Load-Life-Damage Hybrid Approach for Substantiation of Composite Aircraft Structures

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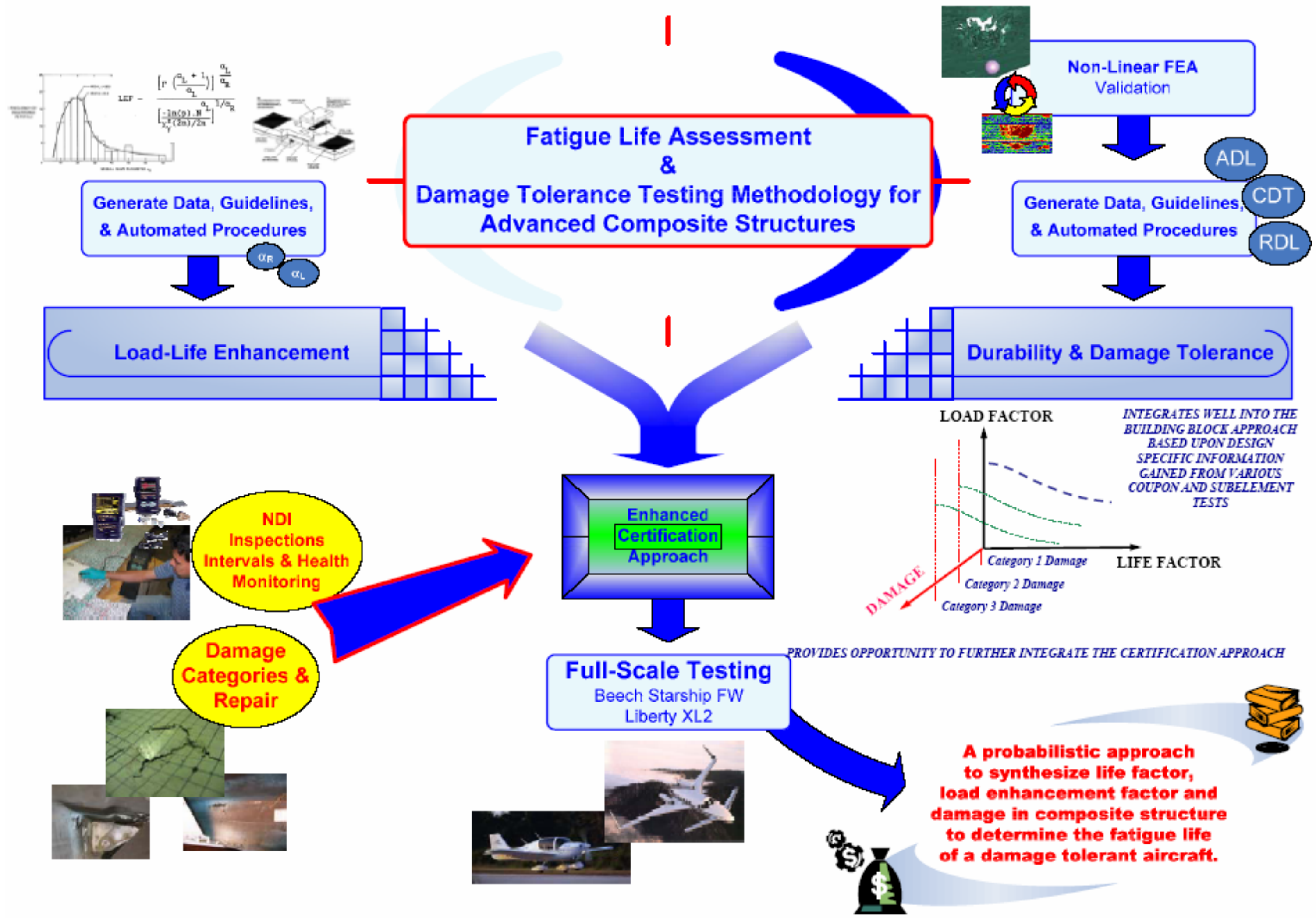
The Joint Advanced Materials and Structures Center of Excellence

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

- **Motivation and Key Issues**
  - Produce a guideline FAA document, which demonstrates a "best practice" procedure for full-scale testing protocols for composite airframe structures ***with examples***
- **Objective**
  - *Demonstrate acceptable means of compliance for fatigue, damage tolerance and static strength substantiation of composite airframe structures*
  - Evaluate existing analysis methods and building-block database needs as applied to practical problems crucial to composite airframe structural substantiation
  - Investigate realistic service damage scenarios and the inspection & repair procedures suitable for field practice

Approach



Fatigue Life Assessment
&
Damage Tolerance Testing Methodology for
Advanced Composite Structures
Non-Linear FEA
Validation
Generate Data, Guidelines,
& Automated Procedures
ADL
CDT
RDL
Generate Data, Guidelines,
& Automated Procedures
Load-Life Enhancement
Durability & Damage Tolerance
LOAD FACTOR
LIFE FACTOR
DAMAGE
Category 1 Damage
Category 2 Damage
Category 3 Damage
INTEGRATES WELL INTO THE BUILDING BLOCK APPROACH BASED UPON DESIGN SPECIFIC INFORMATION GAINED FROM VARIOUS COUPON AND SUBELEMENT TESTS
NDI
Inspections
Intervals & Health
Monitoring
Damage
Categories &
Repair
Enhanced
Certification
Approach
Full-Scale Testing
Beech Starship FW
Liberty XL2
PROVIDES OPPORTUNITY TO FURTHER INTEGRATE THE CERTIFICATION APPROACH
A probabilistic approach
to synthesize life factor,
load enhancement factor and
damage in composite structure
to determine the fatigue life
of a damage tolerant aircraft.

FAA Sponsored Project Information

- **National Institute for Aviation Research**
  - John Tomblin, *PhD* (Executive Director)
  - Waruna Seneviratne, *PhD* (Research Scientist)

- **Federal Aviation Administration**
  - Curtis Davies
    - Program Manager (FAA William J. Hughes Technical Center, NJ)
  - Larry Ilcewicz, PhD
    - FAA Chief Scientific and Technical Advisor for Composite Materials (FAA/Seattle Aircraft Cert. Office)
  - Peter Shyprykevich
    - Consultant (Ret. FAA)

Workshops for Composite
<u>Damage Tolerance & Maintenance</u>

2009 FAA/CACRC/EASA – Tokyo, Japan

2008 AIRBUS – Toulouse, France

2008 CMH-17: Cocoa Beach, FL and Ottawa, Canada

2007 FAA/CACRC/EASA - Amsterdam, Netherlands

2006 FAA Workshop - Chicago, IL

Research Program Objectives

Primary Objective

Develop a probabilistic approach to synthesize life factor, load factor and damage in composites to ***determine fatigue life of a damage tolerant aircraft***

Secondary Objectives

- Extend the current certification approach to **explore extremely improbable high energy impact threats**, i.e. damages that reduce residual strength of aircraft to limit load capability
  - Investigate realistic service damage scenarios
  - Inspection & repair procedures suitable for field practice
- Incorporating certain **design changes** into full-scale substantiation without the burden of additional time-consuming and costly tests

SCATTER ANALYSIS

Life Factor Approach

Load-Enhancement Factor Approach

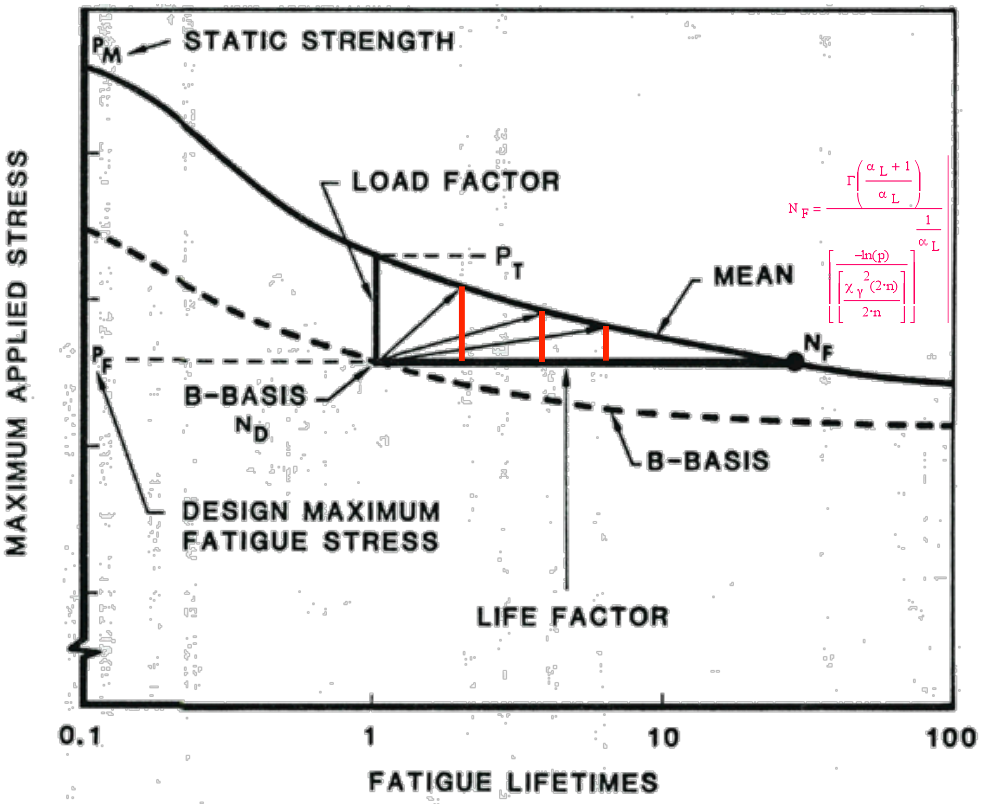
Fatigue Analysis

Application of Load-Life Enhancement Factors

Test Data and Case Studies

Load-Enhancement Factor Approach

- Increase applied loads in fatigue tests so that the **same level of reliability** can be achieved with a shorter test duration
  - Whitehead, et. al (NAVY/FAA research for F-18 certification)



- Load (Scatter) Factor

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

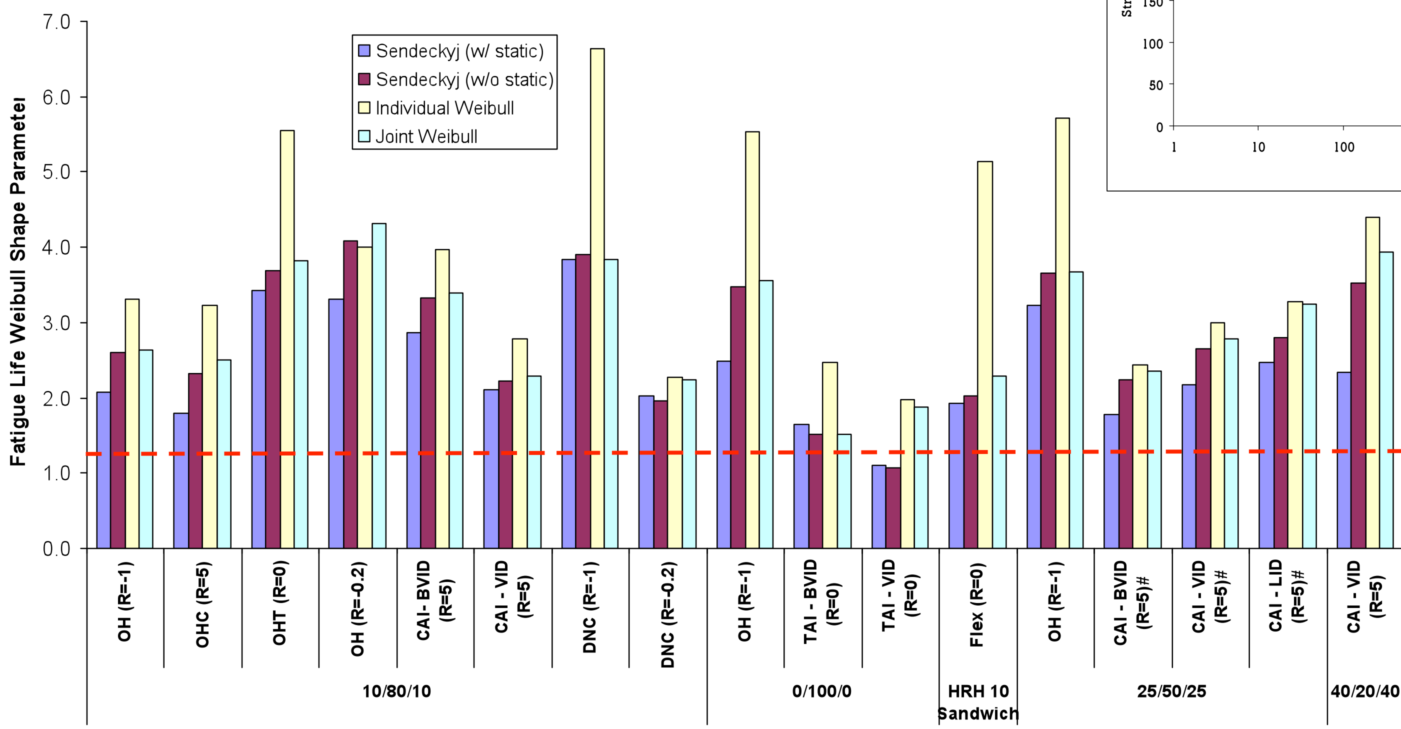
- Load Enhancement Factor (LEF)

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

Fatigue Scatter Analysis Techniques

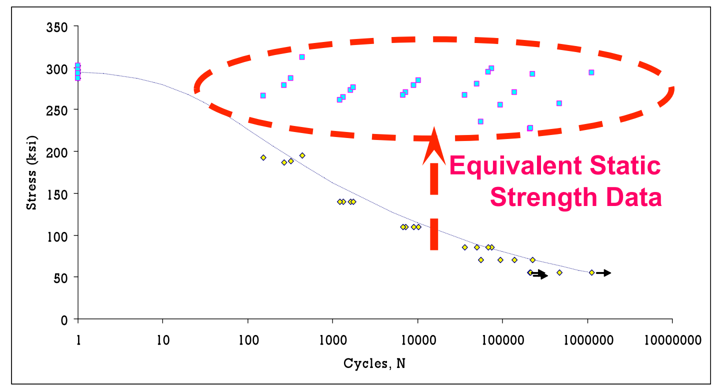
- Individual Weibull
- Joint Weibull
- Sedeckyj Equivalent Strength Model

Data Pooling Techniques



NADC Fatigue Scatter Analysis

$\alpha_I > \alpha_J > \alpha_S$



AS4/E7K8 PW

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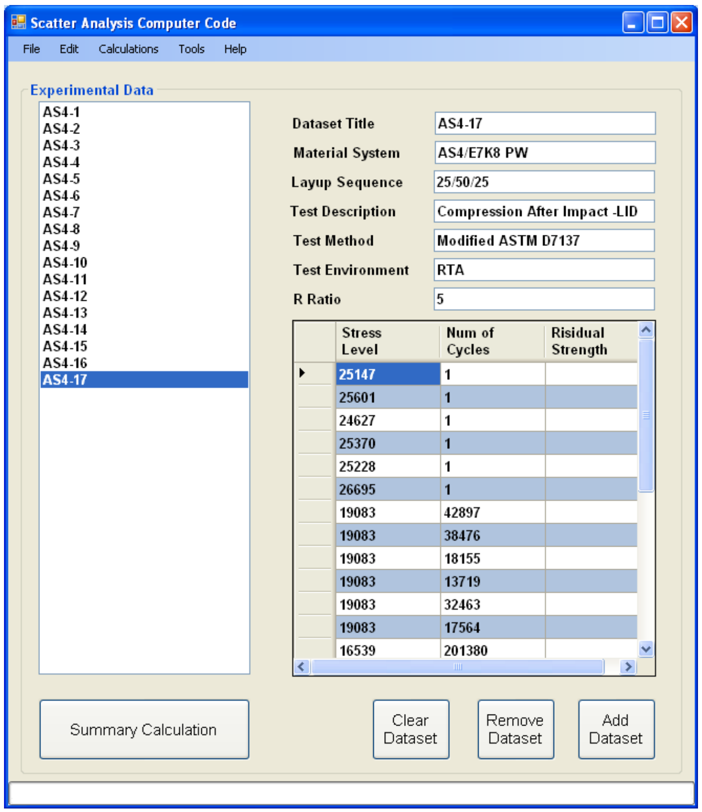
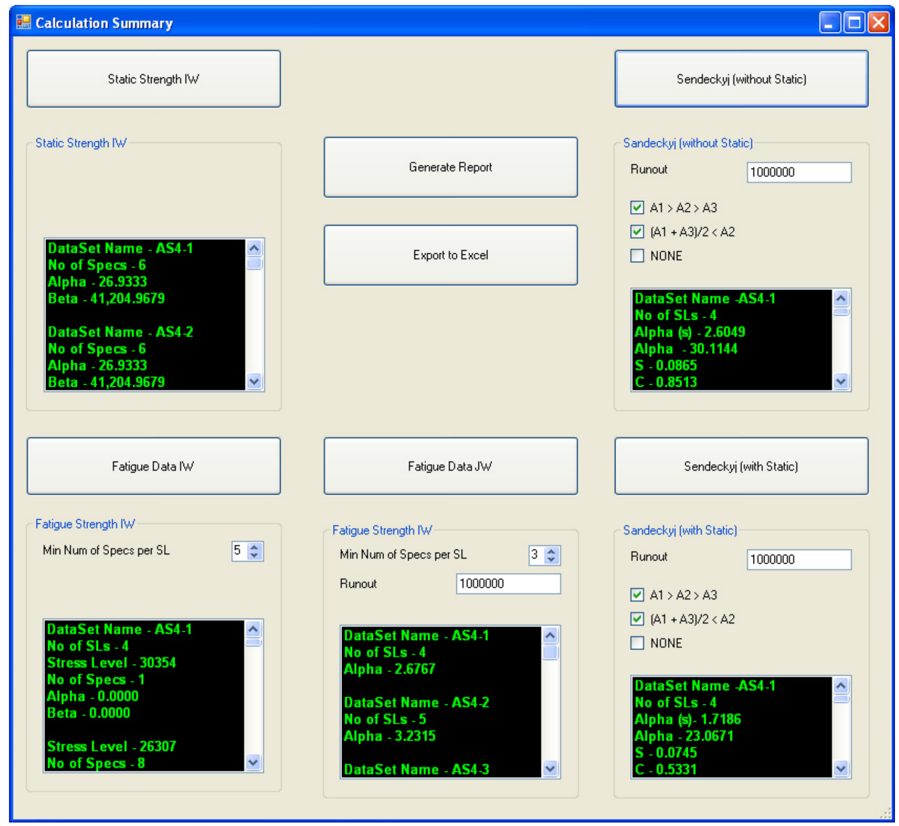
Scatter Analayis Computer Code (SACC)





2nd Generation

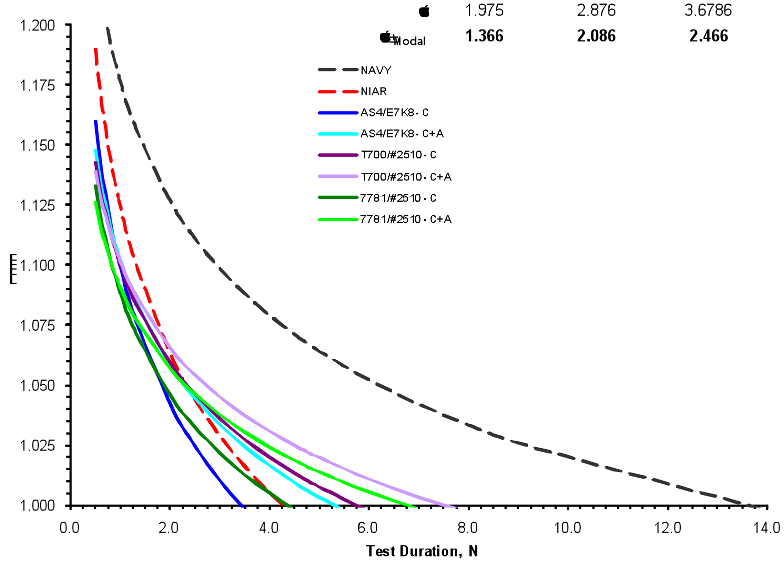
Weibull Shape Parameters

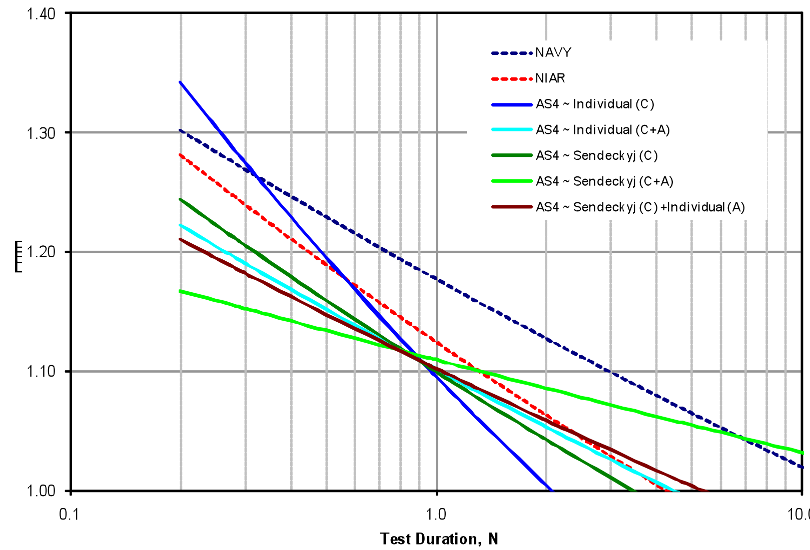
			Sendeckyj (w/static)	Sendeckyj (w/o static)	Individual Weibull (w/o static)	Joint Weibull (w/o static)
Pooled - Composite	MLE		3.342	1.826	1.8255	1.910
			2.408	3.291	4.6023	3.435
		Modal	**2.165**	**2.131**	**2.980**	**2.330**
	RRX		3.900	2.674	2.8007	2.896
			2.371	3.150	4.3619	3.280
		Modal	**2.198**	**2.644**	**3.725**	**2.834**
	RRY		3.656	2.320	2.2853	2.452
			2.394	3.251	4.5609	3.396
		Modal	**2.193**	**2.550**	**3.546**	**2.743**
Pooled - Composite+Adhesive	MLE		2.070	1.698	1.5651	1.647
			1.968	2.917	3.7258	2.822
		Modal	**1.430**	**1.729**	**1.943**	**1.600**
	RRX		2.000	2.206	2.1304	2.221
			1.961	2.826	3.5564	2.708
		Modal	**1.387**	**2.150**	**2.641**	**2.069**
	RRY		1.951	2.063	1.8875	1.991
			1.975	2.876	3.6786	2.788
		Modal	**1.366**	**2.086**	**2.466**	**1.964**

Maximum Likelihood Estimation

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	
5.00	1.064	
6.00	1.052	
7.00	1.042	
8.00	1.034	
9.00	1.026	
13.60	1.000	





Application of LEF/N_F

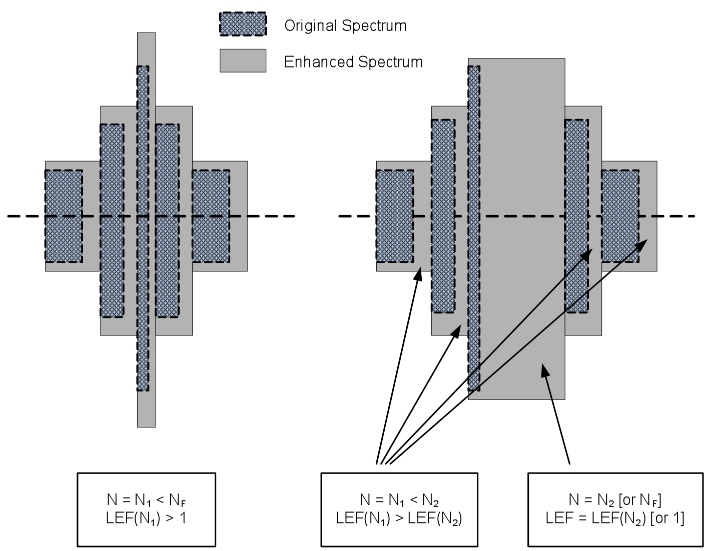
Hybrid Structural Substantiation

Metals:

severe flight loads result in crack-growth retardation

Composites:

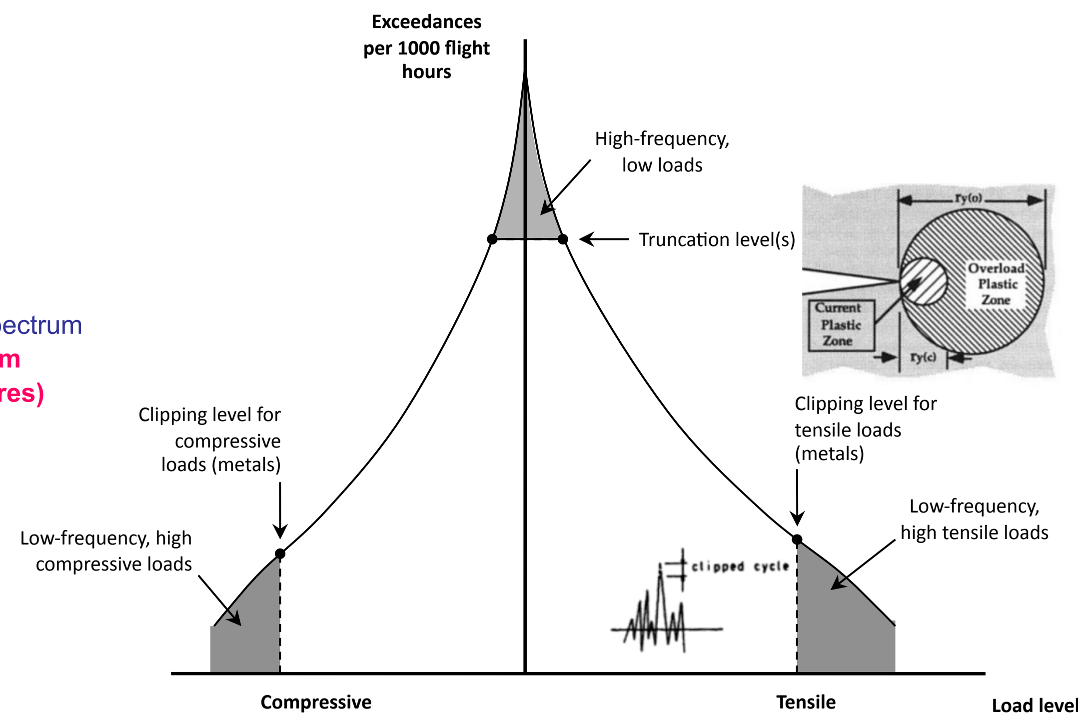
severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life



(a) Combined load-life test (b) Combined load-life spectrum

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

Must preserve the stress ratios



LOAD-LIFE DAMAGE (HYBRID) CERTIFICATION APPROACH

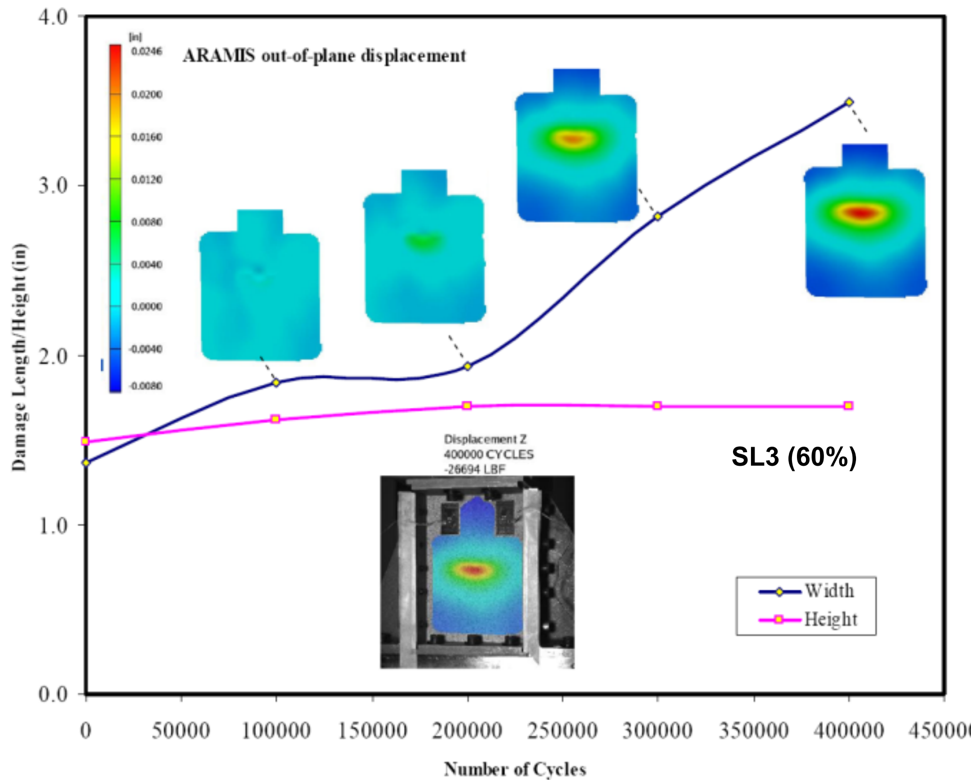
Damage Tolerance Element Testing

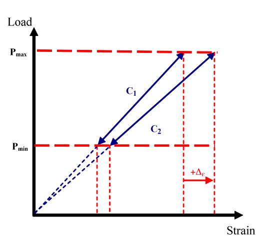
Enhanced Durability & Damage Tolerance Test Substantiation Approach

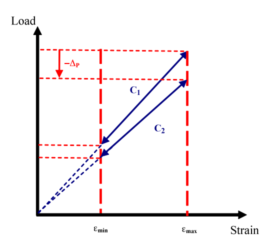
Load-Life Shift Concept

Damage-Tolerance Element Tests

- Scatter analysis or flaw growth threshold
- Scaling
  - Primary load path (LC)
  - Load redistribution (SC)
- Flaw-growth measurements
  - Compliance change
  - Stable or critical growth
- Loading mode
  - Stress ratio

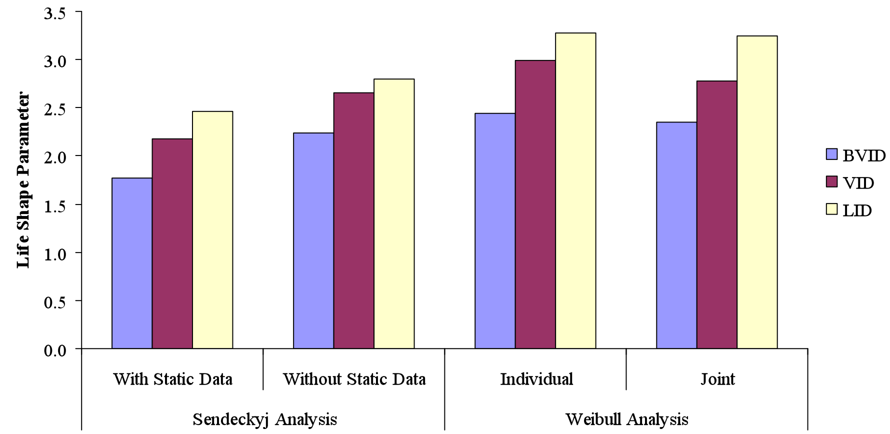


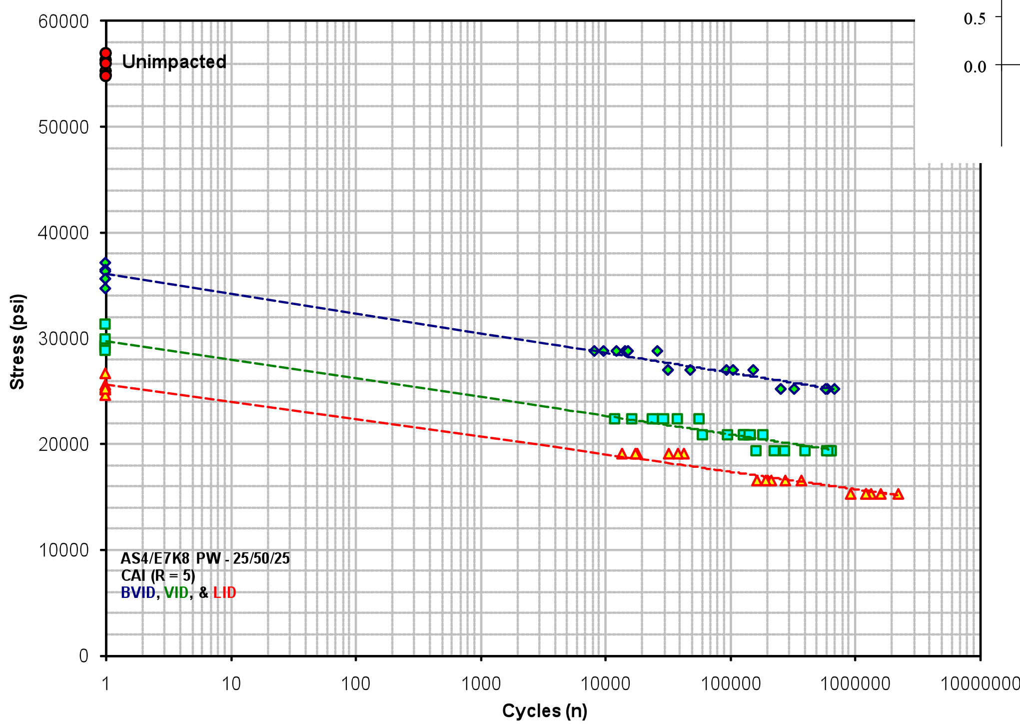


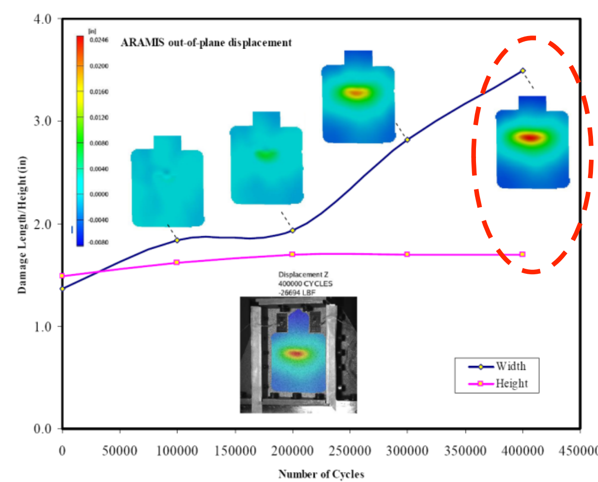


Effects of Damage on α

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







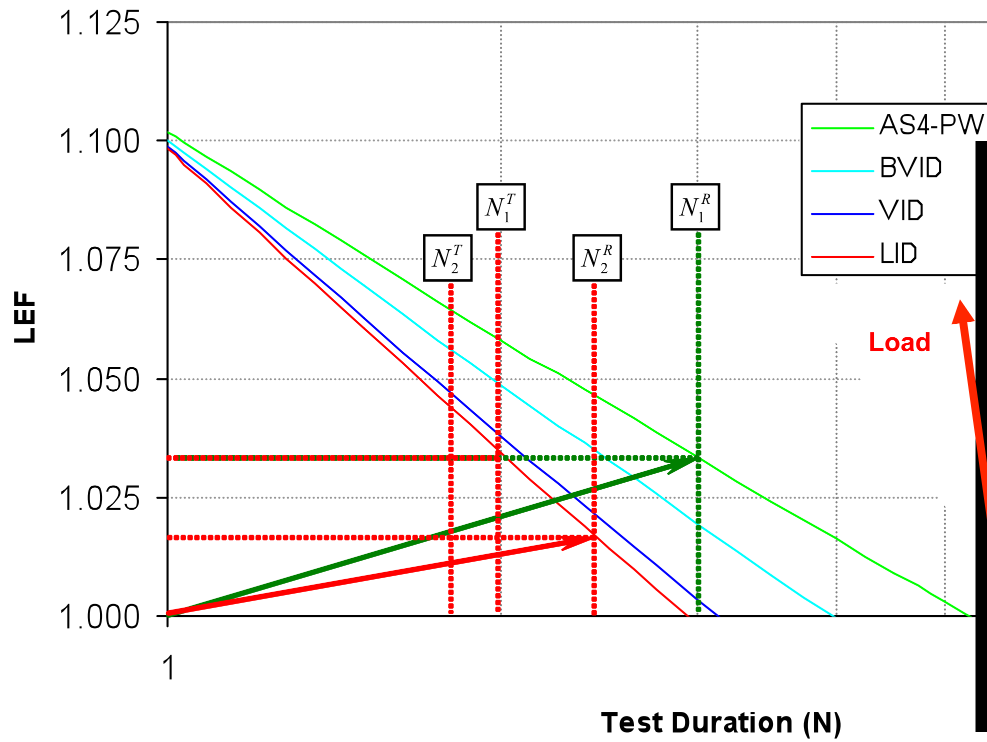
Load-Life Shift

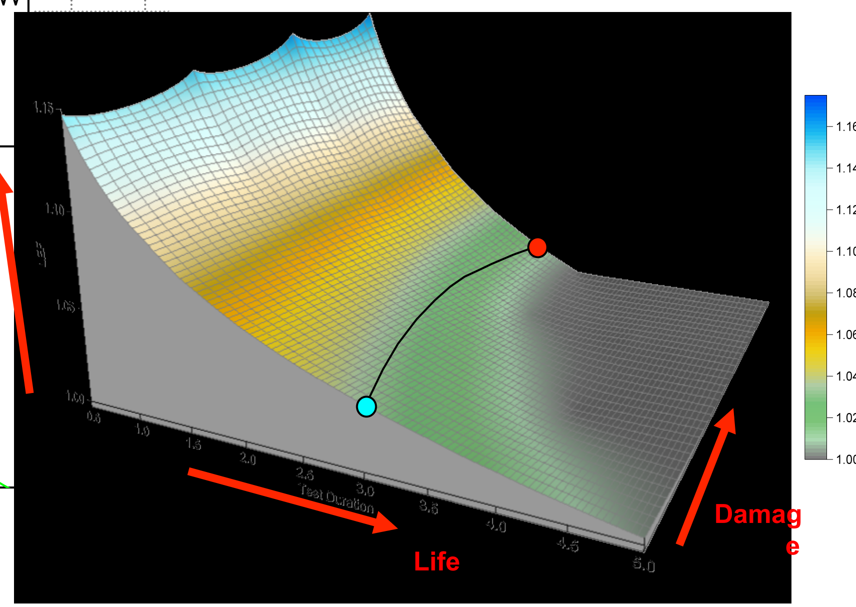
- Example calculation of desired Test Duration:

No Damage (LEF=1.033)		LID (LEF=1.014)		Total
Desired	Test	Desired	Test	
3.0	2.0	2.5	0.8	2.8

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

Load-Life Shift





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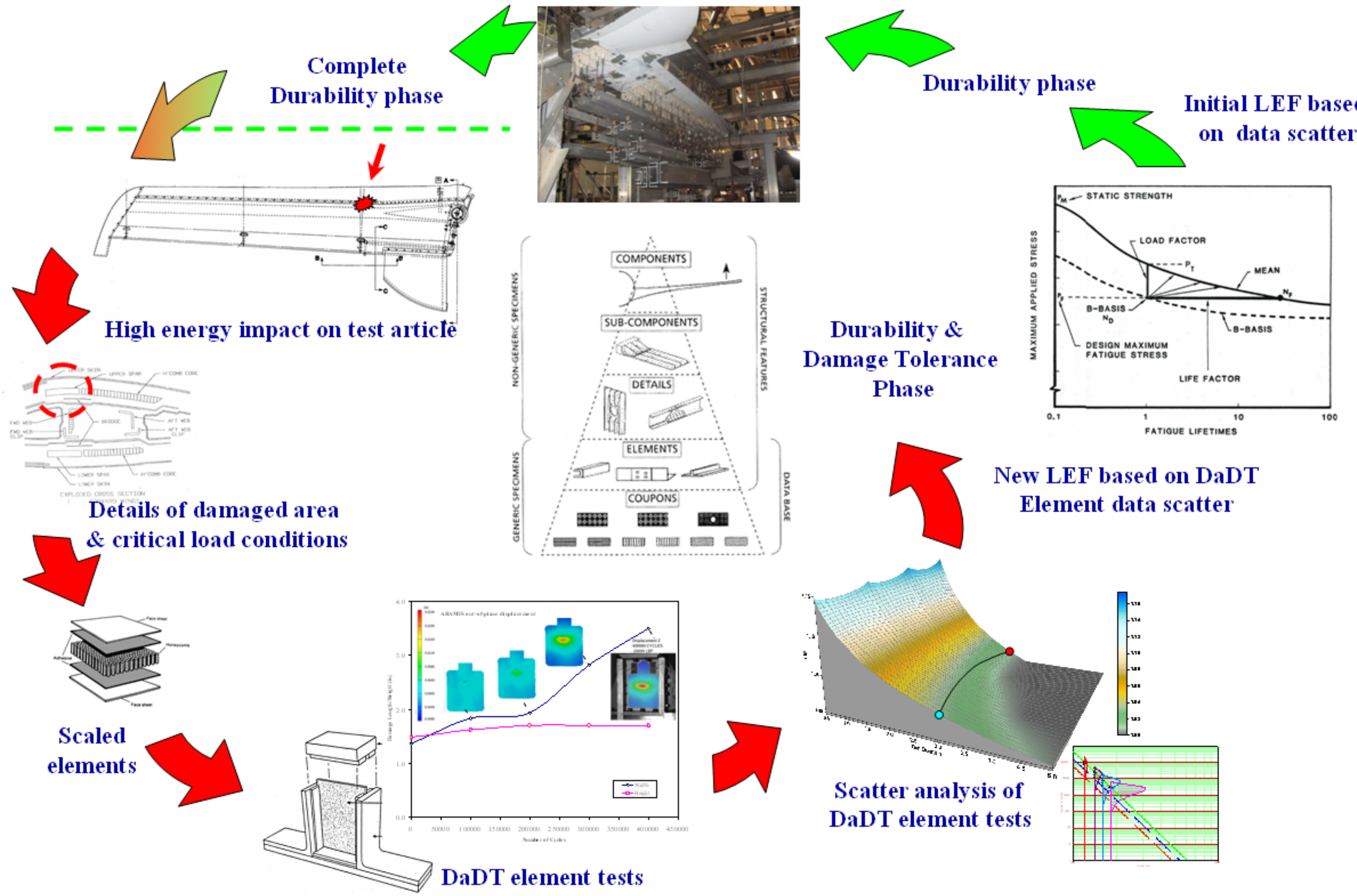
LLD Hybrid Approach



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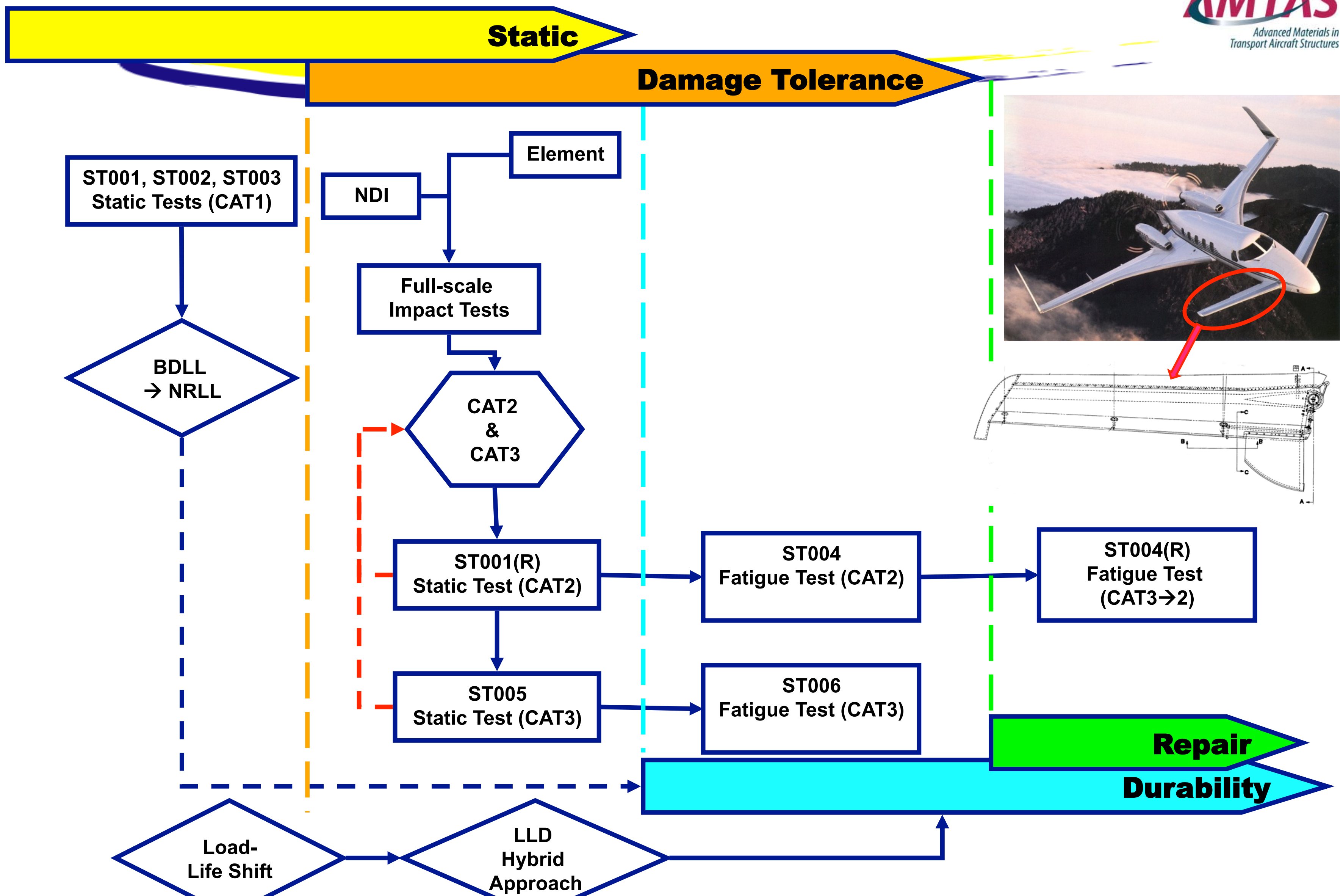
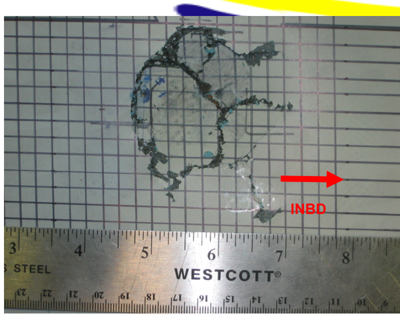
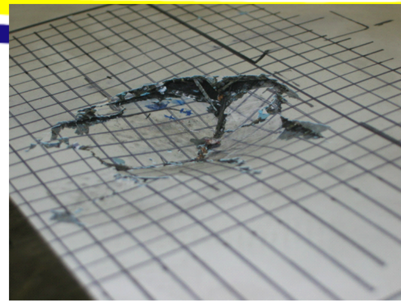
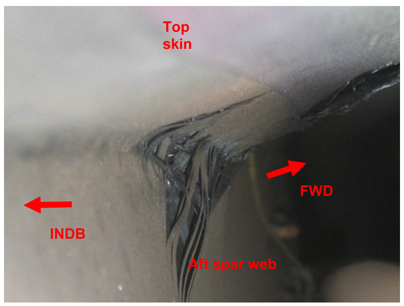
Full-Scale Validation

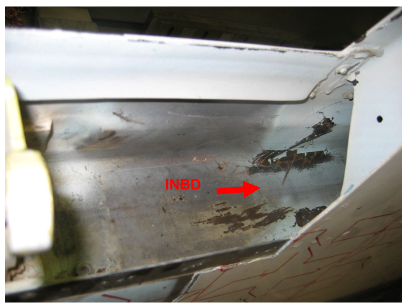


CAT2 – Aft Spar (FWS 45)

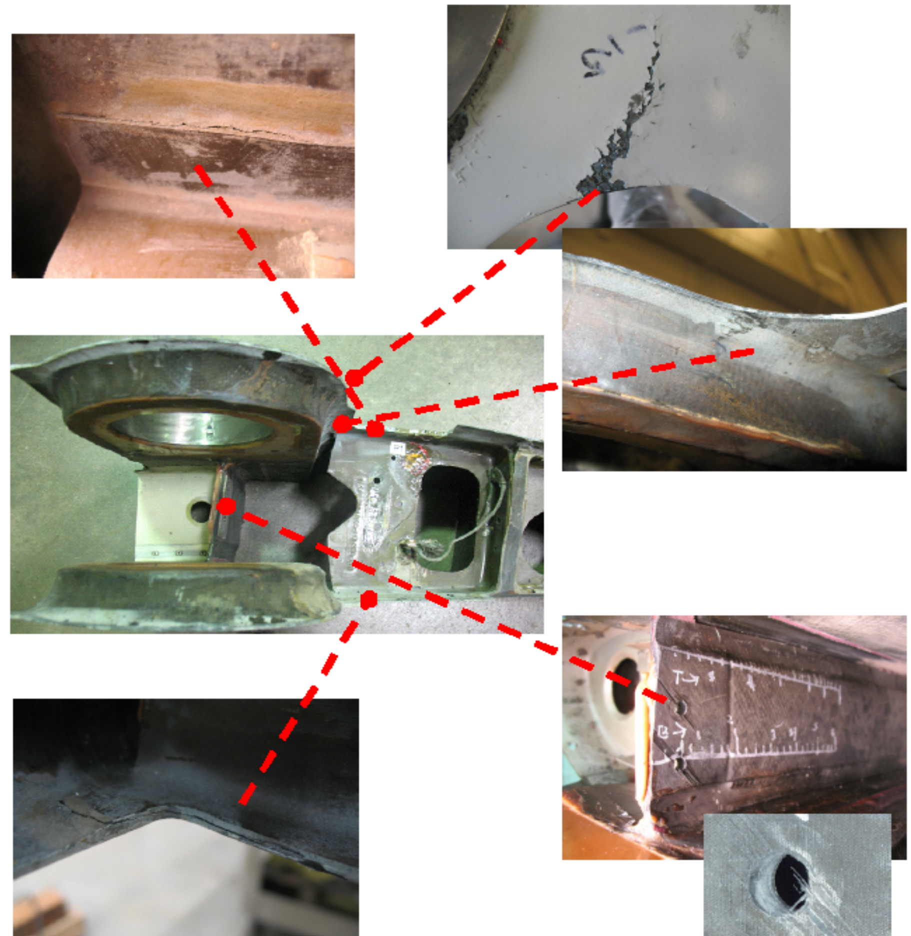


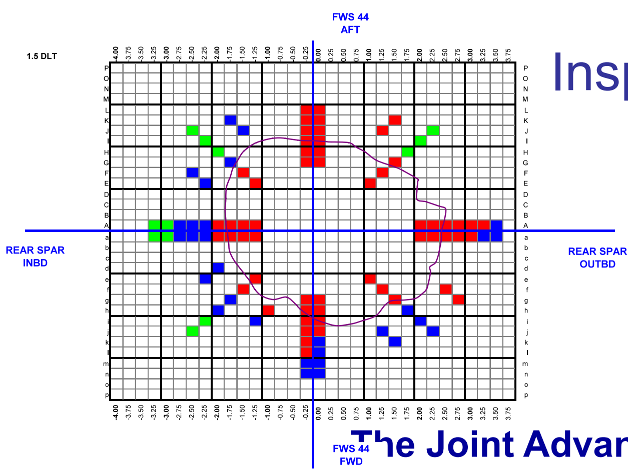






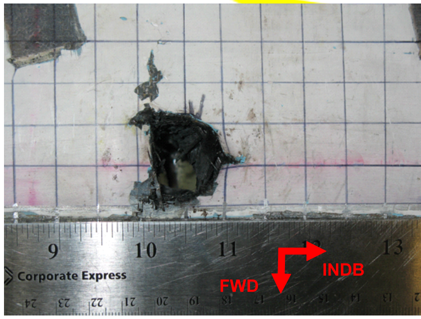
ST004 DaDT (Impact Damage)

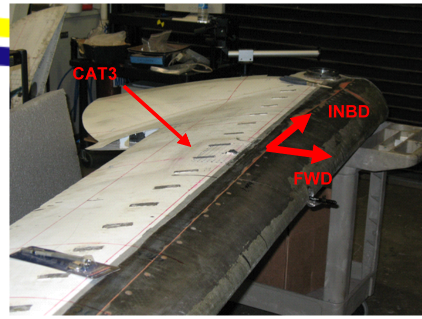




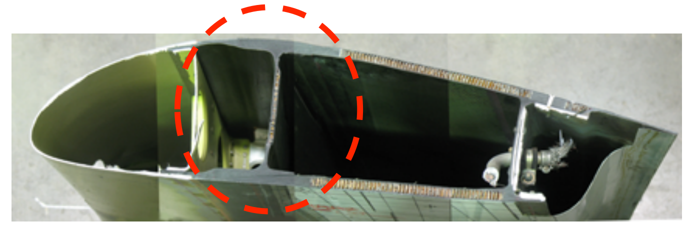
Inspections after 1.5 DLT

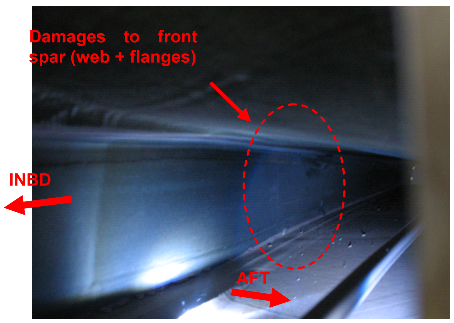
CAT3 – Front Spar (FWS 65)

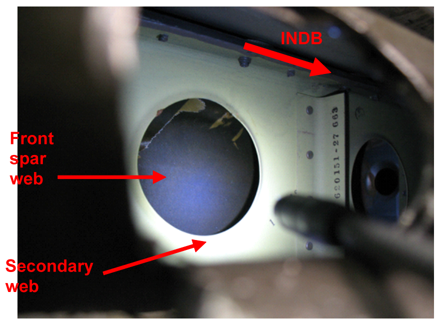


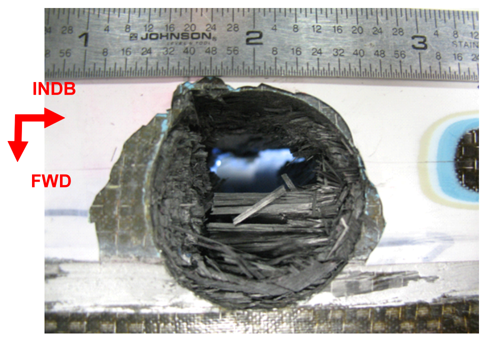


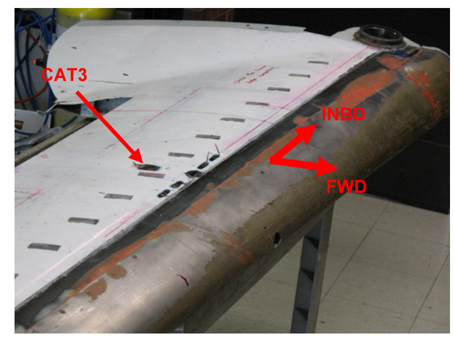
- ST005 Static

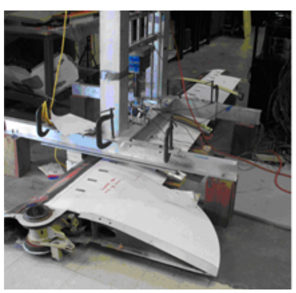


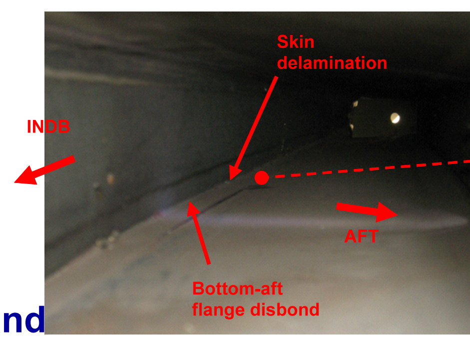


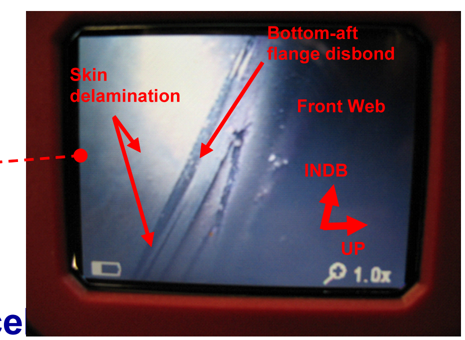






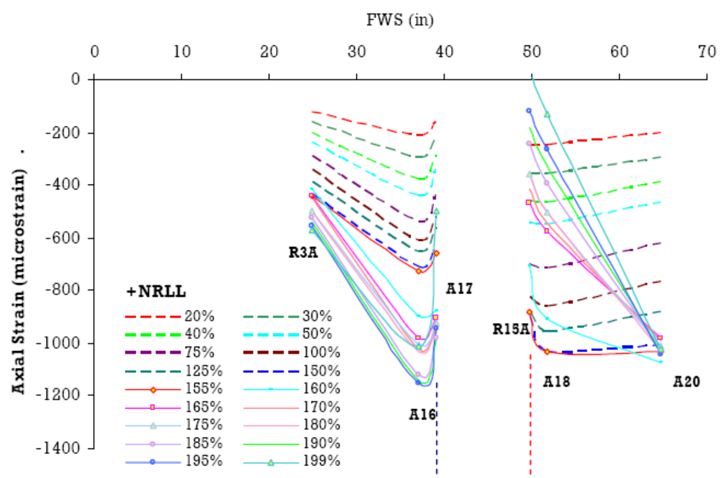


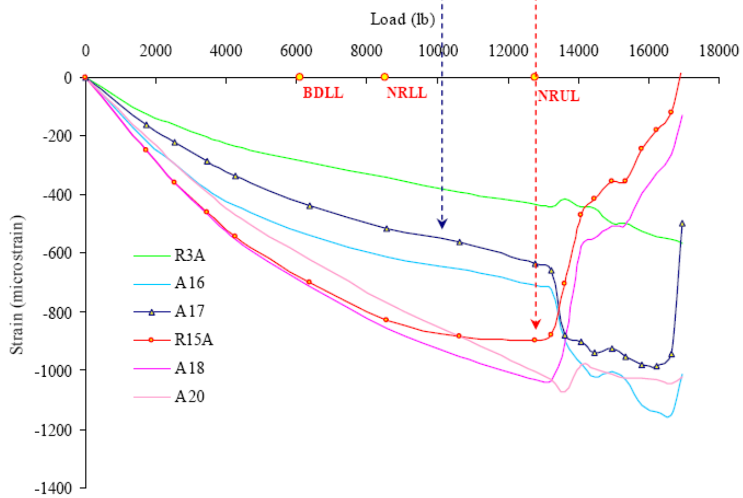


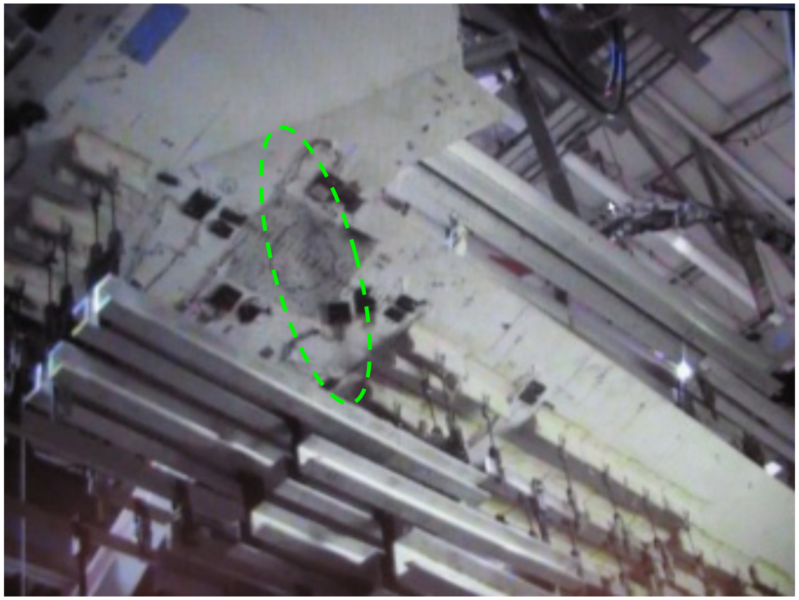


- ST006 DaDT

CAT 2 Residual Strength



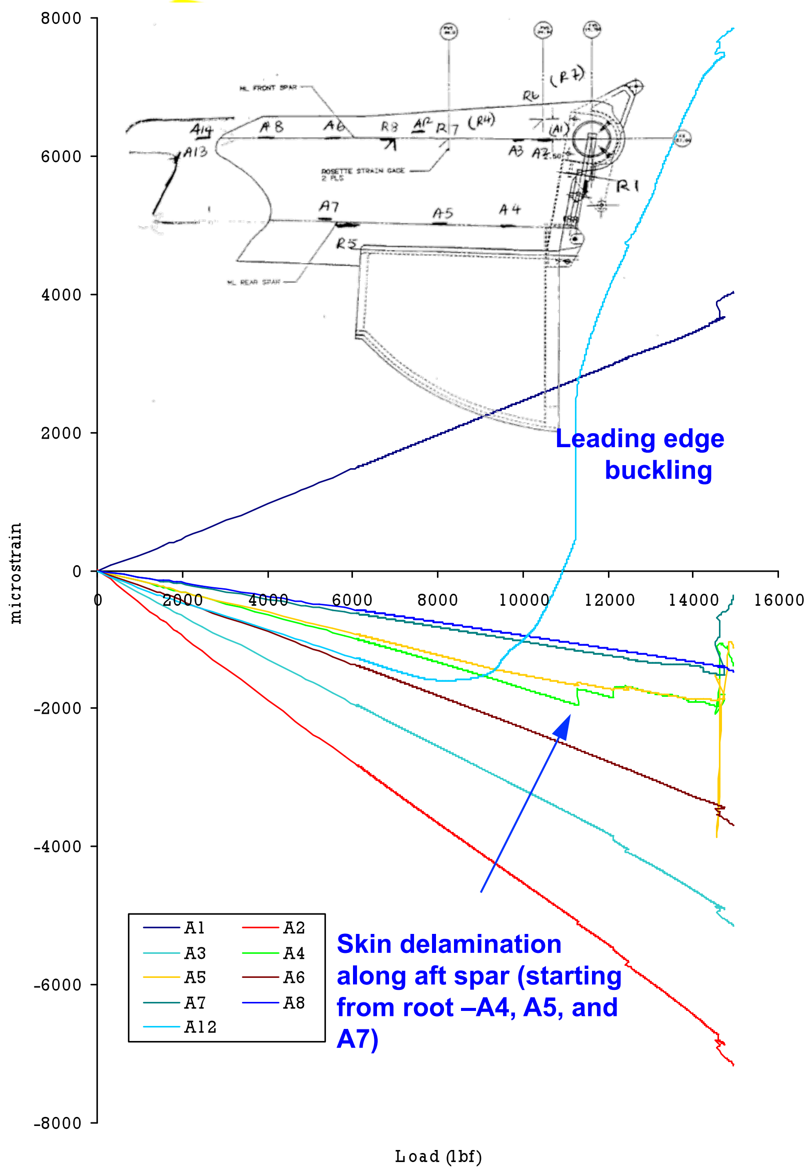


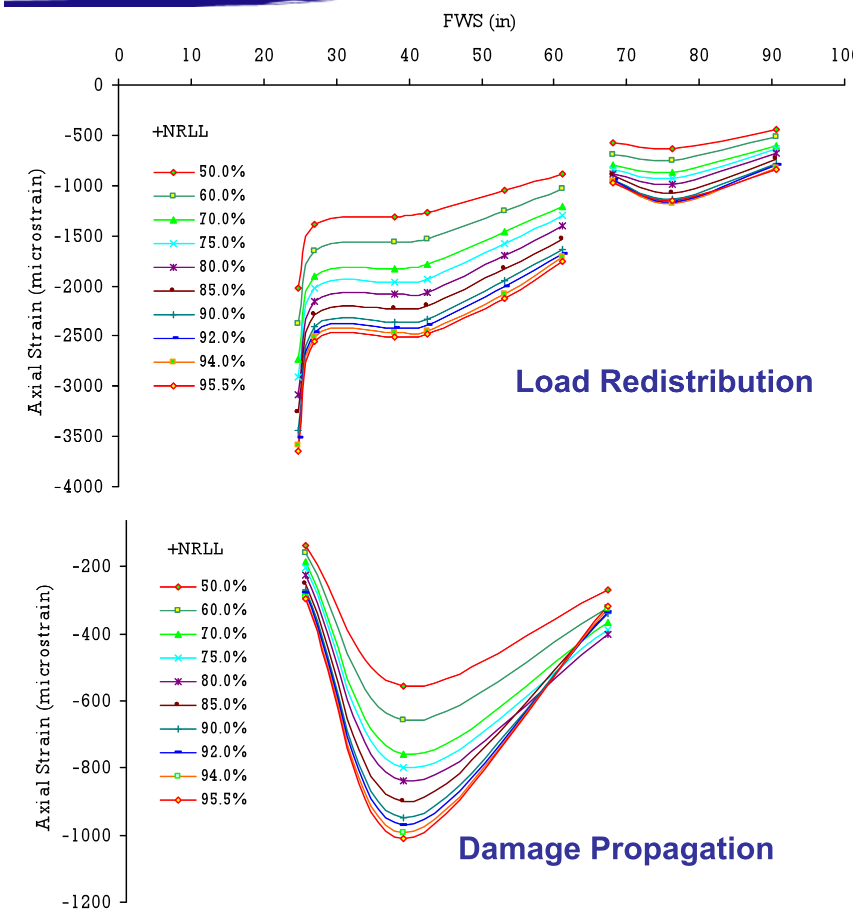


Damage progression along aft spar (top skin) of ST004 (CAT2 damage) during residual strength test after 2-DLT cyclic test with LEF

Large Damage growth across CAT impact damage occur just pass ultimate load (NRUL)

CAT 3 Residual Strength





Fracture across CAT 3 damage just before limit load during residual strength after ½ DLT fatigue test

CUMULATIVE FATIGUE UNRELIABILITY MODEL

Residual Strength Degradation

Inspection Intervals

Full-Scale Test Validation

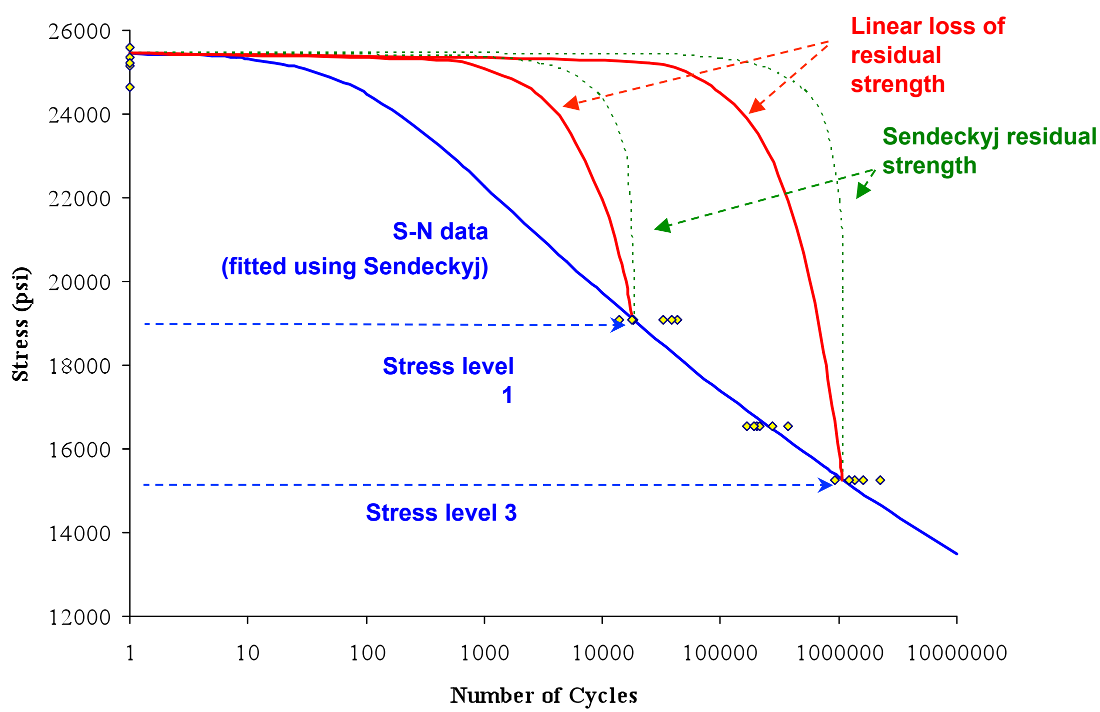
Residual Strength Degradation

- Sendeckyj Wearout Model:

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

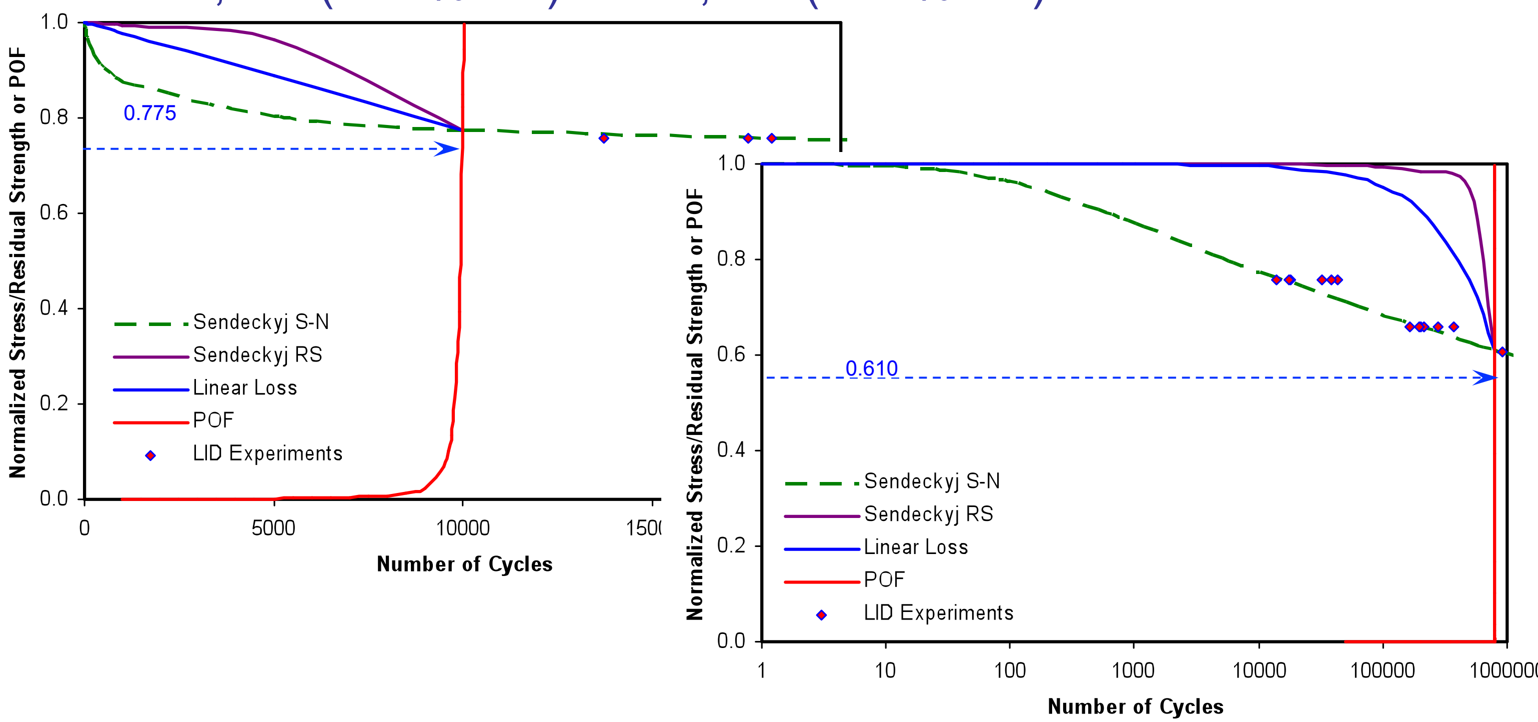
- Linear Loss of Residual Strength:

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

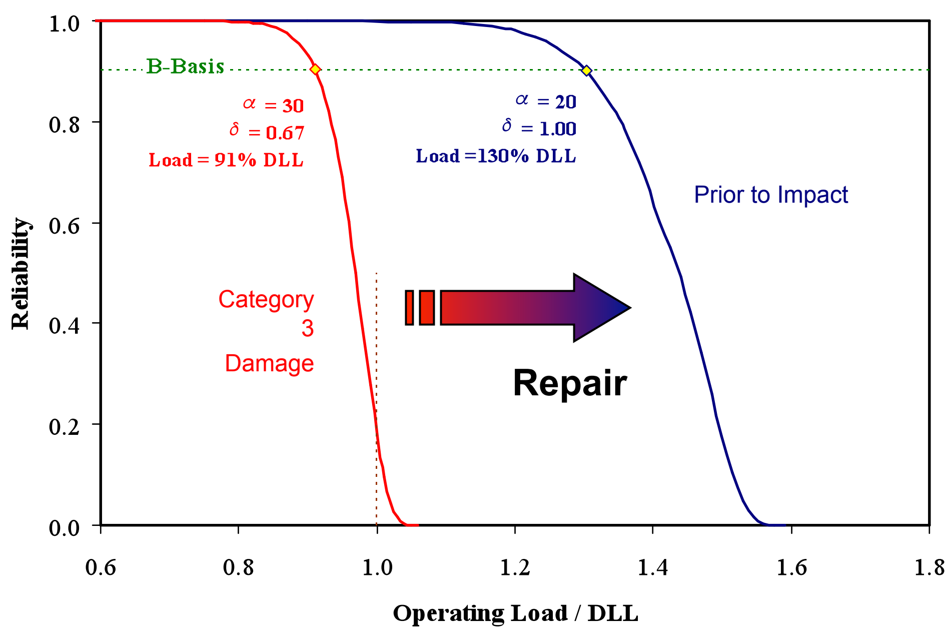


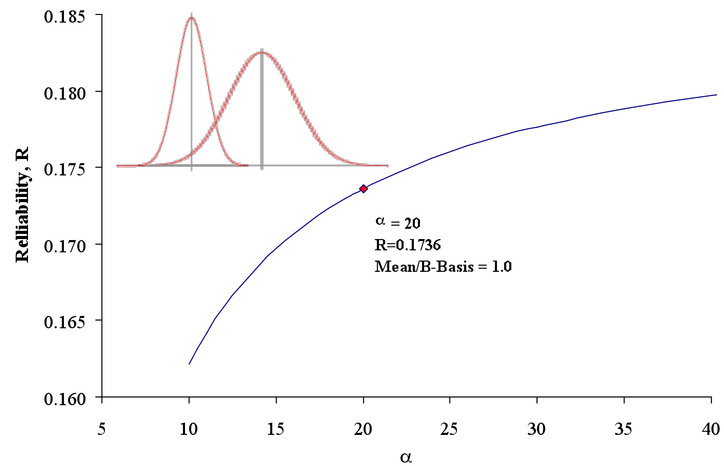
Cumulative Fatigue Unreliability (CFU) Model

- Constant amplitude example (LID)
  - Experimental (Sendeckyj fit for test data):
    - 10,000 (77.5% SS) & 800,000 (61.5% SS)
  - CFU model (Sendeckyj residual strength):
    - 9,625 (77.5% SS) & 799,625 (61.5% SS)



Effects of CAT3 Damage



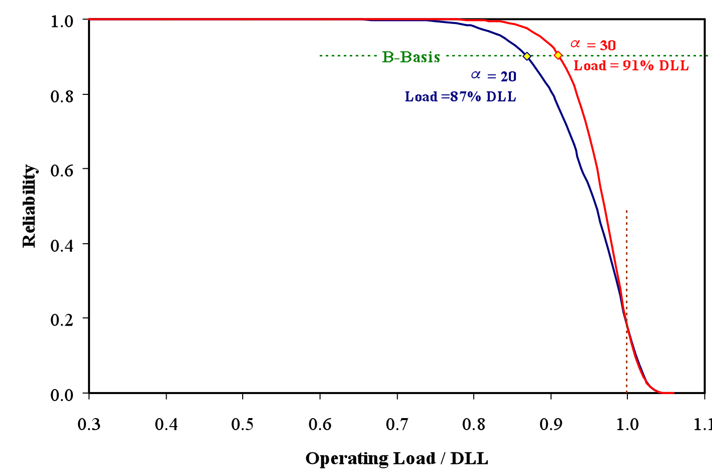


Reliability of Residual Strength after CAT3

Cumulative Fatigue Unreliability

$$P_{f_i} = 1 - \exp\left\{ -\frac{\chi_\gamma^2(2\cdot n)}{2\cdot n} \cdot \left[\frac{\Gamma\left(\frac{\alpha+1}{\alpha}\right)}{\hat{X}_i} \right]^\alpha \right\}$$

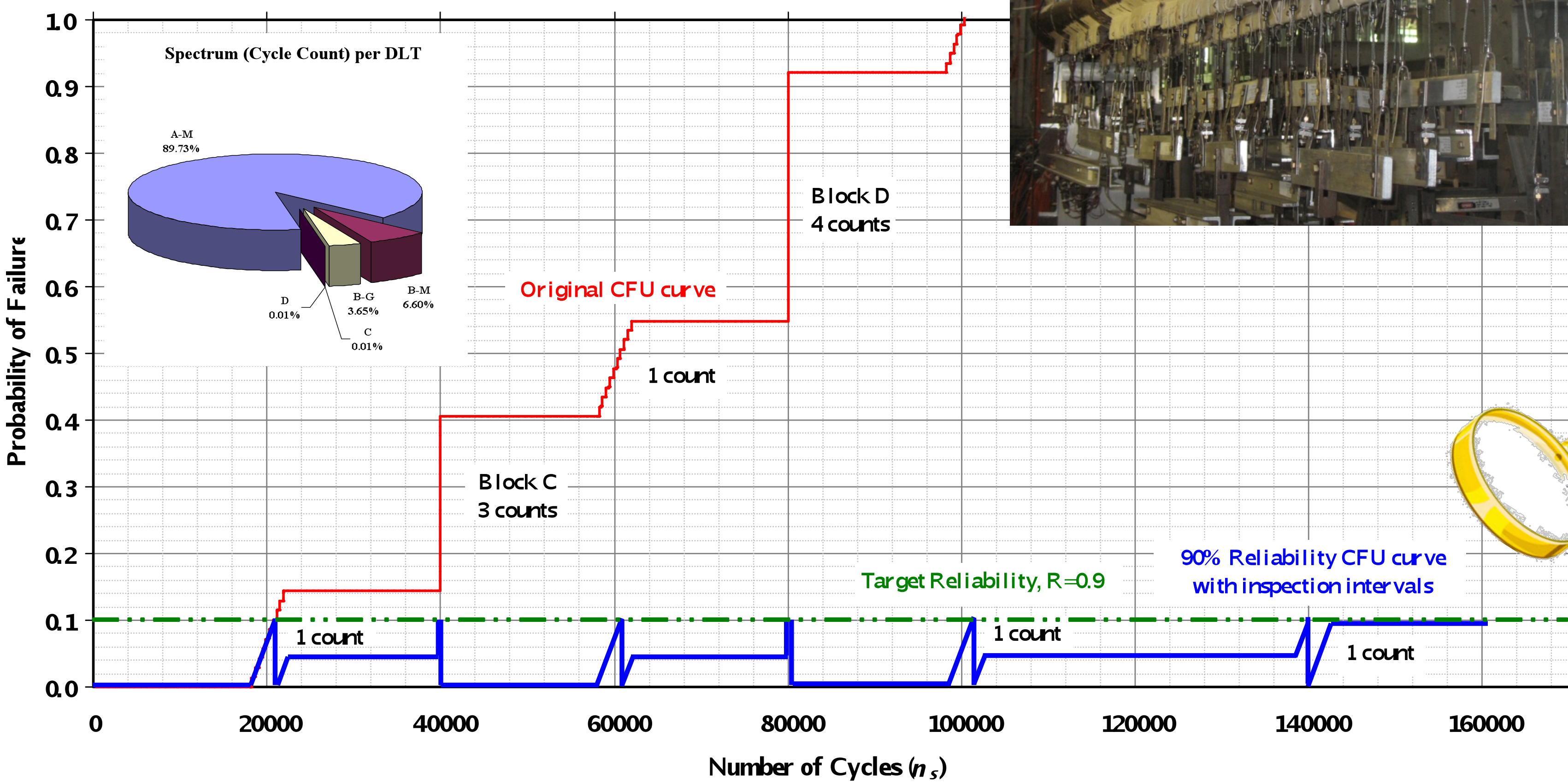
$$P_f = \sum_{i=1}^{n_S} P_{f_i} \quad \Rightarrow \quad P_f \geq 1 - TR \rightarrow Failure$$



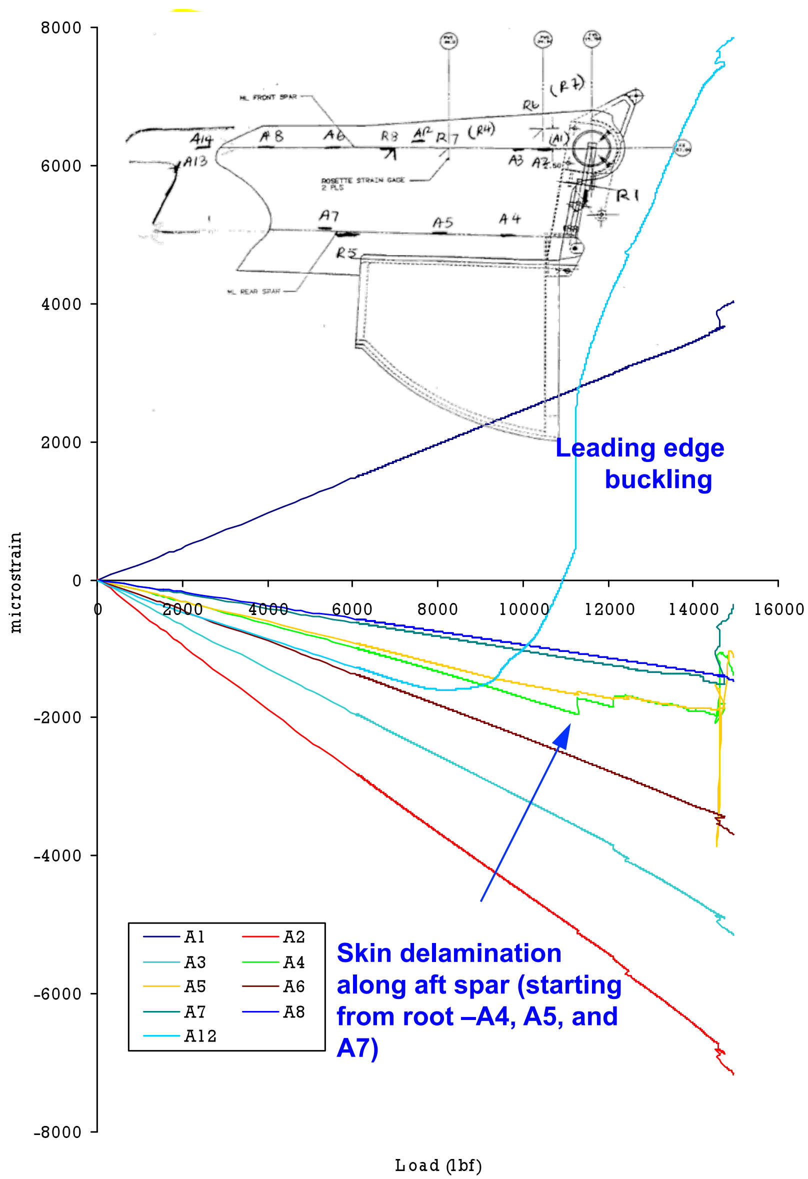
Effects of Shape Parameter of CAT3 Distribution

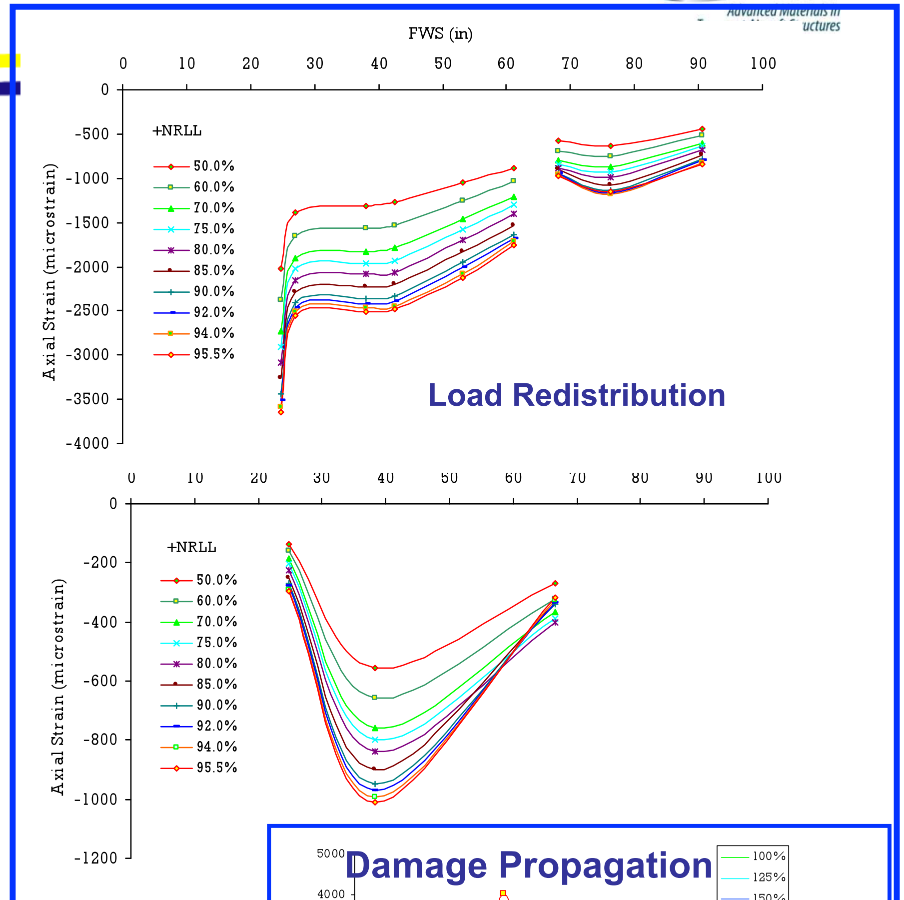
Inspection Intervals

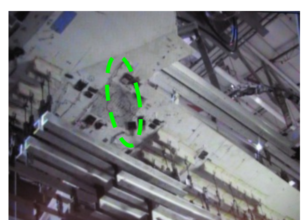
- Target Reliability = 0.90
  - Critical Damage Threshold
  - POF Threshold ➔ 0.10



Health Monitoring & Damage Evolution







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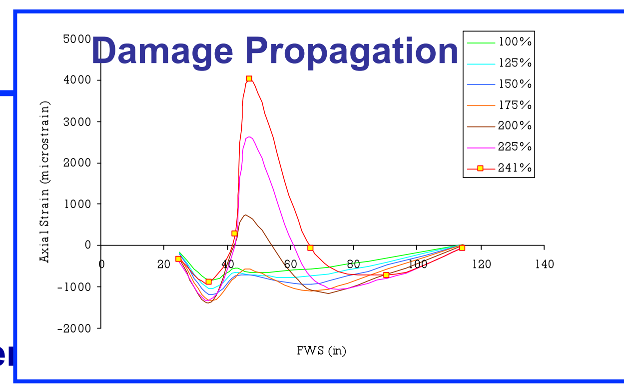
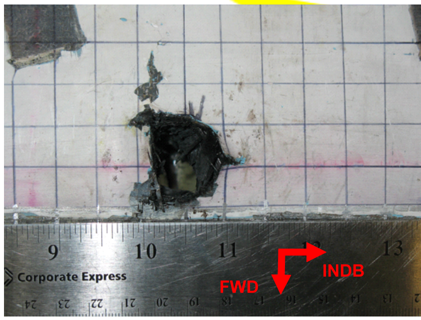
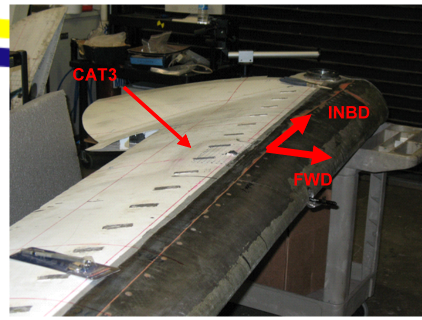
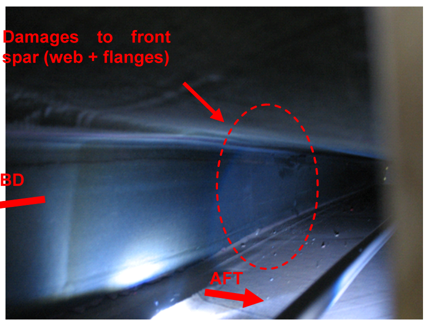
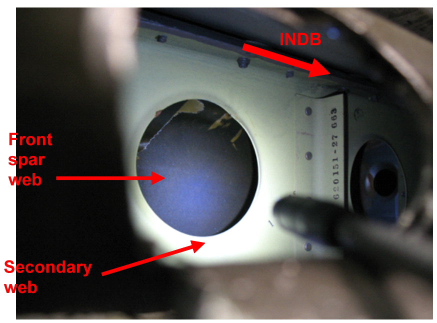


CAT3 – Front Spar (FWS 65)

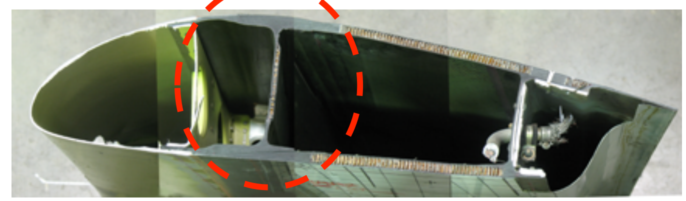


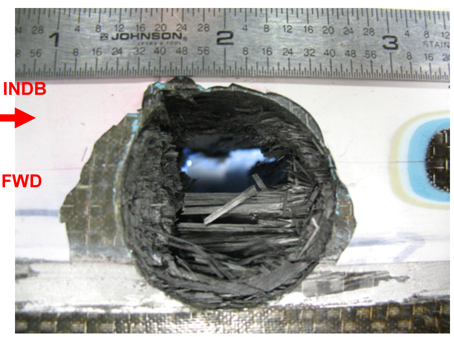


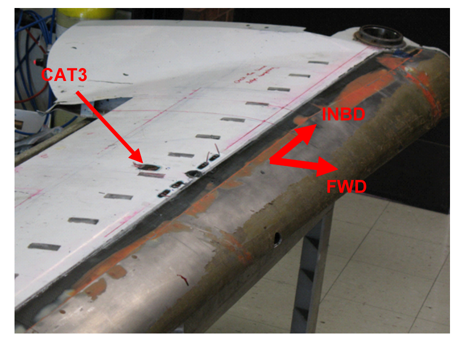


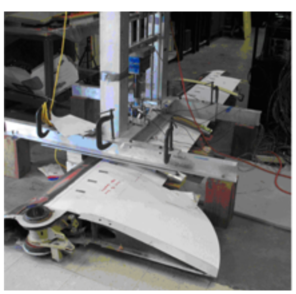


- ST005 Static

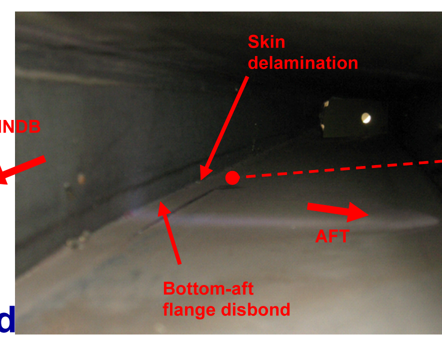


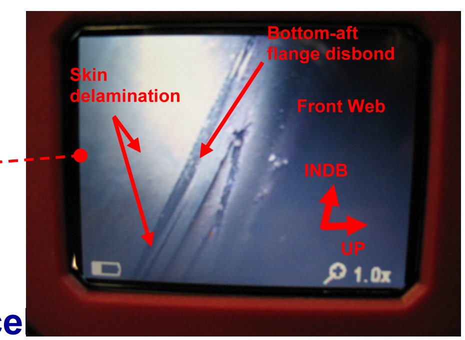




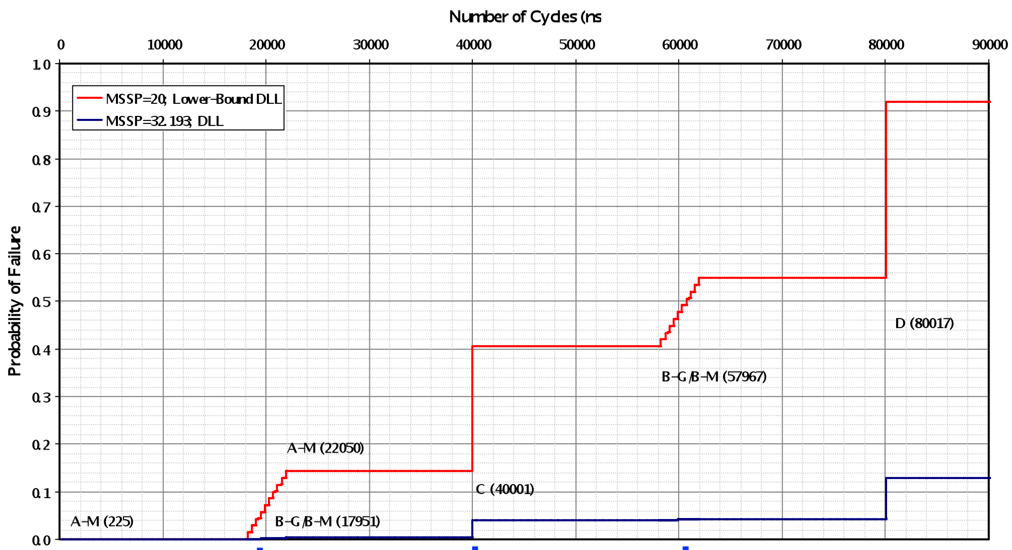


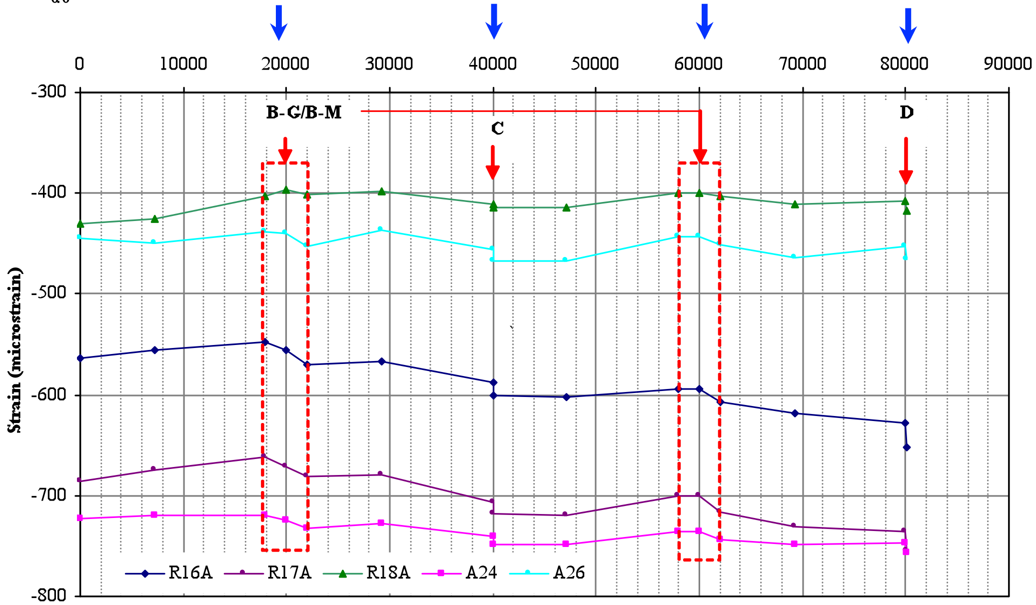
- ST006 DaDT

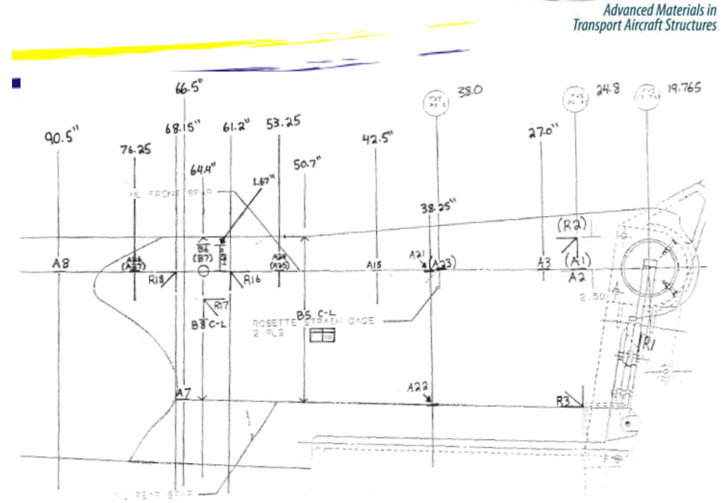


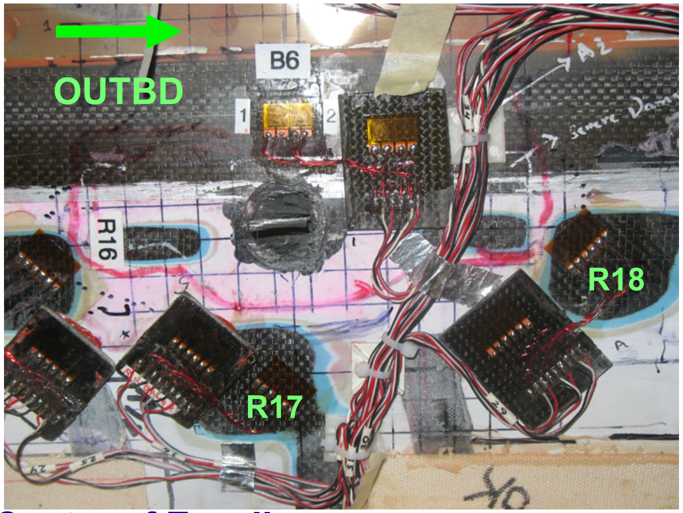


CAT3 DaDT – ST006



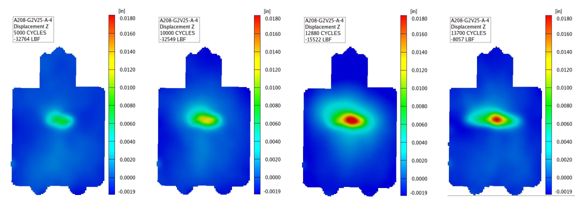


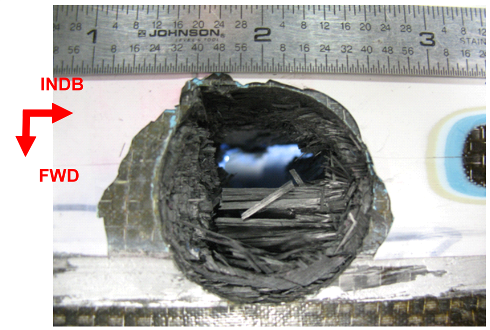




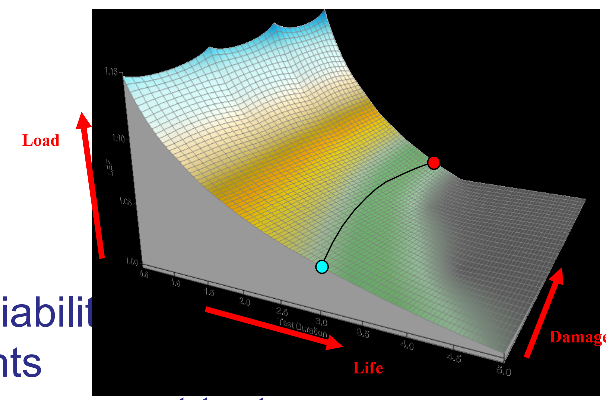
– Summary –

- **Incorporation of damage into scatter analysis**
  - Investigate large VID damage
  - Scaling
  - Detectability





- **Load-Life Shift**
  - Investigate different categories of damages/repairs in the same full-scale test article damage
  - Design change substantiation, i.e. gross weight increase
  - LEF during certification vs. improved LEF
  - Life extension or determination of retirement life
- **Damage Threats and Inspections**
  - Probability of threats/occurrences
  - Probability of detectability
  - Mitigate risks of unintentional failure
    - Inspection intervals using CFU model (cost and reliabilit
    - Strategic placement of health monitoring equipments
    - Progressive damage analysis (NLFEA) or scaled component tests



A Look Forward

- Benefit to Aviation
  - Guidelines on developing LEF and application
  - Database of shape parameter for currently-used composites
  - Enhanced certification approach (economical and time saving) that allows investigating the effects of extremely-improbable high-energy impact threats
  - Incorporating certain design changes into full-scale substantiation without the burden of additional time-consuming and costly tests
- Future needs
  - Develop cumulative fatigue unreliability (CFU) model for field inspections
  - Model development for damage analysis of composites