Aircraft structures
–
Certification

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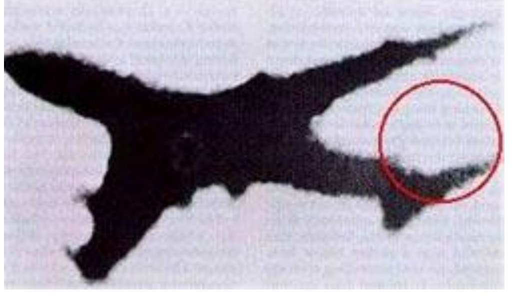
Introduction

- Purpose of certification for airliners
  - To guarantee the safety of people who are
    - Transported
    - Flown over
  - To achieve an acceptable safety risk
    - Target: 10^{-7} fatal accidents per flight hour

- Actual risk
  - < 10^{-6} / flight hour (higher for rotorcrafts or private aircrafts)
  - Equivalent to one fatality for +/- 3 300 millions of seat-kilometers
  - One of the most safe transportation mean
  - Other transportation means (1998)
    - Bus: 1.3 times higher
    - Train: 3.3 times higher
    - Car: 13.3 times higher
    - Motorbike: 323.3 times higher

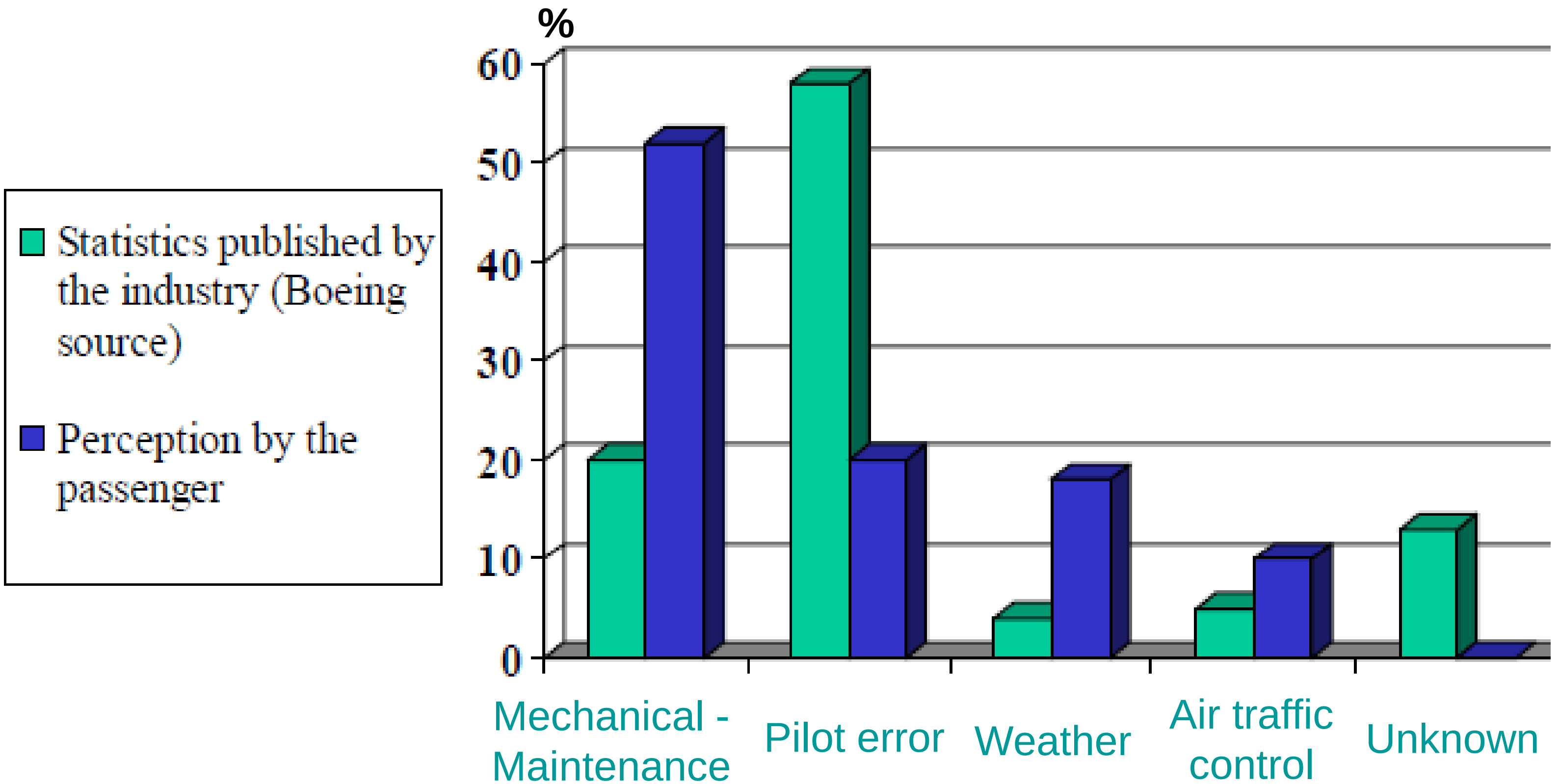
Royal society for the prevention of accidents (UK, 1998)

- Aircraft crashes - Examples
  - Tenerife disaster – 2 B747's collision (1977)
    - 583 causalities
    - Cause: **pilot error** from the 1st plane who misunderstood clearance for take off + dense fog. This plane attempted to take off and collided with a 2nd taxiing plane.
  - B747 - Japan Airlines Flight 123 (1985)
    - 520 people died
    - Cause: **improper aft pressure bulkhead repair** caused explosive decompression and the lost of the vertical stabilizer and of all hydraulic lines. The plane became incontrollable and crashed on a mountain.



  - A320 - US Airways Flight 1549 (2009)
    - 0 victims
    - Cause: **bird strike** just after take off resulted in a lost of both engines.
    - The plane could successfully ditch in the Hudson river

- Main causes of accident:



Journal of transport management, N°6, 2000

- How to achieve the safety risk objective ?
  - Create airworthiness codes (regulation) that ensure and control:
    - **The quality of the aircraft:**
      - **Certification (consists in validating the operational domain in which we operate safely for its entire lifespan)**
      - **Maintenance during its whole life**
    - Safe operating conditions (not covered here):
      - Crew qualification/formation
      - Air traffic rules
      - Airport facilities
      - Operating conditions and limits (bad weather,…)

- Regulation and specifications are a compromise between:
  - Technical feasibility (depends on technology)
  - Economic feasibility (how much can we pay to afford it)
  - Human expectations (zero accident)

Airworthiness standards

- Airworthiness authorities:
  - Prepare further standards, regulate, check, approve, control and sanction
  - Existing organisations:
    - Minimum requirements imposed by the International Civil Aviation Organisation (ICAO)
    - In Europe: European Aviation Safety Agency (EASA) publishes the Certification Specifications (CS)
    - In US: Federal Aviation Administration (FAA) prepares the Federal Aviation Regulations (FAR)
- Airworthiness standards (= CS xx):
  - Depend on the type of aircraft
    - From very light aeroplanes (UAV,…) to large aeroplanes, sailplanes, rotorcraft,…
    - Example: CS 25 for civil transport aircrafts
  - Content:
    - Rules related to the flight, structure, design, material qualification, equipment, operating limits, maintenance and repair, testing,…

Airworthiness standards

- Certification steps
  - Application letter incorporating preliminary data (drawing, basic data, performances,…) by the manufacturer
  - Definition of the “Certification Basis” by the Airworthiness Authorities.
    - Including special conditions for unusual/novel or reputed unsafe design
  - Demonstration of the compliance by the manufacturer

  ➔ Acceptance by “type certificate”

- Two different kinds of certificates needed
  - “Type” certificate:

    covers all aircrafts of pre-defined types (applied by the manufacturer)
  - Certificate of airworthiness:

    relates to each individual aircraft, effective over a prescribed period of time, provided if maintenance is properly performed (applied by the owner)

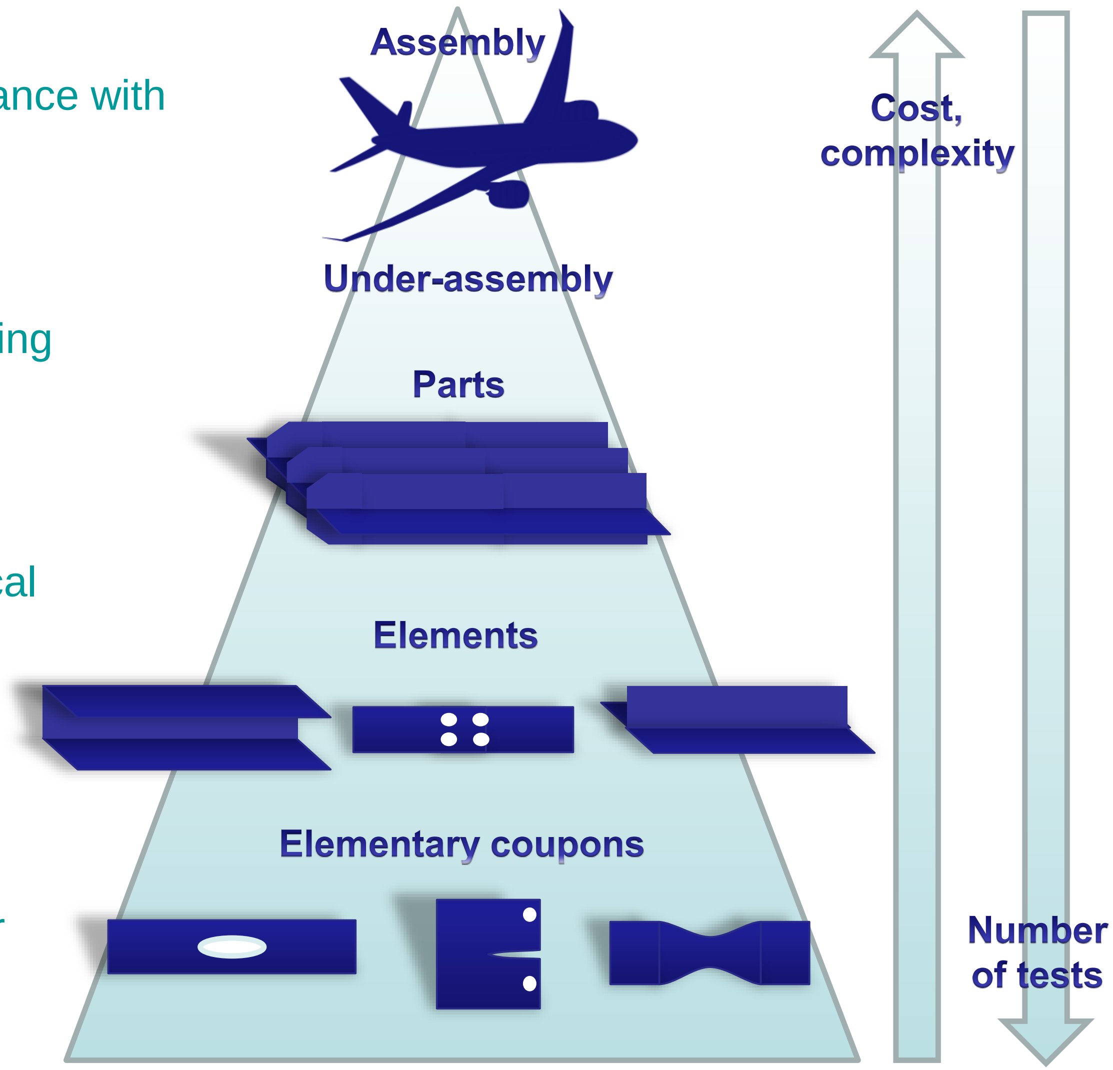
- Major types of requirements concerning the aircraft that have to be ensured:
  - Static strength
    - Resistance to an exceptional event (limit and ultimate loads caused by maneuvers, gusts,…)
  - Endurance – Fatigue/damage tolerant design
    - Capability to resist during its entire service life
  - Accidental hazards
    - Lightning strikes, bird impact, fast decompression, fire resistance,…
  - Others
    - Emergency landing, flutter, quality control,…
- Compliance to the requirements has to be proven by tests (and not only by calculations)
  - Expensive

- Flight tests:
  - Cruise and climb performances
  - Flutter tests:
    - Analyze of the vibratory behavior of the aircraft structure throughout the flight envelope. The structure has to be adequately damped in order to avoid flutter (=dangerous undamped vibration mode caused by aerodynamics/structural response coupling).
  - Vmu (Minimum Unstick Speed) test:
    - Validate the minimum take-off speed (at maximum achievable pitch angle)
  - Cold soak / hot and high test:
    - To prove full functionality of the aircraft under extreme weather conditions (at low temperature or at high temperature and altitude).
  - Autoland test:
    - Landing and roll-out operations with autopilot, in several conditions (poor visibility, wind,…)
  - Water ingestion test
  - Acoustic test (noise pollution)
  - Lightning strike test
  - …

- Structural tests:
  - Reaction of structure facing loads met during lifetime.
  - Performed on non-flyable airframes (for technical reasons) by hydraulic actuators
  - Many others tests already realised on smaller parts
  - Two kinds of tests are operated:
    - Static tests
      - Behaviour under normal and exceptional loads encountered during flight conditions:
        - » Limit-load campaign
        - » Ultimate load campaign
        - » Breaking point (has to occur at or beyond the predicted design load level)
    - Fatigue & damage tests
      - Structure response to repeated operational conditions over the lifetime (simulate a large number of cycles (taxiing, take-off, cruising and landing)).

Structural test on wings, *Boeing*

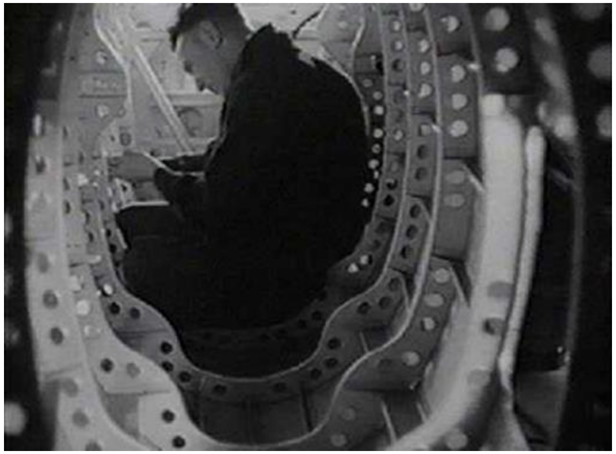
- Various test levels: the pyramid of tests
  - Whole /under-assembly
    - Final checking
    - Demonstration of compliance with CS requirements
  - Parts
    - Control of preliminary sizing
  - Elements
    - Evaluation of design properties for non-classical design or with low calculation accessibility
  - Elementary coupons
    - Evaluation of mechanical properties for classical design

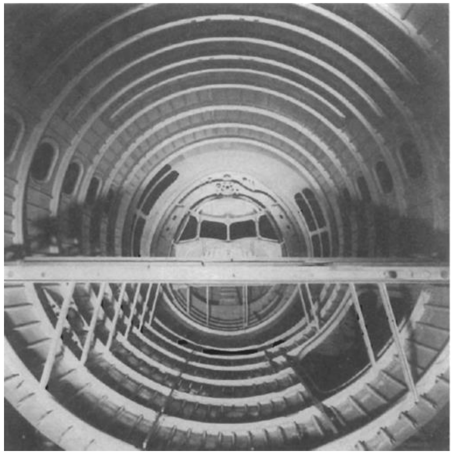


- Semi-monocoque structures
  - Monocoque structure are subject to buckling
  - The skin is usually reinforced by
    - Longitudinal stiffening members
    - Transverse frames

  fixed on it to resist to bending,

  compressive and torsional loads without buckling





➔ Which material should we choose ?

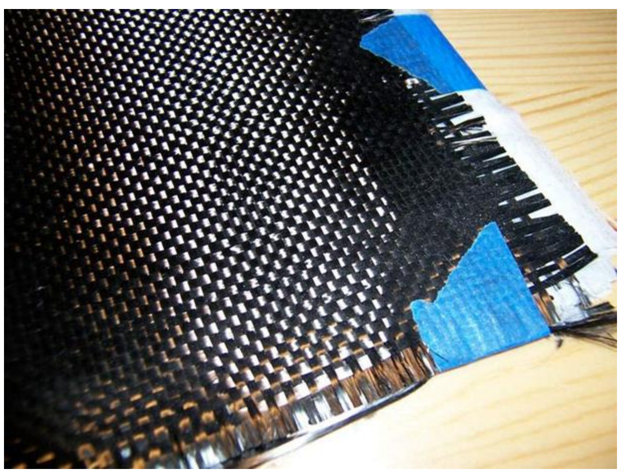
Material selection

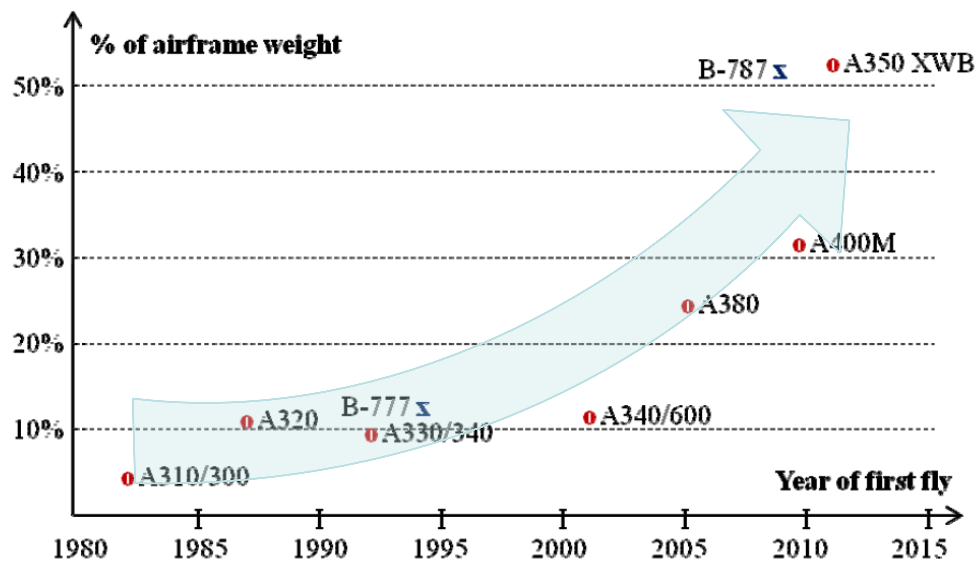
- Basic principles for airworthiness:
  - New technology must not lead to any reduction of the currently existing level of safety!
    - So, any new material has to be at least as safe as much as “classical” ones…

- Before introducing new materials, it has to be qualified (CS 25.603):
  - Demonstrate the minimum performances for the foreseen application
  - Prove the absence of any hazardous constituent, unexpected rogue behaviours and compliance with the environment (T°, humidity, insensitivity to service fluids)
  - Define a tolerance for material production key parameters and quality assurance (= how to verify this tolerance?)

Material selection

- Material for airliners needs to a high strength/weight ratio:
  - Aluminium alloy and other metals alloys (well-known behaviour)
  - More and more composite materials
    - Strong glass or carbon fibres in a plastic or epoxy resin
    - First introduced in the 80's to save weight
    - For new airliners, composite materials represent around 50% in weight (50% for B787, 53% for A350)

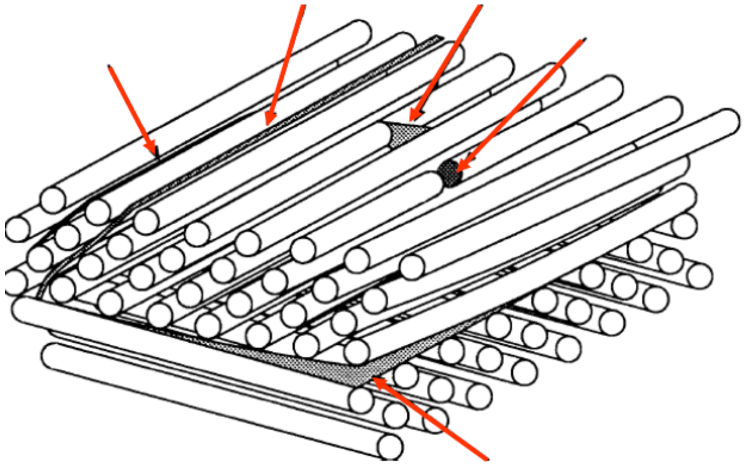




Composites uses in aircraft structures

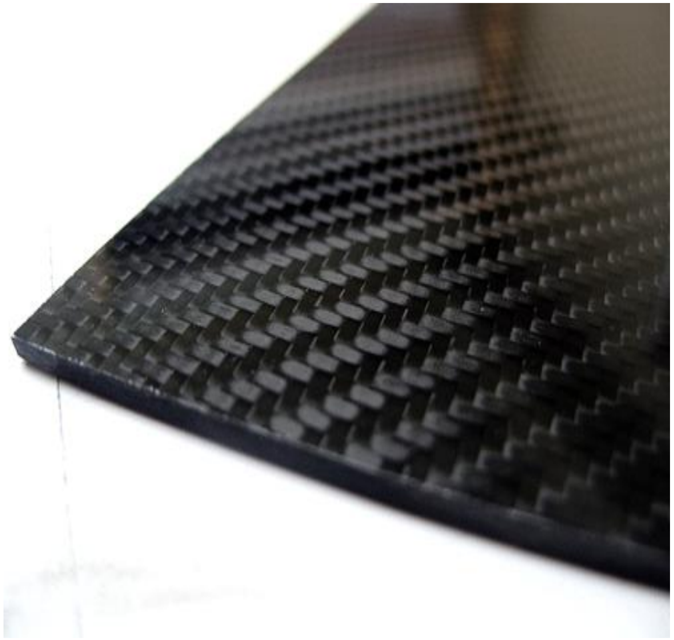
NLR-TP-2009-221

- What is different compared with metals ?
  - Anisotropic behavior
  - Scattered properties
  - Complex failure modes
    - Transverse/Longitudinal matrix fracture
    - Fiber rupture
    - Fiber debonding
    - Delamination
    - Macroscopically: no plastic deformation
  - Low accessibility to calculation
  - Laminated construction:
    - Low out-of-plane mechanical properties + low ductility = sensitive to accidental impact damage, resulting in abrupt failure
  - Degradation:
    - Modification of material properties under environmental effects (T° and humidity)
    - Not corrosion-sensitive



Material selection – composite materials

- What is different compared with metals ?
  - Less sensitivity to fatigue
    - No-growth (not a crack) approach can be used
  - The material is made at the same time as the structural component
    - High dependency to manufacturing process
    - Possible built-in defects from it (porosities, voids, delamination,…)
  - Lack of material standardisation
    - No authoritative system to compare equivalent materials
  - No electrical conductivity
    - Problems in case of electromagnetic aggressions or lightning strikes



Material selection – composite materials

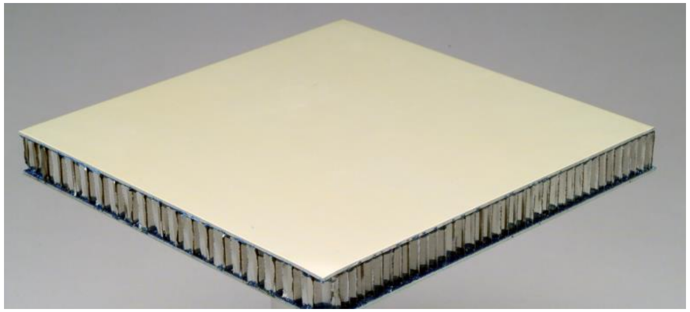
- In general, more tests are needed for composites than for metals:
  - Anisotropic material with various stacking sequences
  - Low accessibility to calculation
    - Need of design values for complex elementary geometries
  - More scattered mechanical properties
    - More test samples are needed to ensure result confidence
  - Environment-sensitivity
    - Various environmental conditions have to be tested
  - No material standardisation
    - At each application is associated a unique product from one manufacturer

3-point bending and compressive strength tests on composite coupons

  - Motivates the development of virtual certifications

Material selection - environmental effects

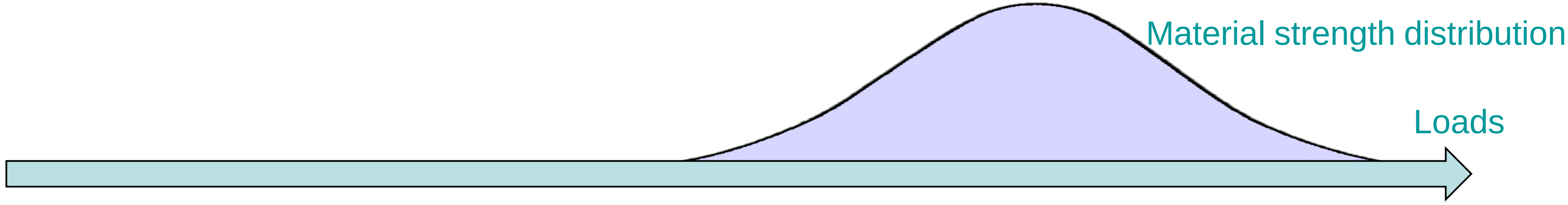
- Encountered conditions (temperature, humidity,…) acting on the structure mechanical properties have to be taken into account:
  - For composite laminates:
    - Moisture absorption and elevated temperatures decrease the matrix-governed strength properties (compression, shear, bearing,…) until +/- 15% in most adverse conditions. But it has low effect on its stiffness.
    - Reduction of the matrix glass transition temperature with moisture.
  - For sandwich structures:
    - Steam pressure or freezing volume expansion induced by infiltrated moisture in honeycomb core or by permeable structure



  - For metallic parts
    - Corrosion (critical in salty atmosphere), galvanic corrosion in contact with composite parts

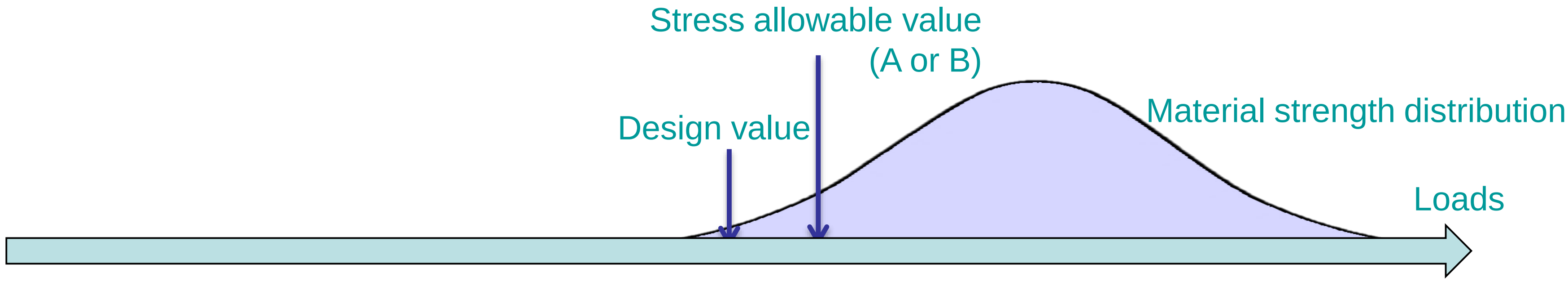
- Which material property values have to be used at the design stage ?
  - Based on tests
  - Expressed in terms of stress, strains, loads, lifetimes,…
  - Have to be chosen to minimise the risk of failure due to material variability
    - Including most adverse environmental effects
      - the environmental conditions applied on (accelerated ageing,…)

      Or,
      - a load/life enhancement factor
    - Considering material variability or material response to the manufacturing process
  - Depends on the redundancy of the component

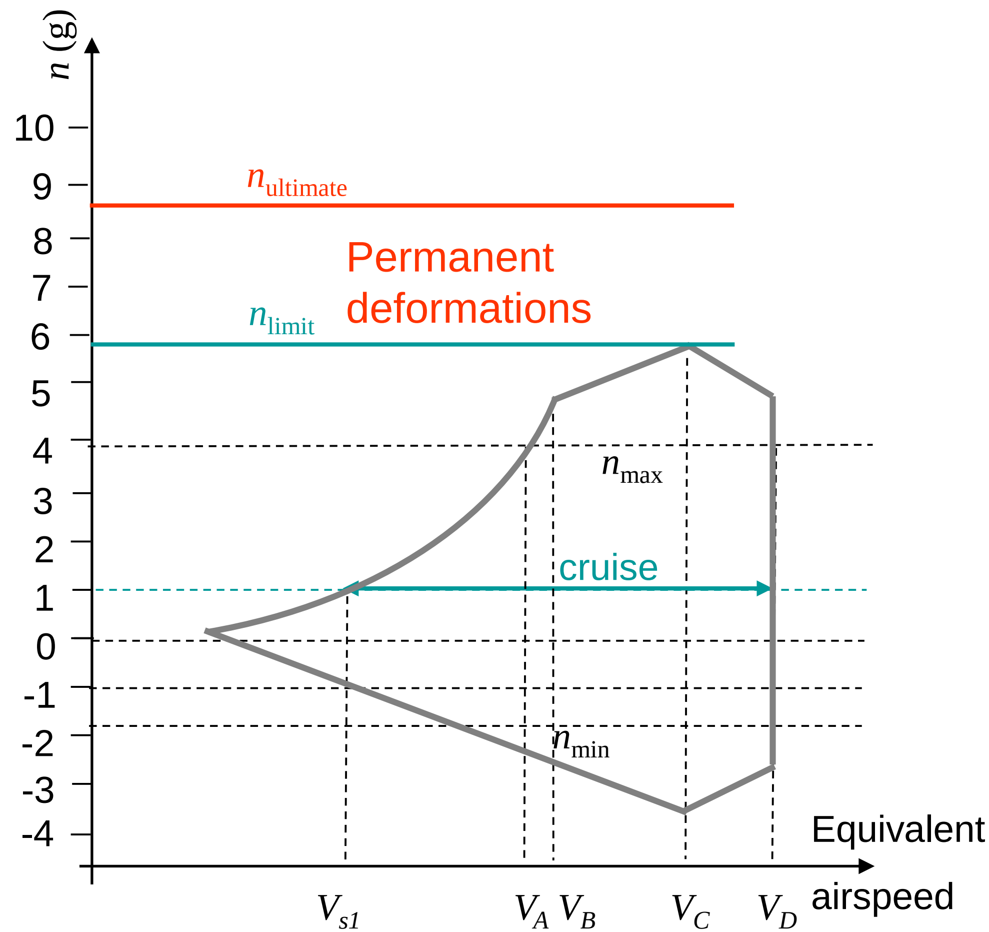


Allowable and design values

- Material properties (CS 25.613)
  - Allowable values
    - Chosen to minimize the risk of failure due to material variability with a high level of confidence (because the exact distribution is unknown)
    - Determined from test data on a statistical basis:
      - "A" values: 99% of probability to resist with a 95% of confidence
      - "B" values: 90% of probability to resist with a 95% of confidence for redundant components
  - Design values
    - Actually chosen values to design the components



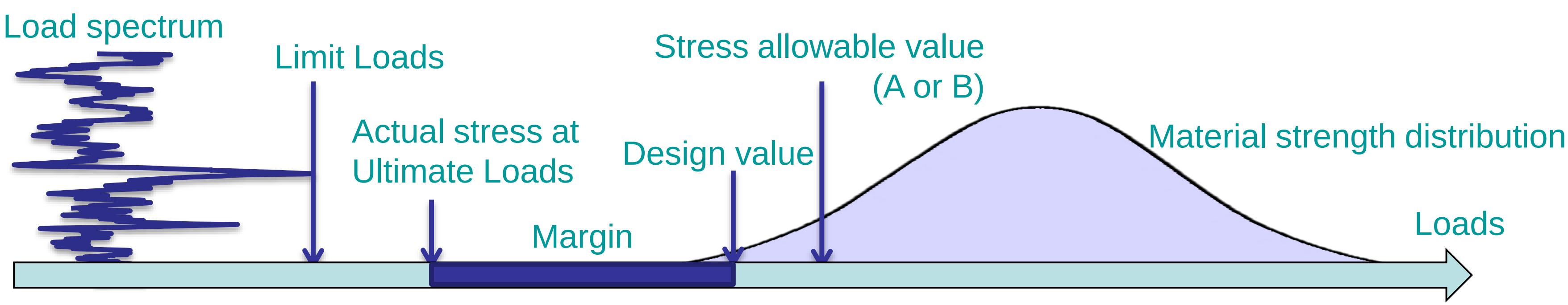
- Structures have to resist to the most critical loads that can be encountered during the life of the aircraft
- Design load factors (CS 25.303)
  - Limit load (LL) factor n_{limit}
    - Maximum expected load during service (from gust envelope, ground loads,…)
    - The plane cannot experience permanent deformations
  - Ultimate load (UL) factor n_{ultimate}
    - Limit load with a security factor from CS (1.5)
    - The plane can experience permanent deformations
    - The structure must be able to withstand the ultimate load for 3 seconds without failure



Allowable and design values

- Material properties (CS 25.613)
  - Load spectrum
    - Loads encountered by the airplane during its entire life
  - Limit loads (LL)
    - Maximum load encountered (see previous slide)
  - Ultimate loads (UL)
    - Limit load with a safety factor (see previous slide)
  - Margin
    - Difference between Design and Ultimate loads

  NB: fatigue, environmental effects and defects/damage have to be taken into account…



Fatigue & Damage tolerance requirements

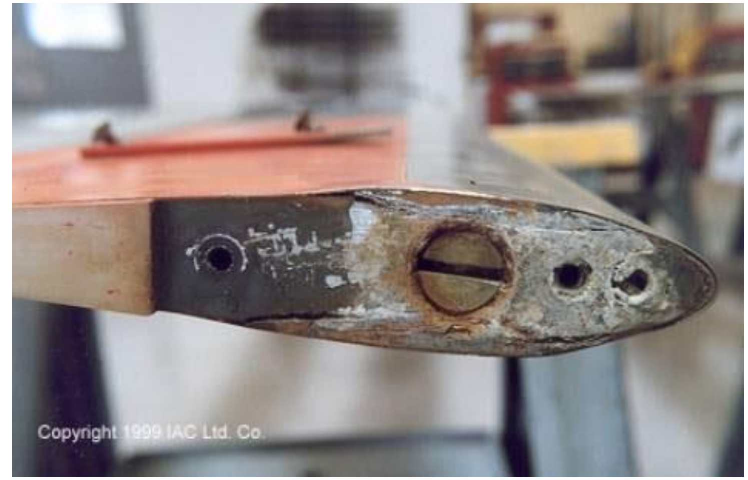
- Rules for fatigue and damage tolerance (CS 25.571):

  "An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane"

- So, in case of damage, catastrophic failure has to be avoided
  - The remaining structure must be able to resist to reasonable loads until damage is detected
  - It's has to be able to withstand "get home loads" in case of large damage in the structure
- Three main sources of damage:
  - Environmental (corrosion, ageing,…)
  - Fatigue (repeated loads under limit load levels)
  - Accidental occurrences (bird impacts, lightning strikes,…) or manufacture defects (present from the beginning)

Environmental effects

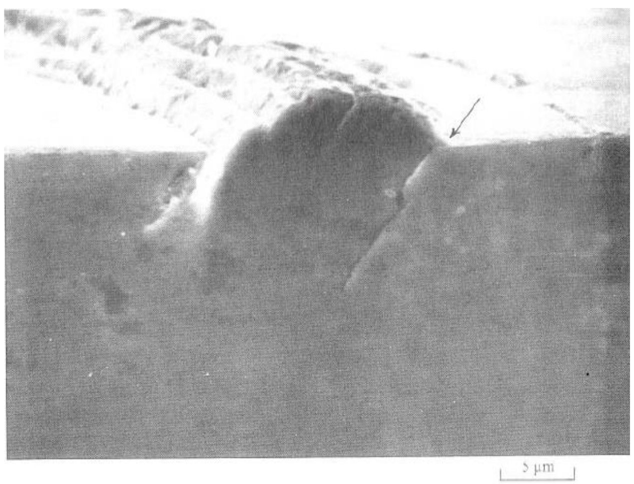
- Corrosion
  - Metals in contact with organic matrix of composites (or others metals) may rust by galvanic corrosion (but not the composites)
  - Design rules:
    - Use insulating materials in between

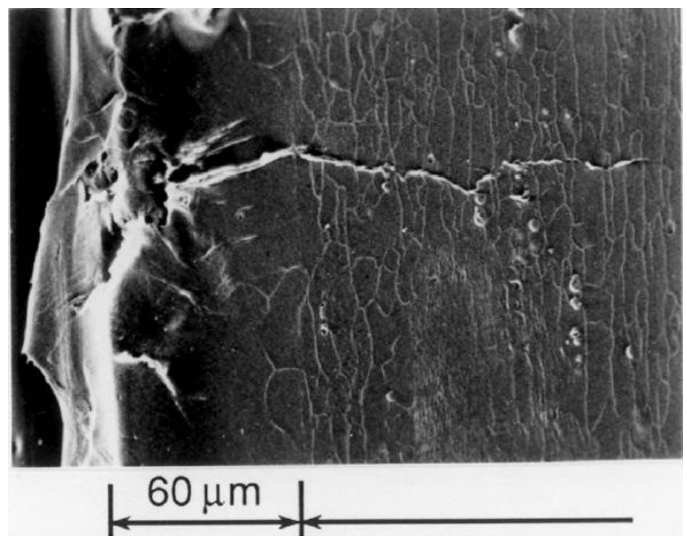


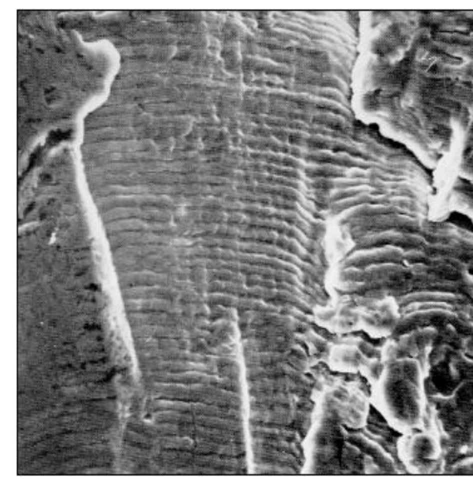
- Ageing (humidity)
  - Degradation of composite structures due to moisture
  - Design rules:
    - Take into account in design values with the most adverse conditions
    - Demonstrated fatigue with a representative amount of ageing in the structure
- Maintenance
  - Control of risk areas

Fatigue for metals

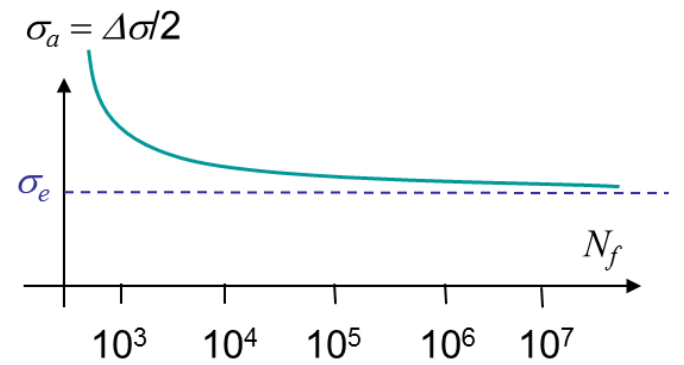
- Fatigue failure process:
  - Crack initiation
    - Cyclic plastic deformations and moving dislocations provoke crack nucleation
  - Crack propagation
    - Stable crack evolution depending on geometry, loads, frequency…
    - Growth prediction with Paris-Erdogan law
  - Final failure
    - Rapid crack growth until static failure (in traction or tearing)



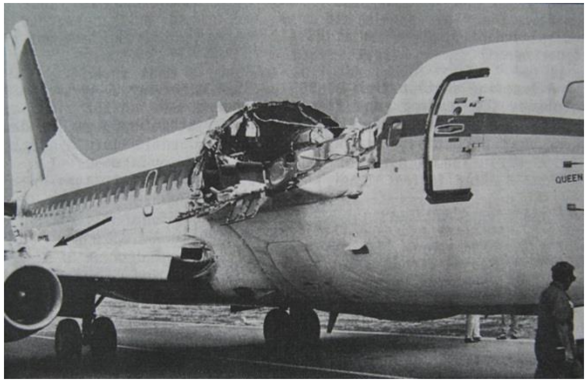




- Former fatigue design philosophies (for metals):
  - "Infinite-life design" (not used in aeronautics):
    - $\sigma_a < \sigma_e$: stress above infinite life stress
    - Too heavy and economically deficient
  - "Safe-life design":
    - At the end of the expected life, the component is changed even if no failure has occurred
    - Use of σ_a–N_f curves (stress life) + a safety factor



  - "Fail-safe design":
    - Even if an individual member of a component fails, there should be sufficient structural integrity to operate safely (various load paths)
    - Example: B737, Aloha Airlines - Flight 243, 1998



- "Damage tolerant design" (for metals):
  - Assume cracks or defects are present (coming from manufacturing, corrosion, fatigue, impact damage,…)
  - Characterize crack evolution and its effects on the structure:
    - Control crack sizes through regular inspections and estimate crack growth rates during service (e.g. via Paris-Erdogan law)
    - Plan conservative inspection intervals (e.g. every so many years, number of flights) to check crack growth
    - Remove or repair old structures from service before predicted end-of-life (fracture) or loss of sufficient load carrying capacity
  - Possible as fatigue of metals is stable and predictable process
- Testing approach:
  - Tests coupled with calculation analyzes

Fatigue for composites

- Fatigue failure process
  - Unlike metals (unique crack transverse to loadings), multiple damages appear parallel to the loading direction
    - Complex trans/intra-laminar cracks and fiber failures at lower scale
    - Stress intensity decreases as the damage increases
  - Failure mode
    - Fatigue induces unacceptable loss of stiffness
    - In compression: buckling bringing static failure
  - Difficult to detect some material degradation with Non-Destructive Testing (NDT) methods

Fatigue for composites

- In practice
  - Few fatigue issues
    - Operational load levels in composites are reduced as one have to limit the high sensitivity to stress raisers (holes …) for static loads
    - Thus loading are sufficiently low to avoid fatigue problems
  - Not expected for membrane loading without out-of-plane stress
  - Delamination is the main issue
- Delamination = encountered failure mode by fatigue:
  - Difficult to have reliable calculations despite continuous improvements
    - Scattered properties
    - Delaminated zones are exposed to environmental conditions (deterioration translaminar properties)
    - Unexpected defects from fabrication

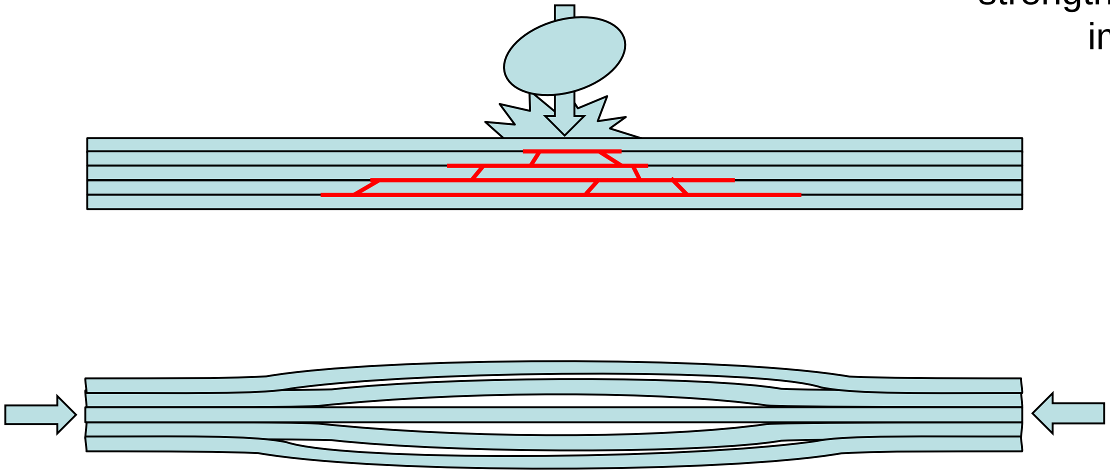
Delamination followed by failure in compression

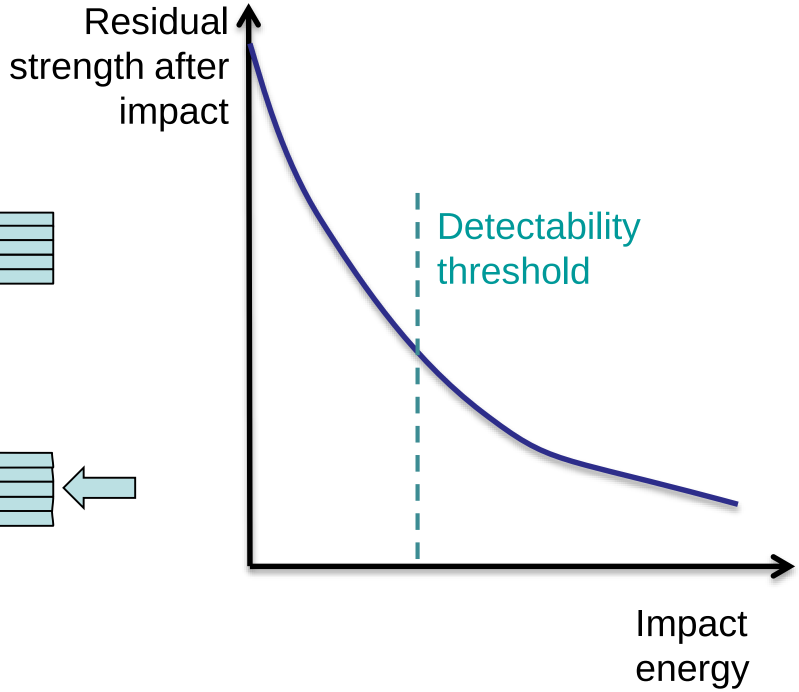
Fatigue for composites

- Design approach:
  - No-growth concept:
    - Maximum strain limited to proven values on similar design will not cause fatigue issues
    - Impossibility to use “slow growth” concept (delamination is generally unstable and growth rate calculation are not possible)
  - Suppress local out-of plane stress to avoid delamination
    - Suppress 3D or out-of plane stress
    - Limit edge effects (see lecture on composite structure failures)
- Testing approach:
  - Demonstration of a crack free life
  - Realised by safe life demonstration at full-scale with the whole structure and all interactions (because fatigue issues will rise in case of 3D stress)

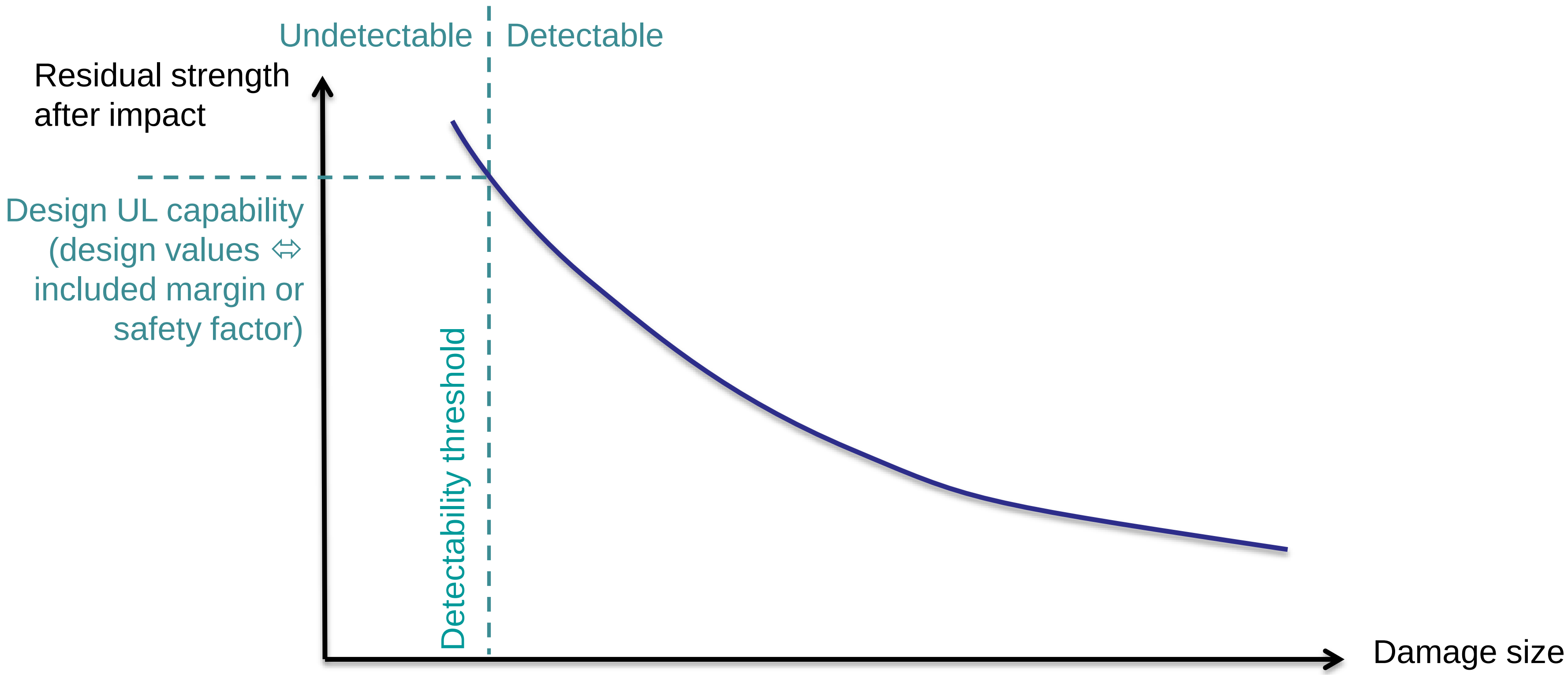
Impact damage

- Composite structures
  - Brittle behaviour + weaker out-of-plane properties = sensitive to low velocity impact
  - Damage not always easily detectable from external inspection
    - Important damaged volume but small dent on the surface
  - Large compressive strength reductions (less severe for tensile) due to delamination and to buckling before this becomes detectable

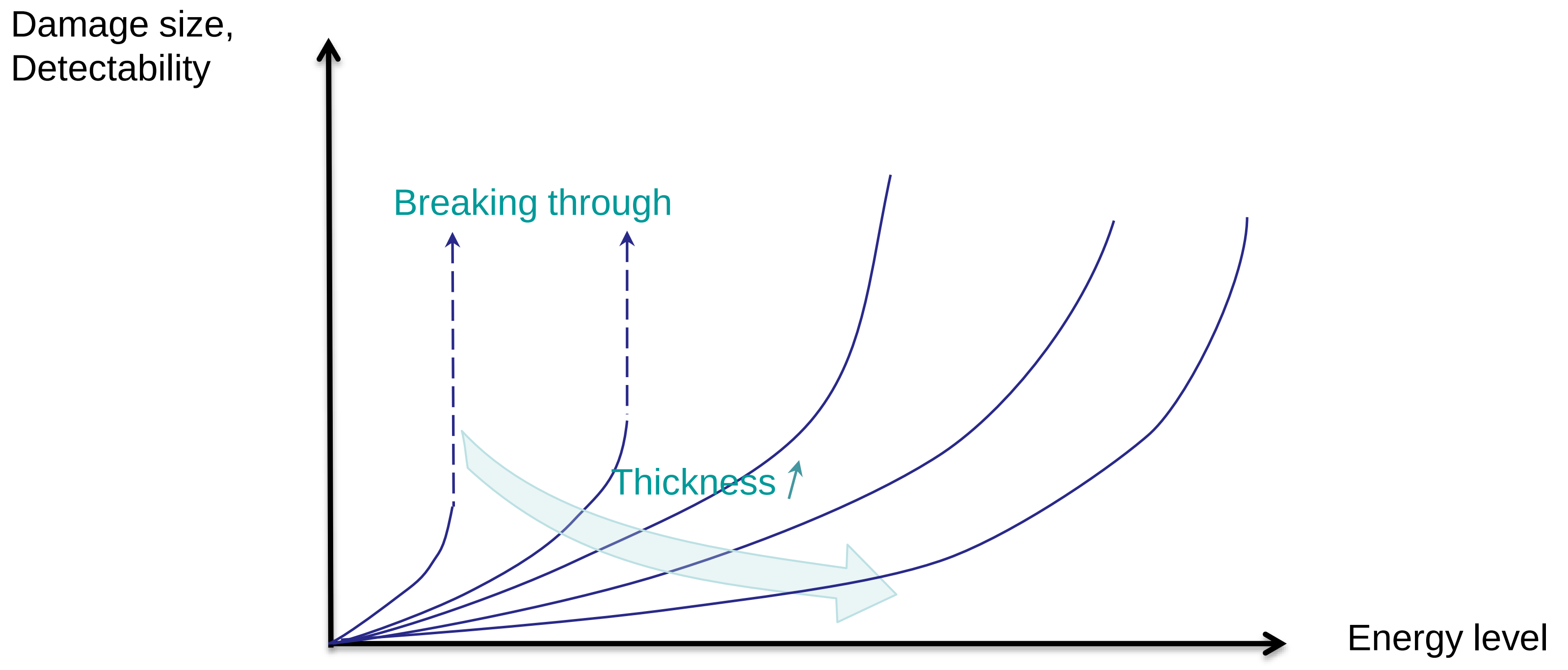




- Damage tolerant design made in terms of detectability
- Structural strength cannot be reduced under ultimate load capability by impact damage that are (CS 25.603):
  - Expected to happen during manufacturing, operations or maintenance
  - Undetectable by practical inspection procedure

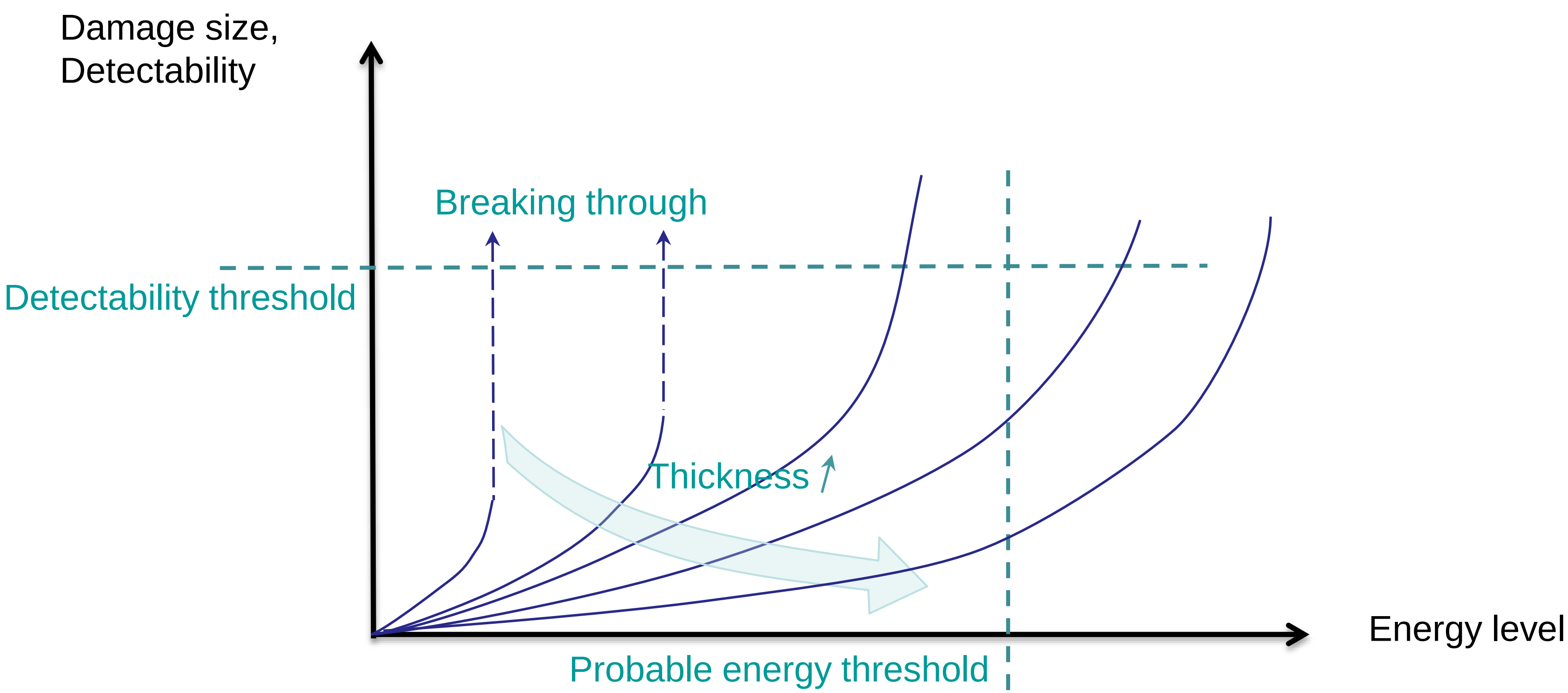


- Detectability / damage size is a function of
  - The impact energy
    - Damage (and detectability) grows with energy
    - Likelihood of occurrence drops with energy
  - The thickness of the composite plates
    - Detectability (and damage size) decreases with an increasing thickness
    - Thin structures can be pierced with enough energy (become easily detectable)

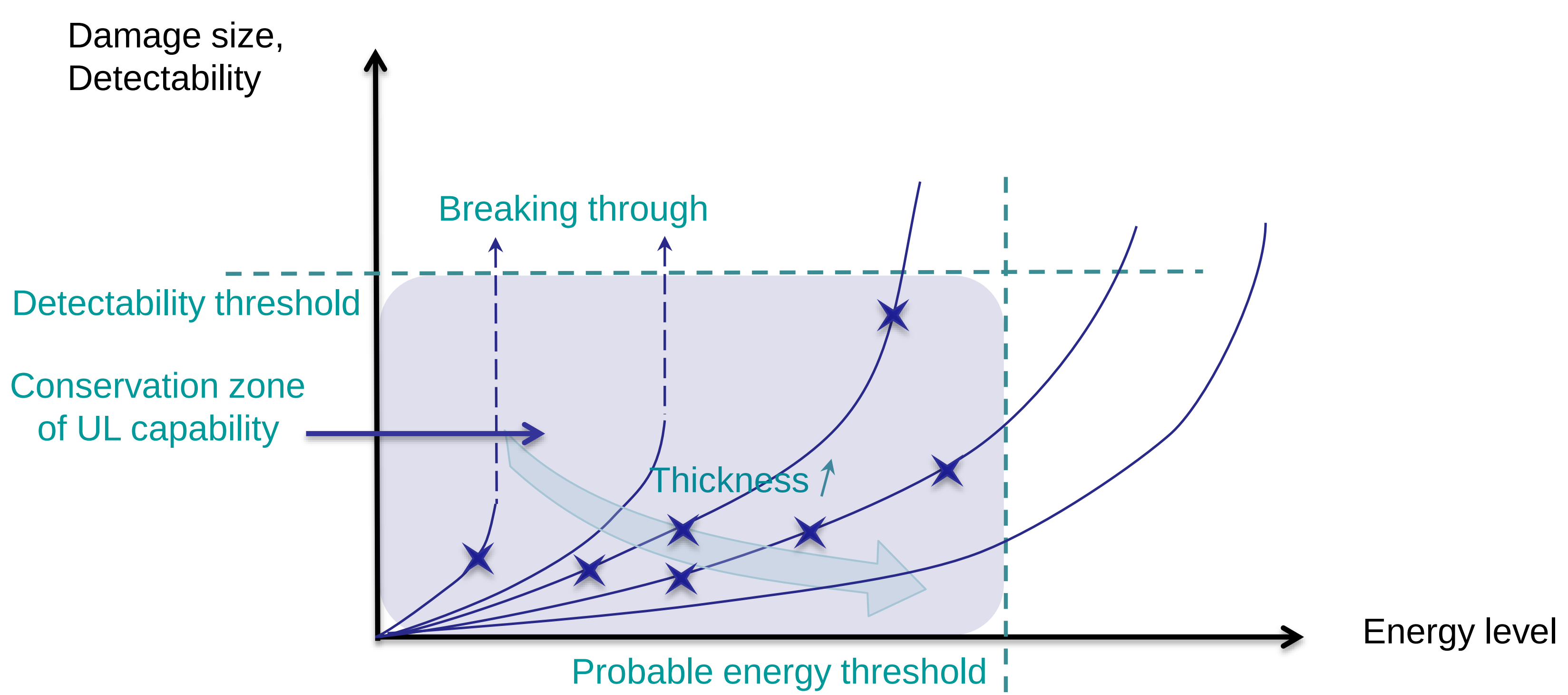


Impact damage

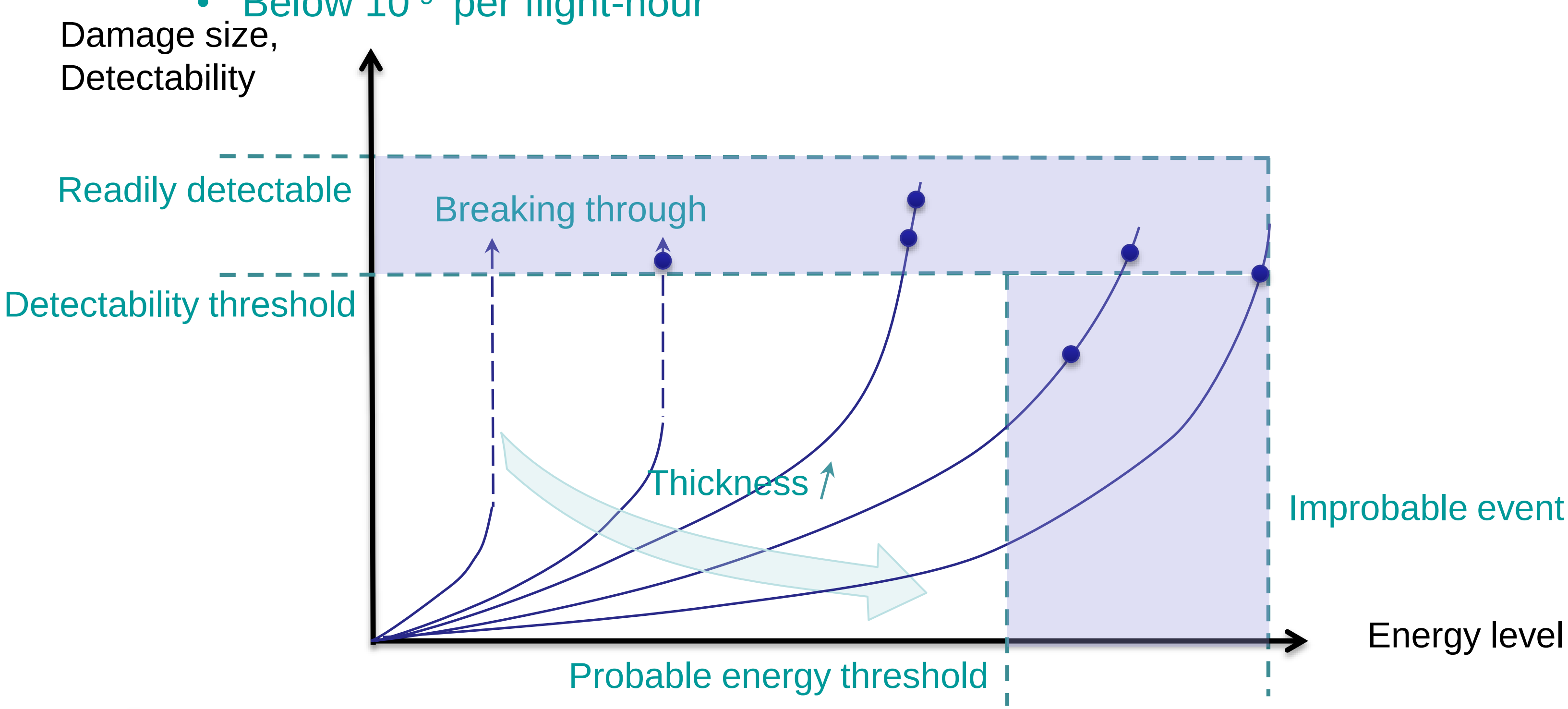
- Detectability / damage size threshold
  - Minimum limit of detectability for chosen detection/inspection method
    - Under this, damage is undetectable (for visual inspection, dent depth of 1mm)
- Maximum impact energy expected
  - Upper bound of expected/probable impact energy during manufacturing and operating lifetime (including maintenance…), obtained by probabilistic approach (= 35J for Airbus)



- Low velocity impact damage (✕)
  - Below detectability and probable energy threshold
    - Impacts cannot reduce ultimate load (UL) bearing capability since the damage will probably occur and cannot be detected
    - Example: maintenance operations, tool or tool box dropping,…
    - Energy threshold could be zone-dependent

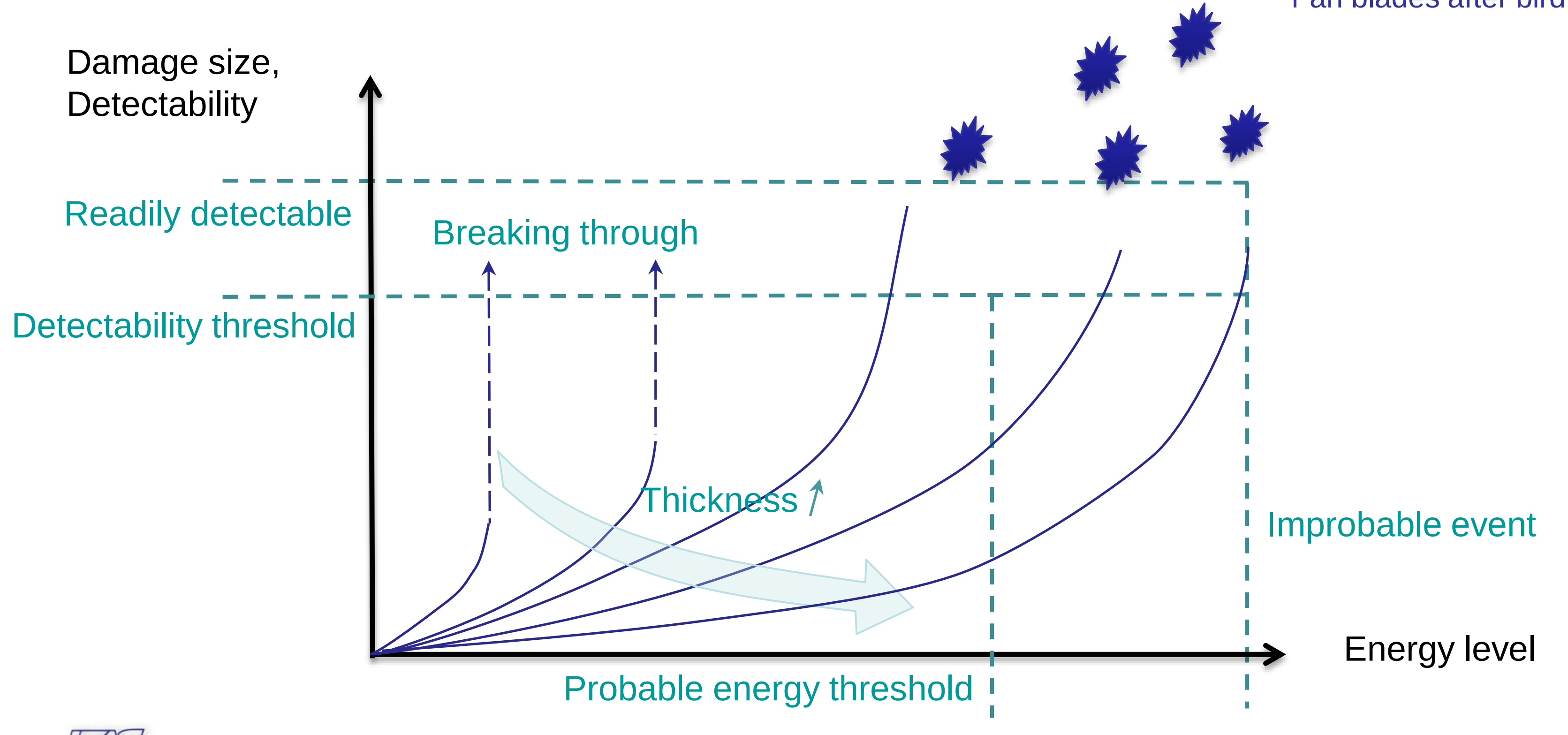


- Higher velocity impact damage (●)
  - More severe impacts have to be included:
    - k x LL (limit load) have to be maintained for detectable damage (during the next inspection)
      - k is function of risk probability
    - LL maintained for readily detectable damage (detectable before the next flight)
  - Energy level analysis cut-off to extremely improbable events (Europe)
    - Below 10^{-9} per flight-hour



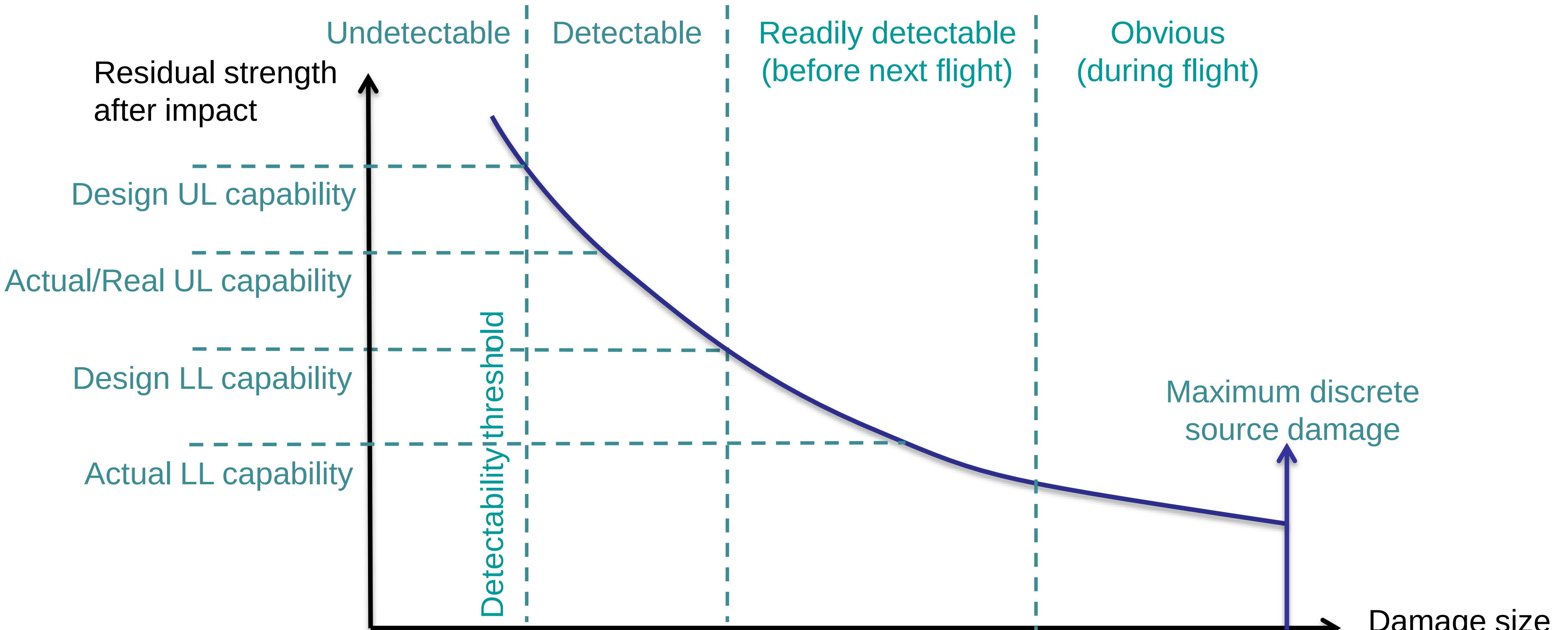
- Discrete damage source ( )
  - Example: bird strike, tire burst,…
  - Damage detectable directly during the flight or pre-flight inspection
    - Possibility of LL capability loss
    - Ensure “Get Home Load” capability

Fan blades after bird strike



Impact damage

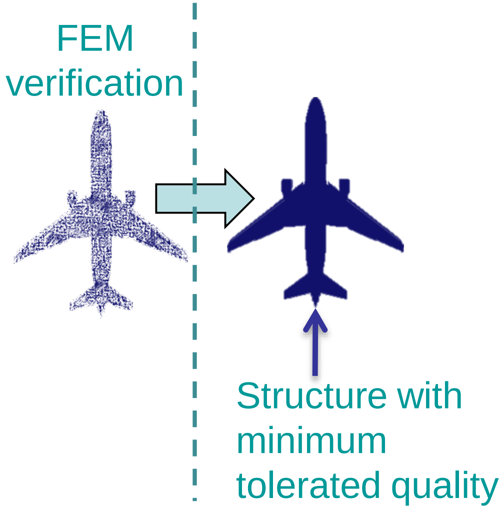
- Summary
  - The more severe the damage, the earlier it should be detected
    - Obvious damage: possibility to deflect the flight (emergency landing) if needed
    - Readily detectable: aircraft take off not authorized before additional investigations since LL capability could not be ensured
    - Detectable: avoid long duration under UL, in terms of the damage severity
    - Undetectable damage: no reduction under UL capability



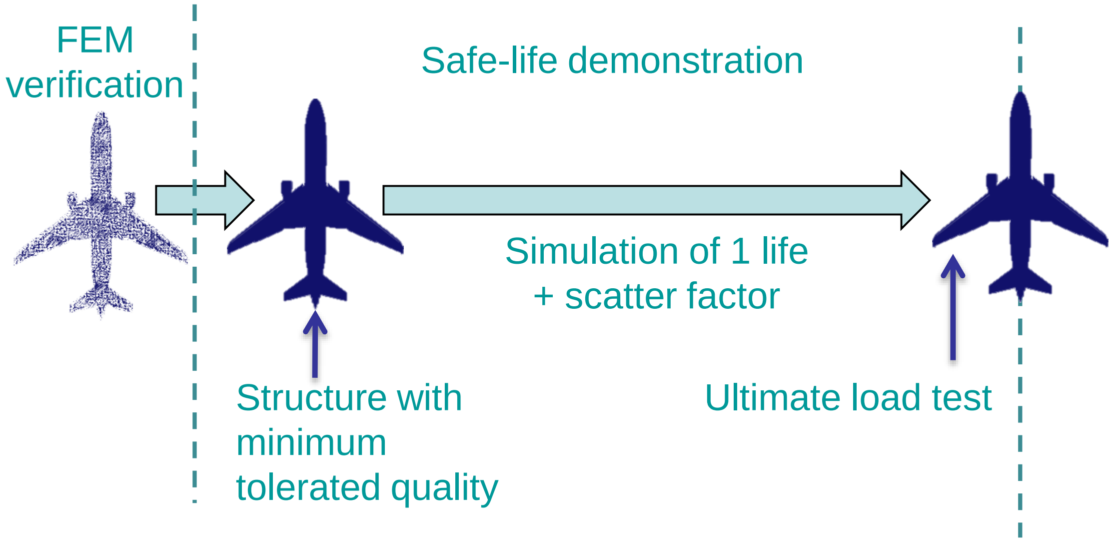
- How to determine inspection intervals?
  - The more severe the damage, the earlier it should be detected and repaired
  - The more likely the damage, the earlier it should be detected and repaired
- Pre-flight visual inspection
  - Detection of easily detectable damage (below LL capability)
- Gross / Detailed inspection and maintenance
  - Chosen interval in order to minimise probability (extremely improbable $\approx 10^{-9}$/h) of the combination of
    - A external load above LL but below UL
    - A residual strength after damage of the same level

Fatigue & Damage tolerance – Test protocol example

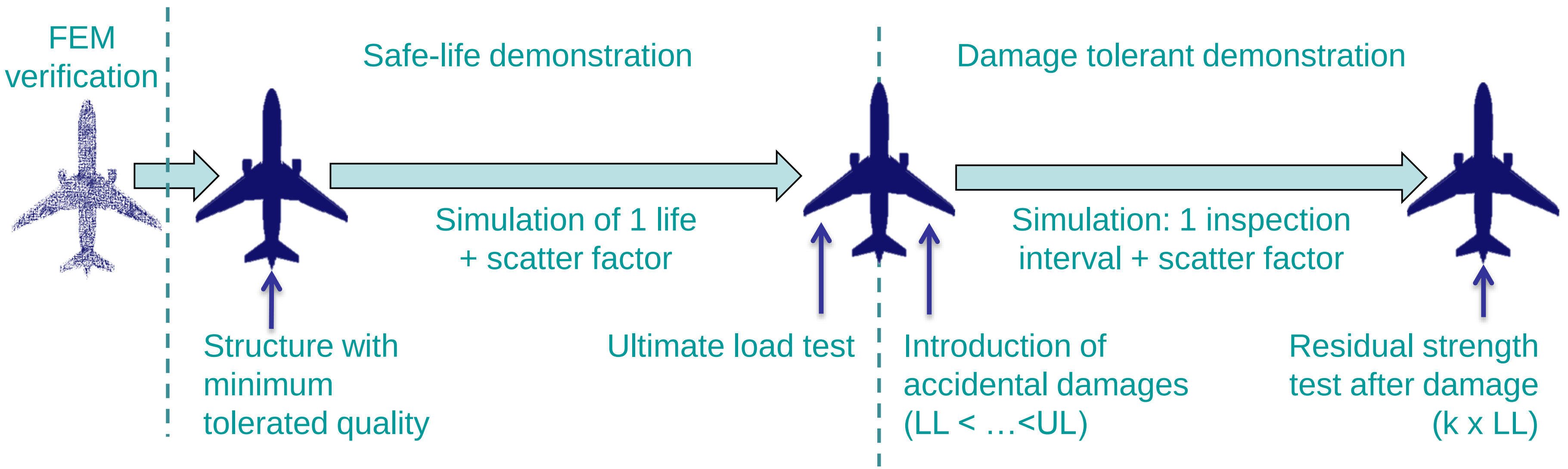
- How to assess fatigue and damage tolerance ?
  - For composites structures, one needs to take into account
    - Manufacturing flaws, undetectable accidental damage and environmental degradation
    - Low accessibility to reliable calculations
  - Use full-scale structures that have to be representative of the minimum expected quality
    - With maximum tolerated manufacturing defects or accidental damages (see sl.36)
    - Quasi-moisterised (60% of maximum moisture content)



- 1st phase: Durability demonstration
  - Demonstration of a fatigue safe-life / flaw tolerant safe-life
    - Life enhanced by a scatter factor from Whitehead method or equivalent (included effects of mechanical properties scattering, typically 1.5 on life and 1.15 on loads)
    - Equivalent to a crack-free life (no fatigue crack initiation)
- 2nd phase: Ultimate load test
  - Demonstration of the residual strength
    - Realised with worst environmental conditions
    - Done after fatigue tests (CS 25.305, 25.307)



- 3rd phase: Damage tolerant evaluation:
  - Demonstration of the no-growth approach:
    - An accidental damage is introduced, reducing UL capability but not LL
    - No subsequent damage growth has to occur during one inspection interval (before we could be able to detect it)
    - Demonstration of the residual strength to a lower level than UL



Lightning strike protection

- Statistically
  - A transport aircraft may be stroked once a year
  - Occurs most of time during climb or descent

- Consequences (worse for poor electrical conductive skin as composites)
  - Direct effects
    - Local destruction of the skin (melt through, resistive heating, missing structure at extremities)
    - Sparking inside fuel tanks
  - Indirect effects
    - Magnetisation of ferromagnetic material
    - Perturbations in electronic equipment or wiring in absence of “Faraday cage effects”
  - In case of strike
    - The airplane can be diverted if required
    - Inspections are mandatory, followed by repair if necessary

- Protection (CS 25.851)
  - Divide the airplane surface in 3 zones in terms of lightning strike risk and adapt protection in function
  - Incorporate acceptable means to conduct electrical current
  - Add aluminium protection straps on most exposed zones (trailing and leading edges, wing tips, tail cone,…)
  - Special composite structure coating/finish
  - …
- Tests are performed to ensure protection reliability

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Conclusions

- Safety issues
  - Achieve an acceptable safety risk comparable to others transportations
  - Compromise between
    - Human aspects
    - Economical aspects
    - Technical aspects
  - Various aspects taken into account
- Overview of mechanical requirements
  - Static strength
  - Fatigue & damage tolerant (impact damage, lightning strike,…)
- Further improvements in this sector
  - Enhancement in understanding the material behaviors
    - More reliable calculations for composite structures
    - New models for damaged composites
    - …

- Lecture notes
  - Certification of aircraft composite structures, J. Rouchon, Eurosae, 2007
  - Aircraft certification tests, Airbus Press Office, 2013
  - Fatigue and damage tolerance evaluation of structures - The composite materials response - 22nd Plantema Memorial Lecture, J. Rouchon, 2009, NLR-TP-2009-221
  - Aircraft Structures for engineering students, T. H. G. Megson, Butterworth-Heinemann, An imprint of Elsevier Science, 2003, ISBN 0 340 70588 4