Durability & Damage Tolerance Testing and Analysis Protocols for Composite Structures

Life Factor, Load-Enhancement Factors, and Fatigue Life

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FAA/EASA/Industry Composite Damage Tolerance & Maintenance Workshop
June 1-5, 2009
Tokyo, Japan

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

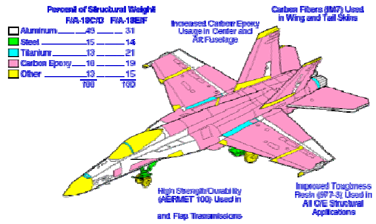
2008 CMH-17: Cocoa Beach, FL and Ottawa, Canada

2007 FAA/CACRC/EASA - Amsterdam, Netherlands

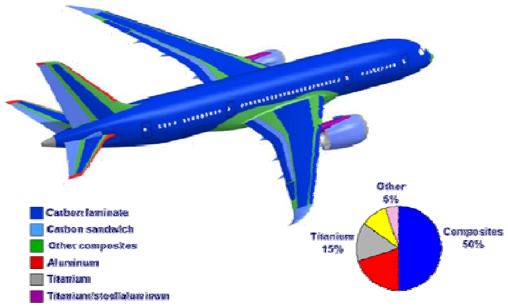
2006 FAA Workshop - Chicago, IL

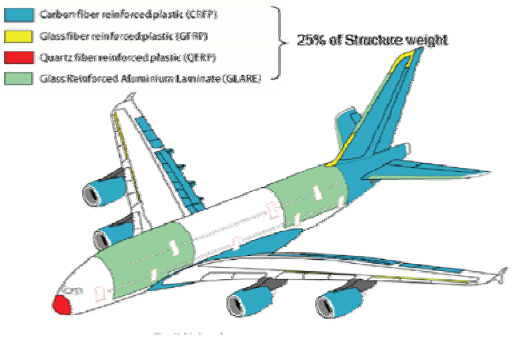
Background - Problem Statement -

- Although the materials, processes, layup, loading modes, failure modes, etc. are significantly different, most of current certification programs use the **load-life factors generated for NAVY F/A-18 program**.
  - Guidance to ensure safe reliable approach
  - Correlate certified "life" to improved LEF (load-life shift)



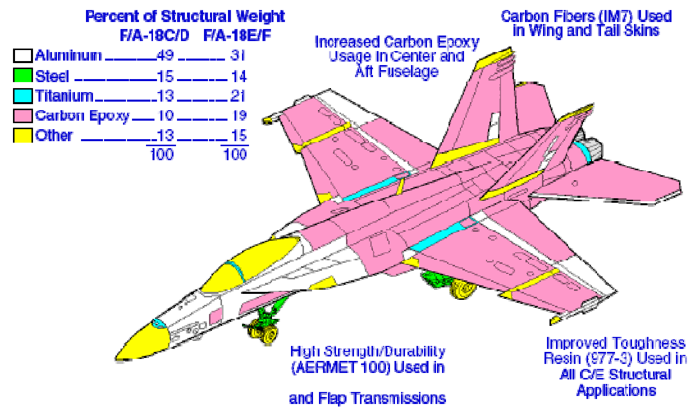
- With increased use of composite materials in primary structures, there is **growing need to investigate extremely improbable high energy impact threats** that reduce the residual strength of a composite structure to limit load.
  - Synthesize damage philosophy into the scatter analysis
  - Multiple LEF for different stage of test substantiation

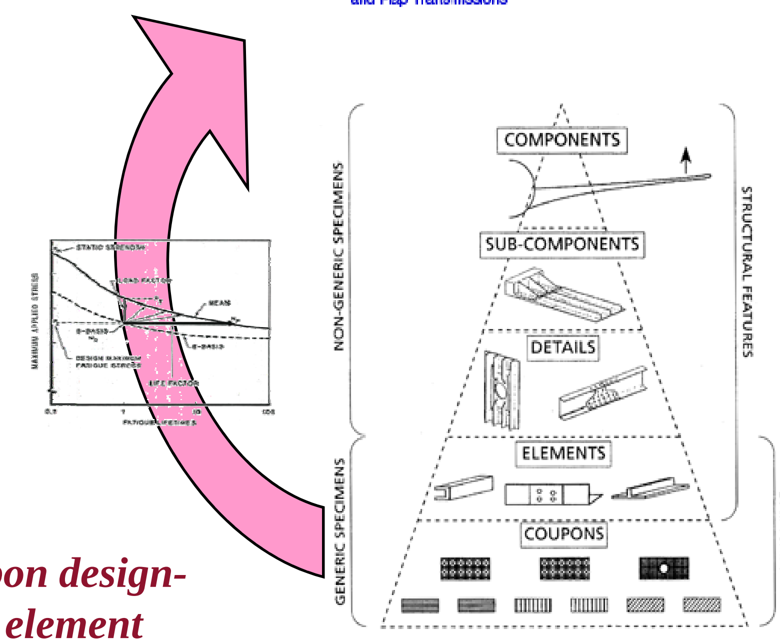




Scatter Analysis

- Background – most test programs reference the Navy/FAA reports by Whitehead, *et. al.*, (1986) and follow that approach
  - Most test programs have used the conclusions developed in this report regardless of design features, failure modes and/or materials





Integrates well into building-block approach based upon design-specific information gained from various coupon and element

Research Program Objectives

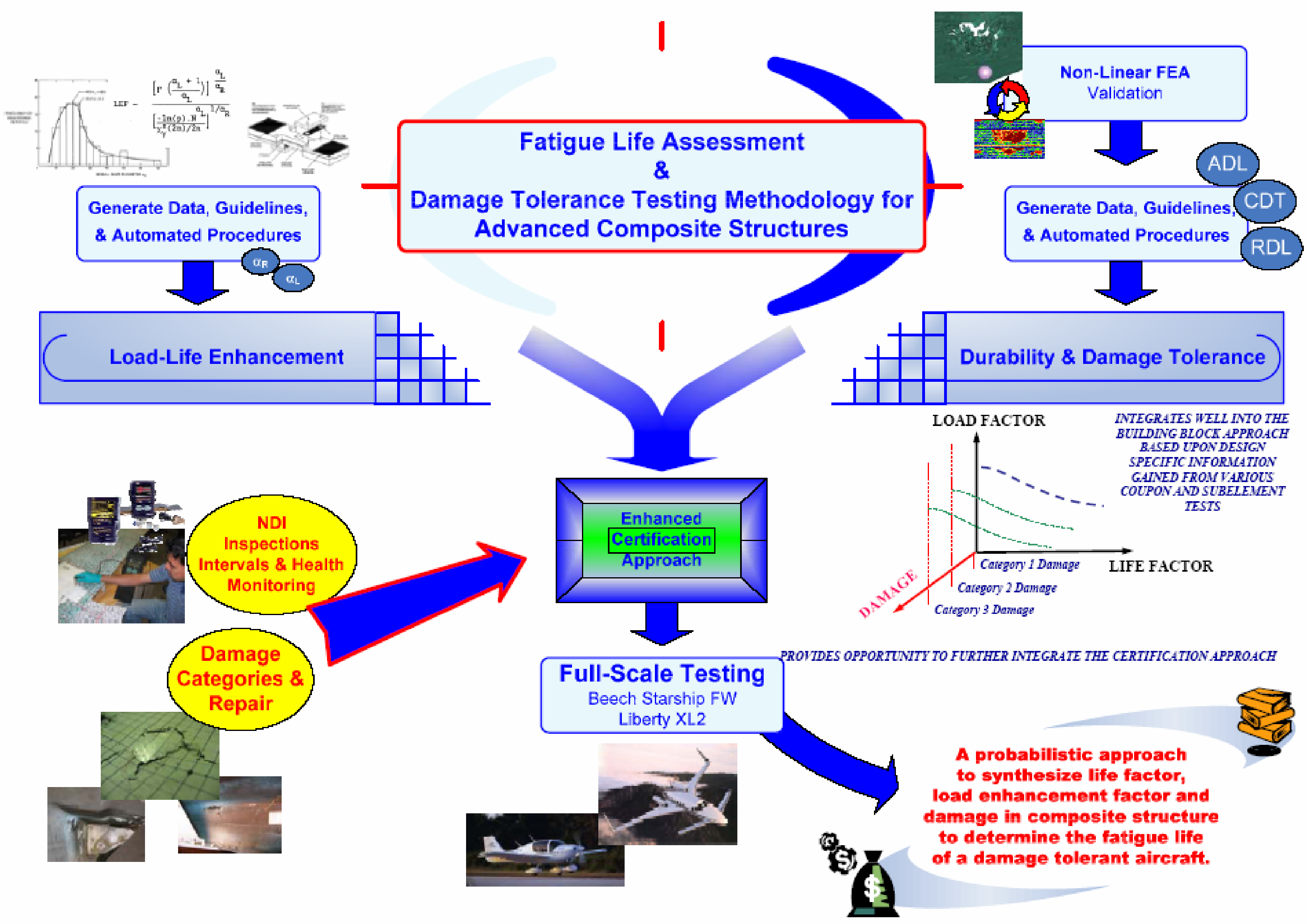
Primary Objective

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

Research Overview



Scatter Analysis of Composite

Static Scatter

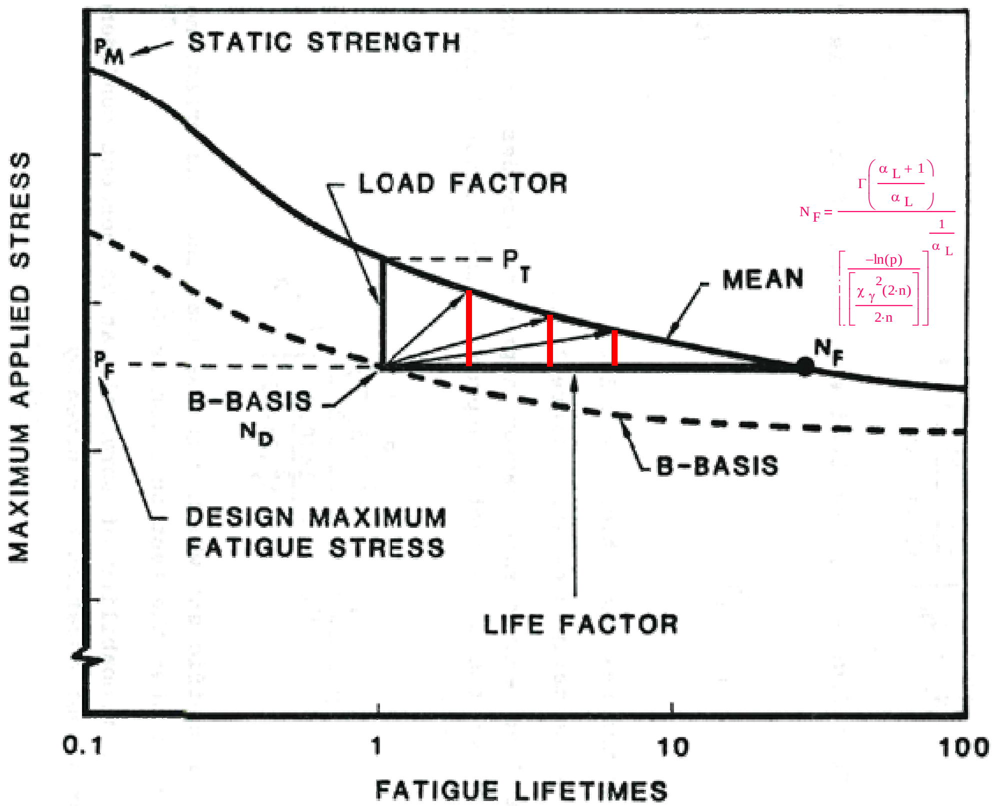
Fatigue Scatter

Life Factor

Load Enhancement Factors

Load Factor Approach

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



- Load (Scatter) Factor

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

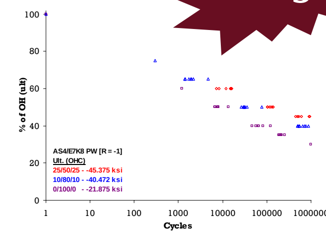
- Load Enhancement Factor (LEF)

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

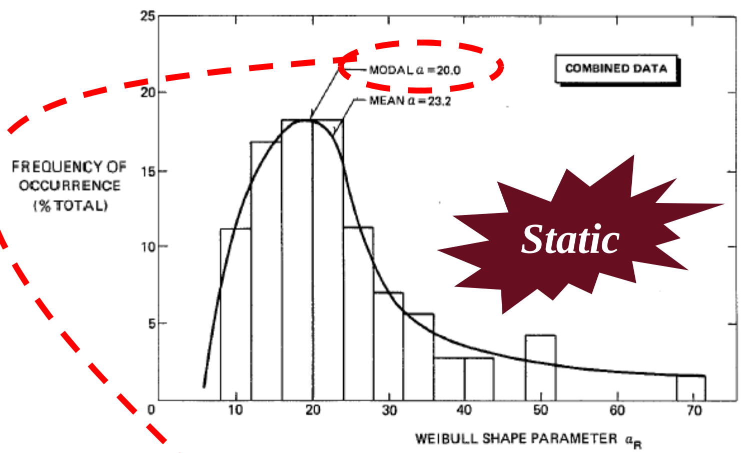
Load Enhancement Factor Approach

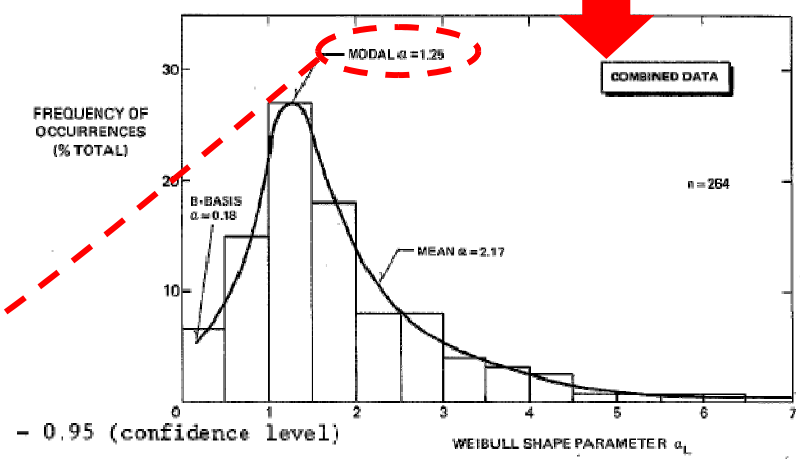
Fatigue

Fatigue Data Fitting Models



Static



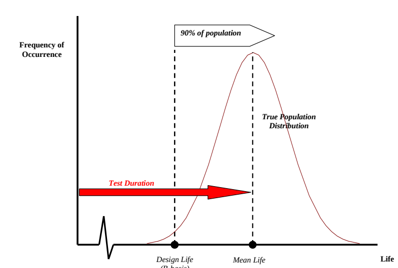


$\alpha_L = 1.25$ n = 1 (one test article)

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

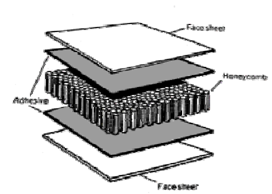
$$LEF = \frac{\left[\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right]^{\frac{\alpha_L}{\alpha_R}}}{\left[\frac{-\ln(p).N}{\chi^2_\gamma(2n)/2n}\right]^{1/\alpha_R}}$$

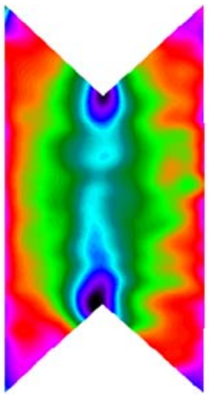
test duration	load enhancement factor	
1.0	1.177	**Load Factor**
1.5	1.148	**LEF**
2.0	1.127	
3.0	1.099	
13.3	1.0	**Life Factor**

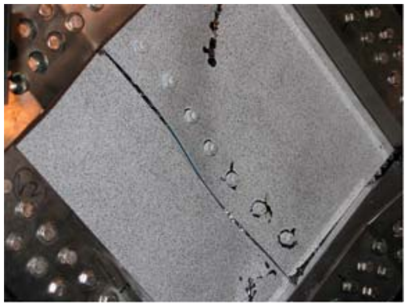


Material Databases

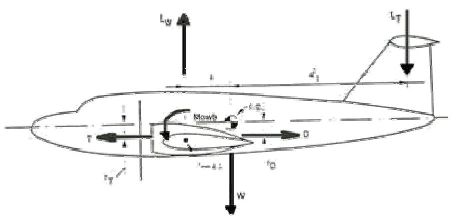
- LEF
  - » AS4/E7K8 **(457/17)**
  - » T700/#2510 PW **(240/7)**
  - » 7781/#2510 8HS **(204/7)**



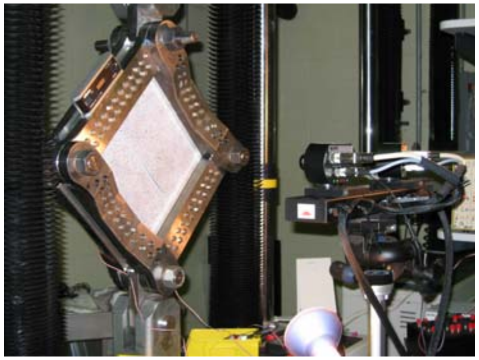




- Laminate Data
  - » T700/#2510 UNI **(853/47)**
  - » T700/#2510 PW **(863/48)**
  - » T700/E765 UNI **(834/47)**
  - » T300/E765 PW **(722/48)**
  - » AS4C/MTM45 UNI **(1151/86)**
  - » AS4C/MTM45 8HS **(1083/78)**

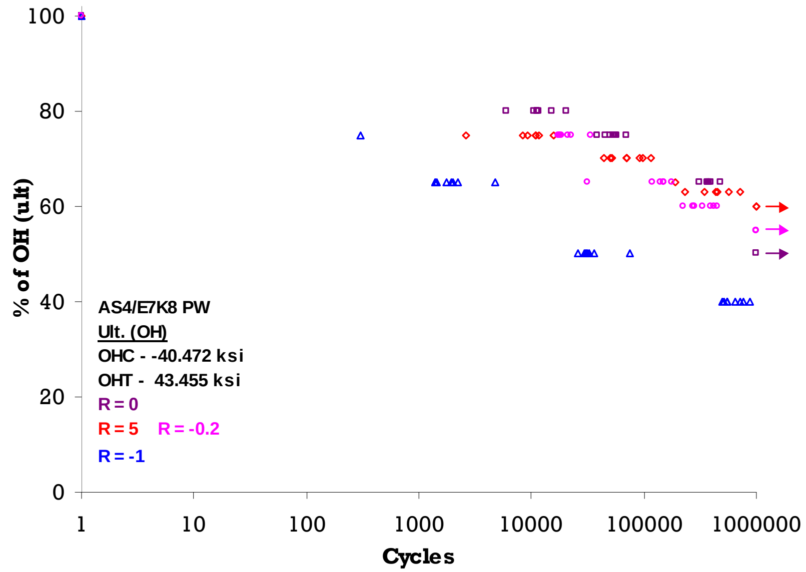


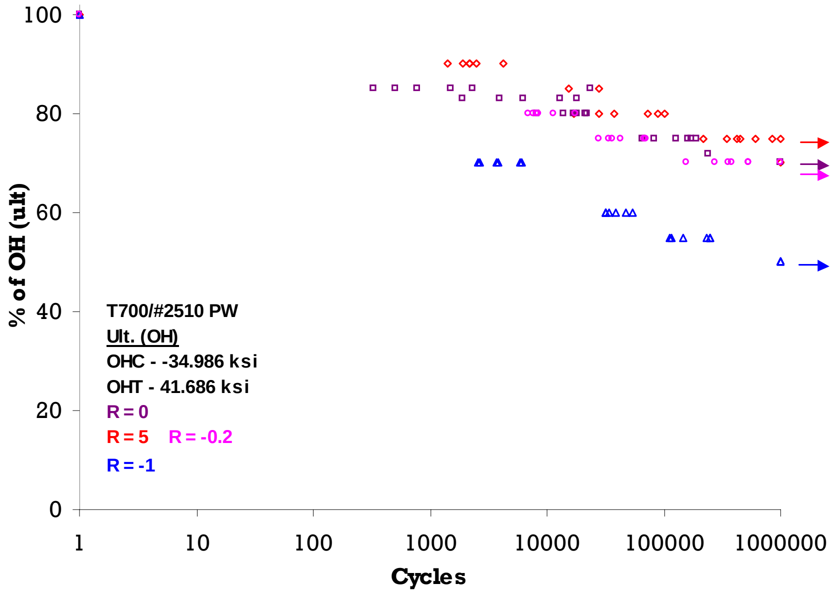
- Adhesive Fatigue **(390 spec./12 data sets)**
  - » Loctite Paste
  - » PTM&W paste (2 bondline thicknesses)
  - » EA 9696 film

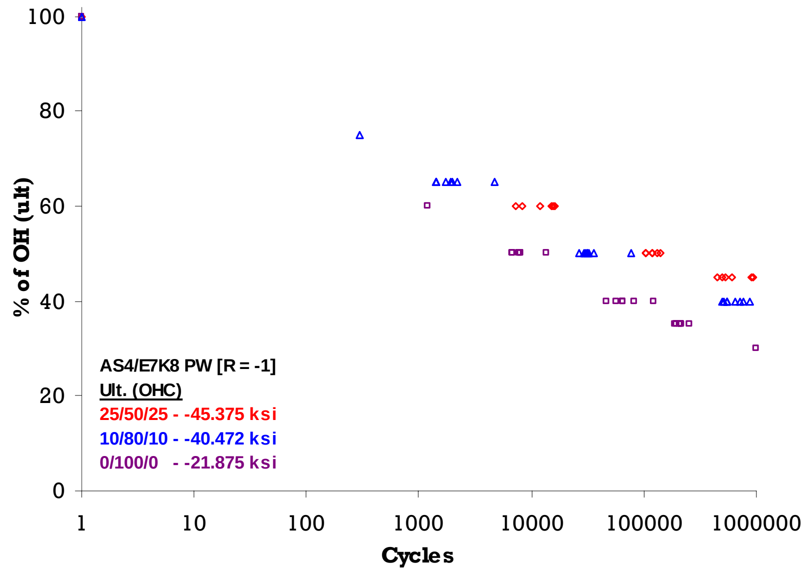


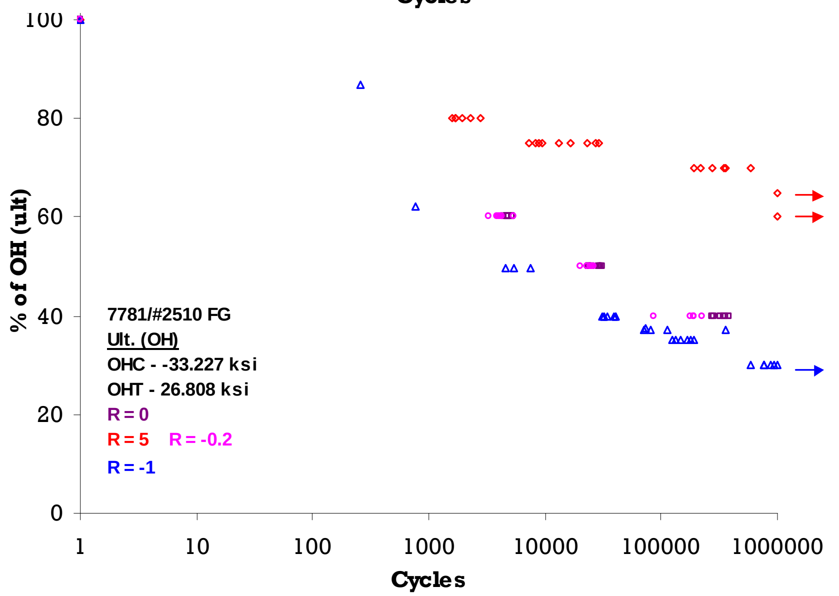
- Adhesive Effects of Defects
  - » T700/#2510 PW & EA9394 –PFS **(70/6)**
  - » T700/3900-2 PW & EA9394 (SLS) **(20)**
  - » T800/3900-2 UNI & EA9394 (SLS) **(20)**
  - » 7781/NB321 8HS & EA9394 (SLS) **(20)**

Sample S-N Curves

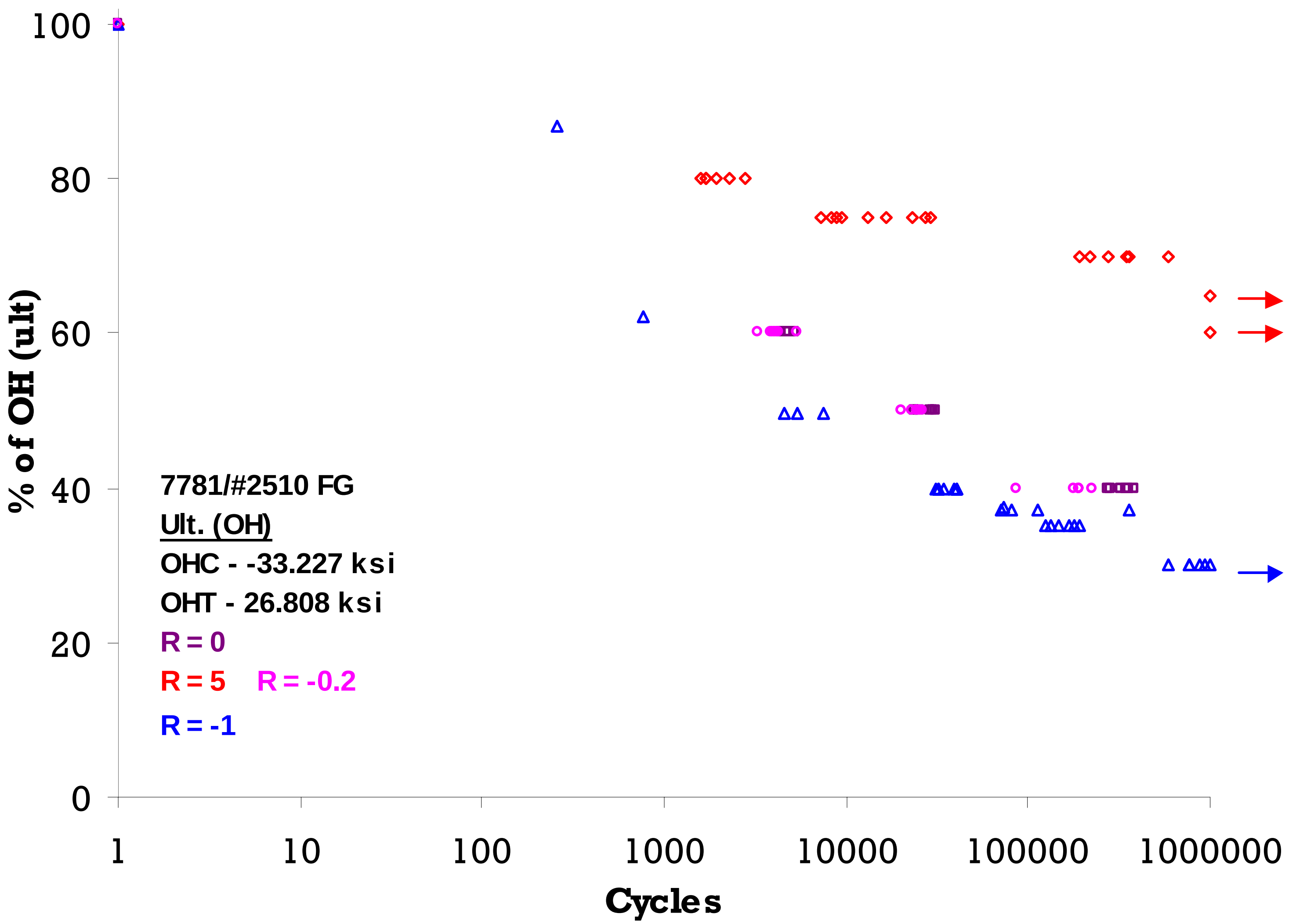








Sample S-N Curves (contd..)



Fatigue Scatter Analysis Techniques

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- Individual Weibull
- Joint Weibull

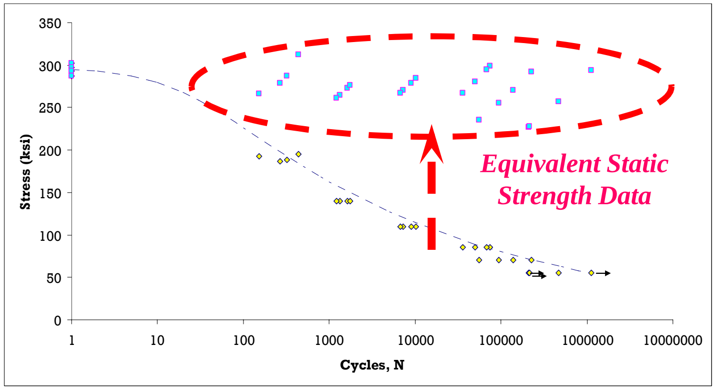
$$\sum_{i=1}^{M}\left[\frac{\sum_{j=1}^{n_i} x_{ij}^{\alpha}\cdot\ln(x_{ij})}{\sum_{j=1}^{n_i} x_{ij}^{\alpha}}\right]-\frac{M}{\alpha}-\sum_{i=1}^{M}\left[\frac{\sum_{j=1}^{n_{fi}}\ln(x_{ij})}{n_{fi}}\right]=0$$

- Sedeckyj Equivalent Strength Model

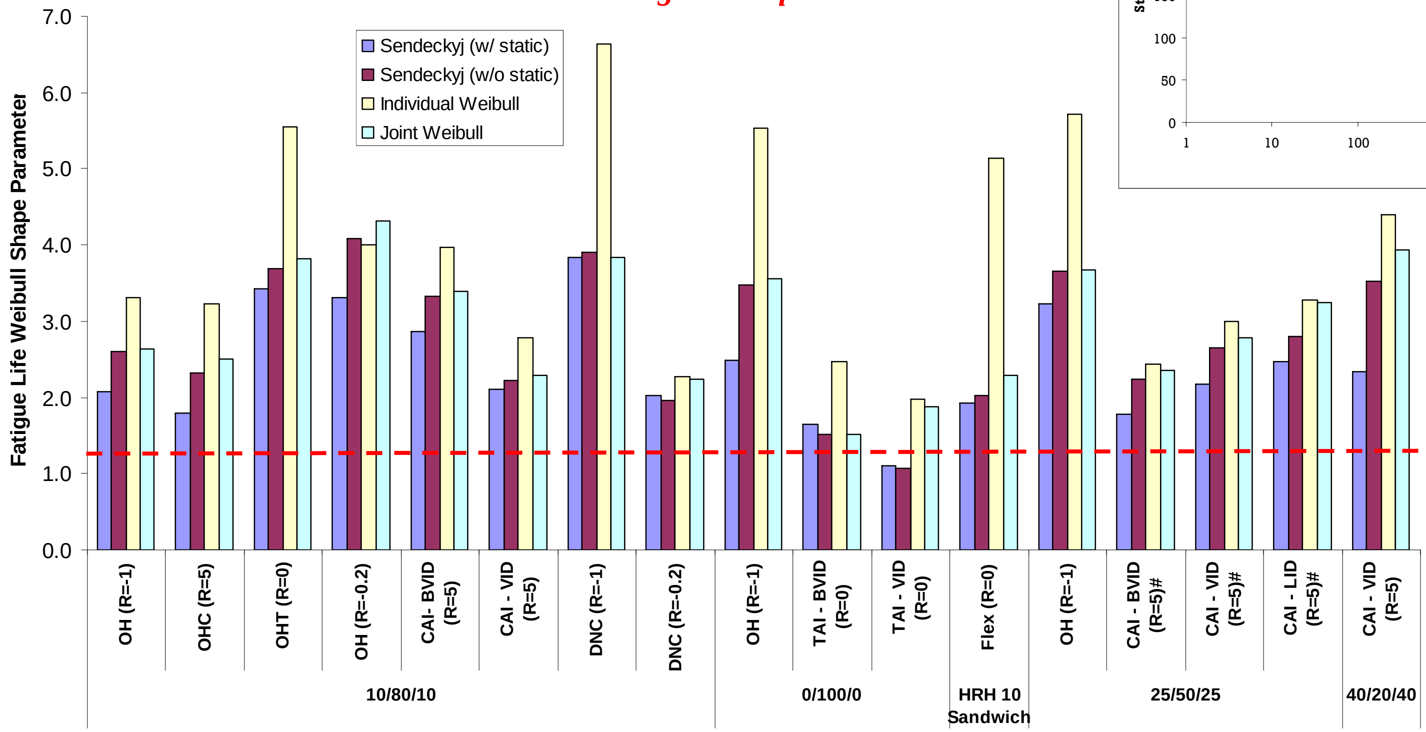
$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

NADC Fatigue Scatter Analysis

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



Data Pooling Techniques



AS4/E7K8 PW

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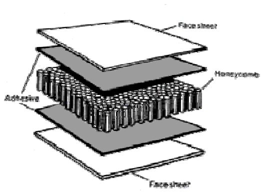
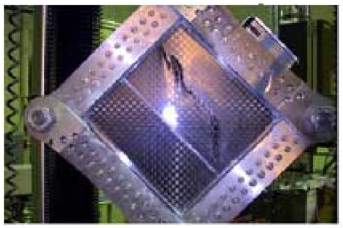
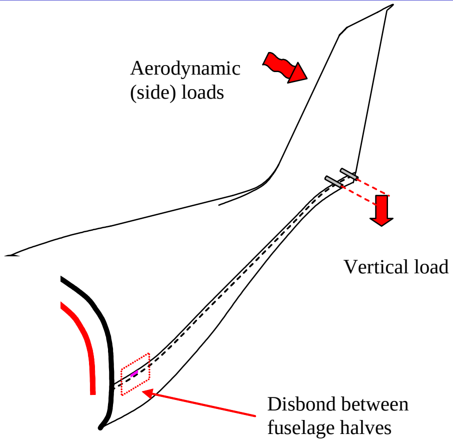
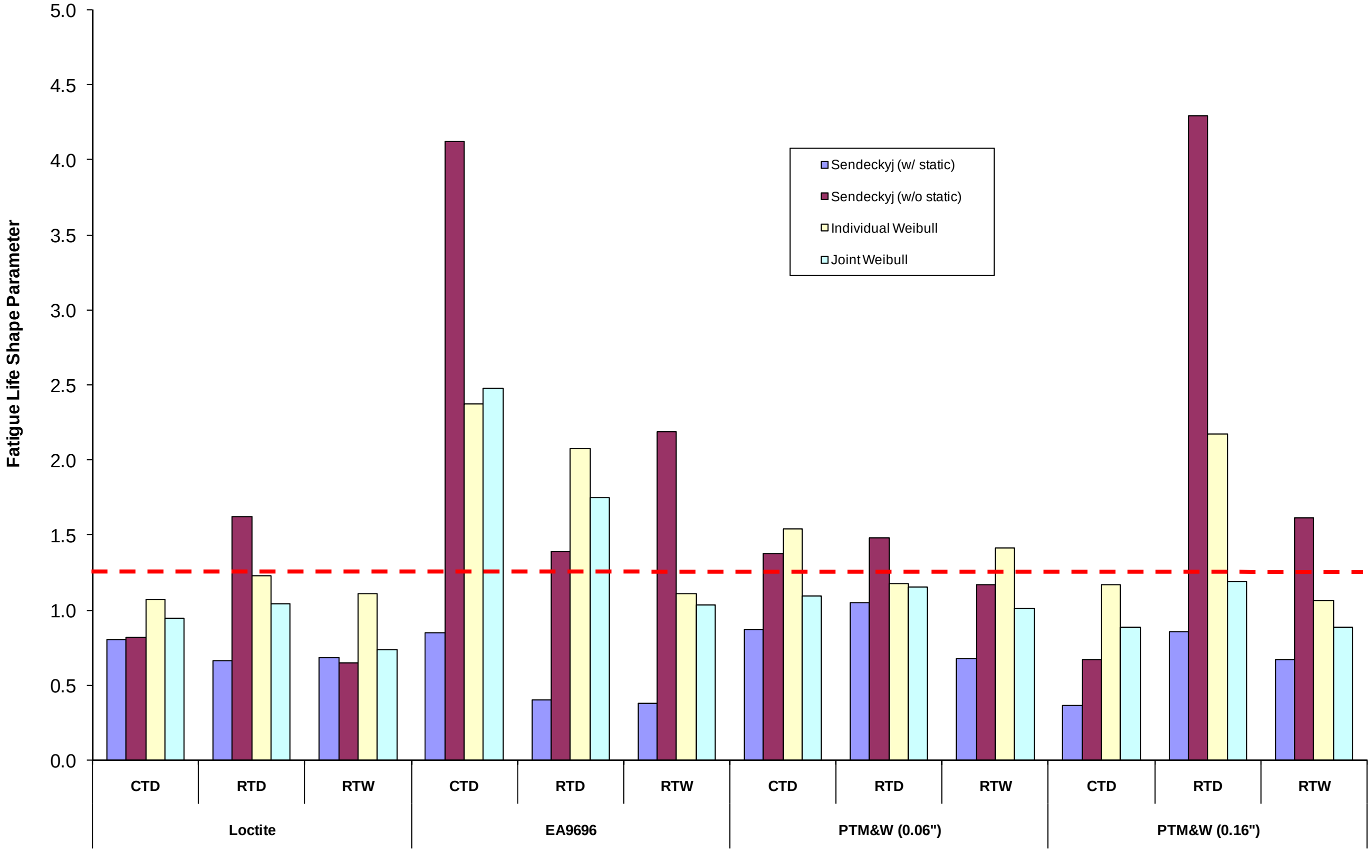
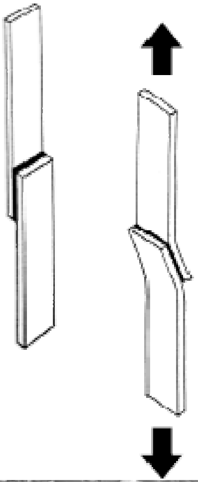
Adhesive Fatigue Scatter

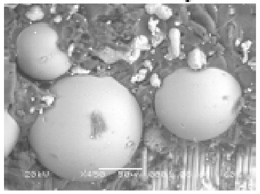




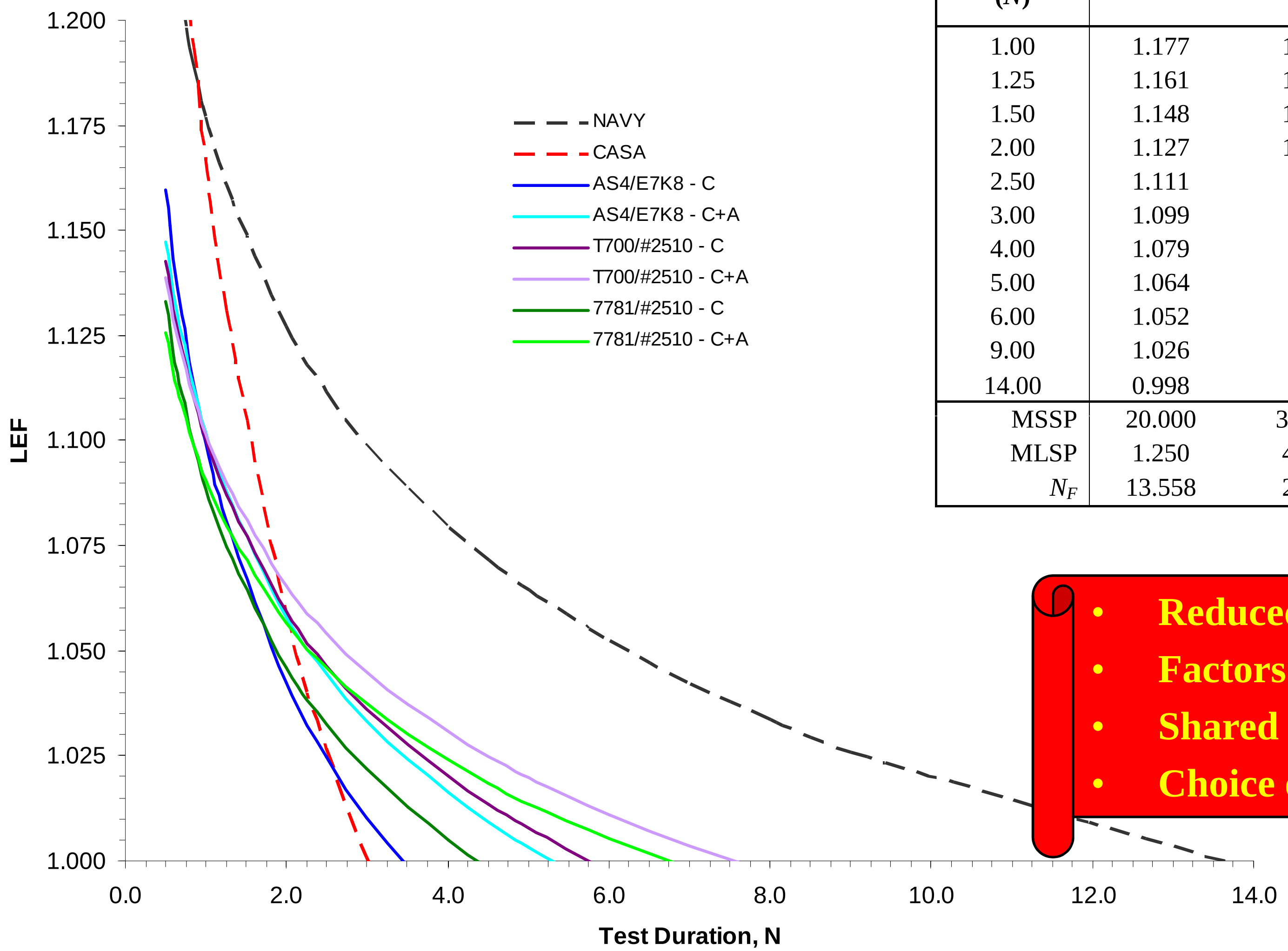








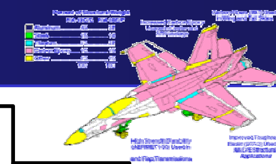
Scatter Analysis Guidelines



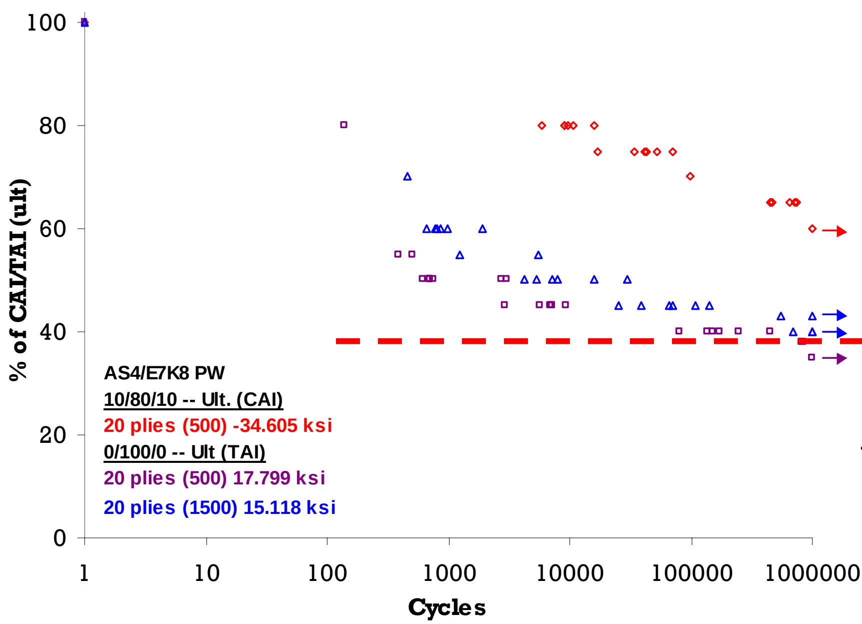
Number of Test Lives (N)	NAVY	Individual (AS4/E7K8)	Sendeckyj (AS4/E7K8)	Sendeckyj (AS4/E7K8) +Individual (Adhesive)
1.00	1.177	1.096	1.099	1.102
1.25	1.161	1.066	1.081	1.088
1.50	1.148	1.041	1.066	1.076
2.00	1.127	1.004	1.042	1.058
2.50	1.111		1.025	1.044
3.00	1.099		1.010	1.033
4.00	1.079			1.016
5.00	1.064			1.003
6.00	1.052			
9.00	1.026			
14.00	0.998			
MSSP	20.000	32.193	32.193	32.193
MLSP	1.250	4.056	2.475	1.880
N_F	13.558	2.070	3.431	5.267

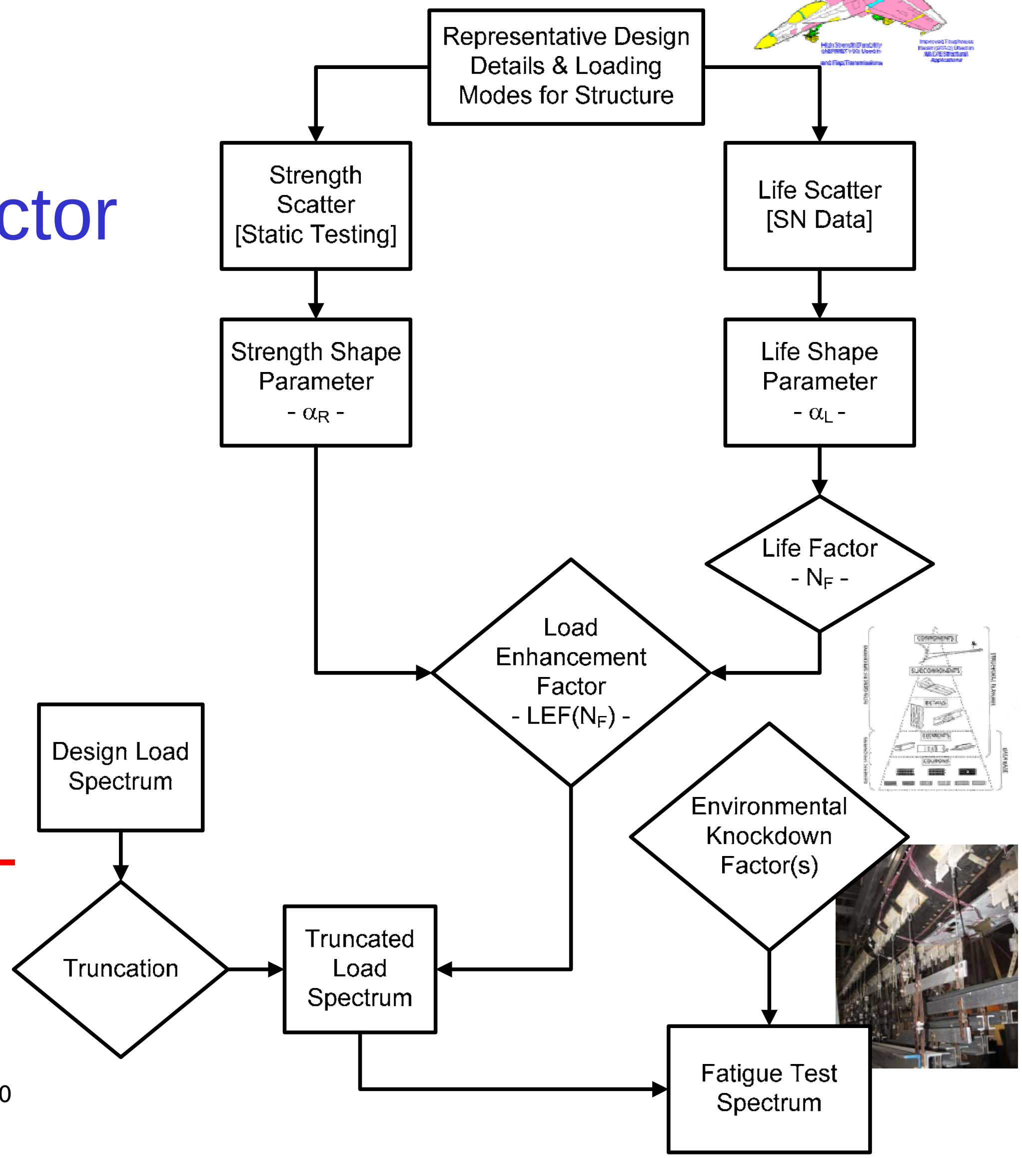
- **Reduced test matrix**
- **Factors affecting LEF**
- **Shared database**
- **Choice of analysis techniques**

Test Spectrum Generation

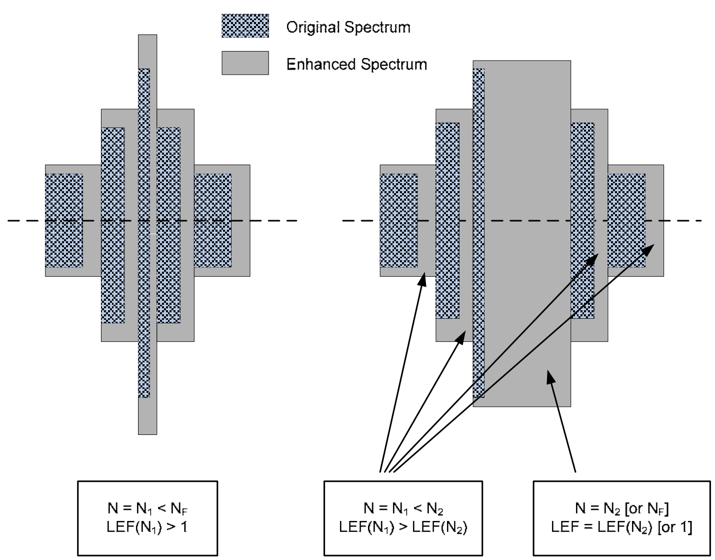


- Life factor
- Load-enhancement factor
- Truncation levels
- Environmental factors





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

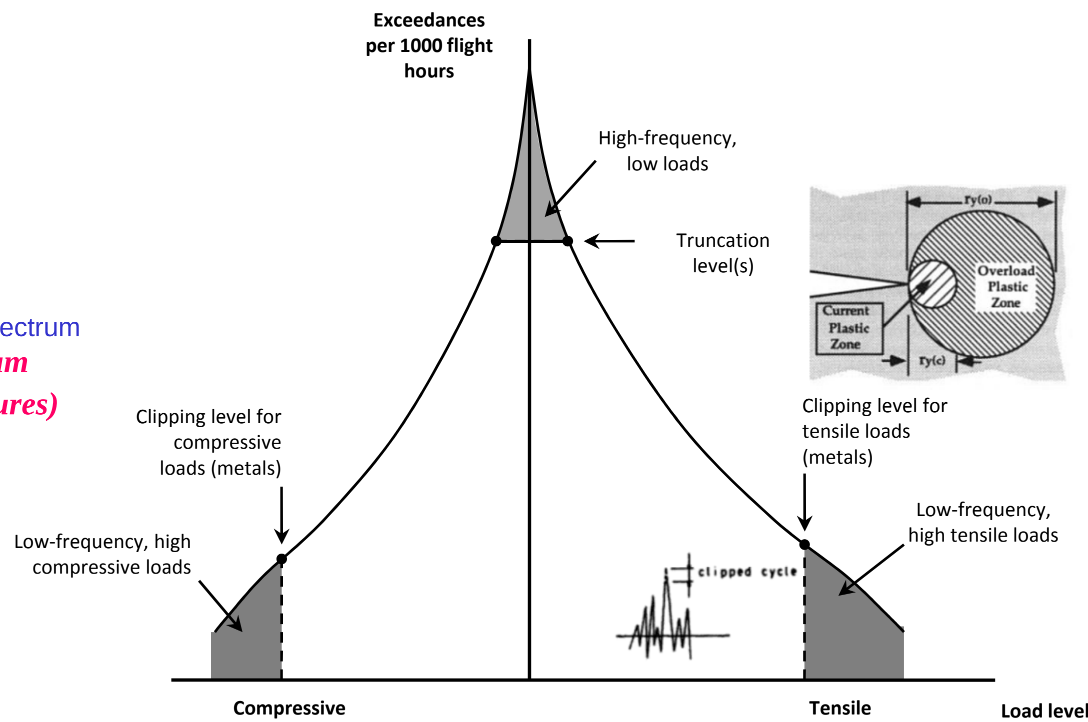
Hybrid Structural Substantiation

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

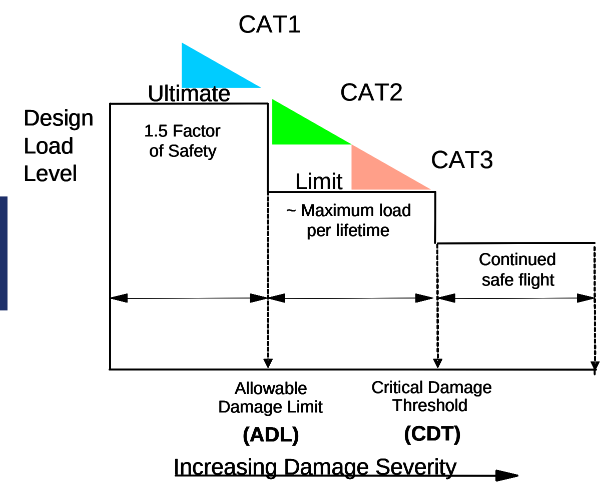
Load-Life Shift

Application of LLD

Damage Scenarios

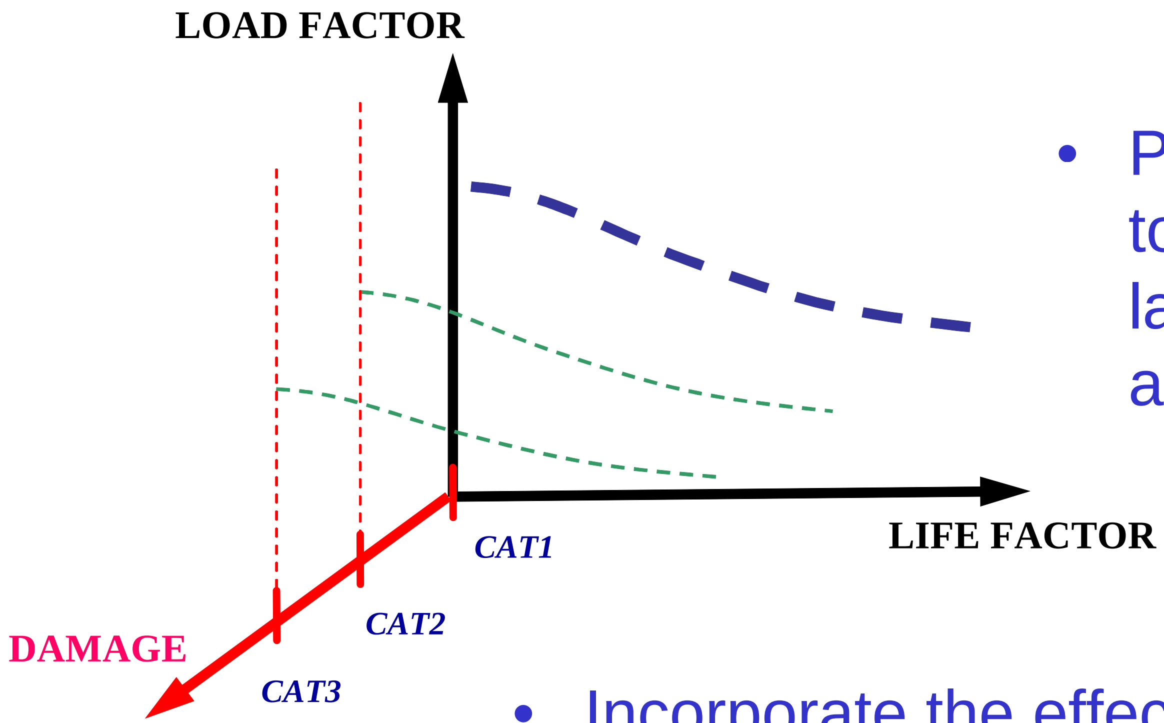
Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

Category	Examples	Safety Considerations (Substantiation, Management)
Category 1: Damage that may go undetected by field inspection methods (or allowable defects)	BVID, minor environmental degradation, scratches, gouges, allowable mfg. defects	Demonstrate reliable service life Retain Ultimate Load capability Design-driven safety
Category 2: Damage detected by field inspection methods @ specified intervals (repair scenario)	VID (ranging small to large), mfg. defects/mistakes, major environmental degradation	Demonstrate reliable inspection Retain Limit Load capability Design, maintenance, mfg.
Category 3: Obvious damage detected within a few flights by operations focal (repair scenario)	Damage obvious to operations in a "walk-around" inspection or due to loss of form/fit/function	Demonstrate quick detection Retain Limit Load capability Design, maintenance, operations
Category 4: Discrete source damage known by pilot to limit flight maneuvers (repair scenario)	Damage in flight from events that are obvious to pilot (rotor burst, bird-strike, lightning)	Defined discrete-source events Retain "Get Home" capability Design, operations, maintenance
Category 5: Severe damage created by anomalous ground or flight events (repair scenario)	Damage occurring due to rare service events or to an extent beyond that considered in design	Requires new substantiation Requires operations awareness for safety (immediate reporting)



REFERRENCE: Ilcewicz, L., "Composite Damage Tolerance and Maintenance Safety Issues," FAA Damage Tolerance and Maintenance Workshop, Rosemont, IL, July, 2006.

Load-Life-Damage (LLD) Hybrid Approach

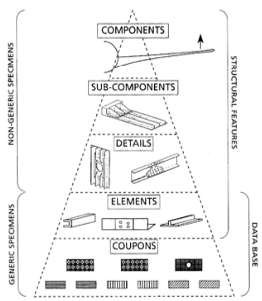


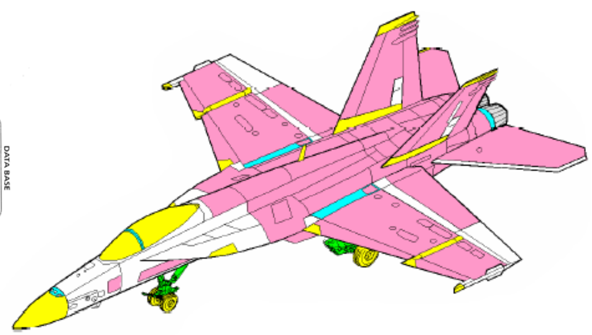
- Provide an opportunity to further investigate large VID without additional test articles

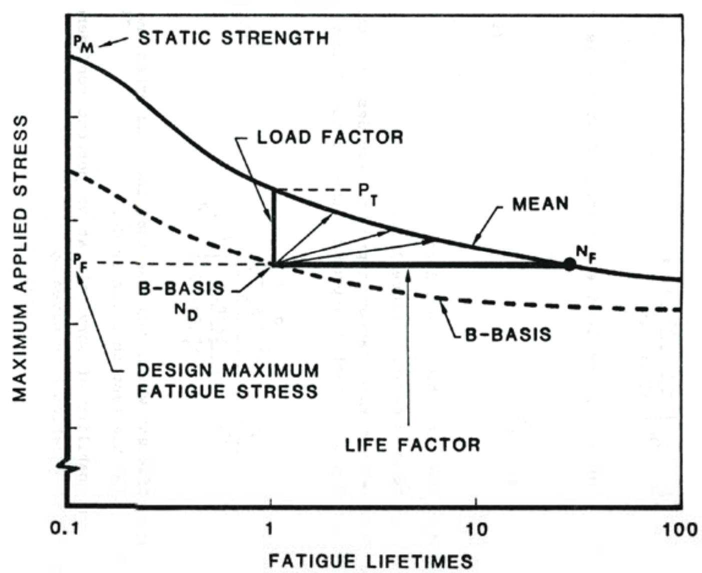
- Incorporate the effects of damage to scatter analysis
- Minimum risk of premature failure of full-scale article
- Application to hybrid structure

Load Enhancement Factors

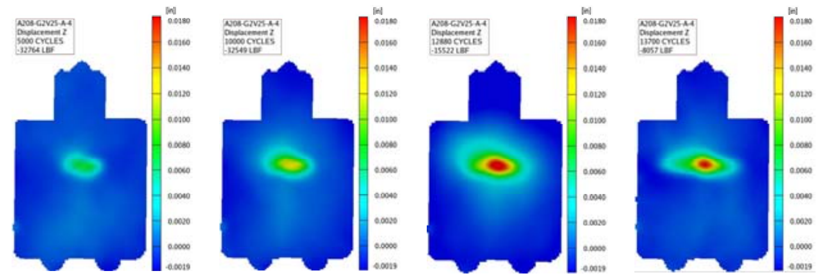
Scatter Analysis

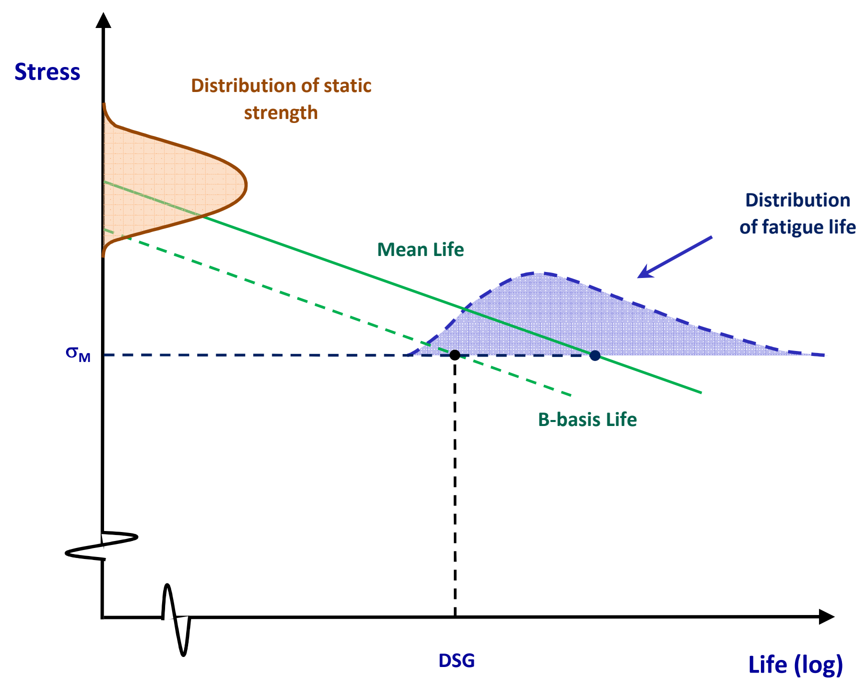




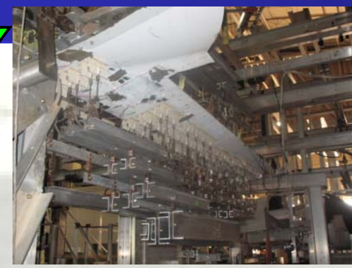


(Onset of) Flaw Growth





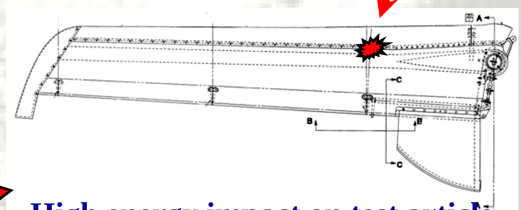
LLD Hybrid Approach



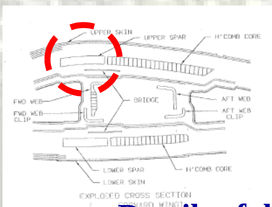
Complete Durability phase

Durability phase

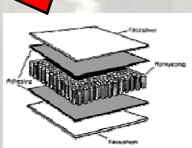
Initial LEF based on data scatter



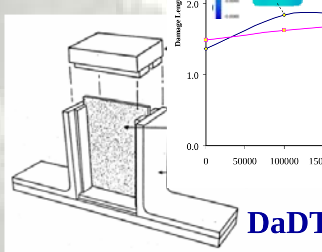
High energy impact on test article

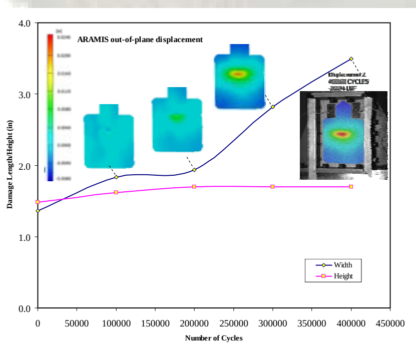


Details of damaged area & critical load conditions

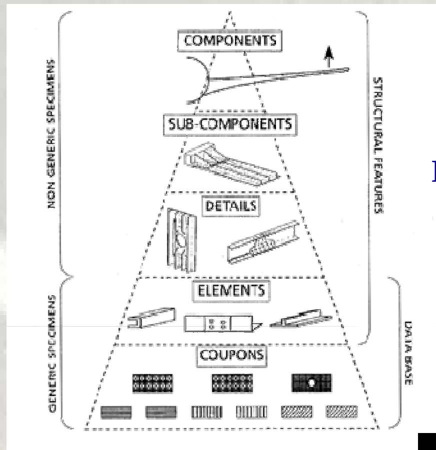


Scaled elements

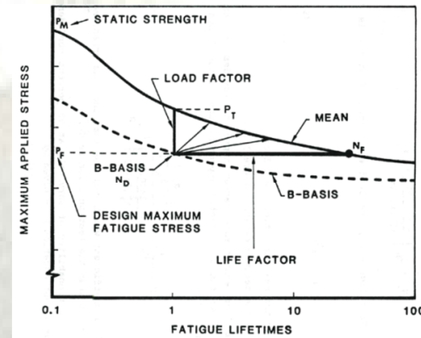




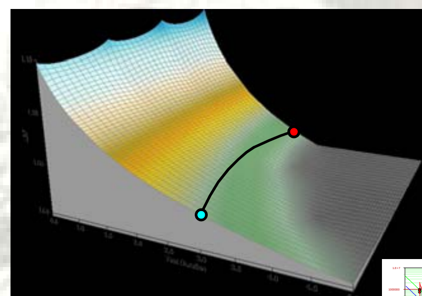
DaDT element tests

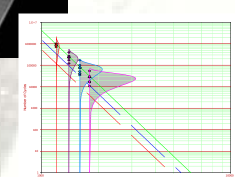


Durability & Damage Tolerance Phase



New LEF based on DaDT Element data scatter





Scatter analysis of DaDT element tests

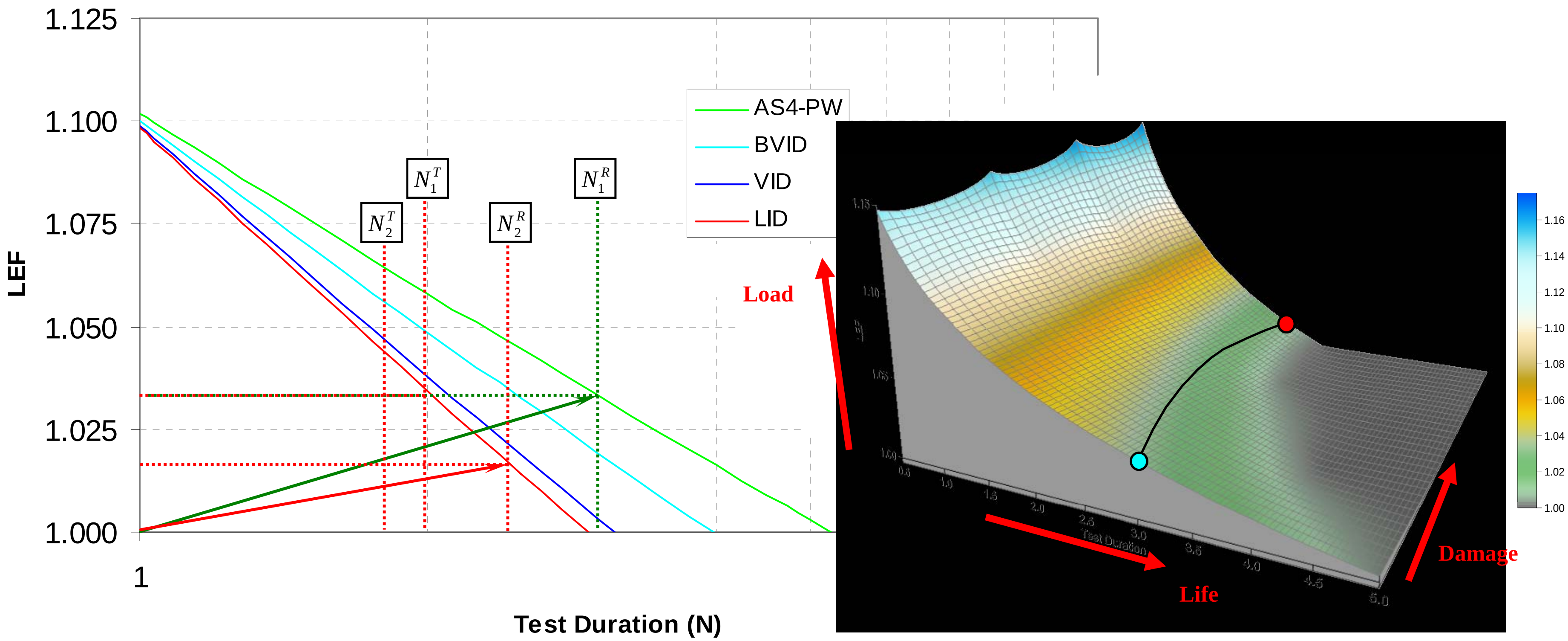
LLD Approach - Example

- New Required Test Duration:

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

Load-Life Shift

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



Composite Test Issues

Progressive Failure

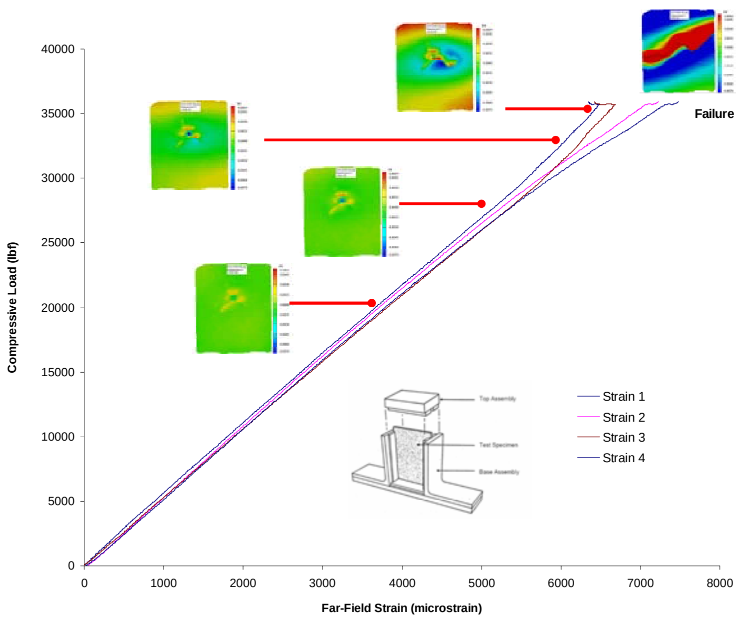
Flow Growth

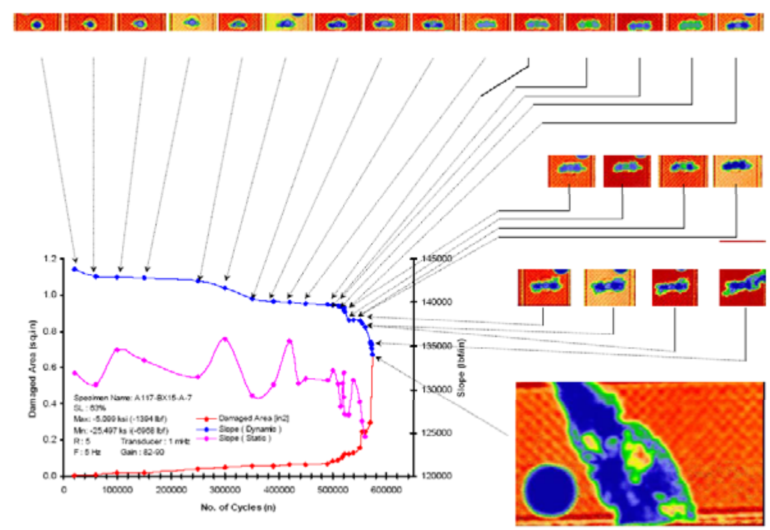
Fatigue & Damage Tolerance

Flaw Growth

- Compliance change is a function of material, layup, test environment, loading mode, stress level, etc.

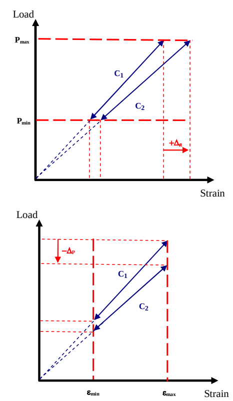
- Complex failure modes
- Require extensive NDI
- Variable B-basis (scatter) at different stress levels
- Truncation levels

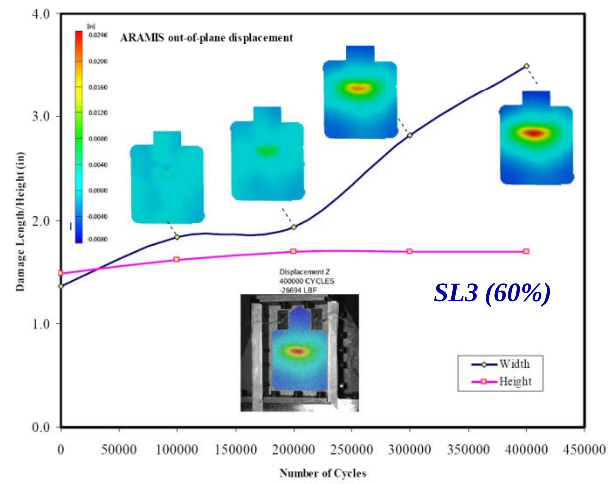


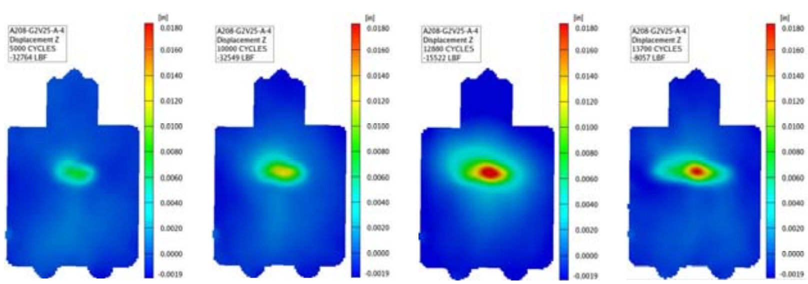


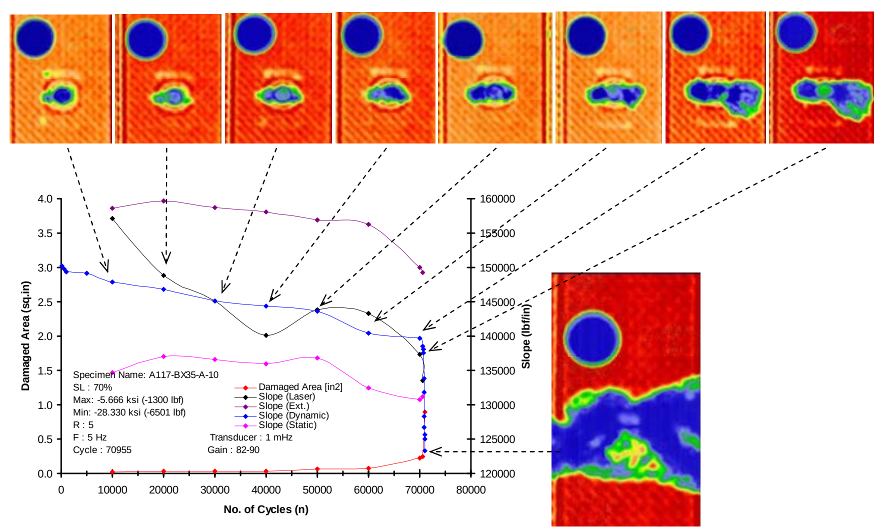
Damage-Tolerance Element Tests

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









Damage Tolerance Element Testing - CAI

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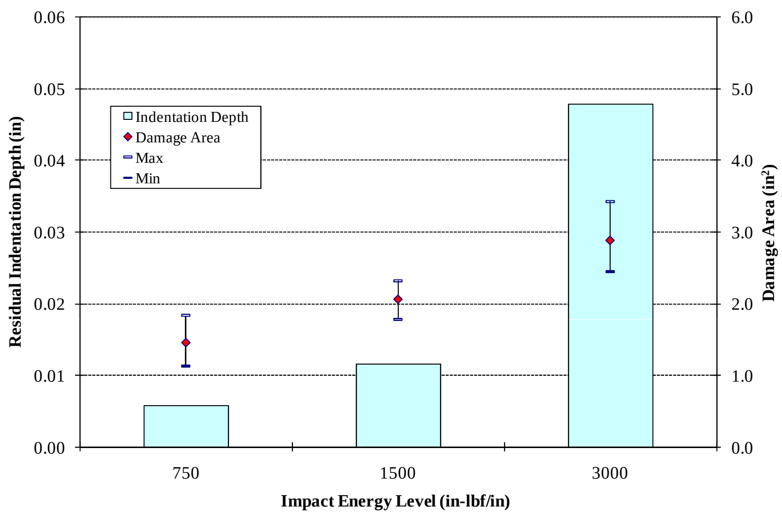
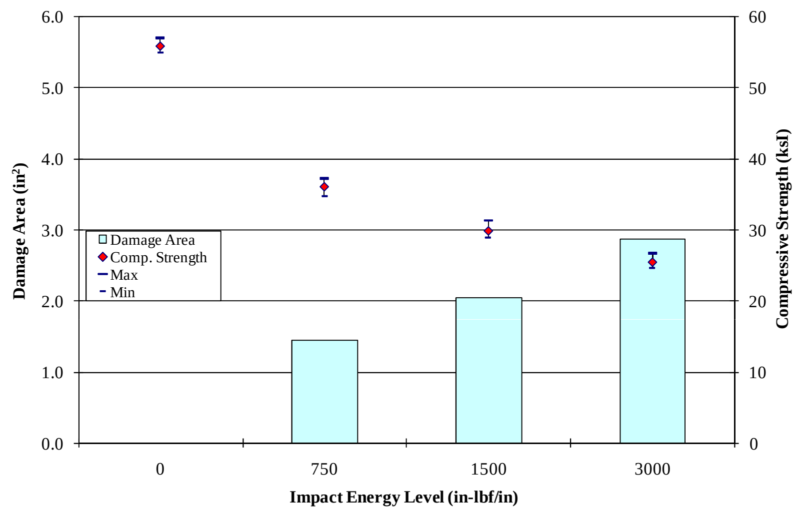
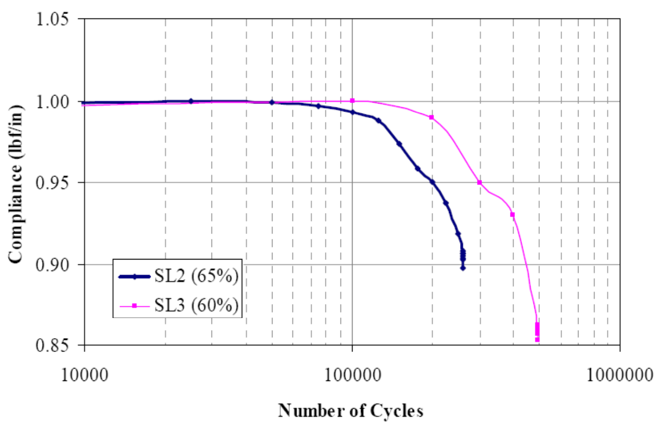
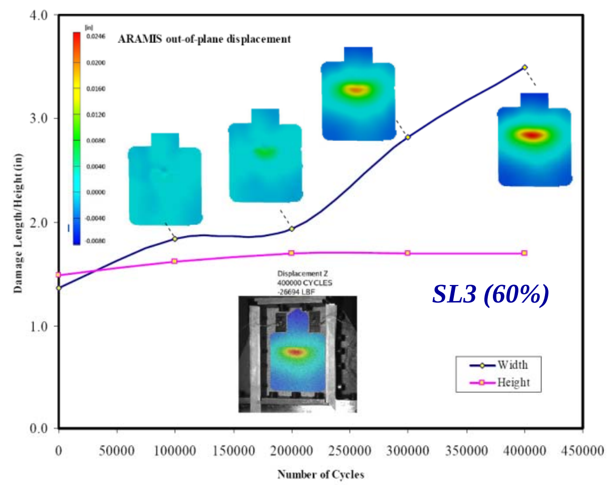


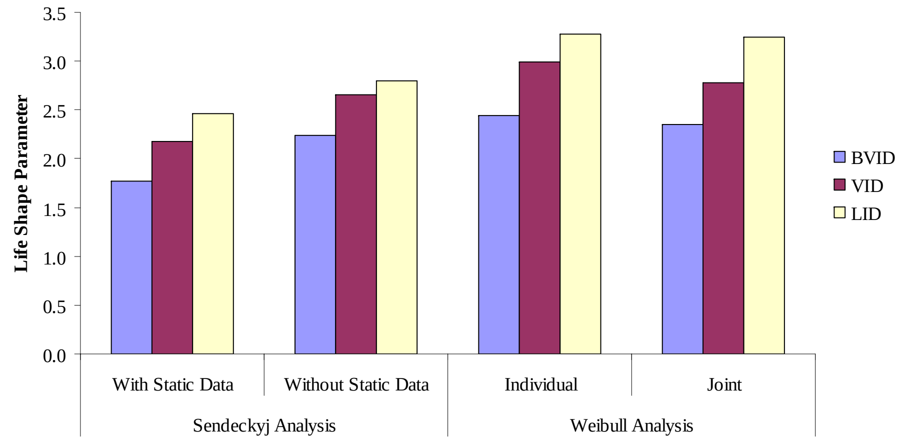


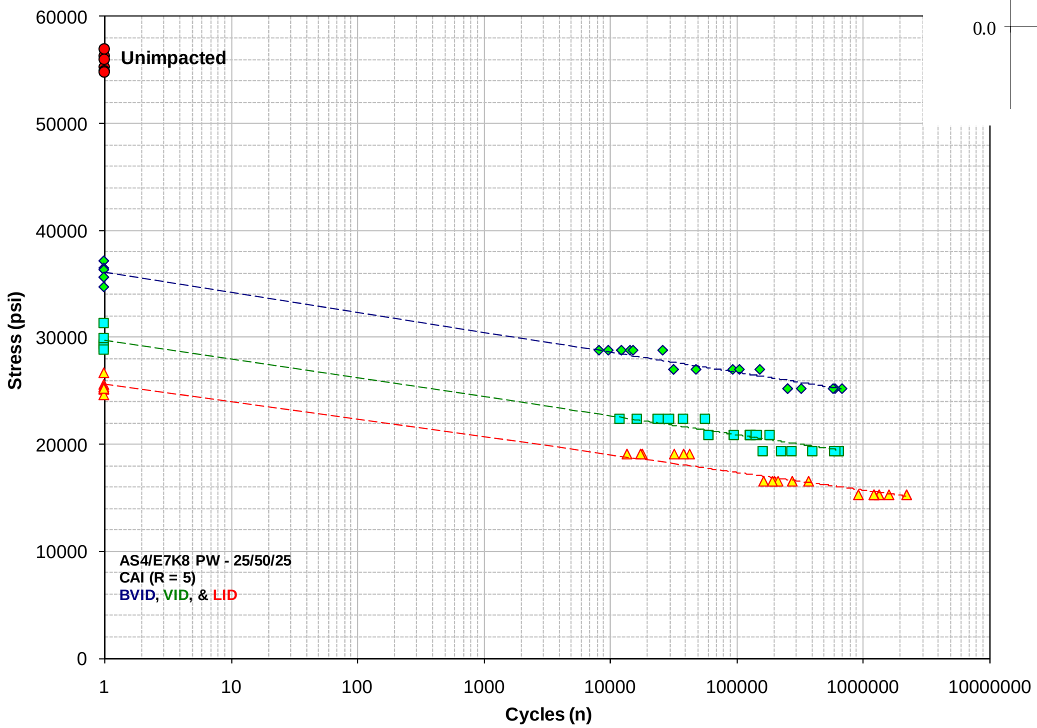


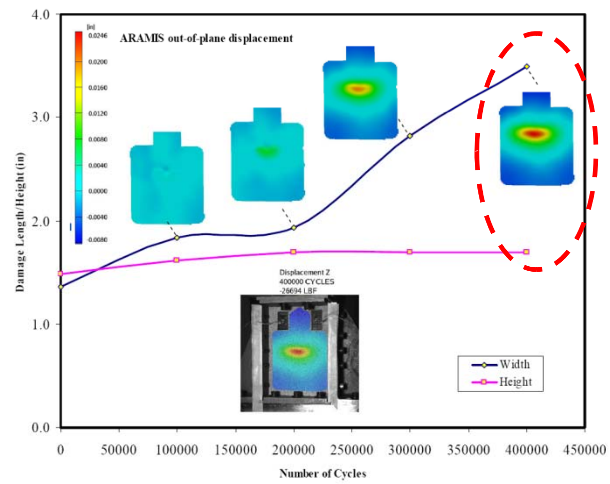


Effects of Damage on α

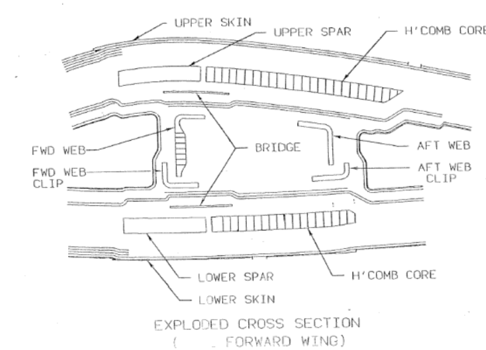
- Damage Tolerance Element Tests
  - Data scatter associated with final failure is conservative or representative of scatter at onset of damage propagation

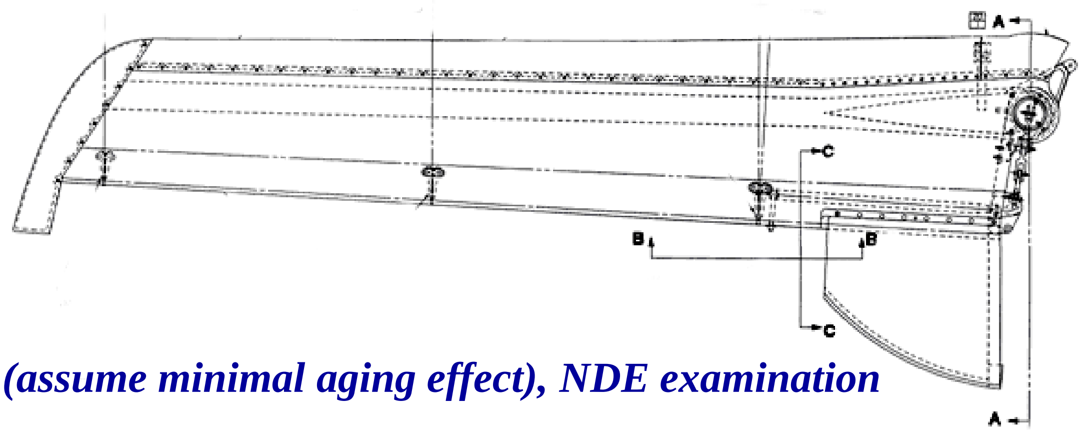






Full-Scale Validation

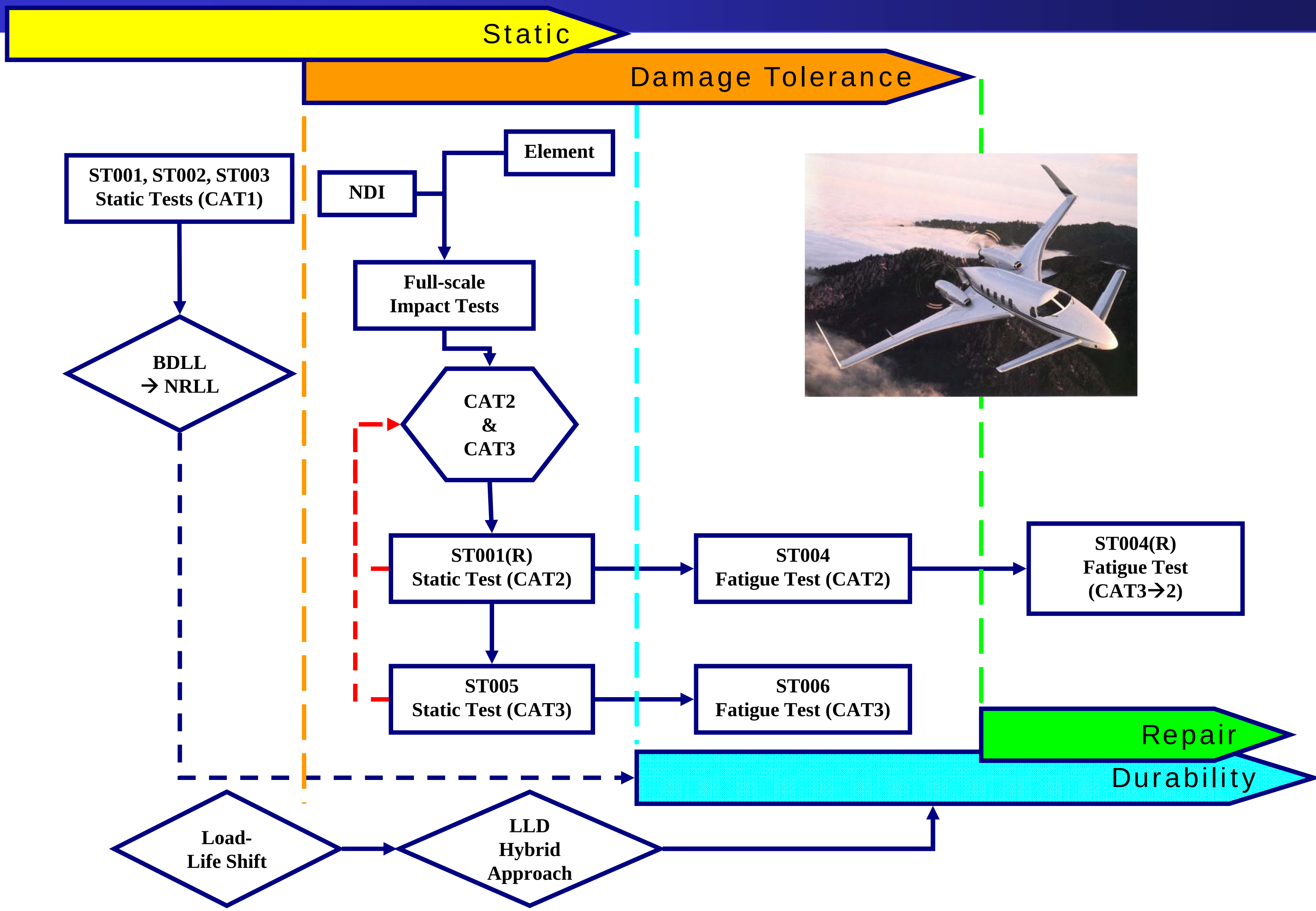




Six Beechcraft Starship Forward Wings (BSFW)

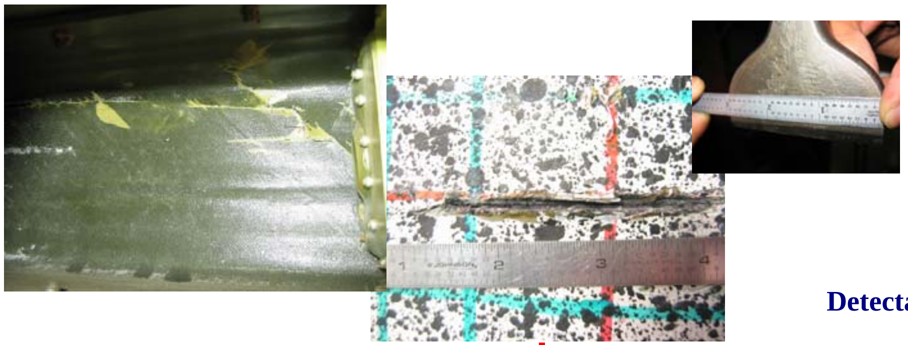
Approx. average of 1000 flight hours (assume minimal aging effect), NDE examination

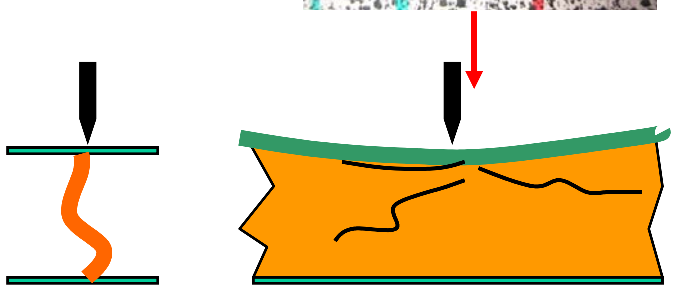
Full-Scale Validation

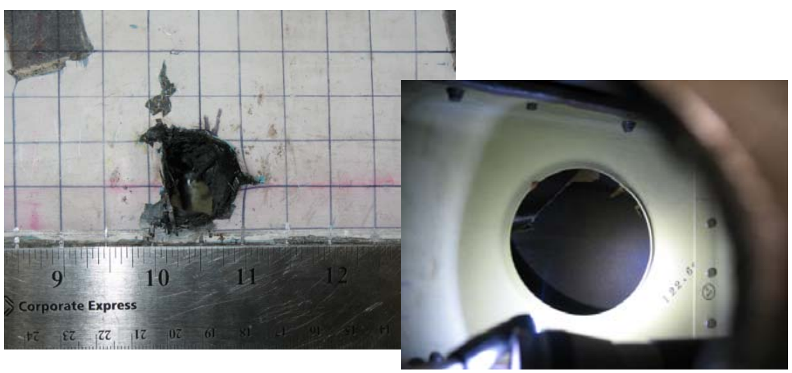


Damage Tolerance Certification

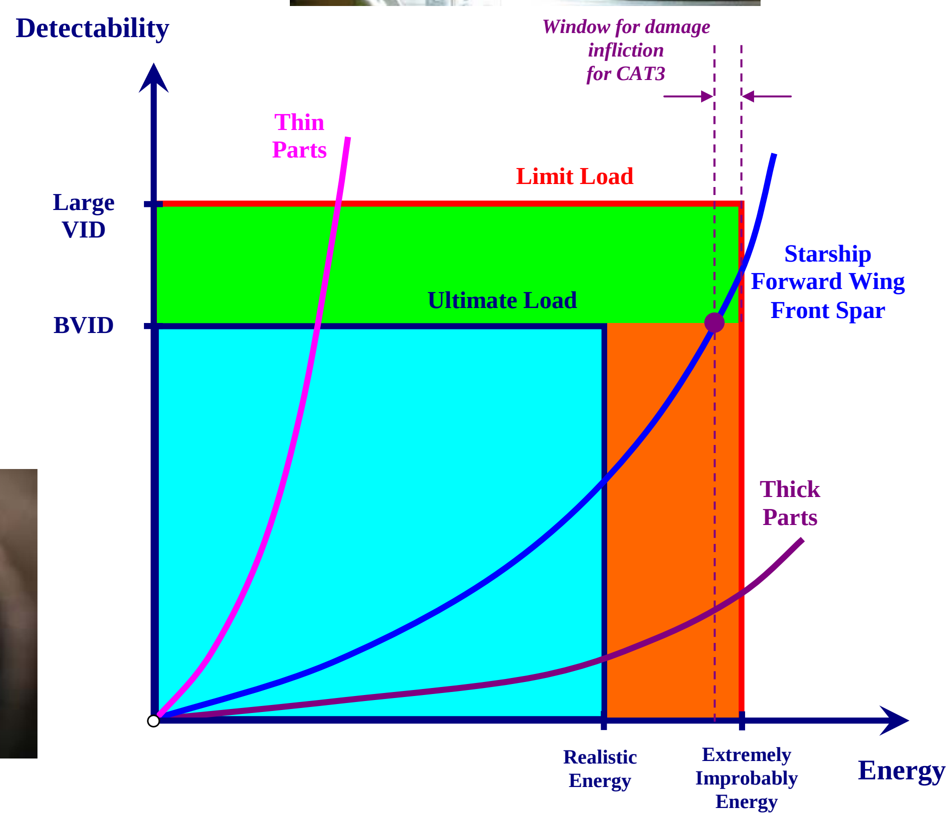
After 1000 ft-lb damage at FWS 66.5 (top skin – front spar)



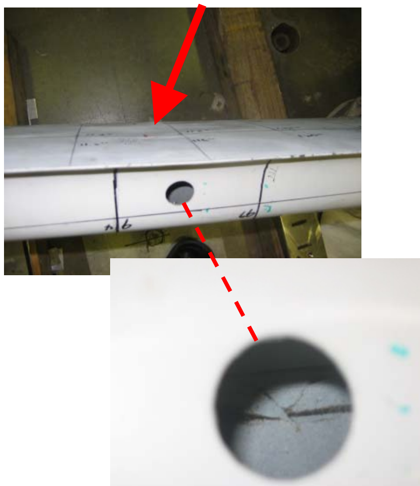




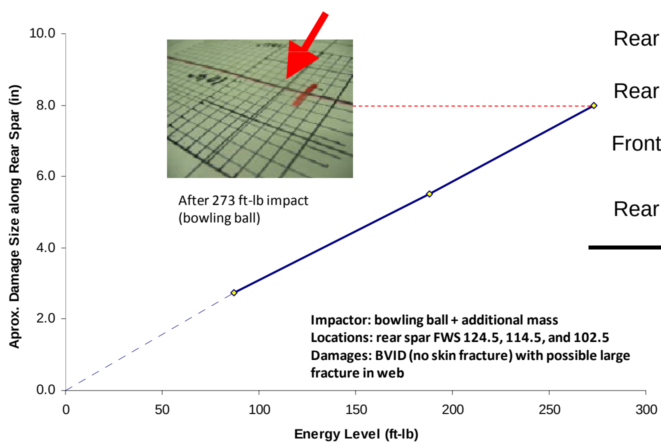
- Threshold of detectability
- Extremely improbable energy levels



Impact Trials



Spar	Location (FWS)	Drop Weight (lb)	Impactor	Support Span (in)	Drop Height (in)	Impact Energy		Notes
						in-lb	ft-lb	
Front	126.0	14.5	Bowling Ball	12	40	580	48	no visible damage on the surface or on the web
Front	126.0	14.5	Bowling Ball	Steel base	80	1160	97	no visible damage on the surface; some fracture along web-flange intersection
Front	126.0	14.5	Bowling Ball	Steel base	110	1595	133	no visible damage on the surface; some fracture along web-flange intersection
Front	112.0	31	3-inch Sphere	16	36	1116	93	no visible damage on the surface; some fracture along web-flange intersection
Front	106.0	31	3-inch Sphere	16	80	2480	207	no visible damage on the surface; some fracture along web-flange intersection
Front	51.0	31	3-inch Sphere	16	110	3410	284	no visible damage on the surface; some fracture along web-flange intersection
Rear	78.7	31	3-inch Sphere	16	72	2232	186	skin fracture + indent (web is not visible)
Rear	54.7	31	3-inch Sphere	16	72	2232	186	skin fracture + indent; no damage to web (close to control surface mount)
Rear	124.5	14.5	Bowling Ball	16	72	1044	87	indent + possible 2.75” fracture in the rear web
Rear	114.5	20.5	Bowling Ball	16	110	2255	188	indent + possible 5.5” fracture in the rear web
Rear	102.5	45.5	Bowling Ball	16	72	3276	273	indent + possible 8” fracture in the rear web
Rear	89.5	37.5	3-inch Sphere	16	72	2700	225	skin fracture + indent (web is not visible)
Front	89.5	37.5	3-inch Sphere	16	72	2700	225	no visible damage on the surface; web fracture
Rear	45.0	37.5	3-inch Sphere	16	72	2700	225	Visible Damage on surface + fracture in the web away from the control surface mount



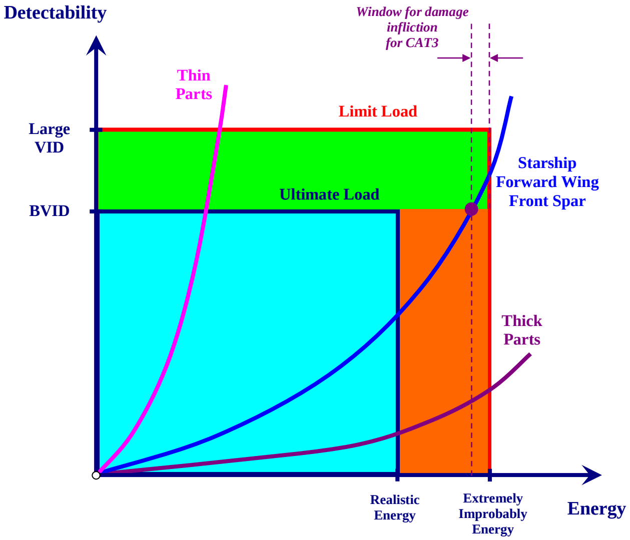
Front spar – no visible damage!!!

Rear spar – Skin fracture + small indent

Impact Trials (contd..)

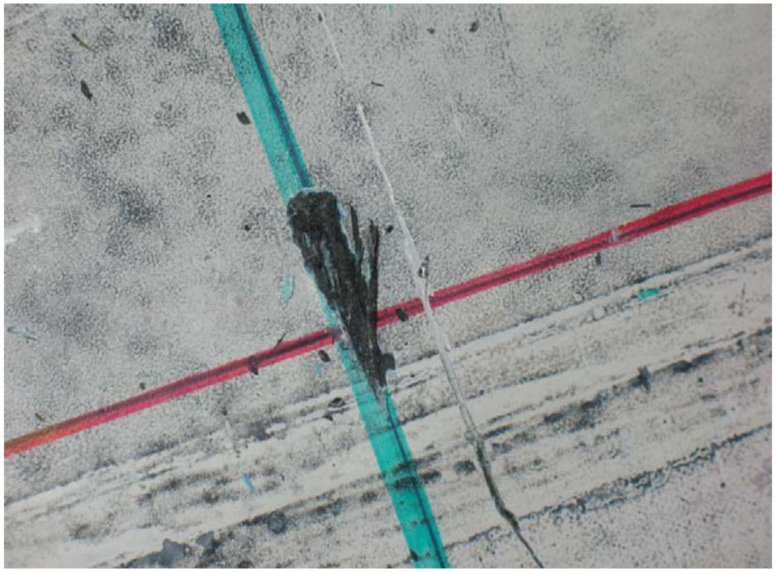
FWS (Front Spar)	Wedge	Mass (lb)	Drop Height (ft)	Energy (ft-lb)	Notes
120.5	1-inch	~15	6	~90	Localized surface damage at wedge contact line.
	1-inch	~15	10	~150	Localized surface damage at wedge contact line.
	1-inch	50.5405	10	~505	Localized surface damage at wedge contact line. Web delamination/fracture.
108.5	3-inch	50.5745	15	~759	Localized surface damage at wedge contact line. Web delamination/fracture.
	3-inch	50.5745	10	~506	Localized surface damage at wedge contact line. Web delamination/fracture.

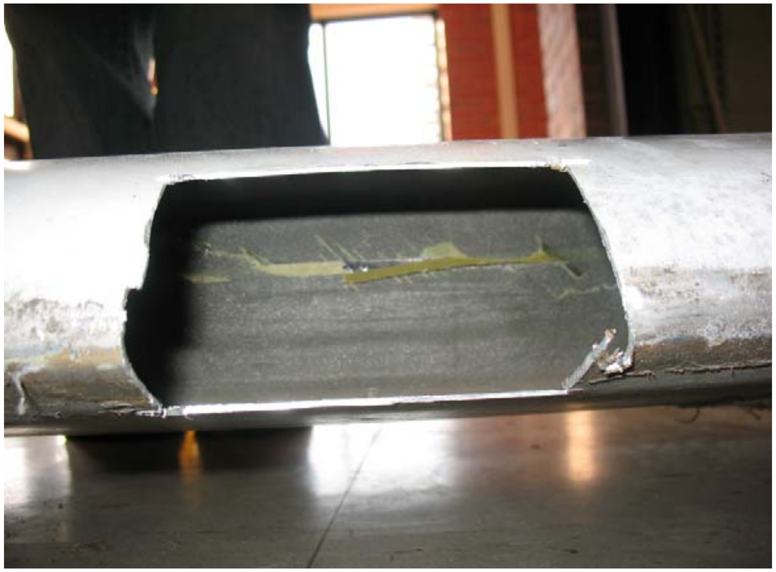
Digital tap hammer and bondmaster NDI revealed that the surface damage is localized and contained within the contact area. Severe damages to front web.



Impact Damage – 1-inch Wedge

- Damage to top skin at front spar (impact location)
- Damages to front web (below the impact location)

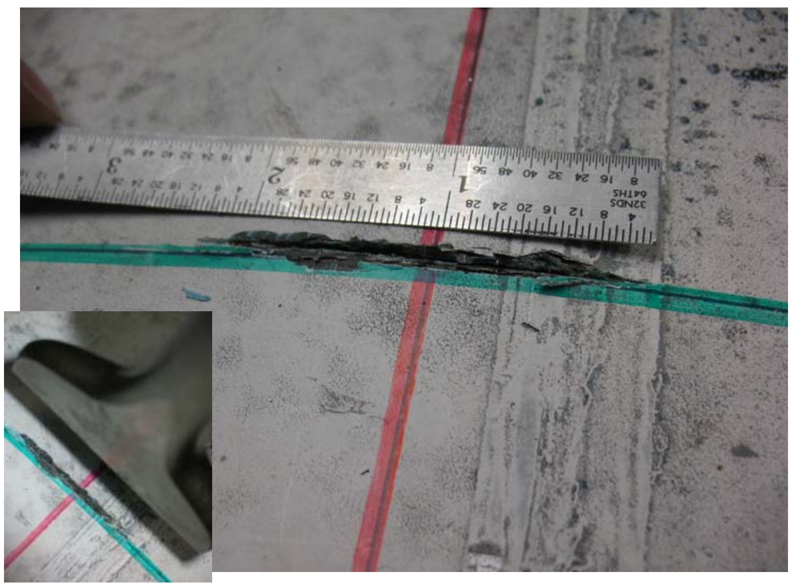


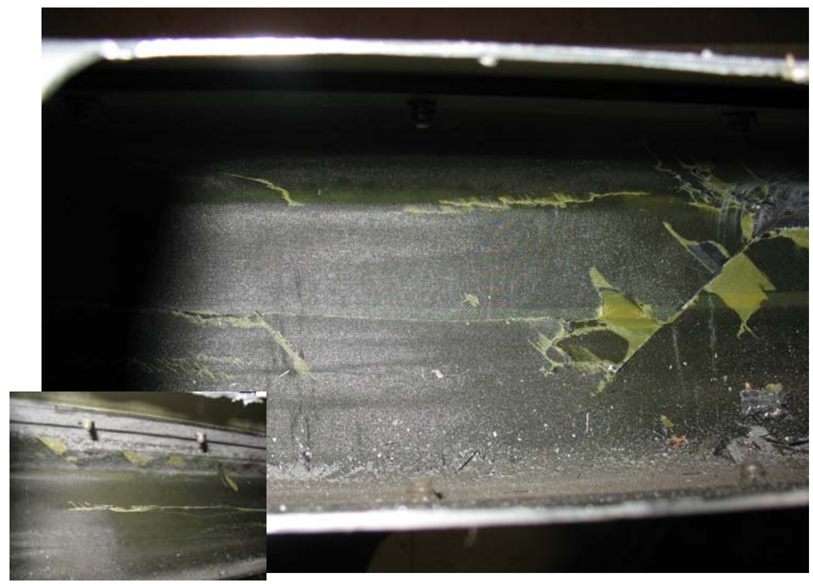


After 90, 150, and 500 ft-lb damages at FWS 120.5 (top skin – front spar)

Impact Damage – 3-inch Wedge

- Damage to top skin at front spar (impact location)
- Damages to front web (below the impact location)





After 750, and 500 ft-lb damages at FWS 108.5 (top skin – front spar)

Impact Parameter Determination

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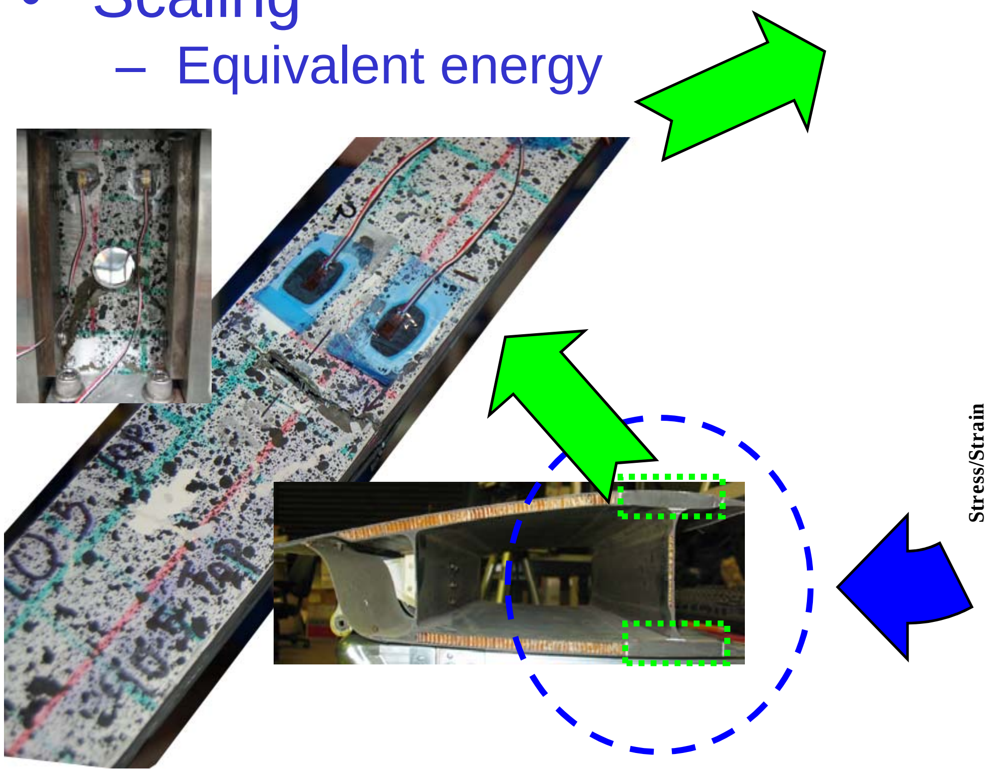
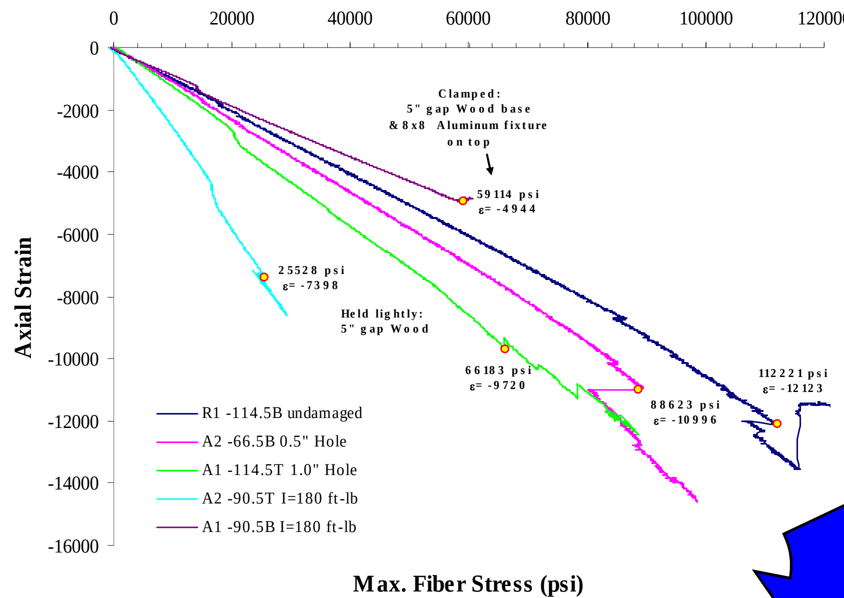
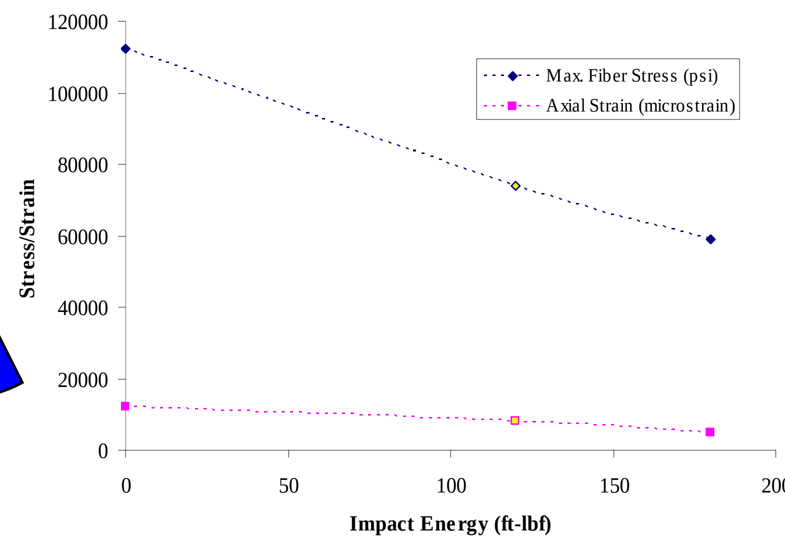
- Conservation of energy!
  - No energy lost!!!
  - Equivalent spring model
  - Impact factor
    - Equiv. static load to W
- Scaling
  - Equivalent energy

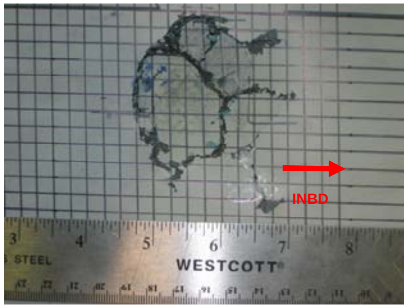


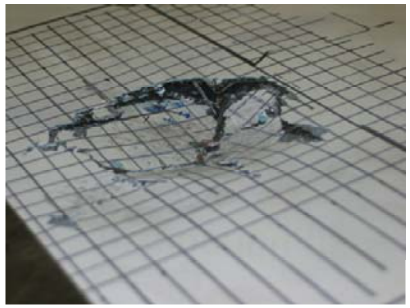


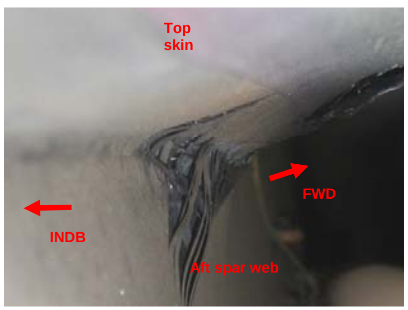


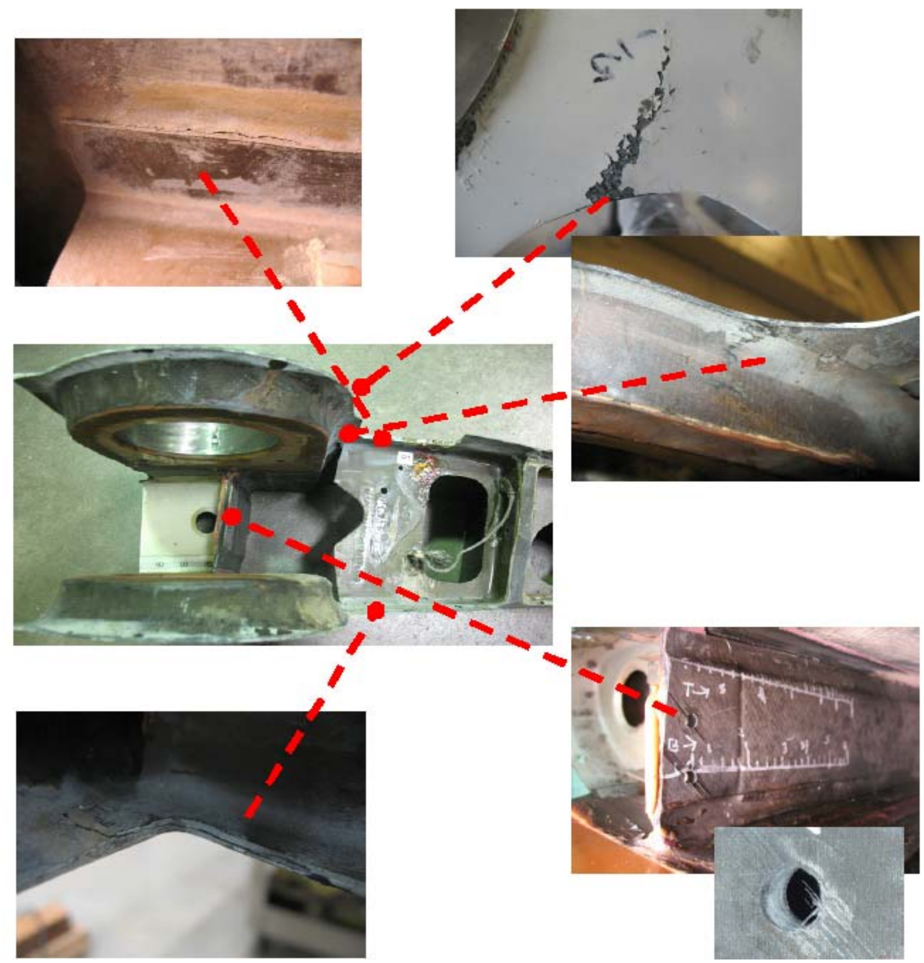
CAT2 – Aft Spar (FWS 45)

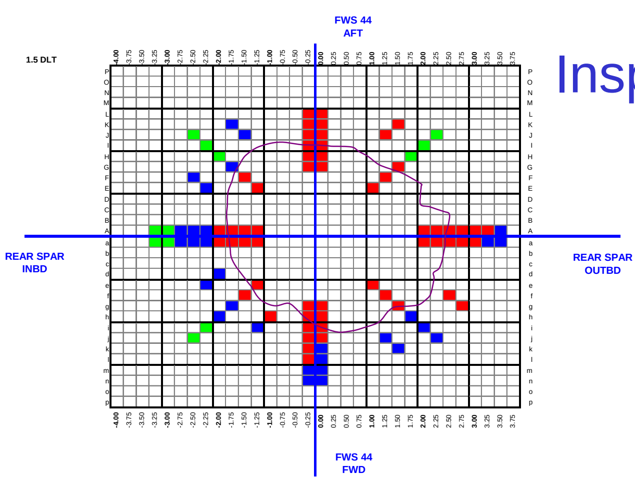
ST004 DaDT (Impact Damage)





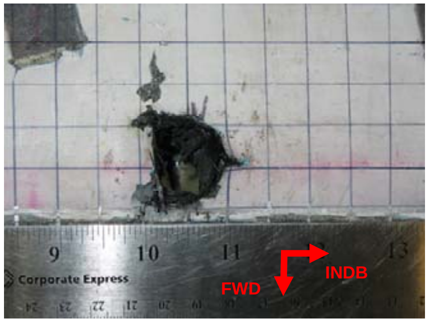


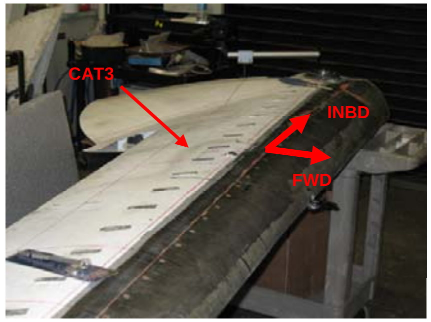


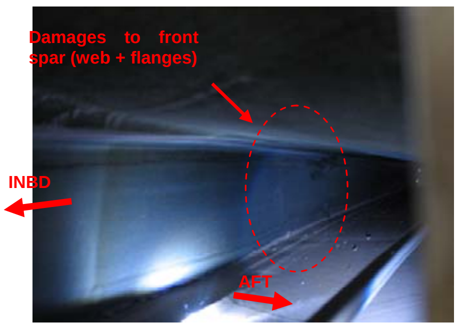


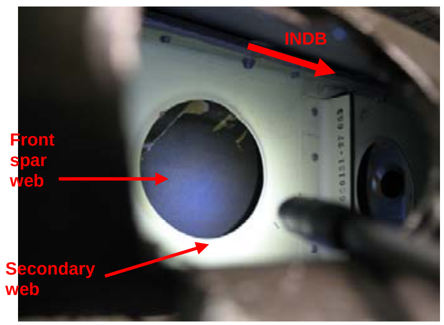
Inspections after 1.5 DLT

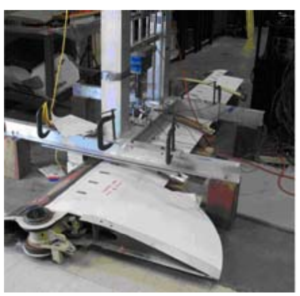
CAT3 – Front Spar (FWS 65)





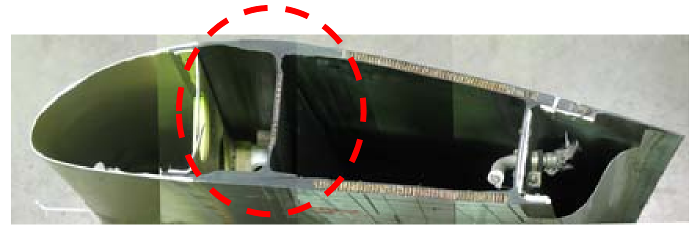


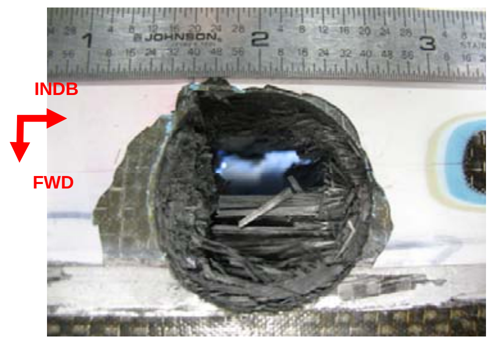


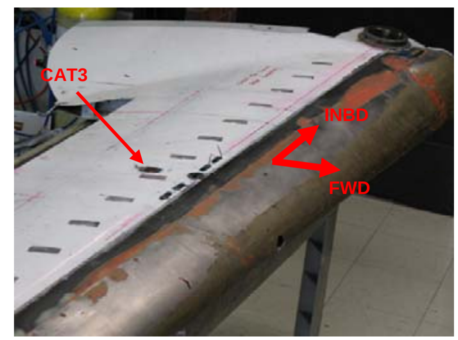


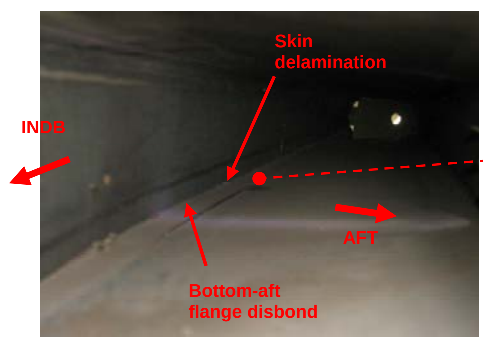
- ST006 DaDT

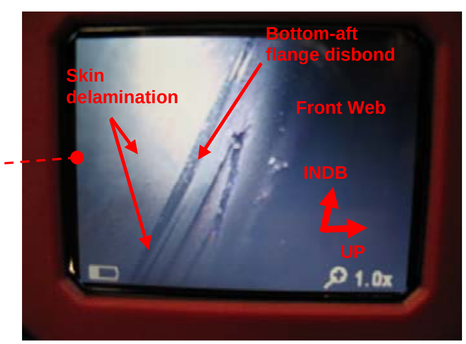
- ST005 Static











Cumulative Fatigue Unreliability

Reliability Analysis

Inspection Intervals

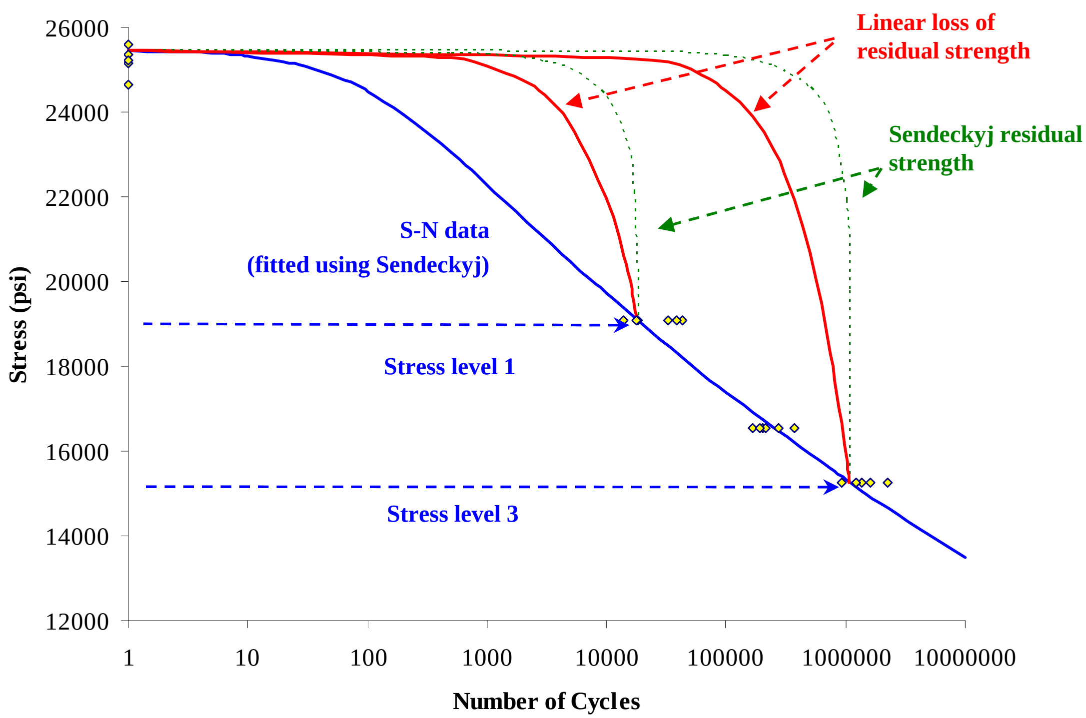
Residual Strength Degradation

- Sendeckyj Wearout Model:

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

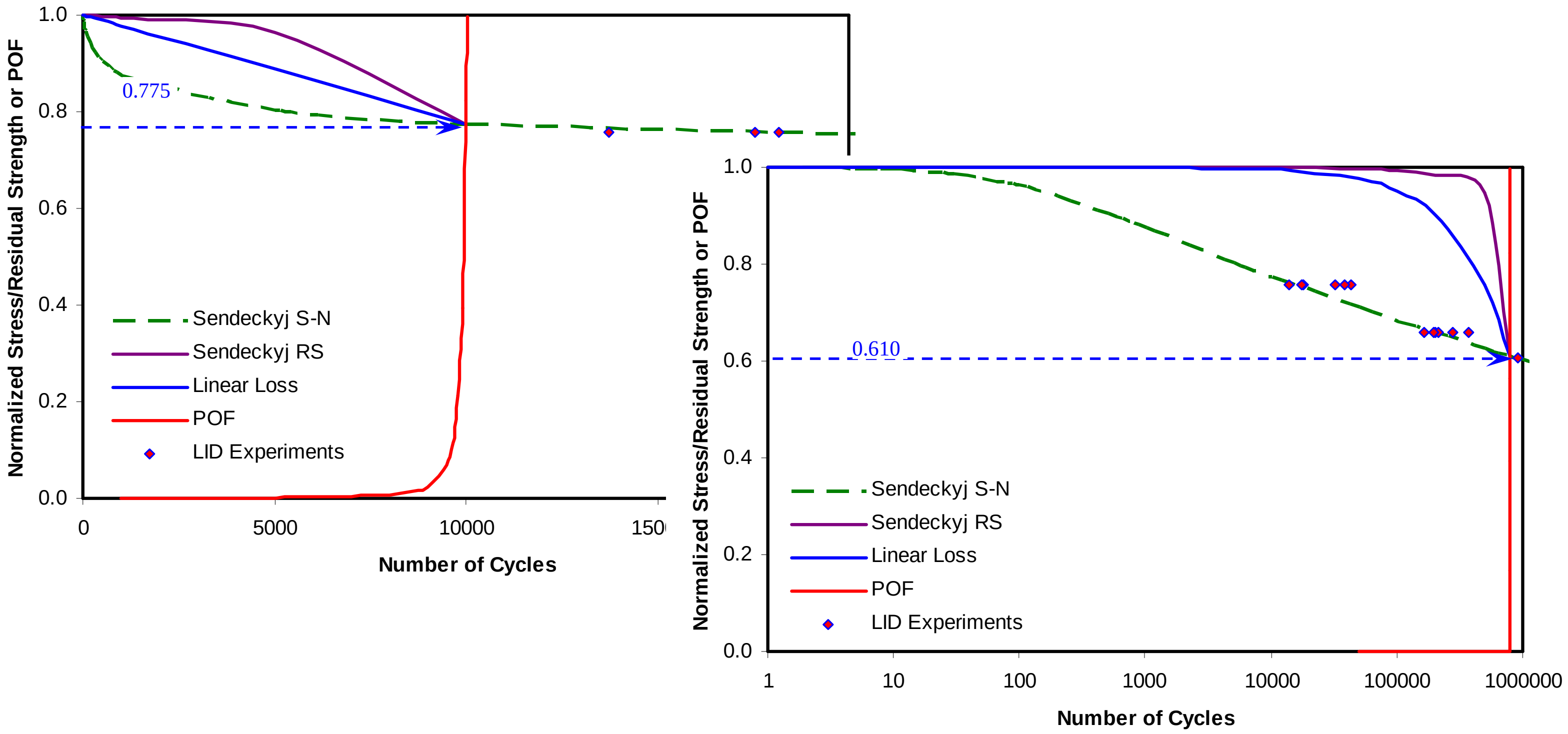
- Linear Loss of Residual Strength:

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



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

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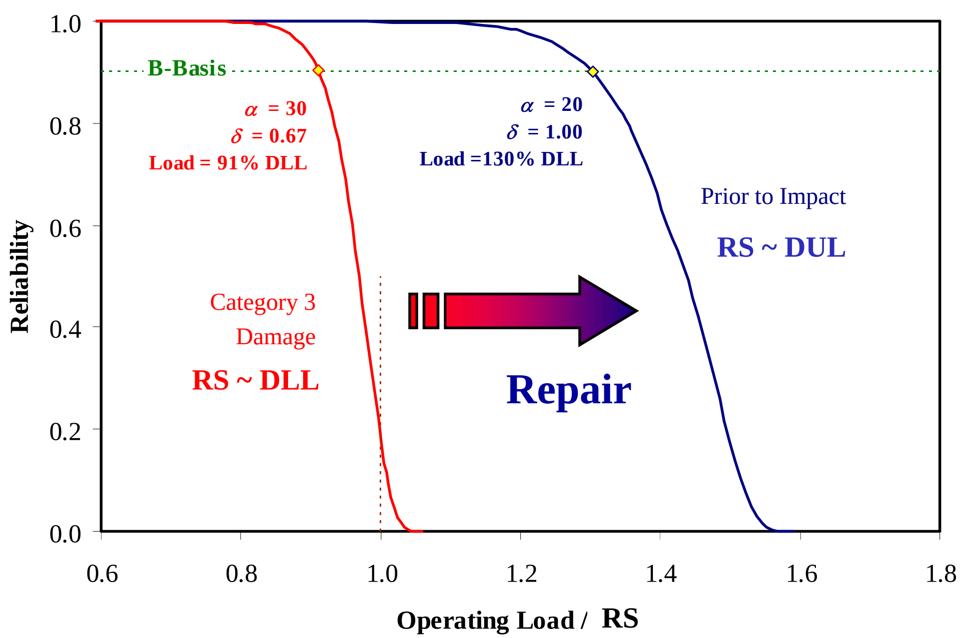
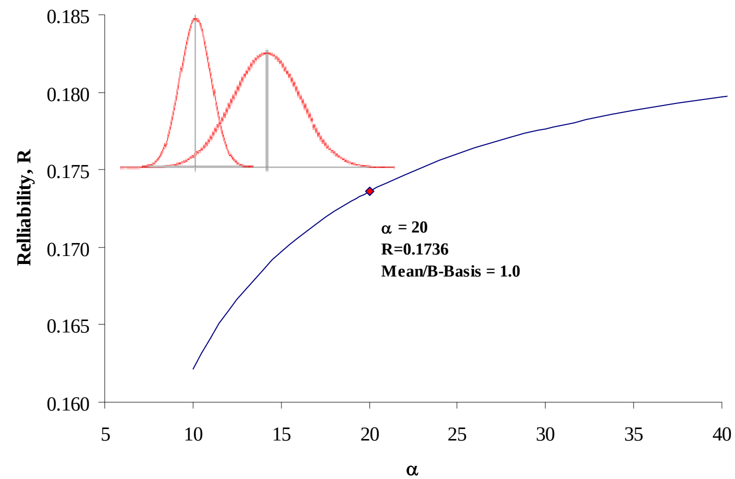


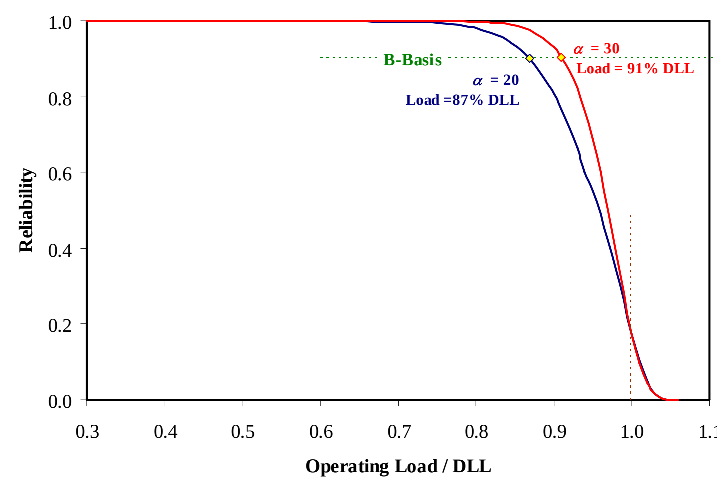


Reliability of Residual Strength after CAT3

Cumulative Fatigue Unreliability

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

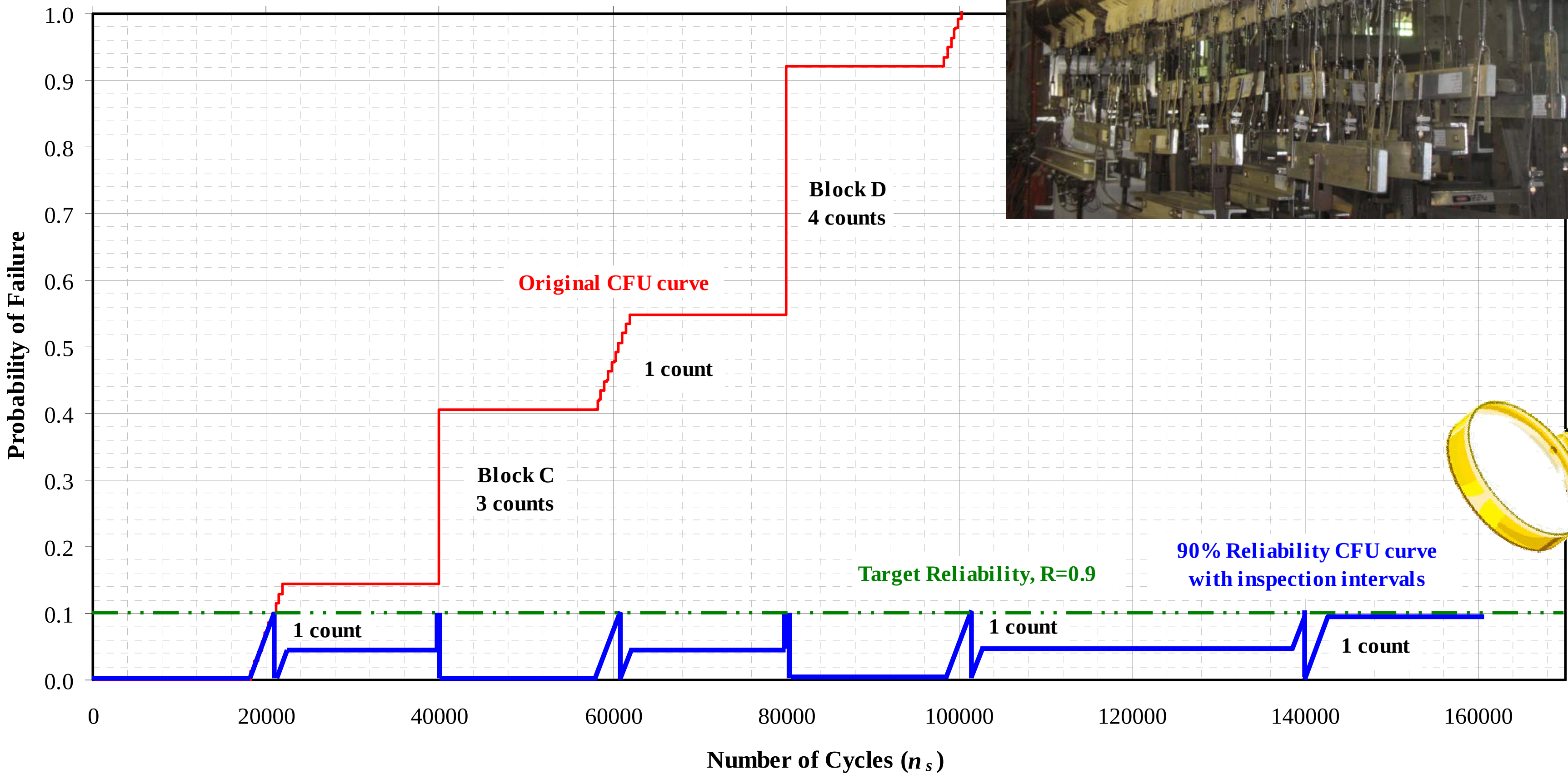
$$P_f = \sum_{i=1}^{n_S} P_{f_i} \quad \Rightarrow \quad P_f \geq 1 - TR \rightarrow Failure$$



Effects of Shape Parameter of CAT3 Distribution

Inspection Intervals

- Full-scale test fatigue spectrum
- Target Reliability = 0.90
  - Critical Damage Threshold
  - POF Threshold ➔ 0.10



Health Monitoring & Damage Evolution

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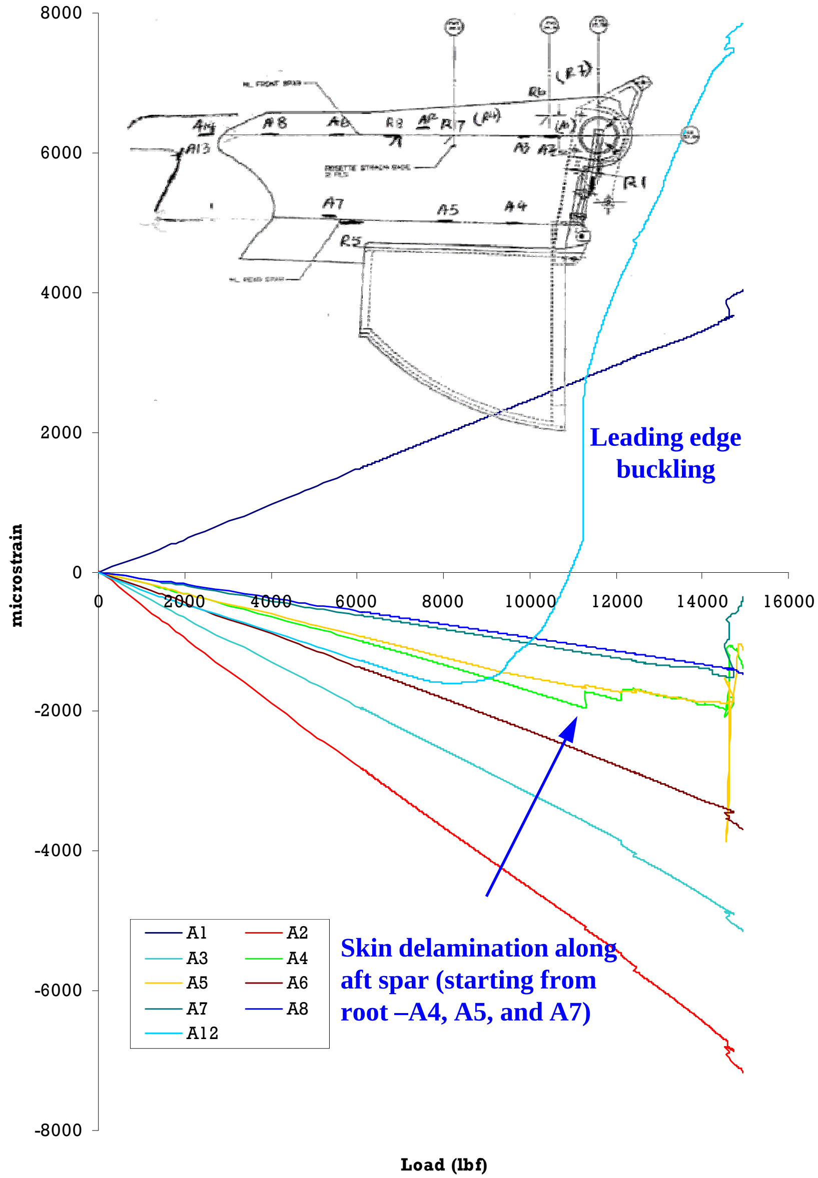

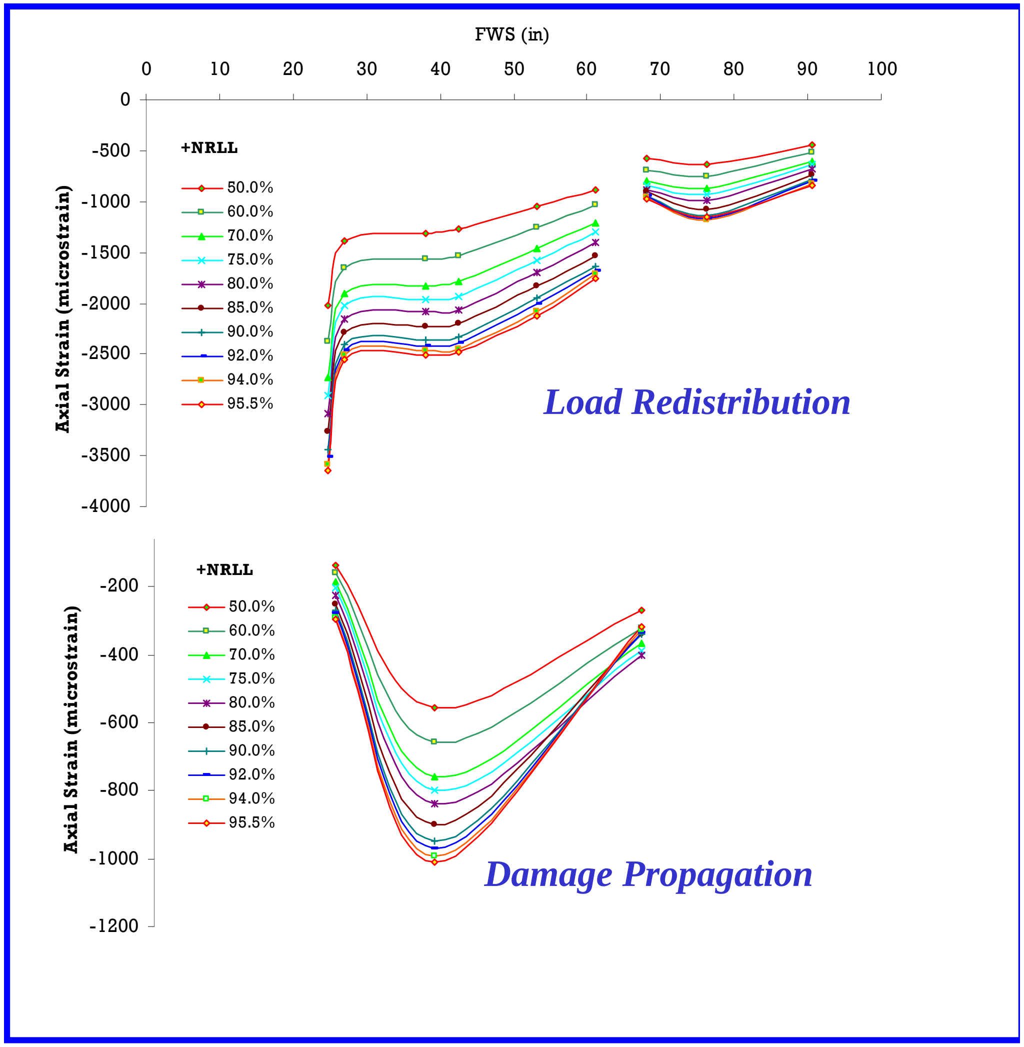

Damage Propagation during Residual Strength Test

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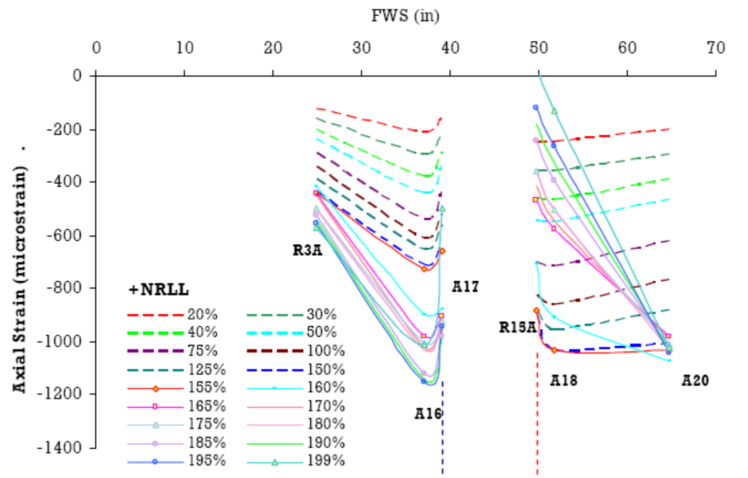
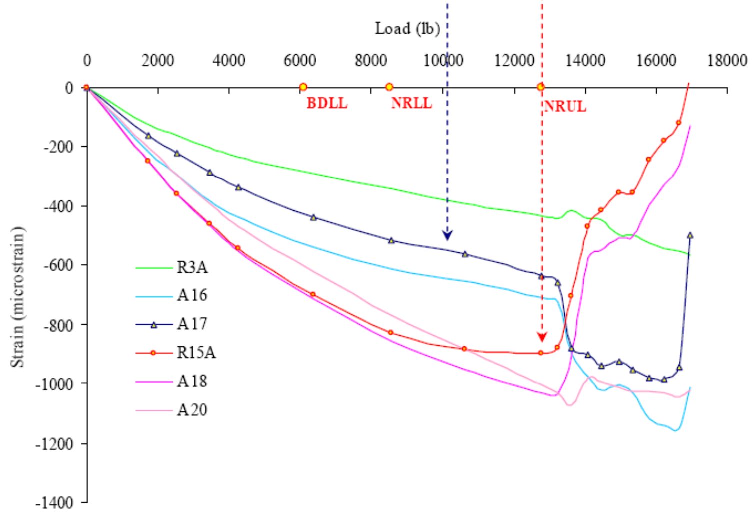
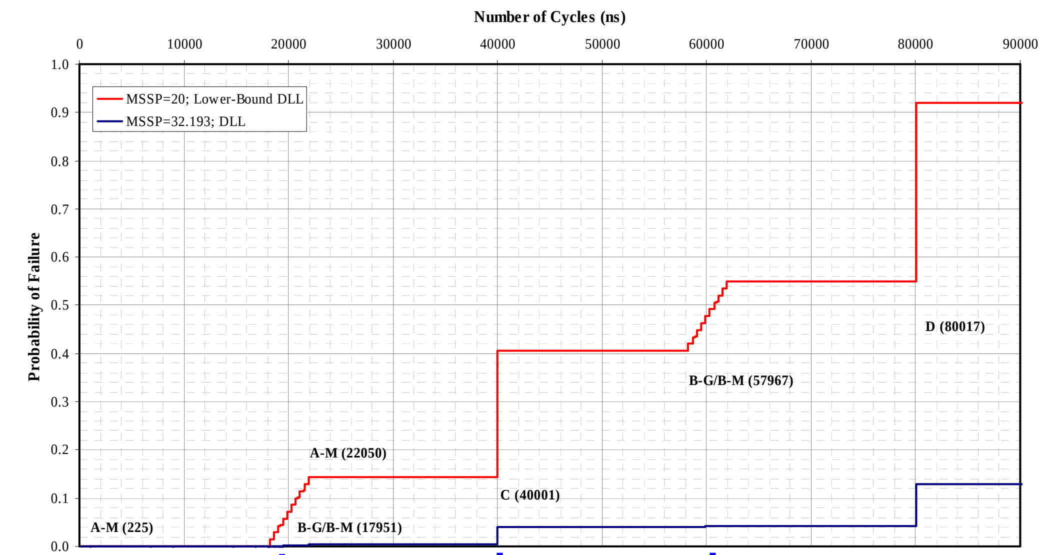
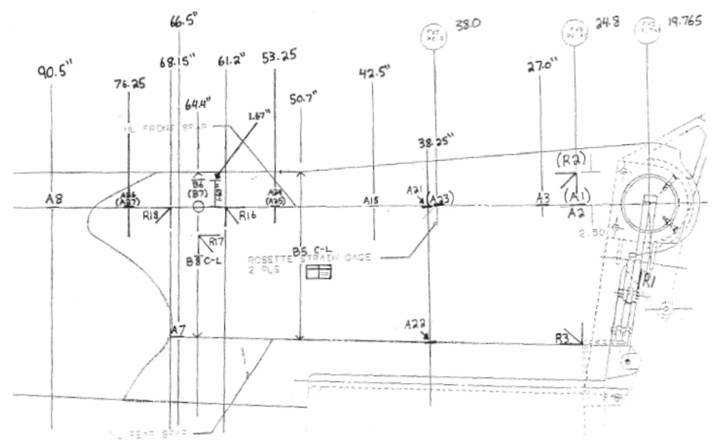


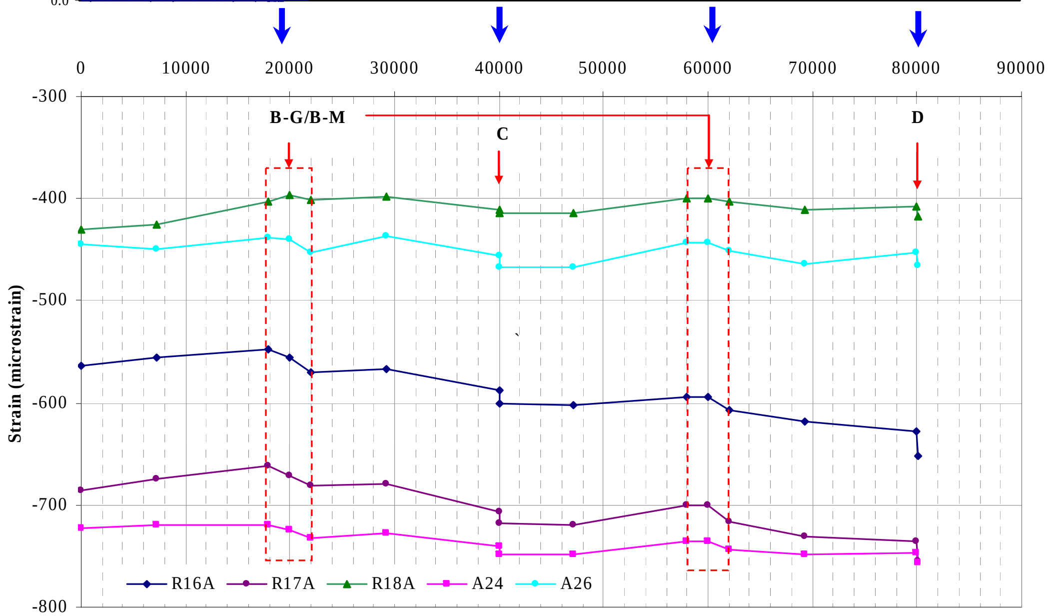


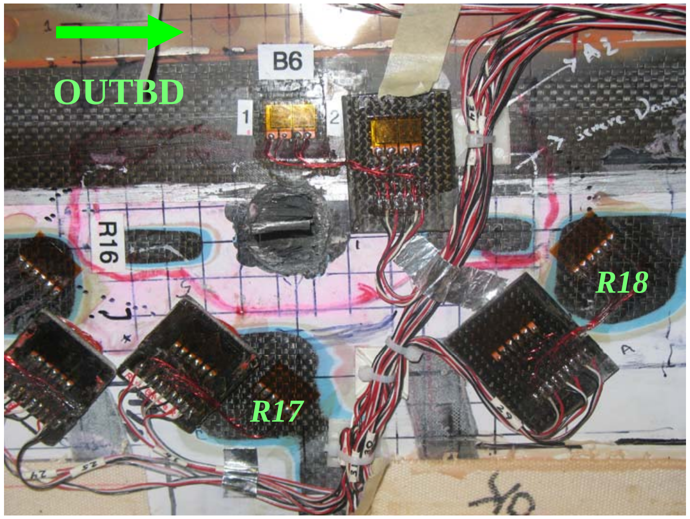
Damage progression along aft spar (top skin) of ST004 (CAT2 damage) during residual strength test after 2-DLT cyclic test

CAT3 DaDT – ST006



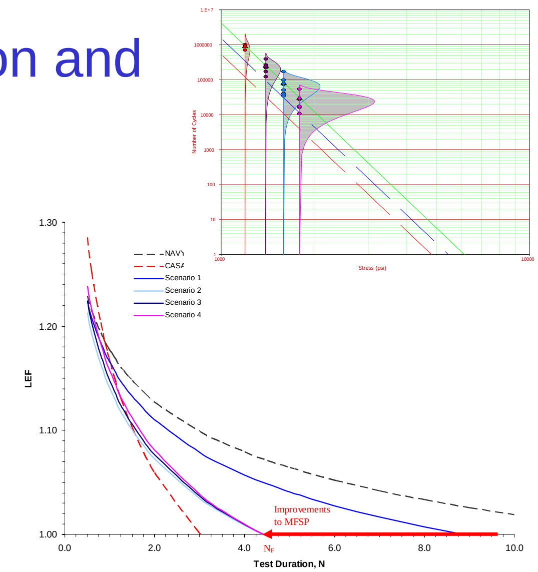


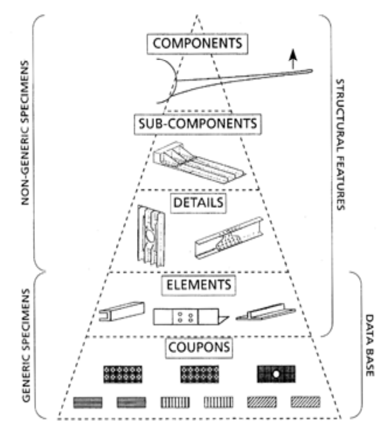




– Summary –
Load Enhancement Factor

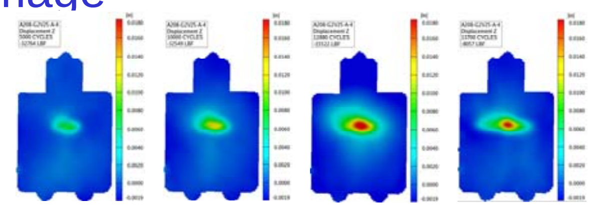
- Integrate design specific details gained from coupon and subelement tests into the LEF approach
  - Layup, loading modes/R ratios, Environments, ..
  - Bonded joints, interlaminar shear, sandwich, ..
- Address evolution/maturity of material systems, manufacturing processes, test techniques, etc.
  - Reduced test matrix
  - Shared database concept
- 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





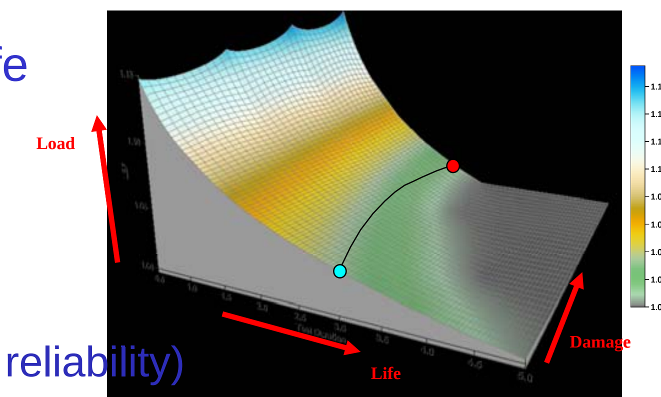
– Summary –
Load-Life-Damage Approach

- **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

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