Durability & Damage Tolerance Testing and Analysis Protocols for Composite Structures

Life Factor, Load-Enhancement Factors, and Fatigue Life

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NIAR
RESEARCH / DESIGN / TESTING / CERTIFICATION

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 of Composite

Static Scatter

Fatigue Scatter

Life Factor

Load Enhancement Factors

Load-Enhancement Factor Approach

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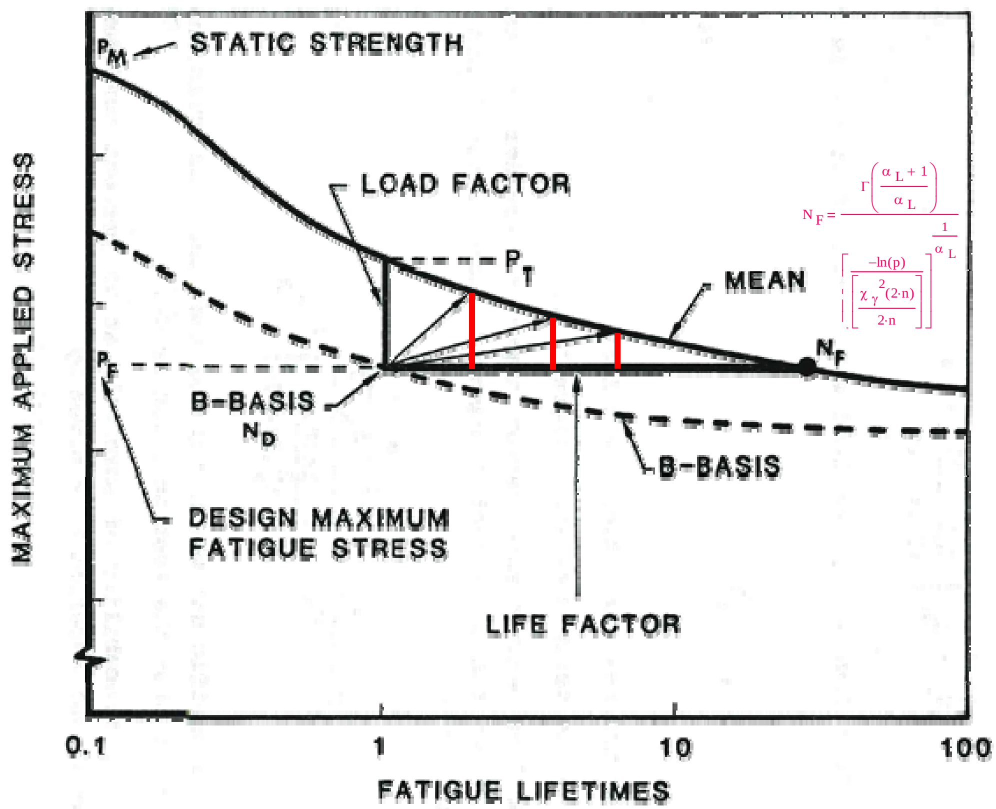
- Increase applied loads in fatigue tests so that the **same level of reliability** can be achieved with a shorter test duration



- Load (Scatter) Factor

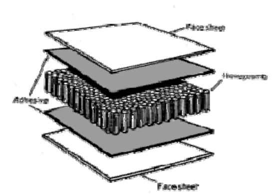
$$LF = \lambda \cdot \frac{\Gamma\left(\frac{\alpha_R + 1}{\alpha_R}\right)}{\left[\frac{-\ln(R)}{\left[\chi_\gamma^2(2n) / 2n\right]}\right]^{1/\alpha_R}}$$

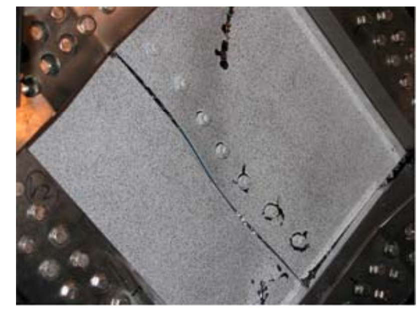
- Load Enhancement Factor (LEF)

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

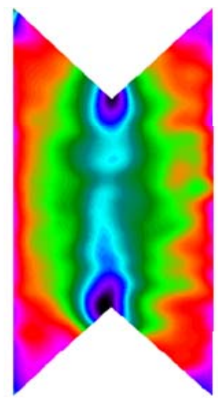
Material Databases

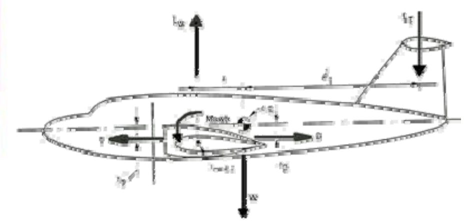
- LEF
  - » AS4/E7K8 **(457/17)**
  - » T700/#2510 PW **(240/7)**
  - » 7781/#2510 8HS **(204/7)**



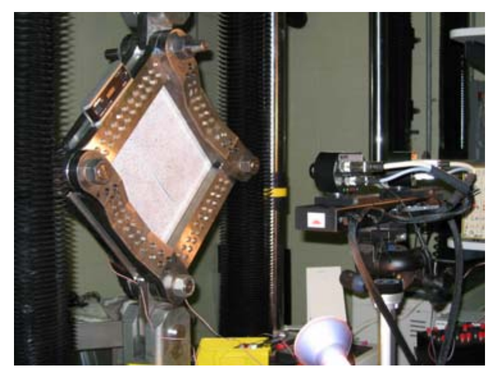


- Laminate Data
  - » T700/#2510 UNI **(853/47)**
  - » T700/#2510 PW **(863/48)**
  - » T700/E765 UNI **(834/47)**
  - » T300/E765 PW **(722/48)**
  - » AS4C/MTM45 UNI **(1151/86)**
  - » AS4C/MTM45 8HS **(1083/78)**

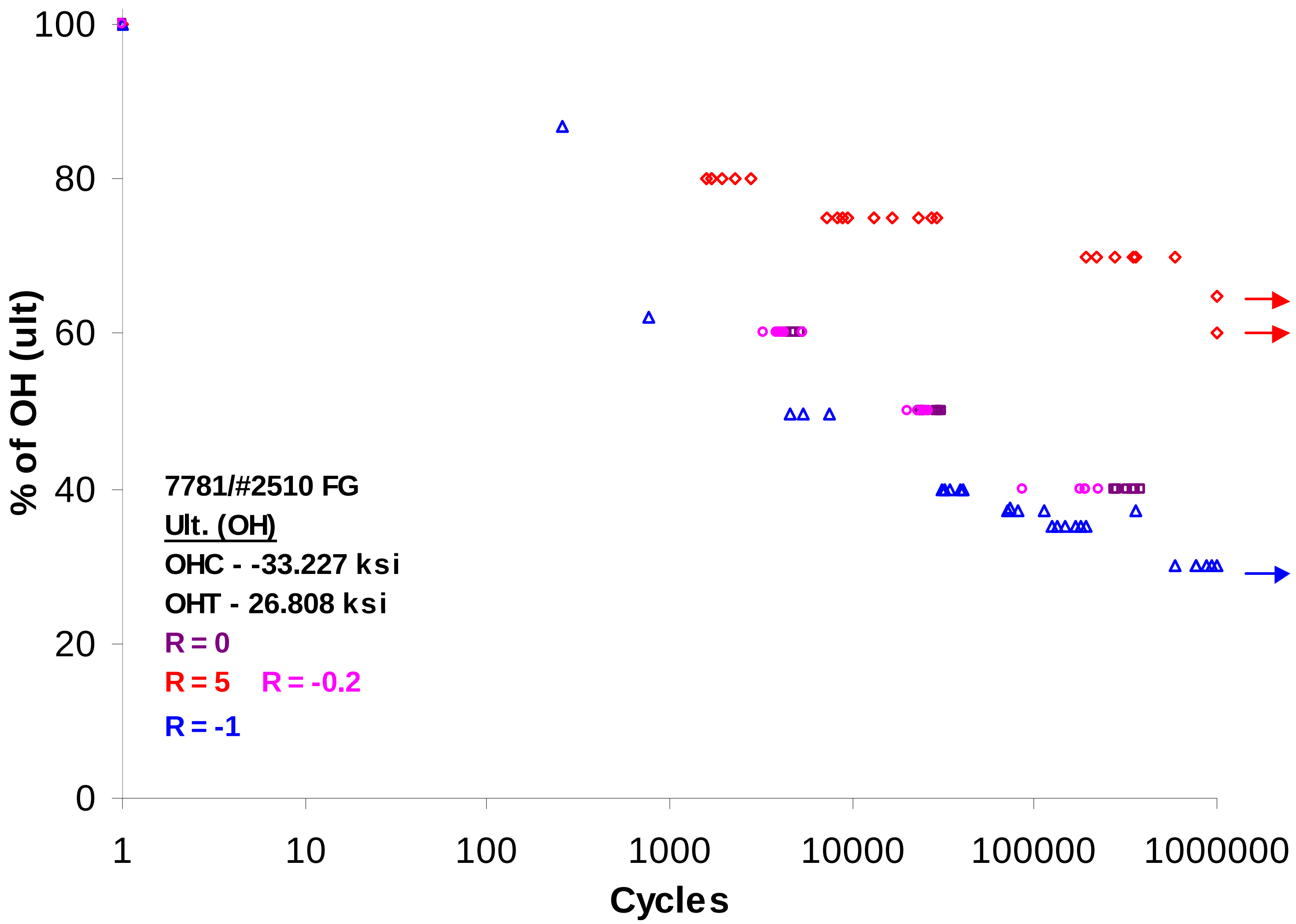




- Adhesive Fatigue **(390 spec./12 data sets)**
  - » Loctite Paste
  - » PTM&W paste (2 bondline thicknesses)
  - » EA 9696 film
- Adhesive Effects of Defects
  - » T700/#2510 PW & EA9394 –PFS **(70/6)**
  - » T700/3900-2 PW & EA9394 (SLS) **(20)**
  - » T800/3900-2 UNI & EA9394 (SLS) **(20)**
  - » 7781/NB321 8HS & EA9394 (SLS) **(20)**



Sample S-N Curves (contd..)



Fatigue Scatter Analysis Techniques

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- Individual Weibull
- Joint Weibull

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

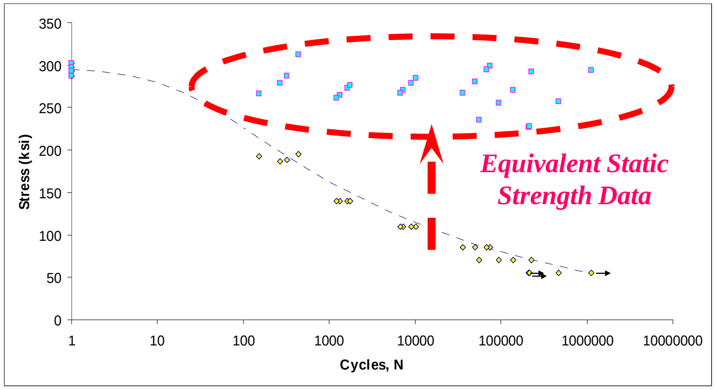
- Sedeckyj Equivalent Strength Model

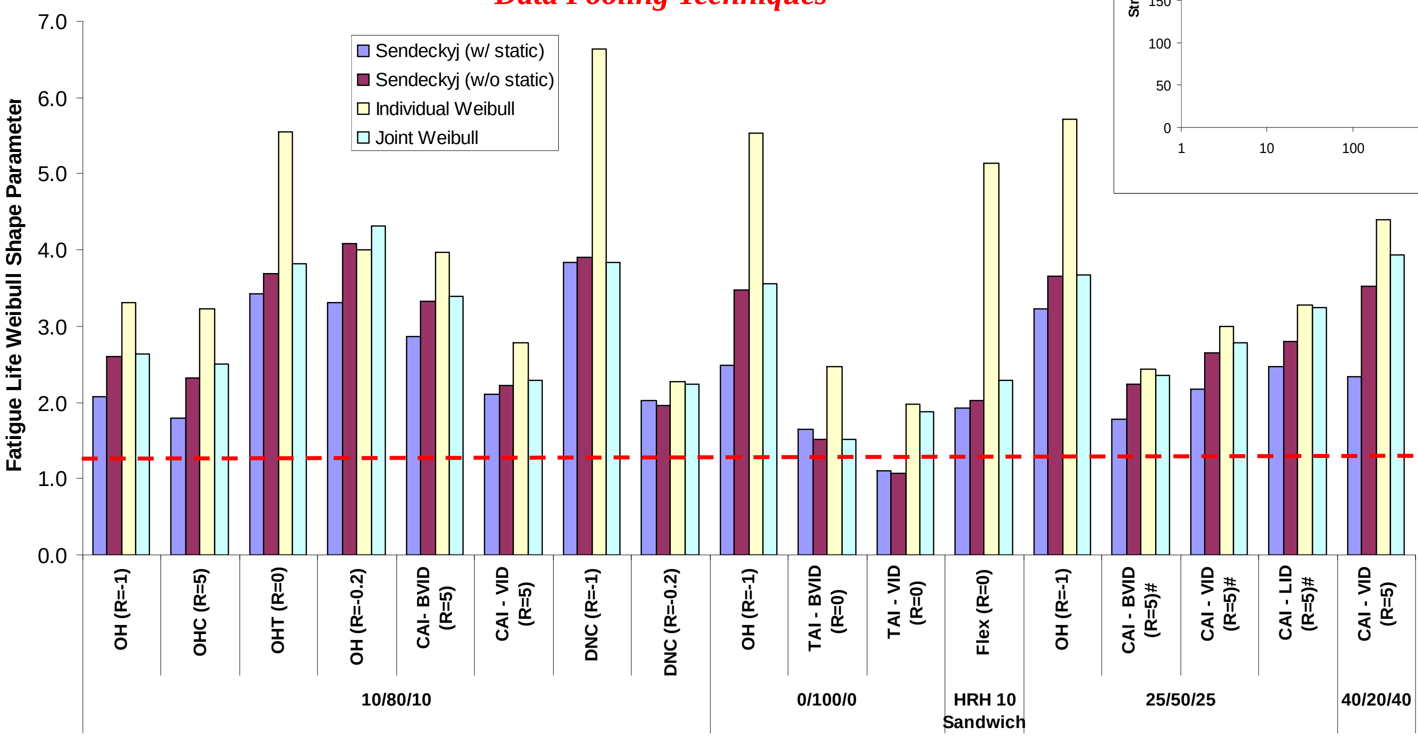
$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

Data Pooling Techniques

NADC Fatigue Scatter Analysis

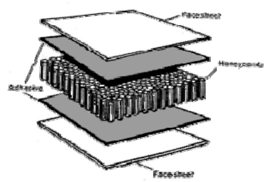
$$\alpha_I > \alpha_J > \alpha_S$$

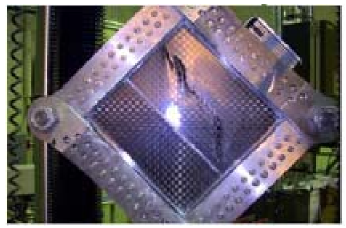


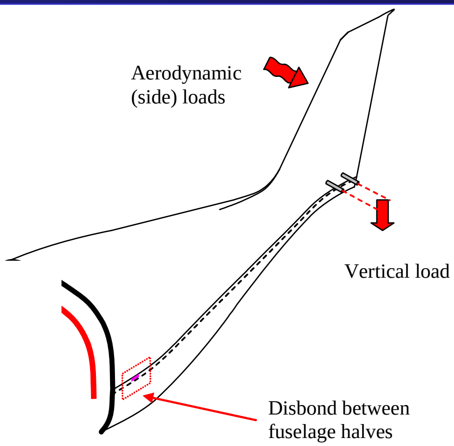


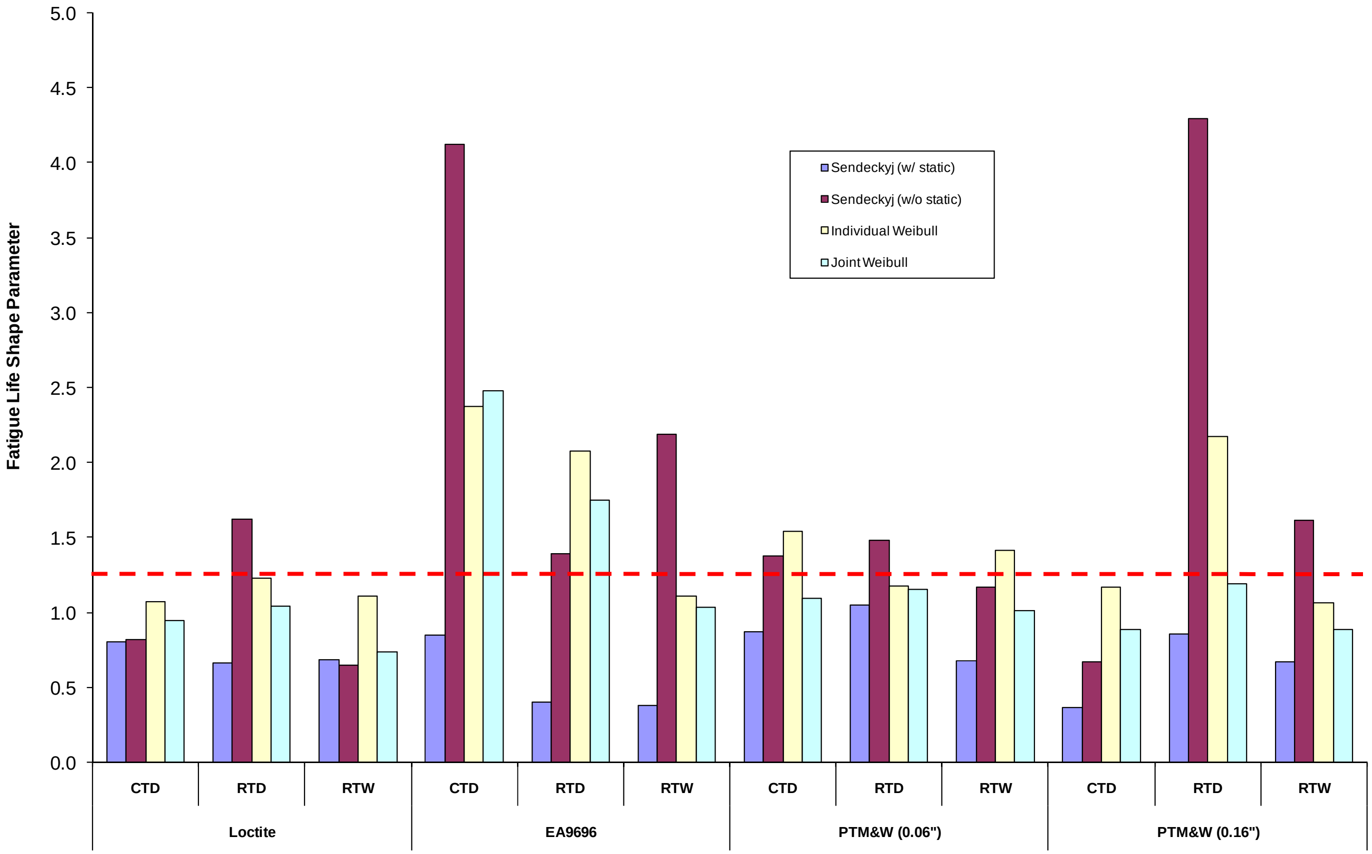
AS4/E7K8 PW

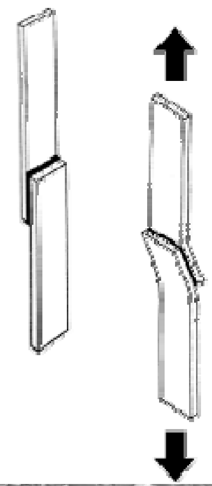
Adhesive Fatigue Scatter

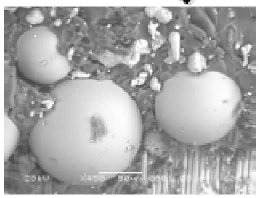












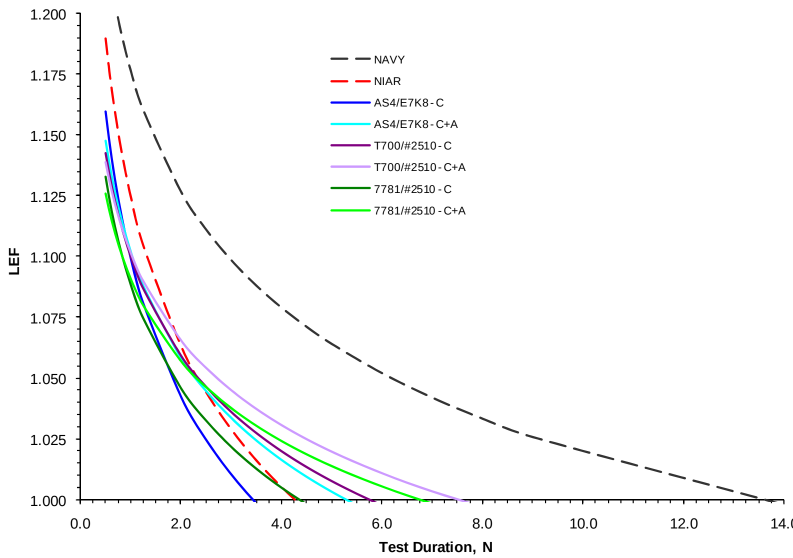
2nd Generation
Weibull Shape Parameters

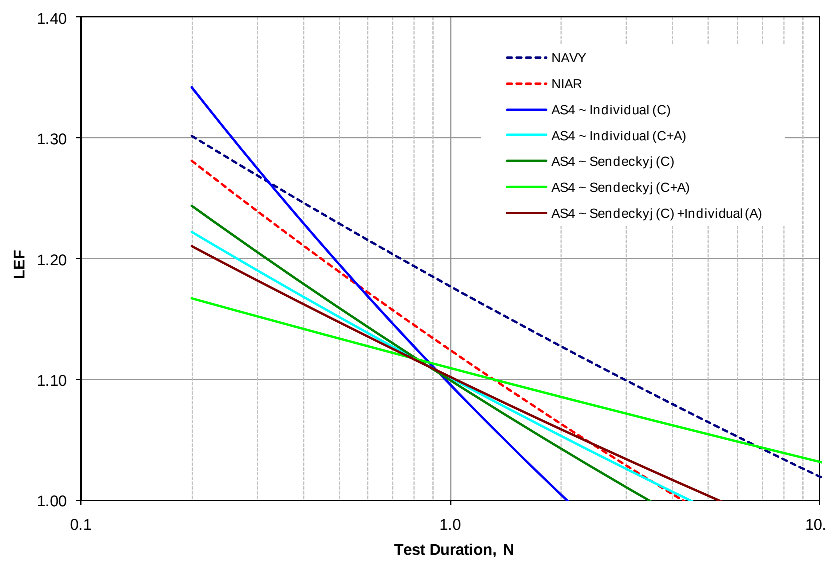
			α Sendeckyj (w/static)	α Sendeckyj (w/o static)	α Individual Weibull (w/o static)	α Joint Weibull (w/o static)
Pooled - Composite	MLE	α	3.342	1.826	1.8255	1.910
		β	2.408	3.291	4.6023	3.435
		α Modal	**2.165**	**2.131**	**2.980**	**2.330**
	RRX	α	3.900	2.674	2.8007	2.896
		β	2.371	3.150	4.3619	3.280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

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

Maximum Likelihood Estimation

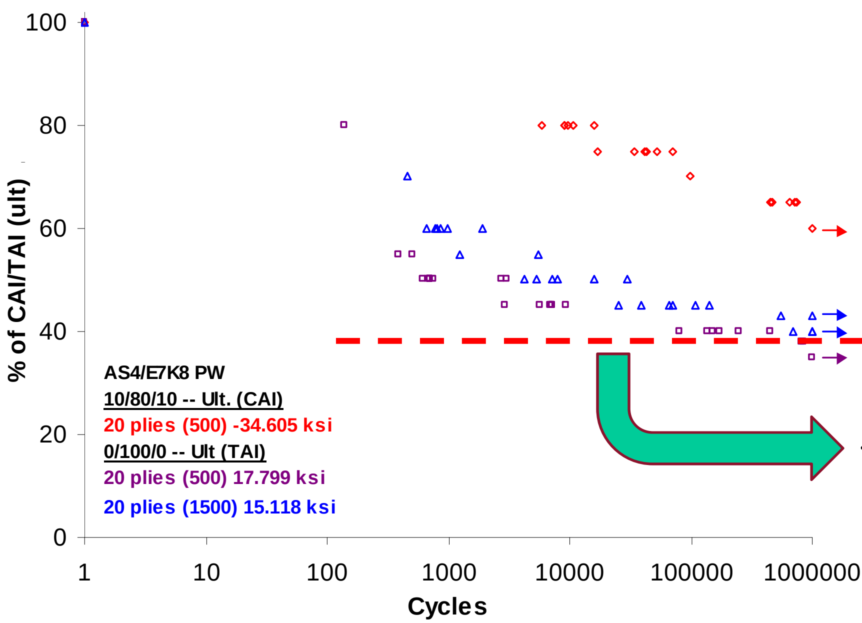
# of Lives (N)	**NAVY**	**NIAR**
1.00	**1.177**	**1.125**
1.50	**1.148**	**1.088**
2.00	1.127	1.063
2.50	1.111	1.044
3.00	**1.099**	**1.029**
3.50	1.088	1.016
4.00	1.079	1.005
4.25	1.075	1.000
4.50	1.071	
5.00	1.064	
6.00	1.052	
7.00	1.042	
8.00	1.034	
9.00	1.026	
13.60	1.000	

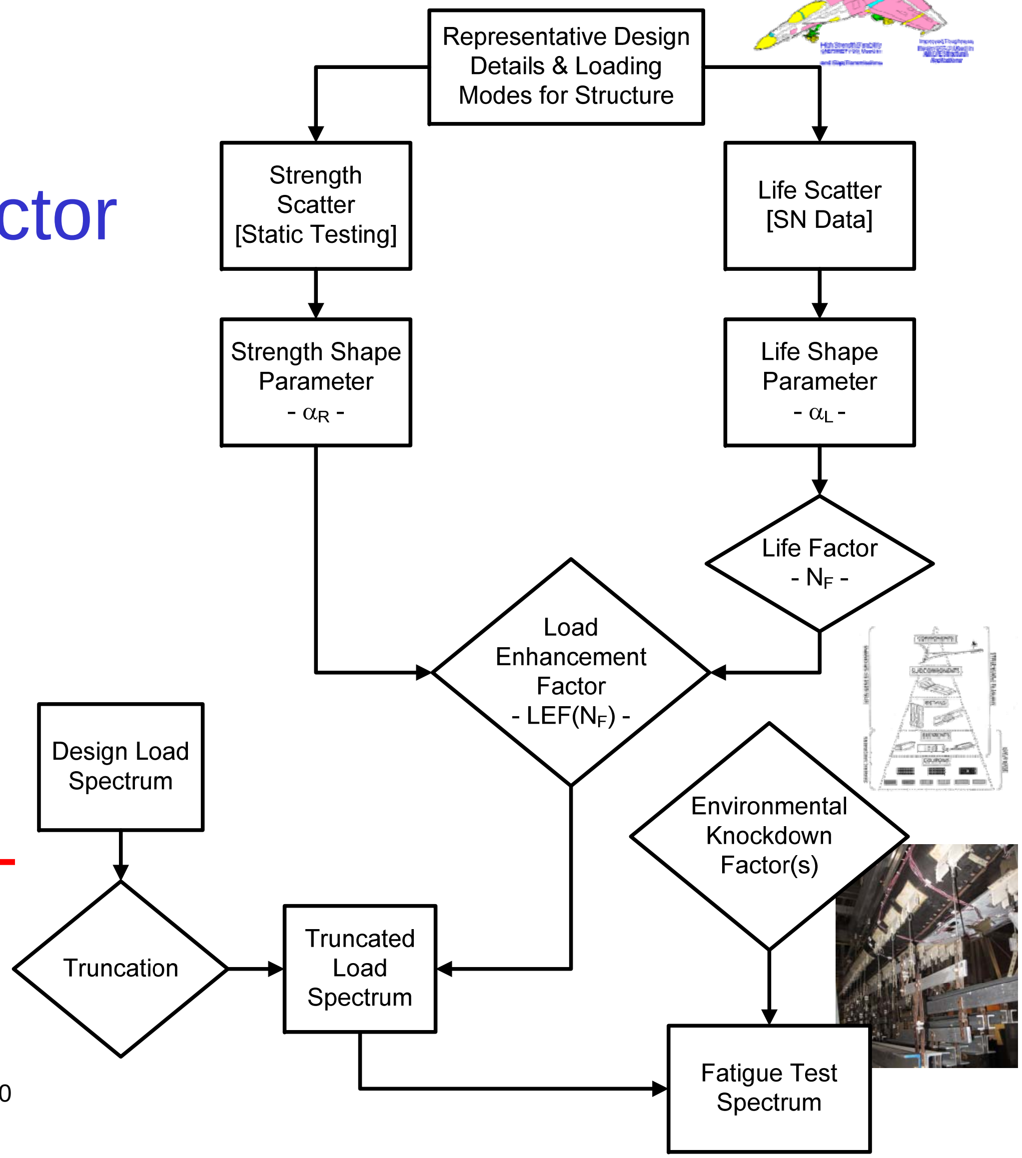




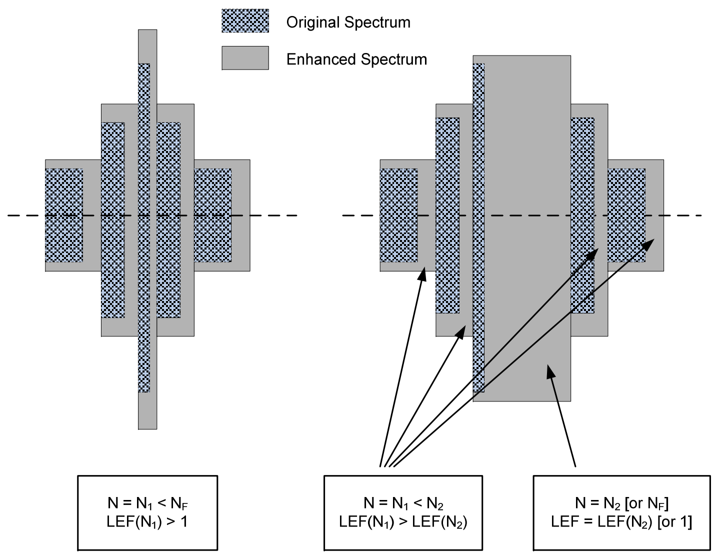
Test Spectrum Generation

- Life factor
- Load-enhancement factor
- Truncation levels
- Environmental factors





Application of LEF / N_F



(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

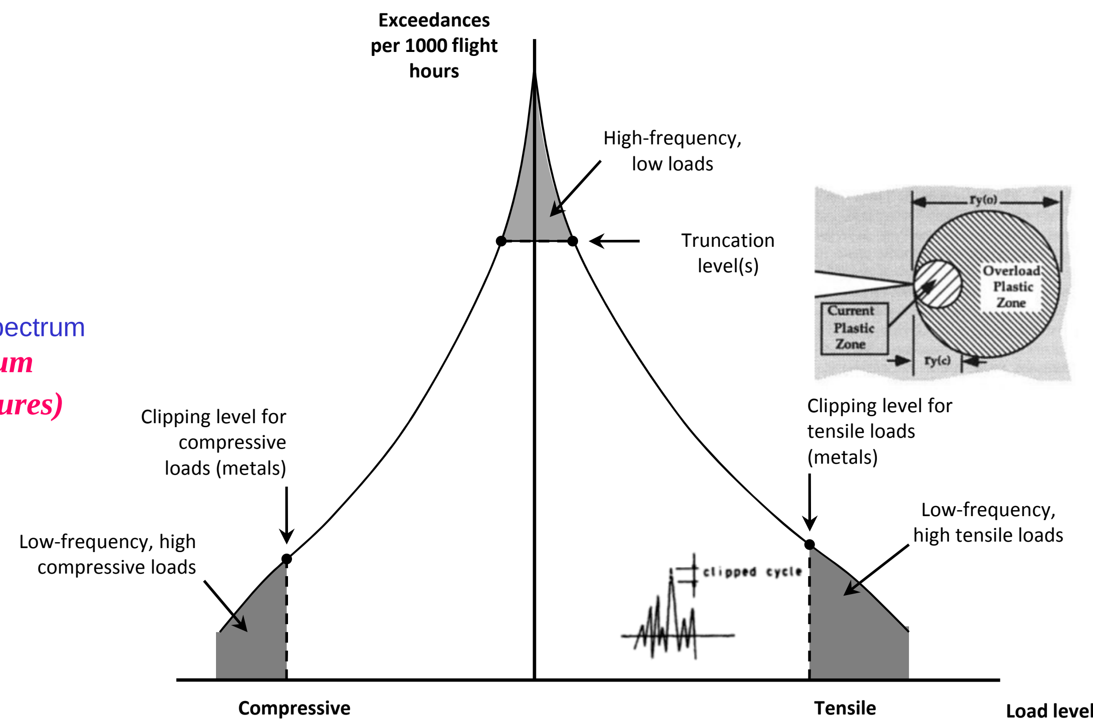
Hybrid Structural Substantiation

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***



Load-Life-Damage Hybrid Approach

LLD Overview

Load-Life Shift

Application of LLD

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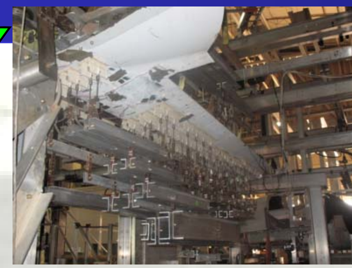
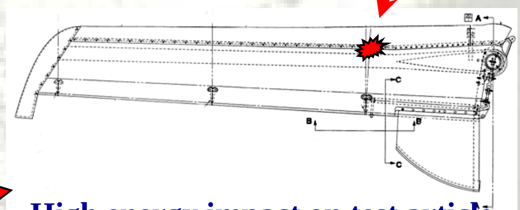
LLD Hybrid Approach



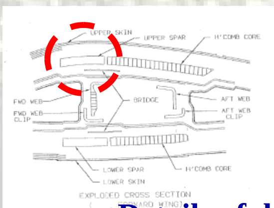
Complete Durability phase

Durability phase

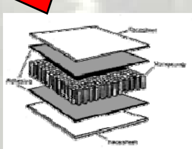
Initial LEF based on data scatter



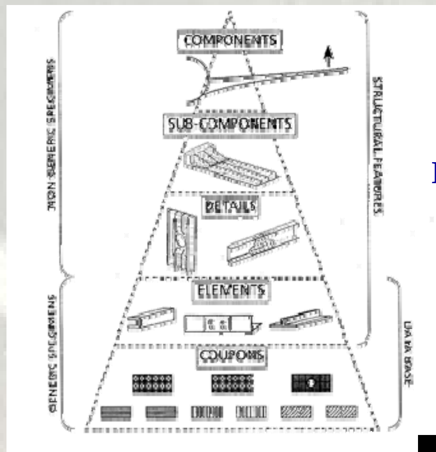
High energy impact on test article



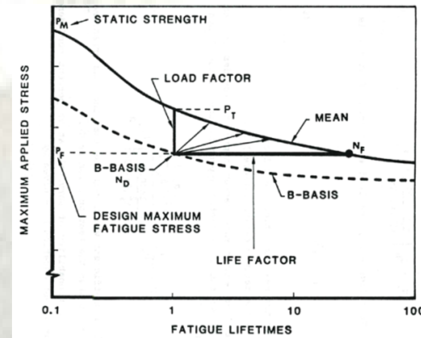
Details of damaged area & critical load conditions



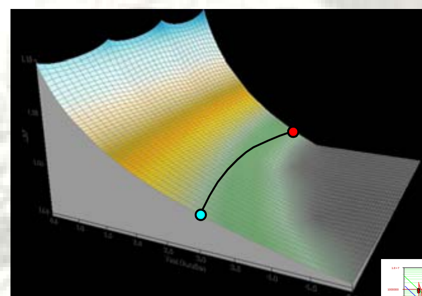
Scaled elements

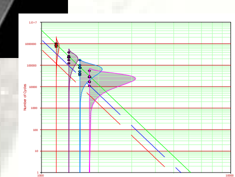


Durability & Damage Tolerance Phase

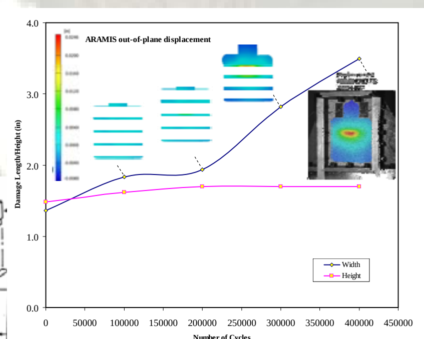


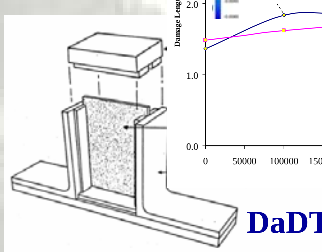
New LEF based on DaDT Element data scatter





Scatter analysis of DaDT element tests





DaDT element tests

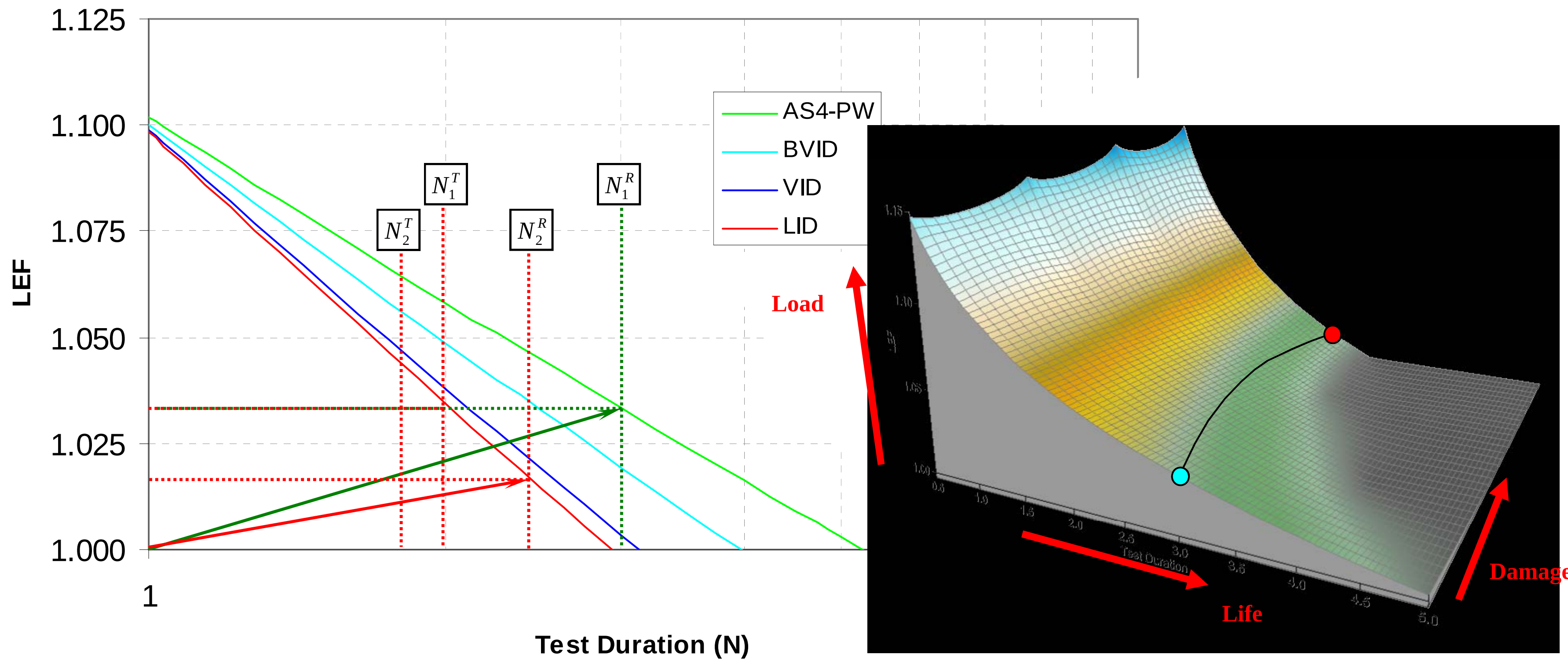
Load-Life Shift

- 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



Composite Test Issues

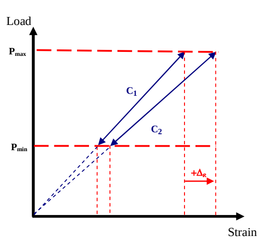
Progressive Failure

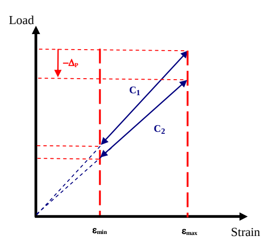
Flow Growth

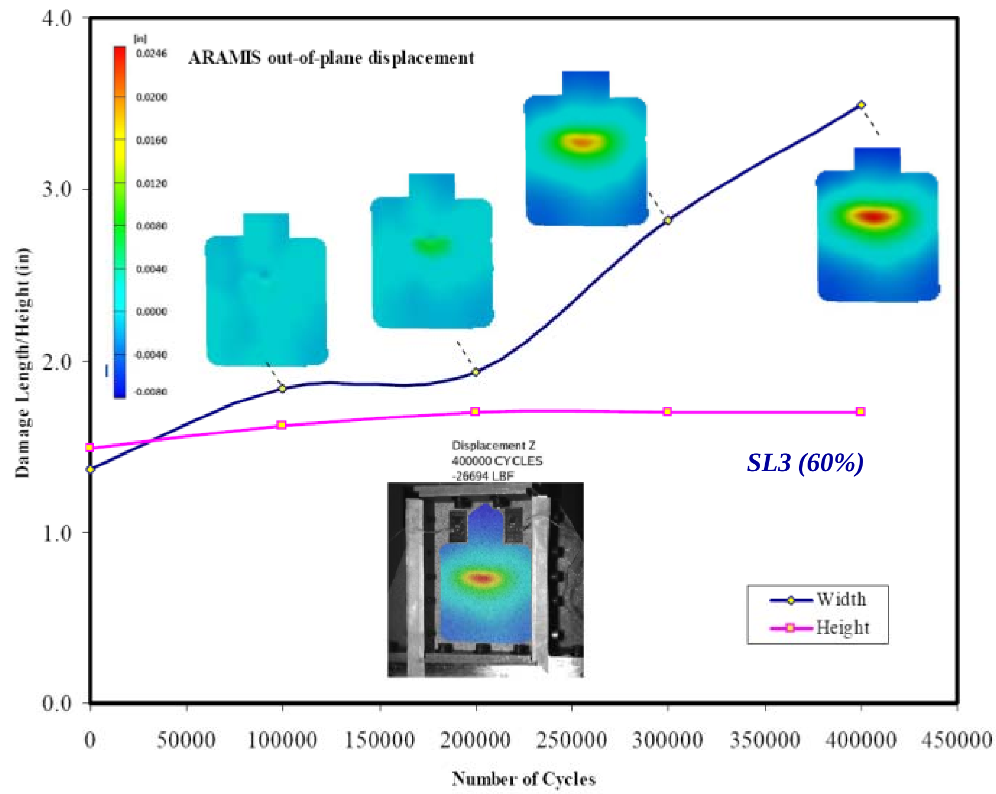
Fatigue & Damage Tolerance

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

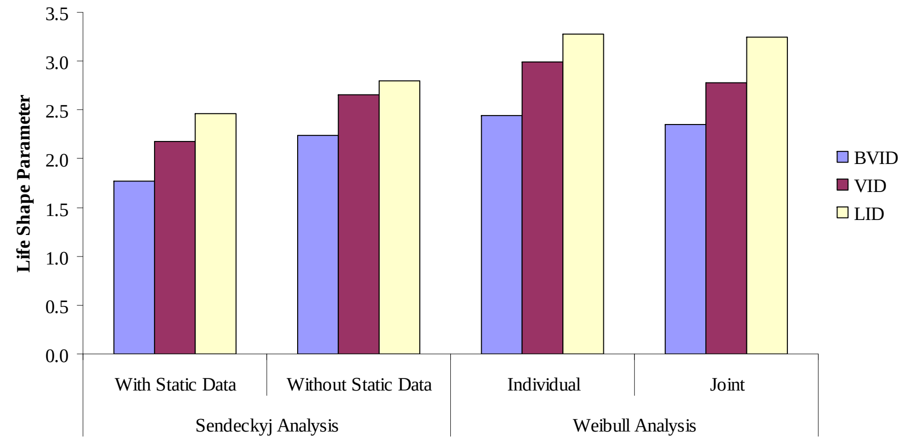


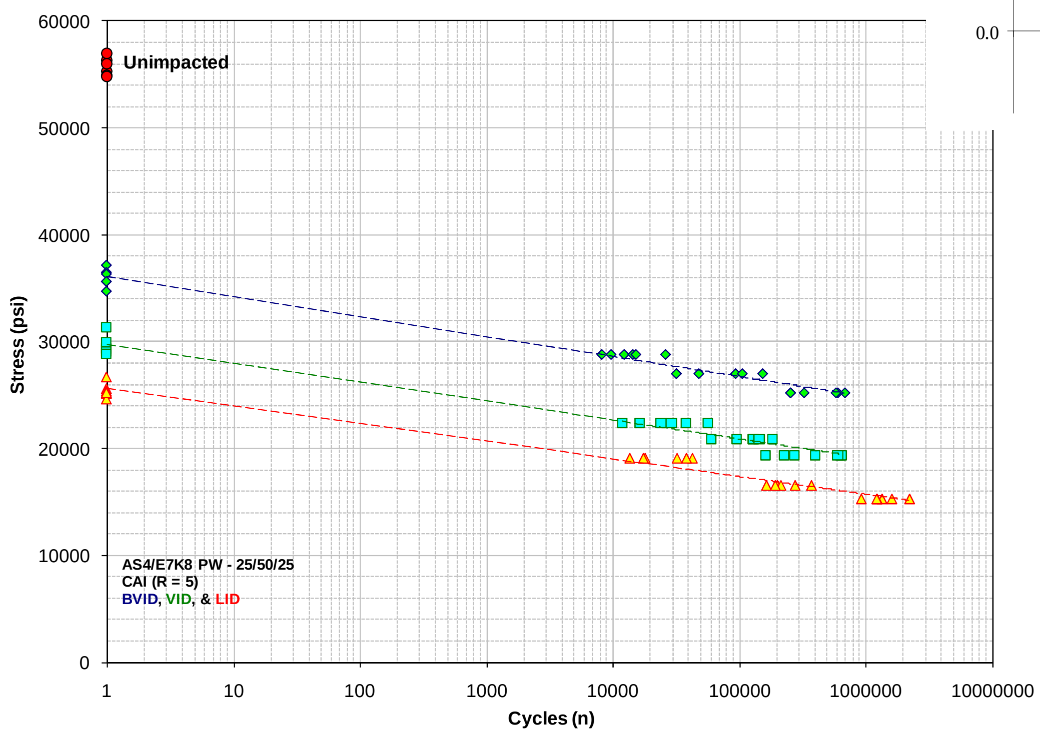


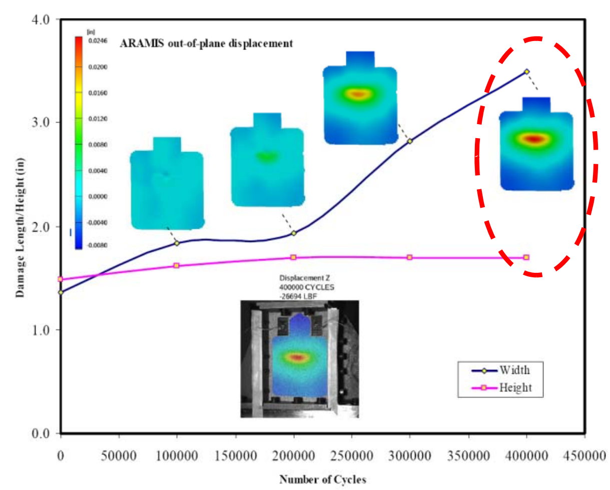


Effects of Damage on α

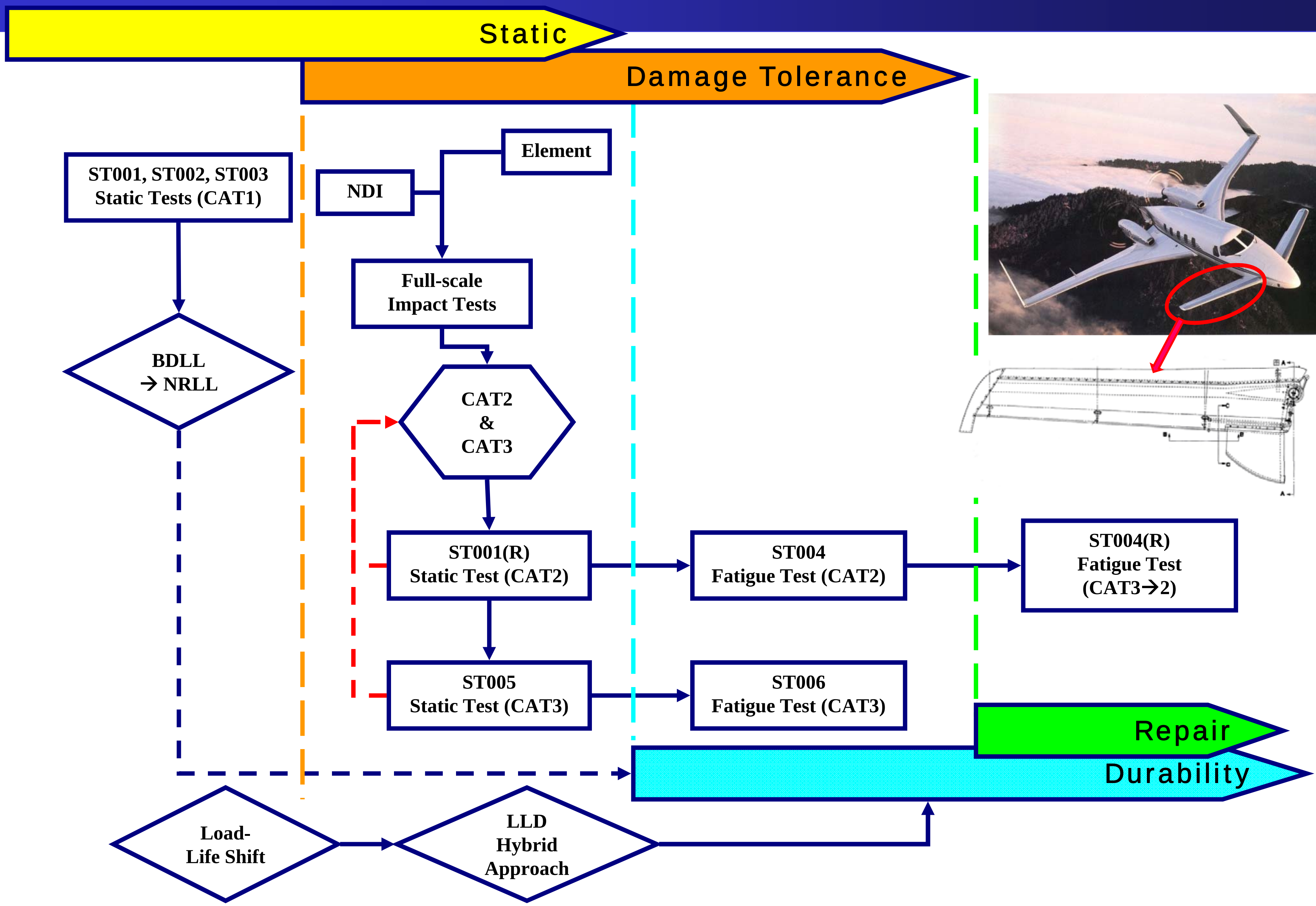
- Damage Tolerance Element Tests
  - Data scatter associated with final failure is conservative or representative of scatter at onset of damage propagation



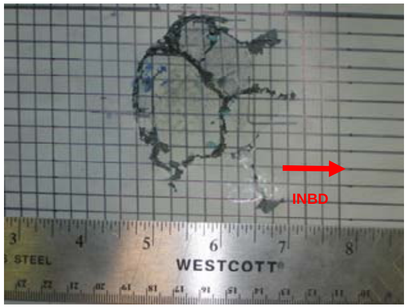


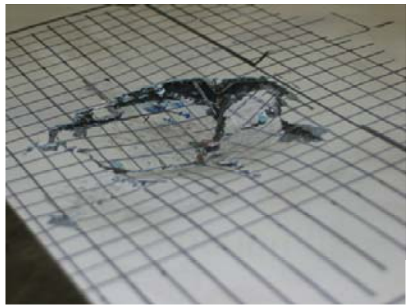


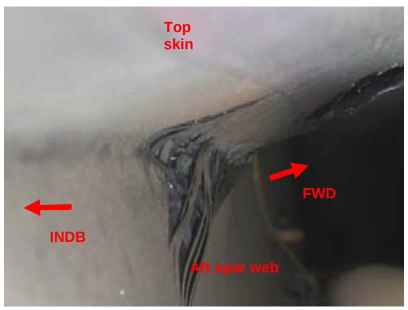
Full-Scale Validation



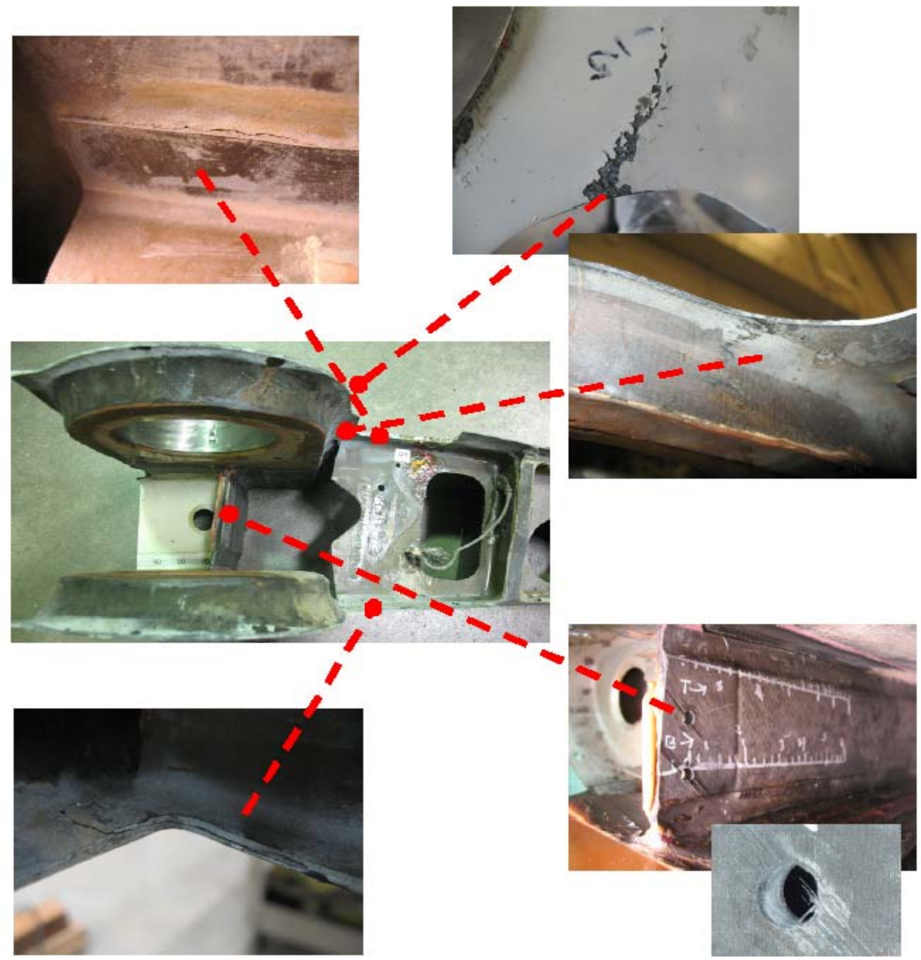
CAT2 – Aft Spar (FWS 45)

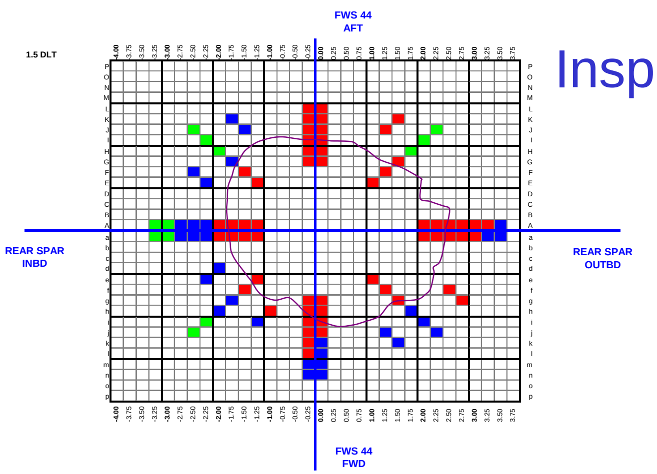






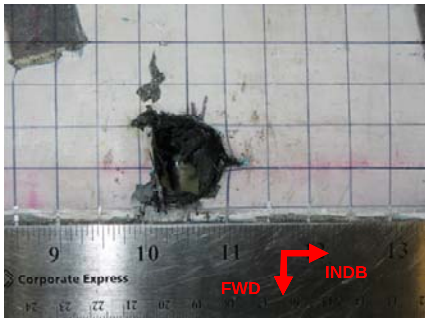
ST004 DaDT (Impact Damage)

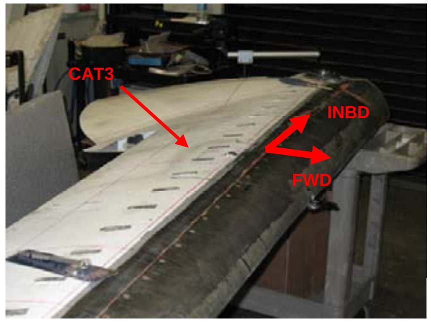


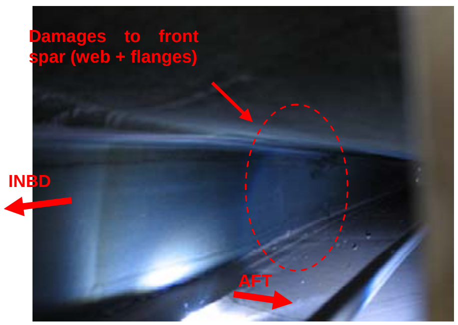


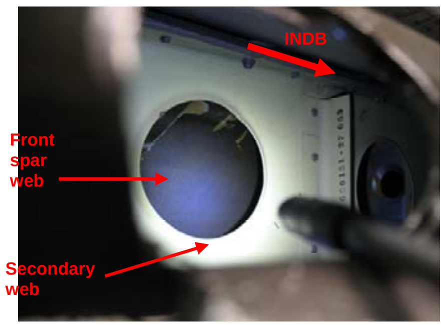
Inspections after 1.5 DLT

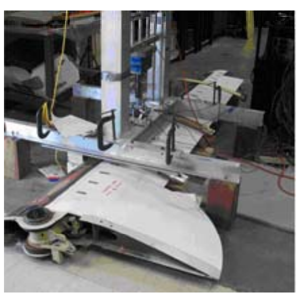
CAT3 – Front Spar (FWS 65)





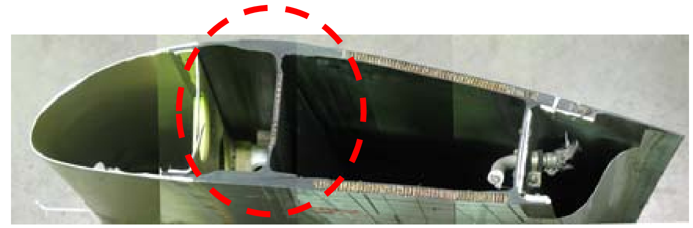


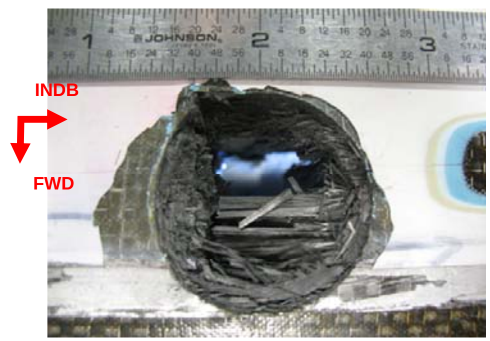


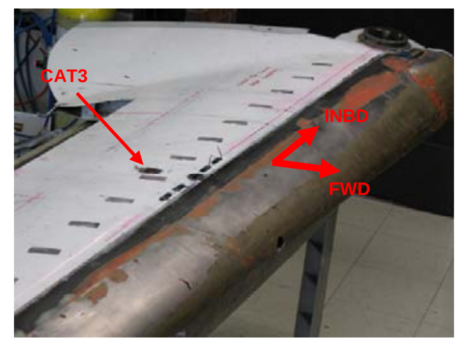


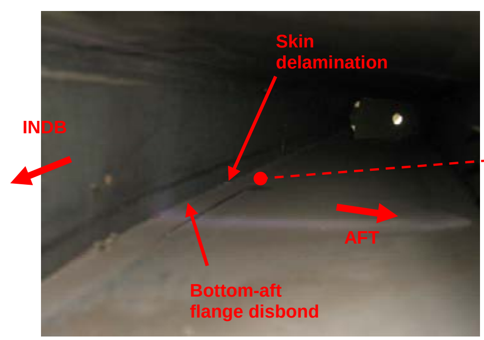
- ST006 DaDT

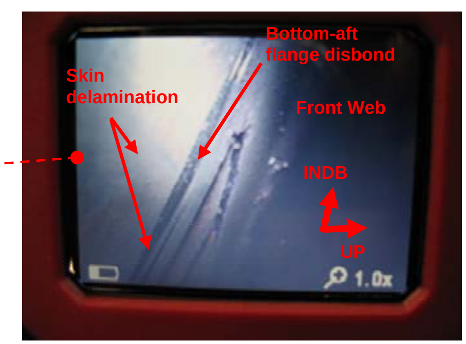
- ST005 Static





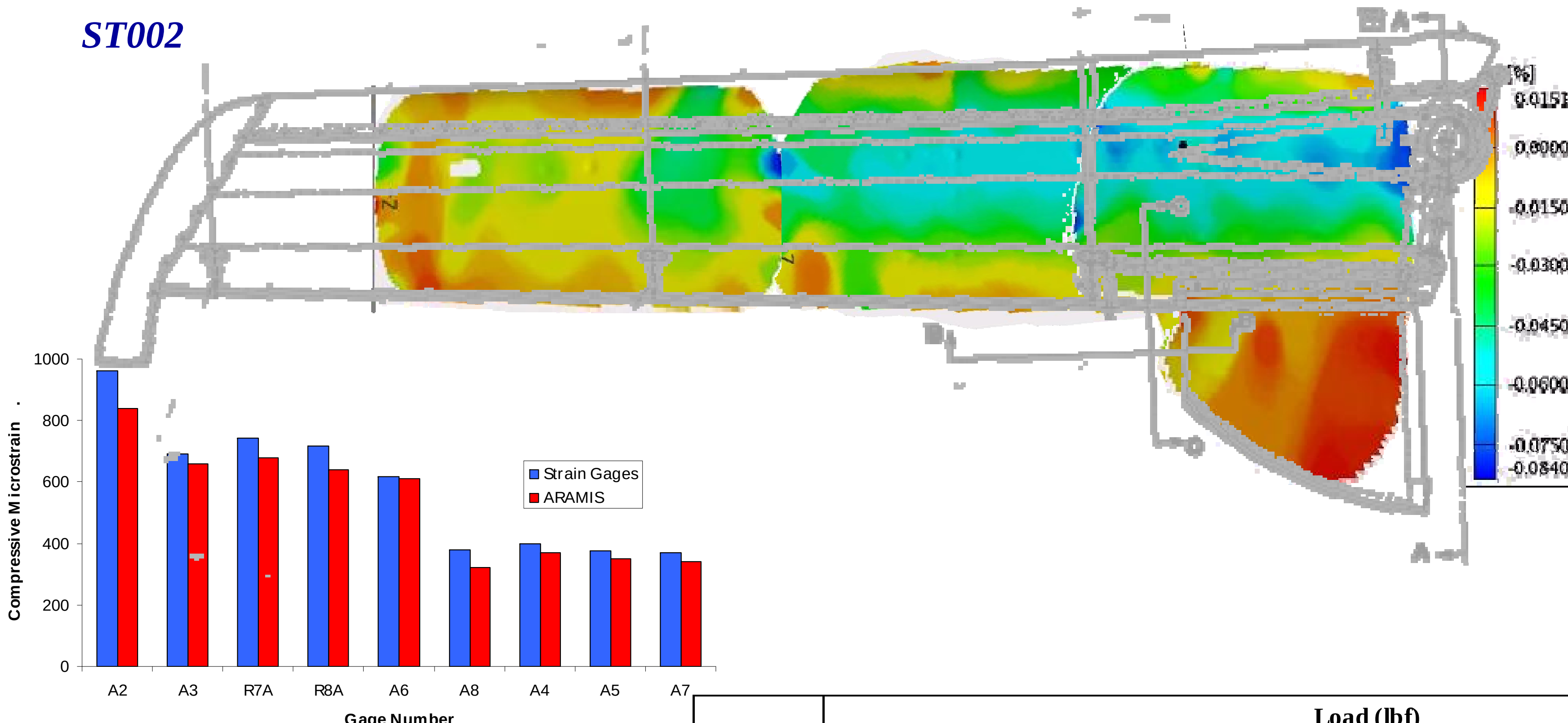






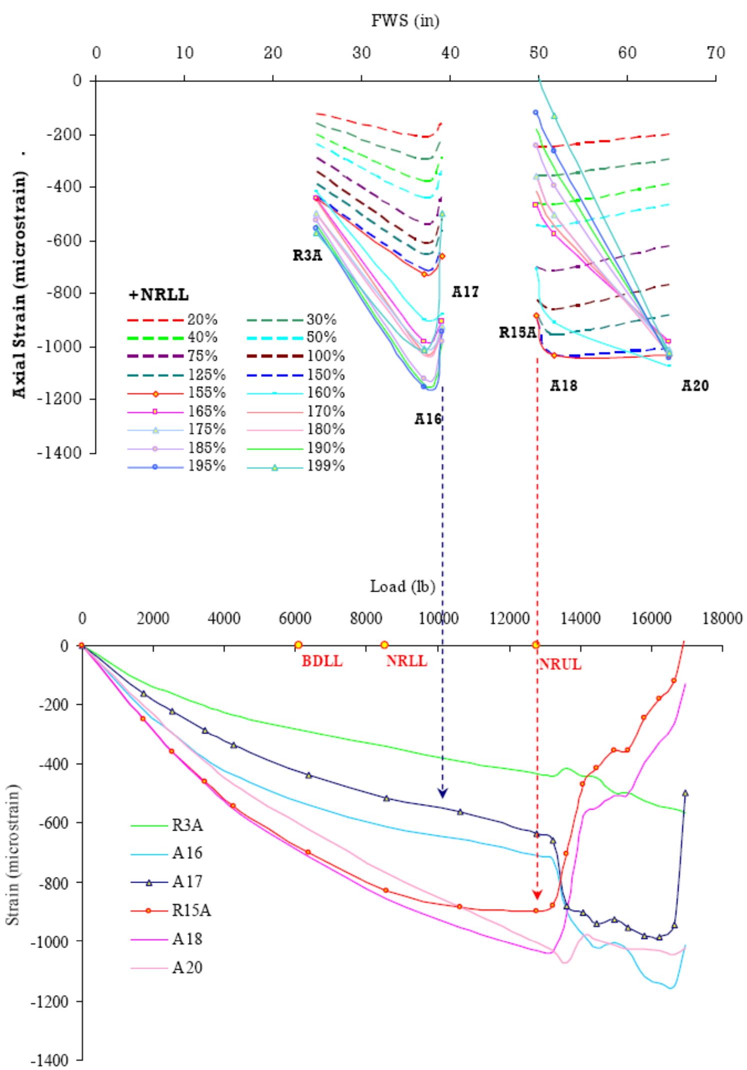
Static Summary

ST002



Test Article	Wing	Damage Category	Load (lbf) Onset of Damage Propagation - Local	First Sign of Fracture - Global	Fracture
ST001	Right	CAT1	-	11091.56	unloaded
ST002	Left	CAT1	-	11304.44	14640.43
ST003	Right	CAT1	-	10231.09	16123.50
ST001(R)	Right	CAT2	9149.90	11627.80	14694.60

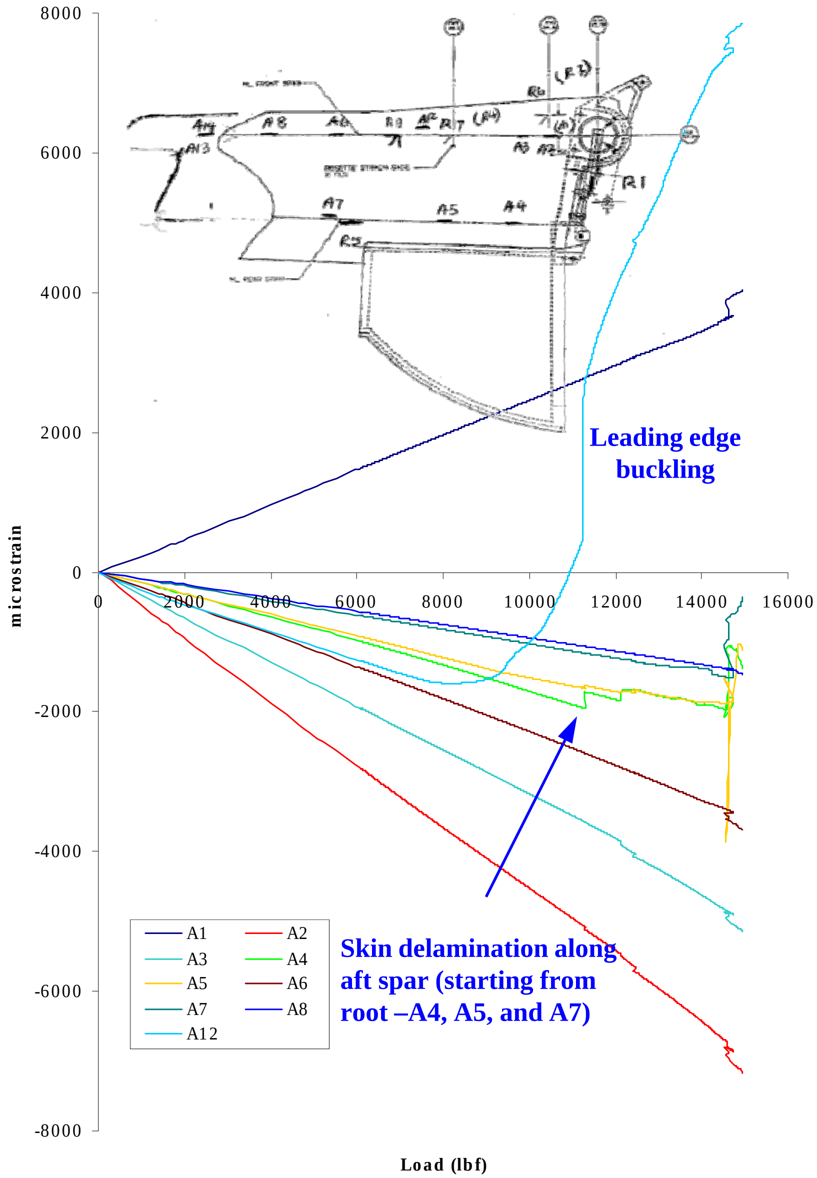
CAT 2 Residual Strength

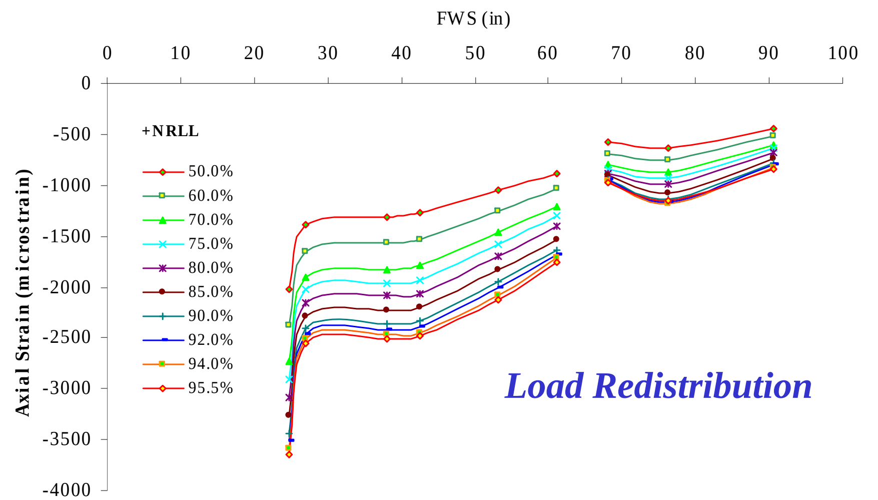


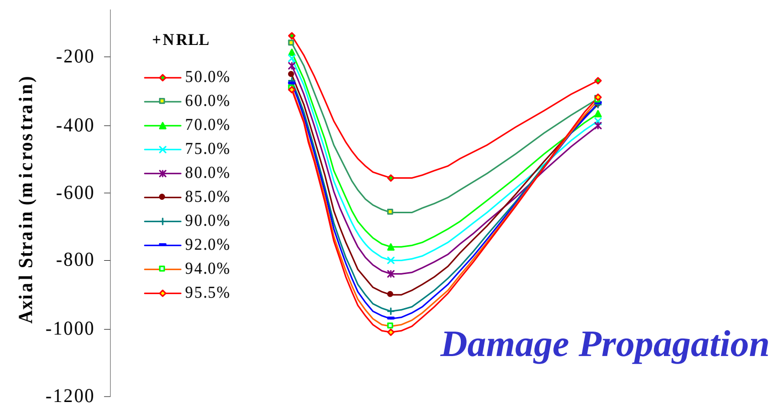
Damage progression along aft spar (top skin) of ST004 (CAT2 damage) during residual strength test after 2-DLT cyclic test with LEF

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

CAT 3 Residual Strength



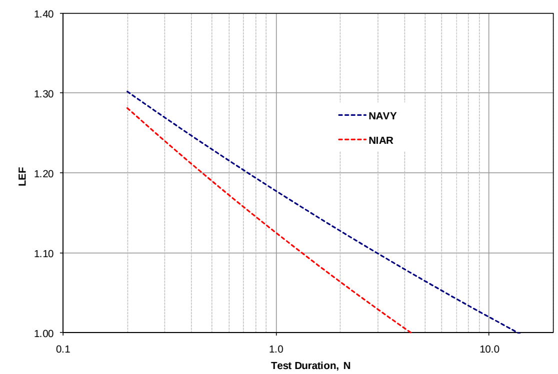


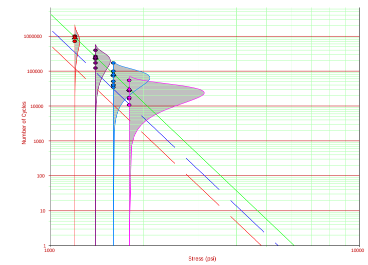


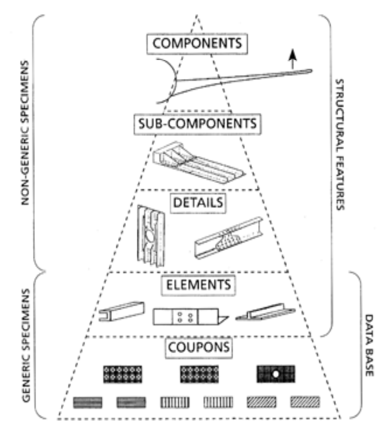
Fracture across CAT 3 damage just before limit load during residual strength after ½ DLT fatigue test

– Summary –
Load Enhancement Factor

- **2nd Generation Weibull shape parameters**
  – Static Strength: ~~20.0~~ → 26.0
  – Fatigue Life: ~~1.25~~ → 2.00
- Address evolution/maturity of material systems, manufacturing processes, test techniques, etc.
  – Reduced test matrix and Shared database concept
- Integrate design specific details gained from coupon and subelement tests into the LEF approach
  – Layup, loading modes/R ratios, Environments, ..
  – Bonded joints, interlaminar shear, sandwich, ..
- Realistic analysis approach for scatter
  – Appropriate analysis techniques for diverse design details
  – User-friendly automated procedures
  – Notch effects on scatter for damage tolerance testing
- Adhesive scatter is a concern (reliability!!!)
- Application of LEF
  - Hybrid structures

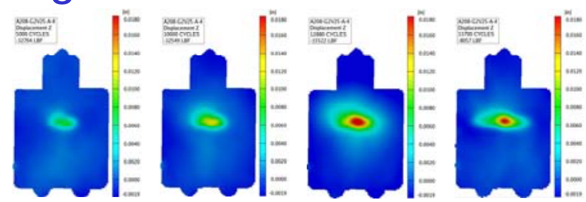


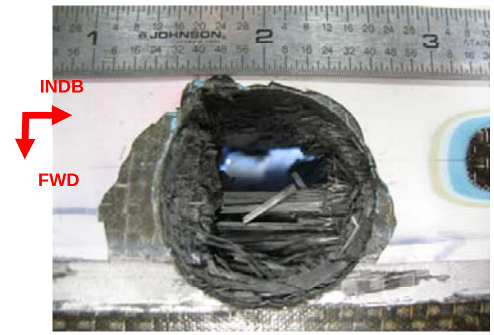




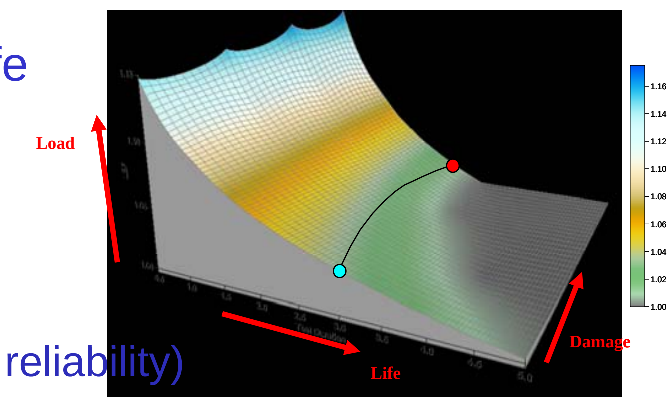
– Summary –
Load-Life-Damage Approach

- **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 reliability)
    - Strategic placement of health monitoring equipments
    - Progressive damage analysis (NLFEA) or scaled component tests

Questions / Notes