CADE30001

Advanced Structures and Materials

Lecture 2: Failure of Materials

Why Study Failure: Case Histories

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Course Content

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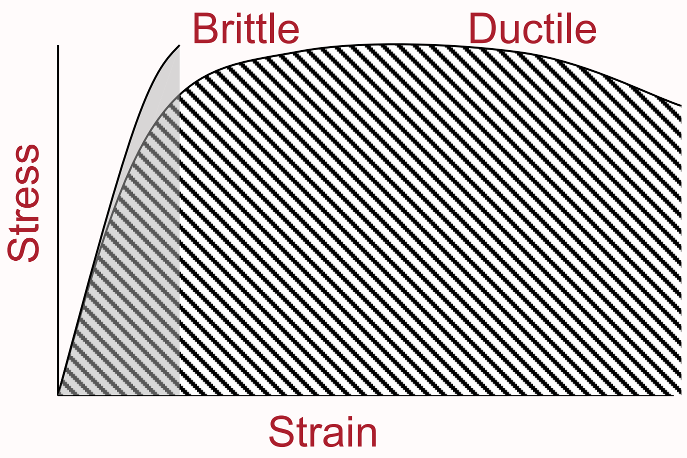
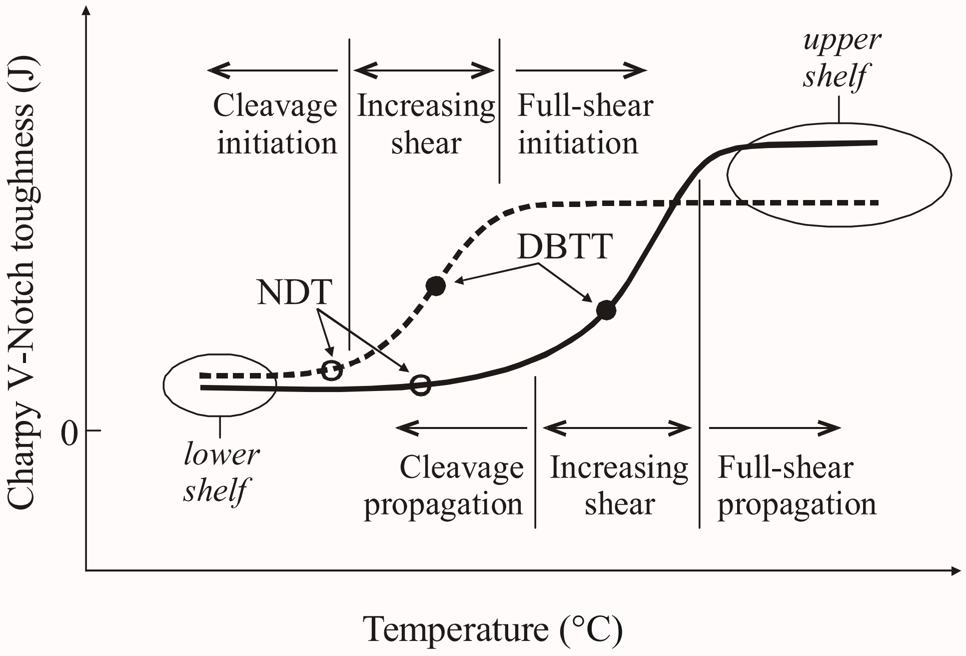
• Why study failure? • Concept of strain energy and toughness • Ductile, brittle failure • Fractography • Factors affecting ductile to brittle transition	• Historical Examples • Design philosophies	• Introduction to fracture mechanics • Theoretical stress approach to fracture • Stress intensity factor	• Griffith's energy balance approach • Irwin's energy balance approach	• Fracture process zone and geometrical considerations • Measuring toughness • Anisotropic materials

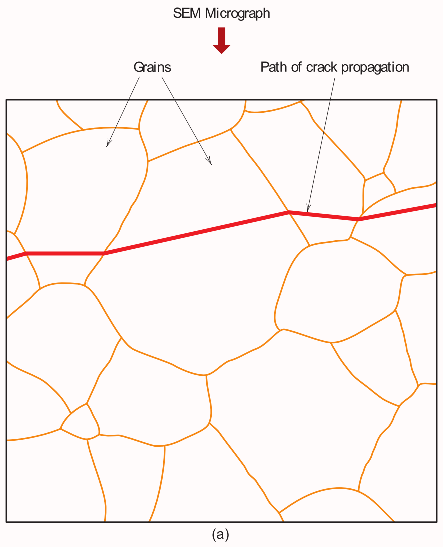
Last week...



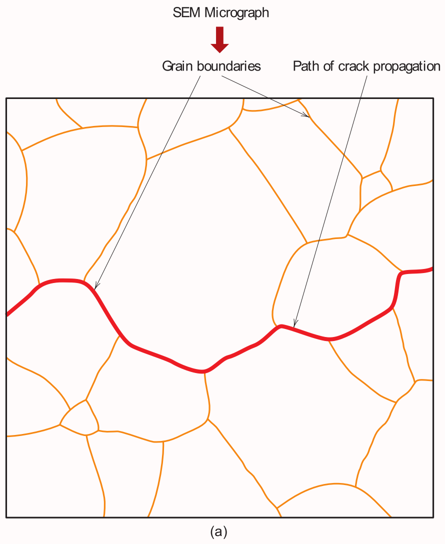
Brittle
Ductile
Stress
Strain



Charpy V-Notch toughness (J)
Temperature (°C)
0
Cleavage initiation
Increasing shear
Full-shear initiation
upper shelf
DBTT
NDT
lower shelf
Cleavage propagation
Increasing shear
Full-shear propagation



SEM Micrograph
Grains
Path of crack propagation
(a)



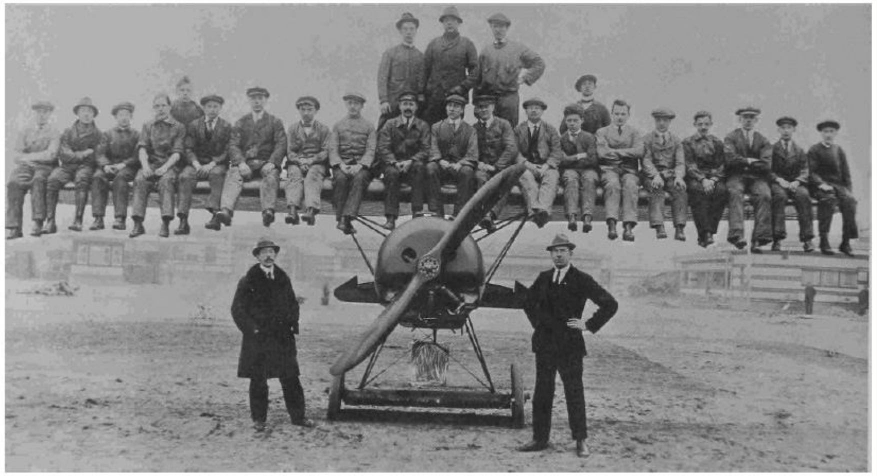
SEM Micrograph
Grain boundaries
Path of crack propagation
(a)

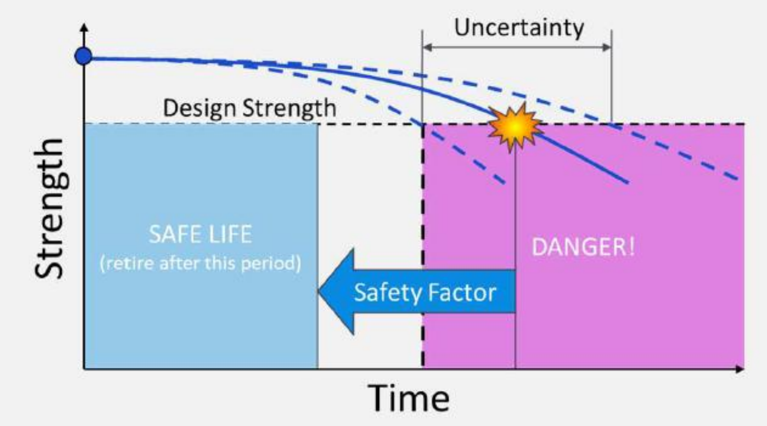
Historical causes of structural failure

This lecture will also provide an overview of (some) key causes of structural failure and the lessons learned in the aerospace industry.

- De Havilland Comet crashes (Mark 1, 1952-1954)
  - Stress concentration of tiny defects and fatigue failure → Fail Safe Philosophy
- General Dynamics F-111 crash (1969)
  - Large manufacturing flaw growing in fatigue → Damage tolerant philosophy
- Dan Air Boeing 707 crash (1977)
  - Extensive testing and inspection necessary → Fully tested certification and regular inspections
- Aloha Airlines Boeing 737 accident (1988)
  - Ageing aircraft will have weakened structures → Ageing structure assessments
- Lockheed C130A Firefighting Tanker accident (2002)
  - Loading spectrum and sudden loads will affect structural life

Safe life

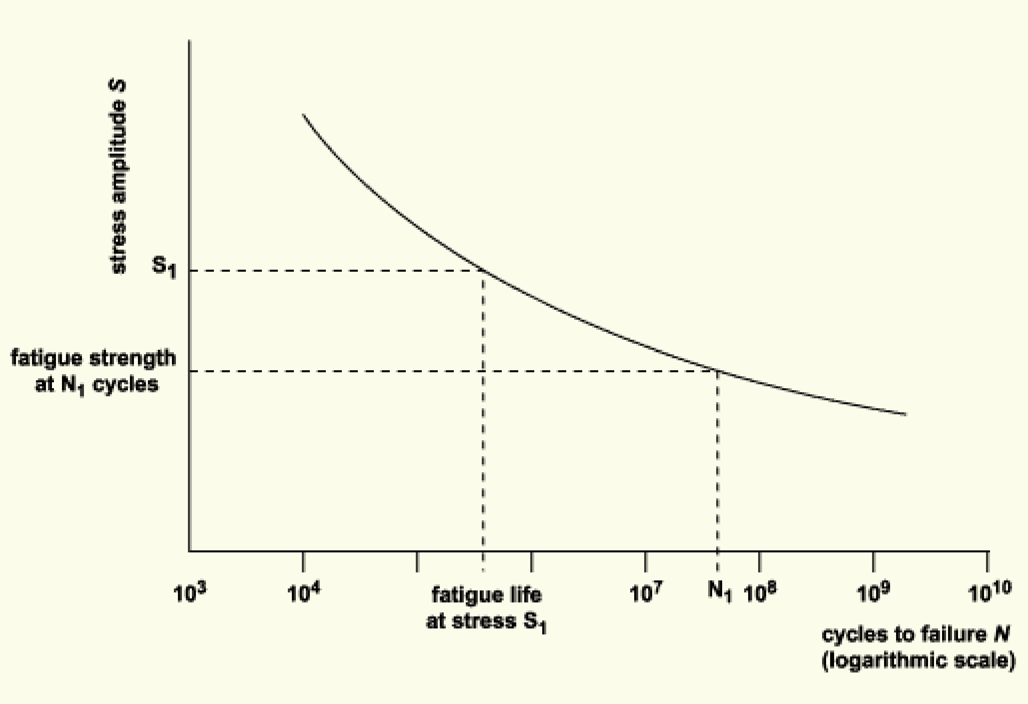




- **Safe-life** is the number of flights, landings, or flight hours, during which there is a low probability that strength will degrade below design strength
- Component is scrapped or replaced at the end of its lifetime
- Aircraft were obsolete before design life was reached

Key slide!

Safe life design philosophy

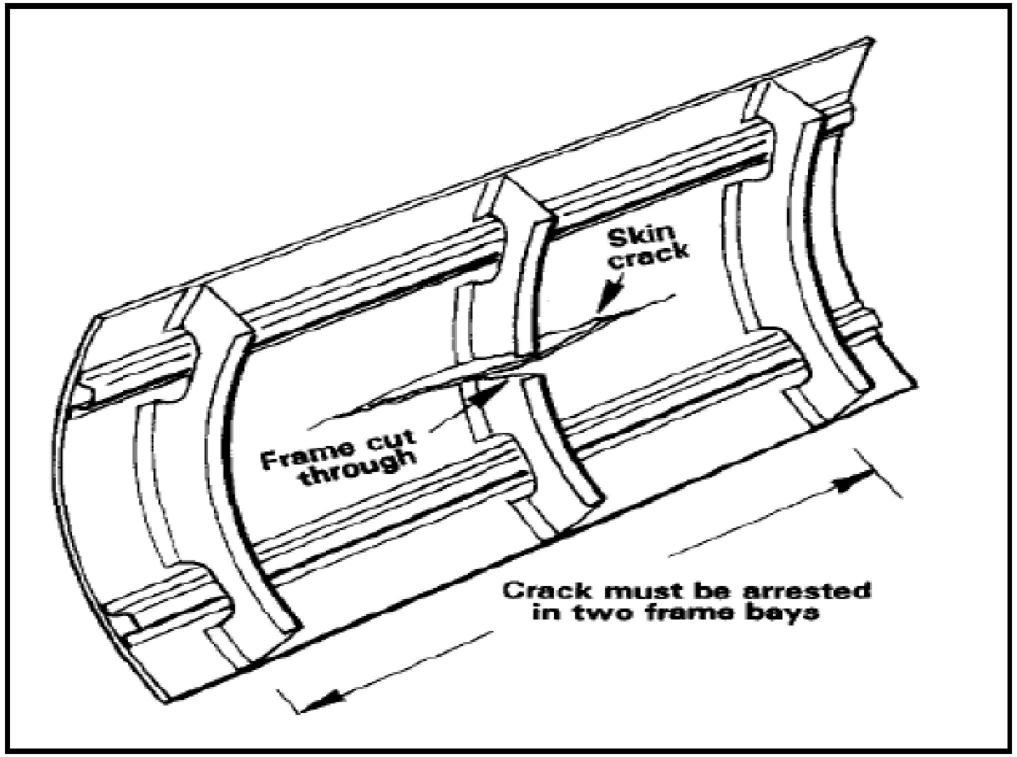


- SN curve relating the magnitude of the **cyclic stress** (S) to the logarithm of the number of cycles to failure (N)
- Ratio of maximum load to minimum load (R-ratio)
- If the stress of the component is below the fatigue strength on the S-N curve, the component is said to be designed for **infinite life**.
- If the stress of the component is above the fatigue strength, the component is **life limited**.
- To ensure that the component does not fail, it should be removed from service at the end of this safe life regardless of its condition.
- Significant **safety factors** are often applied to ensure that catastrophic failures will not occur during operation in the safe life regime.

https://vextec.com/structural-design-concepts-overview-safe-life-damage-tolerance/#fracture_mechanics

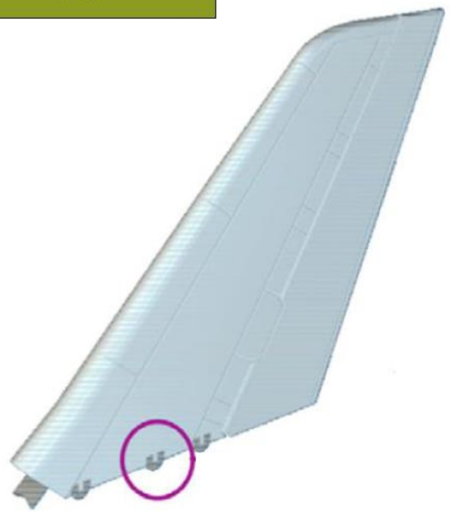
Design philosophy - Fail safe

- This method differs from safe life in that fail safe assumes that a component will fail, and therefore the component is designed to fail in a safe manner.
- **Fail-safe design philosophy** means the structure retains some residual strength for a period of unrepaired use after failure or partial failure of a principal structural element.
- The techniques that are typically used in this method include attempts to reduce the likelihood of single-point failures by creating redundancies.

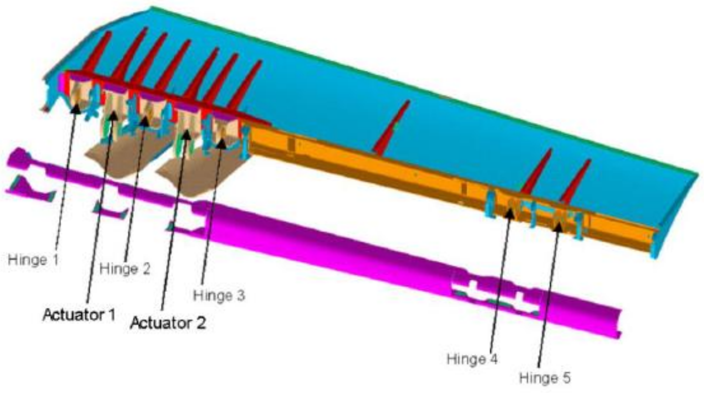


Redundancies

VTP

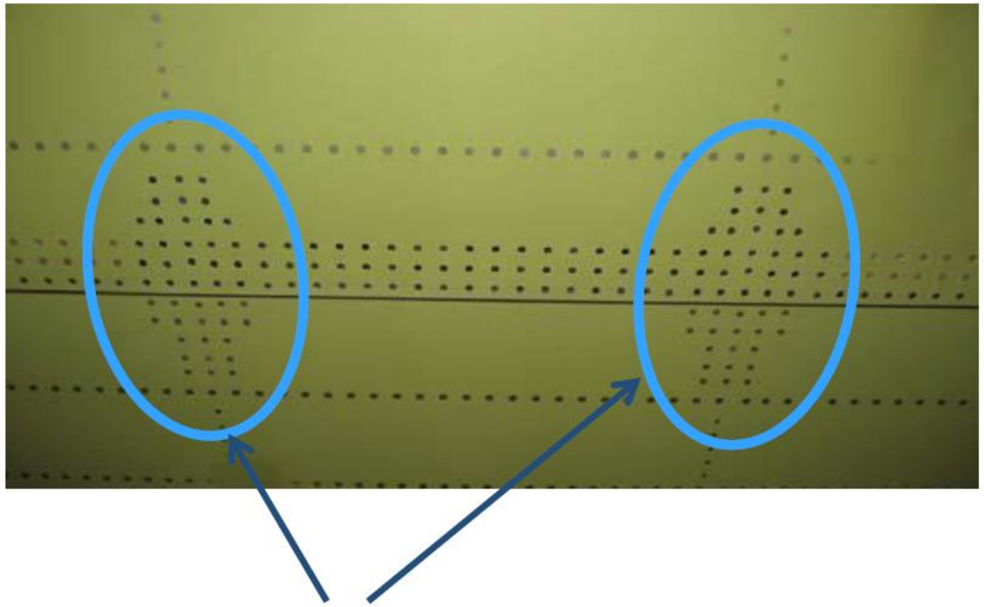


Aileron



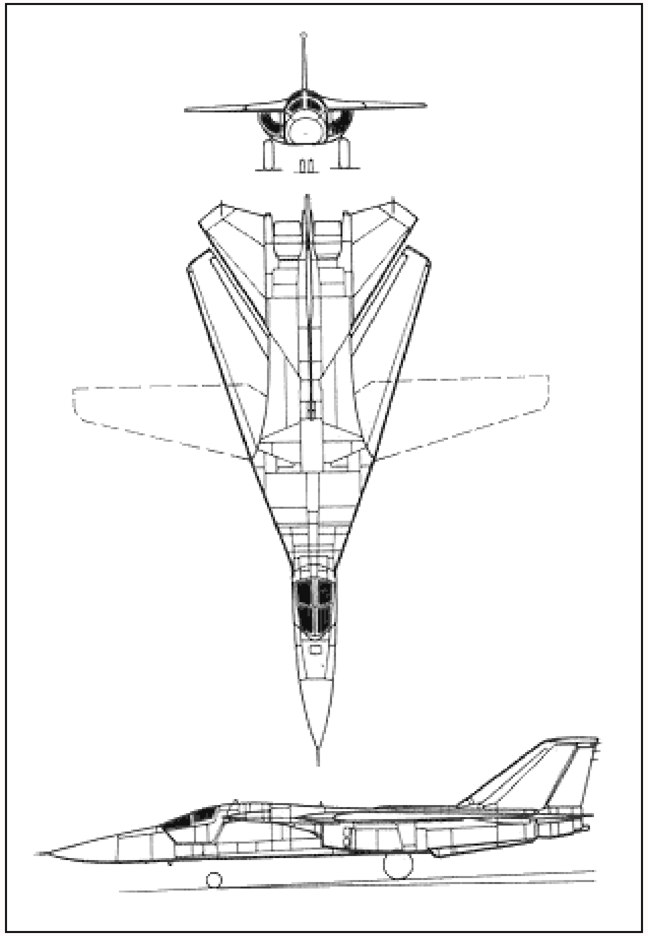
AIRBUS Philosophy for Fail-Safety

Fuselage Skin



Crack stoppers: increase Residual Strength, crack turning effect

- If, for example, a structure is loaded using multiple beams and one fails, the load is re-distributed among the remaining members.
- The overall system does not fail, but the failed member can be detected and repaired or replaced.



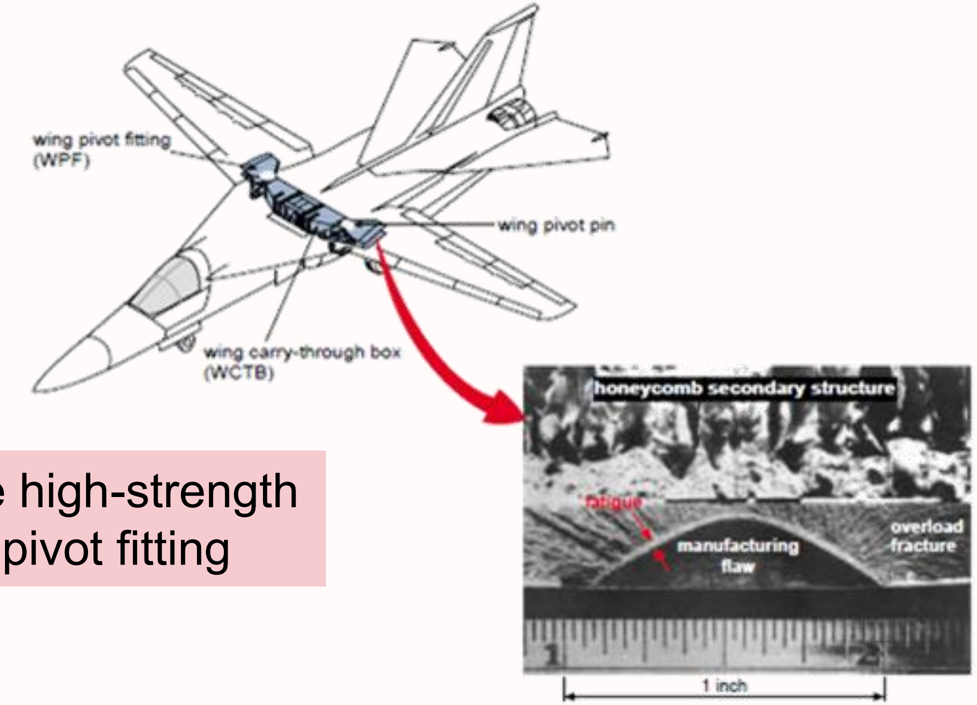
General Dynamics F-111 Crash - 1969

General Dynamics F-111 Crash

- In 1964 the General Dynamics Corporation was awarded a contract for the development and production of the F-111 aircraft, subsequently to be procured by the United States Air Force (USAF) and others.
- The F-111 is an unusual aircraft: it is a variable geometry ‘swing-wing’ (supported by D6AC steel pivot-fittings) fighter-bomber; and it uses high-strength steel in major airframe components, namely the wing carry-through box, wing pivot fittings, some of the centre fuselage longerons and the tail assembly (empennage) carry-through structure.
- The F-111 fighter-bomber, which was designed according to the safe-life philosophy, entered service with the USAF in 1968.

General Dynamics F-111 Crash

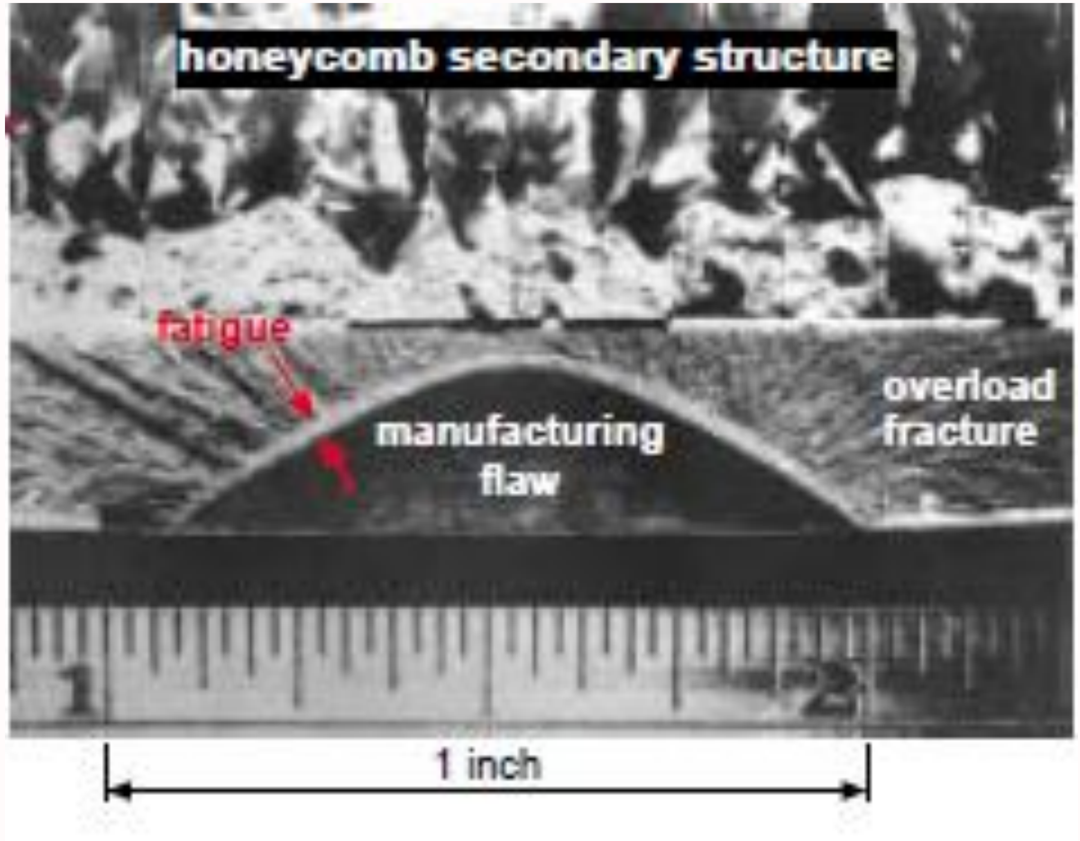
- On December 22, 1969, just over a year after entering service, F-111 #94 lost the left wing during a low-level training flight. The aircraft had accumulated only 107 airframe flight hours, and the failure occurred while it was pulling about 3.5g, less than half the design limit load factor .



Failure origin: a manufacturing flaw in the high-strength steel lower plate of the left-hand wing pivot fitting

General Dynamics F-111 Crash

- An immediate on-site investigation revealed a flaw in the lower plate of the left-hand wing pivot fitting.
- The cause of the failure was traced to an undetectable surface flaw present in the high strength D6AC steel pivot-fitting. The flaw originated during manufacturing and grew until failure, to a semi-elliptical shape of about 24 mm long by 6 mm deep



Lessons Learned

- This failure directly led to the replacement of the **safe-life philosophy** by the **damage tolerance philosophy** by the USAF in 1974, which was also adopted by the FAA in 1978 (see Boeing 707 Accident at Lusaka, next example).

Boeing 707 Accident at Lusaka (1977)

Boeing 707 Accident at Lusaka (1977)

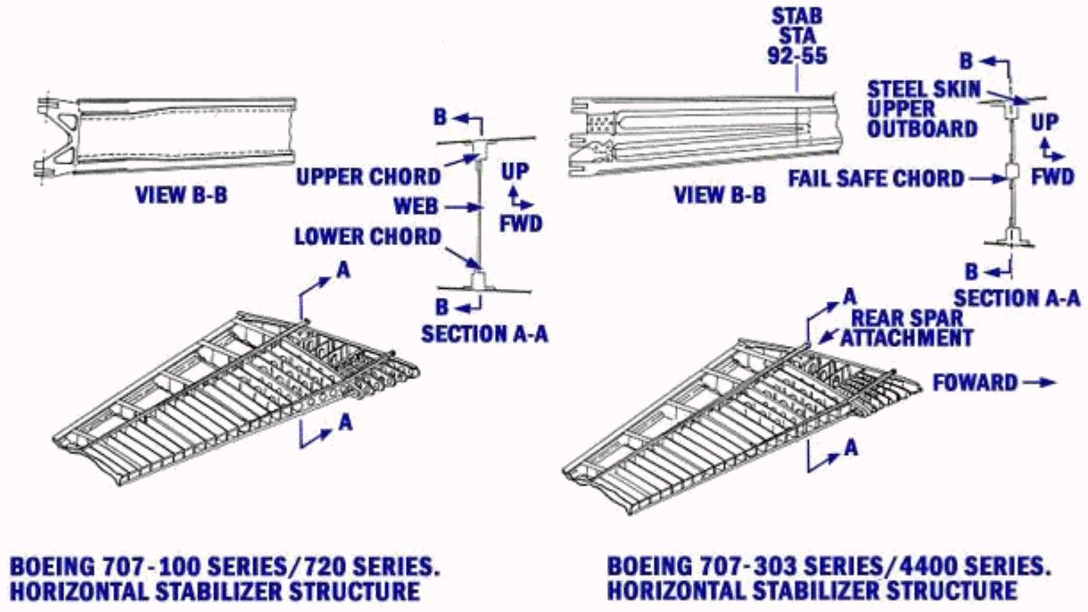
- In 1977, a Dan-Air B707-321C aircraft crashed at Lusaka, Zambia after the entire right-hand horizontal stabilizer separated in flight during the approach to landing. All six passengers were killed.

- The B707-100 series had been designed to the fail-safe philosophy, which was then permitted by the FAA.

  – Fail-Safe Design: This design concept assumes the possibility of multiple load paths and/or crack arrest features in the structure so that a single component failure does not lead to immediate loss of the entire structure. The load carried by the broken member is immediately picked up by adjacent structure and total fracture is avoided. It is essential; however, that the original failure be detected and promptly repaired, because the extra load they carry will shorten the fatigue lives of the remaining components.

Boeing 707 Accident at Lusaka (1977)

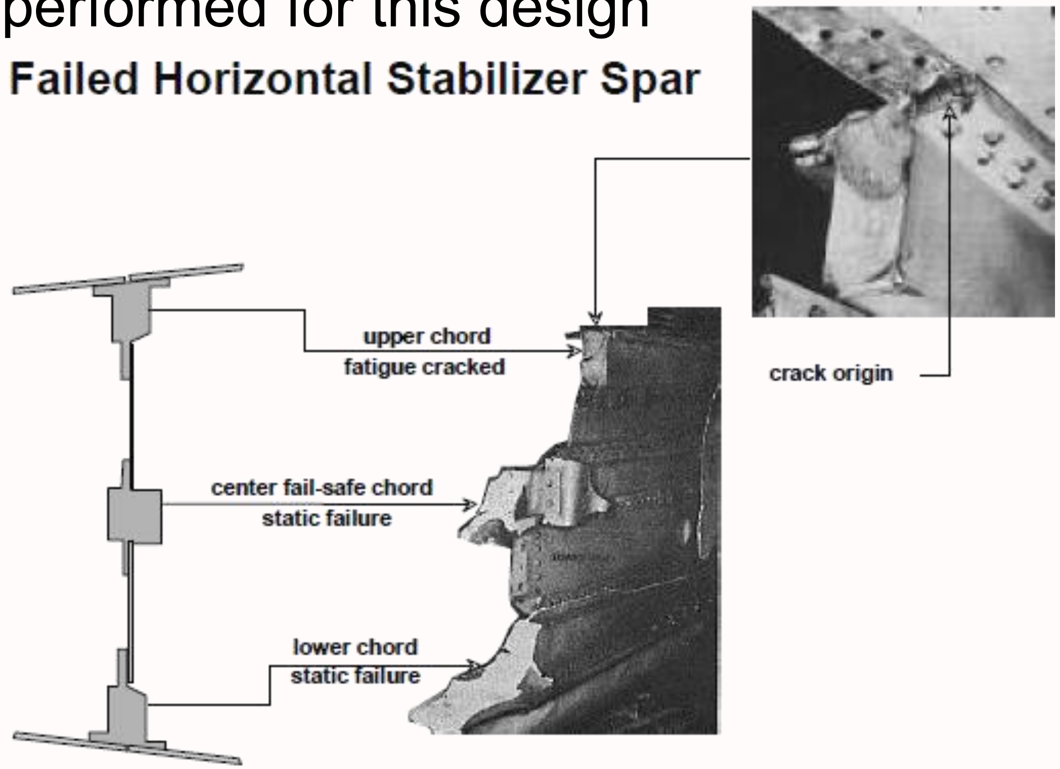
- Boeing assumed that the fail-safe certification for 707-100 Series which was supported by experimentation would also be valid to for the 707-300 Series
- However some key design changes were made. Under the fail-safe philosophy, there was no FAA requirement to specify any periodic structural inspections. Also, there was no FAA requirement to confirm the fail-safe behaviour by testing



Boeing 707 Accident at Lusaka (1977)

- The aircraft had completed 16,723 flights, compared to a design life of 20,000 flights.
- The single-spar horizontal tail structure was designed to be fail-safe by the addition of an additional chord at the centre of the web. In this way, a failure of either the upper or lower chord would allow the design loads to be carried by the two remaining chords.
- No fatigue or fail-safe testing was ever performed for this design

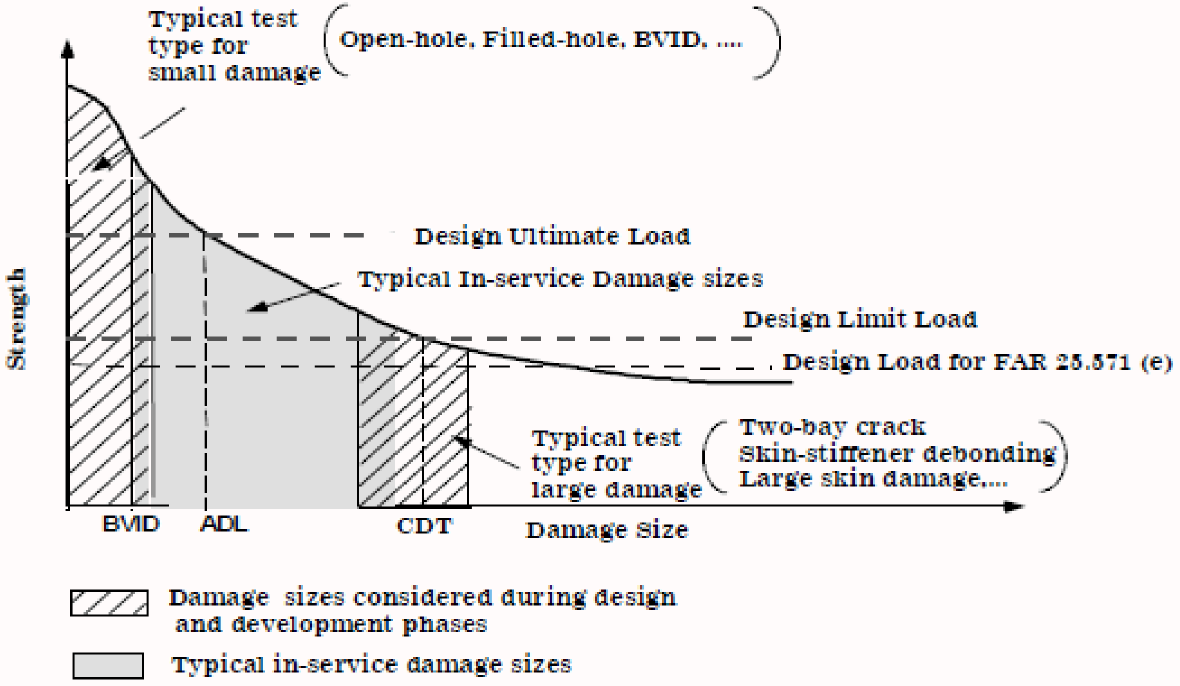
Post-accident measurements showed significant tail oscillatory loads resulting from airbrake deployment after landing. These loads were unknown during the design of the structure!



Lessons Learned

- As a result of this accident, it became generally acknowledged that a fail-safe design is not sufficient to ensure safety, and periodic inspections would also be needed.
- This accident gave the impetus to substitute damage-tolerance requirements (1978) for the fail-safe requirements in the certification of large civilian aircraft.

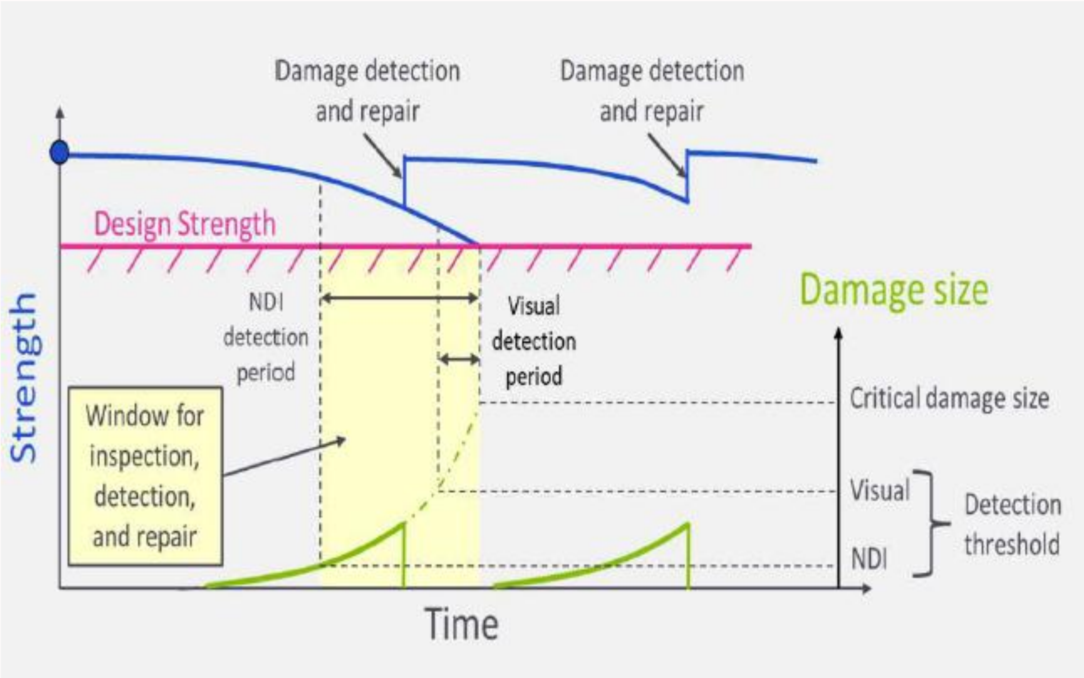
Damage tolerance approach: Residual strength versus damage size relationship



Key slide!

Damage tolerance

- Damage tolerance is defined as the ability of a structure containing a crack or an anomaly in the material to resist fracture.
- The objective of the damage tolerance approach is to detect cracks in critical parts before they propagate to failure.
- The three key elements of a damage tolerance design framework are
  - fatigue crack growth behavior (typically utilizing linear elastic fracture mechanics),
  - residual strength, and
  - non-destructive inspections.



Damage tolerance

- Fracture mechanics provides a physical basis for a crack growing in a structure. It quantifies the energy the crack has in a value called the stress intensity factor (SIF).
- The SIF determines the size and shape of the “plastic zone” ahead of the crack’s tip. This plastic zone size is directly related to the available energy (and the energy, in turn, related to the applied stress) for continued crack growth.
- Without sufficient energy, the formed crack can arrest (stop growing).
- Finite element methods to determine how the stress in a component is spatially distributed. Rather than using a single peak component stress (as in safe life), a stress distribution can be applied to the crack’s growth rate.
- Subtle changes in design (fillet radius, residual stress, etc.) can lead to varied and important differences in a DTA durability prediction.

Non-destructive test methods

- Damage Tolerance Philosophy assumes flaws can exist in materials/ structures from manufacture or service.
- Focuses on **detecting and monitoring cracks before they reach critical size**.
- Requires scheduled inspections based on **crack growth rates and critical damage thresholds**.
- **Non-Destructive Inspection (NDI)** Techniques (e.g., ultrasonic, eddy current, radiography, dye penetrant) used to detect cracks, corrosion, or defects without harming the structure.
  - Detects flaws early.
  - Provides data for maintenance intervals.
  - Ensures structural integrity during service.
  - Prevents catastrophic failure by ensuring cracks remain within safe limits.

Visual inspection

Principle: Direct observation of surface condition using the human eye (aided or unaided).

Applications:

- Detects cracks, corrosion, dents, leaks, loose fasteners, misalignment.
- Often first step before advanced NDI.

Advantages:

- Simple, quick, low-cost.
- Requires minimal equipment (borescope, magnifiers, mirrors, flashlights, cameras).

Limitations:

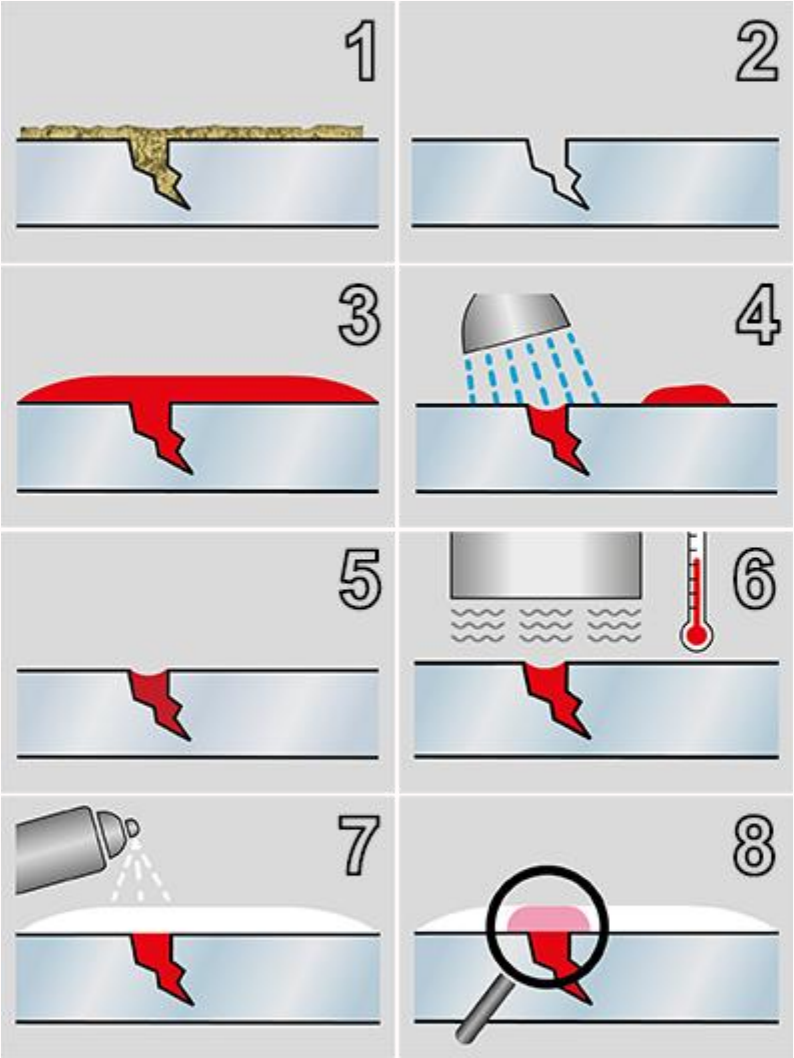
- Restricted to surface flaws.
- Operator skill and lighting conditions critical.
- Fatigue and human error can reduce effectiveness.

Enhancements:

- Remote visual inspection (RVI) tools – e.g., videoscopes, drones.
- Digital imaging & AI-based defect recognition.

http://www.sofemaonline.com/

Liquid penetrant testing



Principle

•Relies on the ability of a low-viscosity liquid (penetrant) to seep into surface-breaking defects by capillary action.

1. Soiled crack
2. Ideally pre-cleaned
3. Application of test agent
4. Intermediate cleaning
5. Optimally cleaned intermediately
6. Drying
7. Application of developer
8. Crack indication

Applications

•Detects cracks, porosity, laps, seams in metals, ceramics, plastics, and composites.

•Widely used in aerospace, automotive, pipelines, and welding inspections.

Advantages

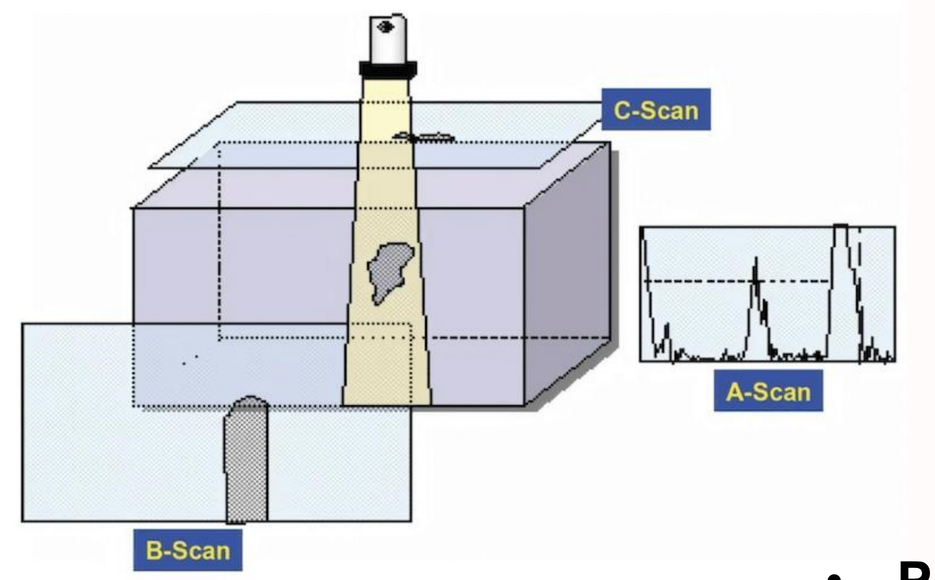
✓ Sensitive to small surface flaws
✓ Simple and inexpensive
✓ Works on complex shapes

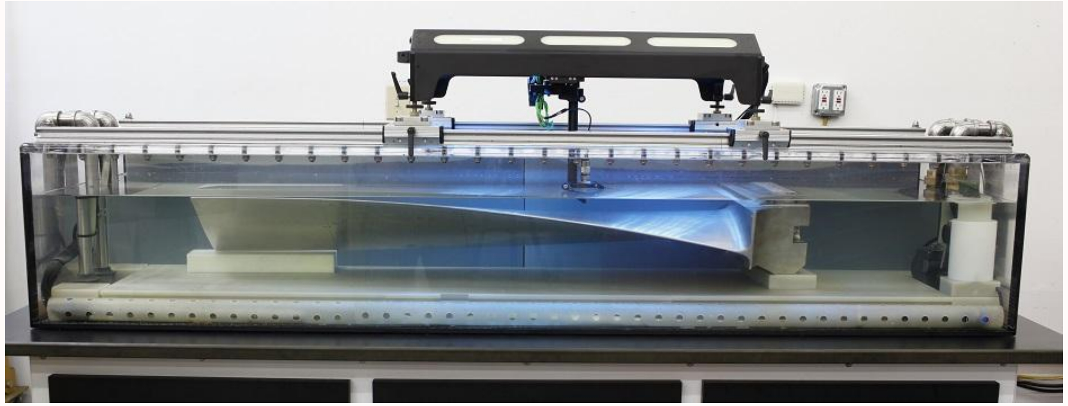
Limitations

✗ Only surface-breaking defects
✗ Requires very clean surfaces
✗ Not suitable for porous materials

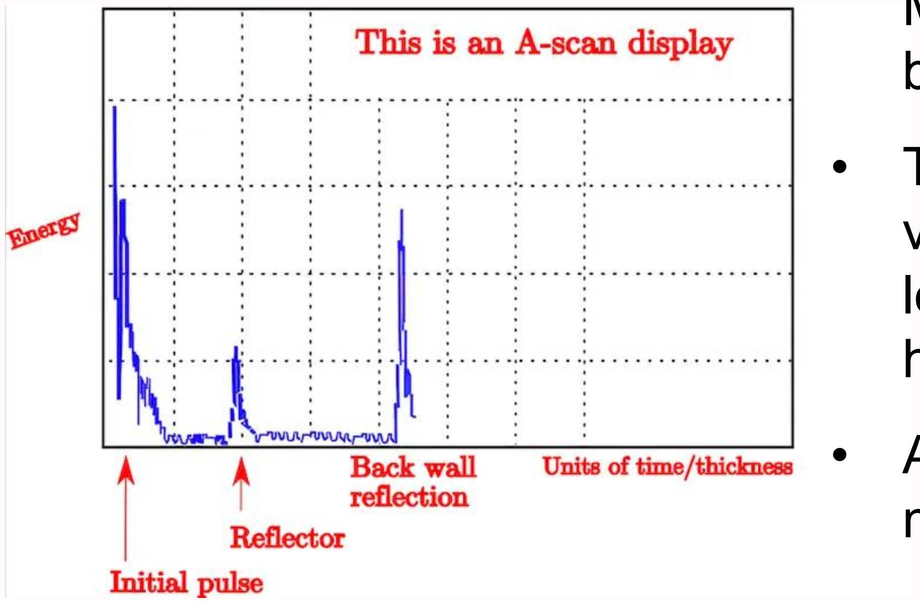
https://www.karldeutsch.de/ndt-knowledge/basic-knowledge/basic-knowledge-about-penetration-or-dye-penetrant-testing/?lang=en

Ultrasonic scanning



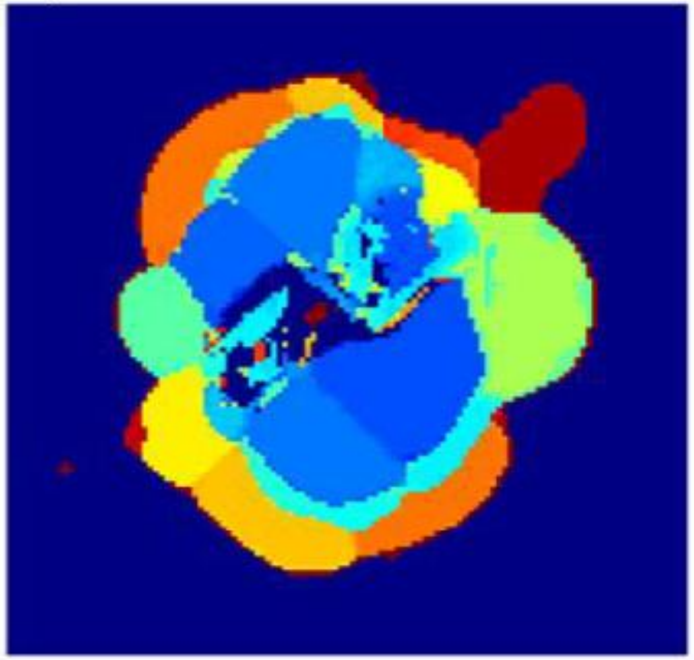


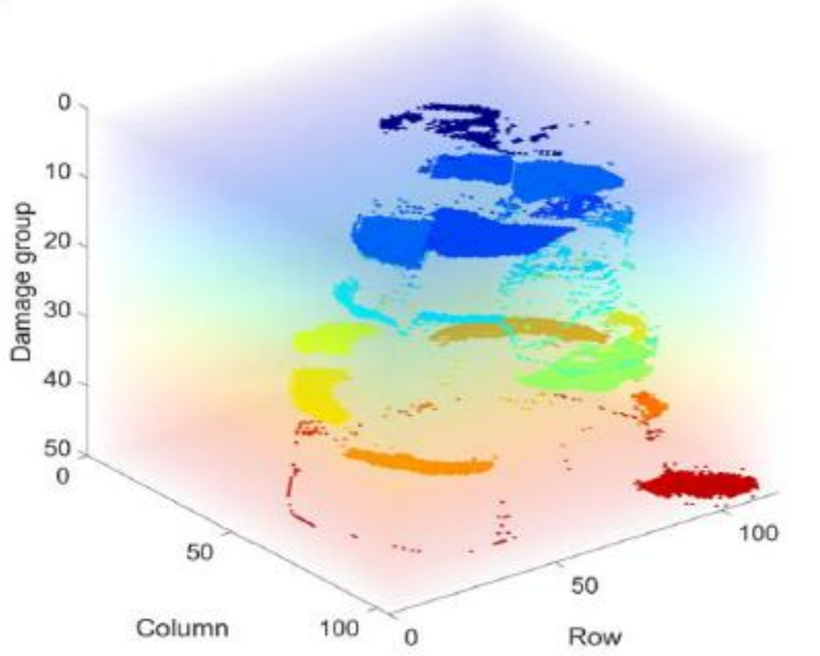
NASA Ames Research Turbine Compressor Fan Blade Inspection



- **Principle:** Uses high-frequency sound waves (0.5–25 MHz).Waves travel through material and reflect at flaws, boundaries, or thickness changes.
- The main application of a C-scan is to analyze cracks that are not visible to the naked eye. It finds cracks on welds and can also locate them inside components such as engine blocks, cylinder heads, valves, etc.
- Additionally, it finds flaws like inclusions or porosity in castings made by sand moulds, delaminations in composites

C-scan of impact damage in composites

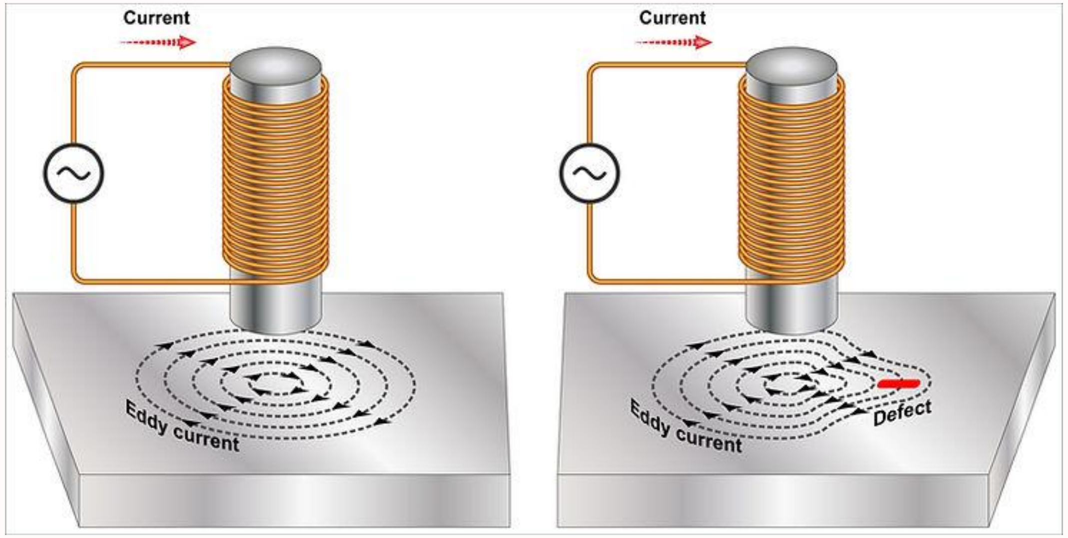




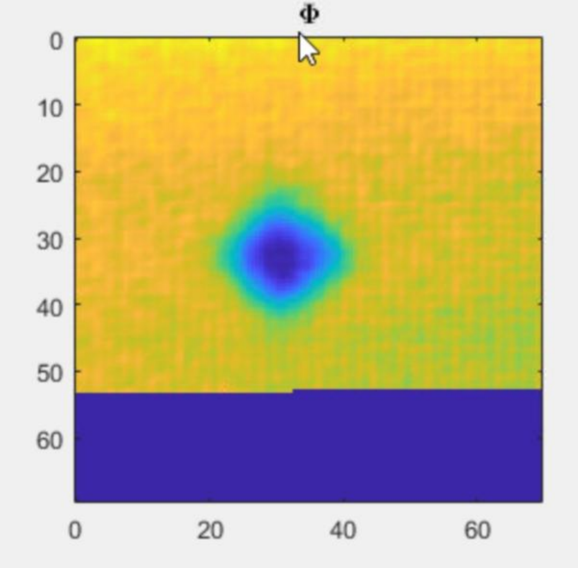
Aims and Objectives:

- Utilise Ultrasonic C-Scan to detect and characterise delamination damage.
- Develop and Implement a MATLAB-based post-processing tool for damage visualisation.
- Investigate the effects of different scanning parameters used in Ultrasonic C-Scanning.

Eddy current



https://www.amssolutions.co.th/post/what-is-eddy-current-testing-et



Principle

•Uses electromagnetic induction to detect surface & near-surface defects.

•Alternating current in probe coil → induces eddy currents in conductive material.

•Defects (cracks, corrosion, thickness changes) disturb current flow → measurable signal.

Applications in Aircraft

•Crack detection around fastener holes.

•Corrosion detection under paint/skins.

•Assessment of heat damage in aluminium alloys.

- **Advantages**

•Sensitive to small surface-breaking flaws.

•No need to remove paint or coatings (to some extent).

•Fast, portable, immediate results.

- **Limitations**

•Only works on conductive materials.

•Limited penetration depth (~few mm).

•Requires skilled interpretation.

Structural Health Monitoring (SHM)

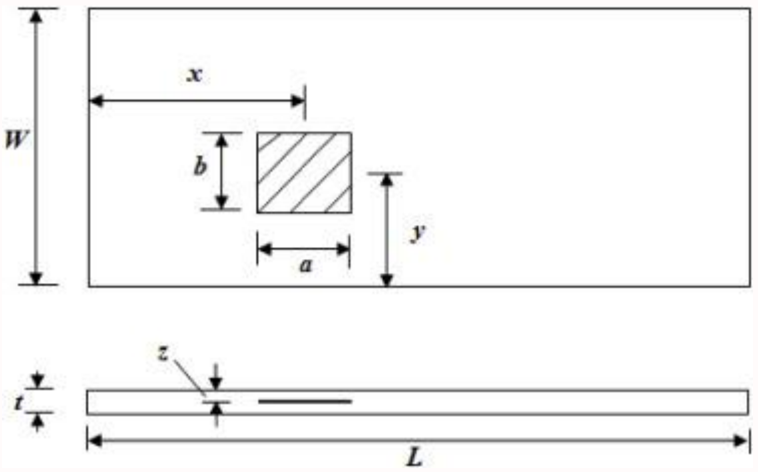
Definition: Continuous or periodic monitoring of aircraft structures using sensors and data analysis to detect damage, fatigue, or degradation.

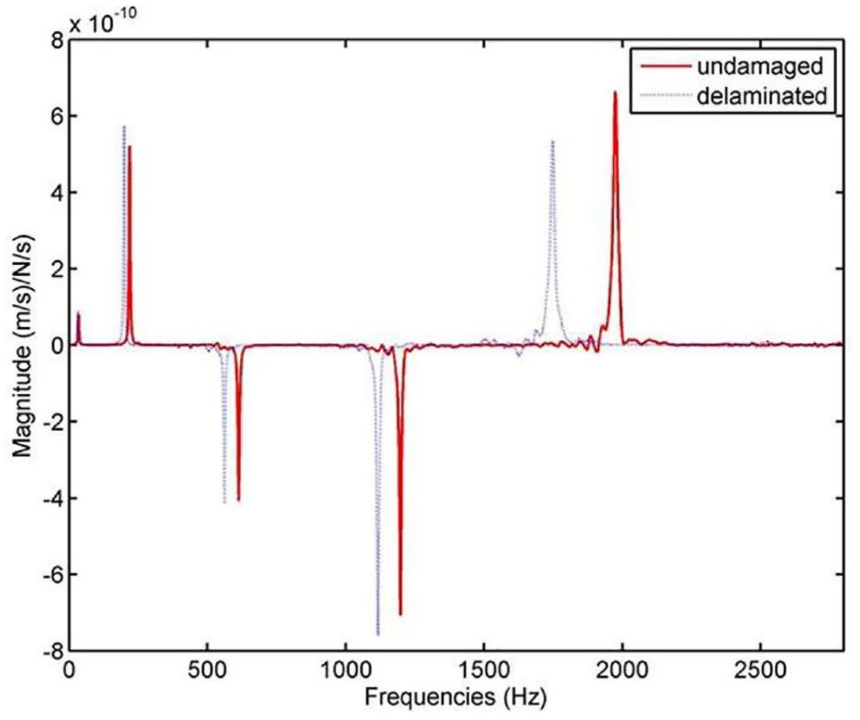
Key Components:

•**Sensors:** Strain gauges, fibre optics, acoustic emission, ultrasonic sensors

•**Data Processing:** Real-time analysis with AI & signal processing

•**Integration:** Embedded in critical structures (wings, fuselage, landing gear)





Benefits:

•Early detection of cracks, corrosion, and fatigue

•Reduced downtime and maintenance costs

•Increased flight safety & reliability

•Supports predictive maintenance strategies

Lessons Learned

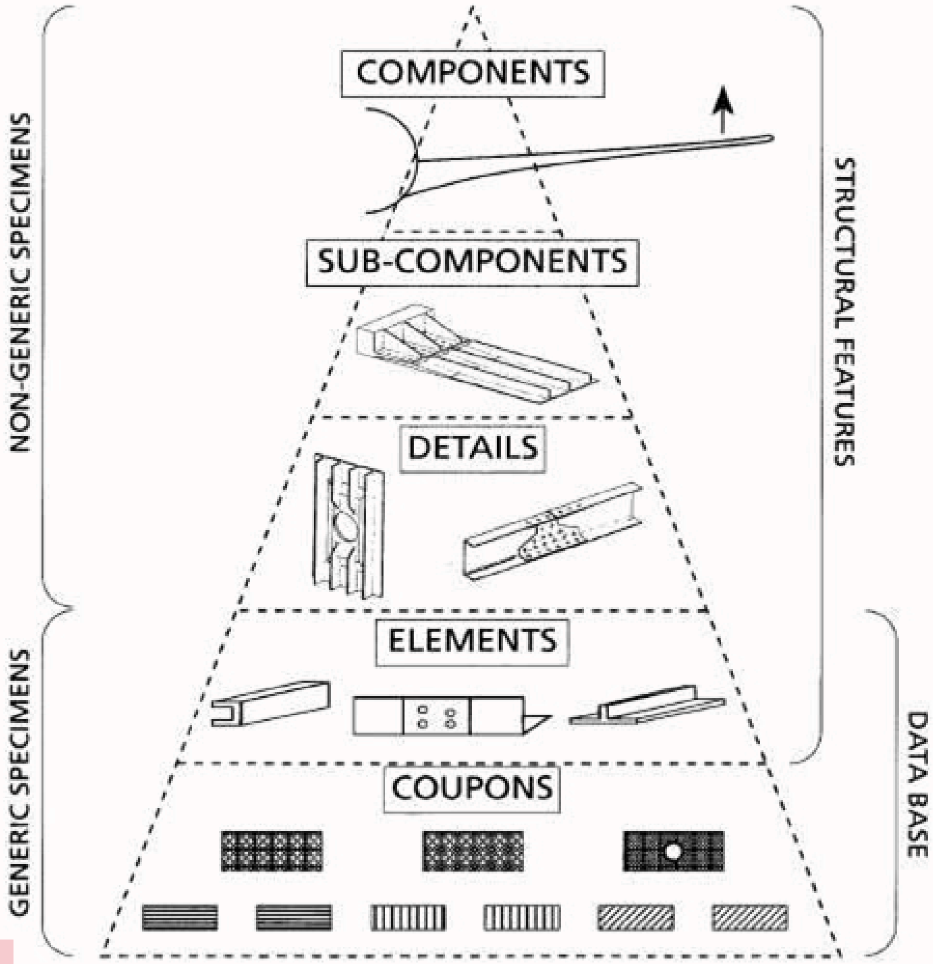
- This accident also demonstrated the need to **measure flight loads** for new designs of aircraft and to perform **full-scale fatigue testing**.

Testing Pyramid in Aircraft Certification

Concept: A structured approach from component level → system → full aircraft to ensure safety, reliability, and compliance with regulations (e.g., EASA CS, FAA).

Levels of the Pyramid

- Unit / Component Testing (Base): Lab tests on individual components (avionics, sensors, actuators).Verifies compliance with design requirements.
- Integration / Subsystem Testing (Middle): Combines components into subsystems (e.g., flight control system).Conducted in system rigs, Hardware-in-the-Loop (HIL) setups, and iron-bird testbeds.
- System & Ground Testing: Functional and environmental testing (EMC, vibration, temperature, lightning).Safety and redundancy checks.
- Flight Testing (Top): Real aircraft validation in operational environment. Confirms compliance with airworthiness requirements and performance standards.



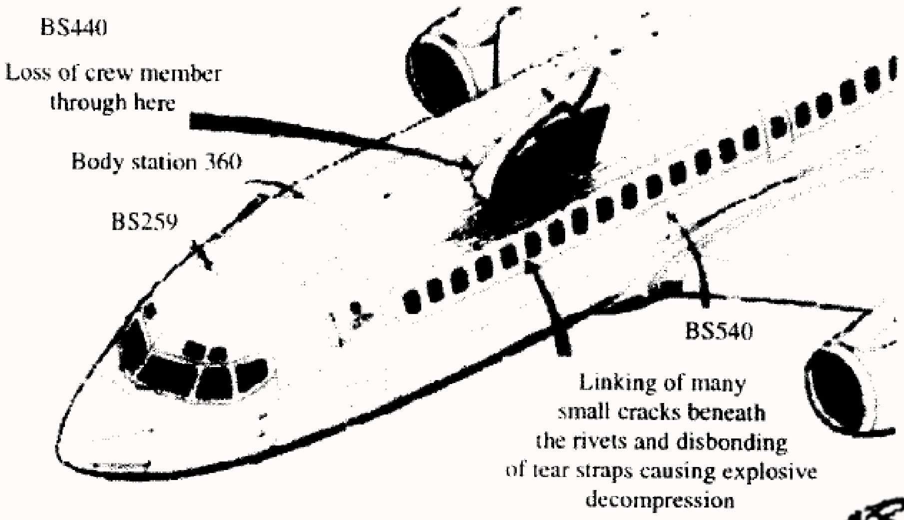
https://www.composites-certest.com/

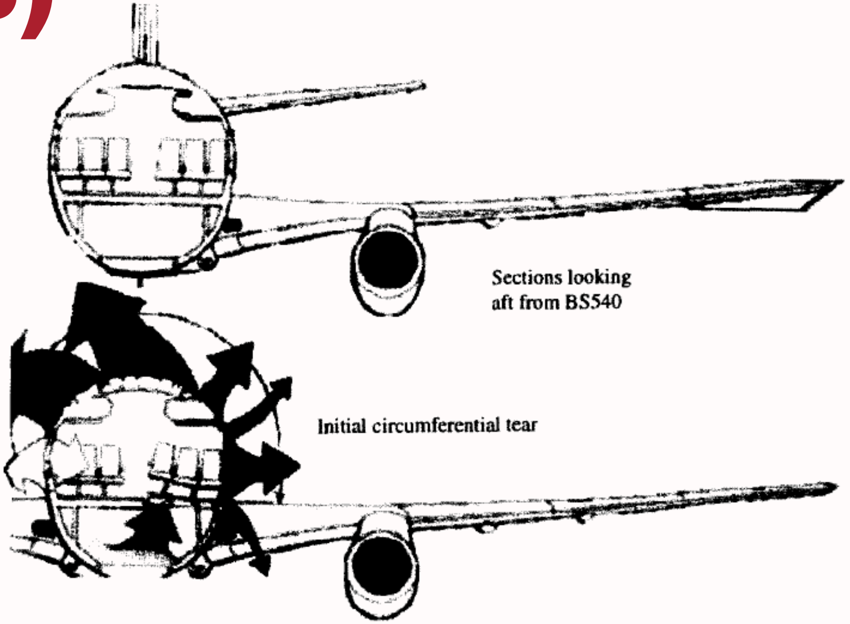
Aloha Airlines Accident (1988)

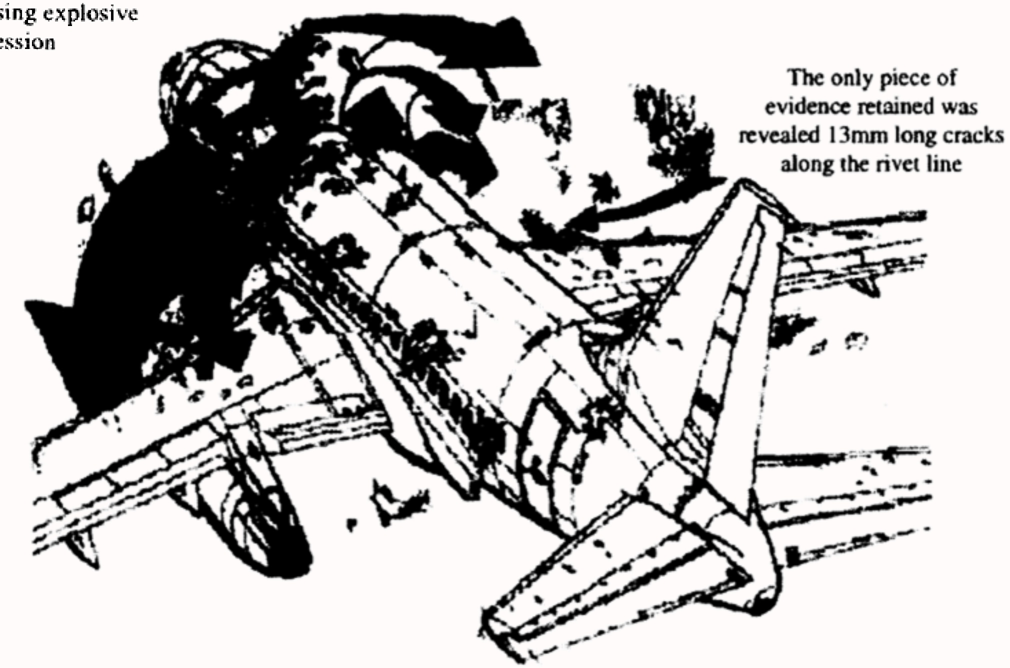
Aloha Airlines Accident (1998)

- In 1988, a Boeing 737-200 aircraft, operated by Aloha Airlines, had a sudden failure of the upper portion of the fuselage at a 24,000 ft. altitude over the Hawaiian Islands.
- The aircraft had flown for 19 years and had accumulated 89,680 flights, (approximately 13 flights a day). The aircraft had been designed for only 75,000 flights.
- The Boeing 737-200 was also designed to the fail-safe concept that was then permitted by the FAA.

Aloha Airlines Accident (1998)







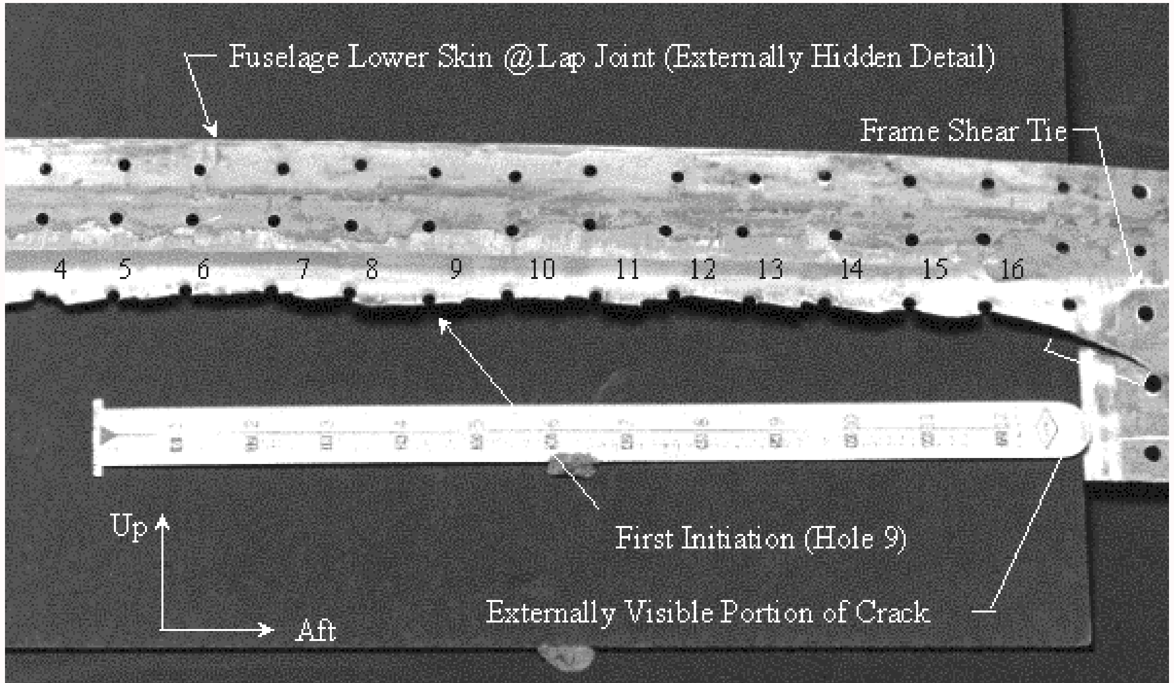
Ref: Multiple-site And Widespread Fatigue Damage In aging aircraft, S. Pitt and R. Jones, *Engineering Failure Analysis, Vol. 4~ No. 4, pp. 237 257, 1997*

Key slide!

Aloha Airlines Accident (1998)

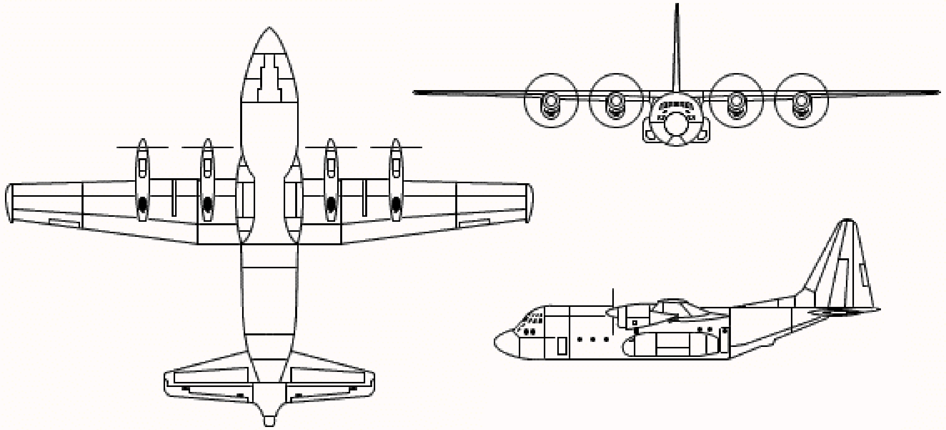
- The failure was attributed to several causes:
  - disbonding of a cold-bonded lap-joint,
  - corrosion at the joint,
  - multiple-site damage, and
  - inadequate inspections.

Example of a Multiple-Site Damage Failure



Lessons Learned

- The Aloha incident led to increased awareness of the aging aircraft phenomenon.
- Special attention was given to the phenomena of multiple-site damage, which can lead to widespread fatigue damage.
- This accident resulted in large-scale R&D by industry, the FAA and NASA on the subject of aging aircraft. This research confirmed that there is an escalating risk of failure of fail-safe structures as the aircraft ages.
- New FAA regulations were written, requiring a damage-tolerance assessment of aging fleets, which had not been originally designed to the damage-tolerance regulations.



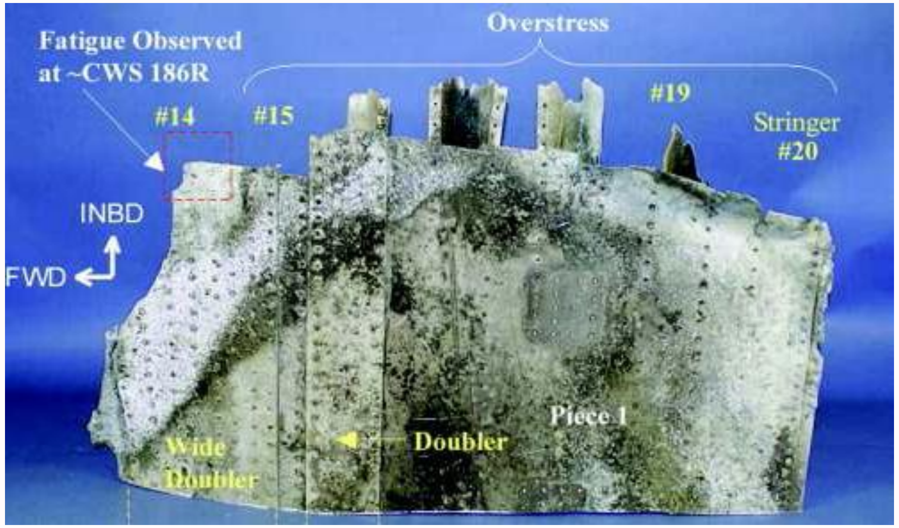
Lockheed C130A Firefighting Tanker (1994,2002)

Lockheed C130A Firefighting Tanker (1994,2002)

- In 1994, a firefighting tanker aircraft had its right wing detached in flight. The accident was originally attributed to an explosion caused by leaking fuel.
- In 2002, a 45 year old C130A firefighting tanker aircraft had its wings fail in flight. Metallurgical investigation of the wreckage showed extensive fatigue damage to the wings.

Lockheed C130A Firefighting Tanker (1994,2002)

- It is believed that the low-level flight, resulting in severe turbulence, together with violent manoeuvres performed during firefighting, were probably responsible for the failures.
- The C130 was not originally designed for this loading spectrum.



Fatigue damage observed on C130A wing

Fatigue damage to center wing of C130A aircraft

Lessons Learned

- The lesson learned from the C130A failures is that new missions can result in new loading spectra that are significantly more severe than the original design spectrum!

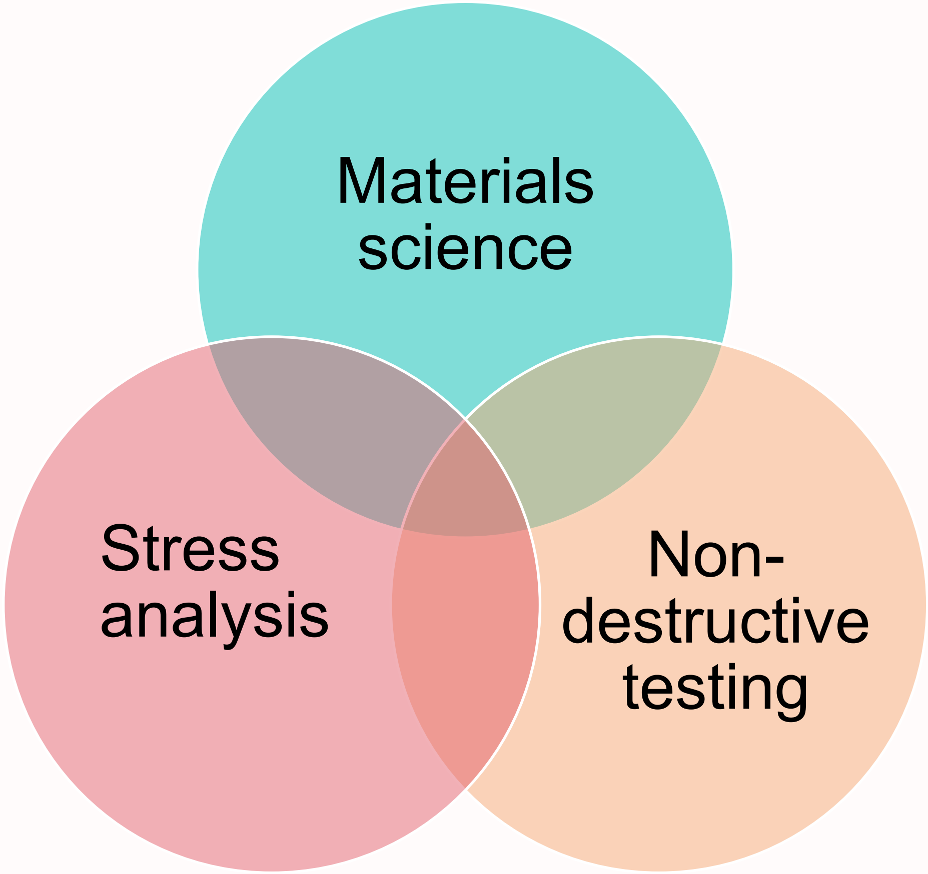
What can history tell us?

Aircraft Structural Integrity - History

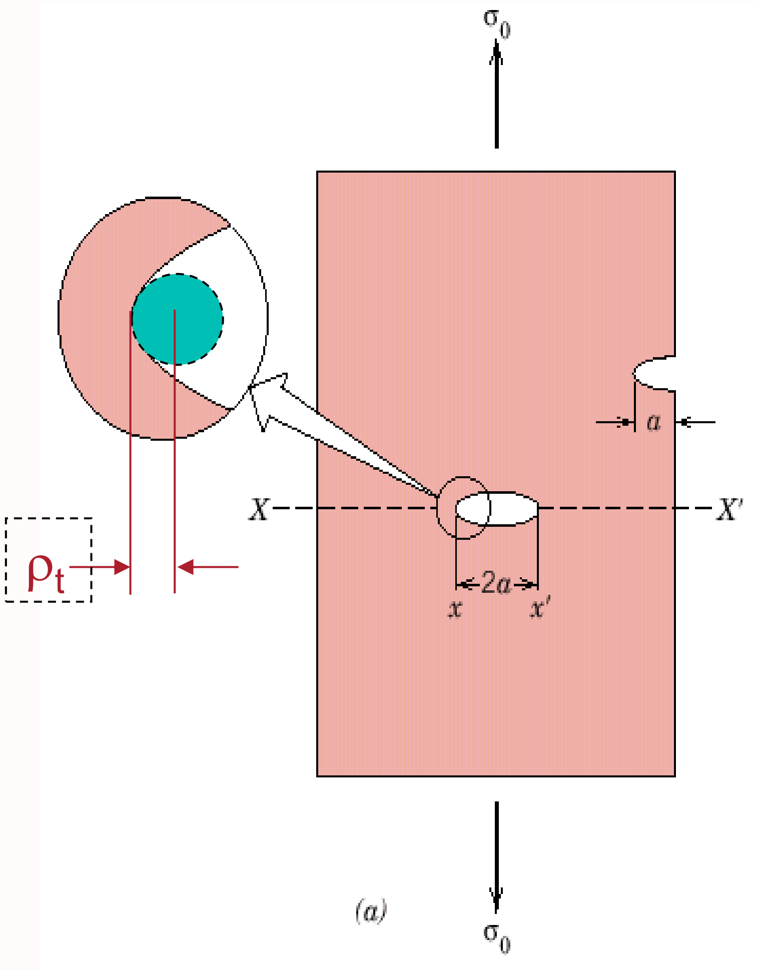
- 1930 – 1940
  – Commercial development of metal aircraft for public transport. Design and analysis emphasized static strength, with little or no consideration of airframe fatigue
- 1940 – 1955
  – Increasing awareness of importance of fatigue for airframe safety. Materials with higher static strengths were developed without corresponding increases in fatigue strength. Design became based on both static and fatigue strengths.
- 1955 – present
  – Development of fail-safe and damage tolerance design methods, which recognise that airframe structures must withstand service loads even when damaged and cracked. Safety to be ensured by testing and analysis of damaged structures, pre-service and in-service inspections, and eventual repairs and replacements.

Fracture mechanics questions

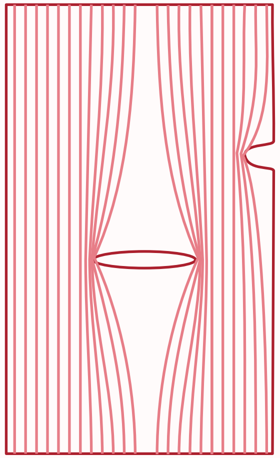
- What is the critical length of crack?
- For a given crack length, what is the residual strength
- What is the time that would take for the crack to grow
- How is the NDT schedule decided
- What causes crack to branch
- What are the energy dissipating mechanisms



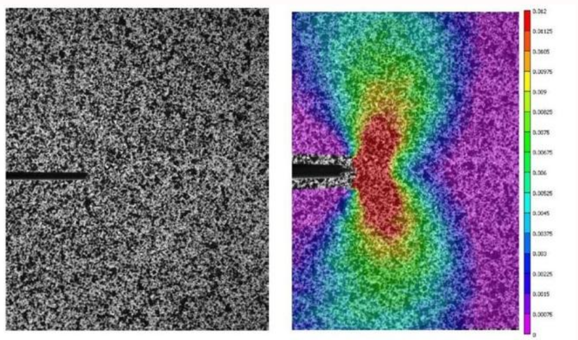
Flaws introduce Stress Concentrations



- Griffith Crack (this will be discussed in detail next time)
- Some important parameters
  - a = crack size
  - ρ_t = radius of curvature
  - σ_o = applied stress
  - σ_m = stress at crack tip



Closer the line spacings, higher the stress



Summary

- Damage-tolerant design is an engineering approach that aims to ensure a structure can continue to perform safely even if it contains defects or damage.
- Key Concepts:
  - Crack Growth: The design considers how small cracks might grow over time under repeated loads (fatigue) and ensures that the structure can tolerate this without catastrophic failure.
  - Inspection Intervals: The design often includes guidelines for regular inspections to monitor any damage, allowing for repairs before a critical failure occurs.
  - Redundancy: Incorporating multiple load paths so that if one fails, others can carry the load.
- In summary, damage-tolerant design focuses on ensuring safety and functionality even in the presence of damage, extending the life and reliability of critical structures.