Research on Structural Test & Analysis Protocol: Progress and Plans

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FEDERAL AVIATION ADMINISTRATION

Commercial Aircraft Composite Repair Committee (CACRC)
Meeting & Workshop for
Composite Damage Tolerance & Maintenance
Amsterdam, Netherlands
May 9-11, 2007

Research Program Objectives

Primary Objective

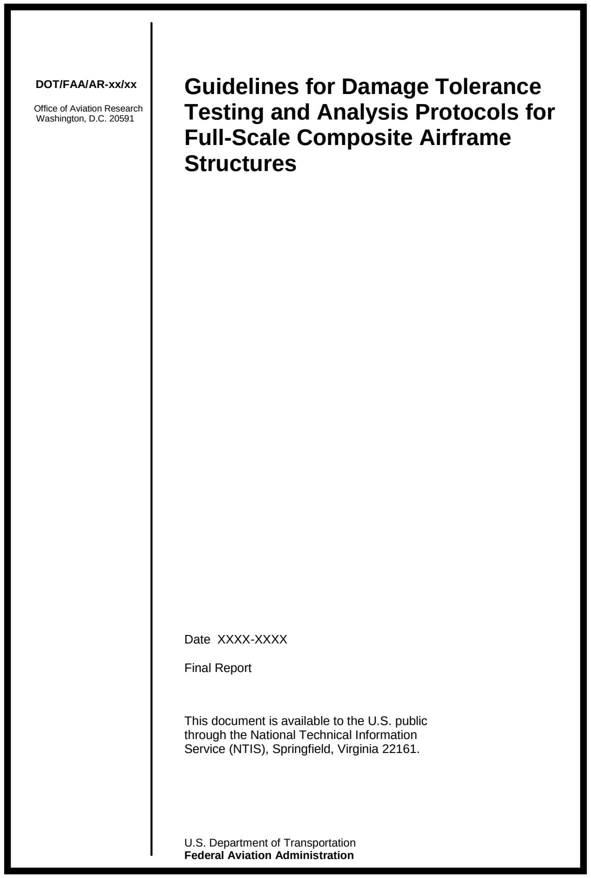
Demonstrate acceptable means of compliance for fatigue, damage tolerance and static strength substantiation of composite airframe structures

Secondary Objectives

- 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

Goals of the Program

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



DOT/FAA/AR-xx/xx

Office of Aviation Research
Washington, D.C. 20591

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

Date XXXX-XXXX

Final Report

This document is available to the U.S. public
through the National Technical Information
Service (NTIS), Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

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

Transport Aircraft Applications

We all think about these applications … but …

Other Applications of Advanced Materials


Cirrus


Lancair


Spectrum


Horizon


Adam Aircraft


Javelin


Premier I


Predator

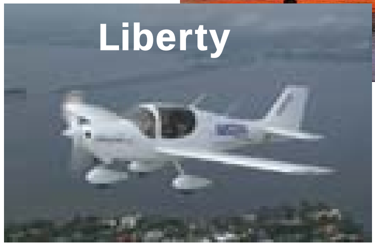

Epic


Honda


Bell Helicopter


Global Hawk


SpaceshipOne


Liberty


Toyota Aircraft

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

FAA Technical Center

FEDERAL AVIATION ADMINISTRATION

Hawker Beechcraft

Cessna
A Textron Company

BOEING

Liberty AEROSPACE

SPIRIT AEROSYSTEMS

CIRRUS DESIGN

TORAY

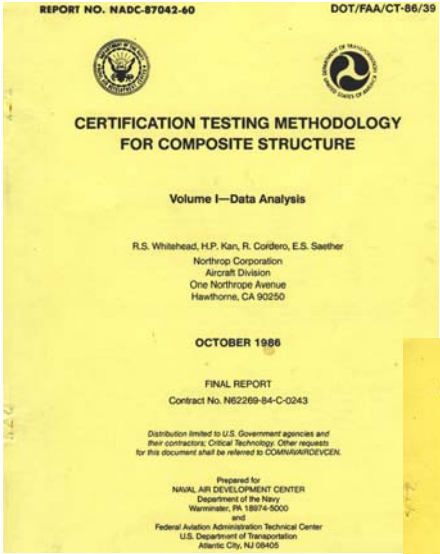
AlphaSTAR CORPORATION

ADAM AIRCRAFT

PLUS OTHER INDUSTRY PARTNERS

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
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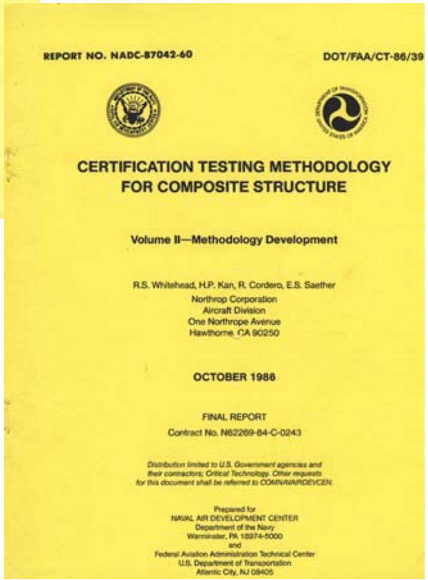
One Northrope Avenue
Hawthorne, CA 90250

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
NAVAL AIR DEVELOPMENT CENTER
Department of the Navy
Warminster, PA 18974-5000
and
Federal Aviation Administration Technical Center
U.S. Department of Transportation
Atlantic City, NJ 08405



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CERTIFICATION TESTING METHODOLOGY
FOR COMPOSITE STRUCTURE

Volume II—Methodology Development

R.S. Whitehead, H.P. Kan, R. Cordero, E.S. Saether
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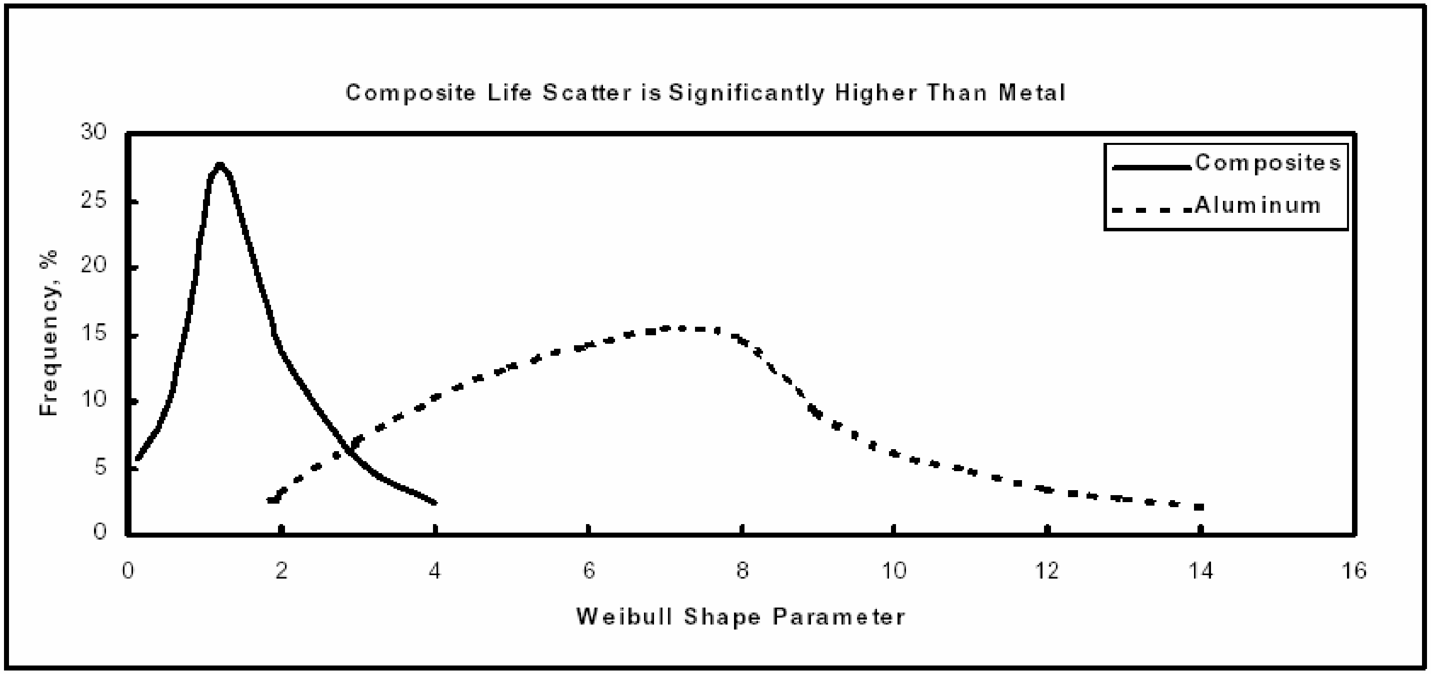
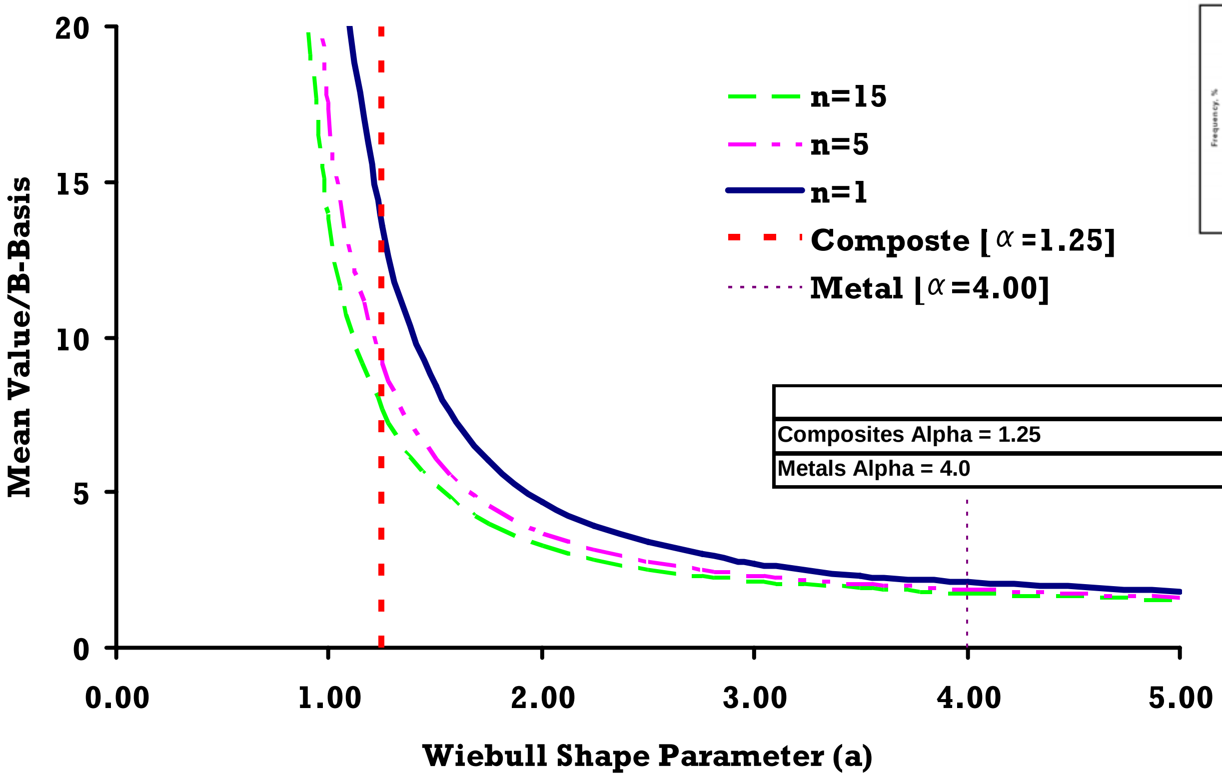
LEF - Overview of Methodology

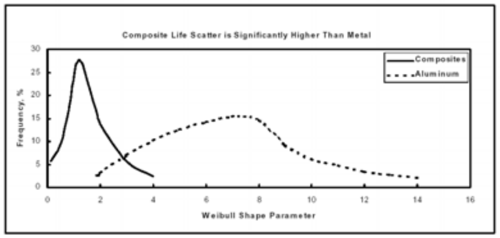


Comparison of graphite-epoxy and aluminum fatigue life scatter distributions

data was pooled on the basis that the life scatter is not significantly influenced by load level, loading mode, laminated layup, fatigue life and failure mode

Life Factor Approach



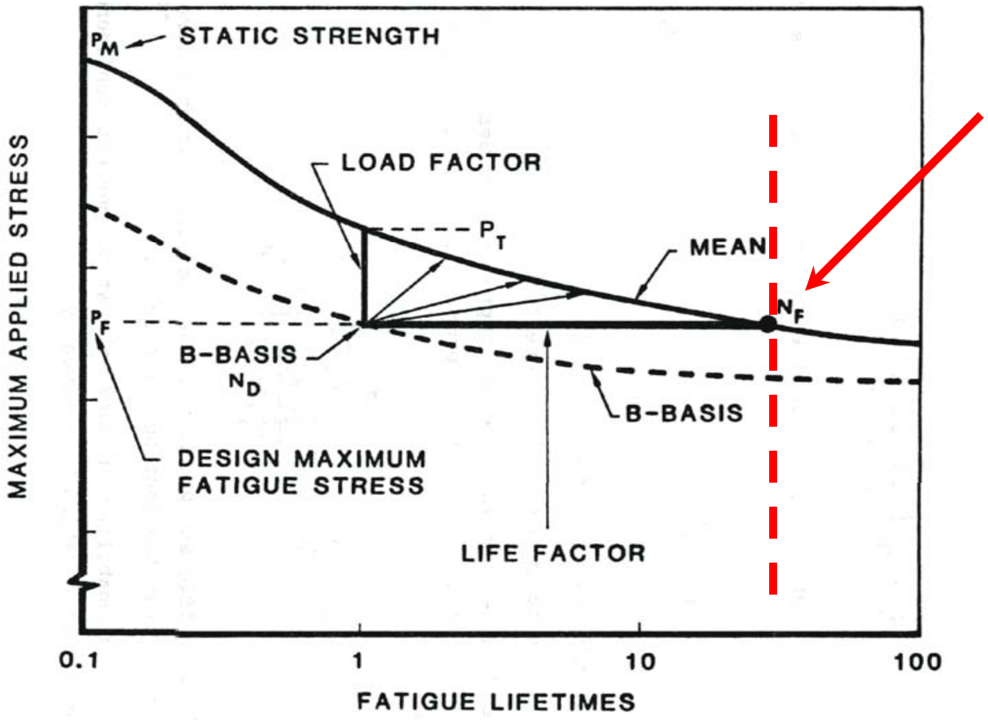


	n = 1	n = 5	n = 15
Composites Alpha = 1.25	13.558	9.143	7.625
Metals Alpha = 4.0	2.093	1.851	1.749

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

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

Load Enhancement



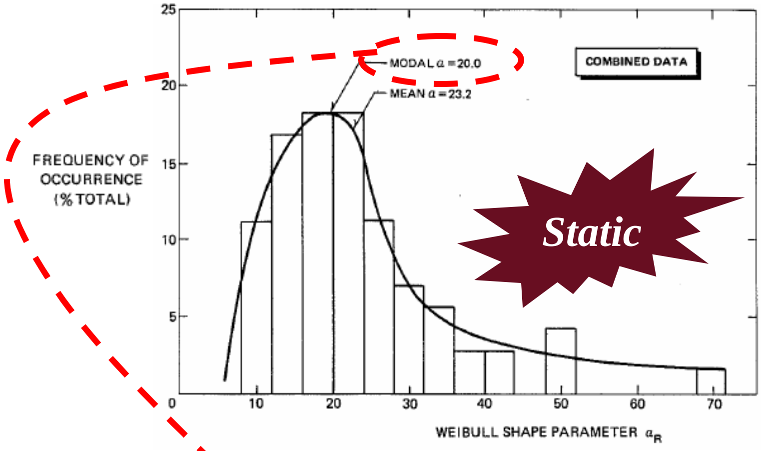
$$N_F = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left[\frac{-\ln(p)}{\left[\frac{\chi_\gamma^2(2\cdot n)}{2\cdot n}\right]}\right]^{\frac{1}{\alpha_L}}}$$

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

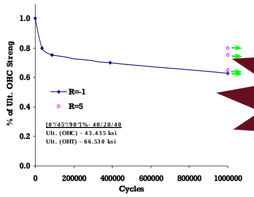
$$LEF = \frac{\left[\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right]^{\frac{\alpha_L}{\alpha_R}}}{\left[\frac{-\ln(p).N^{\alpha_L}}{\chi_\gamma^2(2n)/2n}\right]^{1/\alpha_R}}$$

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

Load Enhancement Factor Approach



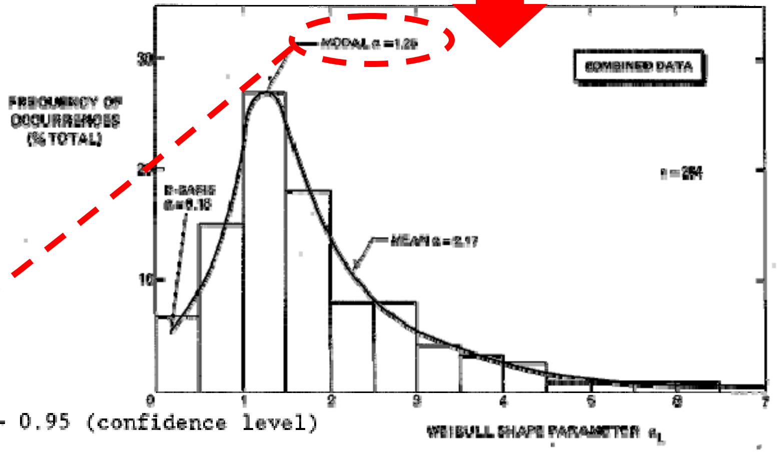
Static



Fatigue

Fatigue Data Fitting Models

Equivalent static strength values for fatigue data



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

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

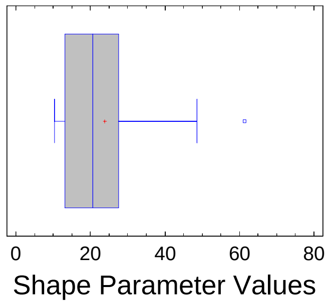
Load Enhancement Factor Approach

Comparisons of NAVY/FAA data and EADS CASA data

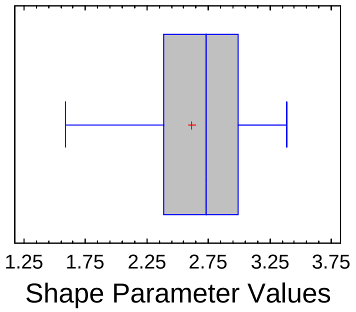
1986 study conservatively estimated static shape parameter at 20

1986 study conservatively estimated fatigue shape parameter at 1.25

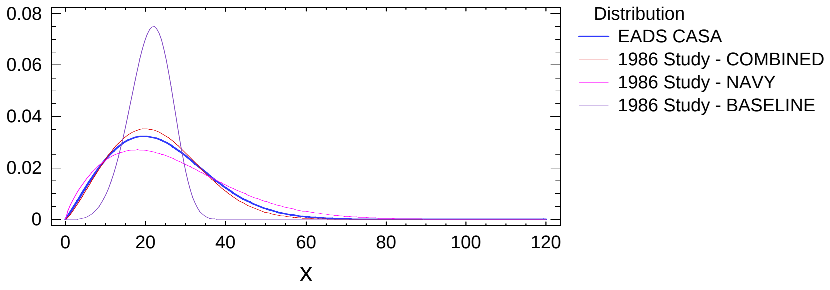
EADS CASA Static Strength tests



EADS CASA Fatigue Strength Tests

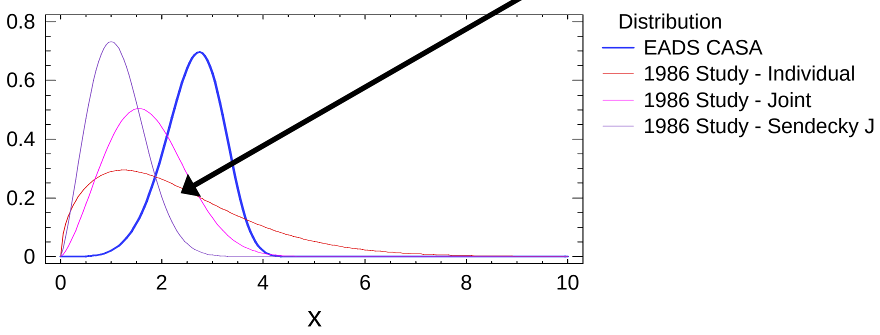


Static Strength Shape Parameter



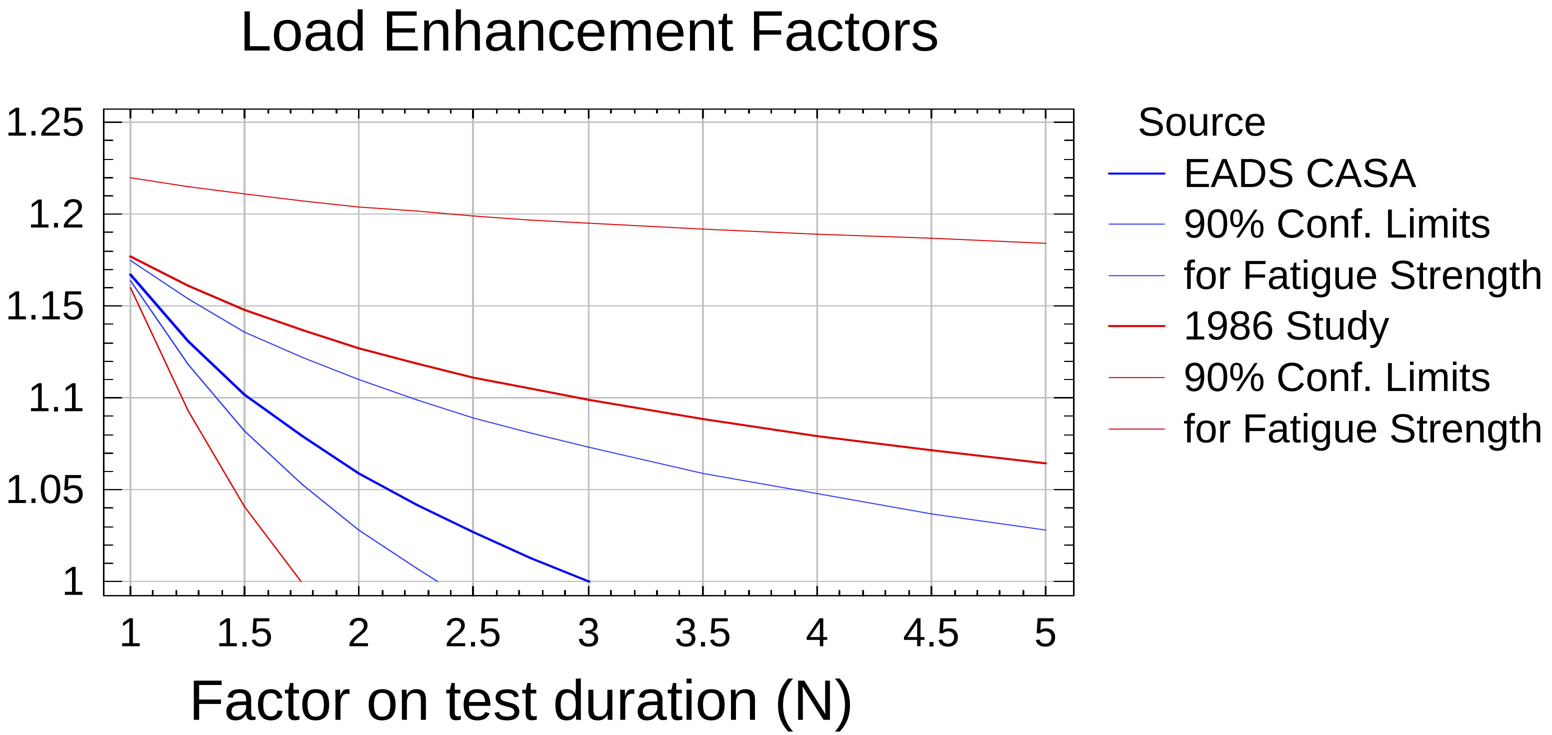
Fatigue Strength Shape Parameter

Leads to conservative LEF



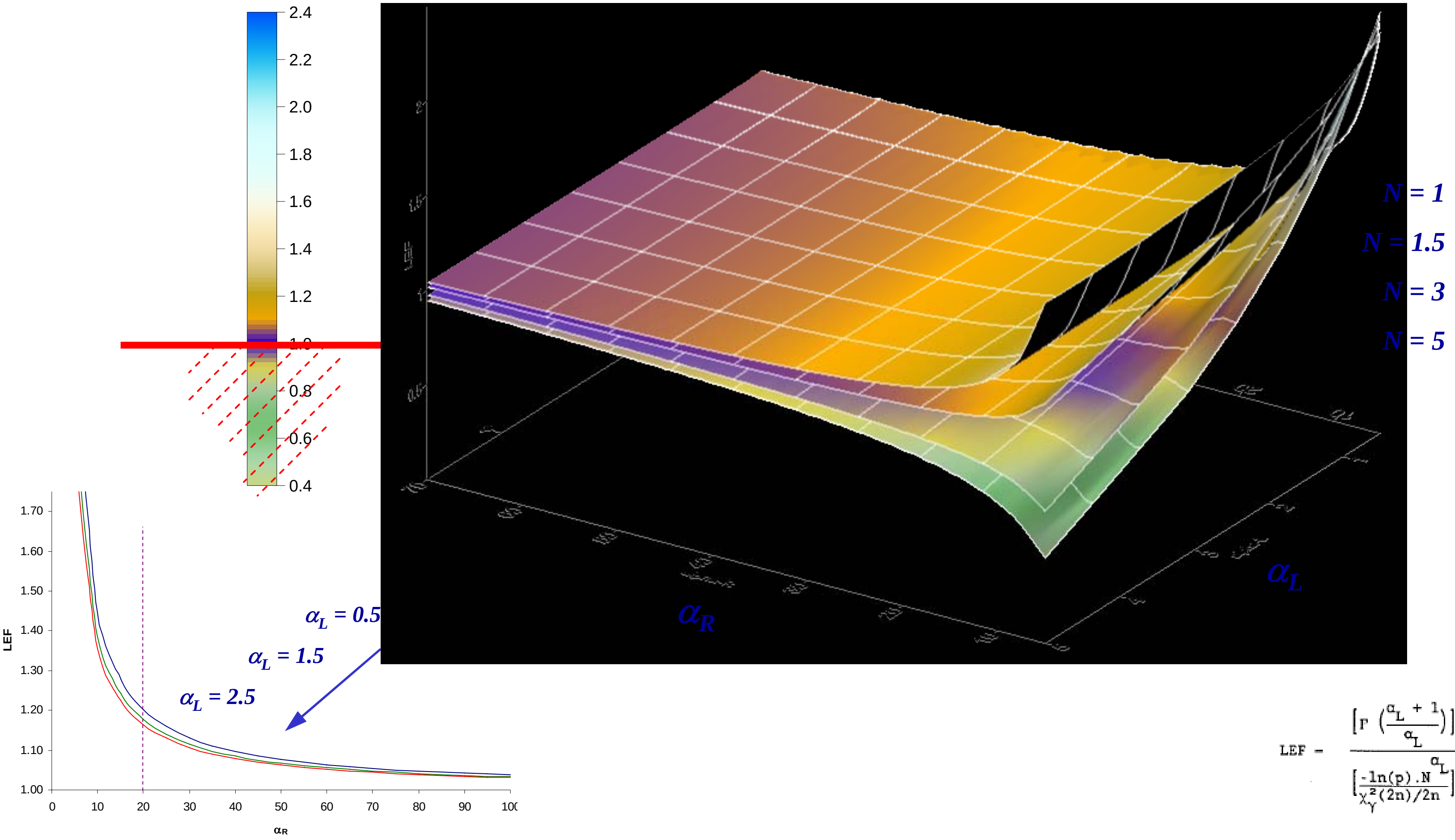
Load Enhancement Factor

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

Load-Life Combined Approach



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

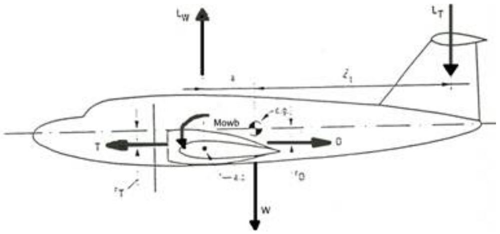
Task Research Objectives

- Generate data and guidelines for the generation of Weibull shape parameters for
  - Different material systems
  - Loading modes and geometries
  - Environments
  - Bonded joints (2 thicknesses)
  - Sandwich construction
  - Multiple R-ratios

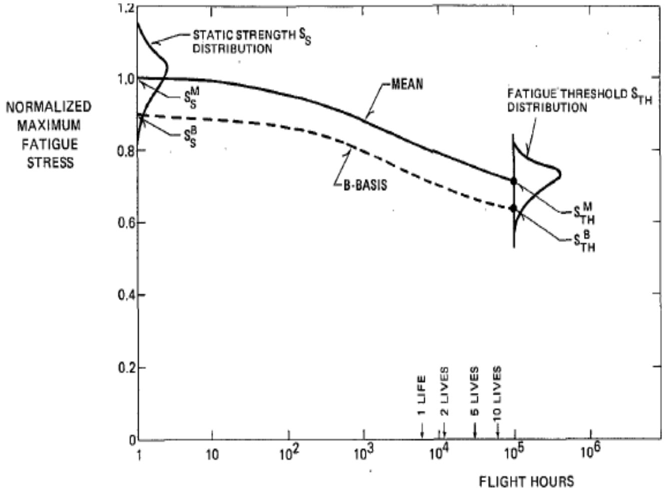
Develop shape parameters for different geometries, environments, layups, and loading modes

Data Development

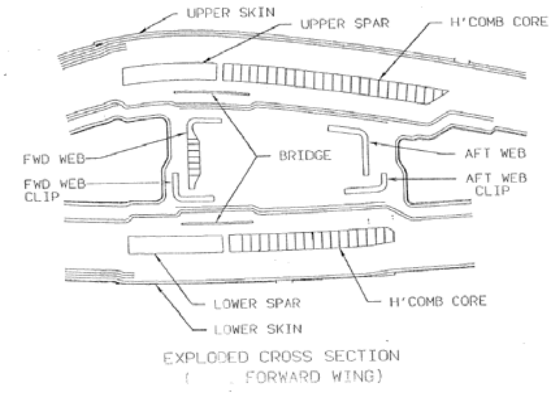
- Use existing lamina and laminate data for static strength
- Static / Fatigue Loading
  - Notched Tension
  - Notched Compression
  - Bonded joints
  - Interlaminar shear
  - Sandwich construction
  - RTD and ETW

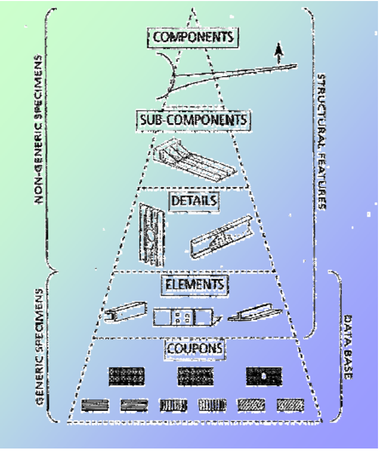


- Fatigue
  - Const. amplitude (5 H*z*)
  - R-ratios
    - 0 (Fuselage)
    - -0.2, 5 (Wing)
    - -1 (Control Surface)



LEF Test Matrix





CYTEC AS4/E7K8 PW

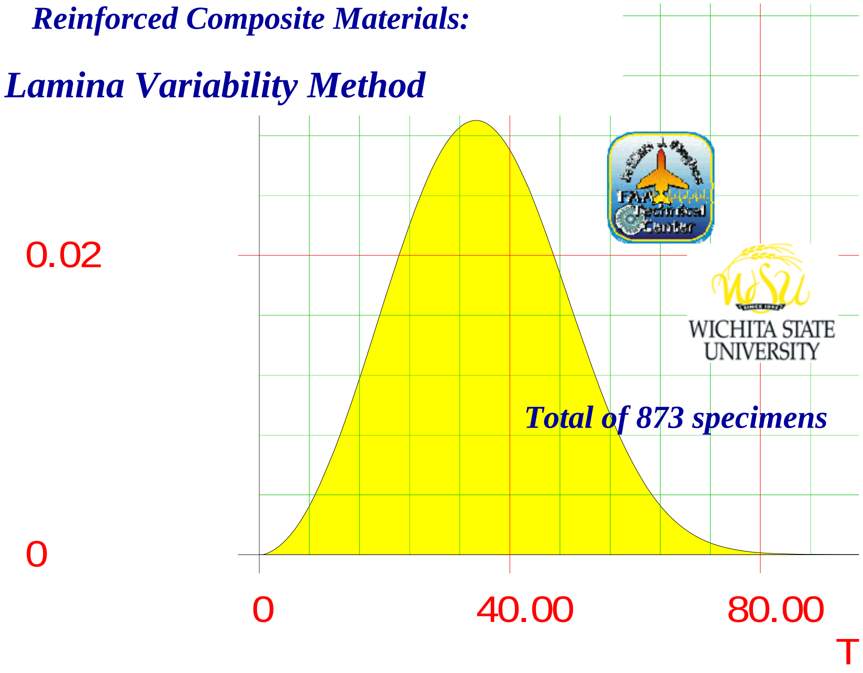
Laminate	Test Method	Loading Condition	Standard	Specimen Dimensions (wxL)	Static Test Environment		RTD - Cyclic Test R ratio (3 Stress Levels)			
					RTD	ETW	-0.2	0	-1	5
10/80/10 Laminate	Open-Hole	Tension	ASTM D5766	1.5x12"	6	6	18	18		18
		Comp.	ASTM D6484		6	6			18	
	Bonded Joint (t=0.01-inch)	Tension	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



Total of 873 specimens

β=2.9412, η=39.8364, ρ=0.9955

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

α	2.941
β	39.836

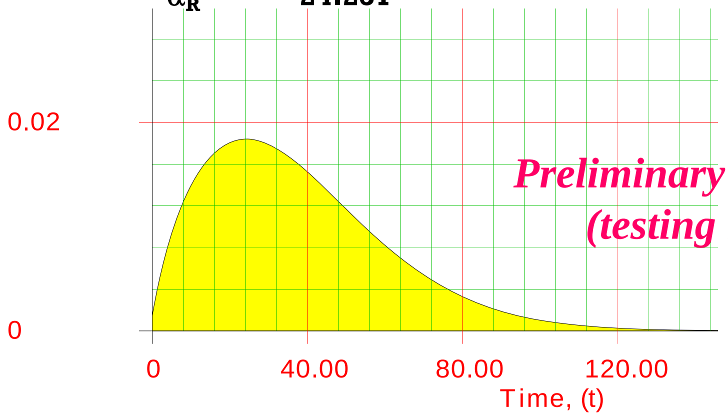
MODAL (EXTREAM)

α_R **34.587**

LEF - AS4/E7K8 & T700/#2510

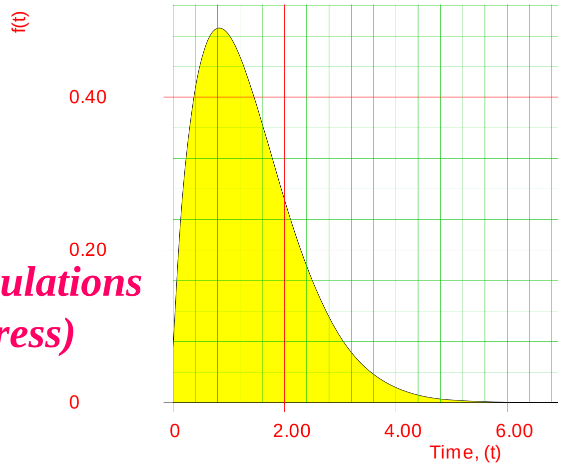
α **1.6647**
β **42.0614**

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

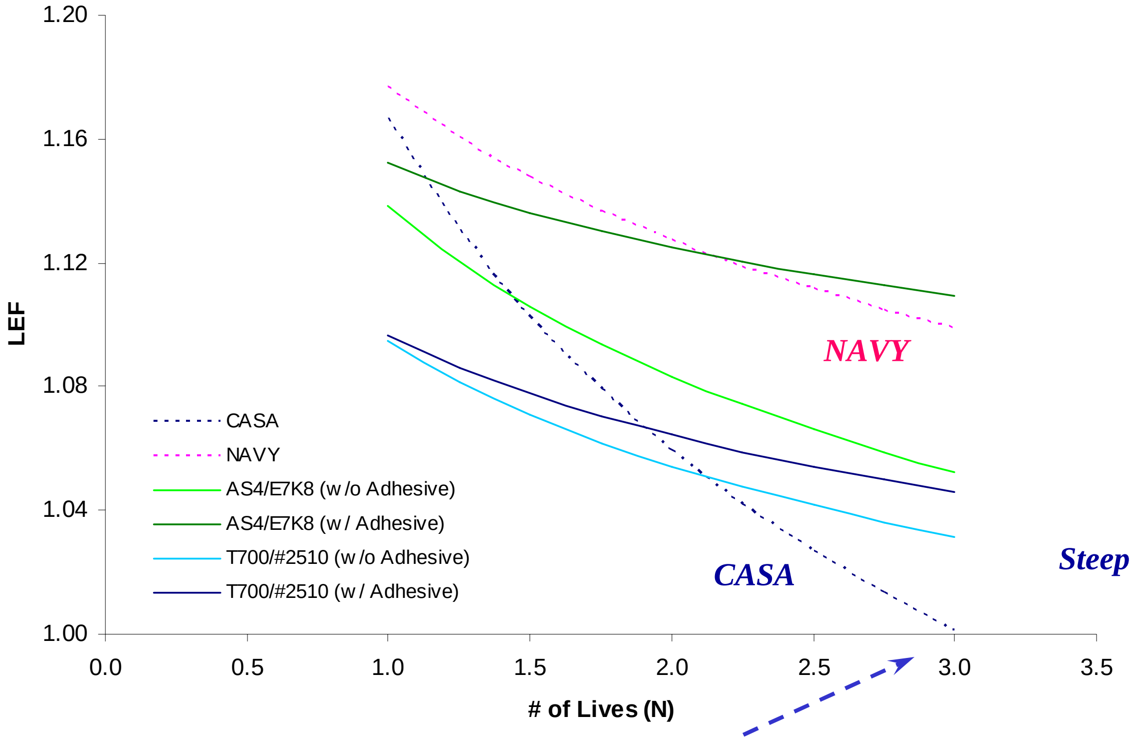
N (# of test articles) = 1

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

Fatigue Life Shape Parameter



CASA Study

[302 static; 48 fatigue specimens]

Interlaminar shear test that exhibited low fatigue life

Relatively less scatter

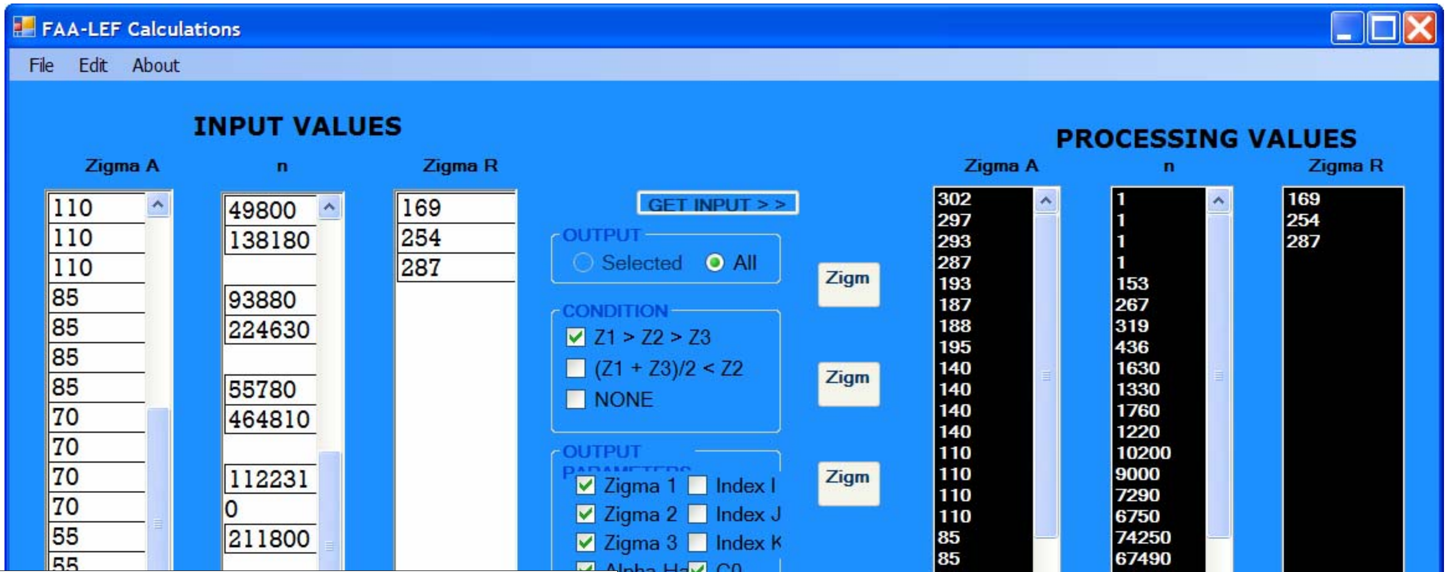
High α_L

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
700/#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

LEF - Automation



INPUT VALUES

Zigma A	n	Zigma R
110	49800	169
110	138180	254
110		287
85	93880	
85	224630	
85		
85	55780	
70	464810	
70		
70	112231	
70	0	
55	211800	
55		

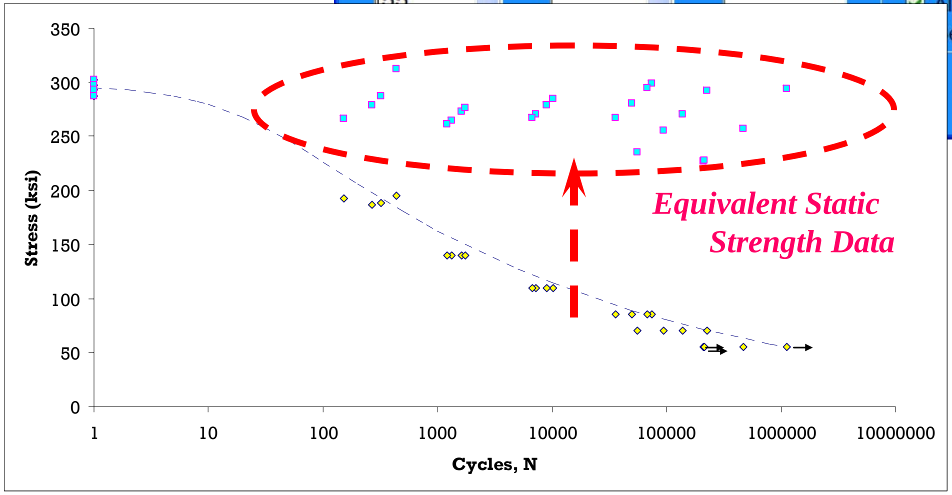
OUTPUT
○ Selected ● All

CONDITION
☑ Z1 > Z2 > Z3
☐ (Z1 + Z3)/2 < Z2
☐ NONE

OUTPUT PARAMETERS
☑ Zigma 1 ☐ Index I
☑ Zigma 2 ☐ Index J
☑ Zigma 3 ☐ Index K
☑ Alpha Ha ☑ C0
eta Hat ☑ S0

PROCESSING VALUES

Zigma A	n	Zigma R
302	1	169
297	1	254
293	1	287
287	1	
193	153	
187	267	
188	319	
195	436	
140	1630	
140	1330	
140	1760	
140	1220	
110	10200	
110	9000	
110	7290	
110	6750	
85	74250	
85	67490	
85	36210	
85	49800	
70	138180	
70	93880	

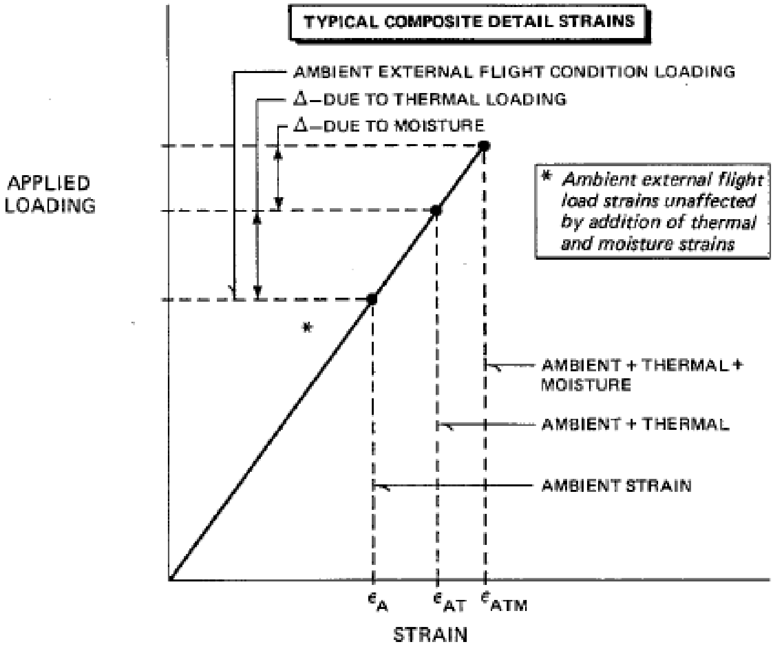


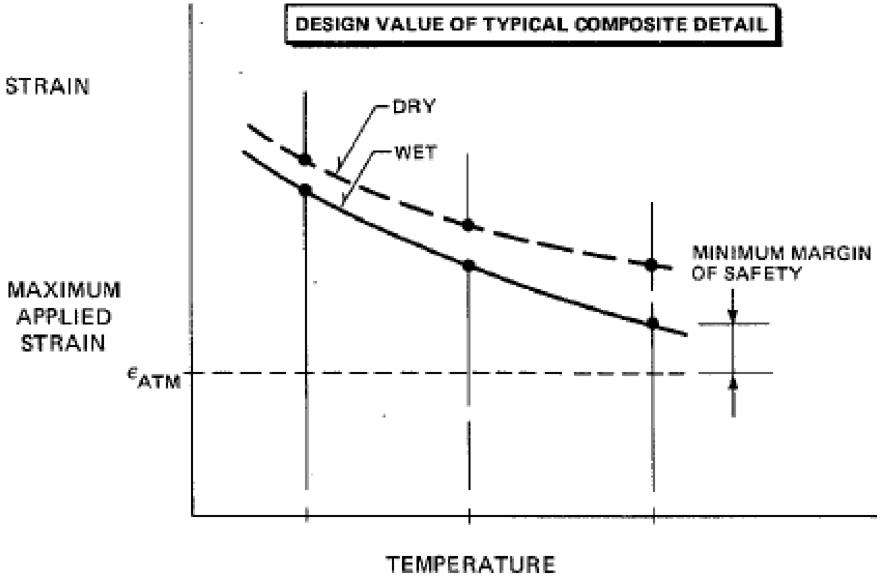
Equivalent Static Strength Data

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

Environmental Enhancement Factor

- Develop guidelines for the development of environmental enhancement factors for static strength loading
- Use data developed at lamina, laminate, element and subcomponent to demonstrate application





Damage Tolerance Substantiation

PROGRAM OBJECTIVES

- 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)

Work Tasks

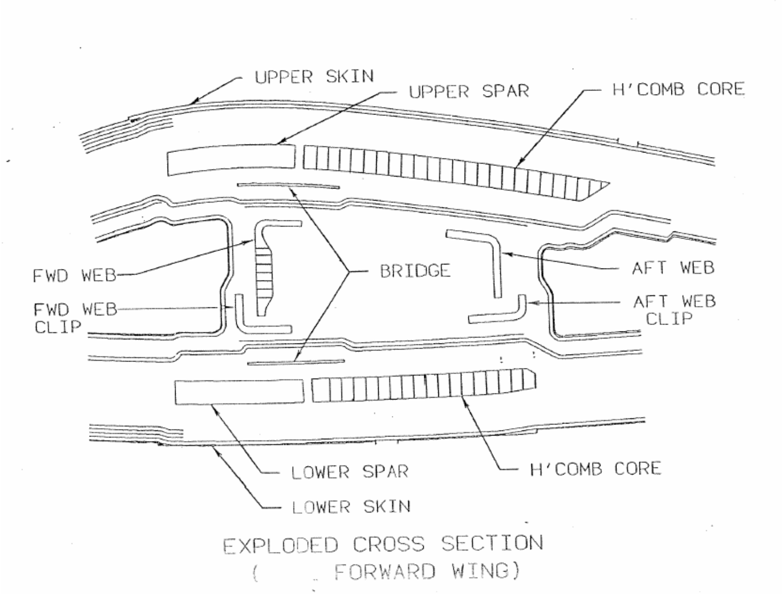
- Fatigue & damage tolerance substantiation after static strength substantiation on a separate test article
- Fatigue, static strength and damage tolerance substantiation using the same test article
- One of the above but with variations in the loading, and/or severity of damage to demonstrate an ability to measure early warnings of failure in the test (and predict a failure)
- Supporting data needs
  - Static load cases and repeated loading envelops
  - Test fixture design, fabrication & setup and test article instrumentation
  - Building block testing to support analysis groups
  - LEF & truncation limits for repeated load testing (shared databases)
  - Environmental factors for residual strength testing

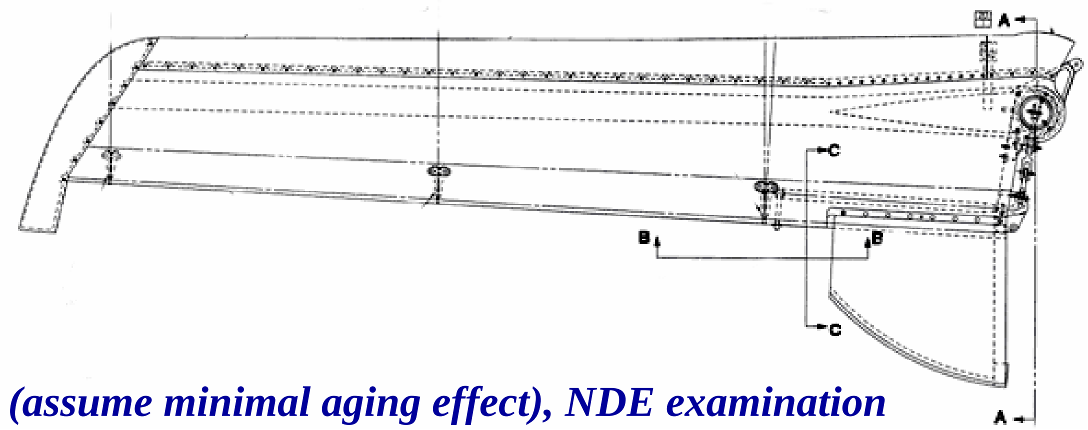
Note: Test plans consider damages ranging from allowable damage limit (ADL) to critical damage threshold (CDT) and repairs up to the repairable damage limit (RDL)

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 age effects as well as DT), NDE examination

Currently 1 article is planned (documentation example)

Full-Scale Specimens

Liberty XL2

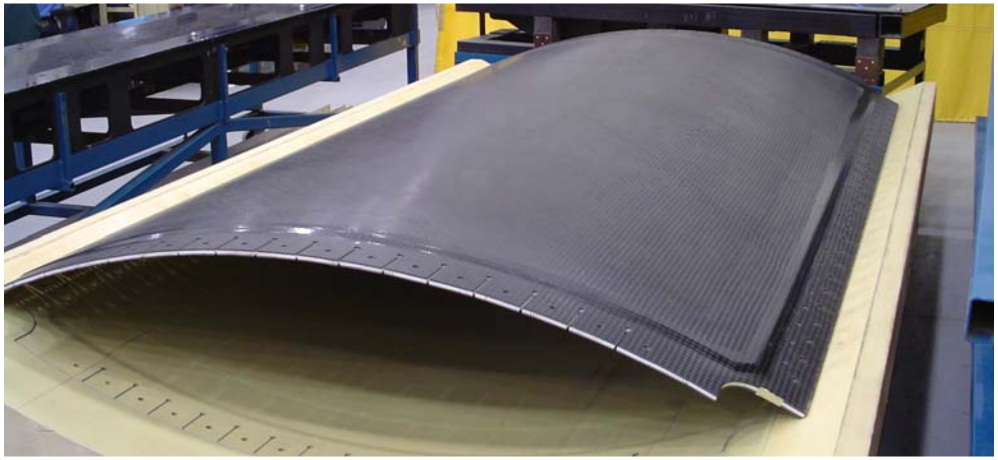
Liberty AEROSPACE

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

Additional Full-Scale Tests

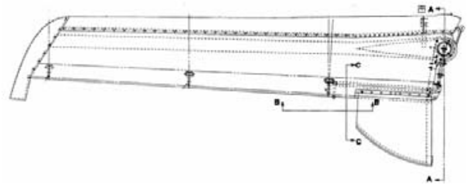
- Using the FASTER facility at the FAA Technical Center (Atlantic City, NJ)
- Fuselage loading – tension loading including pressure
- Test articles are representative of general aviation fuselage (sandwich construction)

ADAM AIRCRAFT



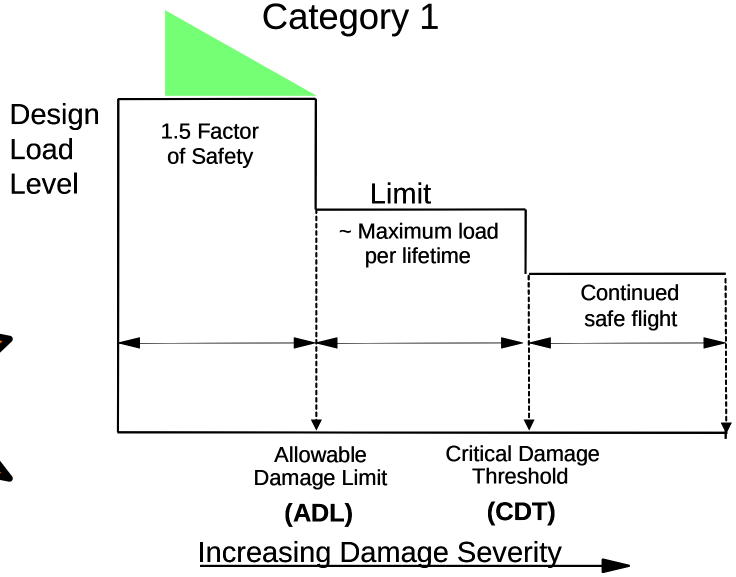
Characterize LEF Baseline Structural State

- ***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



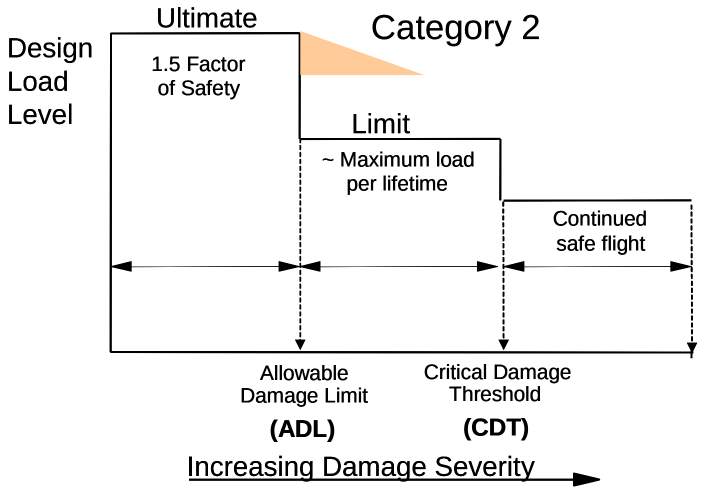
- 1 N
- 2 N
- 4 N

Scaling of LEF

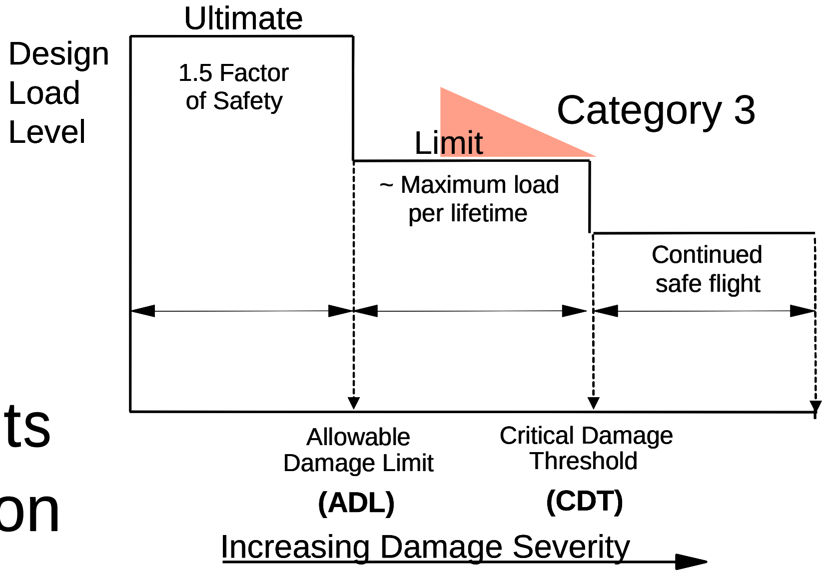


Damage Tolerance Testing

- 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

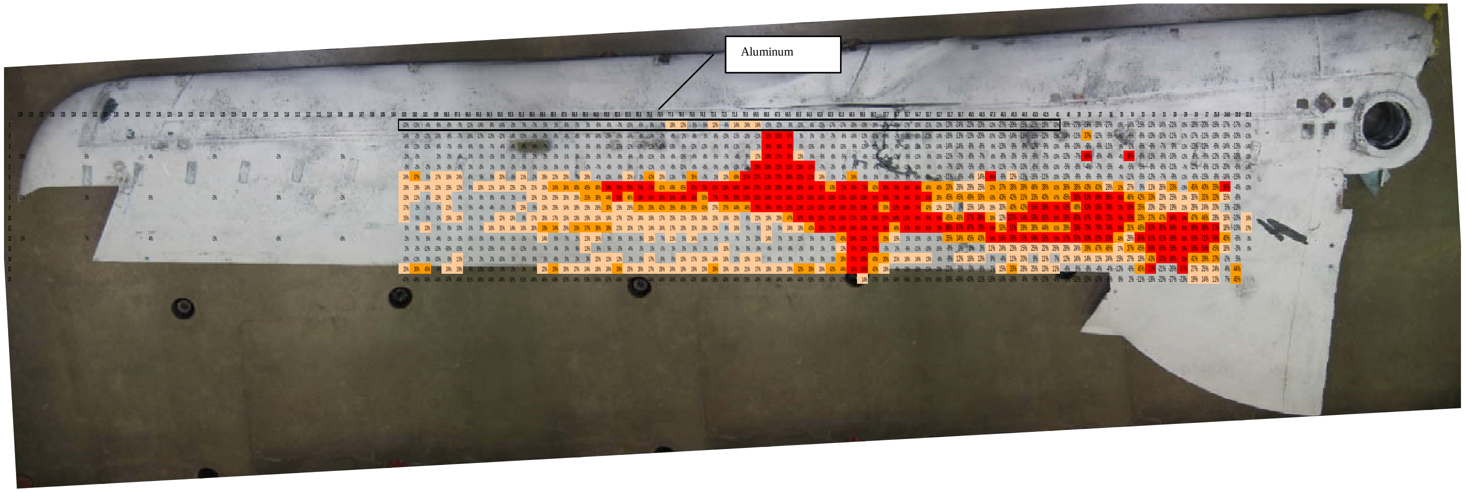


- Category 3 Damage – damage obvious to operator – should be detected within a few flights
- Demonstrate quick detection
- Define damage threshold
- Compression Loading / Impact Damage
- Spectrum Loading (LIMITED CYCLES)
- Retain Limit Load capability

Example of Test Results

Static Strength

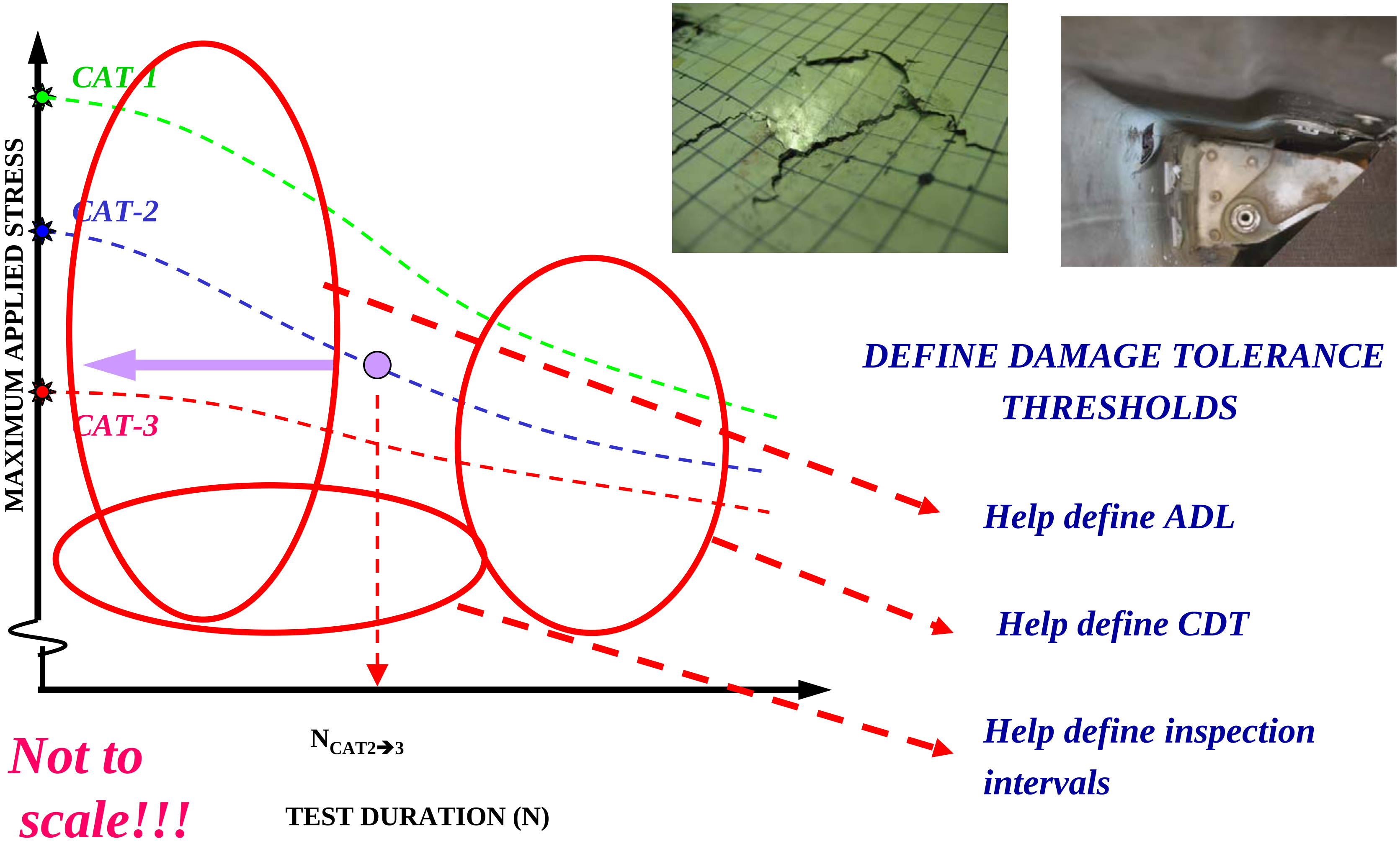
Canard #2 – Failure Analysis



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

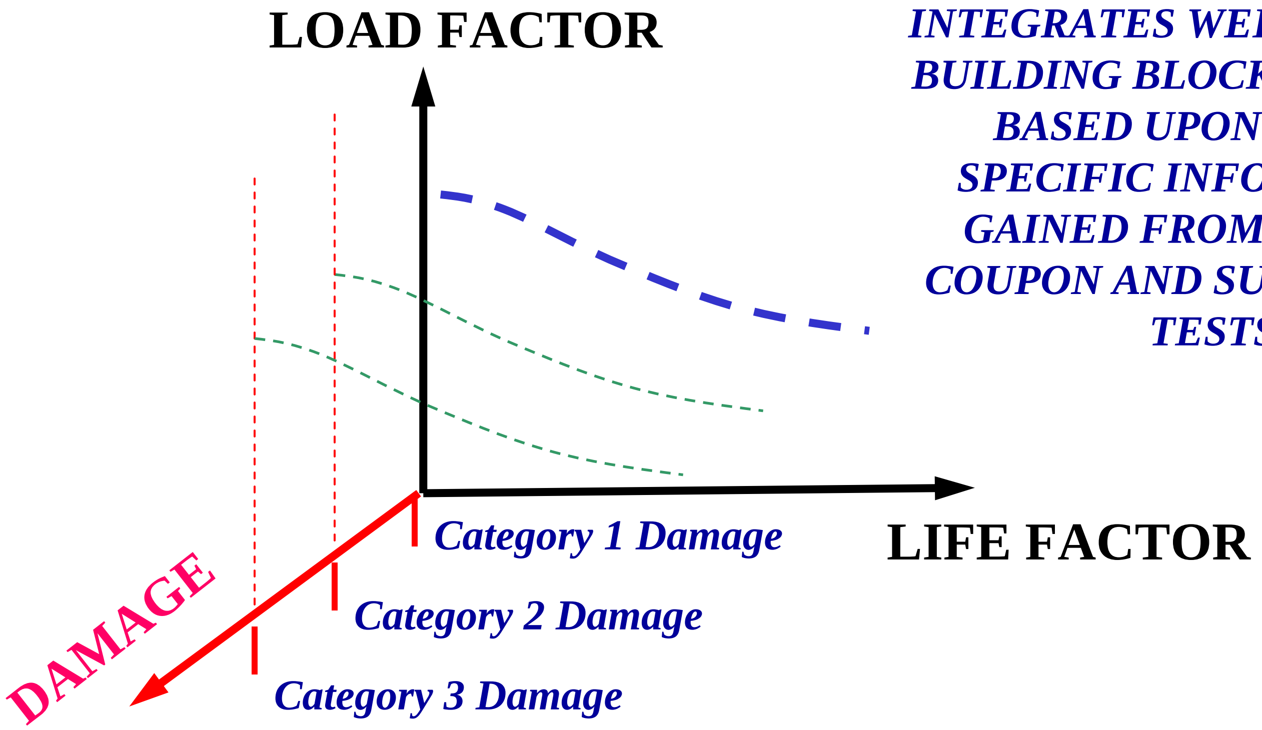
Help define ADL

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

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