MSFC-204 ABSTRACT

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Abstract
Damage Tolerance of Composites

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Fracture control requirements have been developed to address damage tolerance of composites for manned space flight hardware. The requirements provide the framework for critical and noncritical hardware assessment and testing. The need for damage threat assessments, impact damage protection plans, and nondestructive evaluation are also addressed. Hardware intended to be damage tolerant have extensive coupon, sub-element, and full-scale testing requirements in-line with the Building Block Approach concept from the MIL-HDBK-17, Department of Defense Composite Materials Handbook.

MSFC-204_PRESENTATION

Damage Tolerance of Composites

MSFC Engineering Directorate
Materials & Processes Laboratory
Damage Tolerance Assessment Branch

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What is damage tolerance? Mil-HDBK-17-3F, paraphrased

- Ability of a structure to sustain design loads in the presence of damage until the damage is detected, either through inspection or malfunction, and repaired (or replaced)
  - Damage Type? – For composites this includes delaminations, cuts, scratches, gouges, fiber breakage, porosity, microcracking, etc…
  - Damage Cause? – Fatigue, corrosion, environmental effects, accidental events, manufacturing, etc…

Damage tolerance of composites has an integrated role with different aspects of composite structural assessment & test, design, manufacturing, material characterization, inspection, handling, and operation.

Damage Tolerance of Composites

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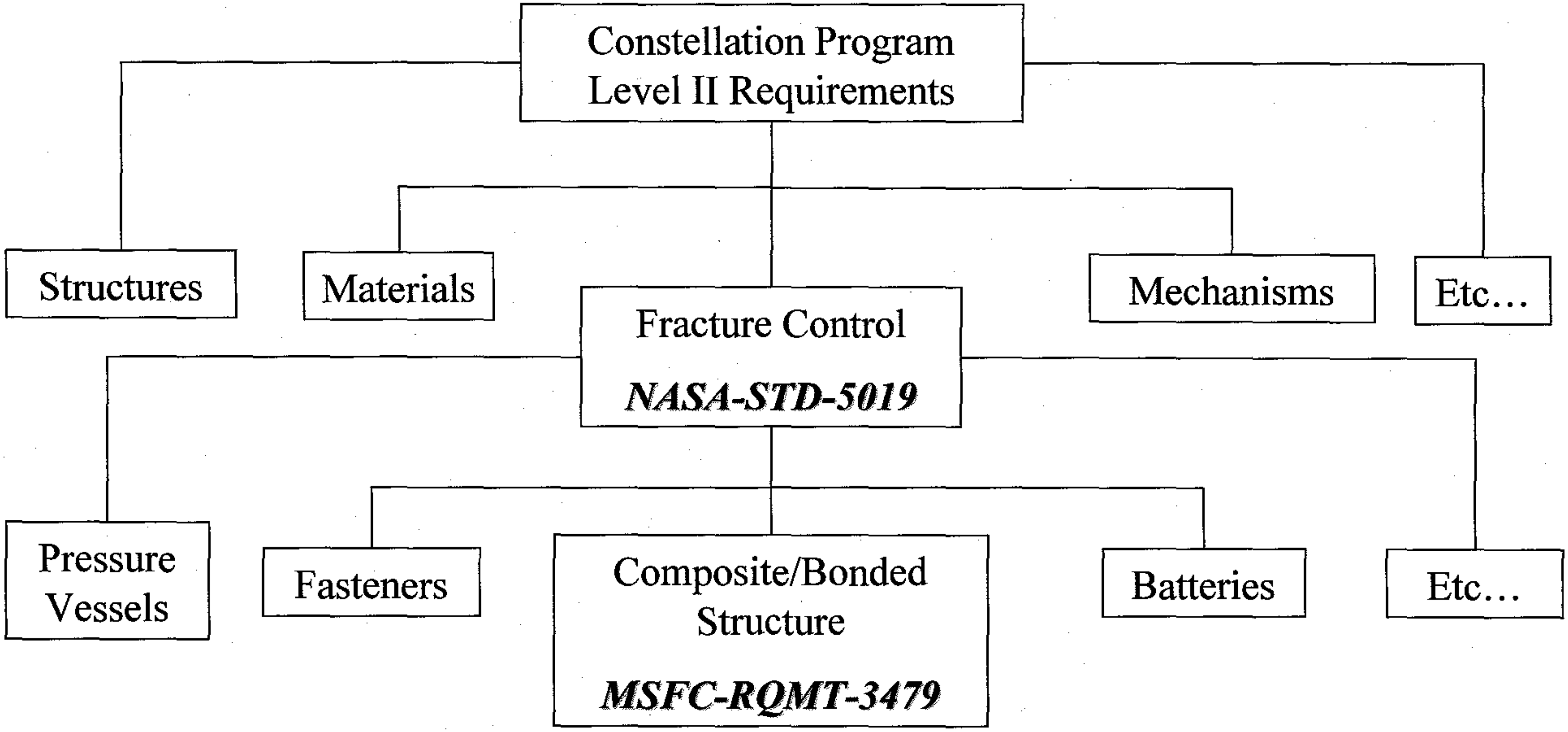
Damage Tolerance Assessment Branch

How does damage tolerance of composites fit within the framework of Constellation requirements?



MSFC-RQMT- 3479 Scope

- Hardware scope.
  - Manned spaceflight hardware including manned launch, retrieval, transport, and landing vehicles, space habitats, and payloads that are launched, retrieved, stored, or operated during any portion of a manned spaceflight mission.
- Materials/structures types.
  - Covered by new standard:
    - Polymer matrix composites.
    - Sandwich construction.
    - Bonded metallics, bonded composites, or bonded metallic-composite.
  - Specifically excluded by new standard:
    - Metal and ceramic matrix composites.
    - Foam.
    - Flexible inflatable structures.
    - Liquid rocket engines.
    - Solid propellants.

MSFC- RQMT-3479 Development Approach

- Cast requirements in the framework and language of existing NASA fracture control requirements.
- Review other requirements in addition to NASA ones:
  - Aircraft – Military – Joint Services Specification Guide (JSSG) 2006
  - Aircraft – Civil – FARs/MIL-HDBK-17F
  - General literature
- Address the shortcomings of previous NASA fracture control requirements.
  - Developed requirements with significant input from NASA Fracture Methodology Panel members during 2004 and 2005
- Rely on ANSI/AIAA S-081-2000 for COPVs.
- Refer to MIL-HDBK-17F for specific methodologies.

Classification of Composite Parts and Bonds for Fracture Control

A part (or bond) is fracture critical if its failure due to the presence of a flaw would result in a catastrophic hazard. All composite parts and bonds shall be classified according to the following:

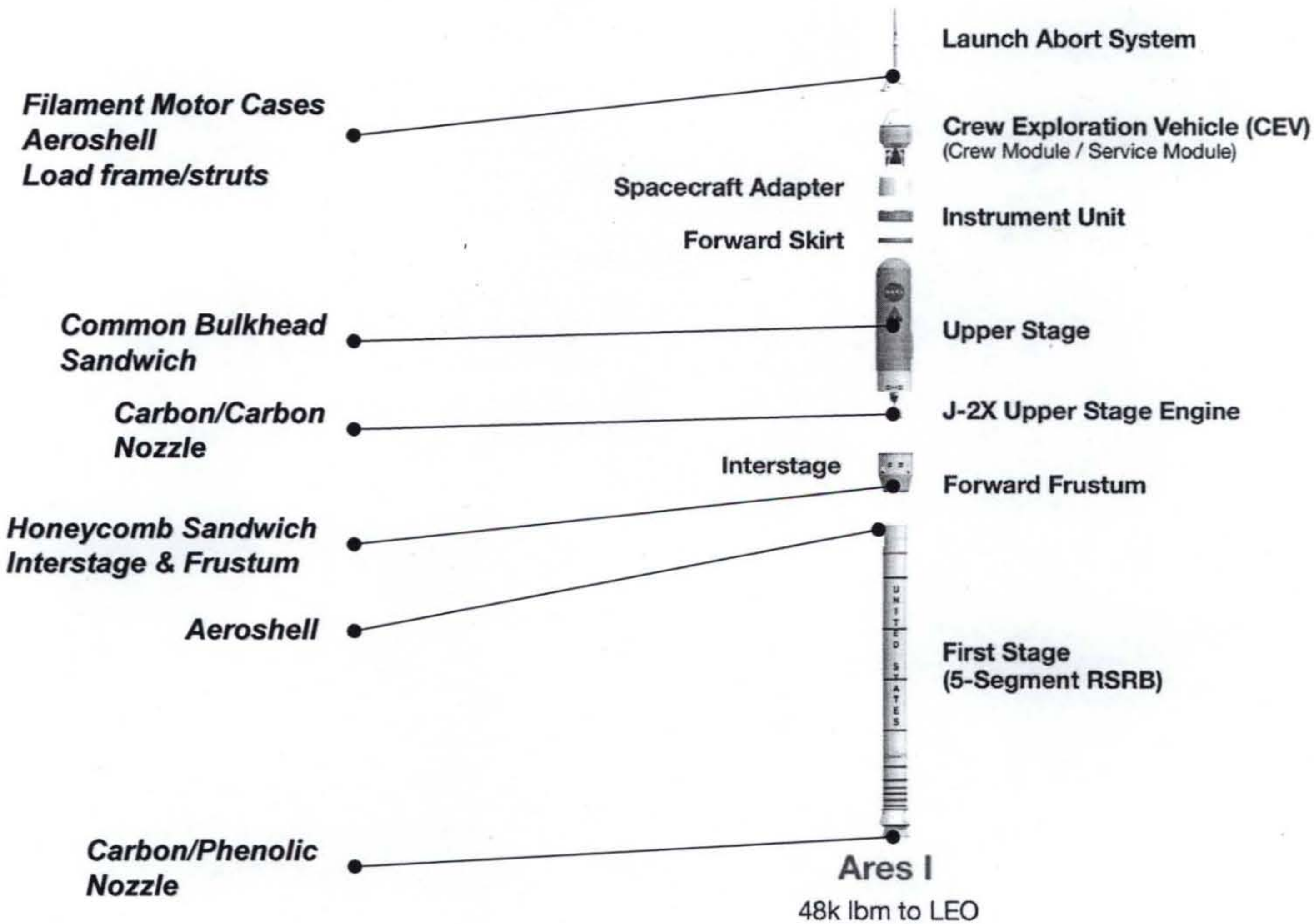
Exempt
- Non-structural and no safety critical function

Non-Fracture Critical
- Low released mass
- Fail safe
- Contained
- Low risk
- Non-hazardous leak before burst (NHLBB)

Fracture Critical
- Proofed
- Damage tolerant

How does this affect hardware development?

Ares I Primary Structure Composite Hardware



Implications for Hardware Development

- Damage Threat Assessment (DTA)

  Different tasks are performed depending on fracture control classification

  - Task 1: Identify the source and type of impact damage that poses a credible threat to the hardware
  - Task 2: Characterize the impact damage size and energy level to be considered during all types of damage tolerant tests
  - Task 3: Generate an as-manufactured initial flaw type and size assessment for the hardware

- Impact Damage Protection Plan (IDPP)
  - Plan required for all hardware except exempt, low released mass, and contained
    - Plan addresses each threat identified in DTA
    - Protection method (or monitoring method) must be addressed for each threat identified in DTA
  - Mitigates risk of impact damage; does not eliminate risk
    - Credible impact damage, identified in the DTA, must be addressed during damage tolerant tests, even for protected hardware

- Inspections & NDE
  - Methods discussed in MIL-HDBK-17; POD information typically not available (no 90/95 standard sizes); special visual & walk-around inspections are included
  - Damage used to develop residual strength and life curves must be detectable by some form of inspection

Implications for Hardware Development

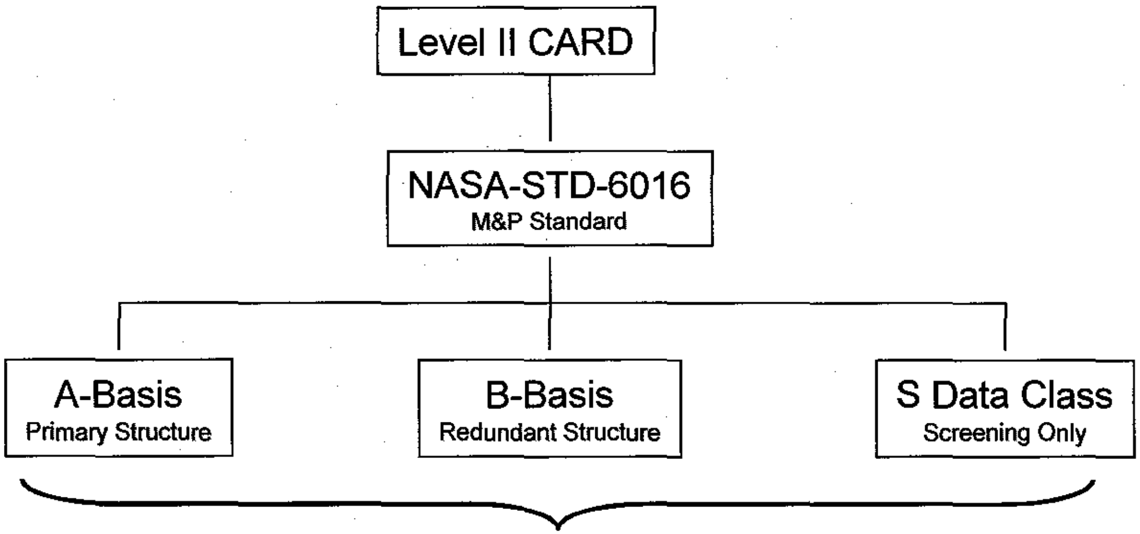
- Damage Tolerance Tests
  - Building Block Approach based on MIL-HDBK-17
    - Coupon Tests
      - Generate a family of life and residual strength curves with damage in appropriate environment
      - Determine damage configuration and sizes from the DTA (Task 2 & 3)and NDE capability
      - Establish no-growth threshold strain for low risk parts
      - Support analysis and design to assure success of full-scale tests
    - Development Tests
      - Evaluate structural elements representative of flight design
      - Demonstrate residual strength and life capability for the design spectrum with damage
      - Assist in any anomaly resolution & guide the design toward successful full-scale tests
    - Full-Scale Component Tests
      - Verify full-scale flight-like components with induced damage sites
      - Demonstrate the ability of the structure to sustain design loads for 1 lifetime, including a load enhancement factor (LEF), and a subsequent design ultimate load (DUL) with no damage growth or initiation
      - Demonstrate the ability of the structure to sustain design loads for 4 lifetimes, including an LEF, and a subsequent design limit load (DLL) with no damage initiation and no structural failure

Implications for Hardware Development

- Analysis
  - Primary purpose is to assist in assuring a successful full-scale damage tolerance test
  - Potential methods
    - Strength assessment with residual strength allowables
    - Advanced methods such as the virtual crack closure technique (VCCT)
    - Future updates to MIL-HDBK-17
- Data
  - Statistical basis
    - A-Basis (99/95) for Ultimate Strength per MIL-HDBK-17
    - Load Enhancement Factor (LEF) per MIL-HDBK-17
      - LEF for fatigue spectrum sufficient to establish A-Basis reliability on life
      - Requires Weibull shape parameters for residual strength and fatigue life tests
  - Damage tolerance coupon tests
    - Sufficient number to develop Weibull shape parameters
    - Sufficient number to encompass DTA and NDE damage sizes
  - Impact testing
    - Sufficient number to develop impact energy, size, and configuration curves

Composite Material Strength Allowables

The material property requirements for the Constellation Program flow from the Level II Constellation Architecture Requirements Document (CARD) to NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft. Specifically, Section 4.1.6, Material Design Allowables, describes which values shall be used for strength allowables. A-Basis strength allowables (99% reliability / 95% confidence level) are required for primary structure unless redundancy exists; B-Basis (90/95) may be used for redundant structure. S-Basis allowables are discussed for metallic components; composites do not use S-Basis allowables (spec minimum with least statistical confidence).

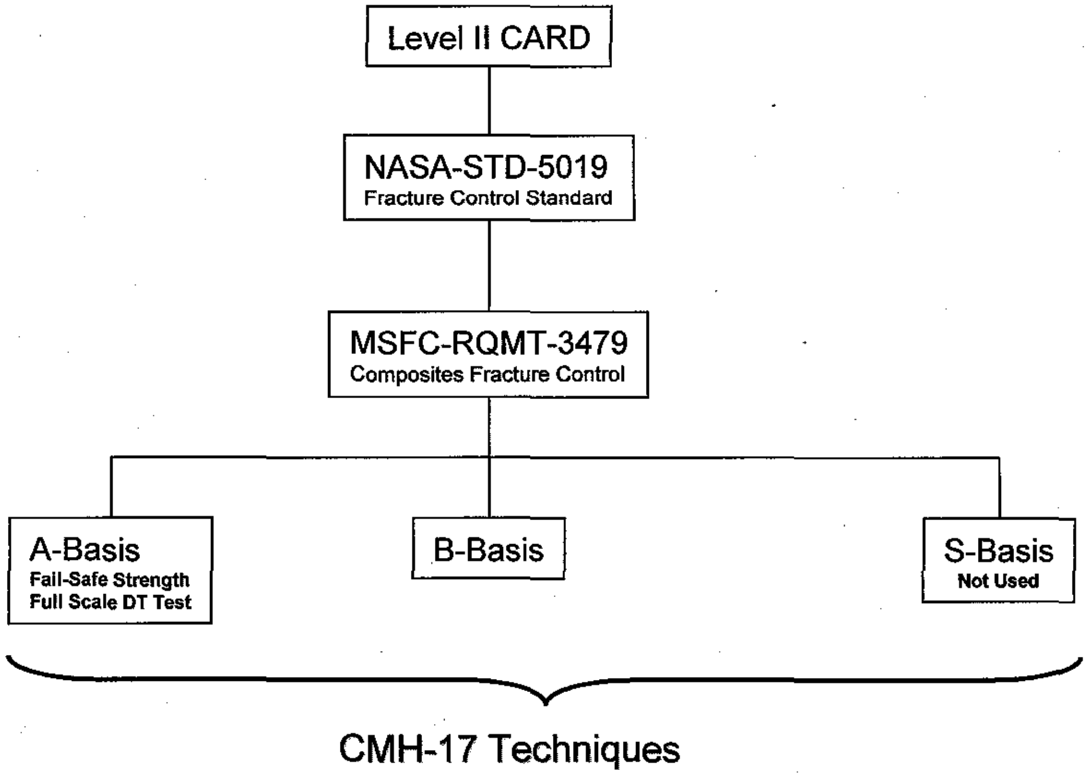


MIL-HDBK-17 Techniques
(New Designation: CMH-17)

Damage Tolerance Design Values

The composite damage tolerance requirements flow from the Level II CARD to NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware, into MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures. Specific requirements for use of statistical based approaches are discussed for the "Fail-Safe" category and for the full-scale damage tolerance test. No specific requirements are listed for development of damage tolerance design values.

Damage tolerance design values are not "material properties" in the traditional sense. These values are dependent on geometry, material system, and configuration.



M&P Approach for strength allowables and damage tolerance design values

Composite material strength allowables used for qualification of flight hardware shall be determined using the A-Basis statistical techniques as defined in MIL-HDBK-17, or an MSFC-approved equivalent approach.

Consistent with NASA-STD-6016

Composite damage tolerance and no-growth threshold design values used for qualification of flight hardware shall be determined from the B-Basis statistical techniques as defined in MIL-HDBK-17, or an MSFC-approved equivalent approach.

Appropriate for Fracture Control/Damage Tolerance of Composites

Why is A-Basis necessary for strength allowables?

- Provides greatest level of confidence for margin of safety prediction
- Meets requirements in NASA-STD-6016

Why is B-Basis sufficient for damage tolerance design values?

- Full-scale damage tolerance test will include demonstration for 99/95 capability based on MIL-HDBK-17 load enhancement factor approach
- Fracture control premise is to address damage tolerance capability of composites with <u>assumed</u> damage site. Known damage typically requires repair or more stringent use-as-is rationale
- Current available data in MIL-HDBK-17, Volume 2, Data Annex is B-Basis
- Commercial aircraft approach uses B-Basis

What is the MIL-HDBK-17 approach to A or B-Basis?

The requirements for publication of data into MIL-HDBK-17 are fairly rigorous.

TABLE 2.5.3. *Minimum sampling requirements for MIL-HDBK-17 data classes.*

			Minimum Requirements	
Designation	Symbol	Description	Number of Batches	Number of Specimens
A75	A	A-Basis – Robust Sampling	10	75
A55	a	A-Basis – Reduced Sampling	5	55
B30	B	B-Basis – Robust Sampling	5	30
B18	b	B-Basis – Reduced Sampling	3	18
M	M	Mean	3	18
I	I	Interim	3	15
S	S	Screening	1	5

Statistical techniques to compute the A (99/95) or B (90/95) value are given in Volume 1 of MIL-HDBK-17

A-Basis (or A-Value) -- A statistically-based material property; a 95% lower confidence bound on the first percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 99% of a specified population.

B-Basis (or B-Value) -- A statistically-based material property; a 95% lower confidence bound on the tenth percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 90% of a specified population. (See Volume 1, Section 8.1.4)

Example of a potential MSFC equivalent approach

Fundamental needs:

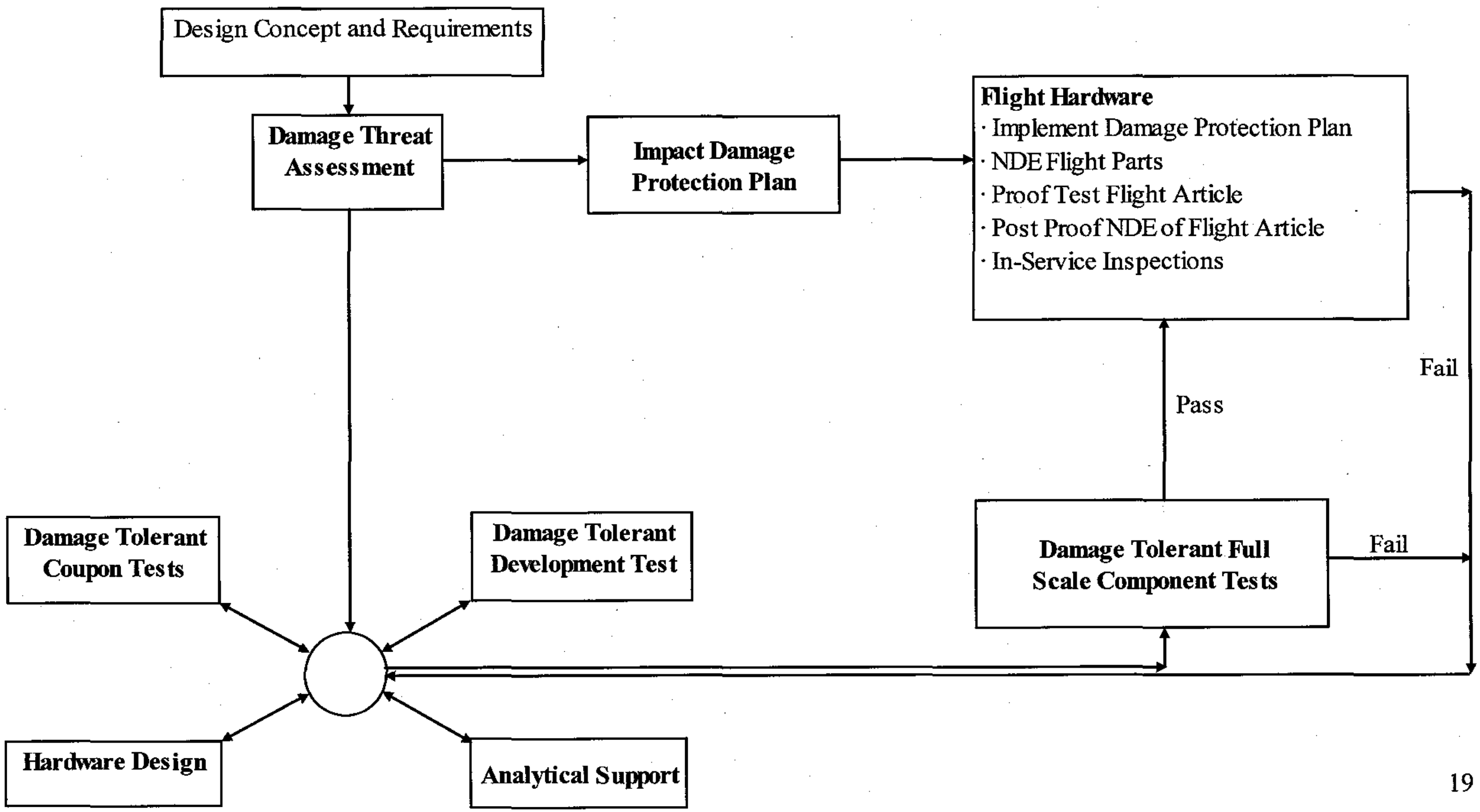
- Demonstrate that variance concerns have been addressed.
  - Provide at least 30 degrees of freedom for 3 lots/batches of material to develop a design curve – 33 data point per design curve to account for variation, temperature, and capability. This will avoid small sample assumptions during statistical assessment.
- Develop sufficient approach for environmental or other knockdowns
  - Provide data for use in reduction of design curves
- Provide for tag-end or witness sample testing for each unit manufactured
  - Acceptance testing provides demonstration that minimum design allowables are maintained for each unit produced in lieu of a full A-Basis data set (data class A75)

Example alternative approach for developing strength allowables

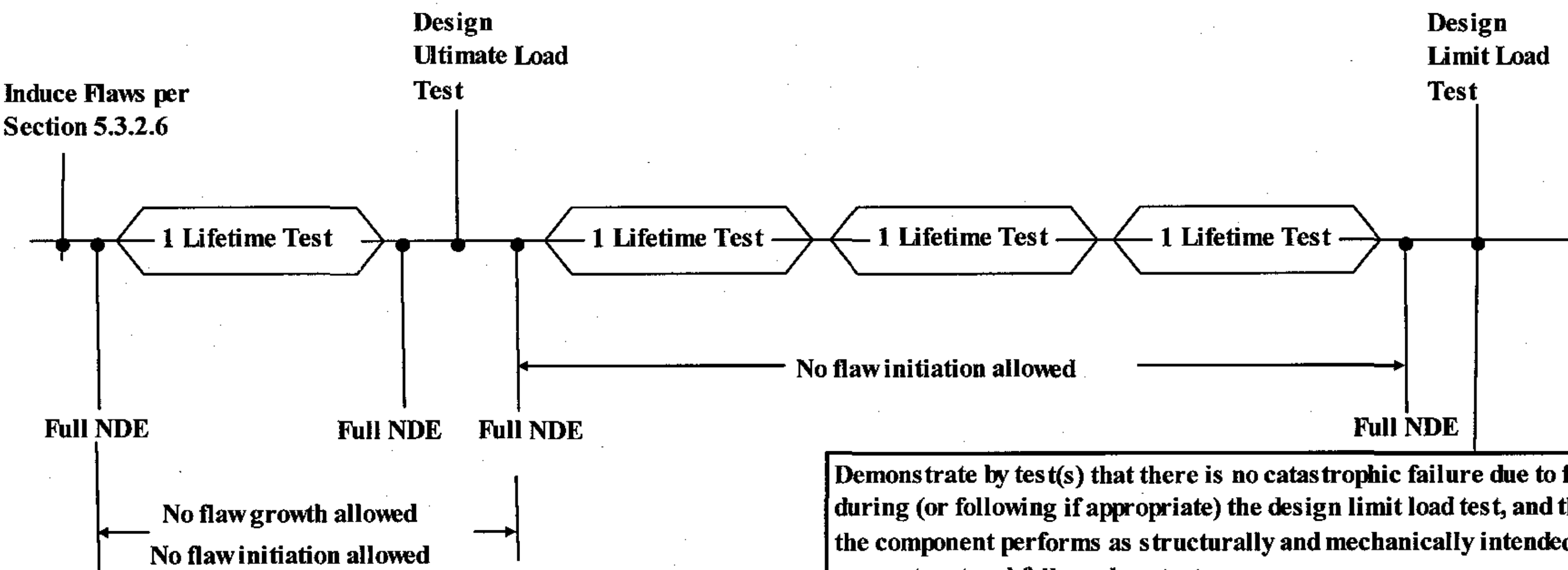
- Determine the failure modes of concern and the associated material capability value needed to assess structural integrity
- Test a sufficient number of batches and specimens to define the distribution type at each temperature and environment of interest. Guidelines for data sample sizes can be found in MIL-HDBK-17F, Volume 1. General guidance is at least 3 lots/33 data points per design curve.
- Use the appropriate statistical knockdown factor to determine the 99% probability/95% confidence predicted allowable (A-Basis equivalent) for the limited data set available.
- Perform tag-end or witness sample tests for each unit manufactured to demonstrate capability greater than the predicted strength allowable for the most critical failure mode
- Maintain and update the database of test information to address potential changes to the A-Basis equivalent capability for the most critical failure mode

Examples of MSFC-RQMT-3479 Criteria

Steps in Establishing Damage Tolerance



Damage Tolerant Full-Scale Component Test



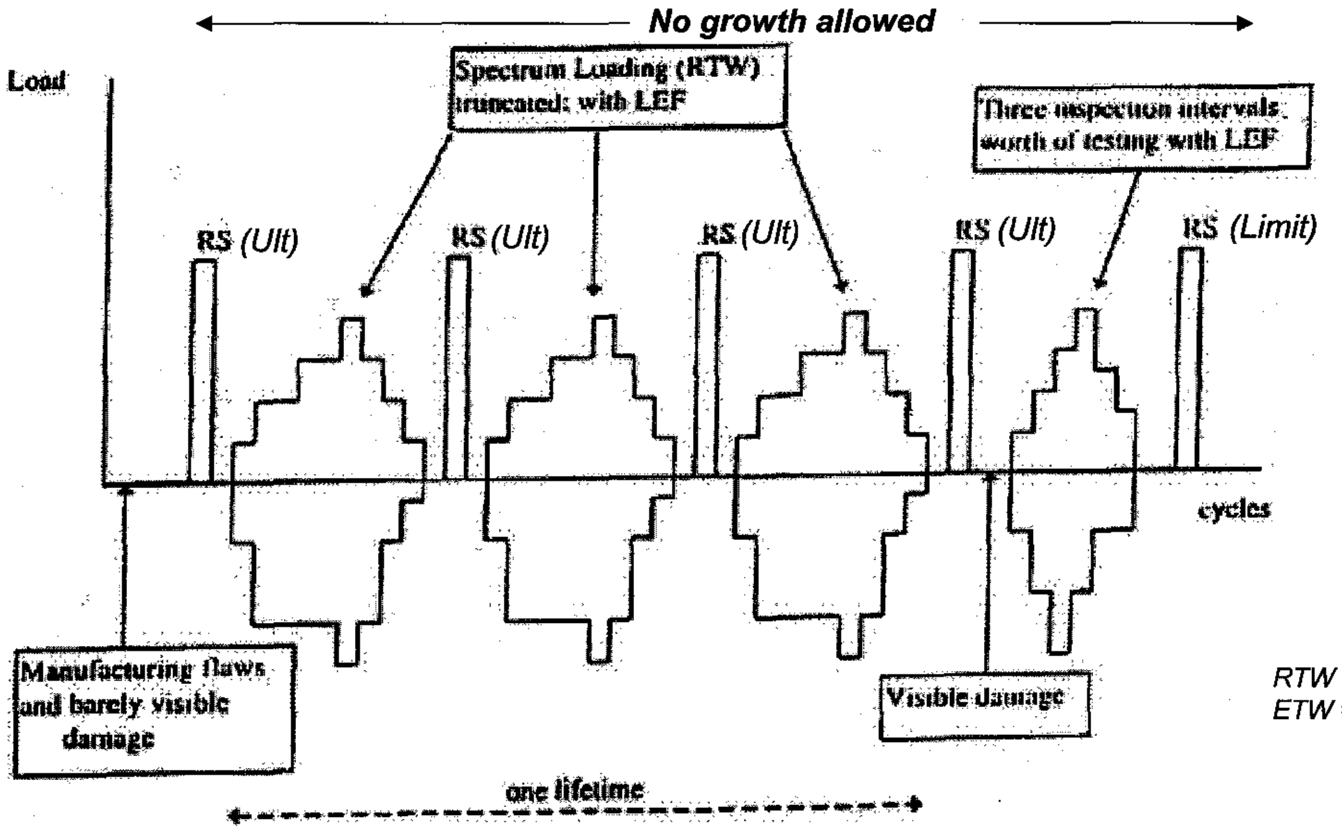
Demonstrate by test(s) that there is no catastrophic failure due to flaws during (or following if appropriate) the design limit load test, and that the component performs as structurally and mechanically intended:

> no structural failure, burst, etc.
> no catastrophic leak due to flaws
> no catastrophic mechanical malfunction
> structurally and mechanically peforms design function

Application/ Examples -MIL-HDBK-17-3F – Figure 7.9.1.6

Rotocraft (Sikorsky)

Damage Tolerant Certification Procedure Schematic



RTW = Room Temp - Wet
ETW = Elevated Temp - Wet

RS: Residual Strength Test (ETW)

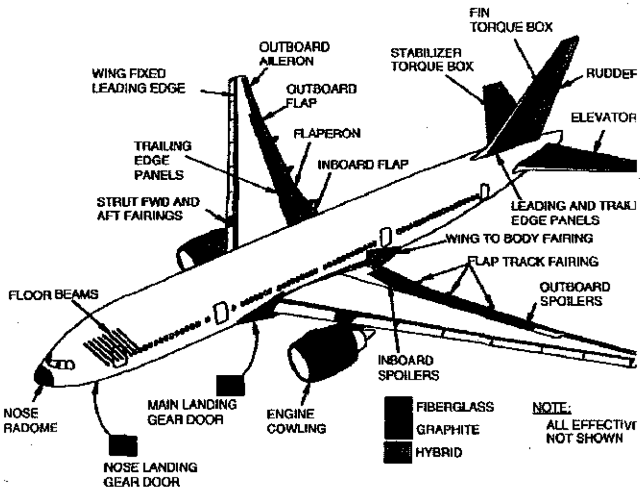
Application/ Examples -MIL-HDBK-17-3F – Section 7.9.2

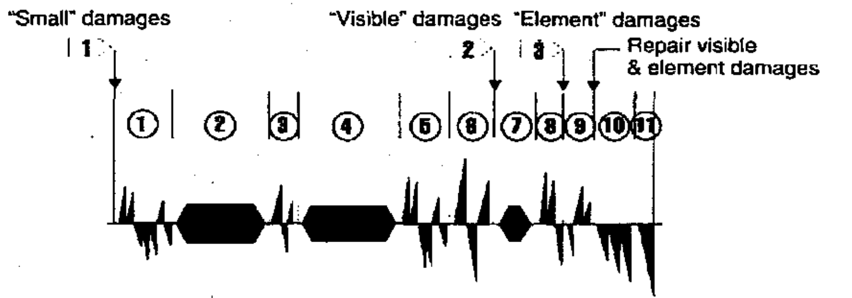
Commercial Aircraft – Boeing 777 Empennage Torque Boxes

Preproduction Horizontal Stabilizer Test Sequence – Demonstrate "No Growth"

Boeing 777 – Composite Usage

- Empennage Torque Boxes
- Passenger Floor Beams
- Aero Fairings and Other Secondary Structures





Apply small damages 1

1. 60% design limit strain survey - 6 conditions
   Flight test instrumentation check-out
2. Fatigue spectrum - 1 lifetime including load enhancement factor
3. 60% design limit strain survey - 3 conditions
4. Fatigue spectrum - 1 lifetime including load enhancement factor
5. Design limit strain survey - 6 conditions
6. * Design ultimate loads - 3 conditions
   Apply visible impact damages 2
7. Fatigue spectrum - including load enhancement factor - two inspection periods
8. Fail safe (limit) loads - 3 conditions
   Apply element damages 3
9. "Get home" loads (approx 70% limit) - 3 conditions
   Repair visible and element damages
10. Design ultimate loads - 3 conditions
11. Destruction test

1 "Small" damages - impacts at an energy level less than 1200 in-lb whose resulting damage is visible at a distance of less than 5 feet.

2 "Visible" damages - readily detectable during the scheduled inspection plan.

3 "Element" damages - complete or partial failure of one or more structural units.

Summary Sheet - Composite Fracture Control Classifications and Requirements

Requirements	Non-Fracture Critical						Fracture Critical	
			Contained					
	Low Released Mass	Fail Safe	Metallic Enclosure	Composite Enclosure	Low Risk	NHLBB	Proof Tested	Damage Tolerant
Reference Section	5.2.1	5.2.2	5.2.3.A	5.2.3.B	5.2.4	5.2.5	5.3.1	5.3.2
No catastrophic hazard/loss of SCF	x	x	x	x		x		
Part must be larger than open holes			x	x				
Enclosure/container not FC				x		x		
Not a pressure vessel					x	x		
No hazardous fluid					x	x		
FOS on containment			1.0 Fty, analysis or test	1.15 p'tratn test, or 1.15 p'tratn anlys s/b test				
DUL capability	NFC impacted parts - verf by test			w/impact damage > NDE, from loose part, DTA, or imposed - verf by test	w/impact damage > NDE, DTA, or imposed - verf by test	at Ult FOS x MDP w/impact damage > NDE, DTA, or imposed - verf by test		Per Fig. 5
Inspections								
1. Visual								
a. Walkaround								between each flight
b. Special Visual		pre and post proof, and between flights		pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and after every 3rd flight
2. NDE		pre and post proof		pre and post proof	pre and post proof	pre and post proof	pre and post proof	pre and post proof
Proof tested (<80% Ult) [1]	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	1.2 x limit, initially and between flights	Initially, 1.05 min x limit
DTA Task 1		x		x	x	x	x	x
DTA Task 2				x^{2}	$x^{2,3}$	x^{2}		x
DTA Task 3					x^{3}			x
IDPP		x		x	x	x	x	x

Damage Tolerance of Composites

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Damage Tolerance Assessment Branch

Summary Sheet - Composite Fracture Control Classifications and Requirements

	Non-Fracture Critical						Fracture Critical	
			Contained					
Requirements	**Low Released Mass**	**Fail Safe**	**Metallic Enclosure**	**Composite Enclosure**	**Low Risk**	**NHLBB**	**Proof Tested**	**Damage Tolerant**
Reference Section	5.2.1	5.2.2	5.2.3.A	5.2.3.B	5.2.4	5.2.5	5.3.1	5.3.2
Damage tolerant coupon tests					x[3]			x
Damage tolerant development tests								x
Damage tolerant full-scale component tests	FC impacted parts	FC impacted parts						Per Fig. 5
Traceability (Section 6.4)		x		x	x	x	x	x
Unique Requirements								
Pressurized enclosures shall have the characteristic of being NHLBB				x				
Walls shall leak ≤ MDP, Verf. by test						for TTF 10 t or 1 inch		
Wall shall not burst @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch		
Flaw shall not grow @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch		
No repressurization as pressure leaks down						x		
Generally limited to payloads							x	
Internal to payload,vehicle, module	x		implied	implied				
Debris shall meet low mass		x						
Below no-growth threshold strain					x			
Remaining struc analytically assessed at 1.15 x redistributed dyn load		x - analytical meth verified by test						
Remaining impacted struc must support 1.15 x redistributed limit load		x - NFC parts - verf by test						
See also 5003 for Shuttle payload	x							
No HERM, HMRM, hab mod, SPF bond					x			

Foot Notes:
1. NASA-STD-5001 requires proof test of all composite parts/structures to 1.05/1.20.
2. Required to the extent needed to establish impact damage size for DUL capability test (Line 11).
3. Required to the extent needed to determine no-growth threshold strain (Line 35).

BACKUP

Example of Technical Issue Investigated during Development of MSFC-RQMT-3479

No-growth Threshold Strain

- The no-growth threshold strain is the strain level below which flaws of interest do not grow in 10^6 (10^8 for rotating hardware) cycles at the applicable load ratio.
- The no-growth threshold strain is establish by test.
- This strain is needed for the low risk classification or in the truncation of tests spectra.
- The issue was:
  - Can we specify a default value, say "some" percent of ultimate strength that would be applicable for all situations and avoid testing to establish the no-growth threshold strain?

Review of the Literature

- Threshold strains not addressed in ASTM standards.
- Literature confusing, can be misleading and easily misunderstood.
- "Threshold" may refer to undamaged state as in "endurance limit".
- Thresholds are sometimes addressed as percent of static undamaged strength and sometimes as percent of strength after damage. Also addressed as a percent of the critical strain energy release rate.
- Strain range (R) is important as well as strain magnitude.
- Numbers quoted as thresholds are generally application specific.
- Look at a specific case to gain some insight:
  - Han, H. T., Mitrovic, M., and Turkgenc, O., "The effects of Loading Parameters on Fatigue of Composite Laminates: Part III", DOT/FAA/AR-99/22, June 1999.

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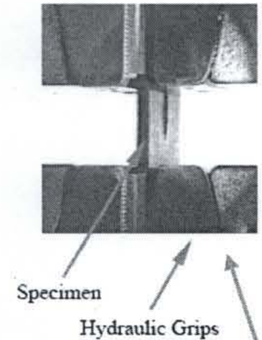
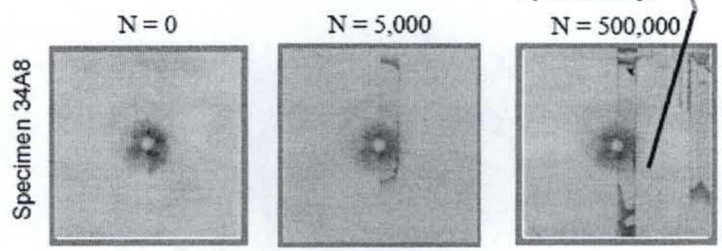
Constant Amplitude Loading

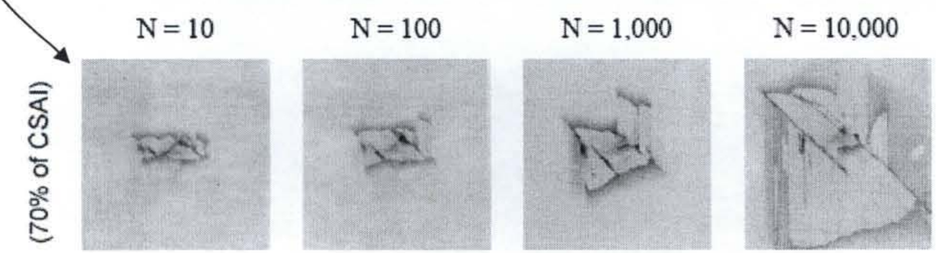
Constant-Amplitude Compression-Compression (R = ∞)

Specimen Number	Load Level [% of CSAI]	N Number of Cycles	Impact-Induced Damage Growth
32A6	40%	1,000,000	no
32A7	40%	1,000,000	no
31C7	40%	1,000,000	no
33B1	50%	1,000,000	no
31D4	50%	1,000,000	no
33B4	50%	1,000,000	no
31E5	60%	1,000,000	no
34A8	60%	>500,000	yes
31D3	60%	1,000,000	no
33B2	70%	141,607*	yes
31F2	70%	>10,000**	yes
35A6	70%	>100,000	yes
33F3	80%	136*	yes
31E1	80%	587*	yes
33C3	80%	>1,000	yes

* indicates cycles to final failure
** indicates number of cycles that causes propagation of delamination to the tab region







- At 70% load level, always get growth.

No-growth at 60% CSAI is misleading.

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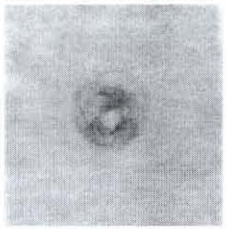
Spectrum Loading - High/Low

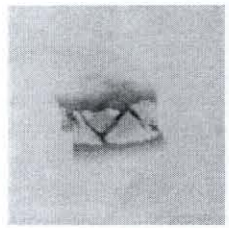
High first

N = 0



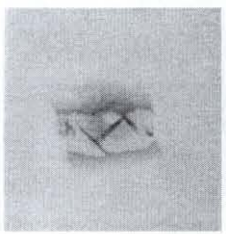
100 cycles @ 70%

N = 100

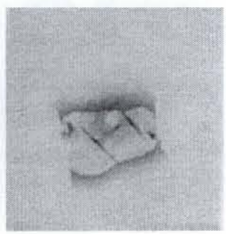


Then low
@ 30%

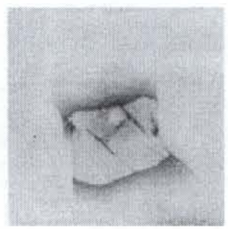
N = 10,000



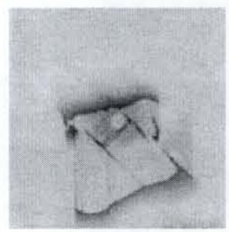
N = 100,000



N = 500,000

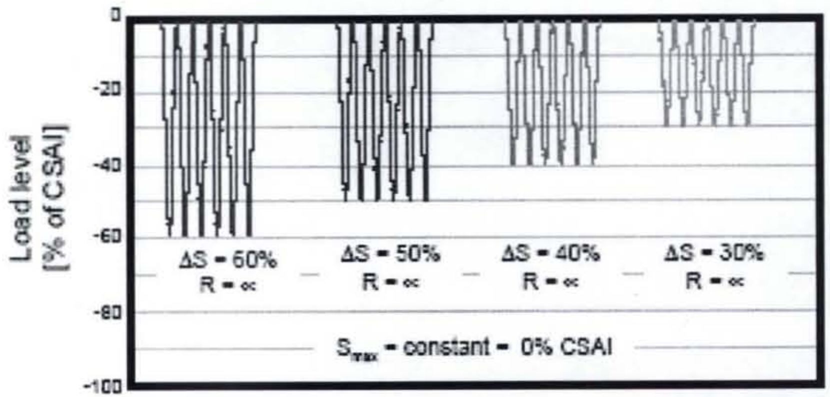


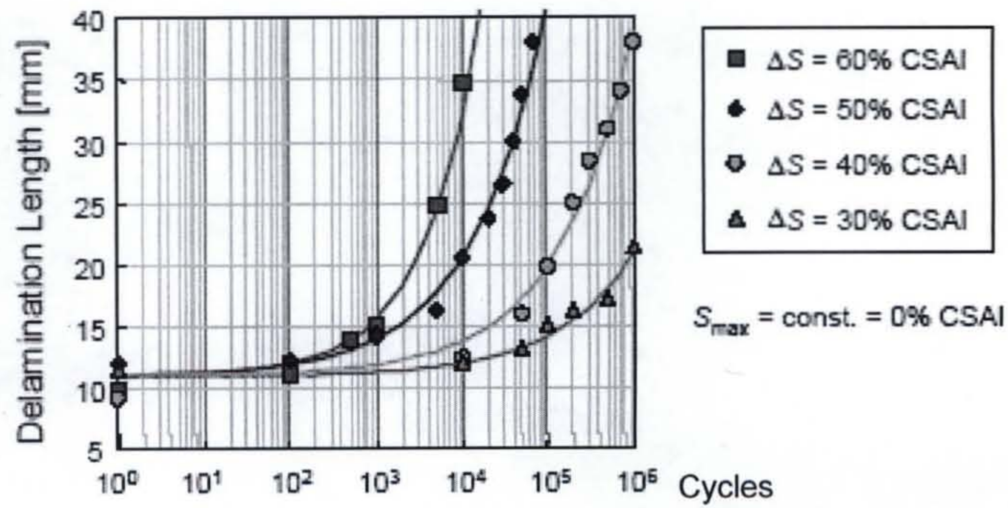
N = 1,000,000



Note growth at 30% CSAI, 2^{nd} block

Spectrum Loading - High/Low - 2nd Block Growth





Load Cases

Constant maximum load, variable load range

- S_{max} = constant = 0% CSAI
- ΔS = 30, 40, 50, 60% CSAI

Note growth at 30% CSAI

No-Growth Threshold Issue Example Conclusion and Recommendation

- Data exist that show flaw growth can occur at cyclic loads that are quite low (< 30% CSAI), whereas other data show quite high loads are required to initiate flaw growth.
- Thresholds discussed in the literature are application specific.
- Specifying a generic threshold lets the developers off the hook for understanding their hardware and its application.
- Not comfortable with choosing a single number for all applications.
- Recommendation:
    - Require developers who need a threshold value to generate one by test.
    - Allow use of existing data if verified by tests for current application.