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Damage Tolerance for GA

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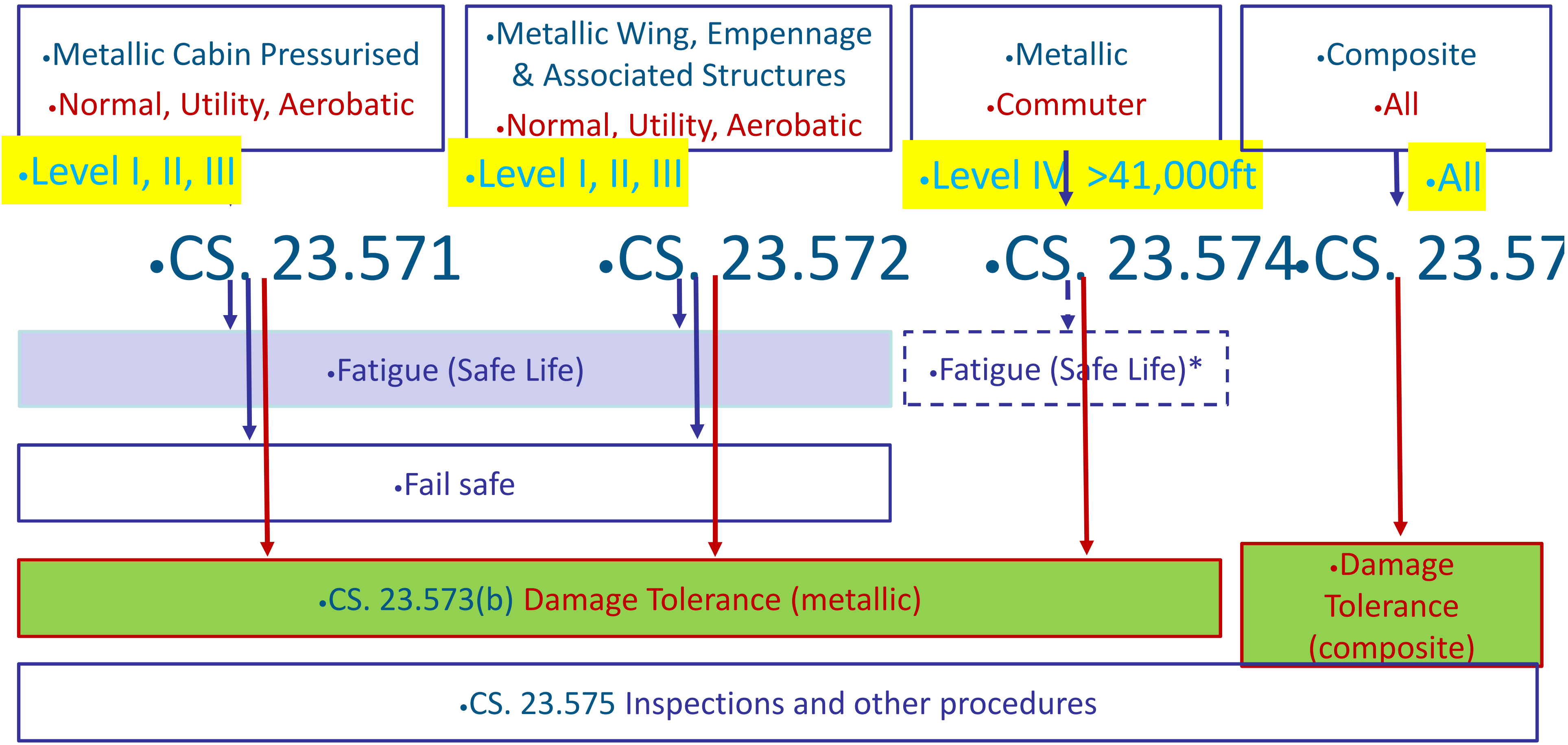
Requirements CS-23 Amendment 4

- CS 23.571, 23.572, 23.573, 23.574, 23.575



•* if it can be established that the application of those requirements is impractical for a particular structure

•Level I metallic unpressurised as current CS-VLA

CS 23.2240 Structural durability

- **F3115/F3115M – 15 Damage tolerance**
- Option
  - Level I, II, III metallic
  - Composite (recommended)

- Required:
  - High altitude >41000 ft Fuselage
  - High energy fragments
  - Level IV

Metallic Structure DT (ASTM 3115-15 4.6) I

- Evaluation of probable and critical location and mode of damages due
  - Fatigue
  - Corrosion
  - Accidental damage (including high energy debris)
- Multiple site damage
- Repeated load and static analyses supported by test
- Except impractical: Relatively narrow and highly loaded structures where possible crack would propagate too quickly and fail safe not practical. E.g. landing gear parts

Metallic structure (ASTM 3115-15 4.6) II/II

- Fatigue spectrum
- Crack growth under repeated loads
- Residual strength
- Detectability
- Inspection program (ALS of the ICA)

CS 23: Damage tolerance- Definitions

- Damage Tolerance:

  'Damage tolerance' is the attribute of the structure that permits it to retain its required residual strength without detrimental structural deformation for a period of use after the structure has sustained a given level of fatigue, environmental, accidental, or discrete source damage.

- Fail-safe:

  'Fail-safe' is the attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element.

CS 23: Fail safe/Damage tolerant design

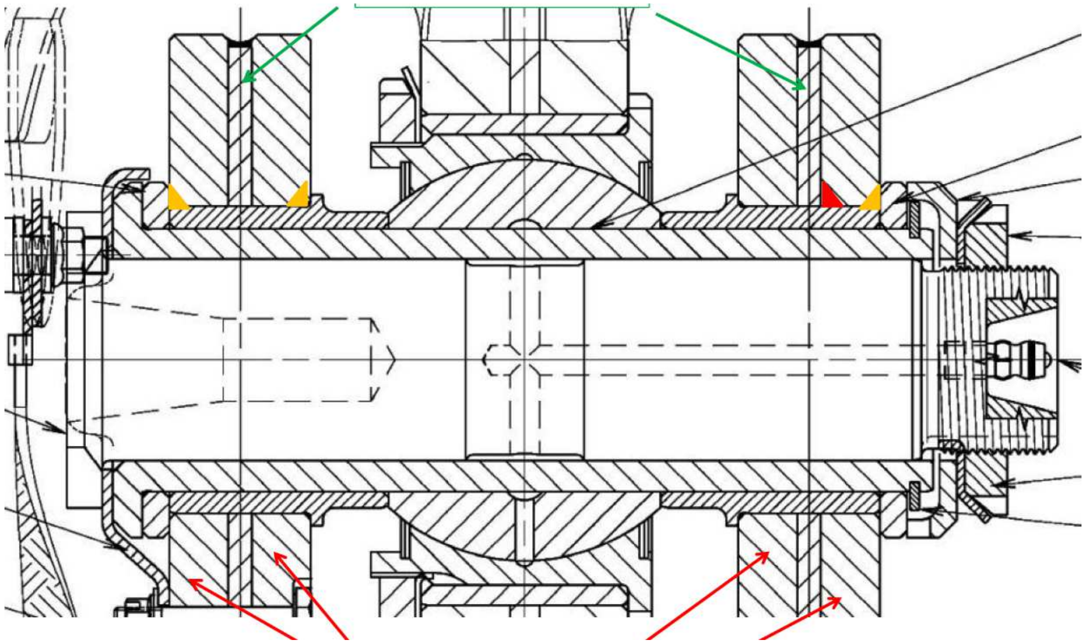
a) Use of multipath construction and providing crack/damage stoppers to limit the growth of damage.
b) Use of duplicate structures with a second member available that can assume the extra load if the primary member fails.
c) Selection of stress levels and materials that provide a controlled slow rate of crack propagation combined with a high residual strength after initiation of cracks.
d) Easy detection before allowed loss of strength. Design to allow replacement or repair.

Guidance

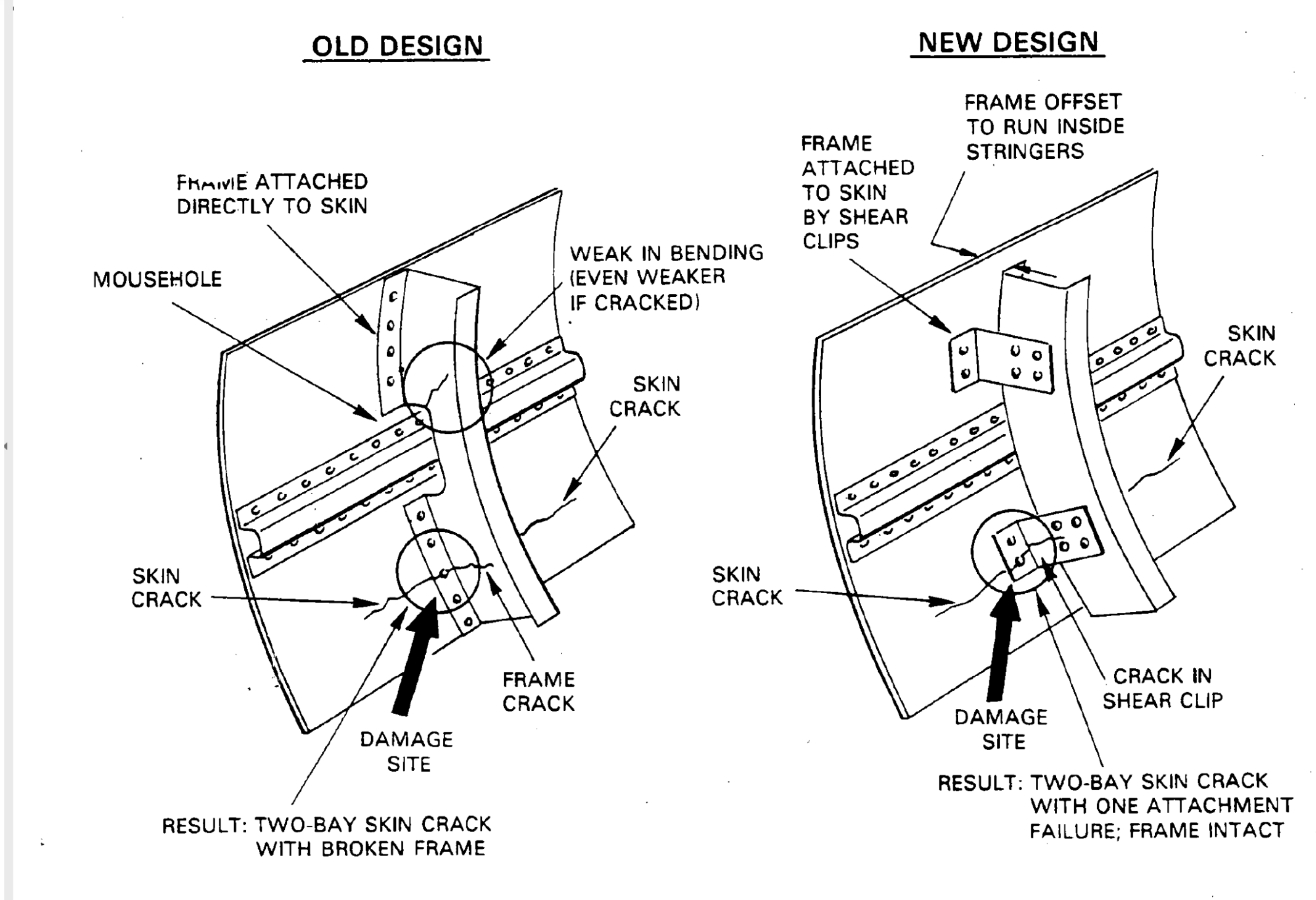
- There isn't AMC/AC guidance unique to part 23 damage tolerance evaluations. AMC 25.571 (CS-25 Amdt 19) and AMC 20-20 can be consulted.
- Follow the general guidance in AC 23-13A sections 2-4, 2-7, 2-8, 2-9 for developing the loading spectra, mission profile, and test plan for evaluating your damage tolerant design

Fail safe design

- Duplicate construction

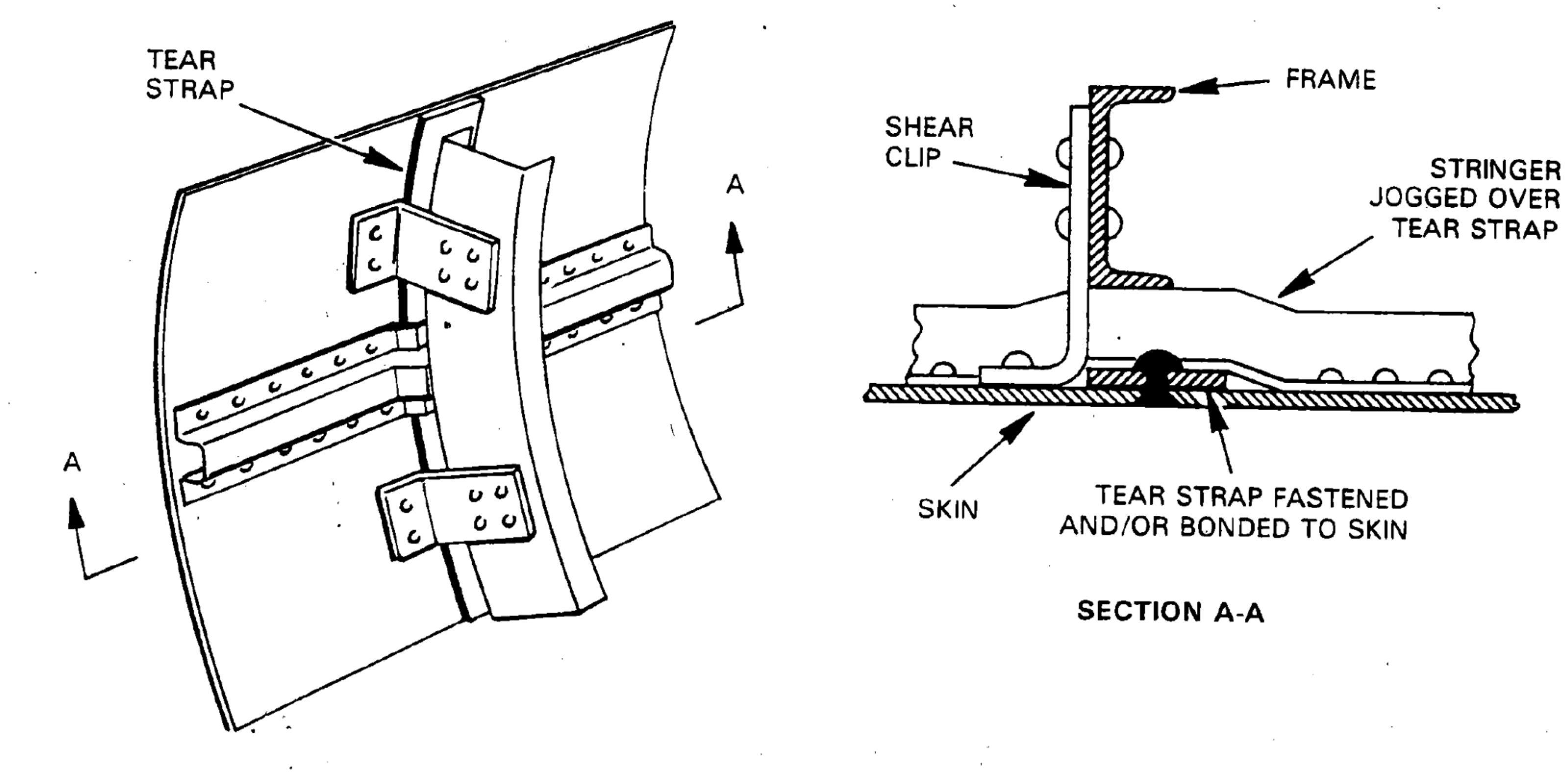


Damage tolerant designs



- Consider splices parallel to principal stress

Tear straps as arrest features



CS 23 Amdt 5: Applicable Structure

- Structure to be assessed for CS-23.2240 ASTM F3115/F3115M-15 (Structural durability for small Airplanes) as a minimum :
  - 4.2 Pressurised cabin
  - 4.3 Wing, empennage, their carry-through and attaching structures:
  - 5. Composite Structure
    - structure the failure of which would result in catastrophic loss of the airplane,
    - wing, empennage, their carry through and attaching structure, moveable control surfaces and their attaching structure, fuselage.

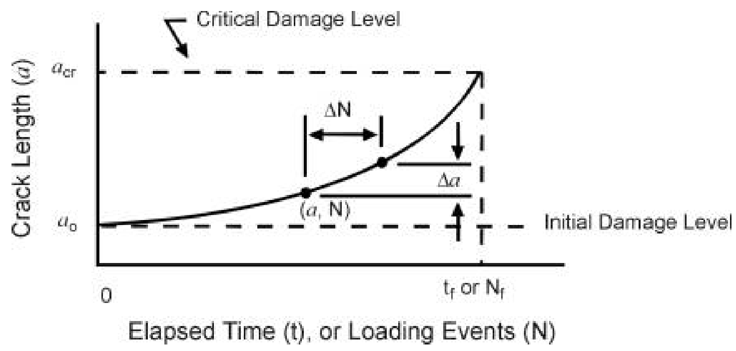
- Principal structural element (PSE) is an element that contributes significantly to carrying flight, ground, or cabin pressurization loads, and whose integrity is essential in maintaining the overall structural integrity of the airplane. (Note: Part 23 fatigue evaluation requirements do not apply to landing gear or unpressurized fuselage structure; however, ground loads are to be included to the extent that they affect wing, empennage, canard or pressurized cabin structure.)

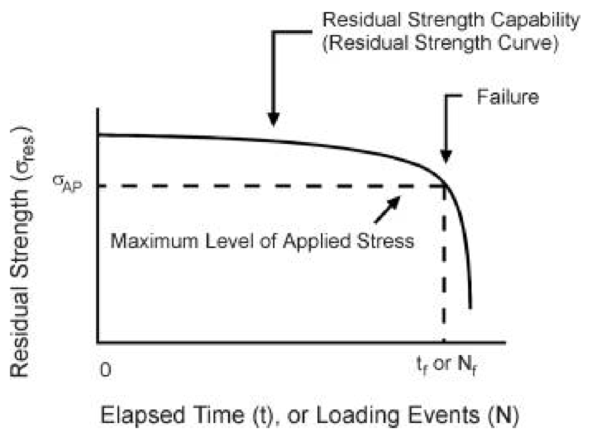
Damage locations (analysis or test)

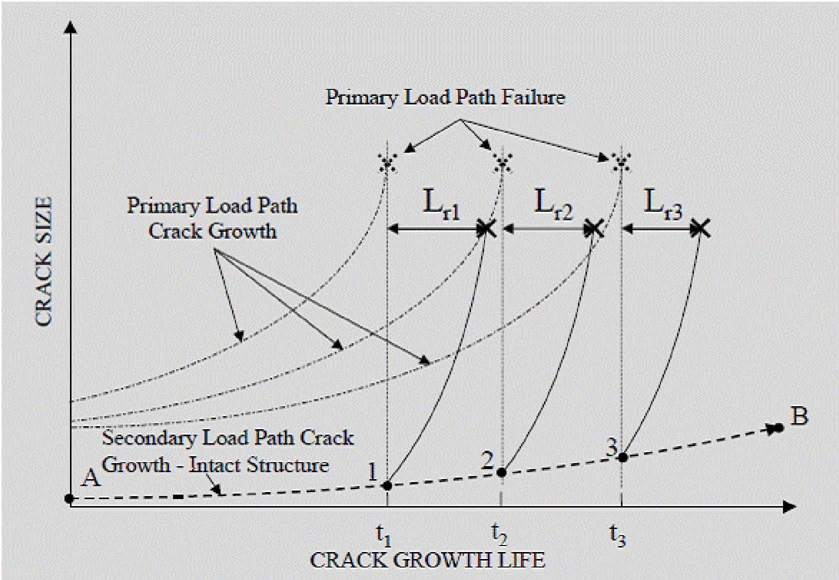
- Splice joints, cutouts
- Cut one element in dual constructions and primary attachments.
- Failure of skin, frames, stringers, and pressure bulkheads in pressurized cabins.
- Critical locations: Low MS, high stress, high concentration, high loss of stiffness, increase of stress
- Locations of probable damage: susceptible to manufacturing damages, in service accidental damage, or corrosion damage. Test findings, quick growth
- Detectability considerations: Ensure detectability. When impossible, assume a crack.

Crack detection before it becomes critical

- Threshold inspection: Initial crack to critical with a SF
- Interval inspection: Detectable to critical with a SF



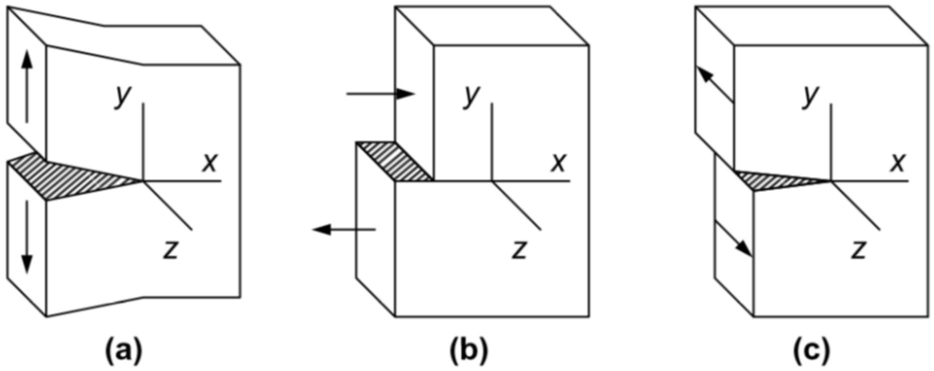




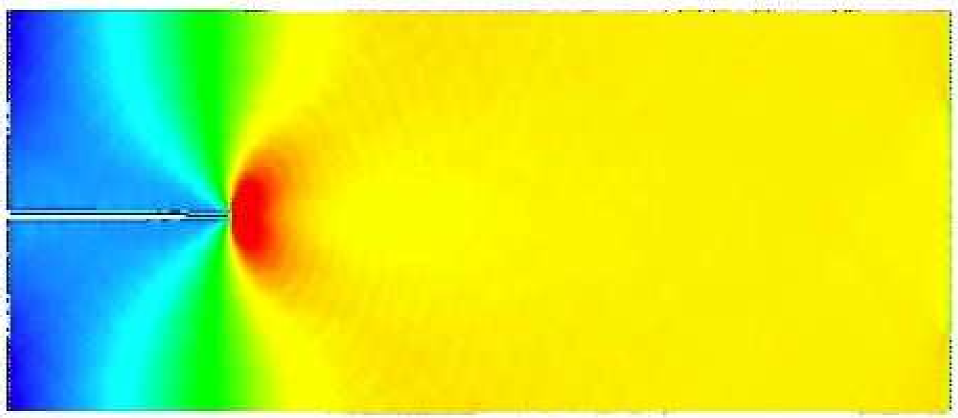
Analysis: Inspection safety factor discussion

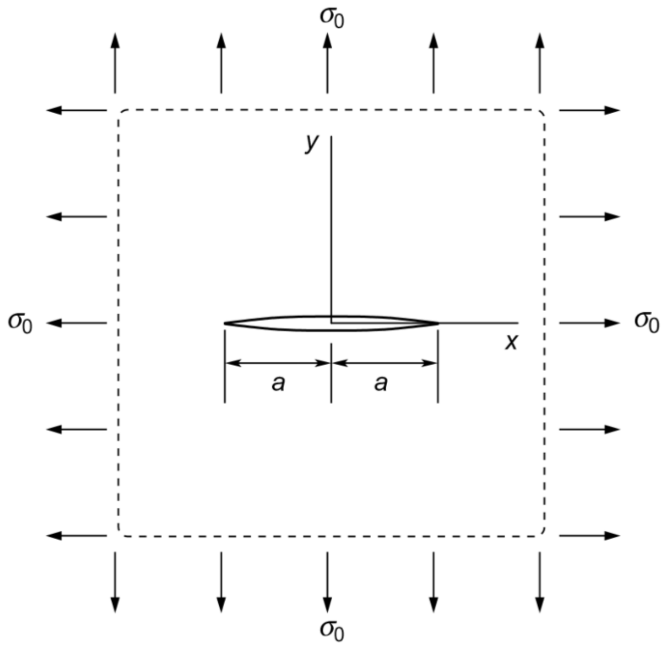
- Depending on uncertainty, criticality, and general conservatism
- A factor of 2 is usually accepted for threshold and interval determination and interval of multiple load path structures.
- A factor of 3 or more is recommended for interval inspection for single load path (Ref. Swift).

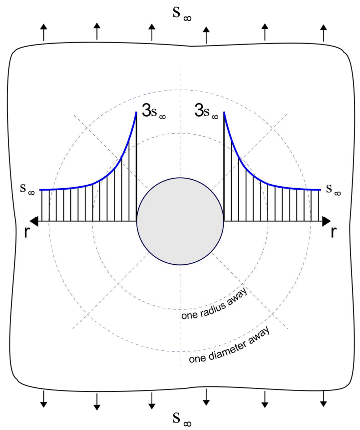
Physics: Singular stress state around a crack stress intensity<>stress concentration



$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi x}} + O(\sqrt{x}), \qquad \sigma_{xy} = \sigma_{yz} = 0$$

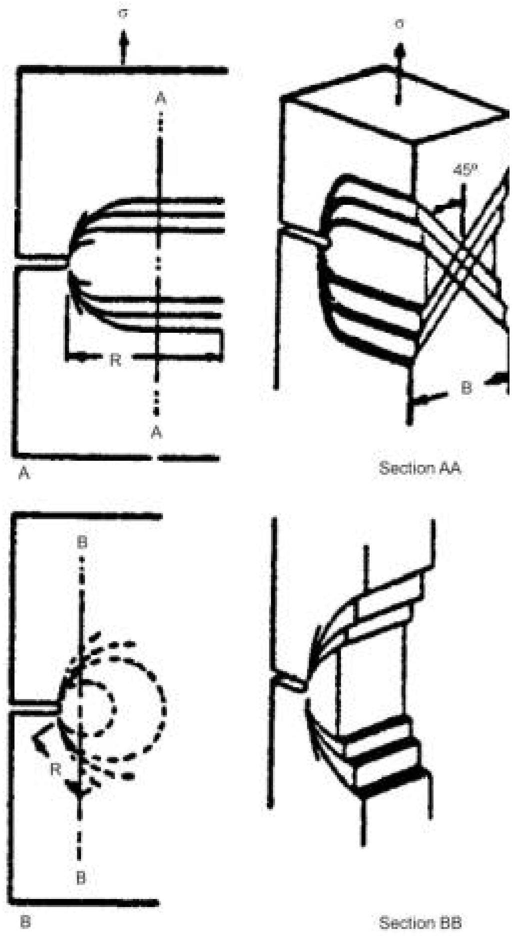






Stress State

- Plane stress (thin)/plane strain (thick). The stress state affects the critical stress intensity.
- While there is a constant K1c for plane strain, for thin sheet and ductile materials there is stable crack growth beyond K1c. Kc for unstable crack growth depends on thickness, initial crack size and geometry.
- Internally calculated by AFGROW
- R-curves for an elaborate approach



Crack growth principles: Linear elastic fracture mechanics with plastic corrections

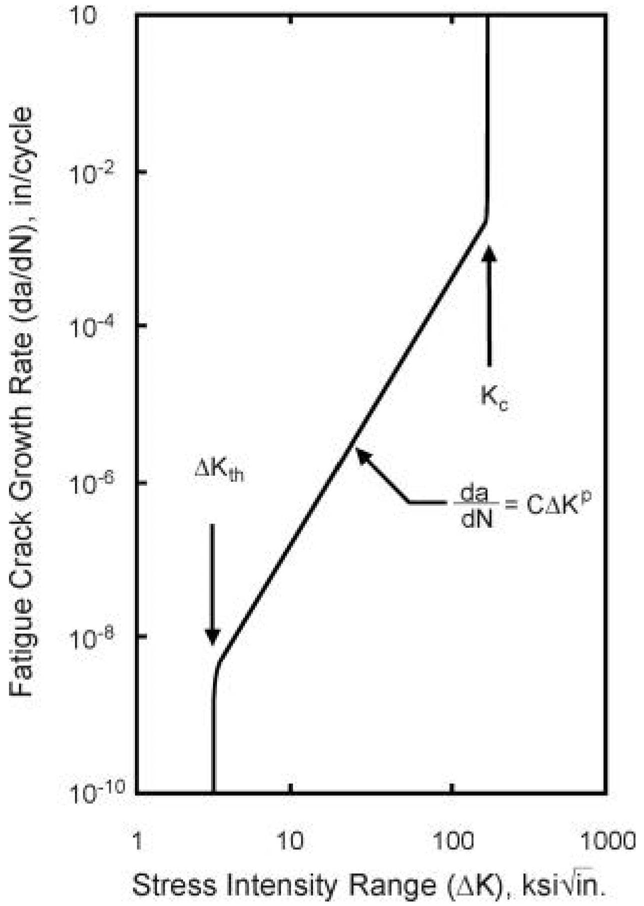
The stress intensity factors for each geometry can be described using the general form:

$$K = \sigma\beta\sqrt{\pi a}$$

$$\frac{da}{dN} = C(\Delta K)^p$$

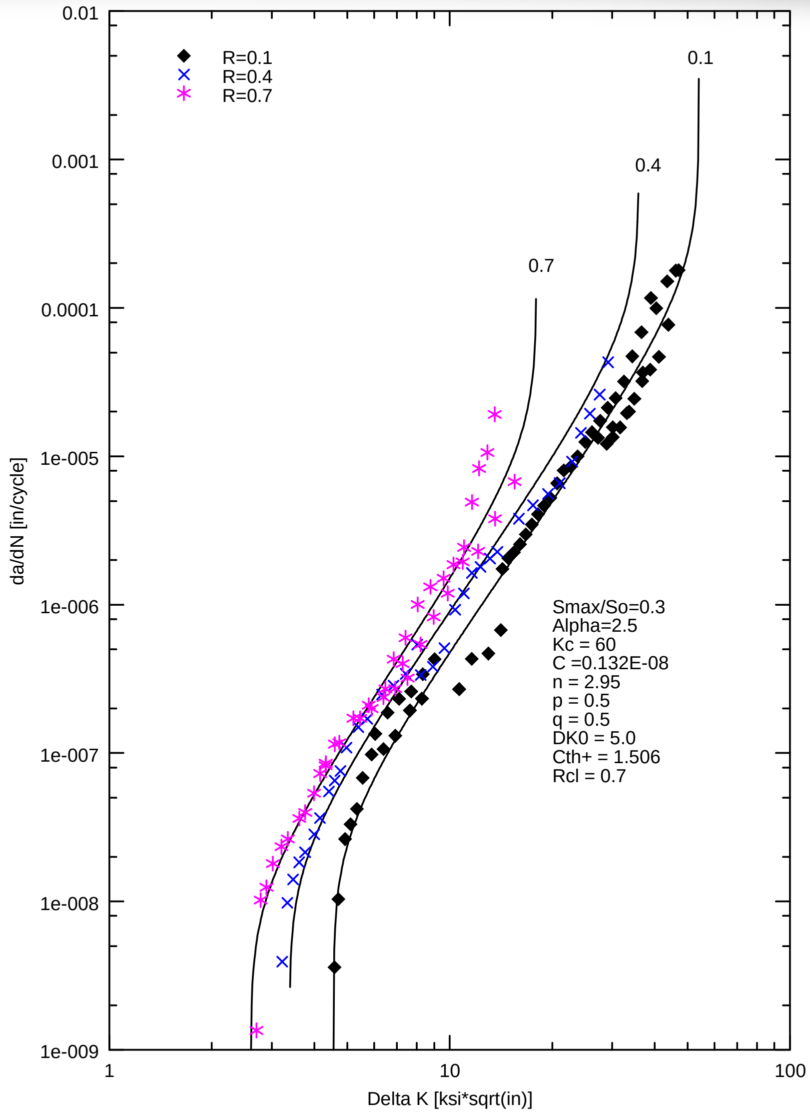
- P~3: Stress, β, high influence
- Conservative approach: no Kth to avoid issues like small crack (e.g. Forman model)
- Failure: Fracture toughness or net-section yield*.

*Kc is reduced as the material exceeds flow stress (btw Fty & Ftu), accelerating failure under residual strength conditions. Ref NASGRO 3.0 manual 2.1.6



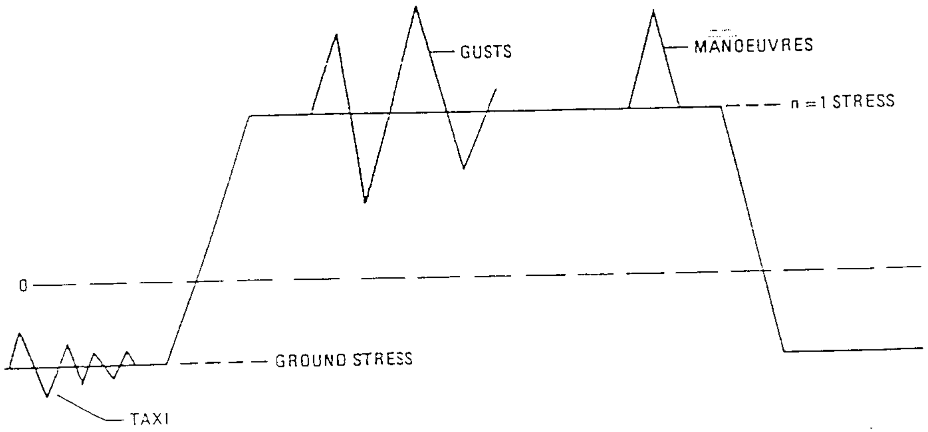
Crack growth principles: Linear elastic fracture mechanics with plastic corrections

- R: Ratio of min to max stress
- Closure effects
- E.g, Walker model, NASGRO equation.

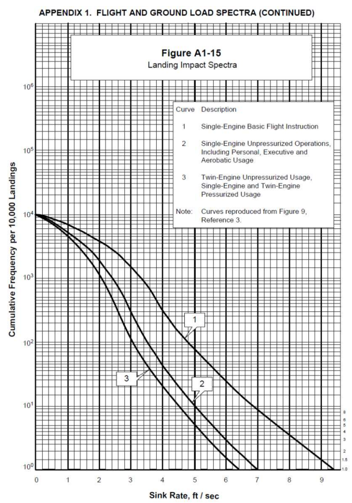


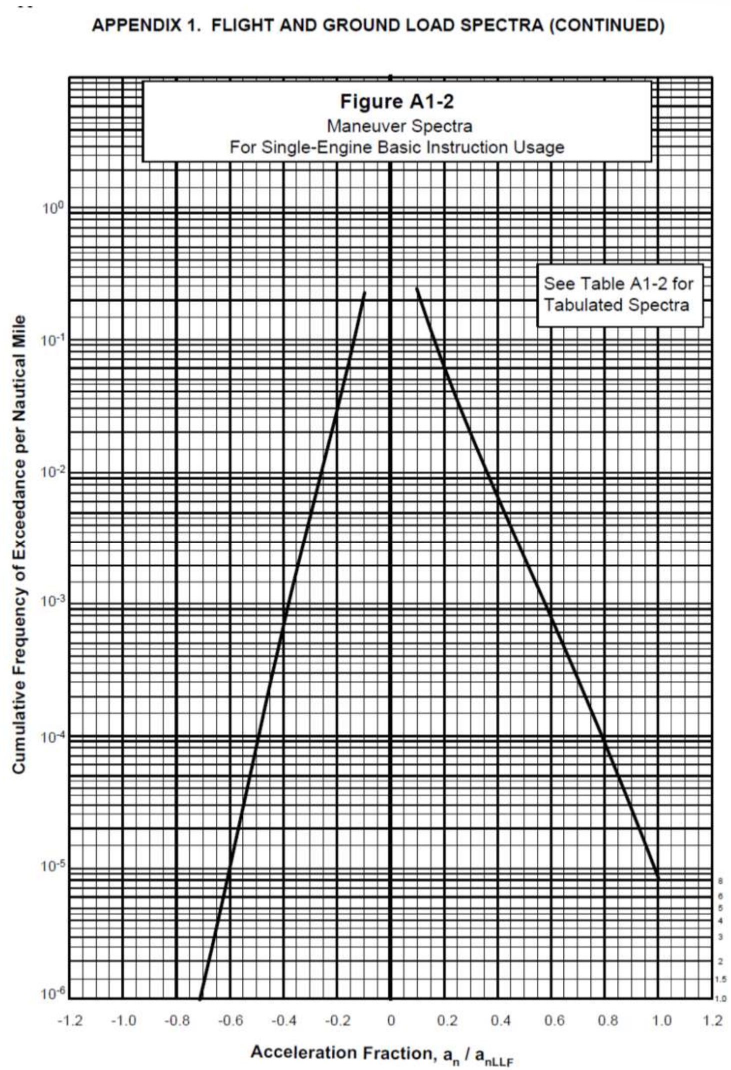
From NASGRO Reference manual

- Appendix 1 of AC 23-13A



- Note LSA/VLA equivalent stress based on non-aerobatic spectrum





Analysis: Initial and critical crack

- Rogue, primary crack: 0.05 “ corner
- Initial secondary crack: the USAF who first created the 0.05 primary and 0.005” corner secondary crack scenario have since 2008 required that a 0.01” corner flaw (plus damage growth until element failure) is used for continuing damage scenarios. (Ref. USAF Structures Bulletin No. EN-SB-08-002)

- Critical crack: Fracture or net section yield under stresses in F3115/F3115M – 15 sect. 4.7

Multi-fastener analysis

- Example of crack propagation steps

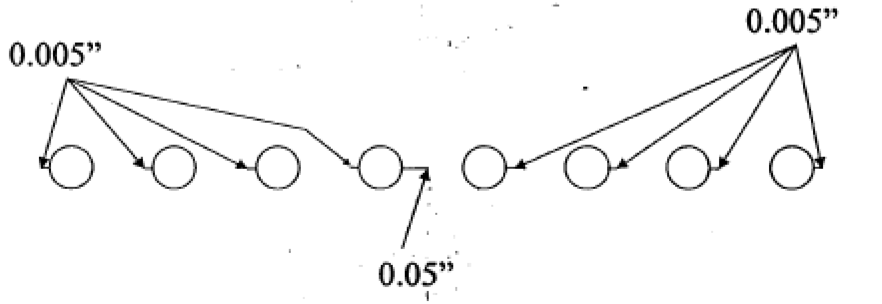


Figure 10 Initial Flaw Assumptions

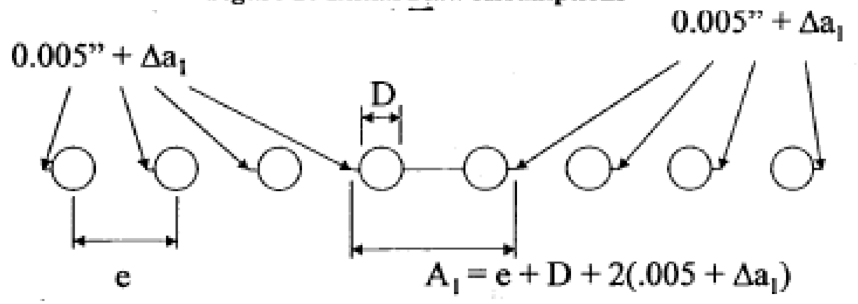


Figure 11 End of First Stage of Continuing Damage

- Common approach to stop crack growth at the first link

Analysis: Detectable crack

- The detectable crack assumed for the inspection interval has to be consistent with the access and validated inspection technique
- The inspection instruction should detail all necessary access (e.g. remove lining etc.) and inspection instructions to ensure this.
- Consider part of the crack hidden by a doubler, antenna, fastener head, etc.

NDT

- NAVAIR technical manual
- NDT Resource Center

TABLE 2. Detectable Crack Sizes Associated with Inspection Techniques (Reference [4])

Method	Description	Detectable Crack Length (inch)
Visual	Unpainted Surface*: 3 to 5x Magnification	1.0 or Hole-to-Edge
	Painted Surface	None
Penetrant	Unpainted Surface: 3 to 5x Magnification Without Magnification	0.125 0.250
	Painted Surface	None
Magnetic Particle	Unpainted Surface: 3 to 5x Magnification Without Magnification	0.0625 0.125
	Painted Surface: Without Magnification	0.250
X-RAY Radiography	Uncovered length of crack in aluminum (not covered by a steel member)	0.75 or Hole-to-Hole or Hole-to-Edge
Ultrasonic Shear-Wave (Angle Beam)	Crack at fastener hole using mini probe (0.25 x 0.25 inch element) at 5 to 10 Mhz	0.125 Long x .0625 Deep
	Crack in Clevis or Lug	0.125 Long x 0.0625 Deep
Ultrasonic Longitudinal Wave (Straight Beam)	Bolts	¼ to 1/3 Diameter
	Crack at Fastener Hole	0.125
Bolt Hole Eddy Current (Faster Removed)	Edge Corner Crack	0.030 x 0.030
	Inside Diameter Surface	0.060 Long x .030 Deep
Eddy Current Surface Probe	Crack at Fastener	0.0625 Uncovered Length
	Crack Away Fastner	0.125

Antenna installations DT

- See 2014 STC workshop Antenna DT presentation for antenna discussion (CS25 focus)

- http://www.easa.europa.eu/newsroom-and-events/events/stc-structural-substantiation-workshop-antenna-installation-damage

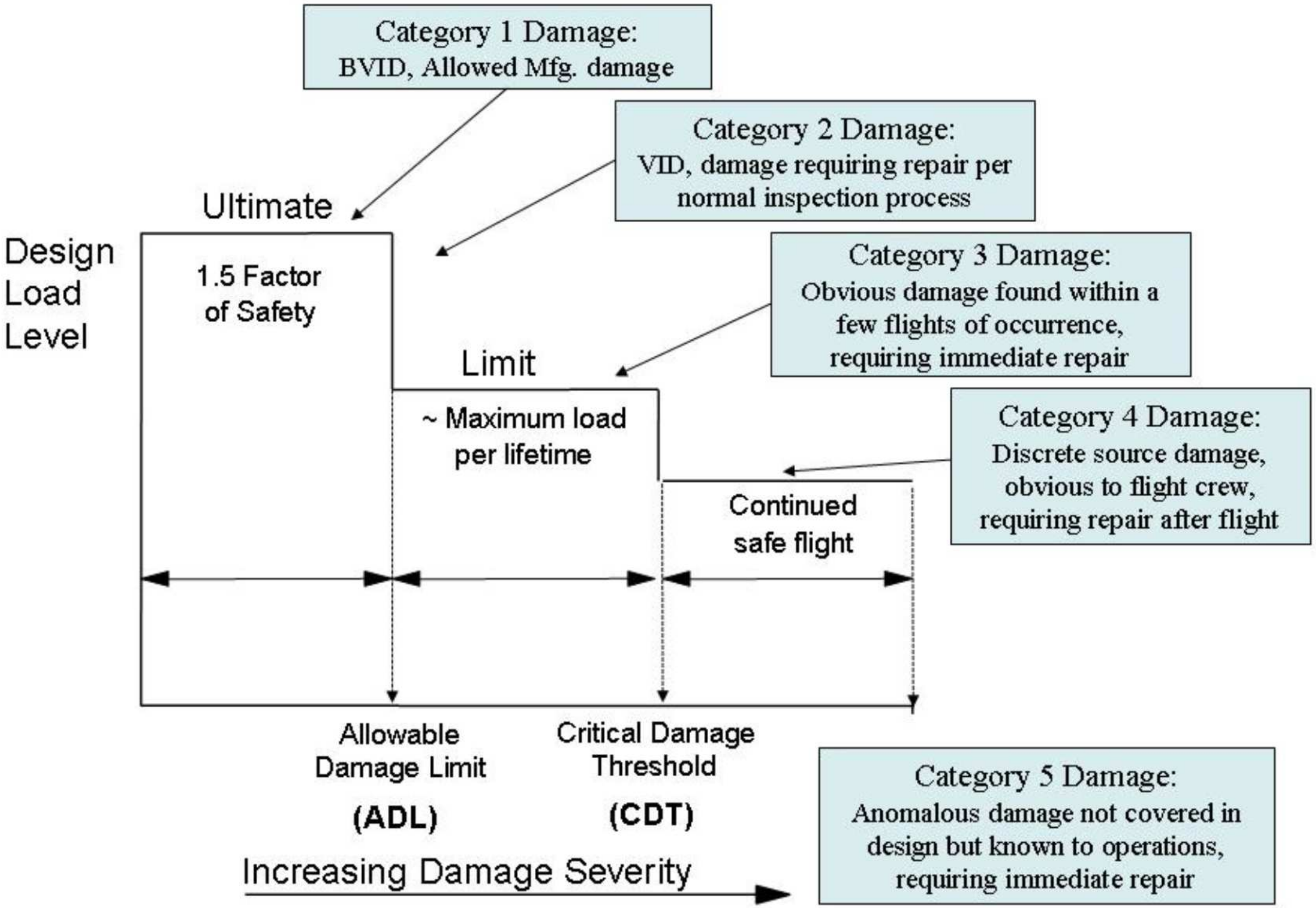
F3115 §5. composite structure

- UL with damage up to the threshold of detectability (BVID)
- The growth rate or no-growth of damage from fatigue, corrosion, manufacturing flaws or impact under repeated loads, established by tests or analysis supported by tests.
- Residual strength
- Fatigue when impractical
- Inspection program (ALS of the ICA)

Composite structure guidance

- AMC 20-29
- CMH-17
- Composite Structural Engineering Technology (CSET) Course
- CM-S-006 Iss 1, Composite light aircraft
- CM-S-005 Iss 1, Bonded repair size limits
- Proposed CM-S-010, Monocoque safe design
- AC 21-26 quality control, to ensure durability and reliability, particularly for bonded and potted joints.

AMC 20-29 Damage threat assessment



Manufacturing defects

- Porosity (micro-voids)
- Macro voids
- Delaminations
- Disbonds
- Inclusions
- Resin pockets
- Dry fibers

Impact damages

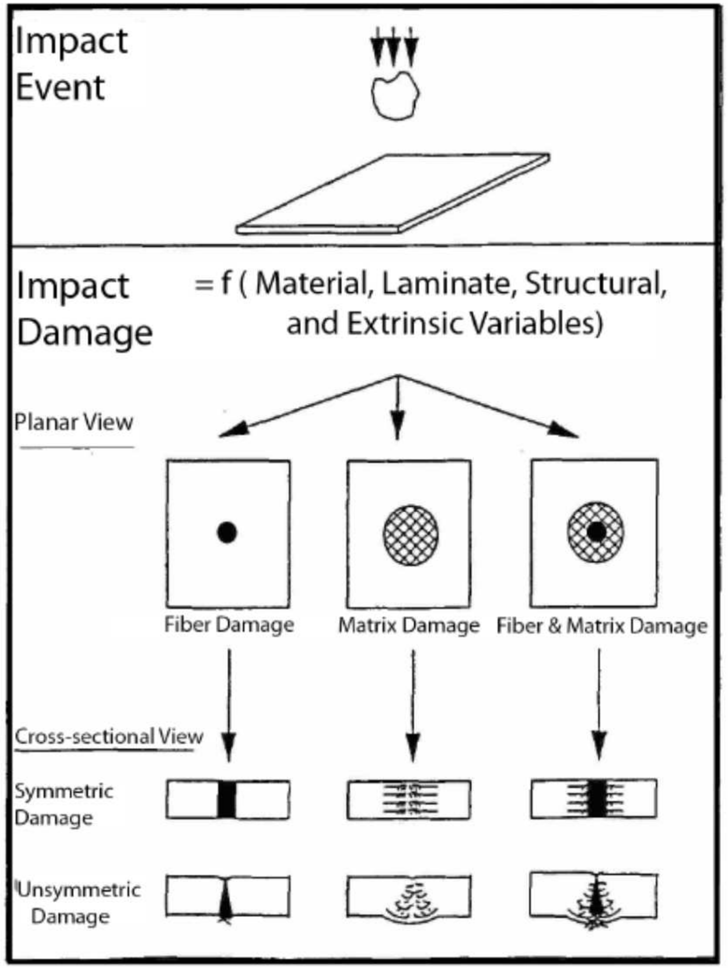
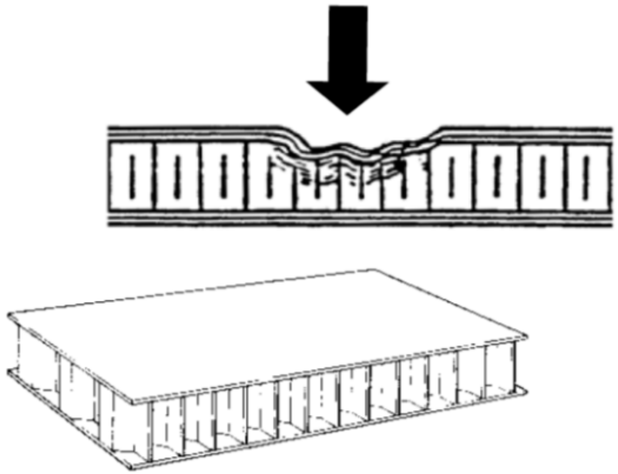


FIGURE 12.7.1.2.7(b) *Potential impact damage states for laminated composites (Reference 12.7.1.2.2(a)).*



Discrete source damage

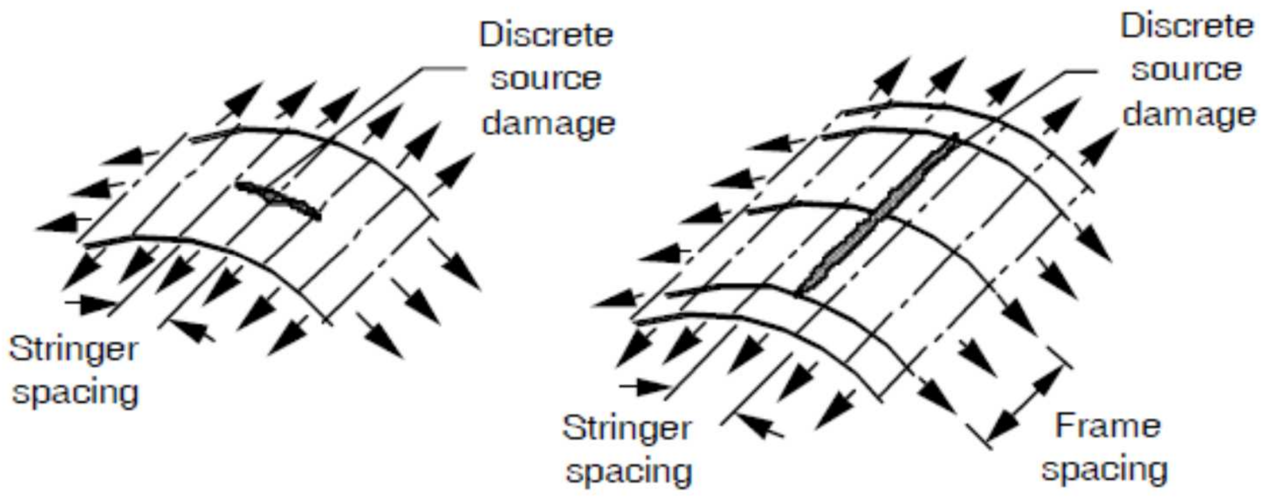
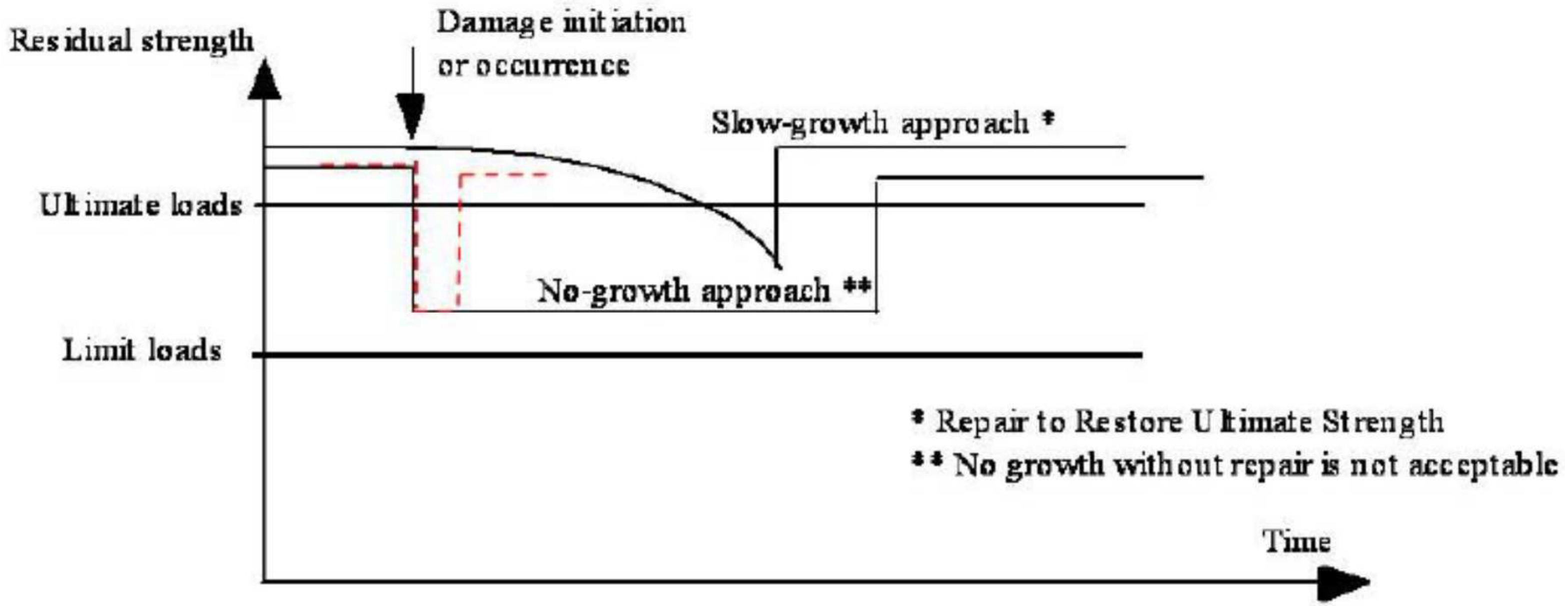


FIGURE 12.7.4.1(a) *Schematics of discrete source damage.*

Typically: no growth approach



------- Shows Acceptable Interval at reduced RS before being repaired (No-growth case).

——— Shows Unacceptable Interval at reduced RS before being repaired (No-growth case).

Figure 4 - Schematic diagram of residual strength illustrating that significant accidental damage with "no-growth" should not be left in the structure without repair for a long time.

Composite damage tolerant design

- Multiple load paths
- Backup and arrest features for bonded joints
- Avoid out of plane stresses on laminates and bonds (e.g. gradual stringer and ply drop-off)
- Sufficient bond lap width
- Material qualification. Manufacturing process: control quality of materials, parts and tools. Control tolerances to avoid build stresses.
- Lightning protection
- Design for maintenance: repair, access, detectability

Damage tolerance as a design strategy

- Below Level IV, composite damage tolerance is an option.
- Damage tolerance may be introduced at early design stages for favourable reliability/cost.
- Damage tolerance for bonded joints: particularly effective risk mitigation.
- Please see CM-S-006 Iss 1, Composite light aircraft, for additional considerations

Typical test sequence CMH-17 transport

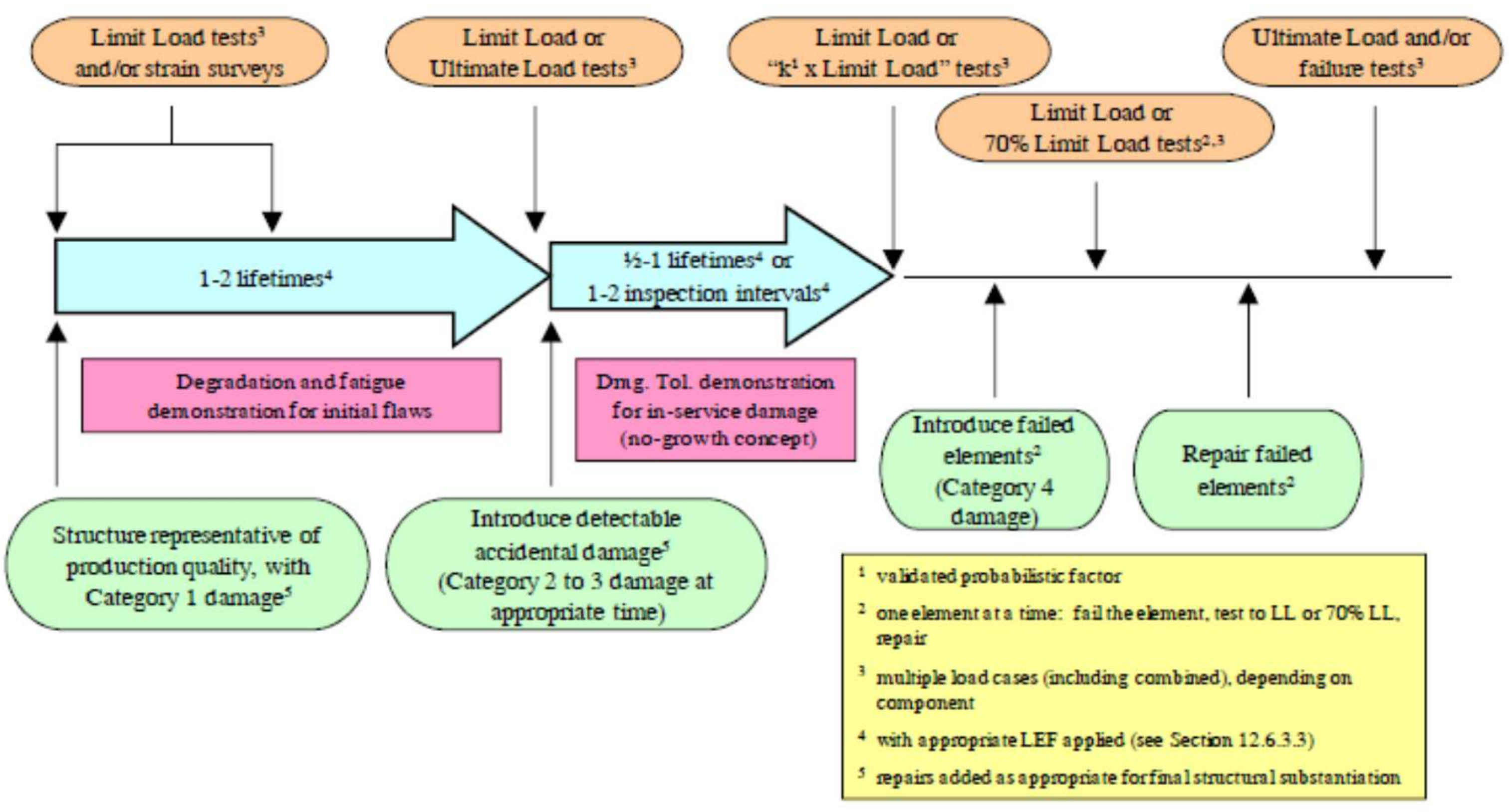


FIGURE 12.3.2.5(a) *Example 1 - Test sequence for full-scale transport aircraft, proof of structure test.*

- Material scatter: substantiated LEF and static overload

Threat assessment

- When using a visual inspection procedure, the likely impact damage at the threshold of reliable detection has been called barely visible impact damage (BVID).
- Substantiation of allowable damage without repair can be substantiated in the CAT1 phase

- Selection of impact sites : Similar to metal, based on experience, criticality and detectability.
- The size and shape of impactors should be consistent with likely impact damage scenarios that may go undetected for the life of an aircraft.

Cyclic loads and environmental exposure

- Environmental exposure: Temperature (fire zones, paint colour!), UV, humidity and contamination.
- Spectrum: Different truncation to metal. No clipping. Compression criticality.
- Environmental factors in full scale cyclic and static test. Derived from coupon campaign.
- Hybrid structure subjected to thermal cycling: analysis supported by lower level test.

Proof of structure for DT

- Residual strength demonstration generally "analysis supported by test".
- Repeated load reliability: generally demonstrated by test.
- Final static strength, F&DT substantiation may be through a single component test article if sufficient building block test evidence exists (typically less testing than for static strength)
- Smaller number of specimens with robust damage can be agreed for lower CS23 levels.

Inspections

- CAT2 and CAT3: An inspection programme should be developed consisting of frequency, extent, and methods of inspection for inclusion in the maintenance plan.
- Inspection intervals should consistent with the test.
- Reliable detection.
- The potential for missed inspections should be considered.
- Conditional inspections for CAT4 and CAT5
- Design for inspection
- Personnel awareness and training, no blame culture

F3115 §6. Bonded joints

- Limit load demonstration
  - Disbond between arrest features (preferred, consistent with CM-S-005 for repairs)
  - Test of each production article
  - Reliable inspection technique

- Specially sensitive to manufacturing quality.
- Disbonds difficult to detect

Bond degradation

- Poor bond quality may only manifest itself after environmental exposure.
- Sensitivity to peel stresses.
- Peel strength and environmental degradation:
- Wedge tests after humidity exposure

- See Laurent’s presentation on bonds.

Sandwich and co-cured structures

- Ref. Proposed CM-S-010 (Monocoque).
- Several significant incidents involving sandwich structures. Lack of arrest features.
- Many competing damage modes, e.g. ref. CMH-17 Volume 6, some not readily detectable, either visually or by NDI
- Failures in sandwich structures are often attributed to a combination of many factors, including deficiencies in design, production and/or continuing airworthiness
- Sensitive to impact. Water Ingress. Repair challenges

Metal: References used and recommended I/IV

- AMC to 25.571
- AMC 20-20
- AC 23-13A
- FAA DT Handbook DOT/FAA/CT-93/69
- “Fatigue of Structures and materials” By Jaap Schijve
- ESDU Series
- Combination of stress fields and cracks ESDU 78036

References used and recommended II/IV

- AFGROW DTD Handbook online
- HSB *Handbuch Struktur Berechnung* ch. 60000
- T. Swift FAA-AIR-90-01 " *Repairs to Damage Tolerant Aircraft*"
- NASGRO *Reference Manual*
- M. Niu "*Airframe Structural Design*"

Crack growth: Sources of material properties

- Material property accepted references:
  - Ar-mmpds
  - Walker coefficients from Chicago Paper
  - ESDU
  - Handbuch Struktur Berechnung Ch. 60000
  - ASM handbook
  - NASGRO/AFGROW database
- In principle not right to extrapolate properties to different materials, tempers or orientations.

Crack growth: References for beta

- Handbuch Struktur Berechnung Ch. 60000
- ESDU Intensity Factors
- NASGRO Manual
- Swift papers/courses

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Any questions?

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Non-destructive methods discussion

NONDESTRUCTIVE TESTING METHODS APPLICATIONS, ADVANTAGES, AND DISADVANTAGES

TYPE OF METHOD EMPLOYED	APPLICATION	ADVANTAGES	DISADVANTAGES
VISUAL OPTICAL	DETECTION OF SURFACE DEFECTS OR STRUCTURAL DAMAGE IN ALL MATERIALS	SIMPLE TO USE IN AREAS WHERE OTHER METHODS ARE IMPRACTICAL. OPTICAL AIDS FURTHER ENHANCE THIS METHOD	RELIABILITY DEPENDS UPON THE ABILITY AND EXPERIENCE OF THE USER. ACCESSIBILITY REQUIRED FOR DIRECT VISIBILITY OR BORESCOPE
PENETRANT	DETECTION OF SURFACE CRACKS IN ALL METALS, CASTINGS, FORGINGS, MACHINED PARTS, WELDMENTS	SIMPLE TO USE. ACCURATE, FAST, EASY TO INTERPRET	DEFECT MUST BE OPEN TO SURFACE AND ACCESSIBLE TO OPERATOR. DEFECT MAY BE COVERED BY SMEARED METAL. PART MUST BE CLEANED BEFORE AND AFTER CHECK
HIGH-FREQUENCY EDDY CURRENT	DETECTION OF SURFACE CRACKS IN METALLIC SURFACES, CRACKS, PITS, INTERGRANULAR CORROSION, AND HEAT TREAT CONDITION. CONDUCTIVITY FOR MEASUREMENT FOR DETERMINING FIRE-DAMAGED AREA	USEFUL FOR CHECKING ATTACHMENT HOLES FOR CRACKS NOT DETECTABLE BY VISUAL OR PENETRANT METHODS. FAST, SENSITIVE, PORTABLE	TRAINED OPERATOR REQUIRED. SENSITIVE COMBINATIONS AND VARIATIONS IN MATERIAL. SPECIAL PROBES REQUIRED FOR EACH APPLICATION. REFERENCE STANDARDS REQUIRED
LOW-FREQUENCY EDDY CURRENT	DETECTION OF SUBSURFACE DEFECTS IN METALLIC MATERIALS, CORROSION THINNING, AND SPACING	USEFUL FOR CHECKING FOR CRACKS WITHOUT REMOVAL OF FASTENERS OR DISASSEMBLY OF SUBSTRUCTURE	TRAINED OPERATOR REQUIRED. LARGER PROBES NEEDED FOR LOWER FREQUENCY USAGE. SPECIAL PROBES REQUIRED FOR EACH APPLICATION. REFERENCE STANDARDS REQUIRED
SONIC	DETECTION OF DELAMINATIONS, DEBONDS, VOIDS, AND CRUSHED CORE IN COMPOSITE AND HONEYCOMB MATERIALS	CAN BE ACCOMPLISHED FROM ONE SURFACE. DIRECT READING. DOES NOT REQUIRE PAINT REMOVAL OR SPECIAL SURFACE PREPARATION	LOSES SENSITIVITY WITH INCREASING MATERIAL THICKNESS. ELECTRICAL SOURCE REQUIRED
X-RAY	DETECTION OF INTERNAL FLAWS AND DEFECTS SUCH AS CRACKS, CORROSION, INCLUSIONS, AND THICKNESS VARIATIONS	ELIMINATES MANY DISASSEMBLY REQUIREMENTS. HAS HIGH SENSITIVITY AND PROVIDES A PERMANENT RECORD ON FILM	RADIATION HAZARD. TRAINED OPERATORS AND FILM PROCESSING EQUIPMENT REQUIRED. CRACK PLANE MUST BE NEARLY PARALLEL TO X-RAY BEAM TO BE DETECTED. ELECTRICAL SOURCE REQUIRED. SPECIAL EQUIPMENT REQUIRED TO POSITION X-RAY TUBE AND FILM
MAGNETIC PARTICLE	DETECTION OF SURFACE OR NEAR-SURFACE DEFECTS IN FERROMAGNETIC MATERIALS OF ANY SHAPE OR HEAT TREAT CONDITION	SIMPLE IN PRINCIPLE, EASY, PORTABLE, FAST. METHOD IS POSITIVE	TRAINED OPERATOR REQUIRED. PARTS MUST BE CLEANED BEFORE AND DEMAGNETIZED AFTER CHECK. MAGNETIC FLUX MUST BE NORMAL TO PLANE OF DEFECT TO YIELD INDICATIONS
ULTRASONIC	DETECTION OF SURFACE AND SUBSURFACE DEFECTS, CRACKS, DEBONDS, LAMINAR FLAWS, AND THICKNESS GAUGING IN MOST METALS BY PULSE ECHO TECHNIQUES	FAST, DEPENDABLE, EASY TO OPERATE. RESULTS ARE IMMEDIATELY KNOWN. HIGHLY ACCURATE, HIGH SENSITIVITY, AND PORTABLE	TRAINED OPERATOR REQUIRED. ELECTRICAL SOURCE REQUIRED. CRACK PLANE ORIENTATION MUST BE KNOWN TO SELECT WAVE MODE TO BE USED. TEST STANDARDS REQUIRED TO ESTABLISH INSTRUMENT SENSITIVITY

METHOD	STRUCTURE	DAMAGE DETECTED	RELIABILITY
Visual	All	Surface damage	Good
Tap test	Thin laminate	Delaminations near surface	Good
	Thin face sheet	Lack of bond	Good
		Disbond near surface	Good
		Voids	Very Poor
		Blown core (core damage)	Poor
		Lack of tie-in at closure	Good
		Lack of tie-in at core splice	Poor
Ultrasonics	All	Delaminations	Good
		Lack of bond	Good
	Sandwich	Crushed core	Poor
		Blown core (core damage)	Poor
		Water in core	Poor
Radiography	All	Disbonds/delaminations	Poor
		Delaminations in corners	Good
	Sandwich	Node separation	Good
		Crushed core	Good
		Blown core (core damage)	Good
		Water in core	Good
Shearography	All	Disbonds/delaminations	Good
Thermography	All	Disbonds/delaminations	Good
	Sandwich	Water in core	Good