Fatigue and Damage Tolerance in Airframe Structures

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Who Am I?

- Benno Vos (Netherlands)
- Employed by Fokker Aircraft from mid 1992 till receivership in March 1996
  - Fokker F27 Mk 050 & 060 on Fatigue & DT certification
- Employed by Fokker Aerostructures 1997 – 2007
  - Airbus A340-500 / -600 “Pressure Bulkhead” Fatigue design & certification
  - NH90 cabin sliding doors, tail and LG Fatigue Qualification
- Been NZ Resident since 2007, working for Flight Structures (Ardmore), now NTech to this date

Objective

- Provide a concise awareness of fatigue requirements and fundamental principles.
- Propose a 2 – 3 day course on F&DT and gauge interest for this
  - Me: Rules, Regs and compliance, and practical tools with the focus on compliance for NZ approved modifications and repairs.
  - LexTech (AFGROW developer): software usage

Significance in airframe structures

Aircraft crashes in the past related to fatigue

- Comet
  - 3 fatal crashes between 1953 – 1954
    - Fatigue cracking at fuselage cutout
- B737 Aloha 1988

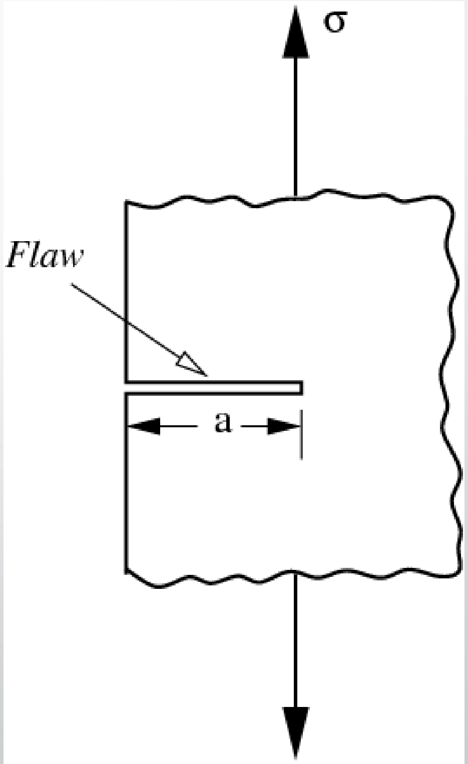
  - Upper fuselage shell broke off
- B747 El-Al AMS 1992
  - Engine mount failure, caused both RH engines to disconnect during flight, damaging hydraulic systems and crash with cargo and fuel on apartment building.

What is metal fatigue?

- Structural failure resulting from repetitive loading below its static strength.
  - Caused by cracking (= intrinsic material property)
  - Repetitive loading occurrences at $10^3 - 10^7$ (or more).
- Fatigue life prediction methods of metallic structure:
  - Fatigue crack initiation: Kt and SN data (crack to come into being)
  - Fatigue crack propagation: crack size, K, Kc, da/dN data (from initial to end size)
    - Do not confuse these two!

What is Damage Tolerance?

- The capability of structure to adequately sustain loads while it does contain damage.
  - Fatigue cracking
  - Corrosive spots
  - Initial defects (surface scratches, flaws, manufacturing defects)
- Damage is to be found and fixed before it becomes critical:
  - Inspectability = key.
  - “Critical Damage” is the damage size at which load of certain magnitude can be sustained without failure.
    - This is “Residual Strength”



Implementation

… for Fatigue:

- Ensure adequate fatigue life to exceed service / retirement life
  - i.e. keep stresses during typical operations well below fatigue limits, by assuming pristine structure.
  - This is the classic fatigue approach and referred to as "Safe Life".

… for Damage Tolerance:

- Inspectability of structure for detecting damage before it becomes critical
  - i.e. assume any mode if damage present at day-1 (non-pristine) and develop inspection regime.
  - Techniques for detecting damage: visual, dye penetrant / fluorescent, Eddy Current, Magnetic particle
  - Depends on accessibility of primary structure
    - Inspection provisions required by FAR 2X.611, Airworthiness Limitations section in ICA lists inspection thresholds and repetitives by FAR 2X.1529

Implementation

For OEM of transport category fixed wing (FAR 25):

- Primary structure of aircraft must be setup in a test rig and be subject to at least 2 x simulated full aircraft service life.
  - Test article is bare primary structure, no interiors or fairings.
  - Test article must must be ahead of the 'flight leader'.
  - Article is full of artificial damages, where it is assumed to propagate.

Fatigue testing in transport cat. fixed wing

A380: Fatigue Tested in Dresden (Germany)

- Initial certification clearance: 5000 simulated flights
- Completion: 19000 x 2.5 = 47500 simulated flights

Fatigue testing in transport cat. fixed wing

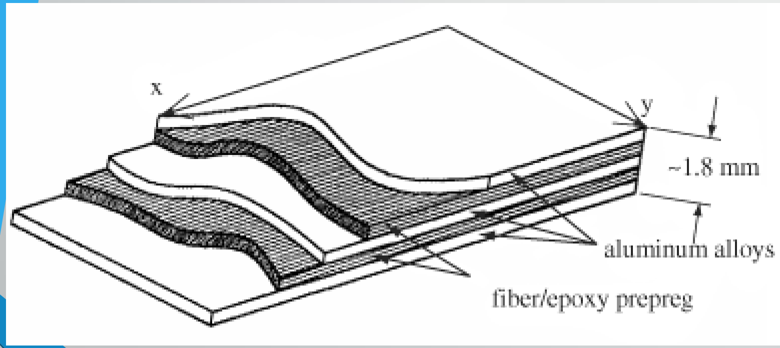
- This is where poor fatigue design comes to the surface (always do).
  - Fokker 100:
    - 'Hernia' (fuselage centre section literally broke in two, poor stringer design from one section to the other).
    - Stabiliser hinge lugs cracking from main frame (due to thrust reverser wake).
    - Longitudinal crack over full fuselage length.
  - Many retrofits and service bulletins
  - In service since 1985, certified to 90.000 flights in 1994.

Composite Damage Tolerance

Composite structures:

- Include voids and imperfections in your test article (in solid laminates)
  - Inspectability and repairs are next to impossible,
  - so show ultimate load strength after 2 full service lives.

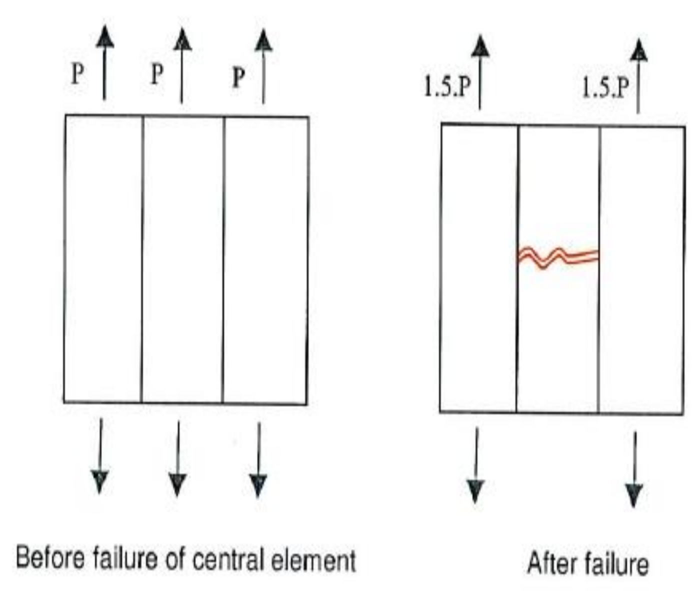
Fibre metal laminates (GLARE)



- "GLAss-REinforced" Fibre Metal Laminate
- Designed to sustain damage and intrinsically superior crack arresting.
- No crack inspections necessary (= selling point of Fokker to use GLARE on A380).
- Design allowables are therefore based on crack fatigued test specimen.

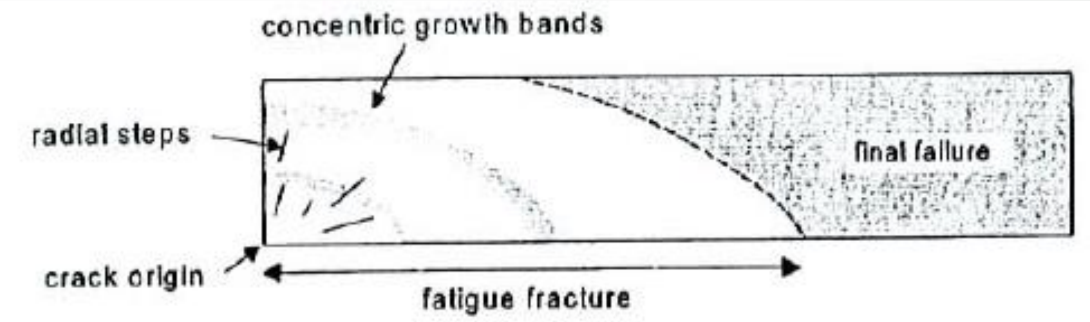
Design Principles

- <u>Safe Life</u> (classic principle, pristine material, not damage tolerant)
- **<u>Fail Safe</u>** (multiple loadpath) principle:
  - Secondary loadpath takes over when primary path has failed.
    - If load paths are <u>visually accessible</u> and primary failure is obvious for the operator:
      - Showing adequate static strength for secondary path is adequate
    - If load paths are <u>*not* visually accessible</u>:
      - Fatigue calcs are necessary for determining inspection regime.
      - Inspection interval of the centre element is calculated by the lowest of the fatigue lives / crack prop lives of the two side ones at **1.5 P**.



Design Principles

- Single Load Path Damage Tolerant '<u>Slow Crack Growth</u>'
  - Single load member that can sustain cracking without failure.
    - Crack propagation analysis
    - Residual strength criterion: Usually net section yield at limit load.



Fundamental differences between fixed wing / rotary

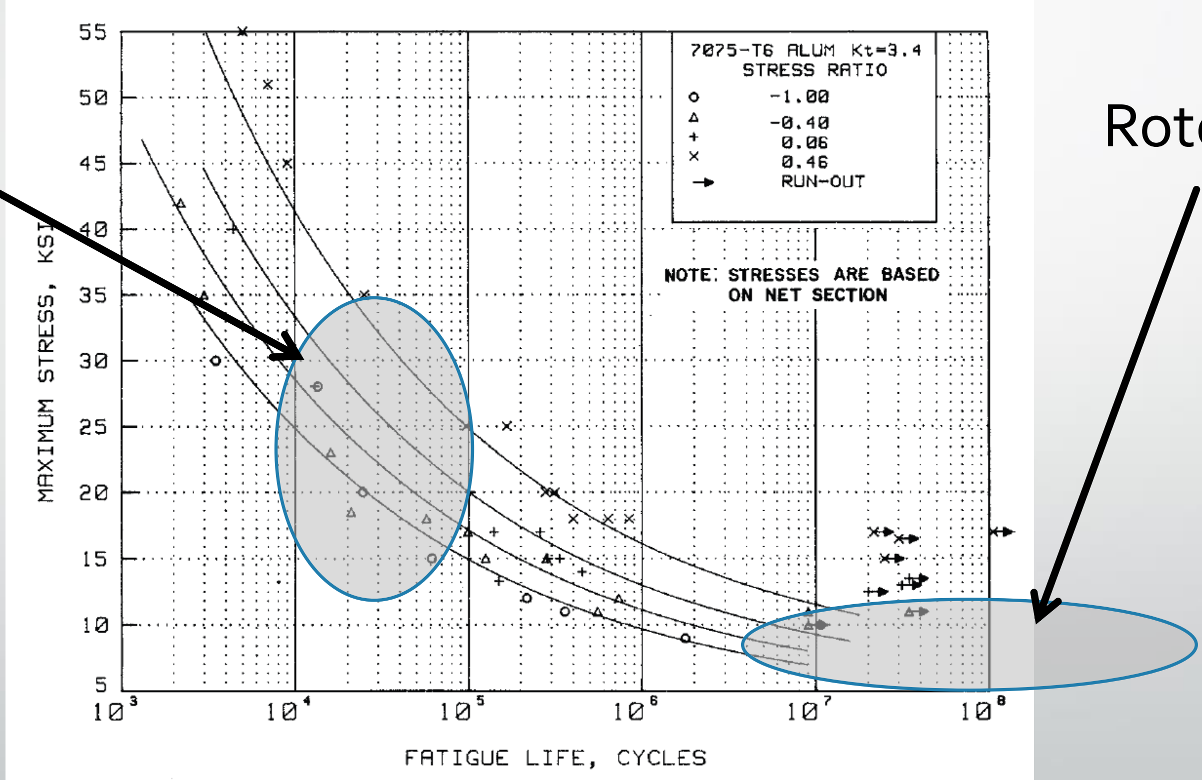
- Loads phenomena Fixed Wing
  - Gusts & Manoeuvres
  - Taxiing (bumps) & ground turning
  - Landing impact
  - Engine runups
  - Braking
  - Thrust reversing
  - Towing
  - Cabin pressurization
  - Expressed in number of flight cycles
- All are reasonably predictable

- Loads phenomena Rotary
  - Aerodynamic interactions between main & tail rotors
  - Rotor CG imbalances
  - Gear tooth harmonics (Rotor RPM)
  - Airspeed
  - Blade angles
  - Ground-air-ground cycles (mainly from idle to hover)
  - Expressed in cycles per hour
- To be measured in flight-strain program

Fundamental Differences between fixed wing / rotary

Fixed Wing

Rotorcraft



Rules & Regs

- FAR 23
- FAR 25 (and FAR26)
- FAR 27
- FAR29

FAR 23 (Normal & Commuter Airplanes)

Main Rules:

- FAR 23.627: Fatigue Strength (design as far as practicable to avoid Kt, originates from CAR 3.307).
- FAR 23.613(d): Minimize the probability of catastrophic fatigue failure, particularly at points of Kt's.
- FAR 23.571: Pressurized cabin structure (since Amnd 0)
- FAR 23.572: Metallic wing and associated structure (Amnd 7 - 1969)
- FAR 23.573: Damage Tolerance & Fatigue Evaluation of Structure (Amnd 45 – 1993)
- FAR 23.574: Metallic Damage Tolerant & Fatigue Evaluation of Commuter category airplanes (Amnd 48 – 1996)
- FAR 23.575: Inspections & Other Procedures (Amnd 48 – 1996)
- FAR 23 Appendix G Sub G23.4: Airworthiness Limitations Section [in ICA] (Amnd 26 – 1980)

FAR 23 (cont'd)

Many rules, key:

- Pressurized Cabin (571) and Wing & empennage (572) to be shown either under fatigue, or fail safe
  - Fail safe with residual strength to 75% of limit loads, to be multiplied by 1.15 covering dynamic effects under static loads.
  - Rules have evolved by including the <u>option</u> for damage tolerance as per 573.
    - Which is however mandatory for operations above 41,000 feet for pressurized cabin.
- <u>Damage Tolerance</u> (573, since 1993)
  - Composites (for PSE's): DT is <u>mandatory</u>.
- Commuter Category Airplanes (574, since 1996): DT has preference over fatigue (safe life), unless shown to be impractical.
- Inspections (575): requires publishing all structural inspections from fatigue & DT into the ICA.

FAR 25 (Transport Category Airplanes)

- FAR 25.571: Fatigue evaluation of flight structure
  - Demonstrate either safe life *or* fail safe (since 1965 from CAR 4b.270).
  - Sonic fatigue for engine mounts since amendment 10.
- Amendment 45 (1978): added 'Damage Tolerance'.
  - Damage Tolerant / Fail safe, or
  - Safe Life if damage tolerance is shown impractical.
  - "Discrete source damage" evaluation: bird impact / engine or propeller failure
- Many amendments, latest amendment 132 has come into force at January 2011.
  - Mainly changes to residual strength criteria (loads versus occidental damage).
  - Limit Of Validity (LOV) is introduced, which is the maximum number of flight cycles to which data remains valid (based on Widespread Fatigue Damage), to be listed in ICA document.

FAR 25 & and FAR 26

- *Removed* from FAR 25:
  - FAR 25.613(d): removed at amendment 112 (2003), now considered adequately under 571, so **still effective on many NZ aircraft under grandfather's**.
  - FAR 25.573: Fatigue evaluation of Landing Gear
    - Effective from 1965, removed at amendment 45 (1978), covered by 571 being the general rule.
- *Added* FAR 26: Continued airworthiness and safety improvements for transport category airplanes
  - Adds Widespread Fatigue Damage to (then) existing requirements from FAR 25.571.
  - Applicable to Aging Aircraft (pre Amendment 45, i.e. non-damage tolerant)
    - OEM is to address continued airworthiness from a DT point of view.
    - By supplying methods to operators to derive inspection regimes from SRM repairs or alterations, based damage tolerance principles.

FAR 27 (Normal Category Rotorcraft)

- FAR 27.571: Fatigue evaluation of flight structure (effective since 1968, Amnd 3), to be either:
    - Fatigue tolerance (safe fatigue life to exceed service life), or
    - Replacement time (safe fatigue life to exceed replacement furnished in ICA), or
    - Failsafe, or
    - A combination of the above.
  - All must include in-flight measurements of loads / stresses of all critical conditions.
- Amendments 12, 18, 26:
  - Redefines "flight structure", references to Appendix A (ICA), adds external cargo ops and ground-air-ground cycles.

FAR 27 – Damage Tolerance?

- FAR 27.573: Damage Tolerance and Fatigue Evaluation of Composite Rotorcraft Structures (new rule since 2012)
  - Requires fatigue evaluation and residual strength using damage tolerance principles, unless shown to be impractical (by showing no-growth principle).
  - Addresses minimal growth under low cycle fatigue and potentially severe accidental damage, as well as process variables (manufacturing defects) and environmental effects.
- FAR 29.573 has been effective as well.
- No damage tolerance requirement for Metallic Structures!

FAR 29 (Transport Category Rotorcraft)

- FAR 29.571 Fatigue evaluation of flight structure (effective since 1968, Amnd 4)
  - Similar to FAR 27.571
- Amendment 28 (1989) rewrites Fatigue Tolerance, by either;
  - Flaw tolerance safe life: essentially fatigue life from flawed notches
  - Fail Safe,
  - Safe Life evaluation: (classic) fatigue life.
- Amendment 55: Added "Metallic" in title (2012), but no "Damage Tolerance"
  - Complete rewrite, abandons classical terms and leaves a level of freedom as to which method is used to demonstrate compliance – it's a bit vague.
  - The Final Rule Making makes a specific comment <u>not</u> to rely on inspection intervals derived from Crack Growth (as in fixed wing), in lieu of inspections and retirement lives.

Proposed Course program

- Shared by LexTech (AFGROW developer) and myself
  - 2 – 3 days, ballpark 1.5k – 2k per participant
  - Venue: Auckland area
- Me:
  - Elaborate into Rules, Regs and AC's
  - Fatigue Initiation Principles
    - Loads phenomena, Statistical Data, Damage accumulation, Miner's rule and Rainflow
    - SN-Curves, Kt, fatigue damage, Scatter
    - Practical how-to's
- LexTech:
  - Principals on LEFM and AFGROW
  - How to program SN-Curves in AFGROW
  - How to run a practical quick run for demonstrating compliance

Thank you

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