Durability & Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures

John Tomblin, *PhD*
Executive Director, NIAR and
Sam Bloomfield Distinguished Professor of Aerospace Engineering

Waruna Seneviratne
Sr. Research Engineer, NIAR

The Joint Advanced Materials and Structures Center of Excellence

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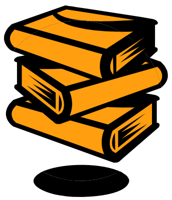
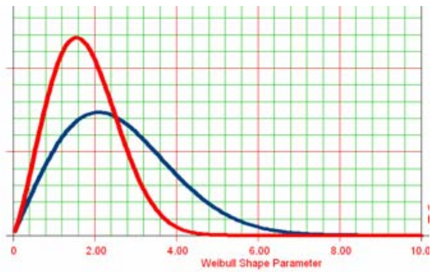


- Motivation and Key Issues
  - Produce a guideline FAA document, which demonstrates a "best practice" procedure for full-scale testing protocols for composite airframe structures ***with examples***
- Objectives
  - *Demonstrate acceptable means of compliance for fatigue, damage tolerance and static 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
  - Several candidate research tasks

Candidate Research Tasks

1. Load Enhancement Factor Approach and Fatigue Life Assessment
   - Various approaches which have been or are currently being used
   - Guidance on Cycle Truncation
   - Address Environmental Factors used during testing
   - Full-Scale Validation and Examples



2. Damage Tolerance and Repair Substantiation
   - Categories of damage
3. Analysis Methods
   - Define procedures necessary to support testing and building block approaches

FAA Sponsored Project Information

- Principal Investigators
  - Dr. John Tomblin and Waruna Seneviratne
- FAA Technical Monitor
  - Curtis Davies
- Other FAA Personnel Involved
  - Dr. Larry Ilcewicz
- Industry Participation
  - Aviation (commercial & general), material suppliers, software developers

Main Working Group

- Federal Aviation Administration
  - Curtis Davies
    - FAA William J. Hughes Technical Center, NJ
  - Larry Ilcewicz
    - FAA/Seattle Aircraft Cert. Office
  - Lester Cheng
    - FAA-Small Airplane Directorate
  - Evangelina Kostopoulos
    - FAA ACO - Chicago
  - David Ostrodka
    - FAA ACO – Wichita
  - Peter Shyprykevich
    - Consultant

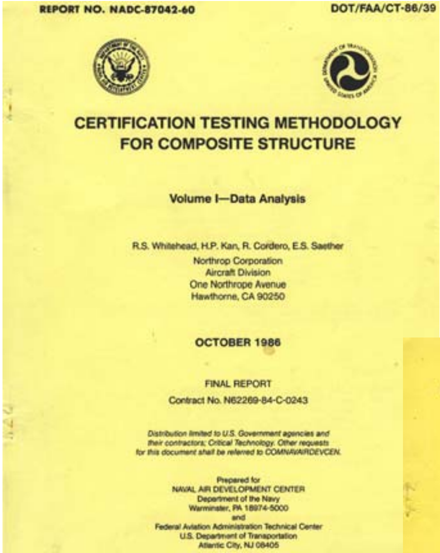
Transport Aircraft Applications

We all think about these applications … but …

Other Applications of Advanced Materials

Load Enhancement Factor Approach and Fatigue Life Assessment

- Background – most test programs reference the Navy/FAA reports by Whitehead, Kan, 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



REPORT NO. NADC-87042-60 DOT/FAA/CT-86/39

CERTIFICATION TESTING METHODOLOGY FOR COMPOSITE STRUCTURE

Volume I—Data Analysis

R.S. Whitehead, H.P. Kan, R. Cordero, E.S. Saether
Northrop Corporation
Aircraft Division
One Northrope Avenue
Hawthorne, CA 90250

OCTOBER 1986

FINAL REPORT
Contract No. N62269-84-C-0243

Distribution limited to U.S. Government agencies and their contractors; Critical Technology. Other requests for this document shall be referred to COMNAVAIRDEVCEN.

Prepared for
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Department of the Navy
Warminster, PA 18974-5000
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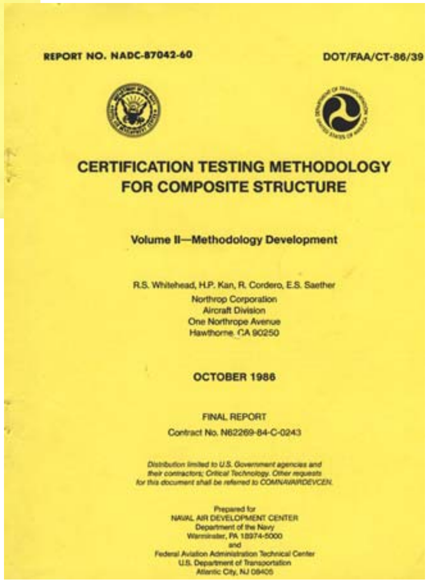

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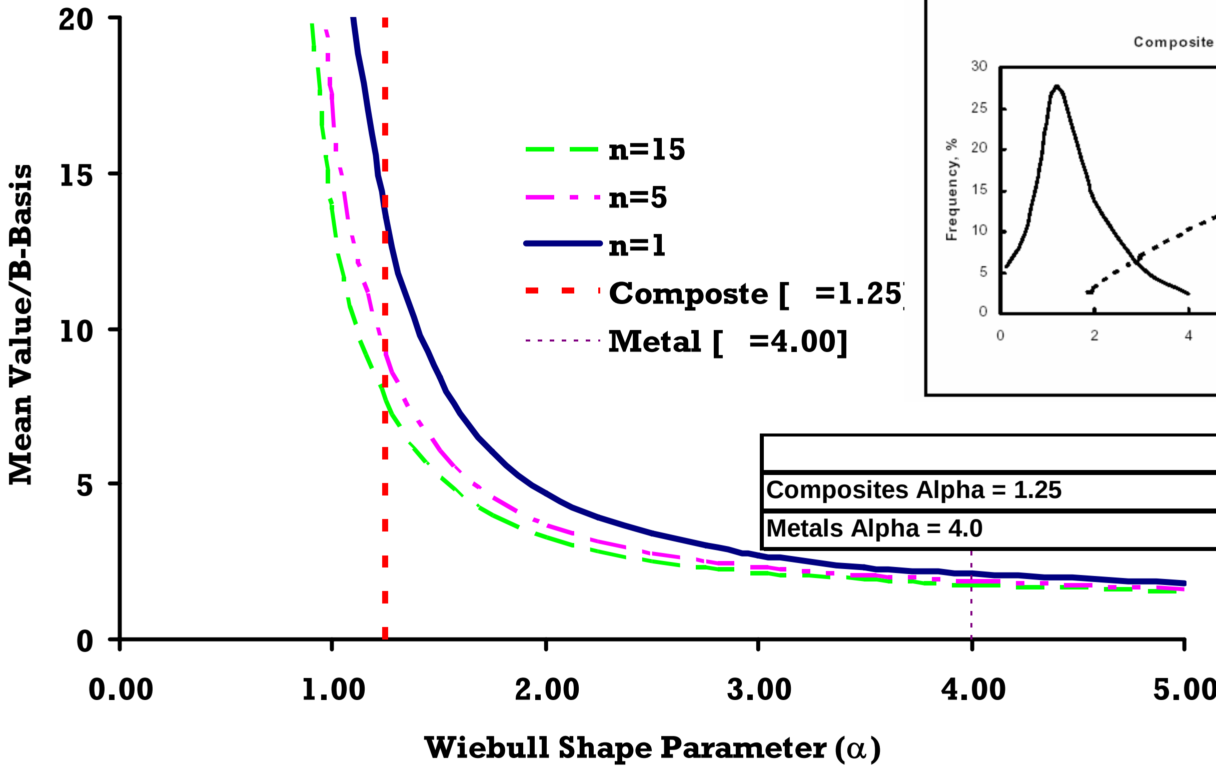
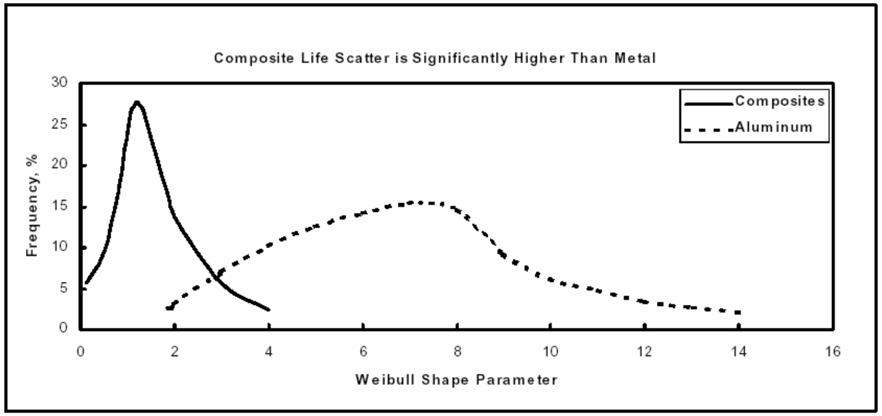
Life Factor Approach

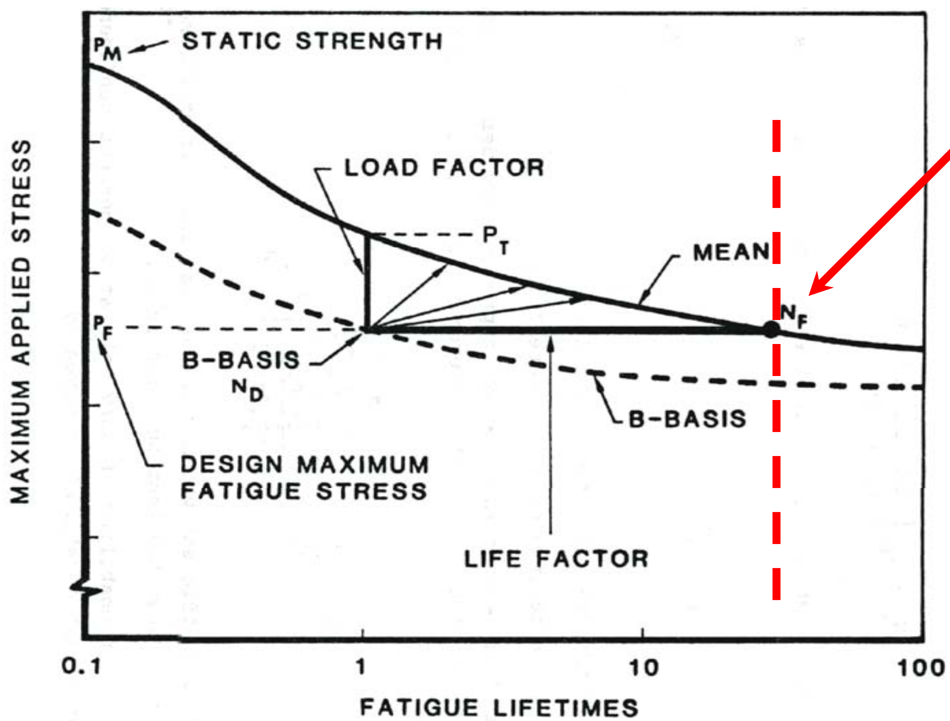




	n = 1	n = 5	n = 15
Composites Alpha = 1.25	13.558	9.143	7.625
Metals Alpha = 4.0	2.093	1.851	1.749

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

Load Enhancement



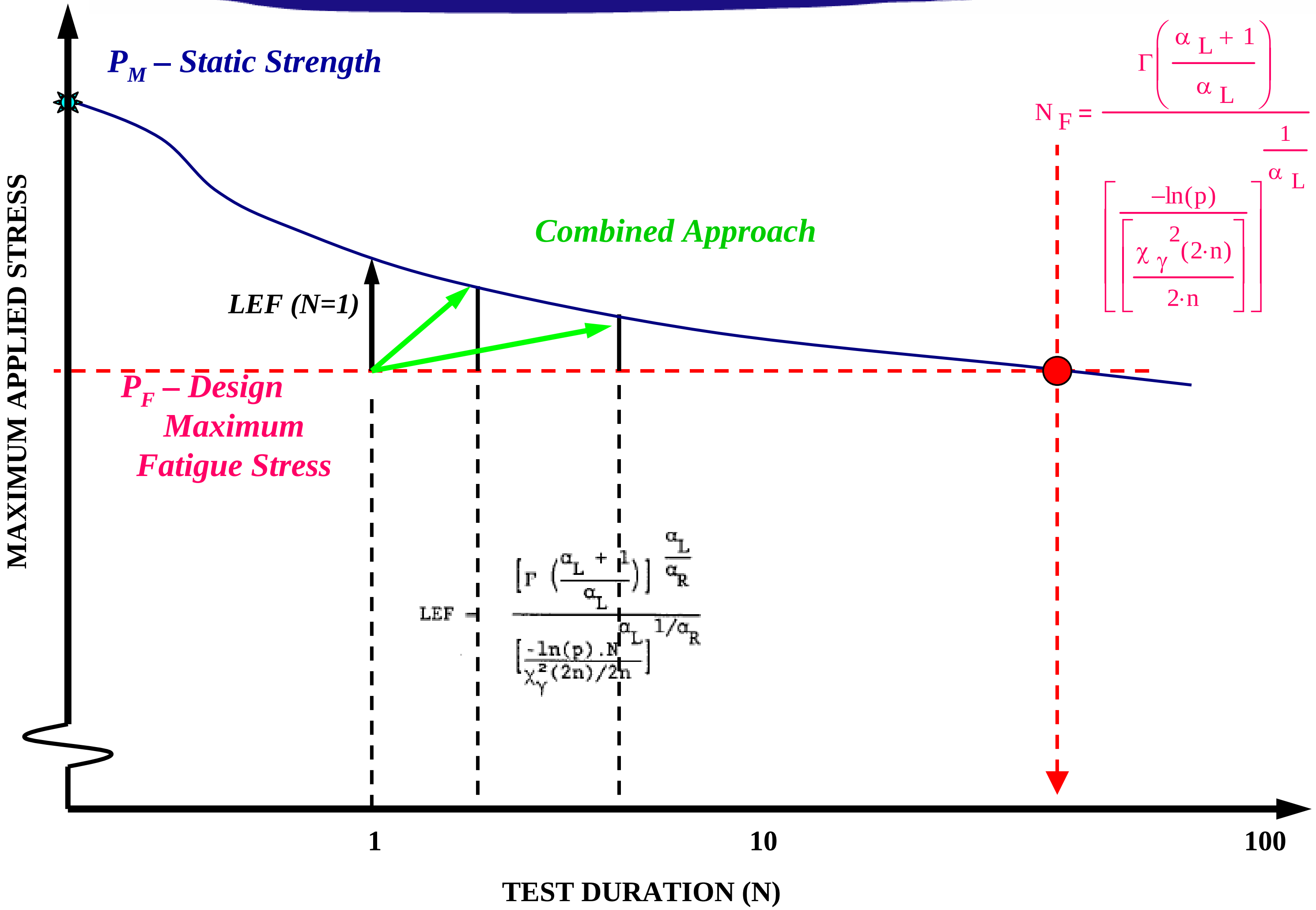
$$N_F = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left[\frac{-\ln(p)}{\left[\frac{\chi_\gamma^{2}(2\cdot n)}{2\cdot n}\right]}\right]^{\frac{1}{\alpha_L}}}$$

Life scatter factor – ratio between the mean fatigue life and the minimum fatigue life (for a given reliability and confidence level)

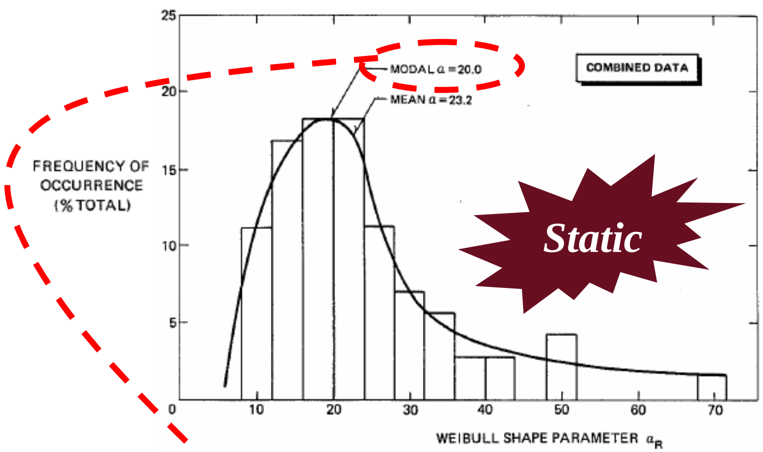
$$\mathrm{LEF} = \frac{\left[\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right]^{\frac{\alpha_L}{\alpha_R}}}{\left[\frac{-\ln(p).N^{\alpha_L}}{\chi_\gamma^2(2n)/2n}\right]^{1/\alpha_R}}$$

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

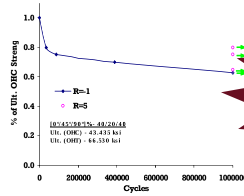
Load / Life Tradeoff



Load Enhancement Factor Approach



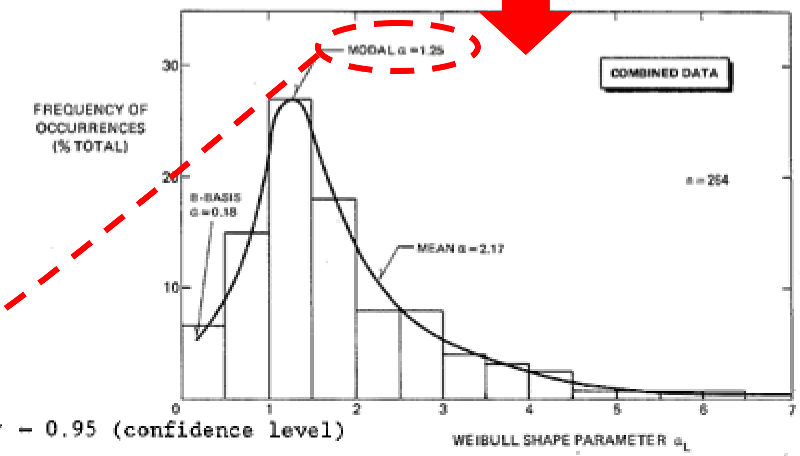
Static



Fatigue

Fatigue Data Fitting Models

Equivalent static strength values for fatigue data



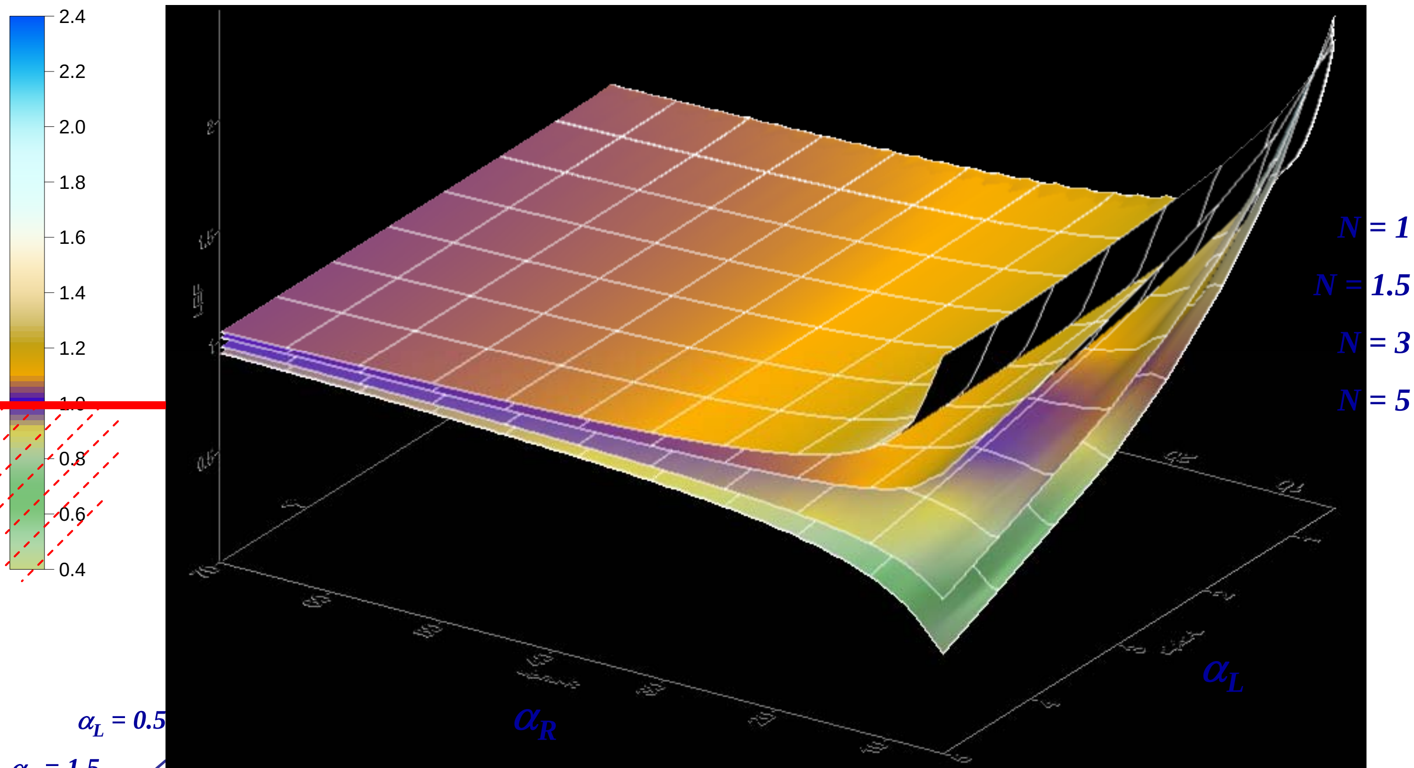
$\alpha_L = 1.25$ $n = 1$ (one test article)

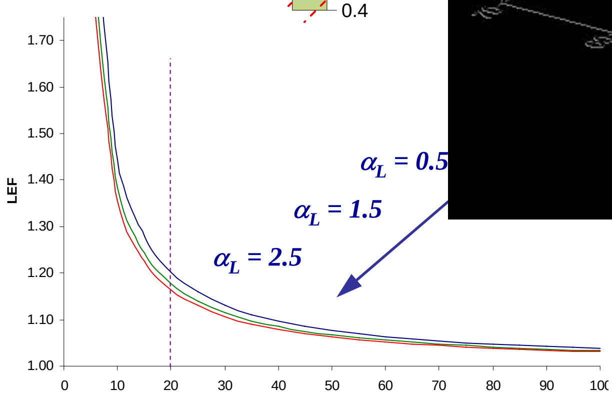
$\alpha_R = 20.0$ $p = 0.9$ (B-Basis) $\gamma = 0.95$ (confidence level)

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

test duration	load enhancement factor
1.0	1.177
1.5	1.148
2.0	1.127
3.0	1.099
13.3	1.0

Load-Life Combined Approach

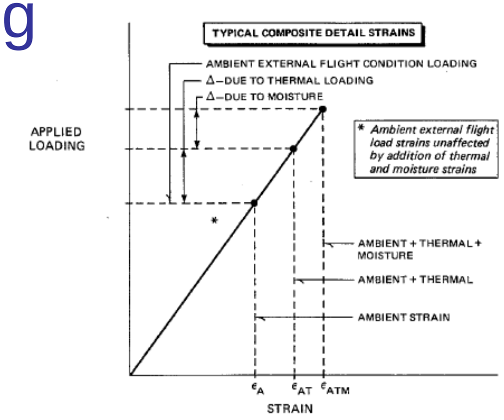


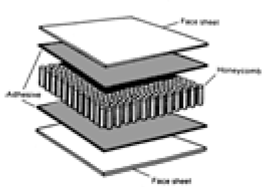


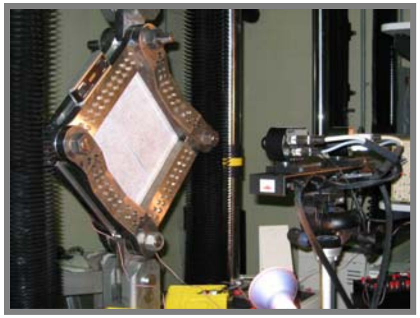
$$\mathrm{LEF} = \frac{\left[\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right]^{\frac{\alpha_L}{\alpha_R}}}{\left[\frac{-\ln(p).N^{\alpha_L}}{\chi^2_\gamma(2n)/2n}\right]^{1/\alpha_R}}$$

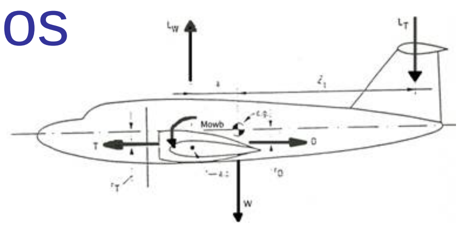
LEF Data Development

- Generate data and guidelines for the generation of Weibull shape parameters for
  - Different material systems and stacking sequences
  - Loading modes and geometries
  - Environments
  - Bonded joints (thickness effects)
  - Sandwich construction
  - Multiple R-ratios





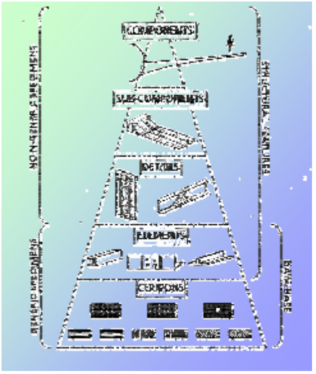


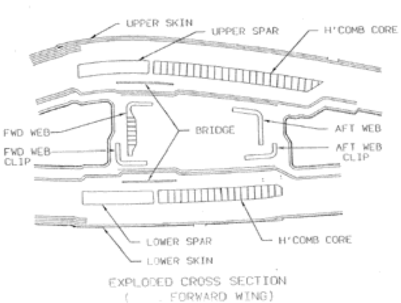


LEF Test Matrix Development

CYTEC AS4/E7K8 PW

Laminate	Test Method	Loading Condition	Standard	Specimen Dimensions (wxL)	Static Test Environment RTD	Static Test Environment ETW	RTD - Cyclic Test R ratio (3 Stress Levels) -0.2	0	-1	5
10/80/10 Laminate	Open-Hole	Tension	ASTM D5766	1.5x12"	6	6	18	18		18
		Comp.	ASTM D6484		6	6			18	
	Bonded Joint (t=0.01-inch)	Tension	Modified ASTM D3165	1.5x12"	6	6	18		18	
	Bonded Joint (t=0.06-inch)				6	6	18		18	
	Double Notch Compression	Interlaminar Shear	ASTM D3846	1.5x12"	6	6	18		18	
	CAI [20 plies]	Comp. -BVID	ASTM D7137	4x6"						
		Comp. -VID			5					18
	CAI [40 plies]	Comp. -BVID	ASTM D7137	4x6"						
		Comp. -VID			6					18
25/50/25 Laminate	Open-Hole	Comp. -RTD	ASTM D6484	1.5x12"					18	
		Comp. -ETW							6	
	CAI	Comp. -BVID/RTD	ASTM D7137	4x6"						18
		Comp. -VID/RTD			6					18
		Comp. -BVID/ETW								6
		Comp. -VID/ETW								18
40/20/40 Laminate	CAI	Comp. -BVID	ASTM D7137	4x6"						
		Comp. -VID			6					18
All 45's	Open-Hole	Comp. -RTD	ASTM D6484	1.5x12"	6				18	
		Comp. -ETW			6				6	
	TAI	Shear - BVID/RTD	Modified ASTM D6148	4x10"						18
		Shear - VID/RTD			6					18
		Shear - BVID/ETW								6
		Shear - VID/ETW								18
Sandwich	3-Ply Facesheet w/ 0.25-inch Core	4-Point Bend	ASTM C393	3x8"	6	6		18		



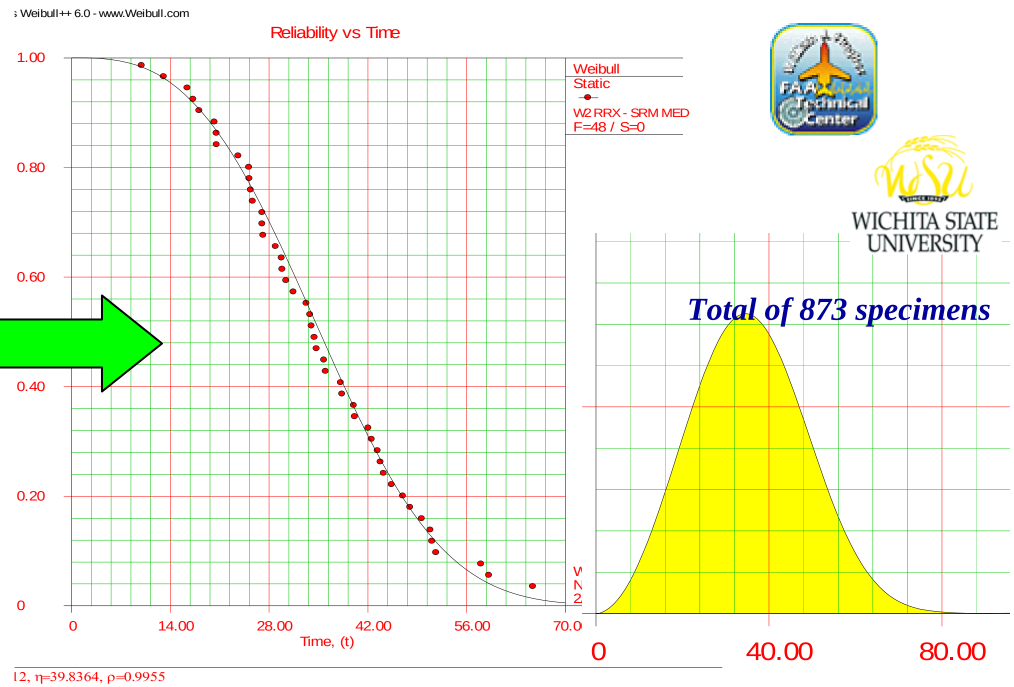


T700SC-12K-50C/#2510 -Plain Weave Fabric

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



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

α	**2.941**
β	**39.836**

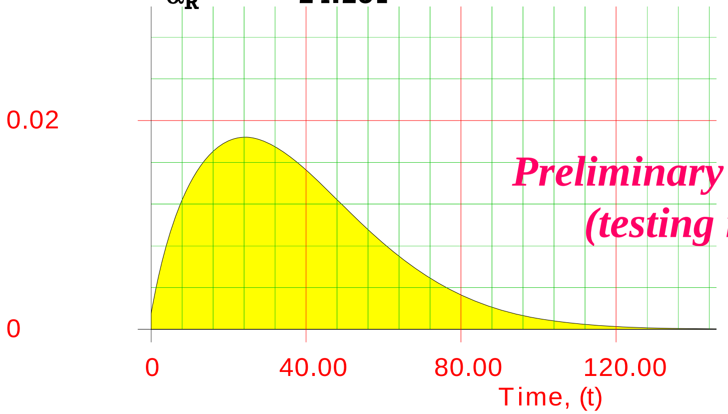
MODAL (EXTREAM)

α_R **34.587**

LEF - AS4/E7K8 & T700/#2510

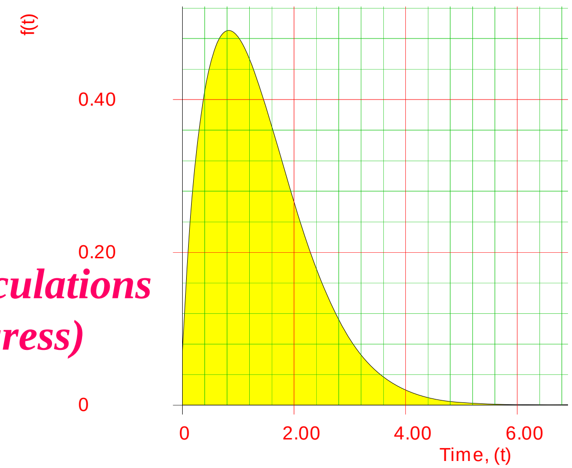
α 1.6647
β 42.0614

MODAL (EXTREAM) V
α_R 24.231



β=1.6647, η=42.0614, ρ=0.9822

Preliminary LEF calculations (testing is in progress)



β=1.5915, η=1.5485

N (test duration) = 1

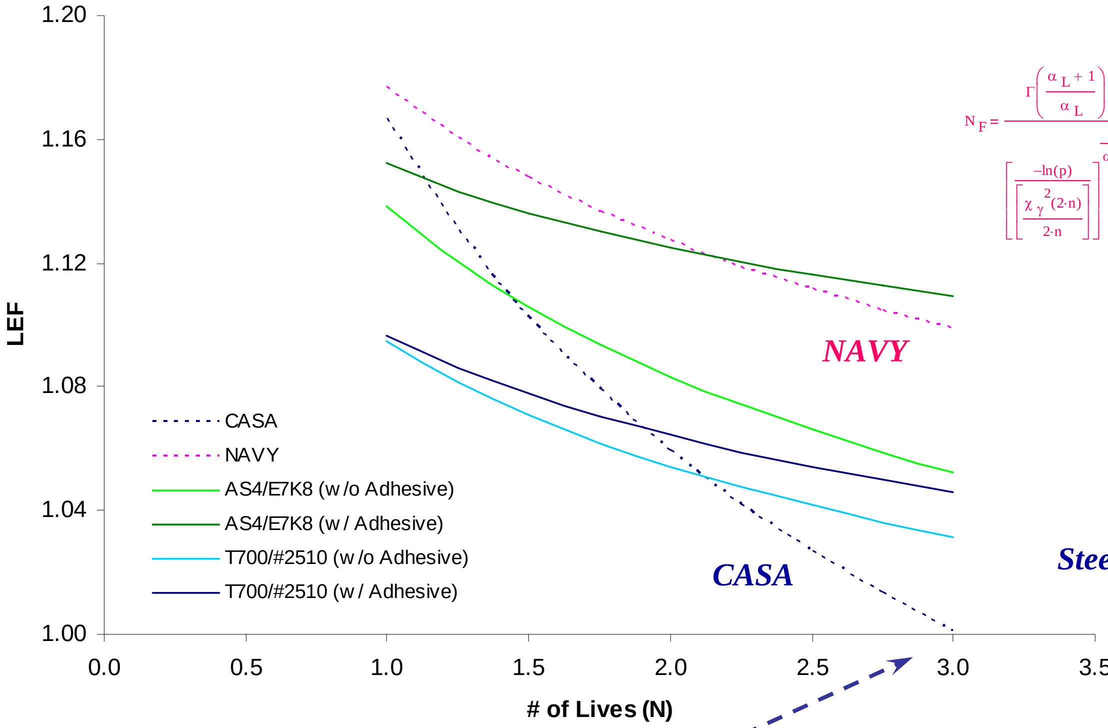
N (# of test articles) = 1

α_R	α_L	N_F	LEF	
19.63	2.74	3.019	**1.167**	**CASA**
20	1.25	13.558	**1.177**	**NAVY**
24.231	1.741	6.094	**1.139**	**AS4/E7K8**
	0.831	62.000	**1.152**	
34.587	1.872	5.308	**1.095**	**T700/#2510**
	1.496	8.463	**1.097**	

Without DOT/FAA/AR-03/56 adhesive fatigue data

With DOT/FAA/AR-03/56 adhesive fatigue data

Comparison of NAVY/FAA, EADS CASA and NIAR/FAA Data



$$N_F = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left[\frac{-\ln(p)}{\left[\frac{\chi_\gamma^2(2\cdot n)}{2\cdot n}\right]}\right]^{\frac{1}{\alpha_L}}}$$

CASA Study

[302 static; 48 fatigue specimens]

Interlaminar shear test that exhibited low fatigue life

Relatively less scatter

High α_L

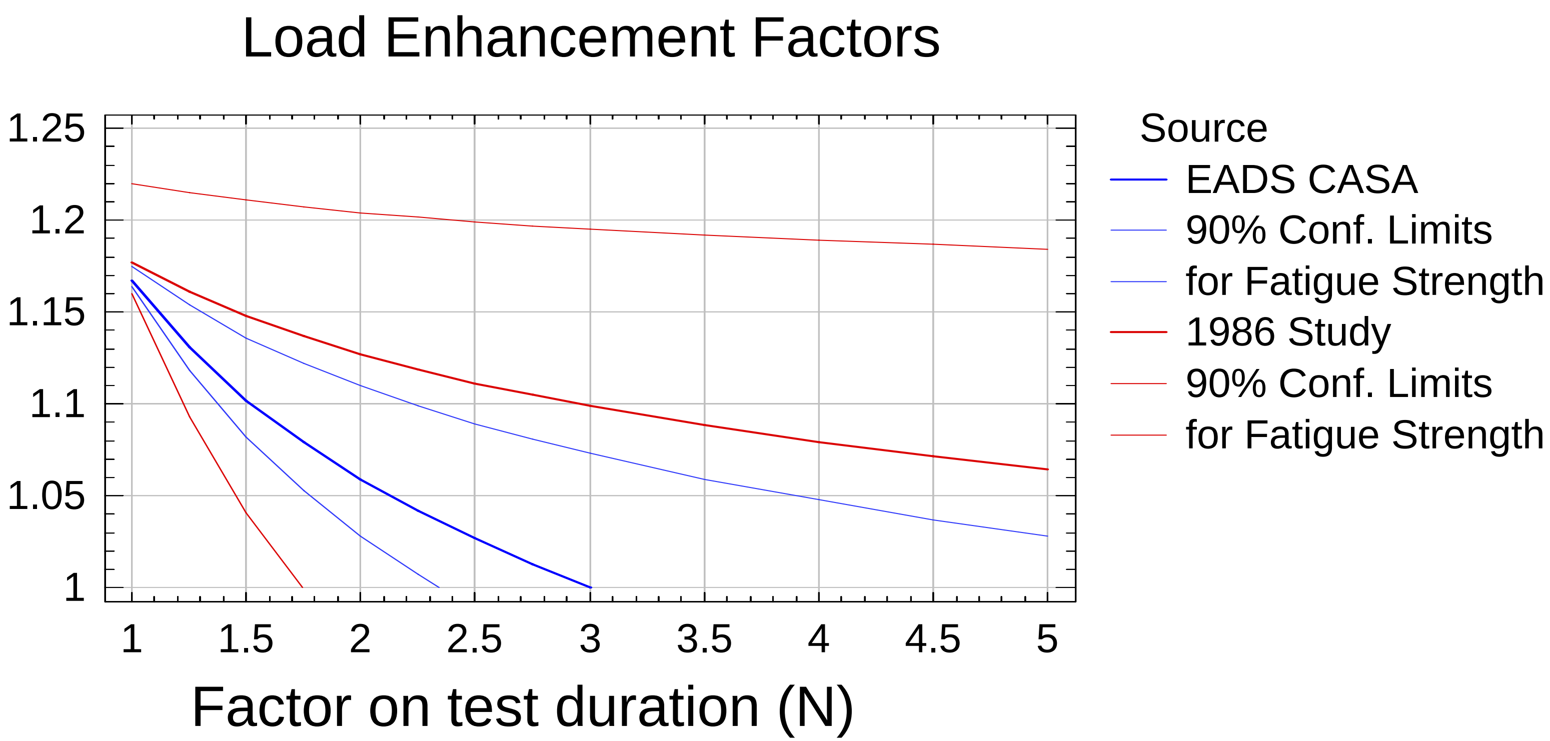
Steep LEF curve & Low N_F

Reliability (p)	0.9
Confidence Level (γ)	0.95
# of Test Articles (n)	1

					Combined Approach							
	α_R	α_L	N_F	**N=1.00**	**N=1.25**	**N=1.50**	**N=1.75**	**N=2.00**	**N=2.25**	**N=2.50**	**N=2.75**	**N=3.00**
CASA	19.63	2.74	3.019	**1.167**	1.131	1.103	1.079	1.059	1.042	1.027	1.013	1.001
NAVY	20	1.25	13.558	**1.177**	1.161	1.148	1.137	1.127	1.119	1.111	1.105	1.099
AS4/E7K8	24.231	1.741	6.094	**1.139**	1.121	1.106	1.094	1.083	1.074	1.066	1.059	1.052
		0.831	62.000	**1.152**	1.143	1.136	1.130	1.125	1.120	1.116	1.113	1.109
T700/#2510	34.587	1.872	5.308	**1.095**	1.081	1.071	1.062	1.054	1.048	1.042	1.036	1.031
		1.496	8.463	**1.097**	1.086	1.078	1.071	1.064	1.059	1.054	1.050	1.046

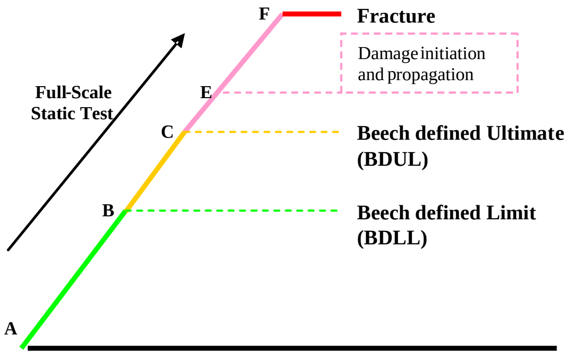
Load Enhancement Factor

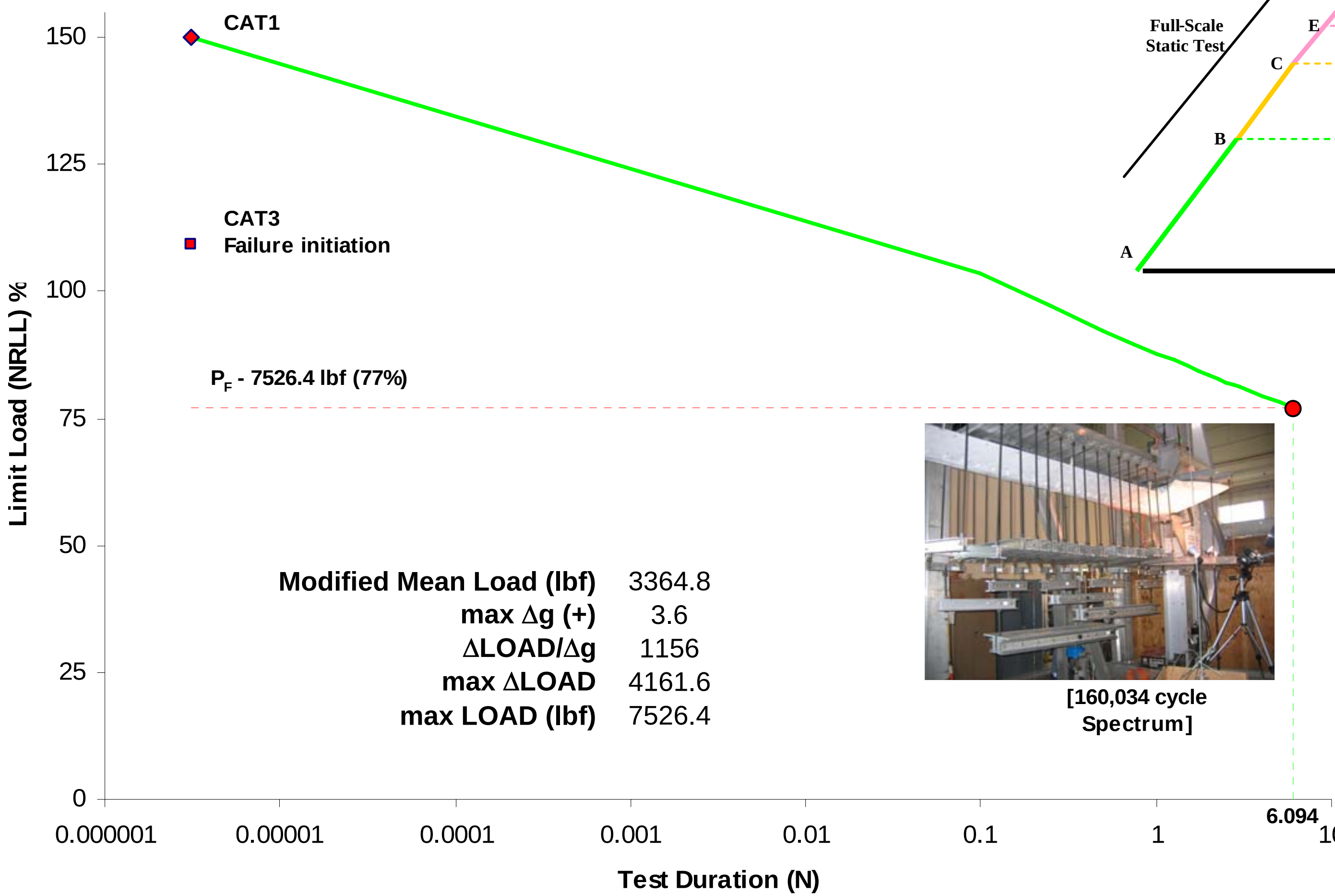
Comparisons of NAVY/FAA data and EADS CASA data



- Confidence limits set based on fatigue strength only since the mean and mode static strength values seem stable

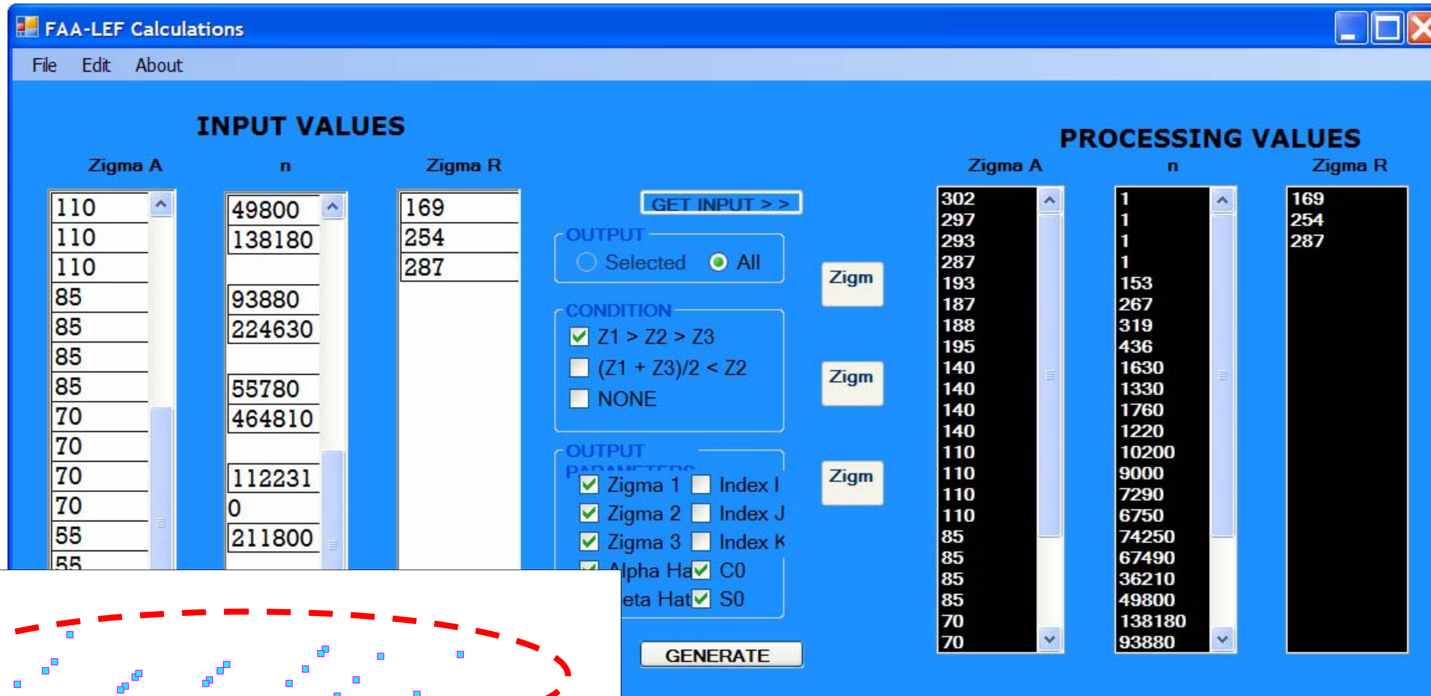
DaDT of Starship FW

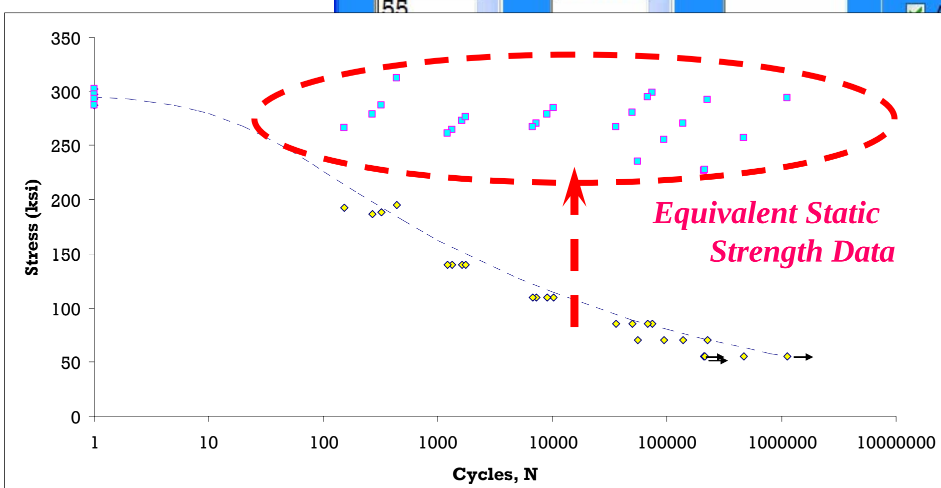




[160,034 cycle Spectrum]

LEF - Automation





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

Damage Tolerance Substantiation

- Provide guidance documentation as to industry “best practices” to damage tolerance substantiation in full-scale test protocols
  – Address different damage categories
  – Address Allowable Damage Limit (ADL)
  – Address damage growth threshold and definition of Critical Damage Threshold (CDT)
  – Assess repairs and repair’s repeated load capability and address Repairable Damage Limit (RDL)

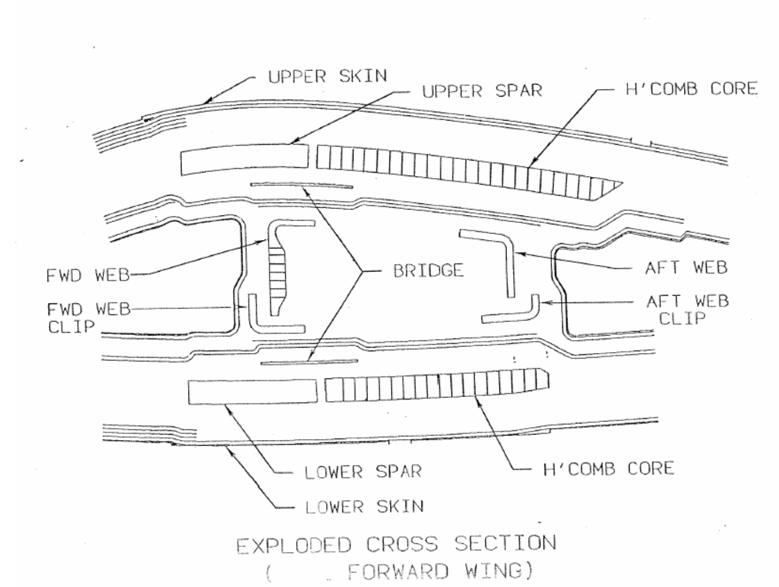
Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

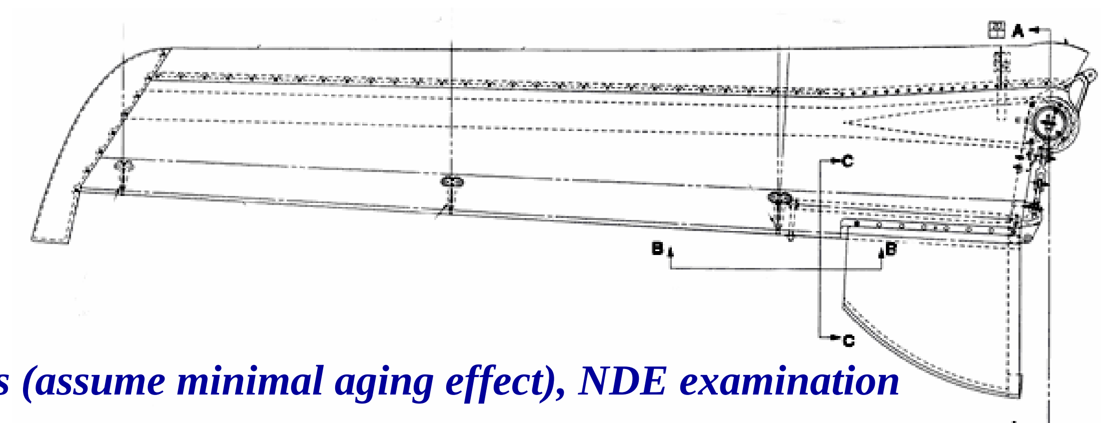
Category	Examples	Safety Considerations (Substantiation, Management)
Category 1: Damage that may go undetected by field inspection methods (or allowable defects)	BVID, minor environmental degradation, scratches, gouges, allowable mfg. defects	Demonstrate reliable service life Retain Ultimate Load capability 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)

Validation and Test Examples on Full-Scale Structures

- Need multiple, representative full-scale structures for testing
  - Demonstrate effects in multiple full-scale tests
  - Characterize load versus life effect on multiple full-scale articles
  - Damage Tolerance substantiation articles for various categories of damage
  - Multiple repair substantiation articles
- Problem ??? - cost of multiple structures for tests

Full-Scale Specimens





14 articles

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

Full-Scale Specimens

FAA programs (assessing any aging effects as well as DT), NDE examination

Currently 1 article is planned (documentation example)

Full-Scale Specimens

Liberty XL2

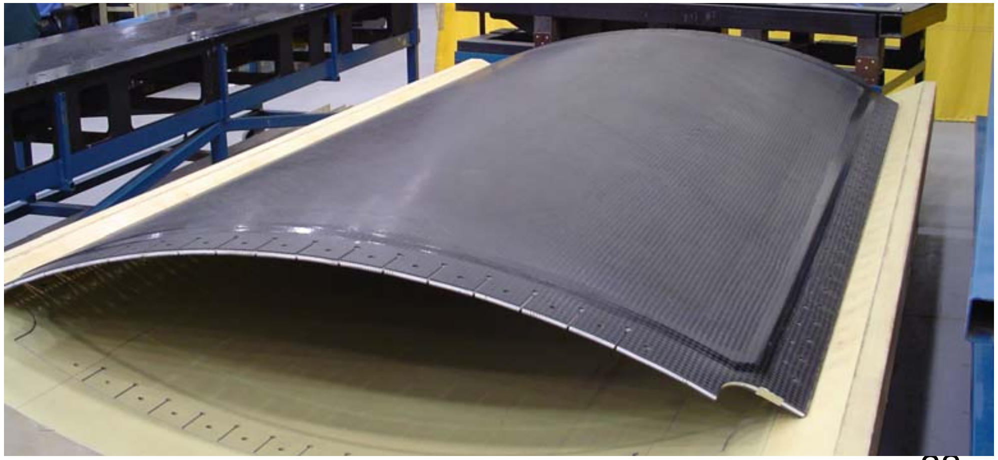
Liberty AEROSPACE

- Two fuselage tests are planned
- Structure is sandwich construction / minimum gage

Additional Full-Scale Tests

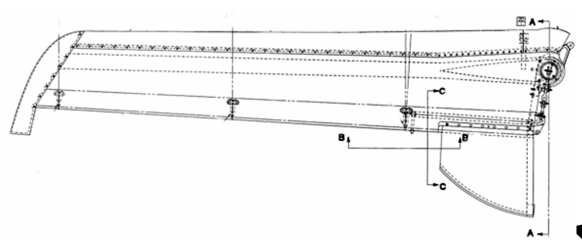
- Using the FASTER facility at the FAA Technical Center (Atlantic City, NJ)
- Fuselage loading – tension loading including pressure
- Test articles are representative of general aviation fuselage (sandwich construction)

ADAM AIRCRAFT

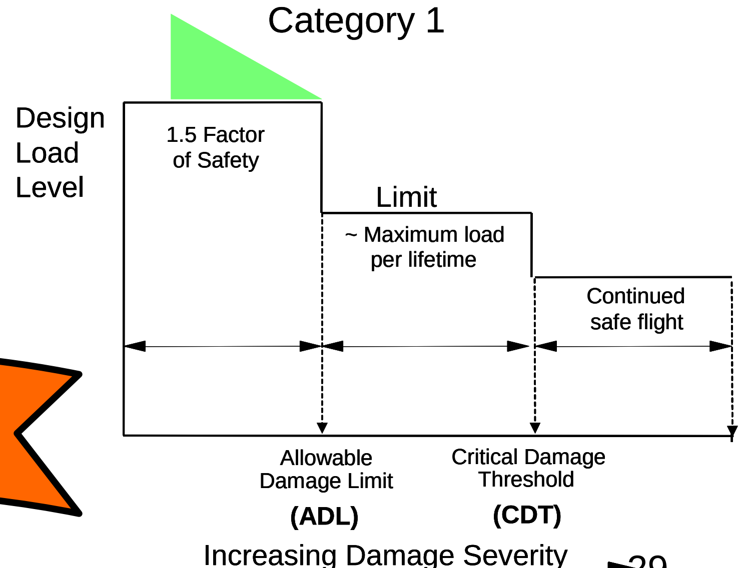


Characterize LEF Baseline Structural State

- ***Category 1 damage state*** – BVID, minor environmental degradation, manufacturing defects, minor service damage
- *Retain ultimate load and reliable service life*
- *Constant amplitude* repeated loading (N)
- N and load levels selected to produce fatigue failures
- Compression dominant
- NDI & Compliance check

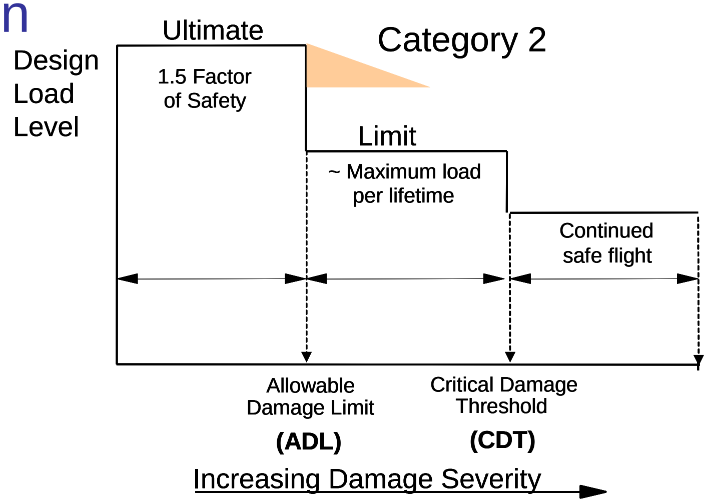


Scaling of LEF

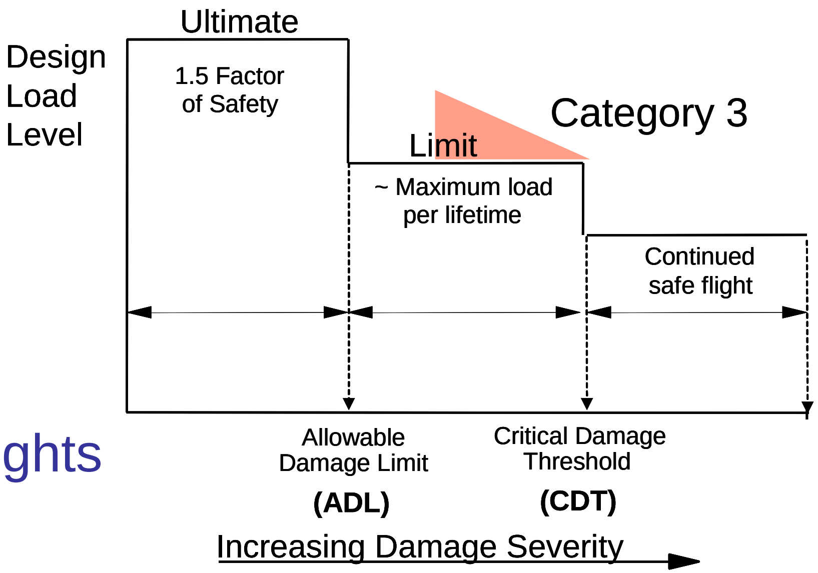


Damage Tolerance Testing

- ***Category 2 Damage***
  - VID, major environmental degradation
- Demonstrate reliable inspection and define intervals
- Compression
- Impact Damage
- Spectrum Loading
- Retain Limit Load capability
- Demonstrate no or minor growth under repeated loading (inspection interval)



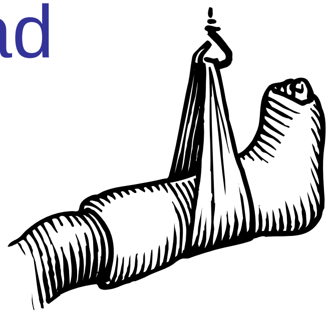
Damage Tolerance Testing



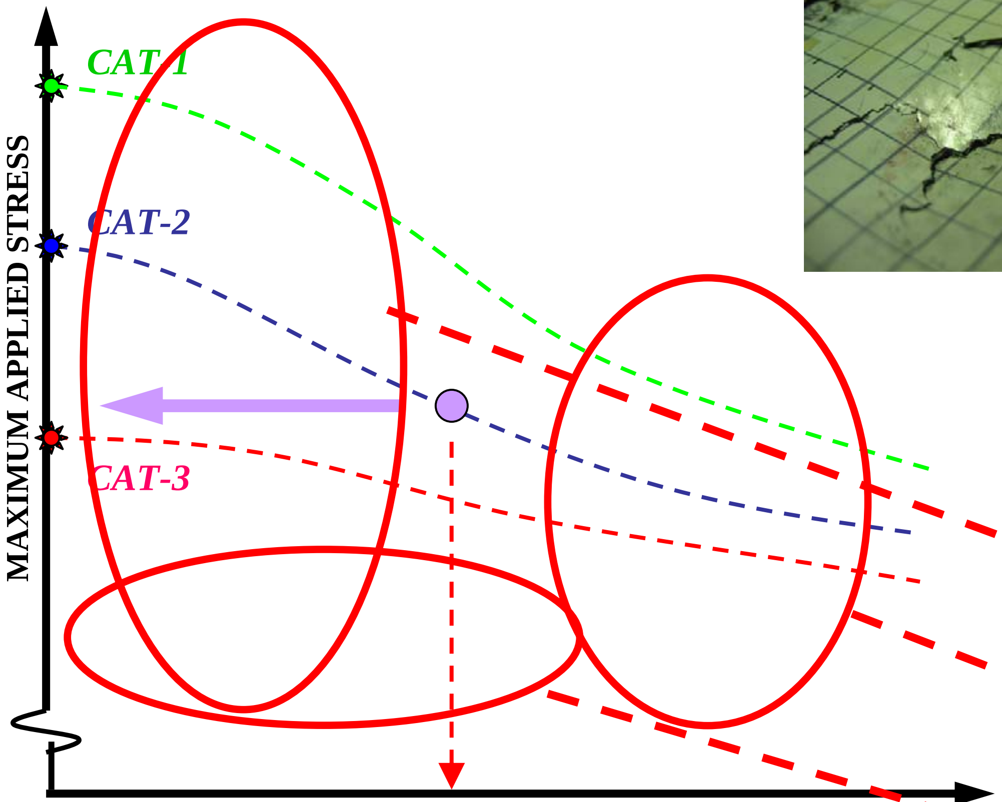
- ***Category 3 Damage***
  - damage obvious to operator
  - should be detected within a few flights
- Demonstrate quick detection
- Define damage threshold
- Compression Loading / Impact Damage
- Spectrum Loading (LIMITED CYCLES)
- Retain Limit Load capability

Repair Substantiation

- Demonstrate repair for category 2 and 3 damage states
- Work with OEM to develop guidelines for Repairable Damage Limit (RDL)
- Demonstrate restoration of full service life under spectrum loading
- Demonstrate restoration of ultimate load



Enhanced Combined Approach [Life-Load-Damage]



DEFINE DAMAGE TOLERANCE THRESHOLDS

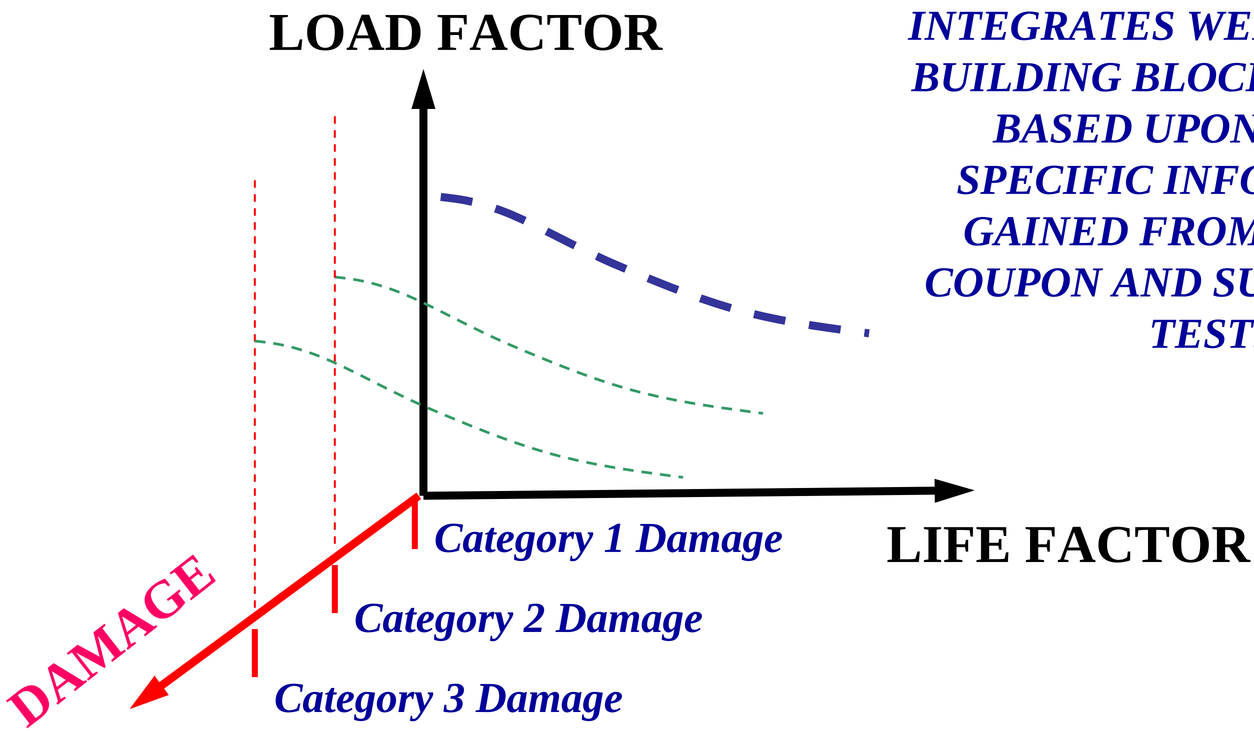
Help define ADL

Help define CDT

Help define inspection intervals

Not to scale!!!

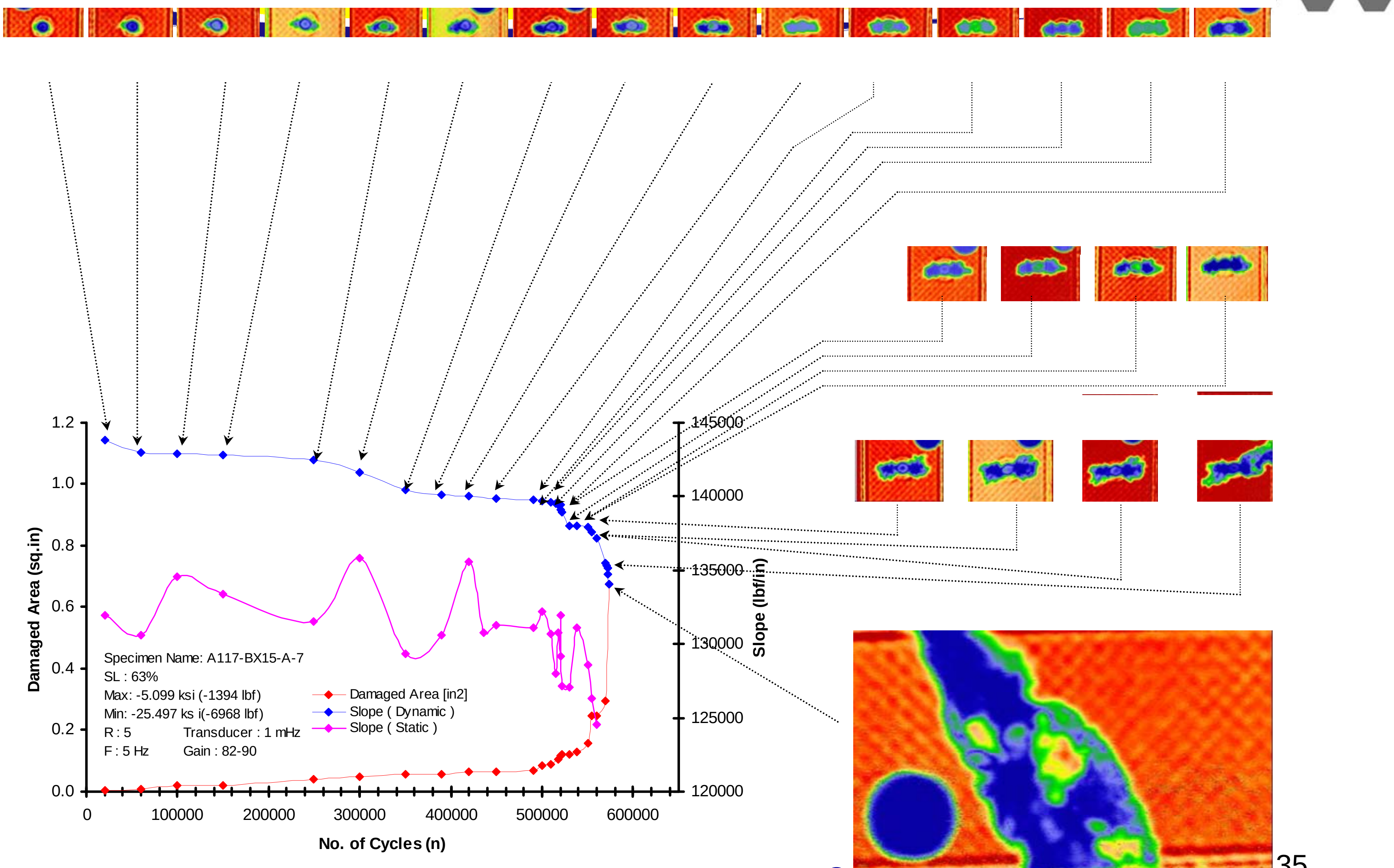
Enhanced Combined Approach [Life-Load-Damage]



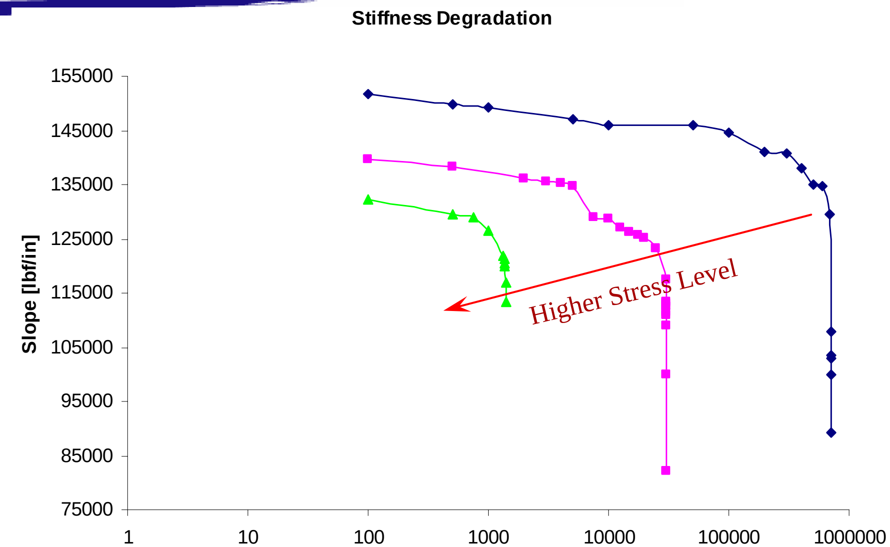
INTEGRATES WELL INTO THE BUILDING BLOCK APPROACH BASED UPON DESIGN SPECIFIC INFORMATION GAINED FROM VARIOUS COUPON AND SUBELEMENT TESTS

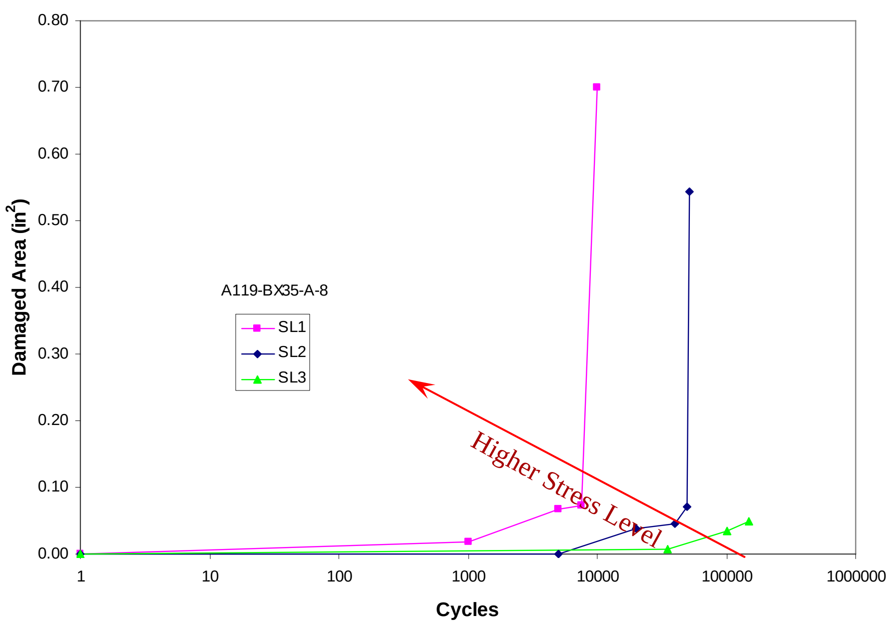
PROVIDES OPPORTUNITY TO FURTHER INTEGRATE THE CERTIFICATION APPROACH

Damage Evolution <> Stiffness Degradation



Fatigue Damage & Stiffness Degradation for Stress Levels

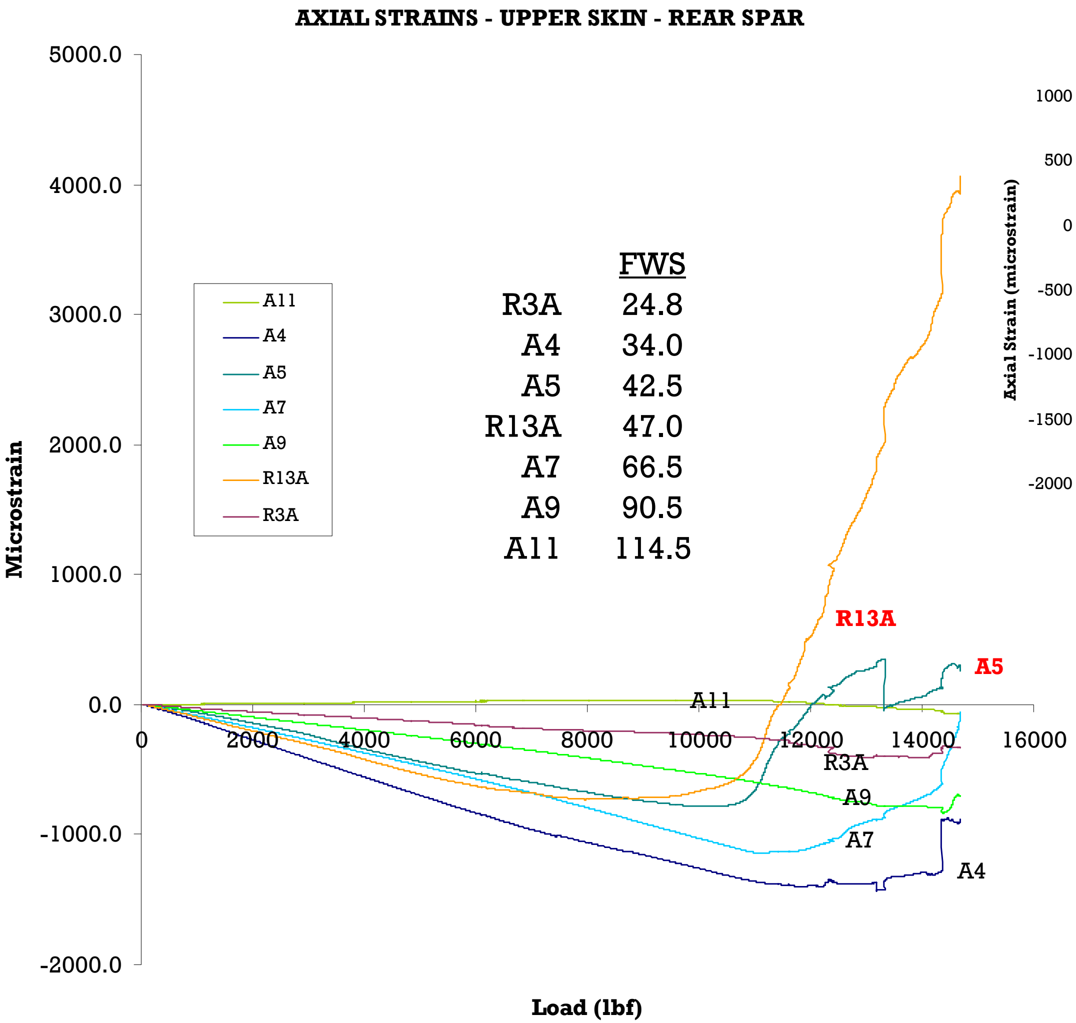


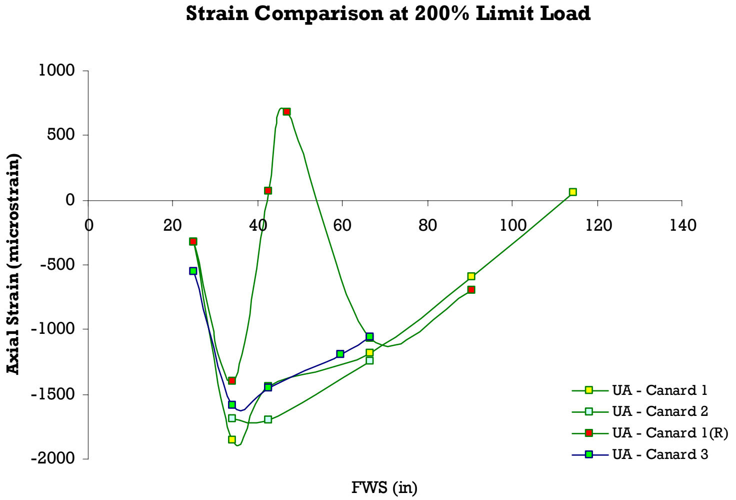


Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

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)

Starship FW - Damage Progression





CATEGORY 3 DAMAGE

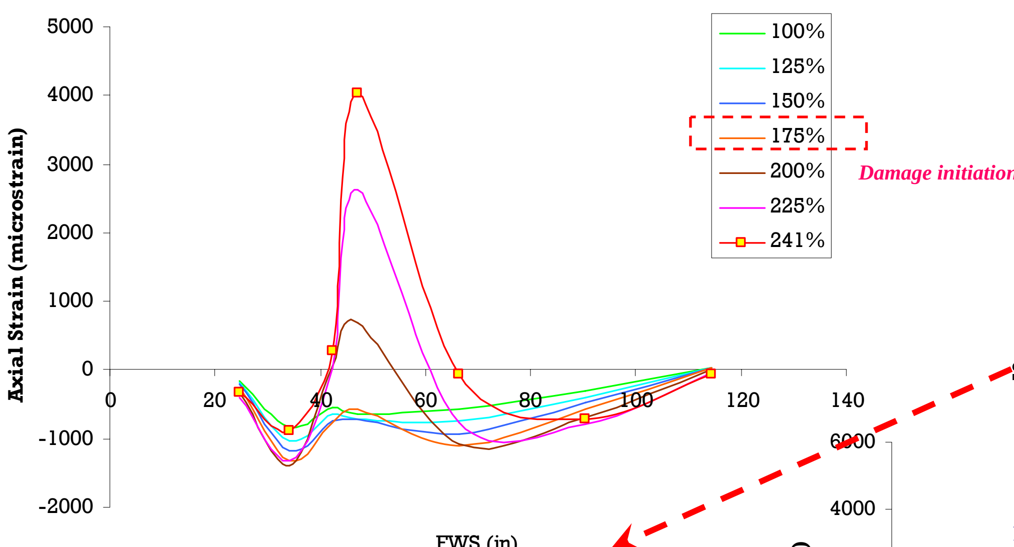
Impact Location: FWS 45 (Rear Spar)

Impact Energy: 225 ft-lb

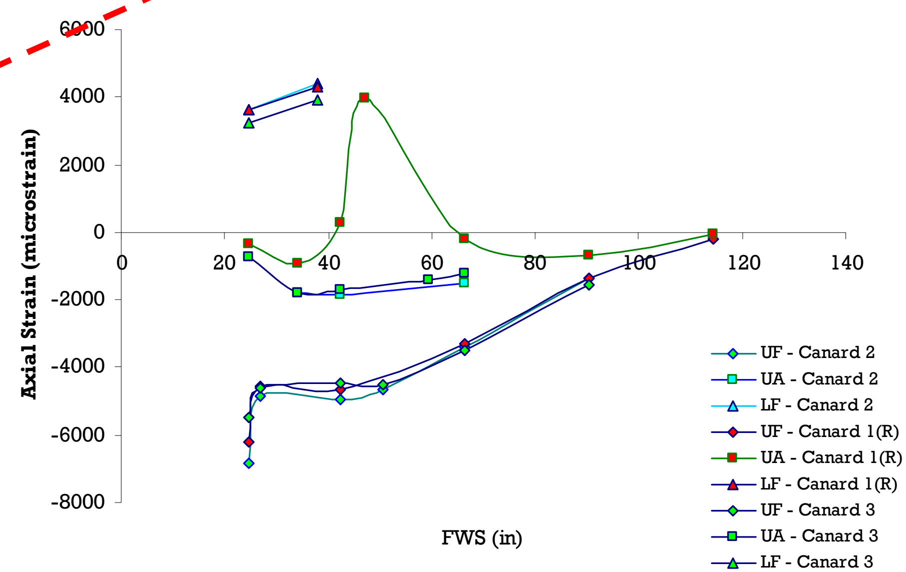
Impactor Diameter: 3-inch

Starship FW - Damage Progression

Strain Comparison - ST001 (R) REAR SPAR [UPPER SKIN]

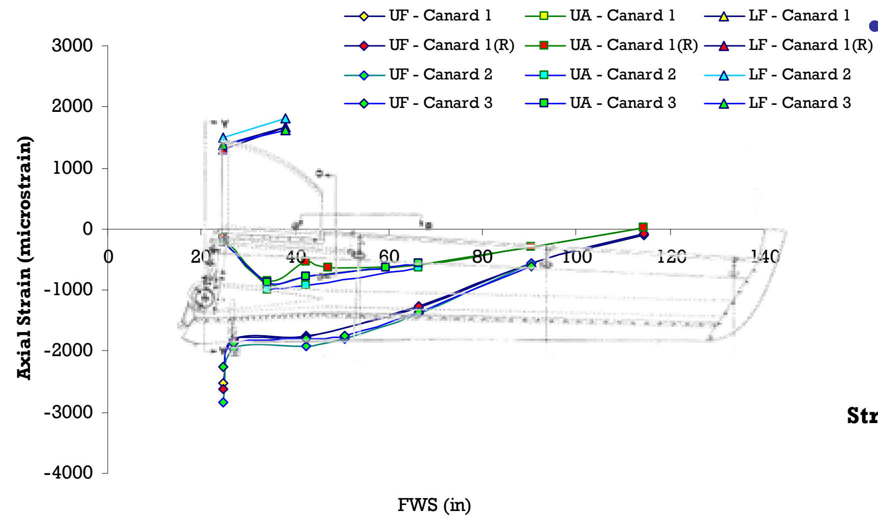


Strain Comparison at 240% Limit Load

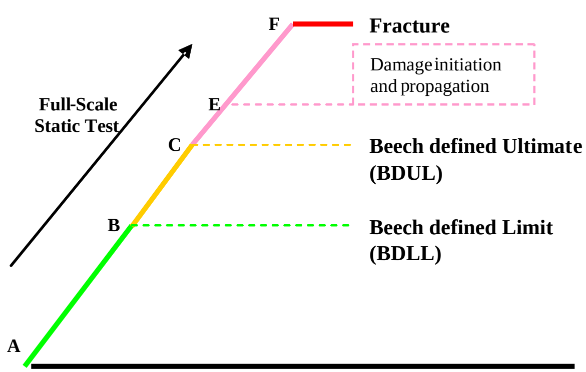


Starship FW - Strain Comparison

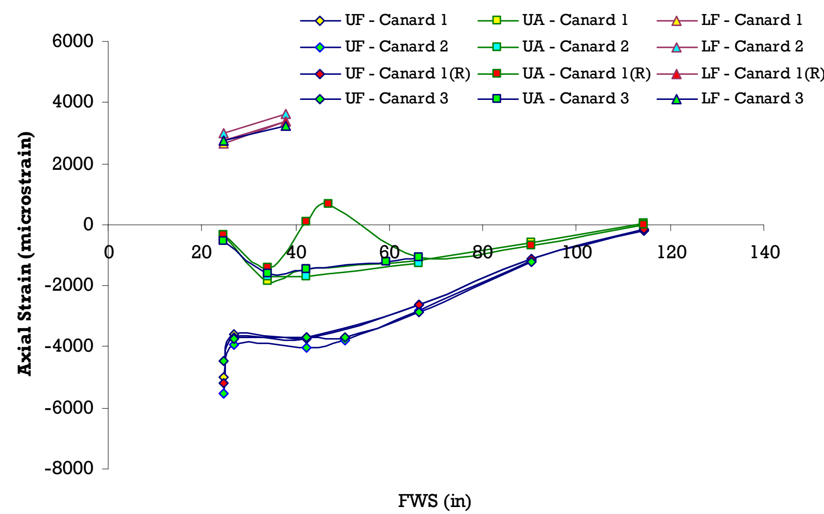
Strain Comparison at 100% Limit Load



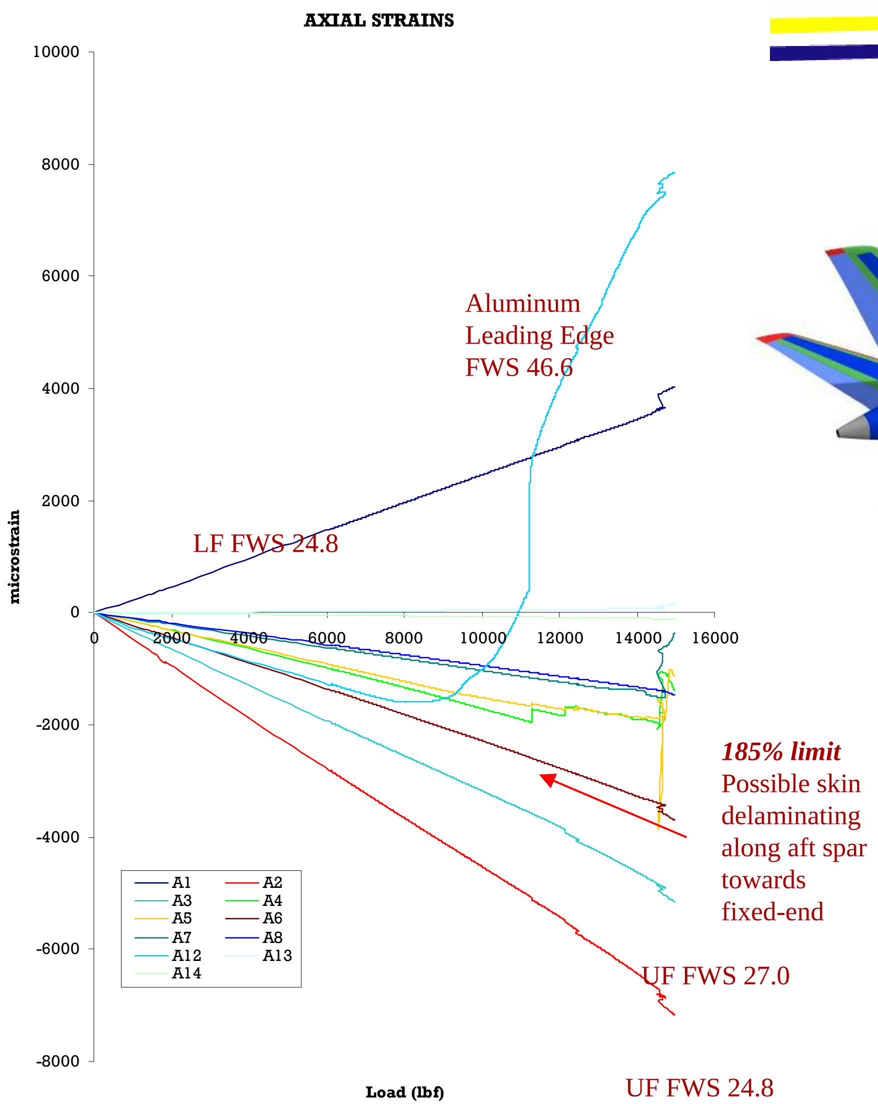
- Strains along the front (F) and aft (A) spar on upper (U) and lower (L) skins
  - Canard 1 was loaded to 200% limit
  - Canard 1(R), 2 and 3 were loaded until fracture/failure
  - Canard 1(R) has a Category 3* damage



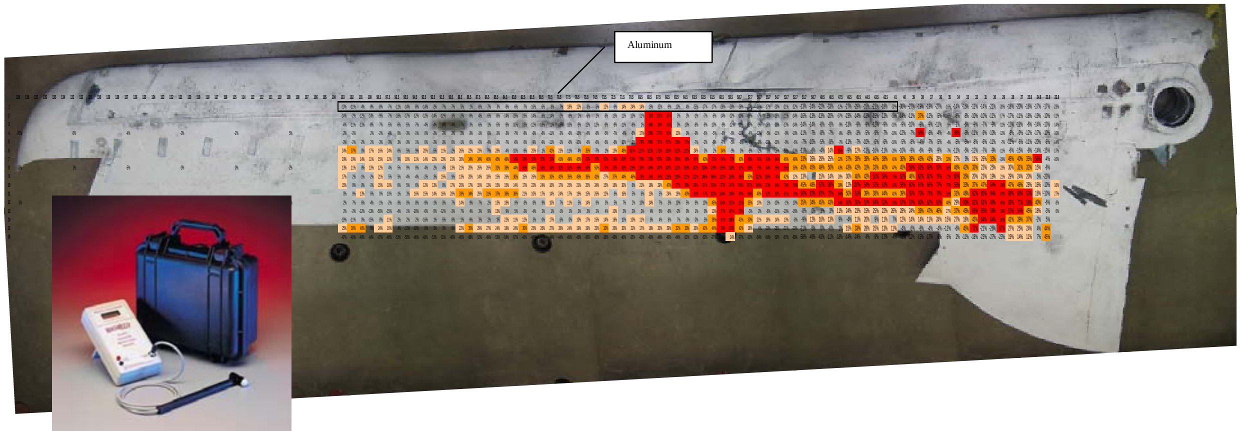
Strain Comparison at 200% Limit Load

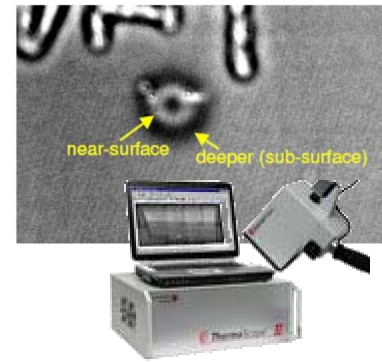


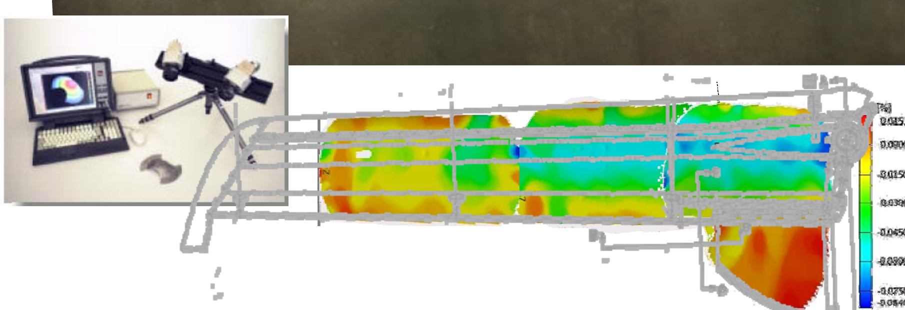
Impact on Hybrid Structures



Health Monitoring & Failure Analysis

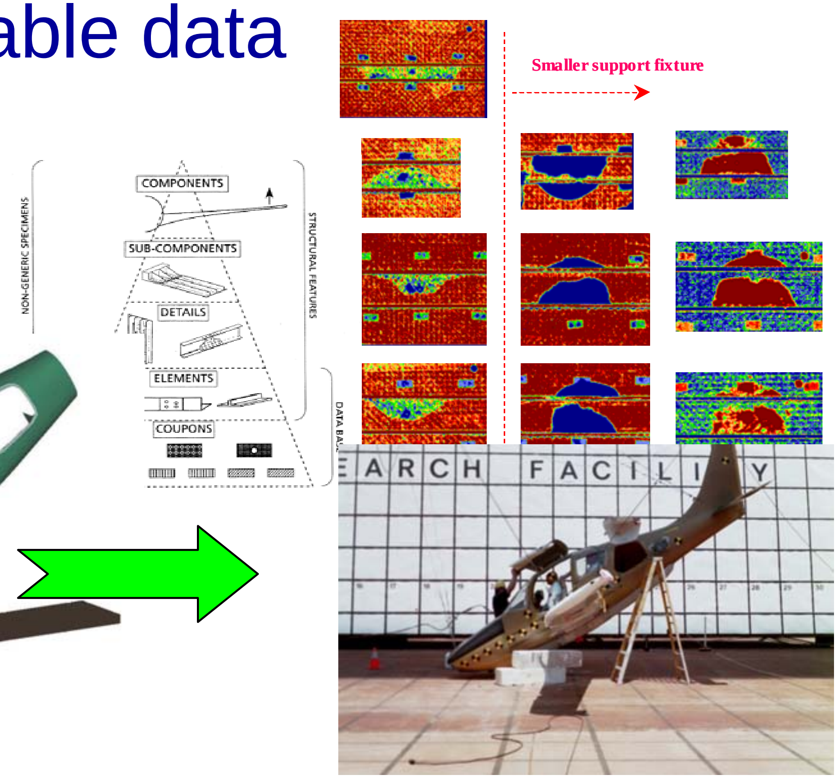


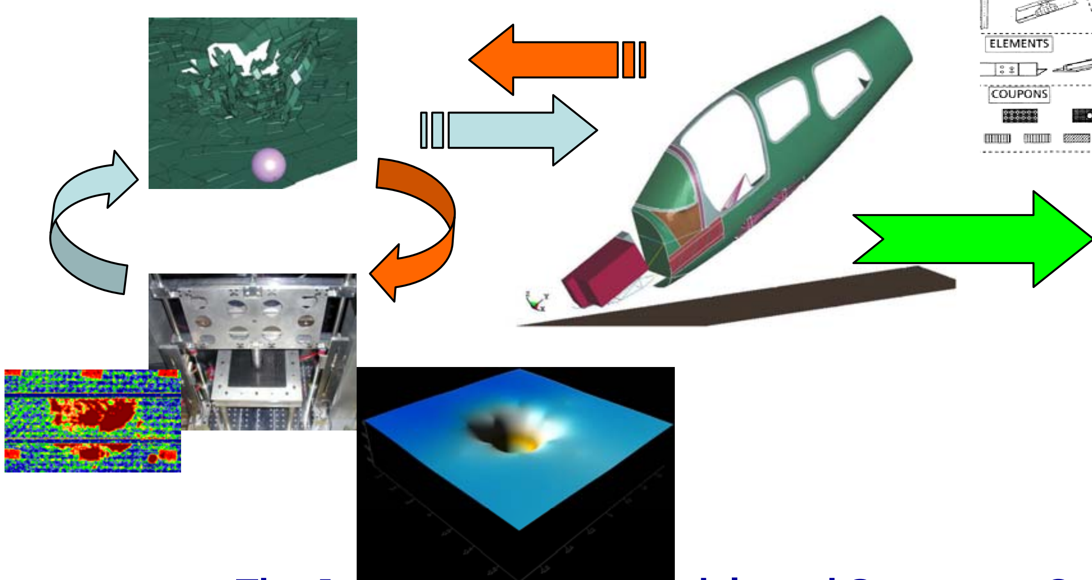




Impact Damage Characterization

- Nonlinear FEA (NLFEA) using ABAQUS Explicit and correlate with available data
  - Damage area
  - Residual indentation





A Look Forward

- Benefit 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)
    - User-friendly automated procedures and analysis guidelines

- Future needs
  - Reliable NDI and health monitoring techniques for damage characterization during full-scale testing
  - Techniques for damage analysis and failure prediction of composite components incorporating various failure modes/mechanisms

Questions