

# The Aging Composite Airframe

by

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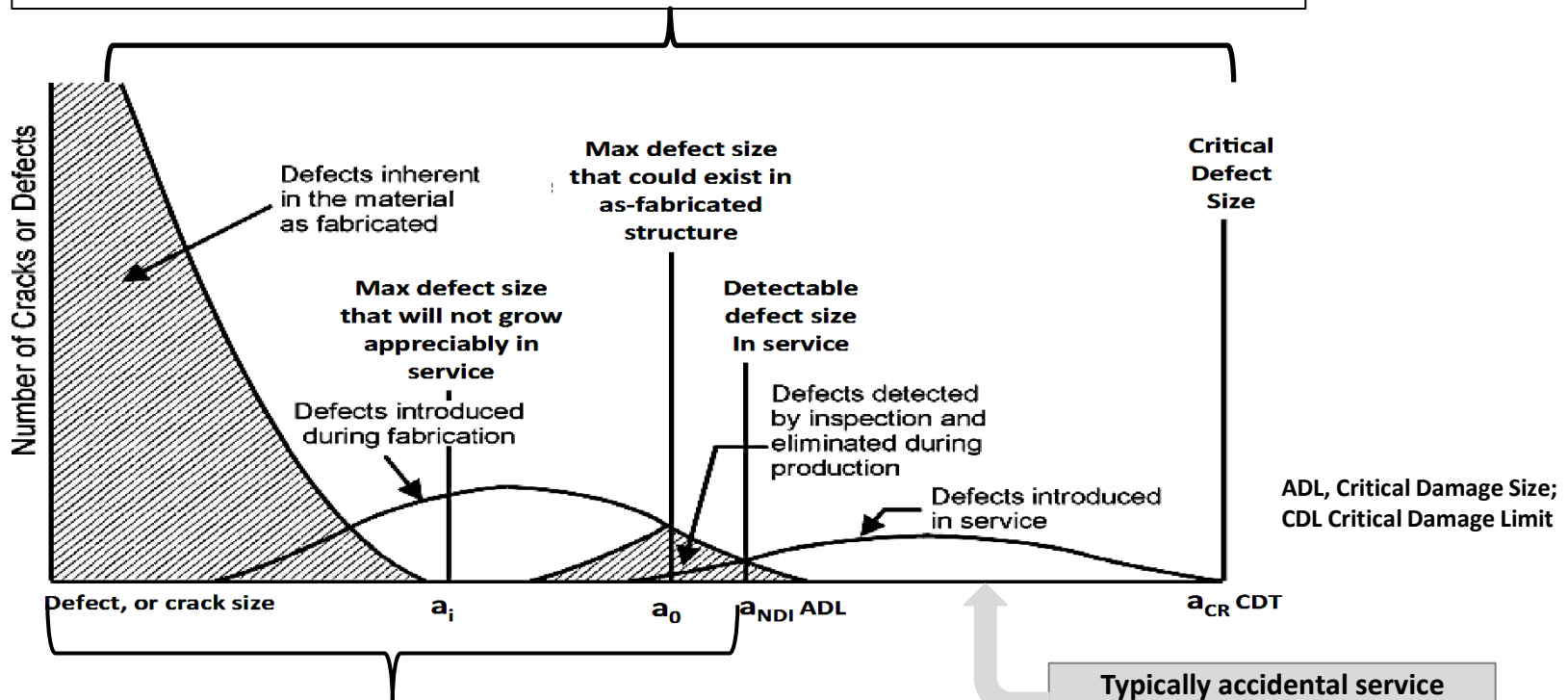
The FAA assigned the Aviation Rulemaking Advisory Committee (ARAC) a new task to provide recommendations regarding revision of the damage-tolerance and fatigue requirements of Title 14, Code of Federal Regulations (14 CFR), part 25, including subparts C and E of 14 CFR part 26, and development of associated advisory material for metallic, composite, and hybrid structures.

# Briefing Context

- **Both fail-safe and slow crack growth design concepts can (and have been) defeated by durability-related fatigue and environmentally assisted cracking in aging metallic airframes (CIVL & MIL)**
  - **Durability-related cracking manifests itself in the literature as the onset of wide spread fatigue damage, WFD.**
  - **Composite airframes accumulate other types of damage over time; a potential for service induced wide spread damage, WSD**
  - **Techniques needed for assessing operational limits for each of the aircraft structural design concepts relative to the onset of WFD (durability-related fatigue cracking) and service induced WSD that can defeat the structure's ability to carry its residual strength requirement.**
  - **Identify and Document the conditions that determine operational limits for potential updates to AC 25.571 and AC 20-107.**
  - **Provide a historical perspective.**

## Widespread Damage, WSD

What is the operational limits relative to the potential for nearly-no-growth durability-related fatigue damage growth & accidental service induced damage that can defeat the structure's ability to carry its residual strength requirement for **aging composite airframes**?

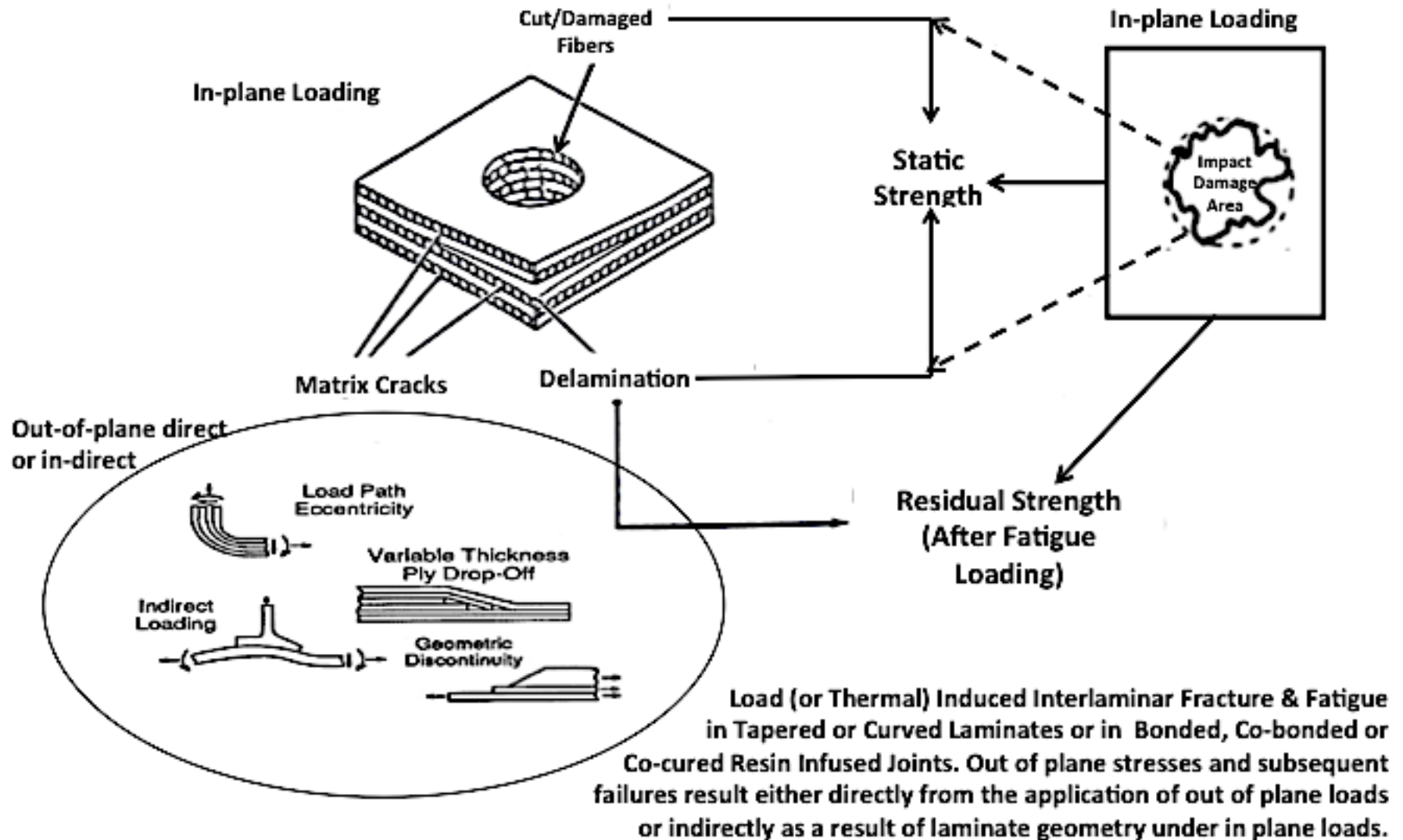


## Widespread Fatigue Damage, WFD

Both fail-safe and slow crack durability growth fatigue design concepts can (and have been) defeated by general durability-related fatigue and environmentally assisted cracking in **aging metallic airframes (CIVL & MIL)**

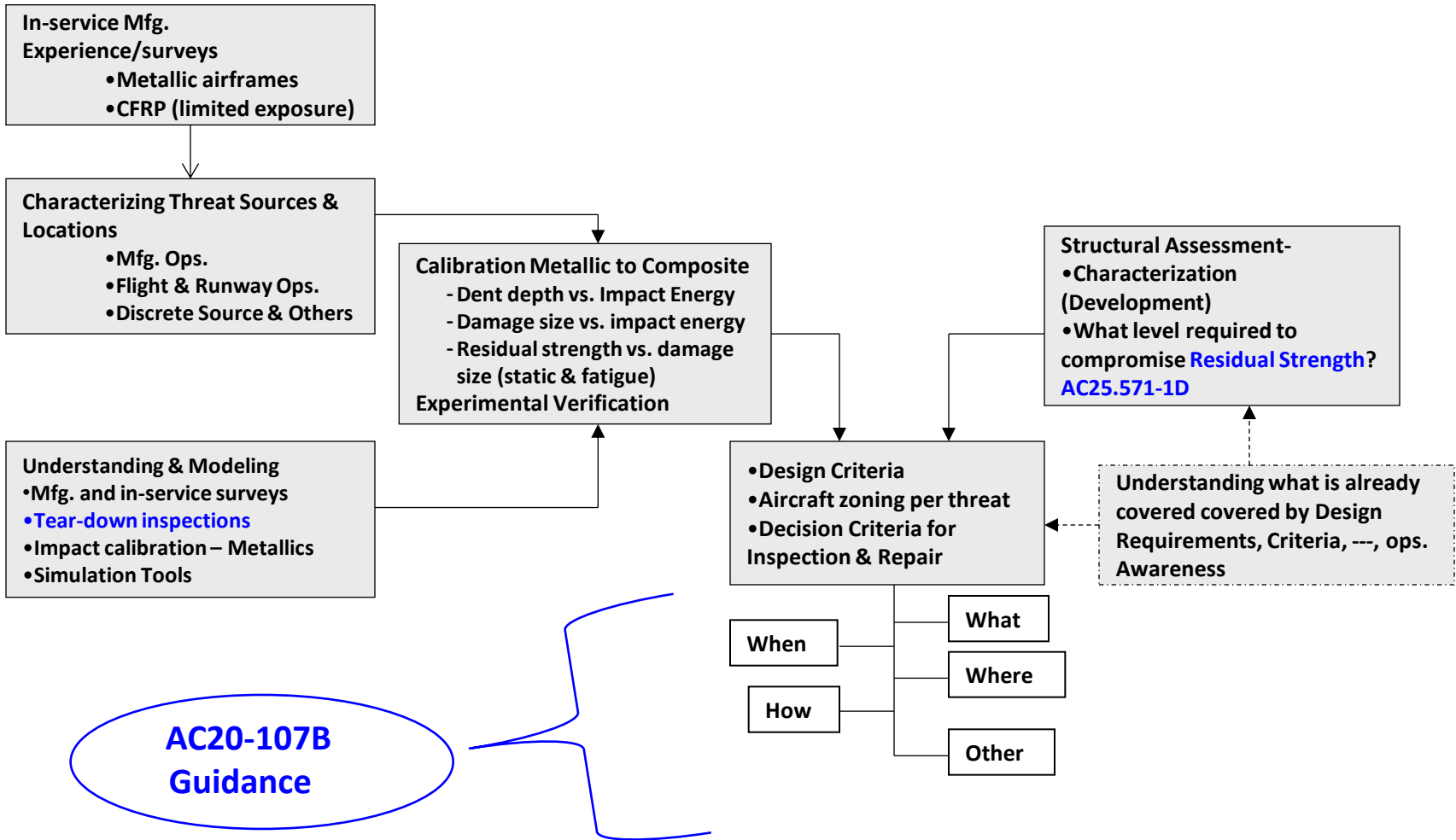
Adapted from E.K. Walker, J.C. Ekvall, and J.E. Rhodes (1979). "Design for Continuing Structural Integrity." Structural Integrity Technology. ASME, NY.

# Damage Sensitivity of Laminated Composite Systems: Primary is in-plane Loading Notch effects & Secondary Induced-out-of-plane Loading Effects.



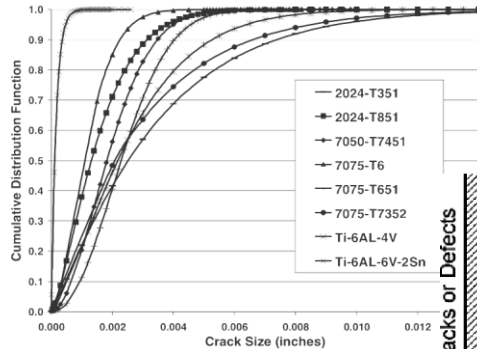
# Logic for Impact Damage Surveys, Assessments & Design Criterion (1980 – 2000)

(Operations, Discrete Sources, -- Metallic and CFRP Composites)



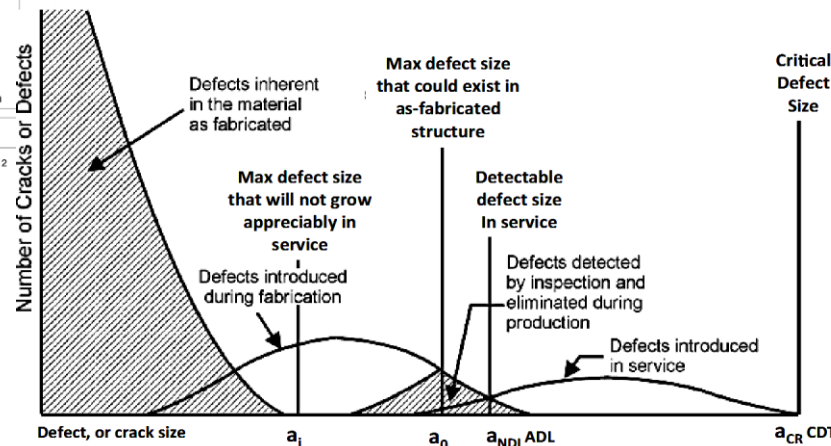
# Teardown Inspections of Fatigue Test Articles and Damage Surveys of In-service Aircraft and Airframe Structural Components removed from Aircraft for Cause

## Provide Basic Data For DT, WFD & WSD.



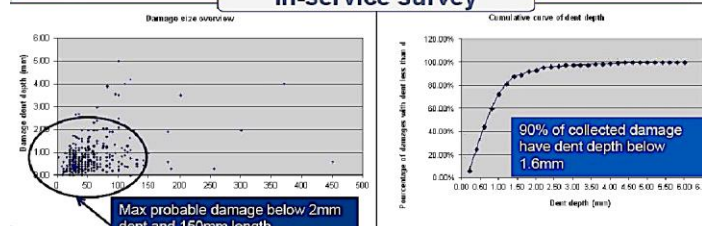
Inherent material defects & defects introduced during fabrication and assembly of **metallic airframes**, EIFS\* determined from a combination of teardown inspections of the fatigue test articles and in-service aircraft and airframe structural components removed from the aircraft for cause.

\*Damage Tolerant Risk Analysis Techniques for Evaluating the Structural Integrity of Aircraft Structures; J P Gallagher, C A Babish, & J C Malas, ICF 11; May2005



Accidental damage introduced in-service determined from visual inspections of in-service composite airframes and structural components removed from aircraft. Size and visual characteristics of the BVID are consistent with the inspection techniques employed during manufacture and in-service maintenance (90%Prob/95%Con).

Example of realistic damage characteristic from one survey (500000 FH, 73 aircraft over three years) used for impact threat assessment within probabilistic DT range – low velocity impact- k\*LL (1<k<1.5)



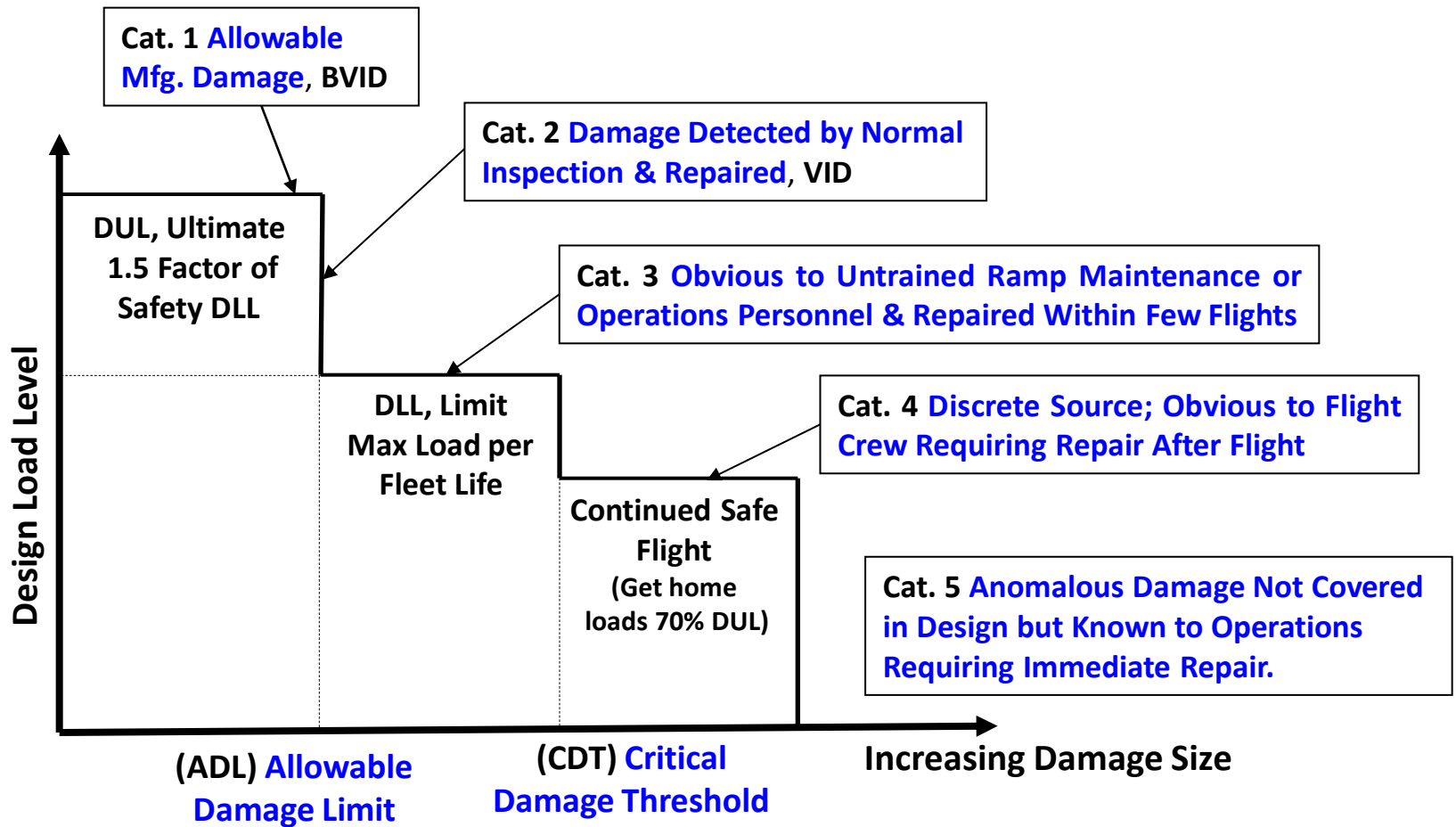
Large dent depth and or large damage size accounted for in the DT analysis (static strength and residual strength substantiation) as probable

→ These damages range complies with CAT 1 & CAT 2 from AC 20 107B

Composites @ Airbus; Damage Tolerance Methodology, FAA Workshop DT & Maintenance; Chicago, July 2006

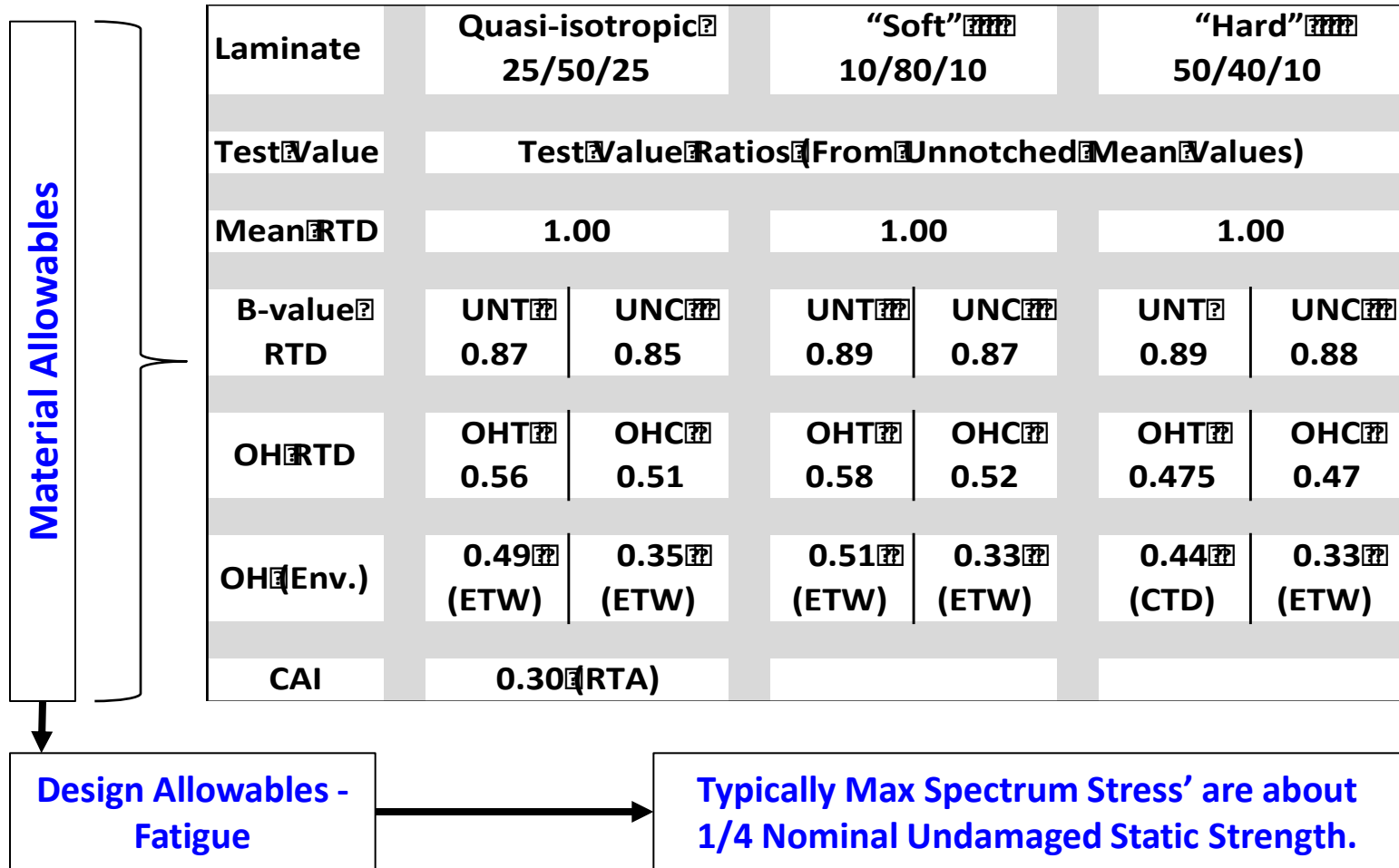
2015 FAA/Bombardier/TCCA/EASA/Industry Composite Transport Damage Tolerance and Maintenance Workshop

# Inspection (Awareness) Thresholds Determine Damage-tolerance Design Requirements



# Typical In-plane Strength Scaling Effect for Notch & Compression After Impact, CAI

Hexcel 8552 IMF7 (NCP-RP-2009-028 – Rev 21/06/2011)

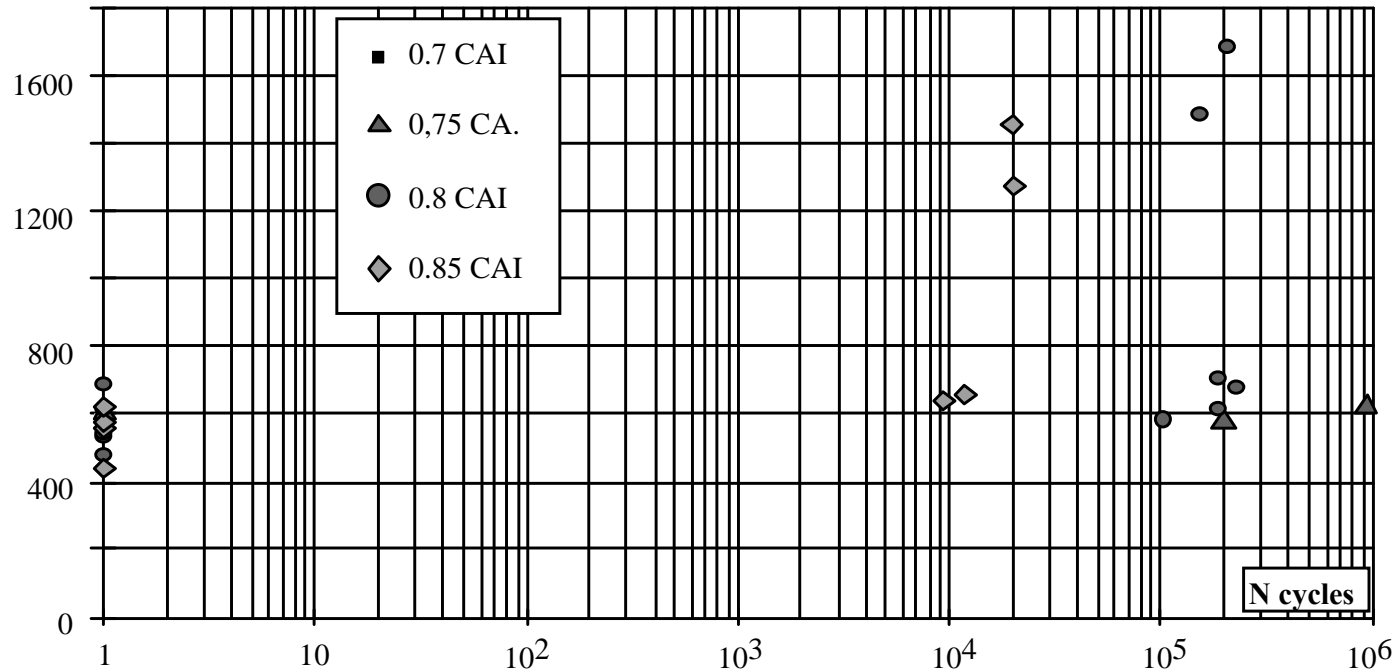




# Impact Damage Growth Threshold

(R.S. Whitehead et al.; Northrop Corporation - Certification Testing Methodology for Composite Structure" Vol I : Data Analysis and Vol II : Methodology Development; Report NADC-87042-60; 1986.)

Delaminated area (mm<sup>2</sup>)



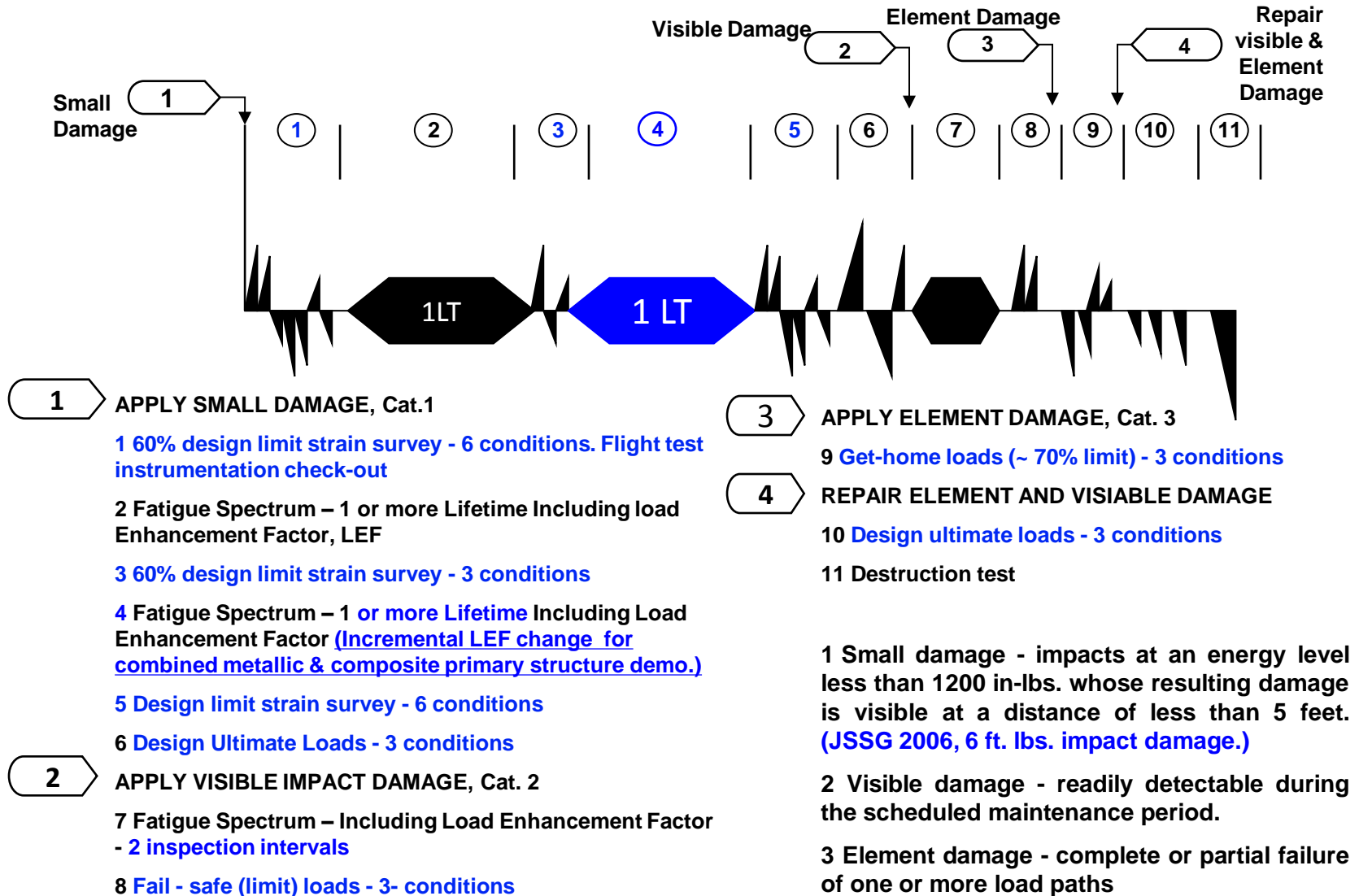
**Example : T800/F655-2 material, impacted at 6 joules (around the BVID).  
Constant amplitude fatigue testing at various ratios of the compression-compression testing, R = 10 after impact (CAI) strength.**

- **High constant amplitude stress values (>0.75 CAI) are required to obtain damage extension**

**NEARLY NO-GROWTH APPROACH LIKELY below 0.75 CAI**

- **Full Scale Fatigue testing Demonstration.**

# A Typical “Composite Airframe” FD&DT Test Sequence



# Full Scale Fatigue (FSFT) and Damage Tolerance Test (Metallics & Composites)

- The early years, MIL requirements;
  - The (USAF) initiated the Aircraft Structural Integrity Program (ASIP) in November 1958 using a “*safe life*” probabilistic approach and relied upon the results of a laboratory test of a full-scale airframe
    - Scatter Factor
    - Early composites
      - $SF \cong 90\%$  probability with 95% confidence
      - Wearout Model (Halpin et al 1973) & power-law damage growth
  - 1975 USAF formally made the damage tolerance approach a part of ASIP with the publication of MIL STD-1530A (metallic focus)
    - Single load path protecting against structural failure using the damage tolerance (DT) concept of slow crack growth and DT-based inspections.
    - Fail-safe design combined with damage tolerance analysis and FSFT tests protect structural safety of civilian and military transport aircraft.
- **2LT fatigue test + 3<sup>rd</sup> life for DT demonstrations.**
- AC 25.571-1 (1978 )implements damage tolerance and LOV concept in 2010
  - Fail-safe option was the predominant approach in the 1960s and 1970s
- AC 20-107A (1984) “No-growth,” Damage Tolerance – Safe Life scatter factor

# The 1970's Debate

- **Deterministic early Damage Tolerance concept:**
  - “Rogue Flaws” define inspection intervals
  - Fracture mechanics (measurable defect, growth and residual Life prediction)
  - Implemented FSFT requirement
- **What should be the duration for the FSFT?**
  - Design Service Goal (DSG) x Scatter Factor (SF)
  - What should be the Scatter Factor?
    - “Safe Life” reliability Scatter Factor (99%prob/95conf)
    - Inspection based Scatter Factor
    - What is the inspection reliability%
      - 90%prob/95% confidence of detection (practical implementation)
    - Damage Tolerance SF = 2 (with reoccurring in-service inspection at ½ of the residual life)

# Illustration of an Early Rational for the $(SF)_{DT} = 2$

A required period of unrepaired service usage was selected as two service lifetimes demonstrated with a FSFT. The Scatter Factor of two was selected to cover various uncertainties associated with damage &/or crack growth during service usage, variability in material properties, manufacturing quality and inspection reliability. Reoccurring in-service inspections at increments of  $\frac{1}{2}$  demonstrated & expected life would accommodate variations in inspection reliability.

FSFT	1st DSG	2nd DSG	DT
Re-occurring In-service inspections	Inspections as % of 1st DSG	Inspection Sequenced as % 2 DSG Test Duration	Initial Defects Missed with (90% prob/95% con) Detection Reliability*
1st.	50%	0.25%	10%
2nd.	75%	0.37%	1%
3rd.	87%	0.44%	0.10%
4th.	93%	0.47%	---

\*Over Simplified, no additional in-service damage

**Simplistic BUT it works.**

# Composites (1980s), What Should be Done?

- **Initial concept was a modified Safe Life concept with a SF reliability of 90%prob/95%conf (the Wear-out model)**
  - Resistance in Composite community and Industry to Damage Tolerance
  - Composite sensitivities differ from metallics
    - Notch sensitivity recognized as manageable
    - Carbon fiber fatigue resistant
  - Sendecky (1981) removes power law from 1973 Wearout model
  - NavAir prefers “safe Life” minimize aircraft carrier workload
    - Whithead et al 1986 -1997 Safe-life reliability
    - Accelerated FSFT using Load enhancement, LEF
  - Composite Scatter factor (**Interlaminar fatigue sensitivity**)
    - A level reliability,  $(SF)_A \cong 42$
    - B level reliability,  $(SF)_B \cong 5$
  - A310/300 composite vertical tail [1984]
    - Safe-life, Minimum MFG quality (Category 1)
    - Damage Tolerance demo.
    - **One Lifetime with Load Enhancement Factor validate “ No-Growth”**
    - $(SF)_B \cong 5$ , for 1 FSFT LEF  $\cong 1.15$
- **Inspection strategy?**
  - Accidental damage

# Entered 2000's with 3 Approaches

- Single load path protecting against structural failure using the damage tolerance (DT) concept of slow crack growth or “nearly-no-growth” and DT-based inspections;
  - FSFT with  $SF \cong 2$
  - Typical (average) fleet usage
- Single load path protecting against structural failure using a reliability based “safe-life” “nearly-no-growth” damage tolerance;
  - FSFT with  $SF \cong$  B-level reliability
  - Load enhancement to accelerate test (interlaminar damage growth)
  - Average to Aggressive (USNav) usage
- Fail-safe design combined with slow crack growth damage tolerance analysis and inspection concept;
  - FSFT with  $SF \cong 2$
  - Typical (average) fleet usage
  - Common inspection (damage detection) B-level reliability

# Inspection Intervals are a Function of Damage Severity and Inspection Capabilities (Notional)

Degree of Inspectability	Typical Inspection Interval (MIL)	Required Residual Strength	Damage Category
In-flight Evident	One Flight	70% DLL	Category 4
Ground Evident	One Flight (?)	—	Category 5
Walk-Around Visual	Ten Flights	≥DLL	Category 3
Special Visual	One Year	≥DLL (≈1.2 DLL)	Category 2* (scheduled inspection)
Repair Depot	1/4 - 1/2 Lifetime*	DUL	Category 1
Non-Inspectable	One Lifetime	DUL	Category 1

\* For MIL transports Nearly No Damage Growth (&/or slow crack growth structure), the required period of unrepaired service usage is two service usage lifetimes, modified for Fail-Safe structure. CIVL transports use the A (FH/cycles), B (TBD months), C (TBD yrs.) & D (TBD yrs.) check system to phase the DT inspections [per (ATA) Maintenance Steering Group's [MSG-3 guidance](#)].

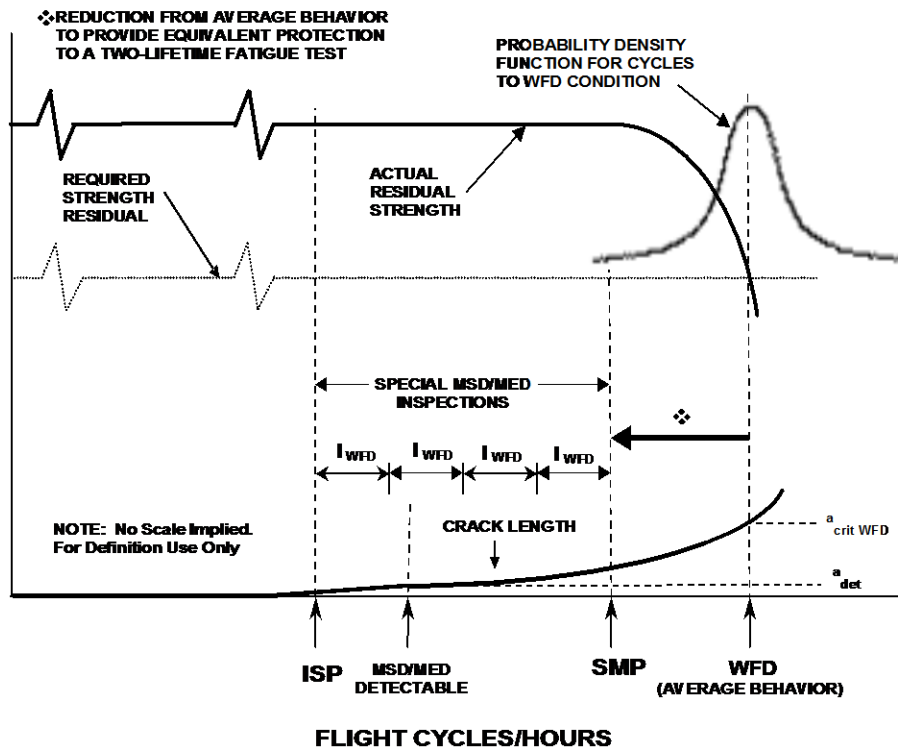


# Composite Airframe F&DT Summary

- Graphite composite structures have demonstrated consistent fatigue resistance
  - Graphite fiber consistent since the 1970's, in-plane fiber control laminates
  - Low in-plane stress due to in-plane static strength sizing for notched and impact damage.
  - Accidental damage continues to be the focus of Damage Tolerance for laminated composite structures (out-of plane impacts).
- Built-up and curved surfaces are potential fatigue sensitive locations - out-of-plane (local) stresses.
  - Lower properties than in-plane
  - Difficult to quantify by analysis
- Environmental durability of bonded composite-to-metal and metal-to-metal load transfer location have similar sensitivities (original & **bonded repairs**).
- Load acceleration fatigue testing focusing on resin and adhesive damage growth, a valid concept similar to da/dn adjustments for load level changes in metallic structure.
- **Wide spread damage, WSD, assessment appropriate:**
  - **Damage Survey's & Tear-down inspection of aging airframe(s)**
  - Intent similar to fatigue critical WFD inspections for metallic structures (ASIP)

# Protecting Residual Strength from Gradual Material Deterioration Subjected to Operational Usage & Environments (AC 120-104\_LOV).

What is the equivalent process for WSD risk for Composite Structure?



Individual Susceptible Element or Area

**WFD**<sub>(average behavior)</sub>

End of deterioration process when structure cannot support residual strength requirement.

**SMP**

Structural Modification or replacement

Point must occur at a fraction of the

**WFD**<sub>(average behavior)</sub> to provide reliability comparable to two-lifetime FSFT.

Reduction factor may be 2 or 3 for cracking damage tolerance (or by fatigue scatter factor for safe life?)

**ISP, Inspection Start Point at**

“Crack Initiation Point” or additional reduction factor (?) as determined by

Initial fatigue testing & teardown, or in-service experience & teardown of similar structure.

Is inspection effective?

AC 120-93, “Damage Tolerance Inspections for Repairs and Alterations”

# Establishing an Operational Limit for Composite Structure (AC 120-104 Appendix 6)

**4) Adjustment of SMP. The SMP may be extended or reduced, based on the following:**

**(a) Extension of SMP. You can extend the SMP if you can show freedom from WFD up to the new SMP. The tasks required to extend the SMP may include any or all of the following:**

- 1 Additional fatigue or residual strength tests, or both, on a full-scale airplane structure or a full-scale component followed by detailed inspections and analyses.**
- 2 Fatigue tests of new structure or structure from in-service airplanes on a smaller scale than full component tests (i.e., sub-component or panel tests, or both). If a sub-component test is used, the SMP would be extended only for that sub-component.**
- 3 Teardown inspections (destructive) on structural components that have been removed from service.**
- 4 Teardown inspections (non-destructive) accomplished by selected, limited disassembly and subsequent reassembly of specific areas of high- time airplanes.**
- 5 Analysis of in-service data (e.g., inspections) from a statistically significant number of airplanes.**

**(b) Reduction of SMP. ---reduction based on data.**

**Assess Operational Limits; WSD Inspection Thresholds for Affected Components either Composite or Metallic Construction.  
Focusing the AC 120-104 Options?**

**Is this an effective option for WSD?**

Would additional Full Scale Fatigue Testing provide additional information concerning the Environmental and Corrosion Durability issues experienced in bonded metallic and/or composite structure and structural elements? **How would an additional Full Scale Fatigue Test develop an understanding concerning the accumulation of Accidental Damage over time?**

**OR**

**✓ Would an alternative aging lead-the-fleet approach supplementing the initial FSFT be more effective involving:**

**A Supplemental Structural Inspection Program, SSI, (to include in-service impact damage, HEWABI & repair accumulation for composites); a revalidation of service loads and the usage fatigue loads spectrum to assess if the “nearly no growth” damage tolerance has been compromised; and Lead-the-fleet teardown of several aging airframes (TBD).**

**Mod. & Implement AC 120-93, “Damage Tolerance Inspections for Repairs and Alterations” for Bonded Repairs & 14 CFR Part 26, Subpart E - Aging Airplane Safety—Damage Tolerance Data for Repairs and Alterations ( § 26.43 — Holders of and applicants for type certificates—Repairs.) for WSD?**

# Summary

- **Several modes of Discrete Source Damage, Accidental Damage & Repairs will accumulate in number, and probably in magnitude over time as an airframe ages.**
- **There is a consistent record of a gradual increase in loads over a typical airframe life ( $\approx 1.07\%/year$  MGTOW, MIL Transports) - this may suggest that a verification of the “nearly no-growth” capability is appropriate. Many of the “durability” associated Damage Tolerance topics would be well managed under the LOV concept provided the emphasis on the metallic WFD is put into a WSD perspective.**
- **There is a potential interlaminar fatigue sensitivity - that may increase as multiple impact events & repairs accumulate over time combined with a gradual increase in the operational loads - potentially more subtle than the through thickness cracking of metallics’.**

**Encourage a Fleet leader program that includes Damage Survey’s, Bonded Repairs & Tear-down Inspections to understand and document aging composite airframe WSD Events affecting WSD Operational Limits. Part 26?**