JAMS

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

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A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

WICHITA STATE UNIVERSITY

NIAR
RESEARCH / DESIGN / TESTING / CERTIFICATION

CECAM
center of excellence for composites and advanced materials

The Joint Advanced Materials and Structures Center of Excellence

Motivation & Key Issues

- **Produce a guideline FAA document, which demonstrates a “best practice” procedure for full-scale testing protocols for composite airframe structures with examples**

- 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

Objectives

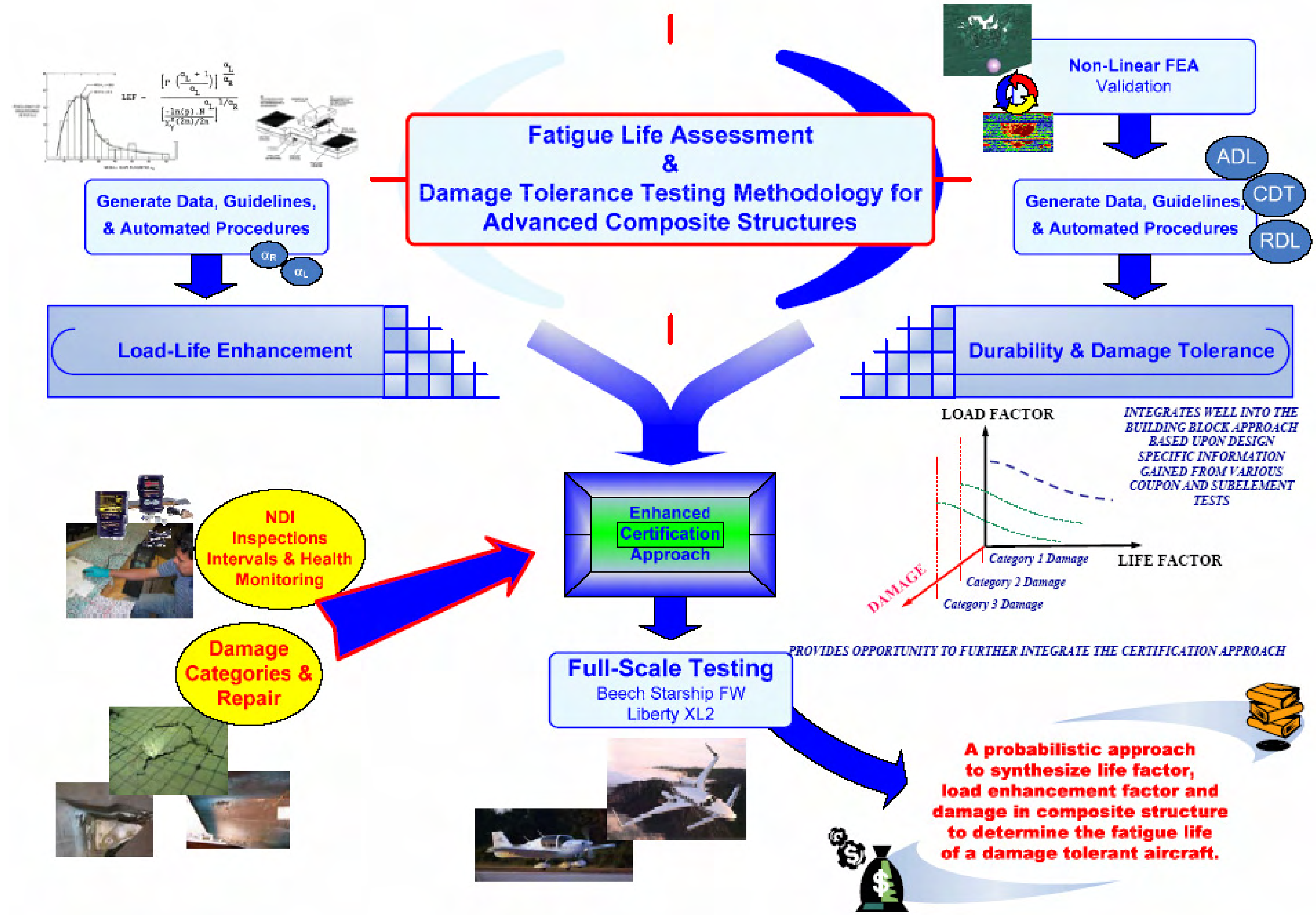
Primary Objective

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

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

Approach


Non-Linear FEA Validation
Fatigue Life Assessment & Damage Tolerance Testing Methodology for Advanced Composite Structures
Generate Data, Guidelines, & Automated Procedures
Generate Data, Guidelines, & Automated Procedures
ADL
CDT
RDL
Load-Life Enhancement
Durability & Damage Tolerance
LOAD FACTOR
INTEGRATES WELL INTO THE BUILDING BLOCK APPROACH BASED UPON DESIGN SPECIFIC INFORMATION GAINED FROM VARIOUS COUPON AND SUBELEMENT TESTS
LIFE FACTOR
DAMAGE
Category 1 Damage
Category 2 Damage
Category 3 Damage
NDI Inspections Intervals & Health Monitoring
Enhanced Certification Approach
Damage Categories & Repair
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.

JAMS FAA Sponsored Project Information

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CECAM

- **Principal Investigators**
  - Dr. John Tomblin and Waruna Seneviratne
- **FAA Technical Monitor**
  - Curt Davis
- **Other FAA Personnel Involved**
  - Dr. Larry Ilcewicz
  - Peter Shyprykevich (consultant ret. FAA)

NIAR
RESEARCH / DESIGN / TESTING / CERTIFICATION

- **Industry Participation**

Cessna A Textron Company
Hawker Beechcraft
TORAY
Liberty AEROSPACE
CIRRUS DESIGN
BOEING
SPIRIT AEROSYSTEMS
ADAM AIRCRAFT
AlphaSTAR CORPORATION

Workshops for Composite
Damage Tolerance & Maintenance

2008 CMH-17: PMC Forum & DTTG Meeting

2007 FAA/CACRC/EASA - Amsterdam, Netherlands

2006 FAA Workshop - Chicago, IL

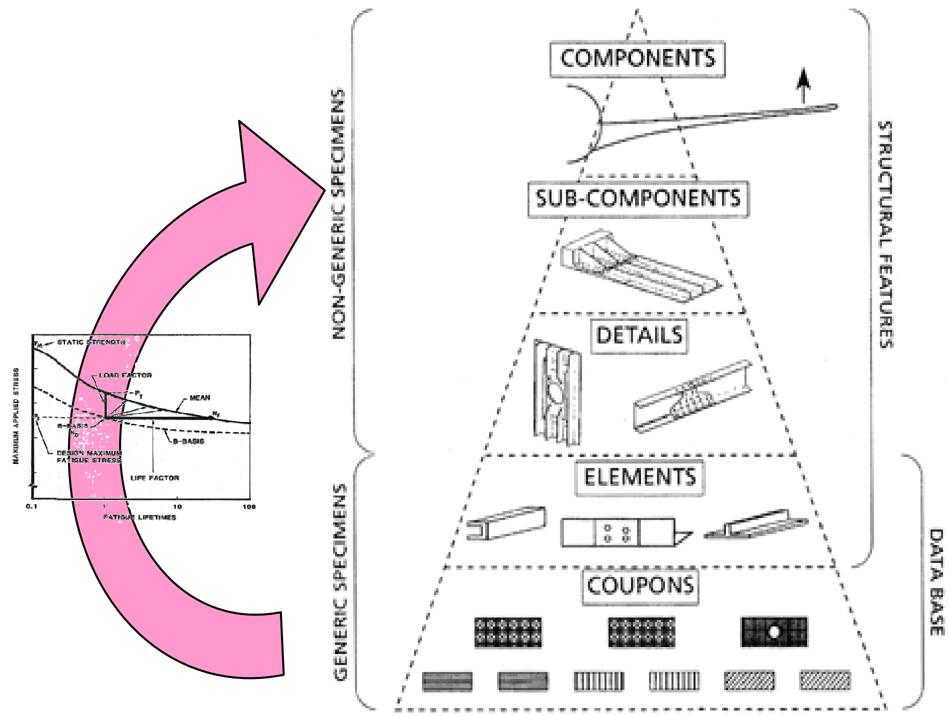
Transport Aircraft Applications

We all think about these applications … but …

Other Applications of Advanced Materials

Scatter Analysis

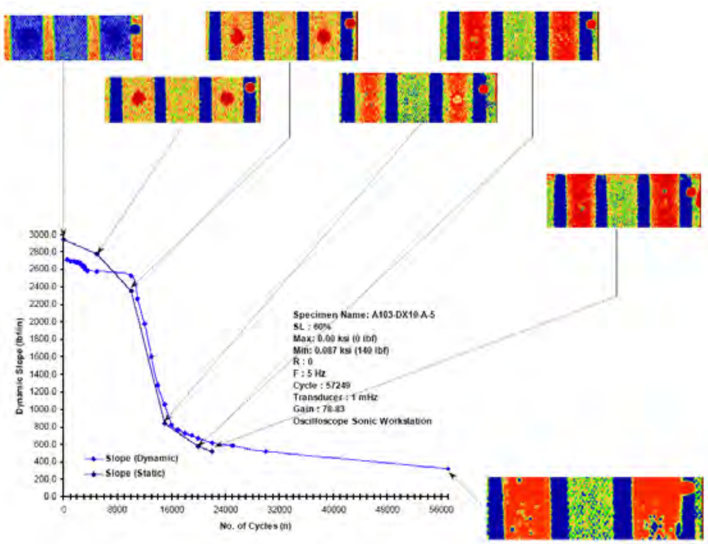
- Background – most test programs reference the Navy/FAA reports by Whitehead, *et. al.*, (1986) and follow that approach
  - Most test programs have used the conclusions developed in this report regardless of design features, failure modes and/or materials
- EADS-CASA study used the same approach (2001) but redefined the shape factors

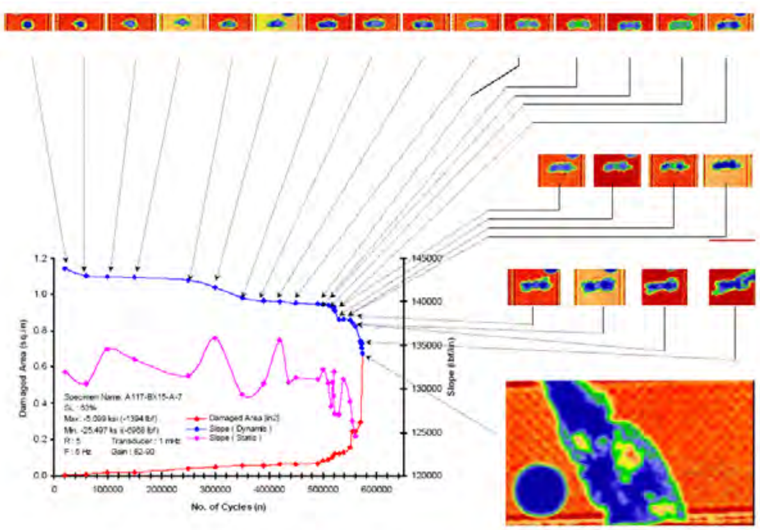


Integrates well into building-block approach based upon design-specific information gained from various coupon and element

Flaw Growth

- Complex failure modes
- Require extensive NDI
- Variable B-basis (scatter) at different stress levels
- Compliance change is a function of material, layup, test environment, loading mode, stress level, etc.





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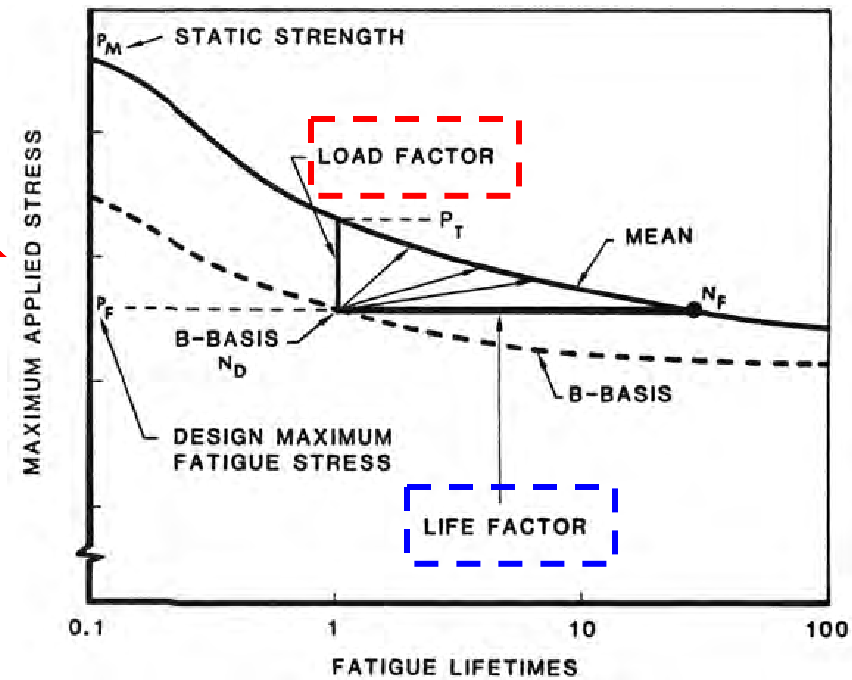
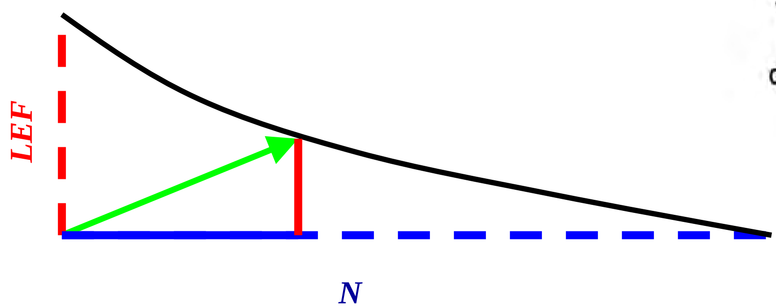
Load-Life Combined Approach

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

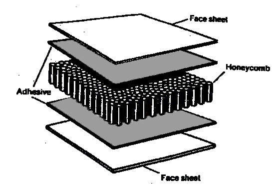


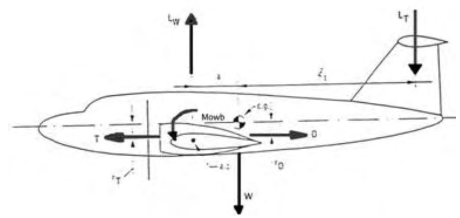


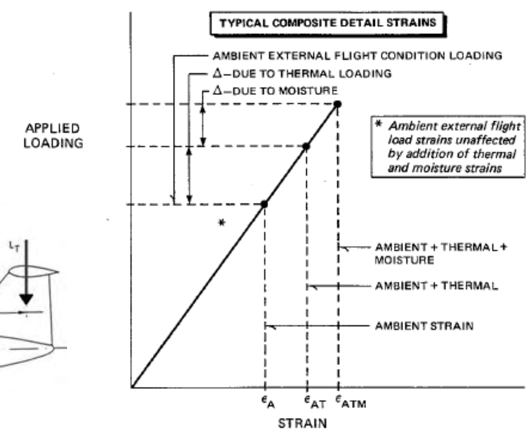
Structure is tested for additional fatigue life to achieve the **desired level of reliability**

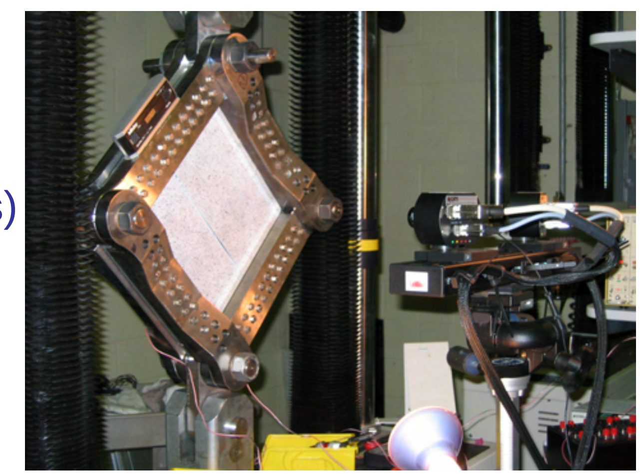
Material Databases

- FAA-LEF
  - » AS4/E7K8 PW
  - » T700/#2510 PW
  - » 7781/#2510 8HS
- FAA-Laminate
  - » T700/#2510 UNI
  - » T700/#2510 PW
  - » T700/E765 UNI
  - » T300/E765 PW
  - » AS4C/MTM45 UNI
  - » AS4C/MTM45 8HS
- FAA-Adhesive Fatigue
  - » Loctite Paste
  - » PTM&W paste (two bondline thicknesses)
  - » EA 9696 film
- FAA-Adhesive Effects of Defects
  - » T700/#2510 PW & EA9394







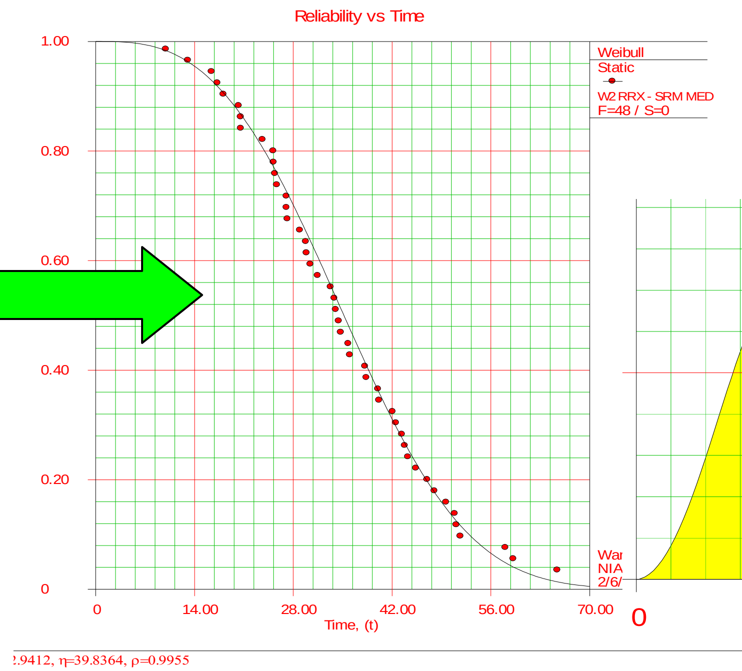


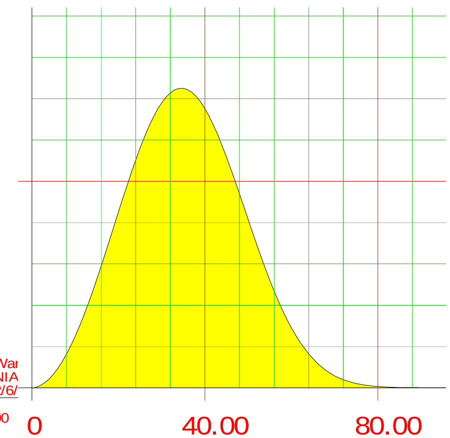
Shared Databases

40/20/40	Single Shear Bearing-Tension -- (RTD)	45.4085
	Double Shear Bearing-Tension -- (RTD)	49.696
	Bearing-Bypass 50%-Tension	43.4258
	Bearing-Bypass 50%-Compression	42.102
	Bearing-Bypass 50%-Tension [t/D=0.475]	40.0401
	Bearing-Bypass 50%-Tension [t/D=0.570]	42.5935
	Bearing-Bypass 50%-Tension [t/D=0.949]	38.1976
	Open Hole-Tension [w/D=6]	27.2021
	Filled Hole-Tension	20.2959
	No Hole-Tension	29.8203
	No Hole-Compression	20.5843
	Open Hole-Compression	30.4534
	Critical Hole-Tension -- (CTD)	29.9075
	Critical Hole-Tension -- (ETD)	25.1923
	V-Notched Rail Shear	59.2079
	Open Hole-Tension [w/D=3]	20.594
	Open Hole-Tension [w/D=4]	27.0538
	Open Hole-Tension [w/D=8]	25.4413
25/50/25	Double Shear Bearing-Tension -- (CTD)	25.7206
	Double Shear Bearing-Tension -- (RTD)	43.8267
	Double Shear Bearing-Tension -- (ETW)	34.7752
	Single Shear Bearing-Tension -- (CTD)	28.956
	Single Shear Bearing-Tension -- (RTD)	18.1315
	Single Shear Bearing-Tension -- (ETW)	33.8501
	Bearing-Bypass 50%-Tension	44.2636
	Bearing-Bypass 50%-Compression	48.0284
	Open Hole-Tension [w/D=6] -- (CTD)	35.8156
	Open Hole-Tension [w/D=6] -- (RTD)	34.0488
	Open Hole-Tension [w/D=6] -- (ETW)	25.2227
	No Hole-Tension -- (CTD)	51.1531
	No Hole-Tension -- (RTD)	40.1864
	No Hole-Tension -- (ETW)	38.383
	No Hole-Compression -- (CTD)	31.498
	No Hole-Compression -- (RTD)	27.0743
	No Hole-Compression -- (ETW)	23.6762
	Open Hole-Compression -- (CTD)	34.4747
	Open Hole-Compression -- (RTD)	46.9989
	Open Hole-Compression -- (ETW)	33.3186
	V-Notched Rail Shear	16.4582
10/80/10	Bearing-Bypass 50%-Tension	65.4454
	Bearing-Bypass 50%-Compression	74.3601
	Open Hole-Tension [w/D=6]	51.7133
	No Hole-Tension	58.0843
	No Hole-Compression	36.0558
	Open Hole-Compression	50.909
	V-Notched Rail Shear -- (CTD)	9.9634
	V-Notched Rail Shear -- (RTD)	17.2784
	V-Notched Rail Shear -- (ETW)	13.1027

Laminate Statistical Allowable Generation for Fiber-Reinforced Composite Materials: Lamina Variability Method

[DOT/FAA/AR-06/53]





T700SC-12K-50C/#2510 -Plain Weave Fabric

863 specimens

α	**2.941**
β	**39.836**

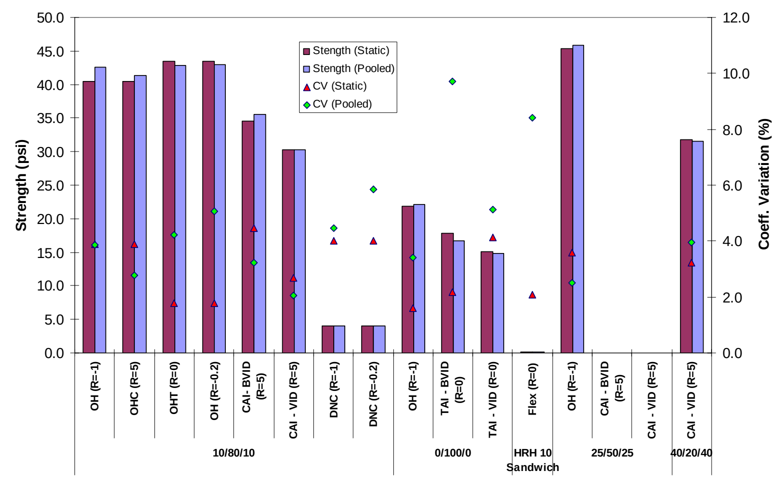
MODAL (EXTREAM)

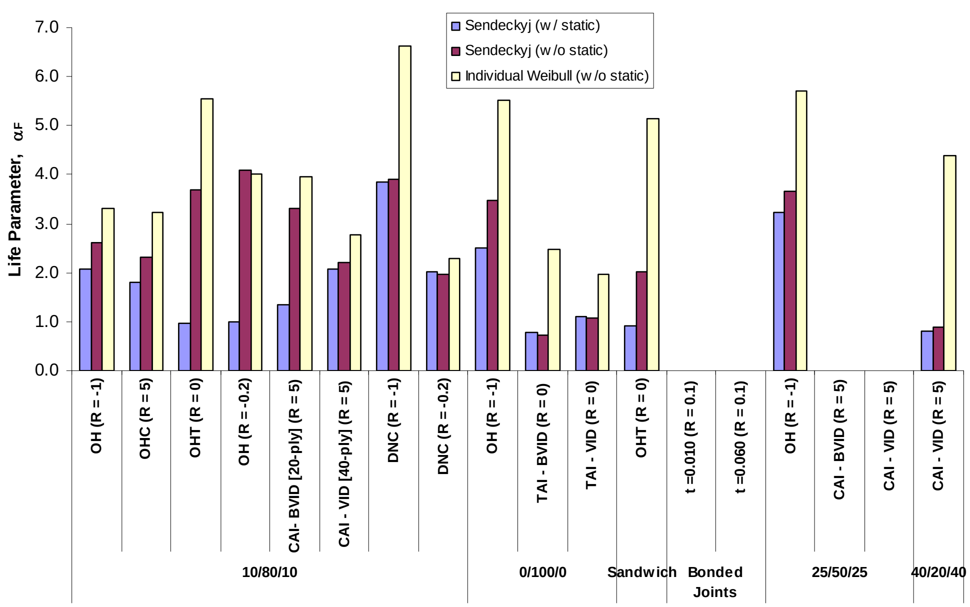
α_R **34.587**

Fatigue Scatter Analysis Techniques

- Individual Weibull
- Joint Weibull
- Sedeckyj Equivalent Strength Model

Data Pooling Techniques





NADC Fatigue Scatter Analysis

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

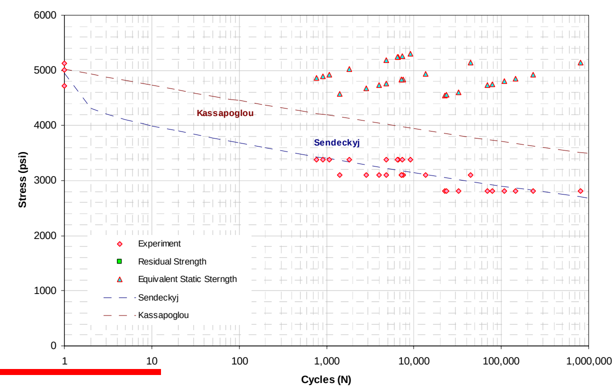
Adhesive Scatter Analysis

Shape Parameters for Fatigue Data [2, 5, and 10 -Hz combined]

w/ Static Data

	CTD	RTD	RTW	# of Specs.
Loctite	0.805	0.662	0.682	95
EA9696	0.847	0.403	0.379	103
PTM&W (0.06")	0.870	1.051	0.681	101
PTM&W (0.16")	0.363	0.856	0.671	91
			Total	**390**

α 3.8538
β 0.7641
Modal Value 0.707



w/o Static Data (Sendeckyj)

	CTD	RTD	RTW	# of Specs.
Loctite	0.821	1.624	0.644	86
EA9696	4.119	1.389	2.189	88
PTM&W (0.06")	1.376	1.483	1.169	92
PTM&W (0.16")	0.669	4.296	1.618	82
			Total	**348**

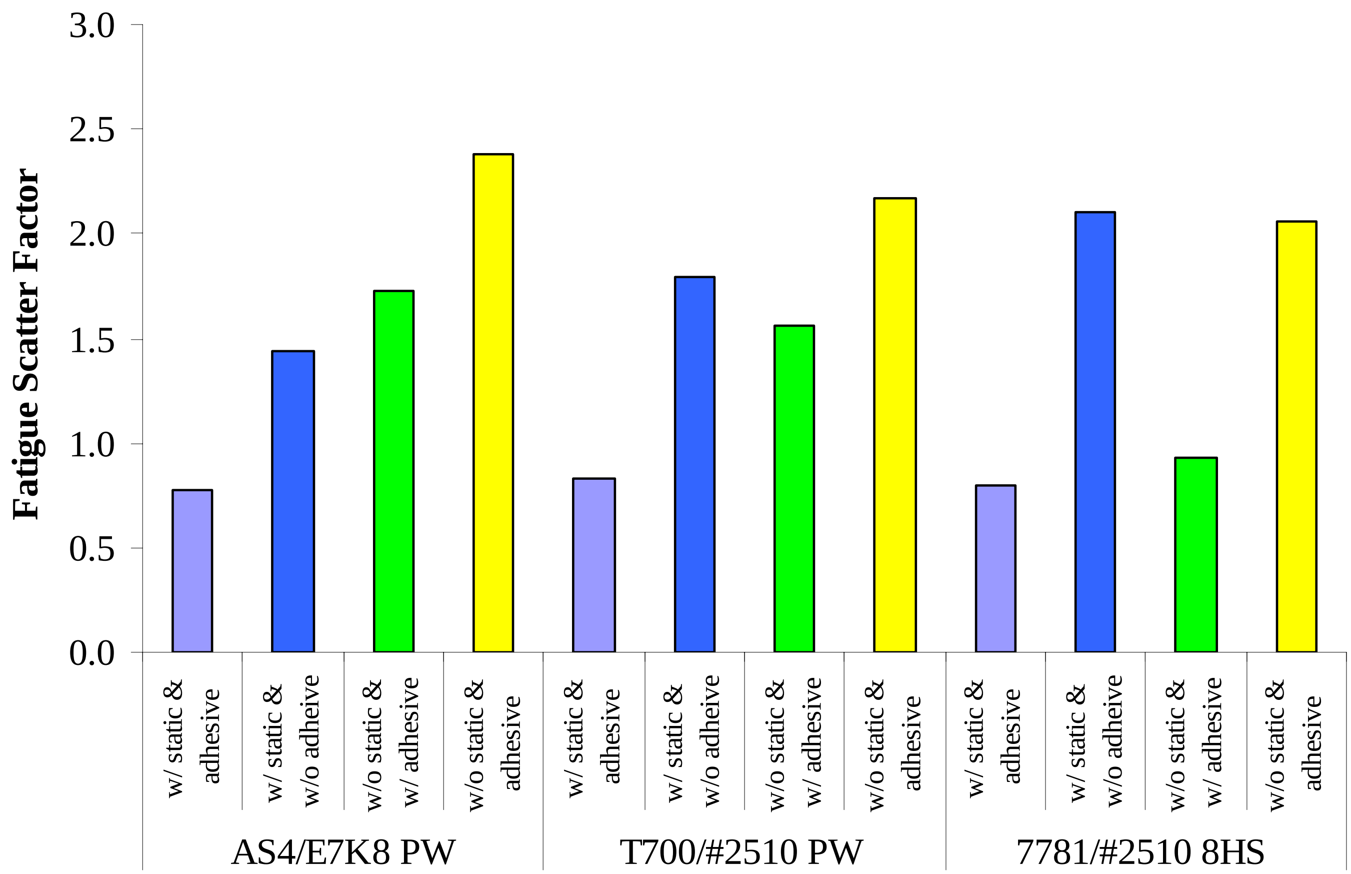
α 1.6789
β 2.016
Modal Value 1.176

w/o Static Data (Individual Weibull)

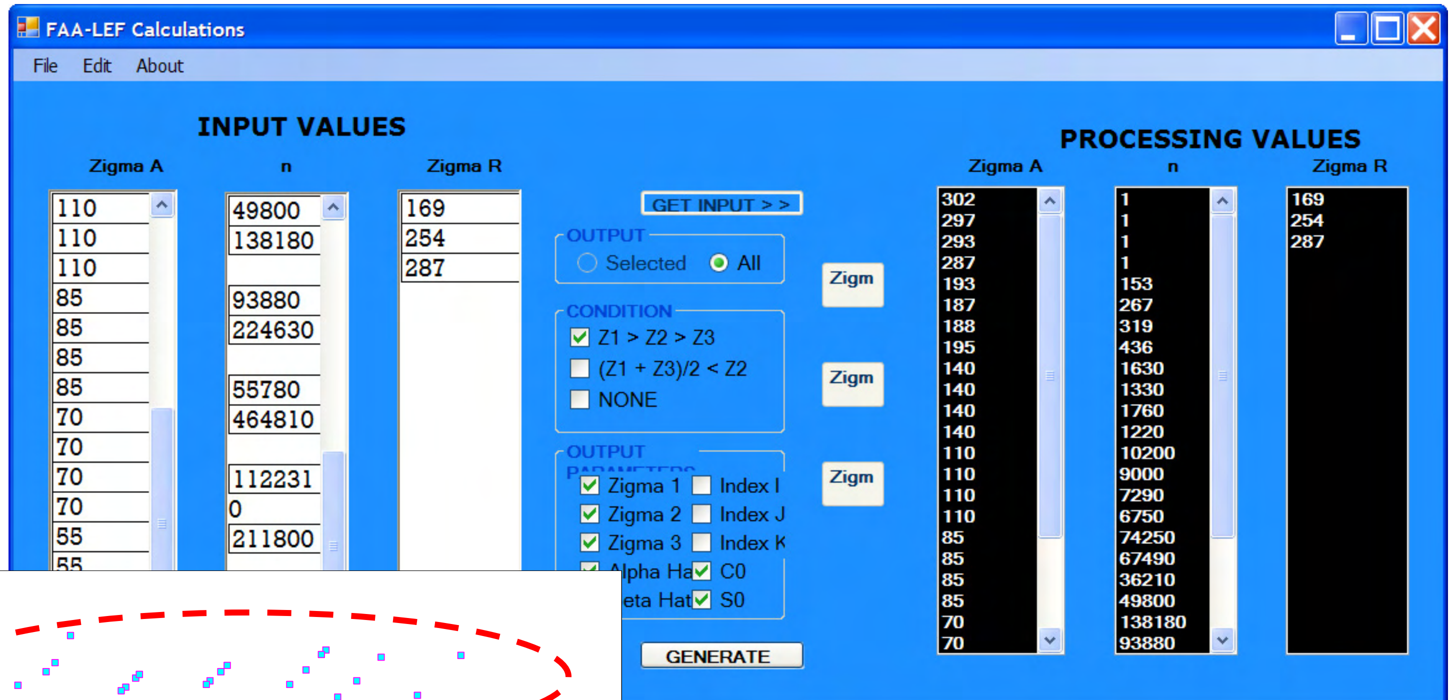
	CTD	RTD	RTW
Loctite	1.069	1.226	1.109
EA9696	2.372	2.077	1.110
PTM&W (0.06")	1.541	1.179	1.417
PTM&W (0.16")	1.165	2.170	1.061

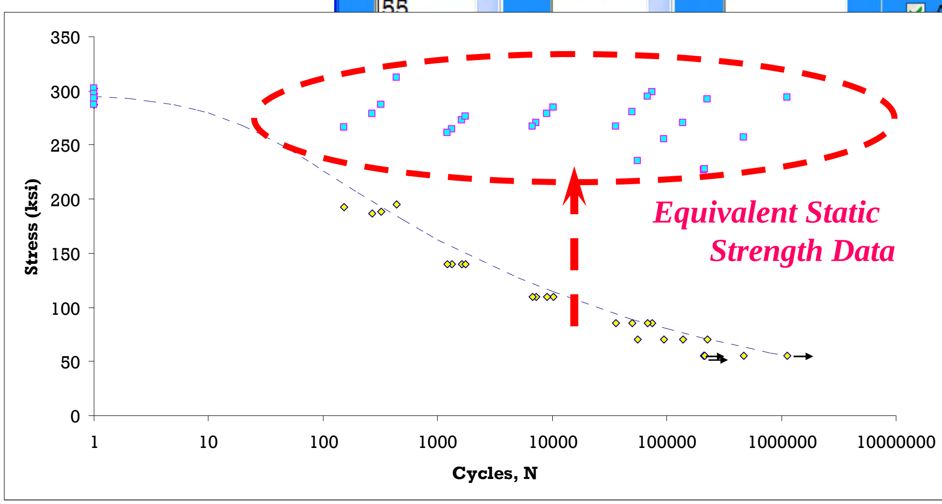
α 3.3394
β 1.6255
Modal Value 1.461

Life Scatter Summary



Methodology Automation

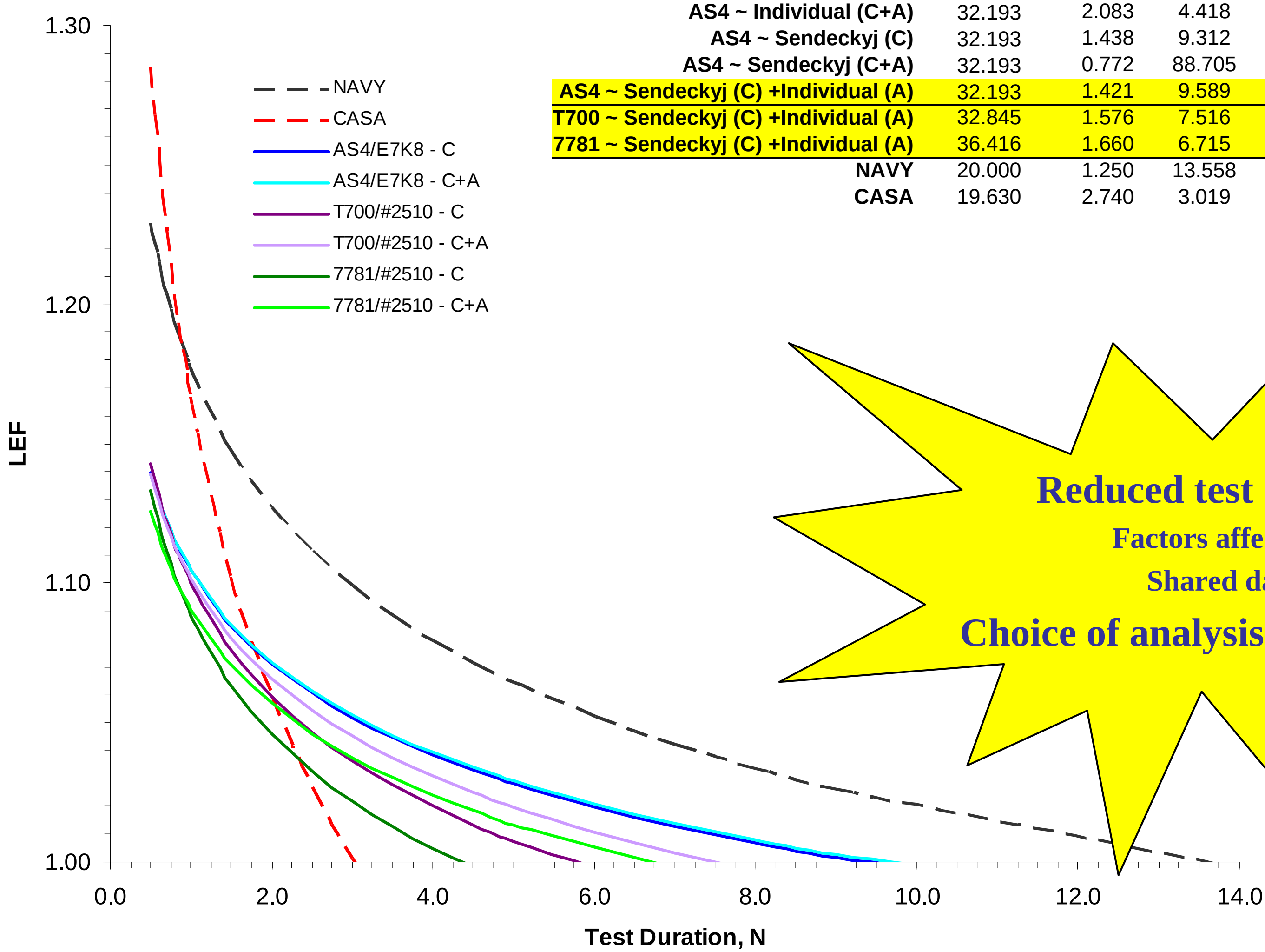




$$LEF = \frac{\left[\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right]^{\frac{\alpha_L}{\alpha_R}}}{\left[\frac{-\ln(p).N}{\chi^2_\gamma(2n)/2n}\right]^{\alpha_L \, 1/\alpha_R}}$$

Scatter Analysis Guidelines

	θ_R	θ_L	N_F	N = 0.5	1.0	1.5	3.0
AS4 ~ Individual (C)	32.193	4.057	2.070	1.196	1.096	1.041	0.954
AS4 ~ Individual (C+A)	32.193	2.083	4.418	**1.151**	1.101	1.072	1.025
AS4 ~ Sendeckyj (C)	32.193	1.438	9.312	1.140	1.105	1.085	1.052
AS4 ~ Sendeckyj (C+A)	32.193	0.772	88.705	1.132	1.114	1.103	1.085
AS4 ~ Sendeckyj (C) +Individual (A)	32.193	1.421	9.589	1.139	1.105	1.085	1.053
T700 ~ Sendeckyj (C) +Individual (A)	32.845	1.576	7.516	1.139	1.102	1.080	1.045
7781 ~ Sendeckyj (C) +Individual (A)	36.416	1.660	6.715	1.126	1.091	1.071	1.037
NAVY	20.000	1.250	13.558	1.229	1.177	1.148	1.099
CASA	19.630	2.740	3.019	1.285	1.167	1.103	1.001



Reduced test matrix

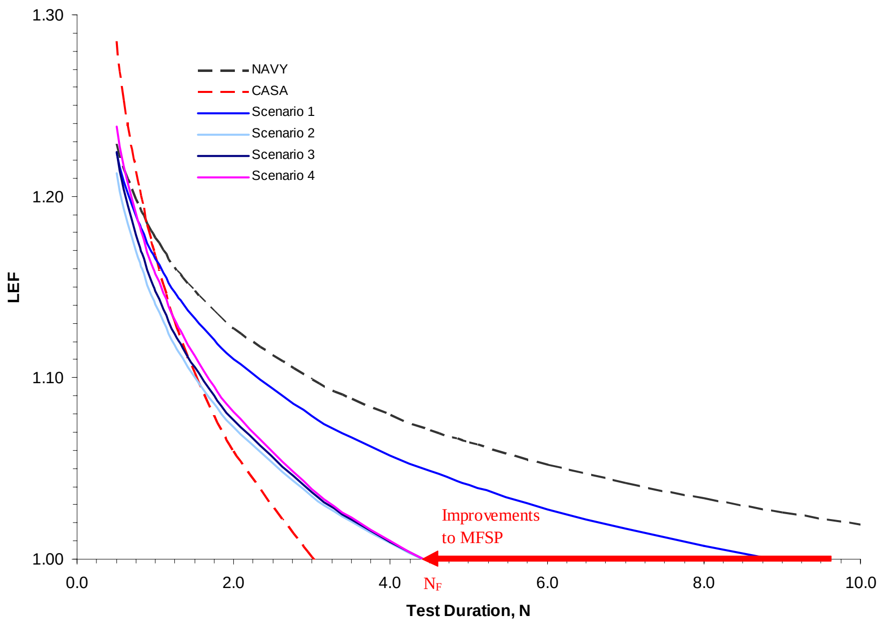
Factors affecting LEF

Shared database

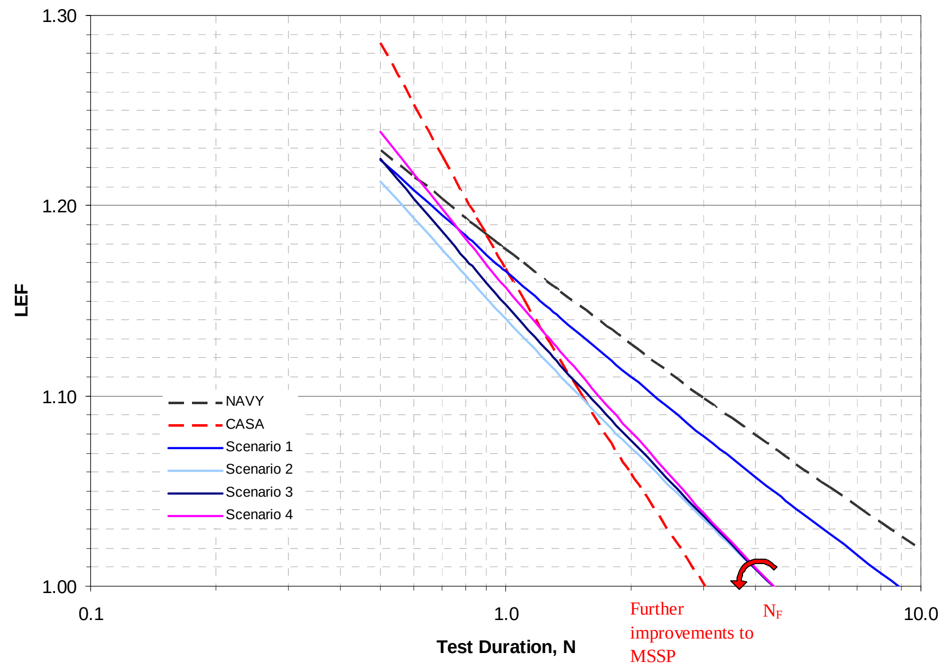
Choice of analysis techniques

ce

Case Studies

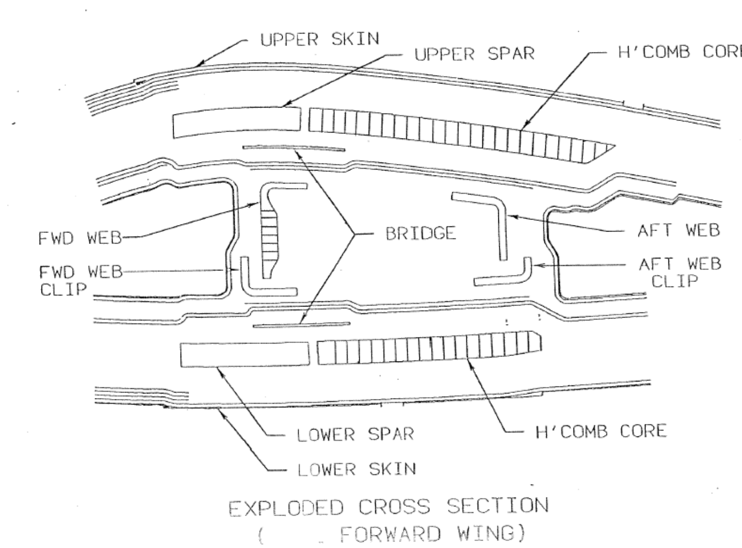


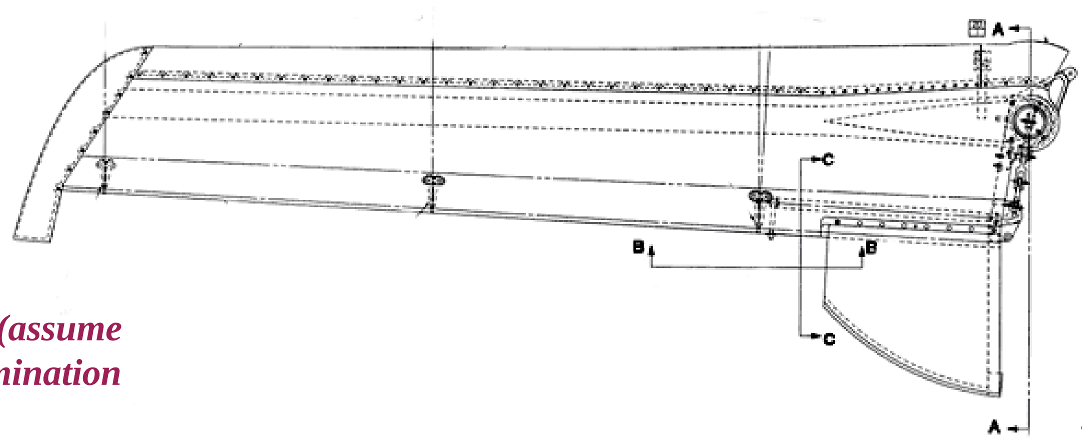
- Shared database
- Multiple scatter analysis techniques



- Improved LEF
- Improved N_F
- Improved "life"
  - Load-life shift

Full-Scale Specimens





Beechcraft Starship

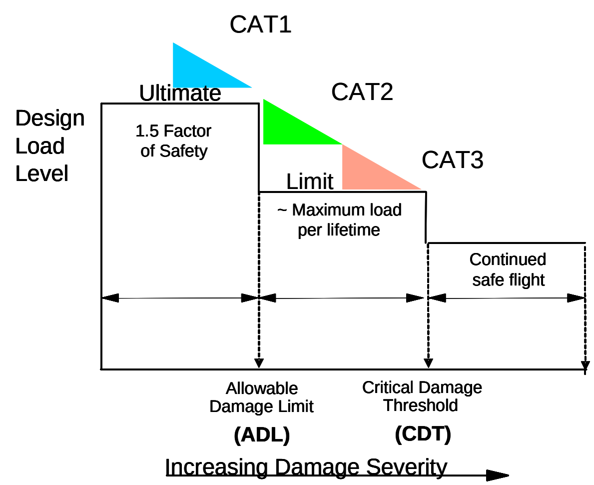
Forward Wings (BSFW)

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

Damage Scenarios

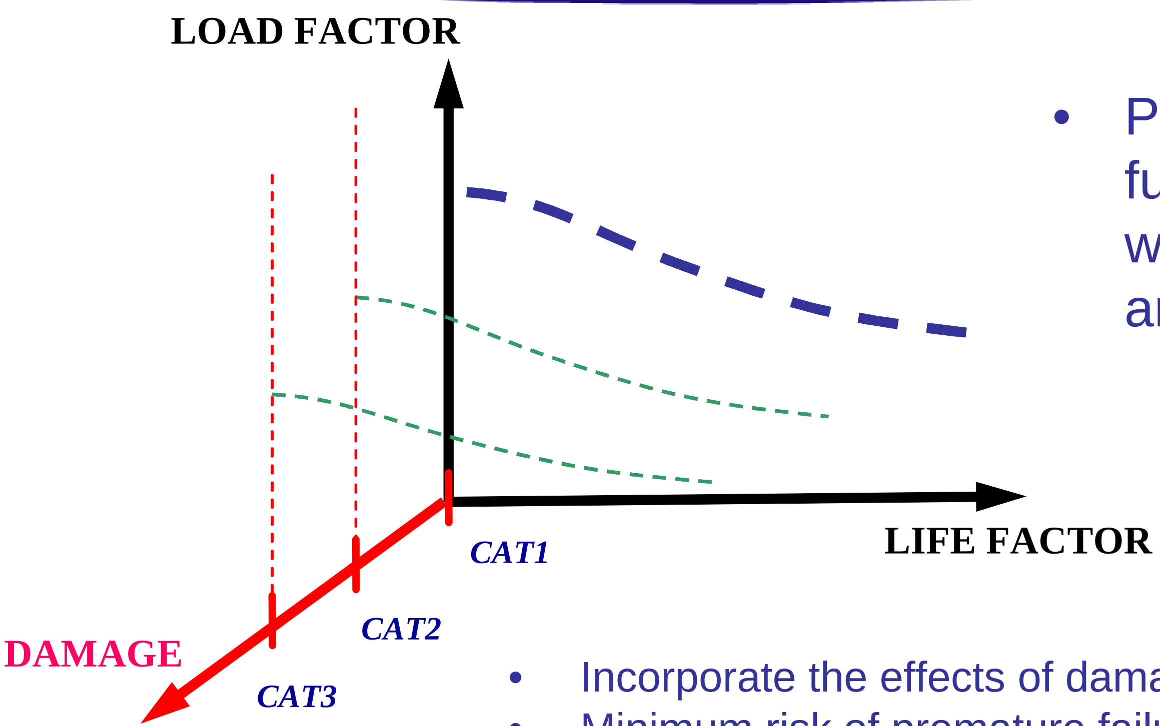
Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

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.

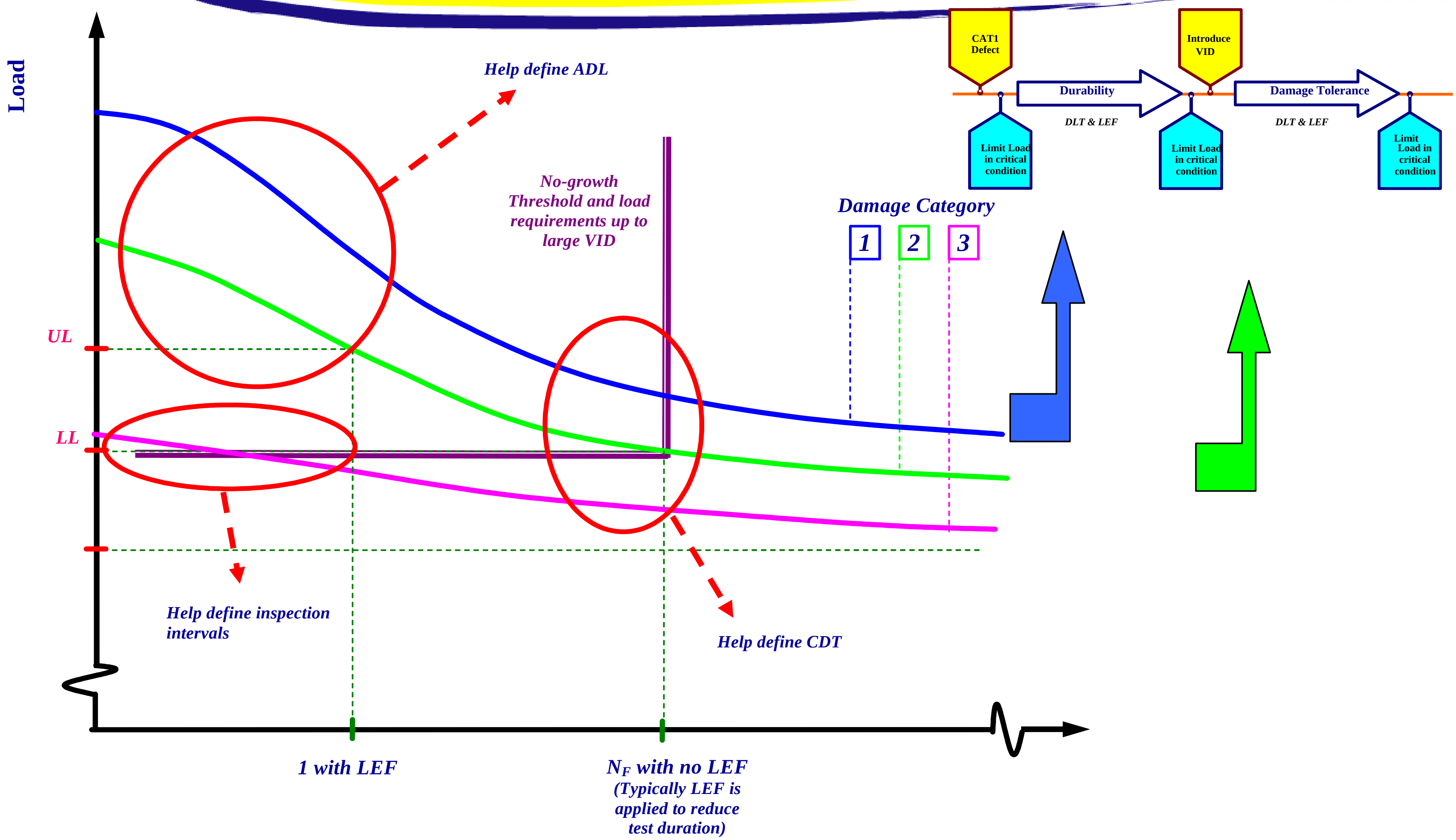
Load-Life-Damage (LLD) Hybrid Approach



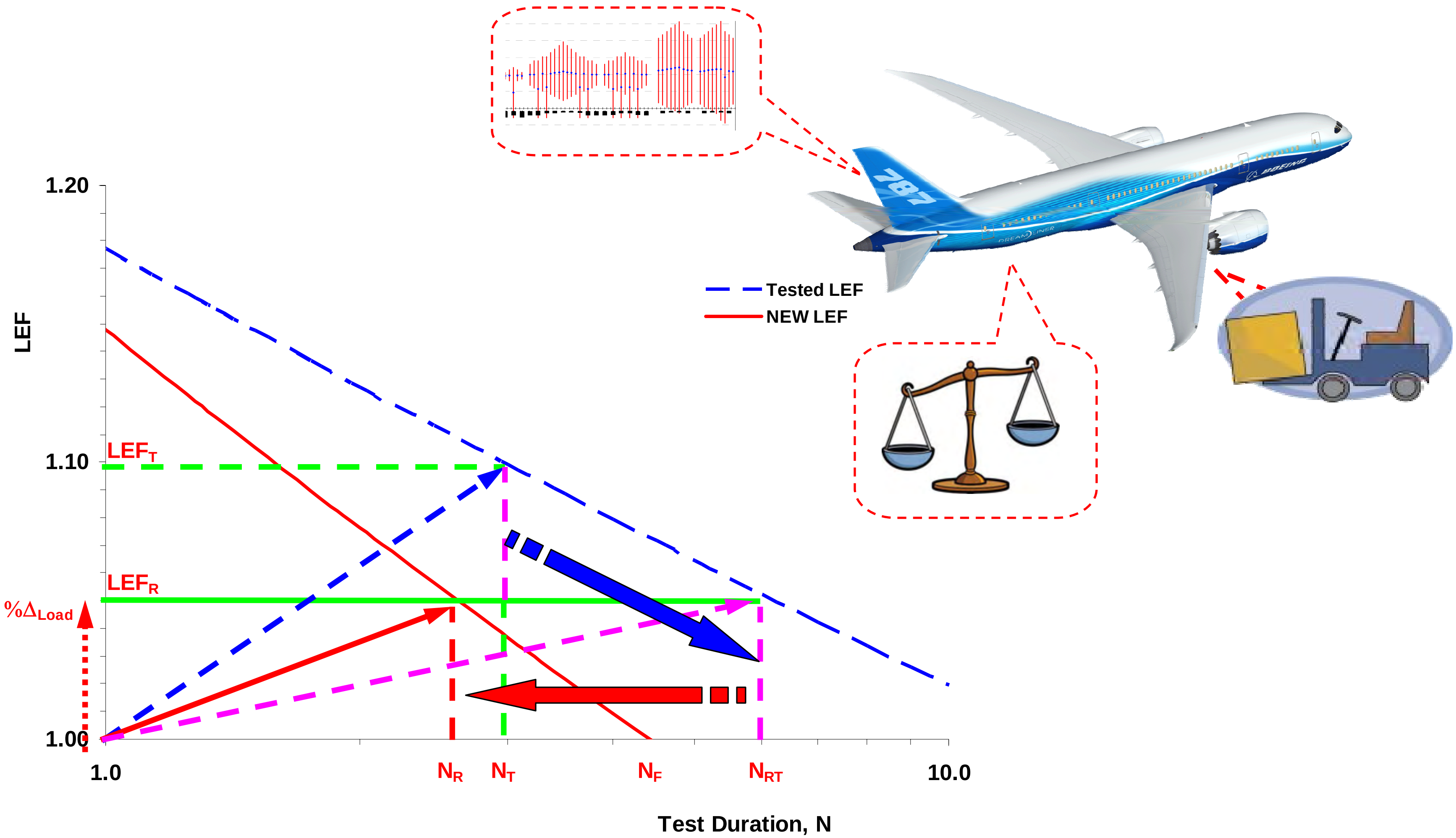
- Provide an opportunity to further investigate large VID without additional test articles

- Incorporate the effects of damage to scatter analysis
- Minimum risk of premature failure of full-scale article
- Application to hybrid structure
- post certification
  - Additional load cases that were not included in the original certification, but found to be significant or worth investigating can be studied

Damage Tolerance Investigation

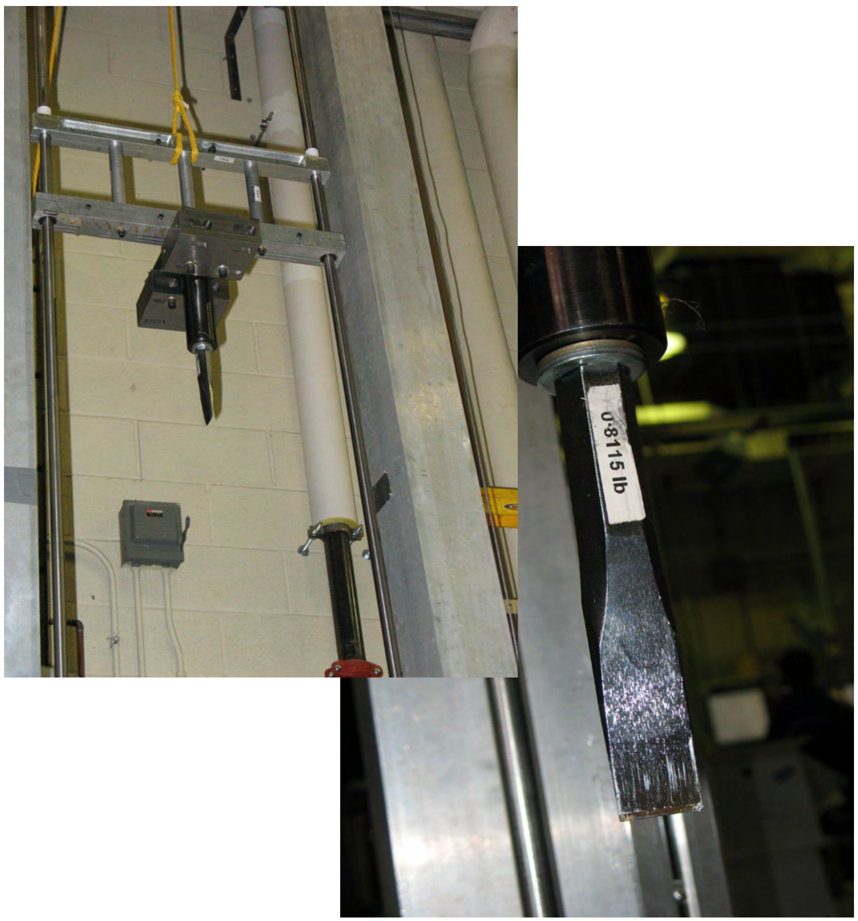


Design Change Substantiation

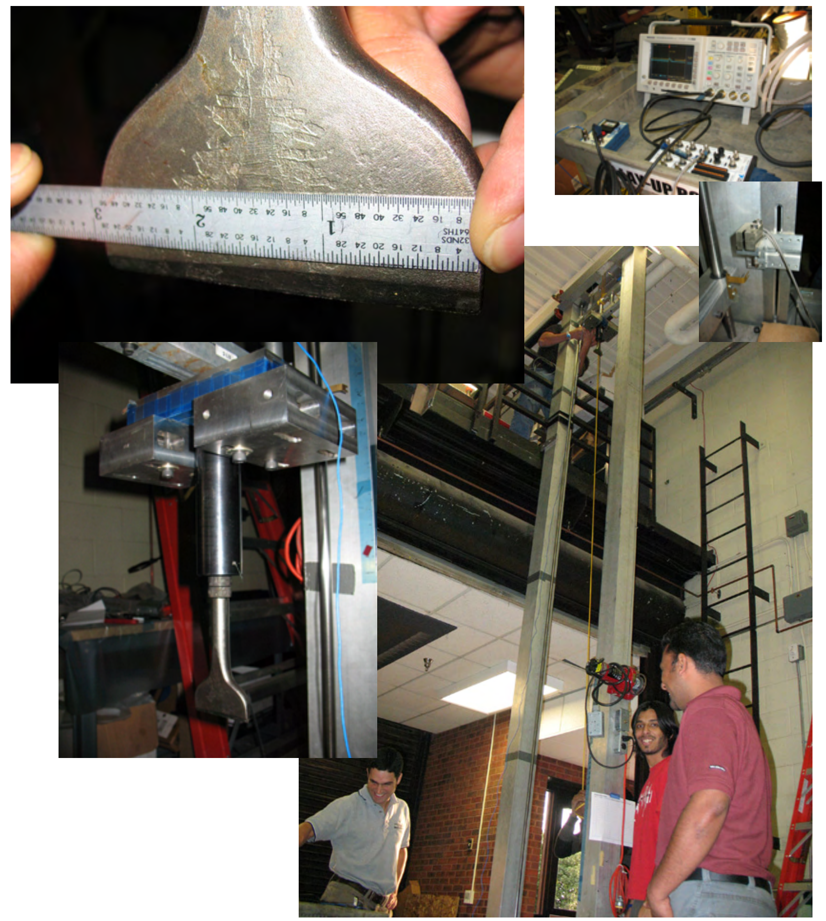


Impactor Setup

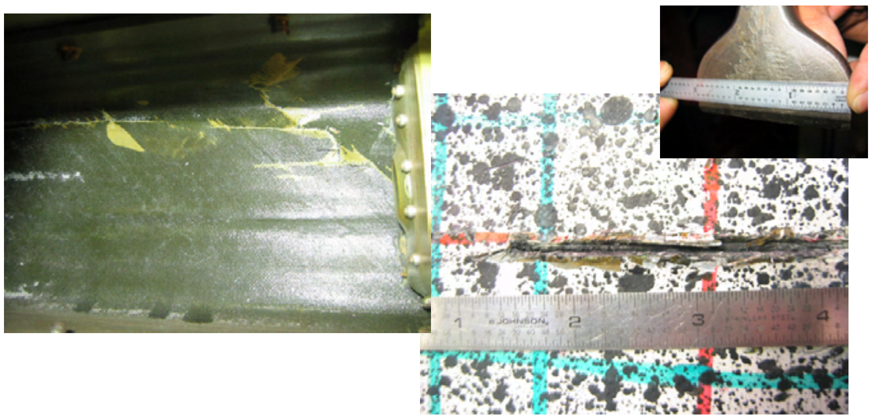
- 1-inch Wedge (pry bar)



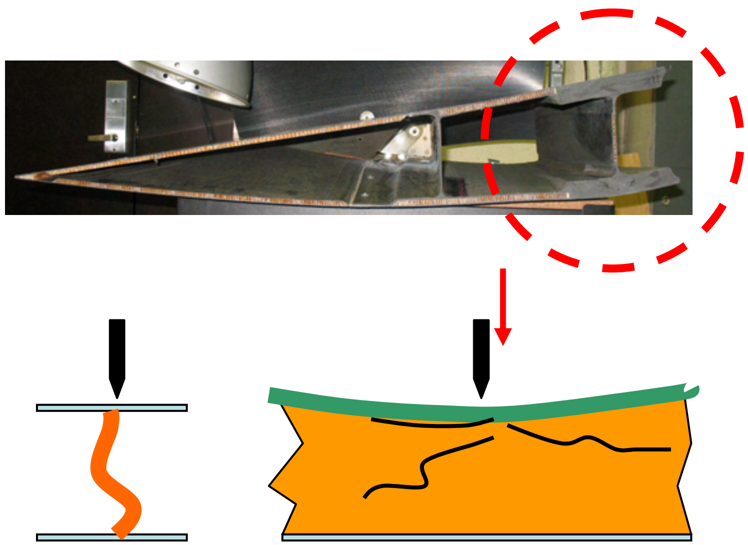
- 3-inch Wedge (wood-splitter)



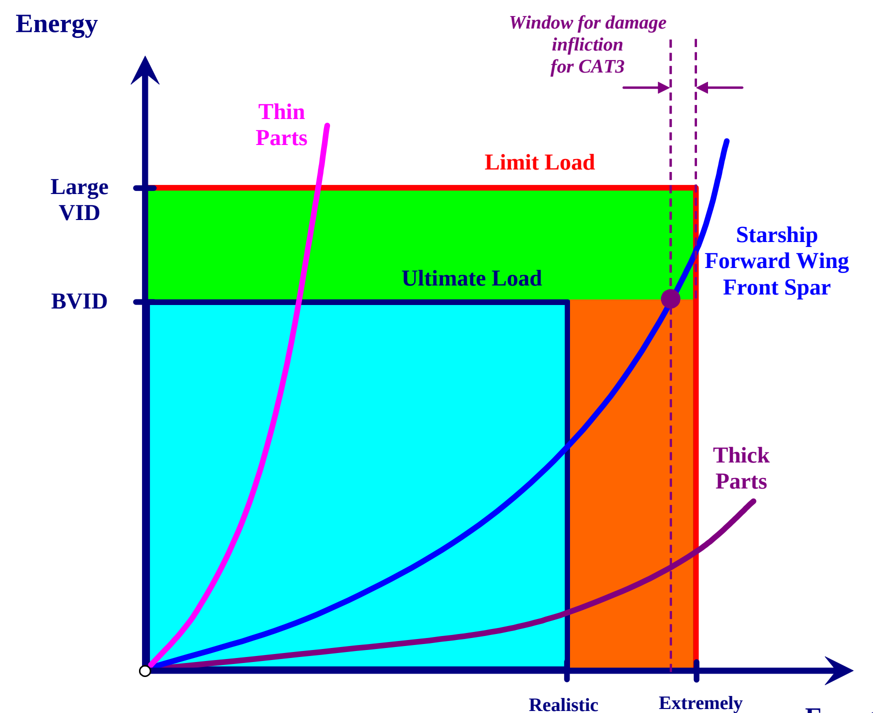
Damage Infliction
- BSFW Front Spar -



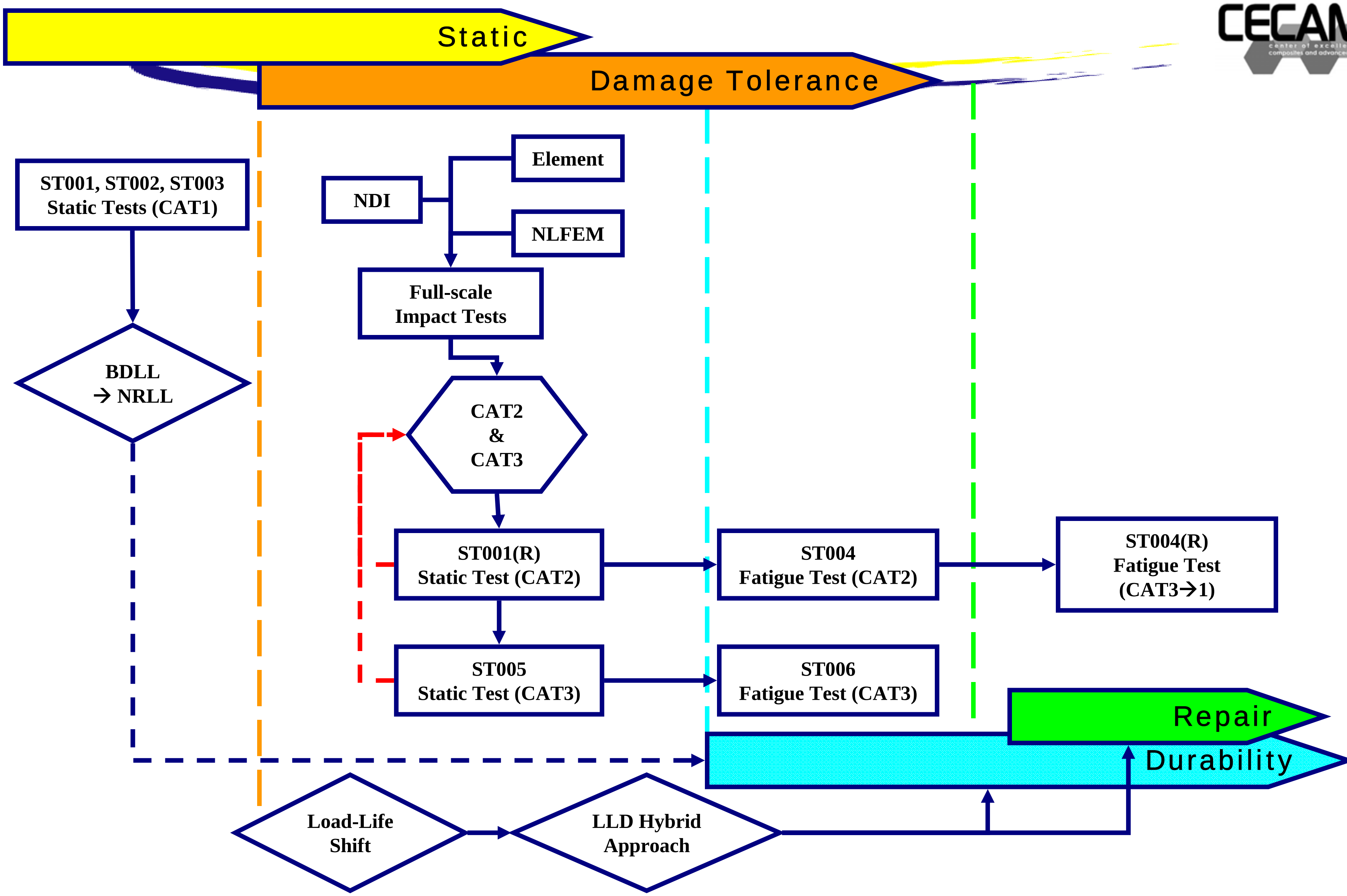
After 1000 ft-lb damage at FWS 66.5 (top skin – front spar)



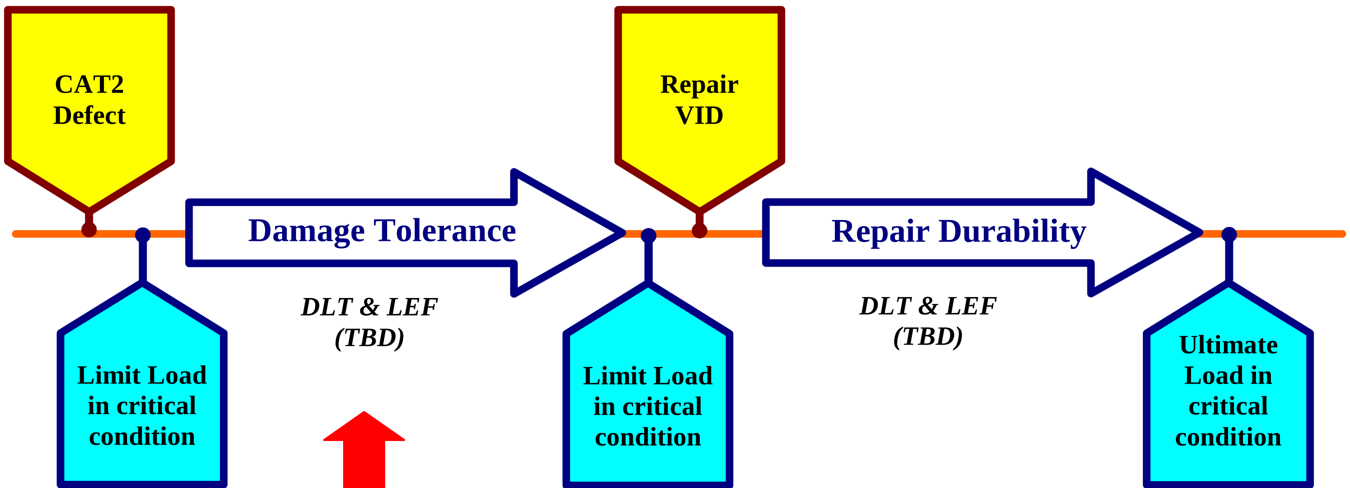
- Primary load path
- Scaling CAT3 damages into full-scale article
- Thick part - unitape
- Wound - no layers



Full-Scale Validation

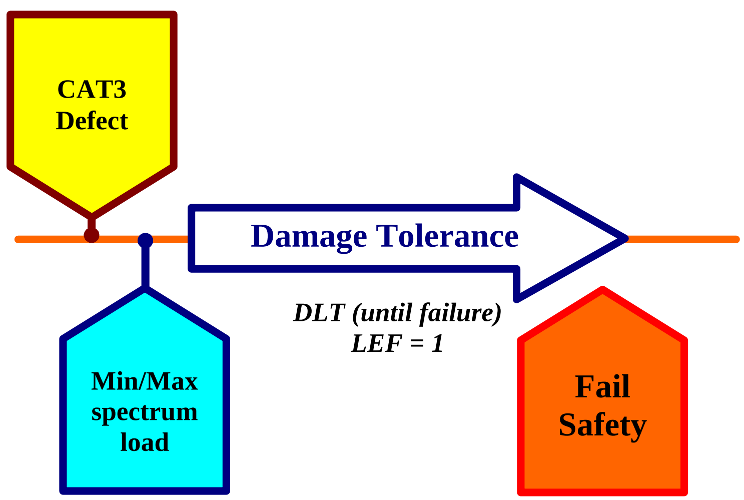


Full-Scale Substantiation - LLD Hybrid Approach -



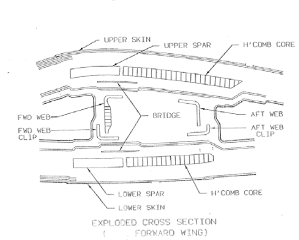
- Demonstrate LLD hybrid approach
- Application of load-life shift

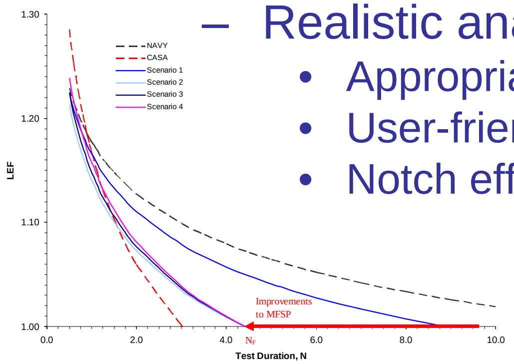
- Determine fail safety
- Fatigue capability of CAT3



Benefits to Aviation

- FAA guideline document, which demonstrates a "best practice" procedure for full-scale testing protocols for composite airframe structures with examples
  - Cost effective and reliable certification approach(s)
  - 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 and analysis guidelines
    - Notch effects on scatter for damage tolerance testing

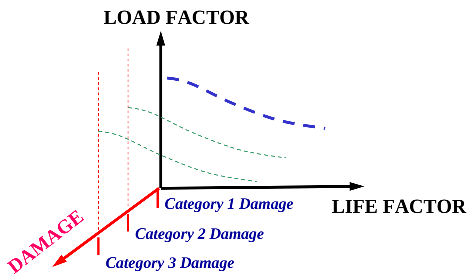




Benefits to Aviation

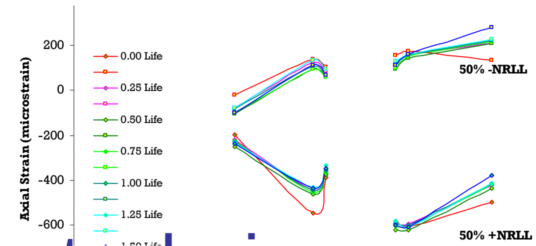
- Incorporation of damage into scatter analysis: Load-Life-Damage
  - Investigate large VID damage
  - Further studies

- Load-Life Shift
  - Investigate different categories of damages/repairs in the same full-scale test article damage
  - Design changes, i.e. gross weight increase
  - LEF during certification vs. improved LEF
    - Reliability of designed life



Future Needs

- Training



- Reliable NDI and health monitoring techniques for damage characterization during full-scale testing and service ~ & Training

- Further studies on extremely improbable high energy impact threats and their impact on the residual strength of the composite structure and inspection intervals

Questions