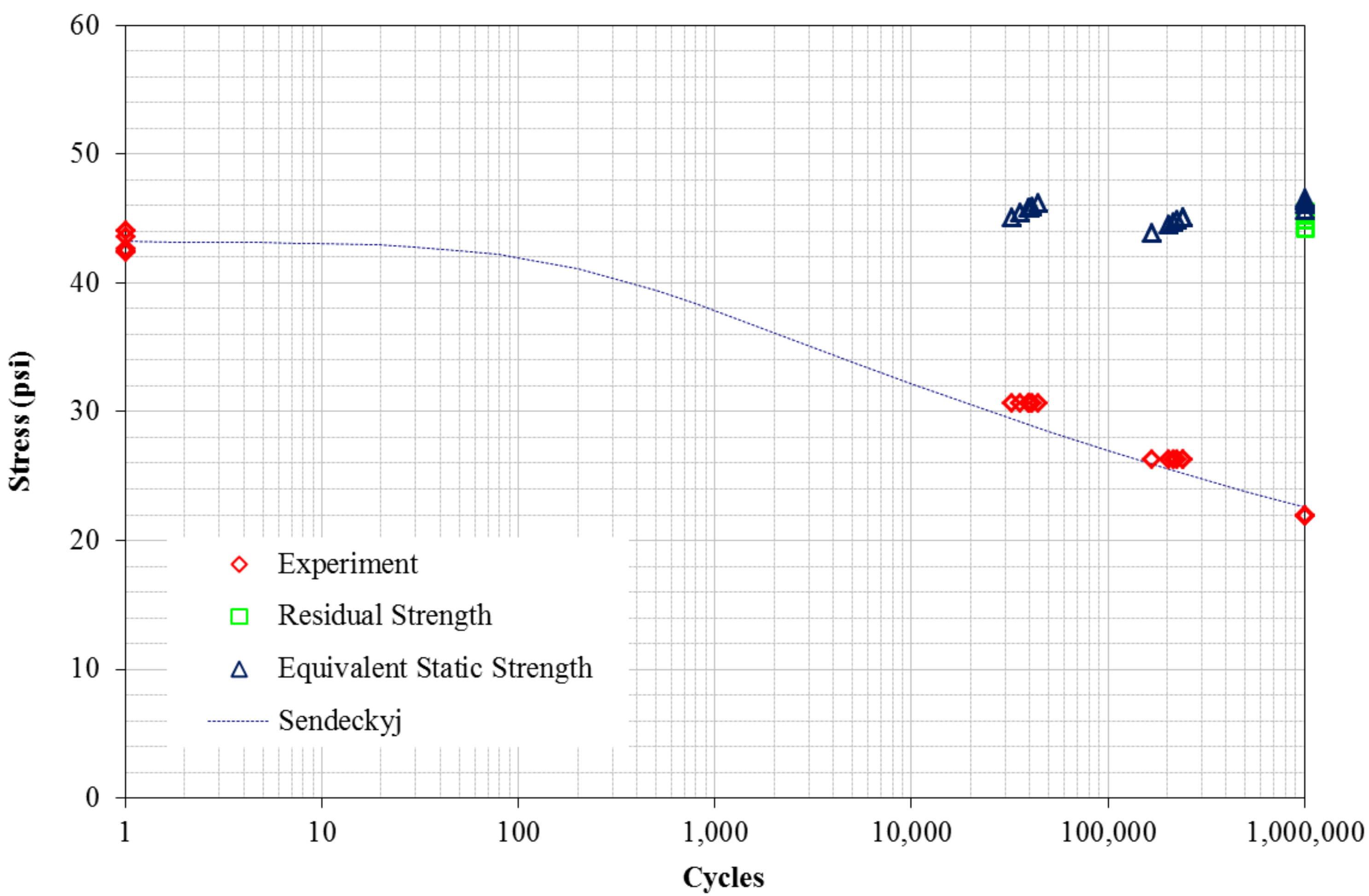
25/50/25 - R = 5



60
50
40
30
20
10
0
Comrepssive Stress (psi)
1
10
100
1,000
10,000
100,000
1,000,000
Cycles
Experiment
Residual Strength
Equivalent Static Strength
Sendeckyj

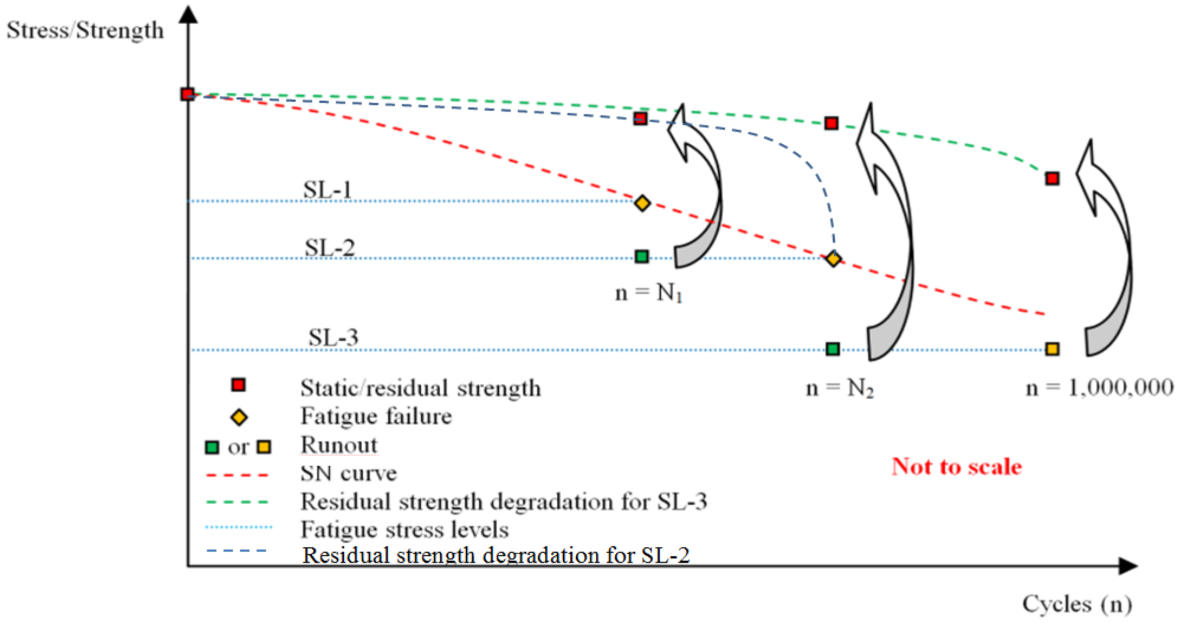
25/50/25 - R = -1



60
50
40
30
20
10
0
Stress (psi)
1
10
100
1,000
10,000
100,000
1,000,000
Cycles
Experiment
Residual Strength
Equivalent Static Strength
Sendeckyj

Residual Strength Tests

- Second set of fatigue specimens to obtain the residual strength at $n=N_1$ and $n=N_2$
  - 6 specimens were fatigued till $n=N_1$ at SL-2 and residual strengths are obtained
  - 6 specimens were fatigued till $n=N_2$ at SL-3 and residual strengths are obtained



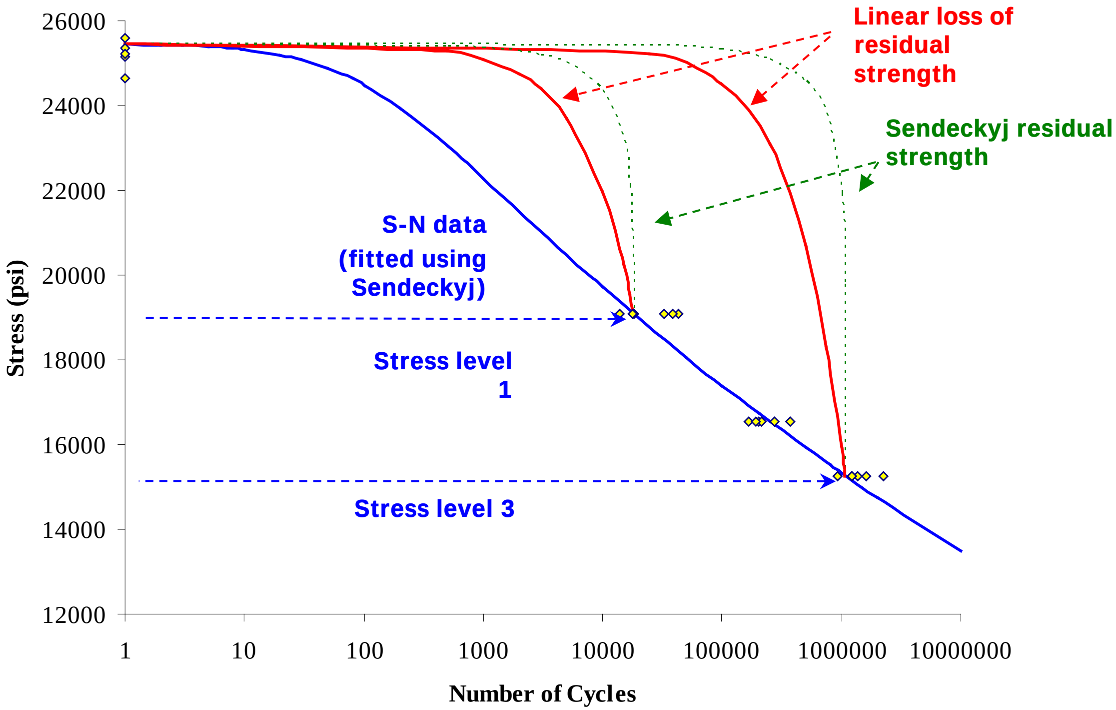
Residual Strength Degradation

- Sendeckyj Wearout Model:

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

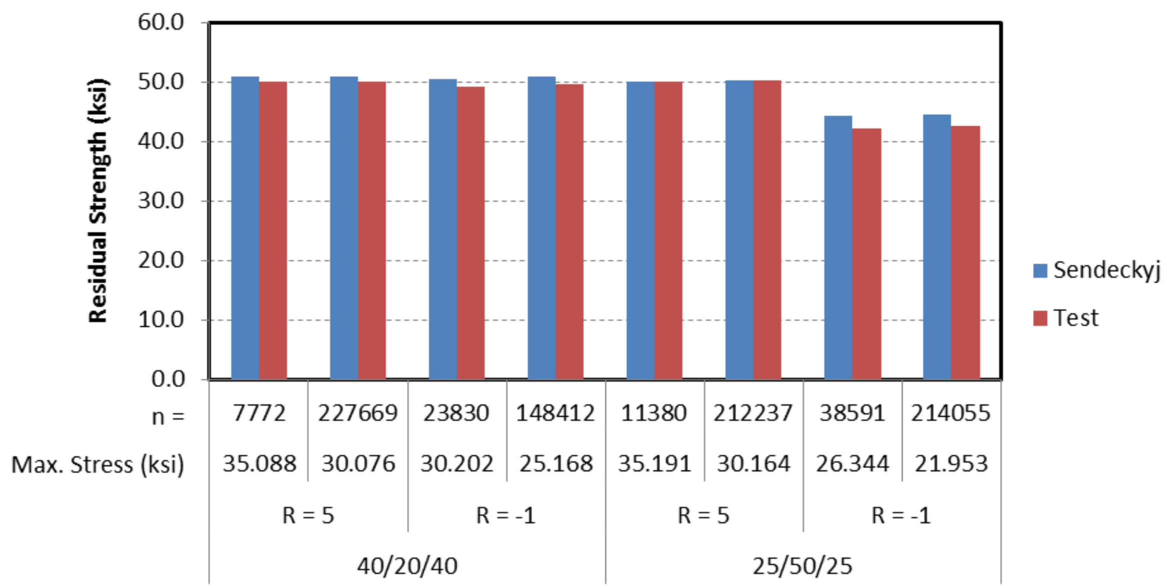
- Linear Loss of Residual Strength:

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



Sendeckyj Residual Strength

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



Test Matrix 2

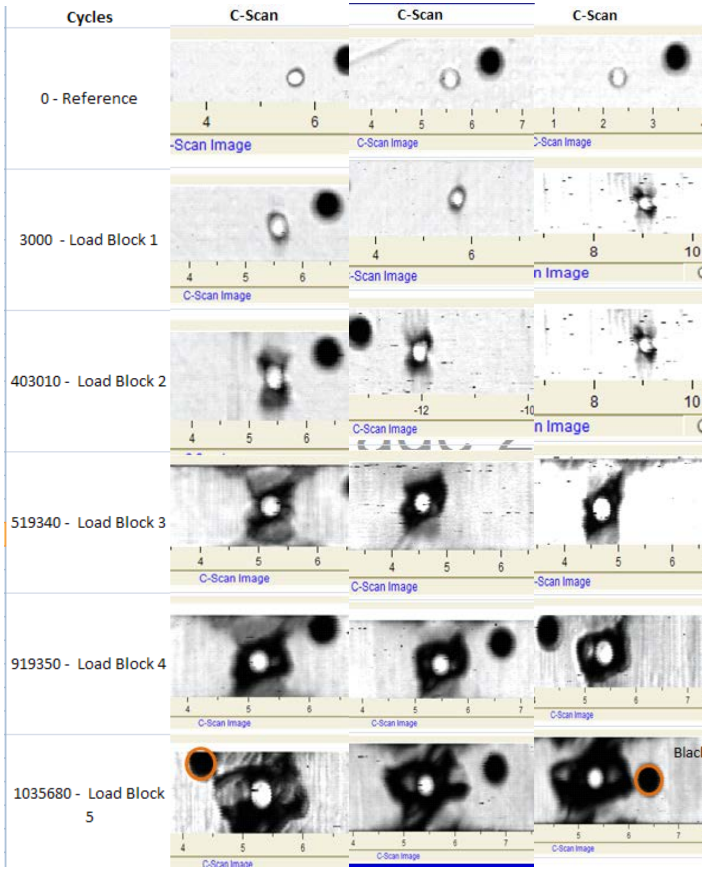
- Spectrum fatigue testing
  - Modified open-hole compression test setup

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

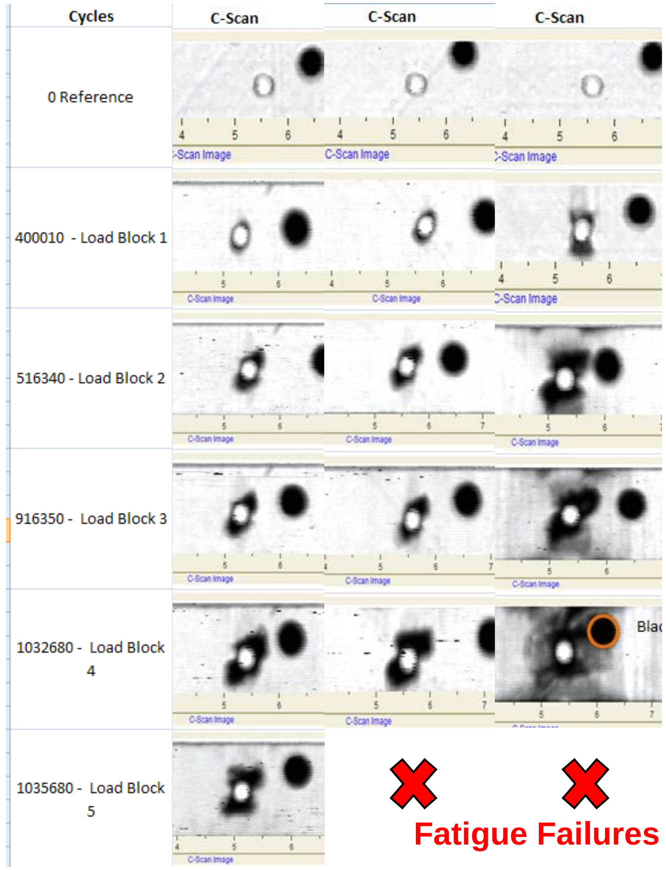
Load Sequencing Effects

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

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



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



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

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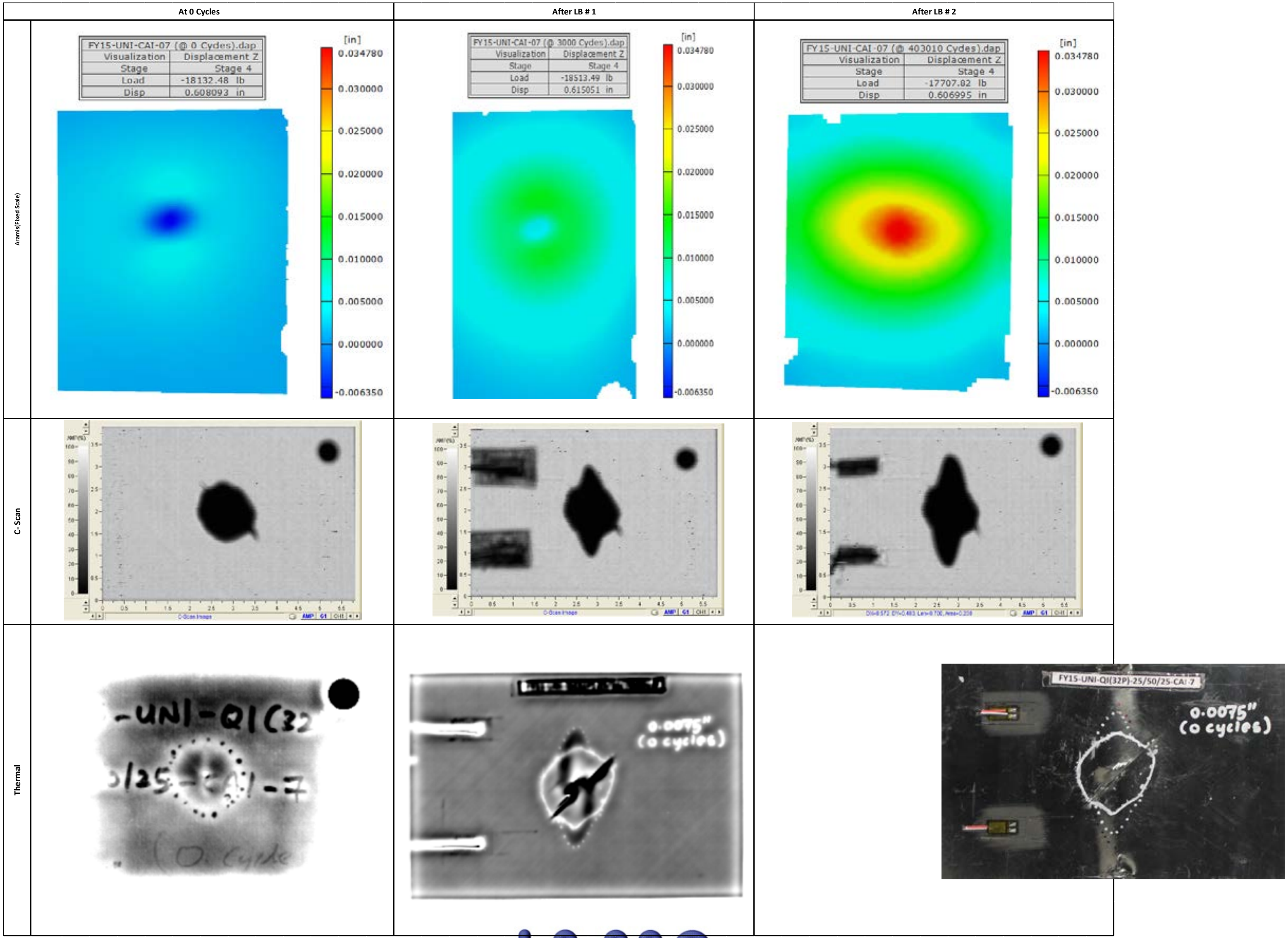
CAI – Sequencing Studies (On-Going)



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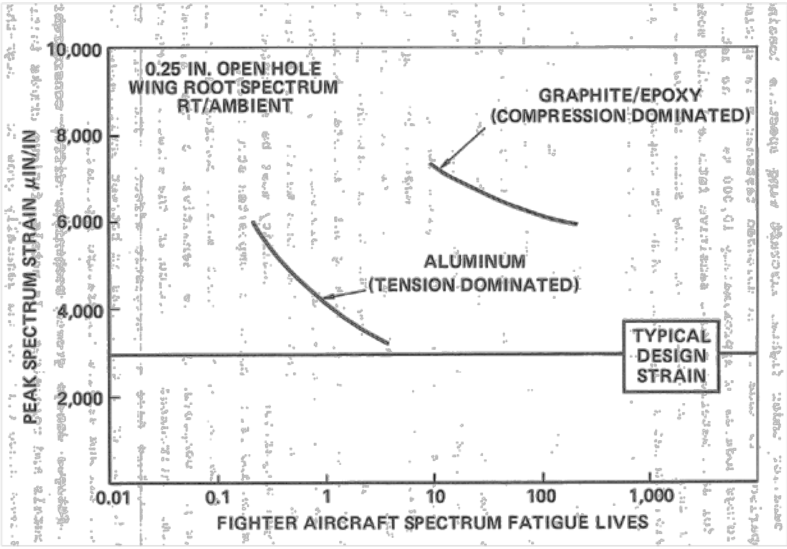
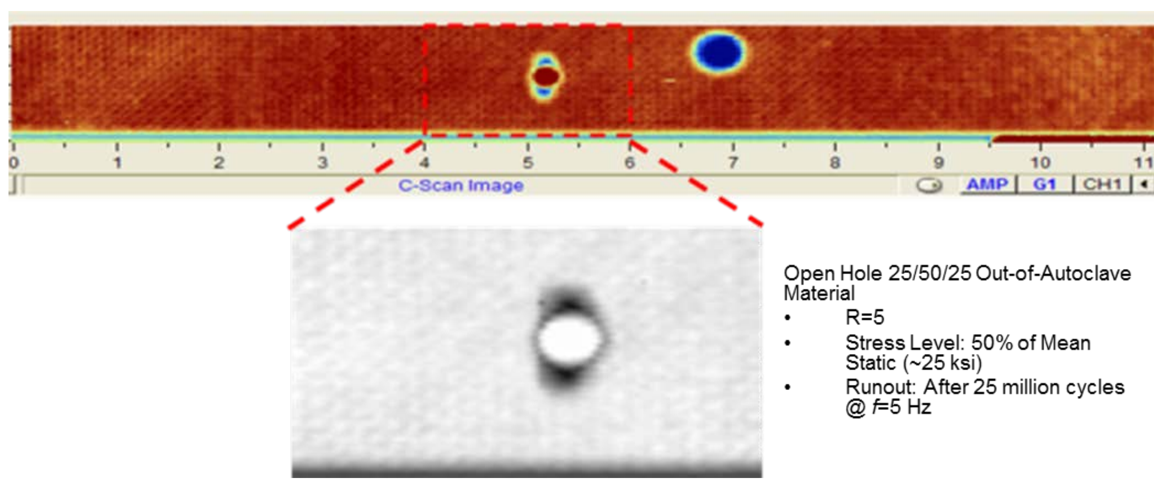
Low Stress Level – High Cycle Fatigue



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

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Summary

- Static and fatigue data scatter in OoA processed T650/5320 plain weave fabric material are analyzed and found that the data scatter is significantly less than that of legacy composite materials and are comparable to most modern prepreg material systems.
- Residual strength predictive capabilities of Sendeckyj wearout is demonstrated through experimental validations.
  - Significant residual strength degradation was **not** observed.
- Load sequencing study of OoA material indicated that the sequencing of high loads such as 70 percent of static strength has a prominent effect on the fatigue life.
  - When the high fatigue loads are applied at high cycles (later in life) to composite with small damages, it is more damaging than applying them at low cycles (early life).
  - Pristine open-hole specimens were able to sustain high loads at low cycles with minimal damage and were able to carry medium to low loads pass million cycles (cumulative) without failure.
  - Further studies conducted at low stress levels for very high cycles (25 million) indicated minimal damage growth. Therefore, at such low stress levels, sequencing effects will not be evident in composites.

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Looking Forward

- **Benefit to Aviation**
  - Efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority.
    - Guidance materials for analysis and large-scale test substantiation of composite-metal hybrid structures.
    - Damage mechanics and competing failure modes (origination and propagation)
    - Guidance for hybrid load spectra and application LEF

- **Future needs**
  - Guidance on spectrum development
  - Validated fatigue analysis methods

End of Presentation.

Thank you.

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