Reliable Products and Structures

John Orr Lecture

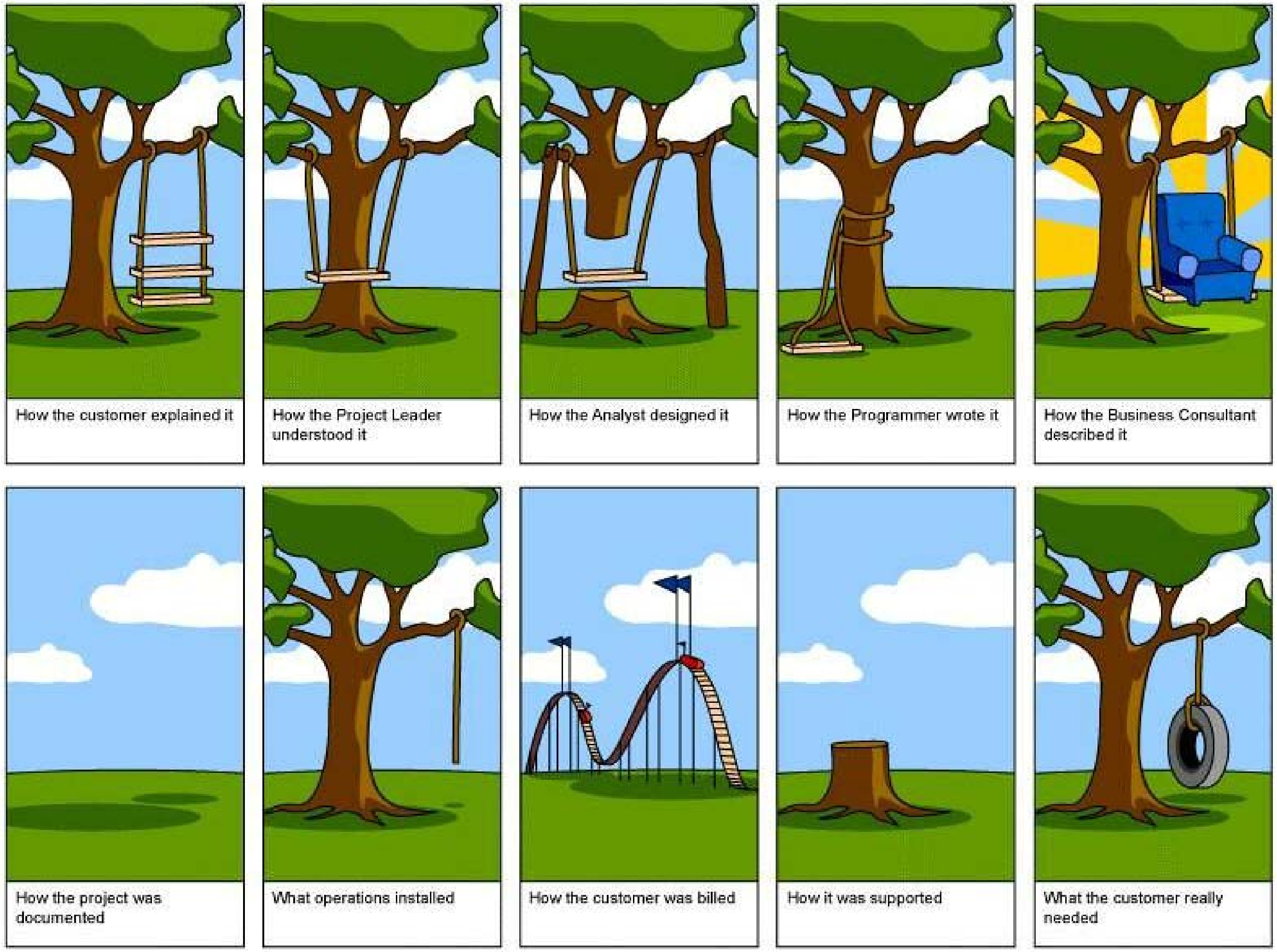
M Neil James

South African Institution of Mechanical Engineering

Outline

- What constitutes reliability?
- Systems analysis and characterisation
- Causes of failure
- Achieving reliability
- Conclusions
- Case studies in failure analysis

Reliability Requires Communication



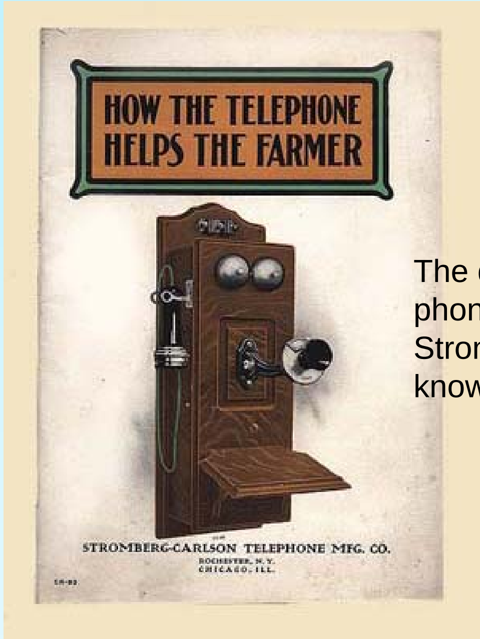
MATERIALS, ENGINEERING & MAN - BENEFITS & RISK

LEVEL OF MATERIAL PROPERTIES	ENGINEERING CAPABILITY	USAGE	BENEFIT	RISK	RELIABILITY
INTRINSIC Glass, Stone, Brick, Wood Native Cu, Sn, Au, Ag, Fe Natural Rubber/Glues	**PRE-INDUSTRIAL** Based on Experience (Guilds) Resolving Power - 1x (Eye) Little Understanding of Structure/Property Links	**LIMITED** Mainly Utility Items Quality Variable With Status High Apparent Craftsmanship at Upper Echelon	**LOW** in Life **HIGH** in Death	**LOW** to User **HIGH** to Maker/Tester **NIL** to Capitalist *Caveat Emptor*	**ACCEPTABLE**
ENHANCED BY ENGINEERING Vulcanised Rubber Stainless Steels Carbon Steels Large Castings Fusion Welding	**PRIMARY INDUSTRIAL (SMOKE STACK)** Basic Property Testing Resolving Power - 1000x (Microscope) Limited Structure/Property Knowledge Life Prediction Impossible Life Assurance by 'Factor of Safety'	**WIDE** Mass Production Craftsmanship Present - Often Bypassed by Poor Function/Performance	**HIGH** in Ease of Living **LOW** in Quality of Life **FAIR** in Death	**HIGH** to Workers **HIGH** to Operator **LOW** to Capitalist **HIGH** to Insurer *Engineering Insurance*	**LOW** (At Frontiers of Knowledge) • Titanic • Liberty Ships • Comet • Cleveland LNG
CONFERRED BY ENGINEERING Materials-Related Composites - Laminated Glass - Fibre and Particle Reinforced Shape Memory Alloys DS and SC Turbine Blades Electronic Materials Optical Materials Processing/Fabrication Near-Net Shape Processing - Extrusions -Investment Casting - Semi Solid Forming Bonding Dissimilar Materials - Explosive Welding - Diffusion Bonding	**SECONDARY INDUSTRIAL (HIGH TECHNOLOGY MICRO-PROCESSOR CONTROL)** Sophisticated Testing Resolving Power - 1 atom (FEM) Deep Understanding of Structure/Processing/Property Relationships Defect Tolerant Design Fracture Control Plans	**GENERAL** Individual Craftsmanship Bypassed by High Quality Automation Change From Spiritual Outlook to Materialistic One?	**'LUXURY'** Items Now Available Generally **JOY** of Ownership **LOW** in Death* (Fast Obsolescence)	**LOW** to Workers **LOW** to Operators **HIGH** to Capitalist **ACCEPTABLE** to Insurer *Product Liability Insurance* *Loss of Profits Insurance*	**HIGH/VERY HIGH** (Occasional Severe Human Error) • Alexander Kielland • Challenger • RO-RO Ferries

Reliability rests on a long history of scientific and engineering achievement

What Constitutes Reliability?

Ceramic bidet



The quality and reliability of its phones in rural areas led Stromberg Carlson to became known as "the farmer's friend"

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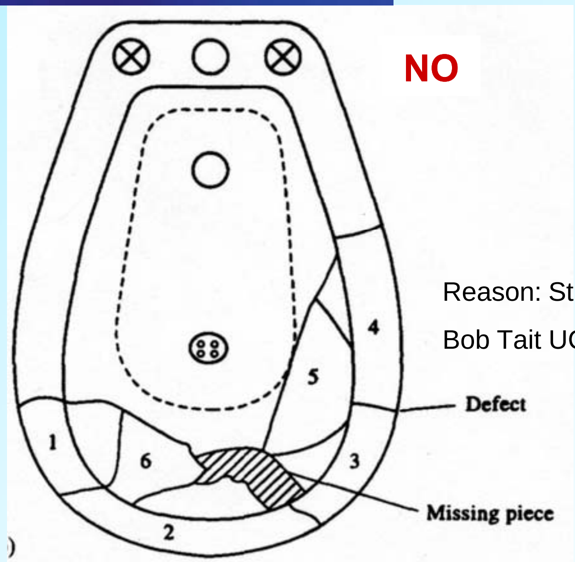
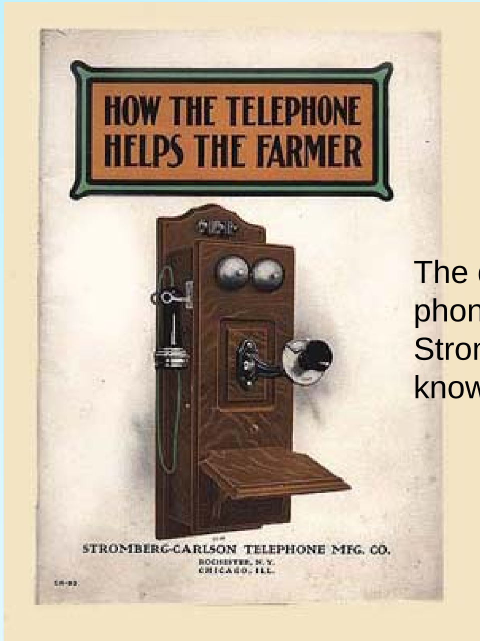


NO

Reason: Stress-corrosion cracking

Bob Tait UCT



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What Constitutes Reliability?

Point Pleasant bridge over Ohio River, West Virginia, December 15 1967

Ariane 5, 1996

Aloha Airways 737 Hawaii, 1988

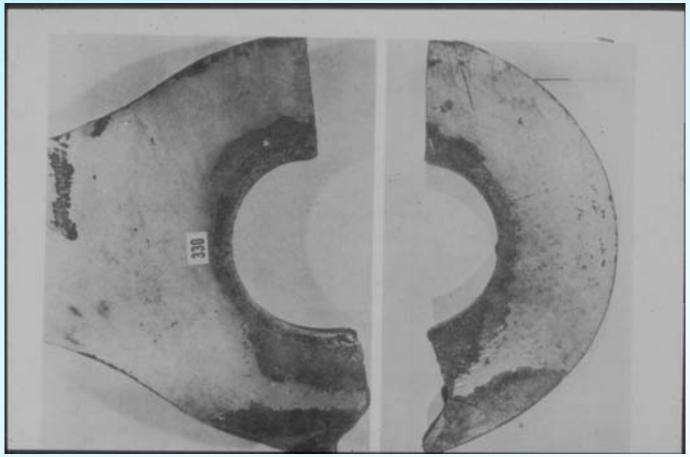
B2 Stealth bomber, 2008

What Constitutes Reliability?

Reason: Stress-corrosion cracking

NO

Point Pleasant bridge over Ohio River, West Virginia, December 16 1967



- Bridge built 1920’s from new high strength steel (UTS = 840 MPa)
- Design stress = 350 MPa, Eye-bar k_t = 2.7
- Fracture from 0.12" (3 mm) crack in tie-bar 55' long, 2" thick, 27.5" across eye
- Paint on fracture surface

What Constitutes Reliability?

- Crashed shortly after take-off at Guam
- Four flight control system computers translate cockpit input into control surface movement
- Moisture distorted air-pressure readings
- Re-calibrated by maintenance crew – then evaporated
- B2_Bomber_Crash_Guam.flv (1:50)

- Pressure differences were miniscule, but they were enough to confuse the FCS
- FCS took control; triggering a premature takeoff, automatically driving the aircraft into a 30-degree, nose-up pitch and overruling the pilot's efforts to regain control

What Constitutes Reliability?

Ariane 5, 40 seconds later 1996

- Ariane 5 launch vehicle failed on its maiden flight in June 1996
- About 40 seconds after lift-off the launcher veered off its flight path, broke up and exploded
- High aerodynamic loads due to an angle of attack > 20° led to separation of the boosters from the main stage, in turn triggering the self-destruct system of the launcher

Software problem arose from a numeric overflow in the Inertial Reference System program during conversion of a 64-bit to a 16-bit number

The piece of code had been originally written for the Ariane 4 and was reused in the Ariane 5

The bug caused both Inertial Reference Systems to crash

Ironically, the code was superfluous once lift-off occurred

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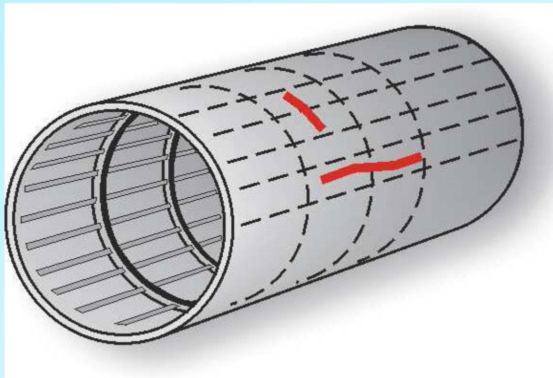
What Constitutes Reliability?

- ‘Cabriolet’ conversion shortly after take-off at 350 mph and 24,000 feet
- Everyone belted in their seat survived
- Illustration of damage-tolerance by fuselage of a ‘two-bay’ crack
- Multi-site corrosion-fatigue cracks at rivet holes on lap joint
- Scrim cloth and adhesives absorbed water and became brittle
- Poor maintenance inspection record
- Passenger noticed a 120 mm crack on embarkation
- Aloha737.mov



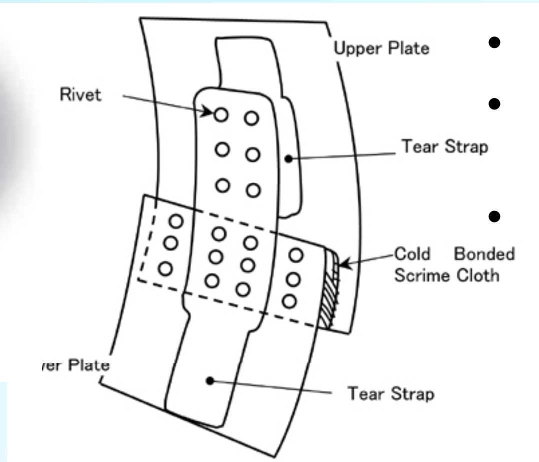


Fig.3 Bonded and Riveted Lap Joint of B-737 Fuselage

What Constitutes Reliability?

Lufthansa A320 Hamburg, 2008

- Strong crosswind as storm cell passes across Germany
- Gusts up to 50 knots (93 km/h)
- Illustration of damage-tolerance of wing under impact conditions
- Just before the final touchdown, there was a gusting crosswind from the side
- Aircraft's left wing-tip struck the runway
  - Bends wing-tip fence
  - Causes minor damage to the wing surface
- Crew aborted landing
- Lufthansa A320 Movie

What Constitutes Reliability?

Depends on viewpoint – user or manufacturer

- User would like zero failures – hence warranty
- Manufacturer accepts a level of failure
  - Design for a statistically reliable failure rate
  - Put in place quality assurance systems
  - Learn from history
- Some SME's do not explicitly consider likelihood and consequences of failure – e.g. bidet

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Define a reliable product or structure as:

One that operates in the expected way, for the anticipated life and with the estimated costs

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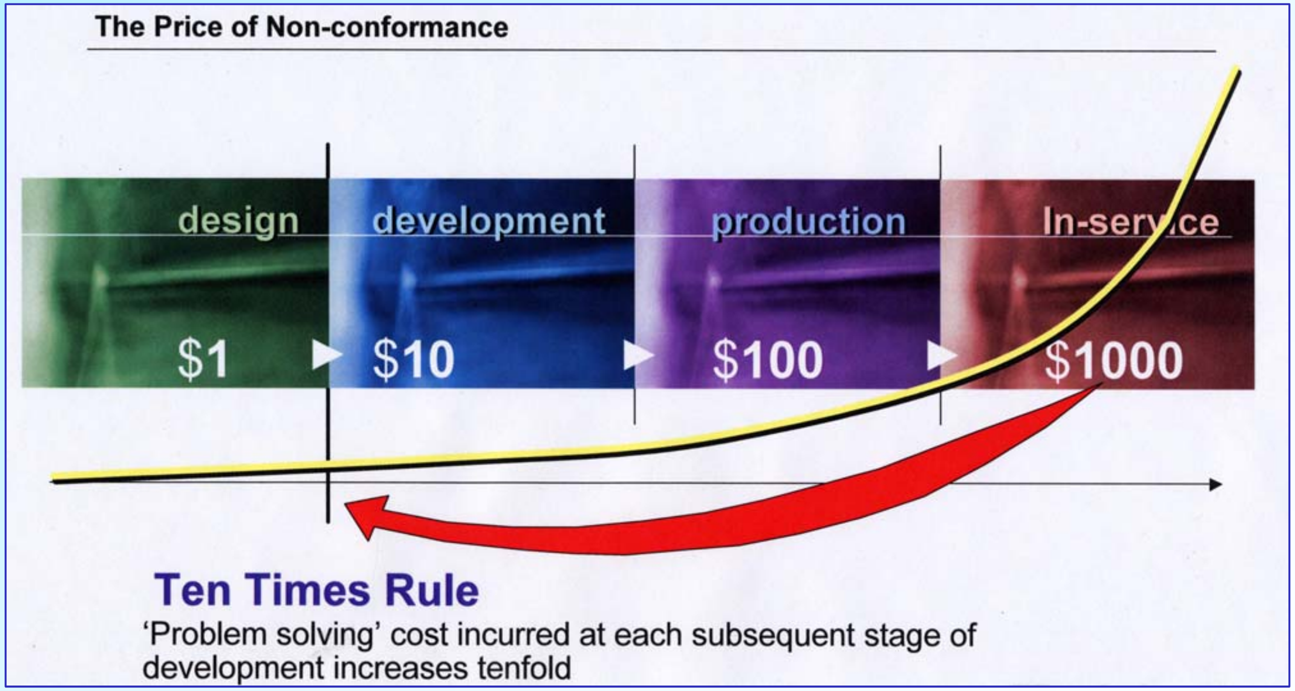
What Constitutes Reliability?

A product or structure that is characterised by:

- Maximised return on investment
  - Cost–optimised manufacture/fabrication, operation and retirement – **develop for reliability**



What Constitutes Reliability?

A product or structure that is characterised by:

- Maximised return on investment
  - Cost–optimised manufacture/fabrication, operation and retirement – **develop for reliability**
  - Requires organisations to become **knowledge-sharing enterprises**
    - Capacity for making explicit the implicit knowledge of employees
      - Best practices
      - Lessons learned
      - Boundary conditions and short cuts
    - Ability to continually develop the knowledge base through fast learning and innovation
    - Proactive real-time knowledge management

The University of Plymouth

What Constitutes Reliability?

A product or structure that is characterised by:

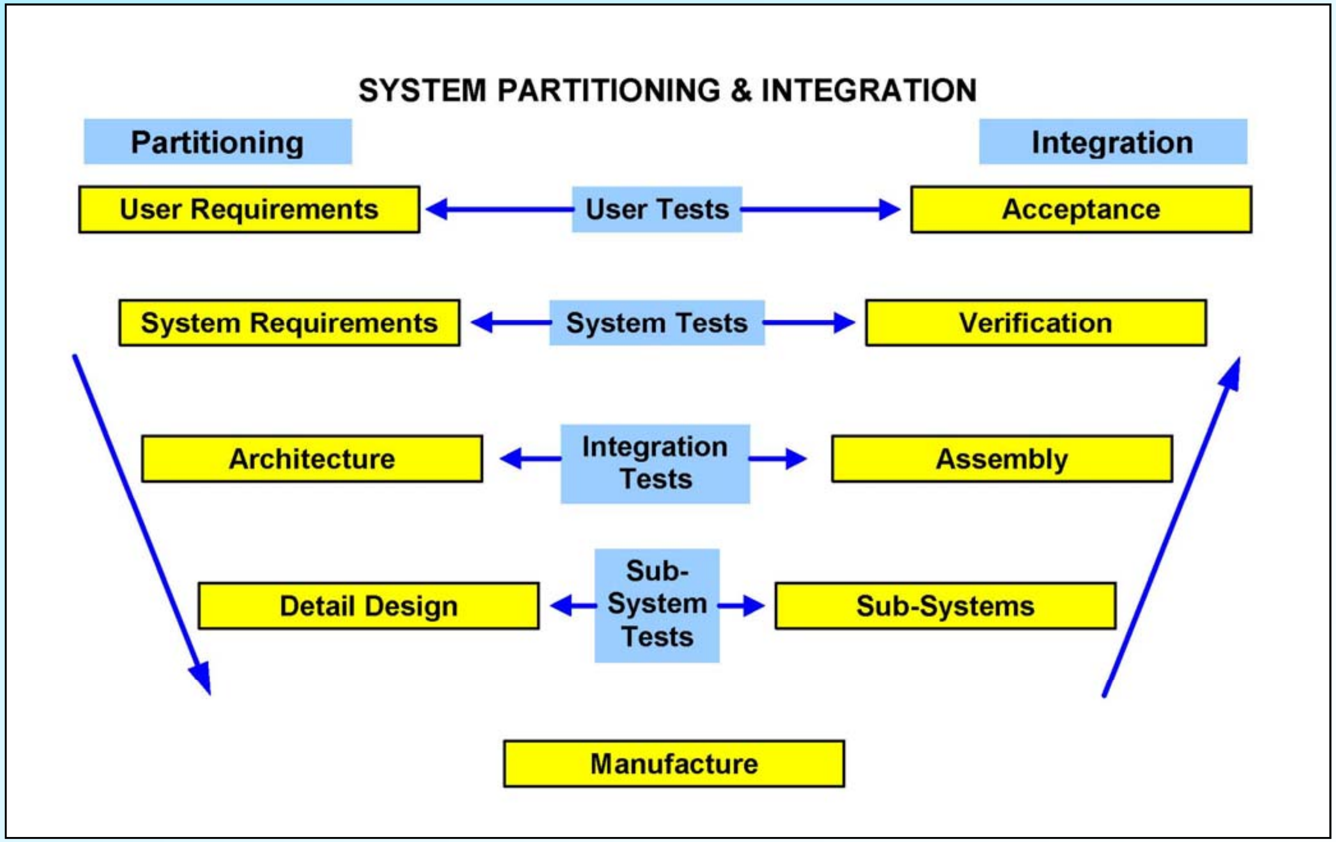
- Achievement of specified service reliability
  - Probabilistic risk assessment
    - Integrate diverse aspects of design and operation in order to assess the risk
  - Appropriate modelling and testing
  - Structural health monitoring through built-in test equipment (BITE)
- Defect-tolerance and fail-safe operation
  - Appropriate inspection intervals and procedures
  - Alternate load paths and critical systems

Complication: Many products and structures are actually complex systems ⟶ difficult analysis

- **Need tools to characterise systems**

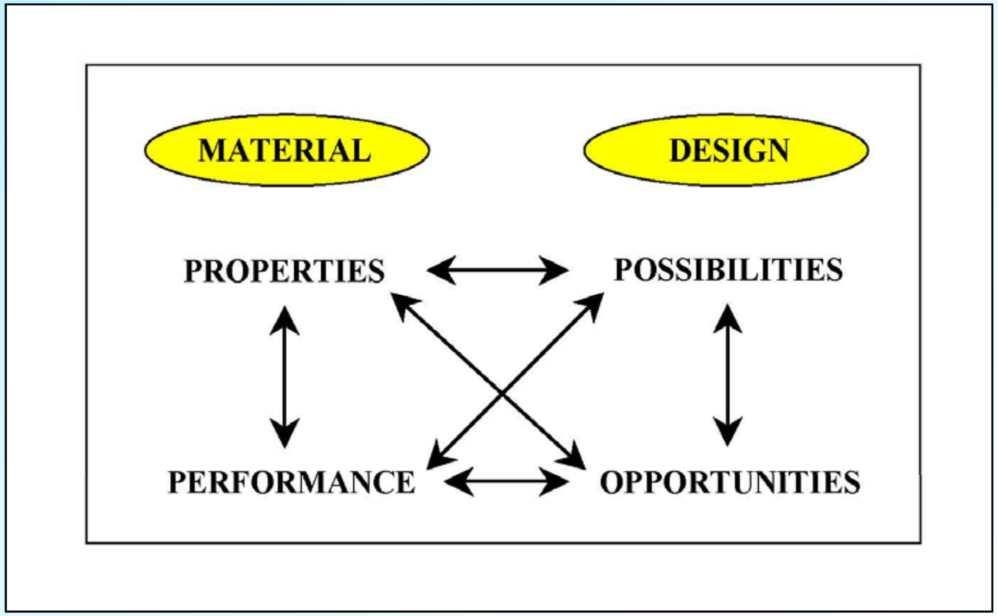
Systems Analysis and Characterisation

- Complex systems require partitioning and concurrent consideration



Systems Analysis and Characterisation

- Have opportunity for innovation at each stage of the analysis
  - ➢ Explicitly consider material/design interactions
  - ➢ Seek opportunities from innovation in materials or fabrication/manufacturing



•below.

Systems Analysis and Characterisation

- Probabilistic reliability/risk assessment of systems and sub-systems involves cause-result analysis
  - Integrate diverse aspects of design and operation in order to assess the risk
  - Develop a set of possible casualty sequences and determine their outcomes
  - System models consist of event trees and fault trees

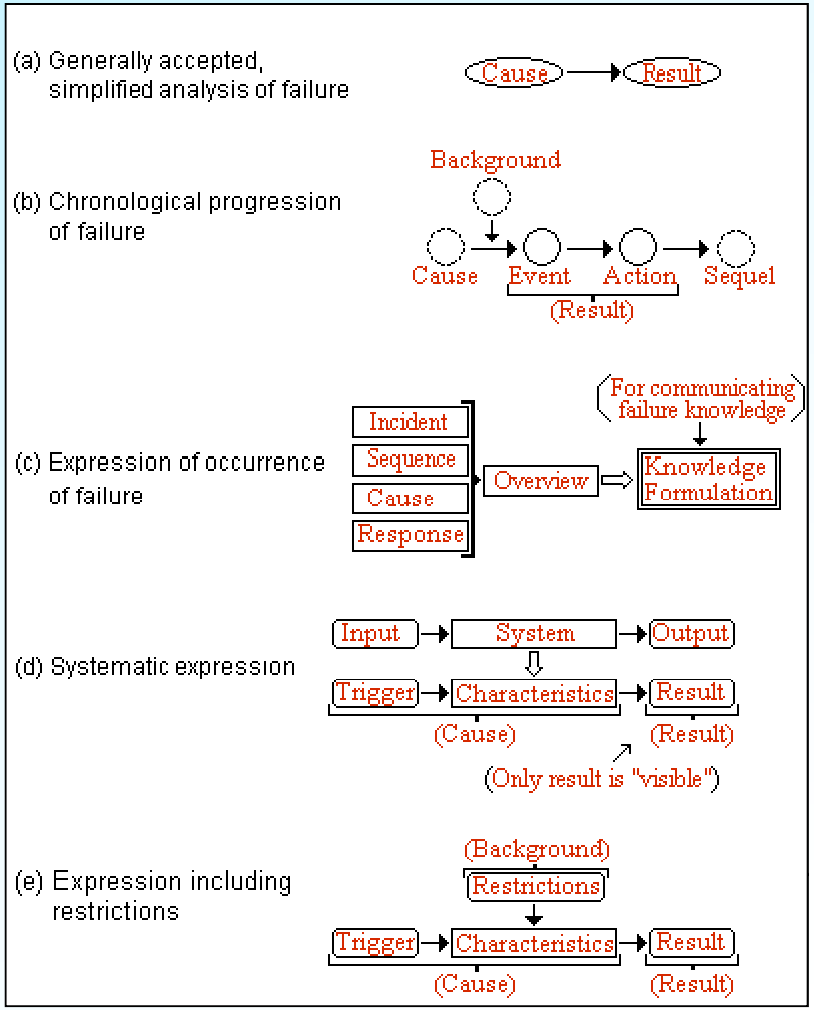


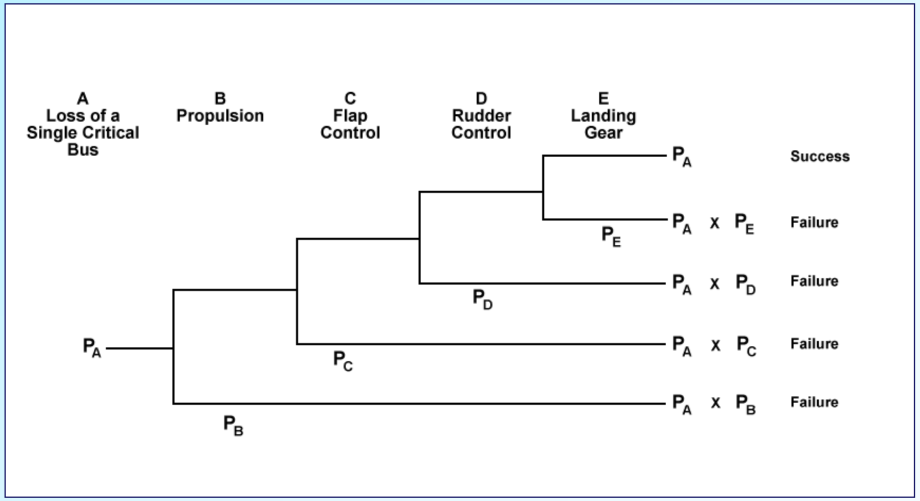
Diagram from Japan Science and Technology Agency website

http://shippai.jst.go.jp/en/Search

Systems Analysis and Characterisation

Systems models to achieve service reliability

- Event trees
  - Depict initiating events and combinations of system successes and failures
  - Event sequence analysis maps how the outcome of a desired objective (e.g. a flight) depends on the performance of critical systems (A-E)



Sum of event sequence failure probability gives aircraft accident probability

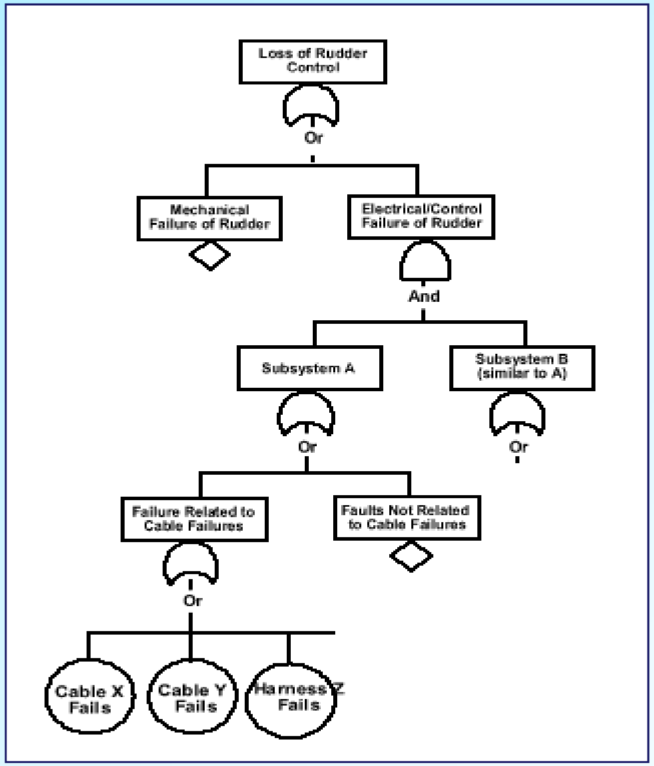
≡ <1 death in 10^8 passenger miles

Sample event tree – event sequence analysis for cable bus

Systems Analysis and Characterisation

Systems models to achieve service reliability

- Fault trees
  - Depict ways in which the system failures represented in the event sequences can occur



- Hierarchical logic model is developed
  - Defines all of the combinations of system, subsystem, component, and subcomponent faults that will result in the top event failure

Sample fault tree – system failures leading to loss of rudder control

Systems Analysis and Characterisation

Systems models to achieve service reliability

- Failure mandalas* - defined by the JST Agency
  - Depict hierarchical relationship between the elements that make up the components of failure

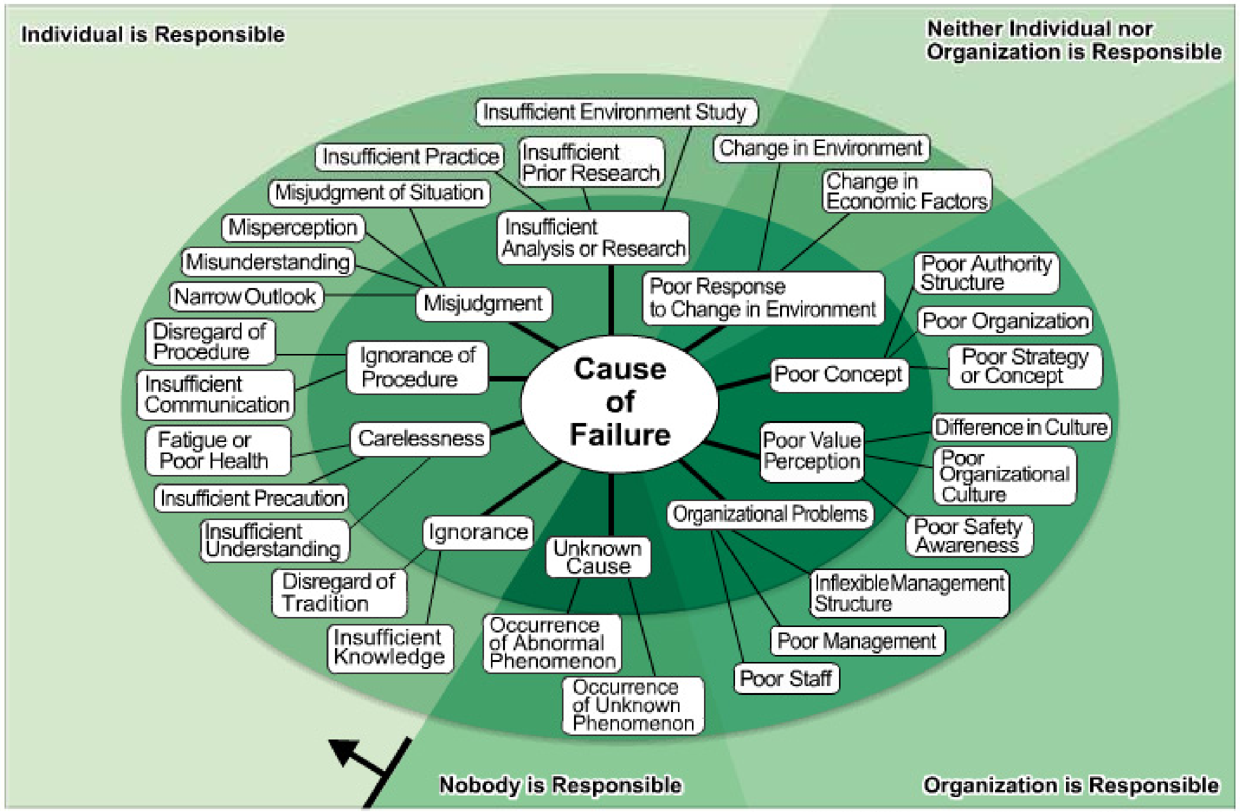
CAUSE → ACTION → RESULT

  - Core concept is at heart of the mandala
  - First and second ring elements are applicable to any field
  - Third level elements are intended to be field specific

*Mandalas are a Buddhist representation of the Universe

Systems Analysis and Characterisation

CAUSE → ACTION → RESULT



by JST Hatamura Committee 2002

Systems Analysis and Characterisation

CAUSE → ACTION → RESULT

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Systems Analysis and Characterisation

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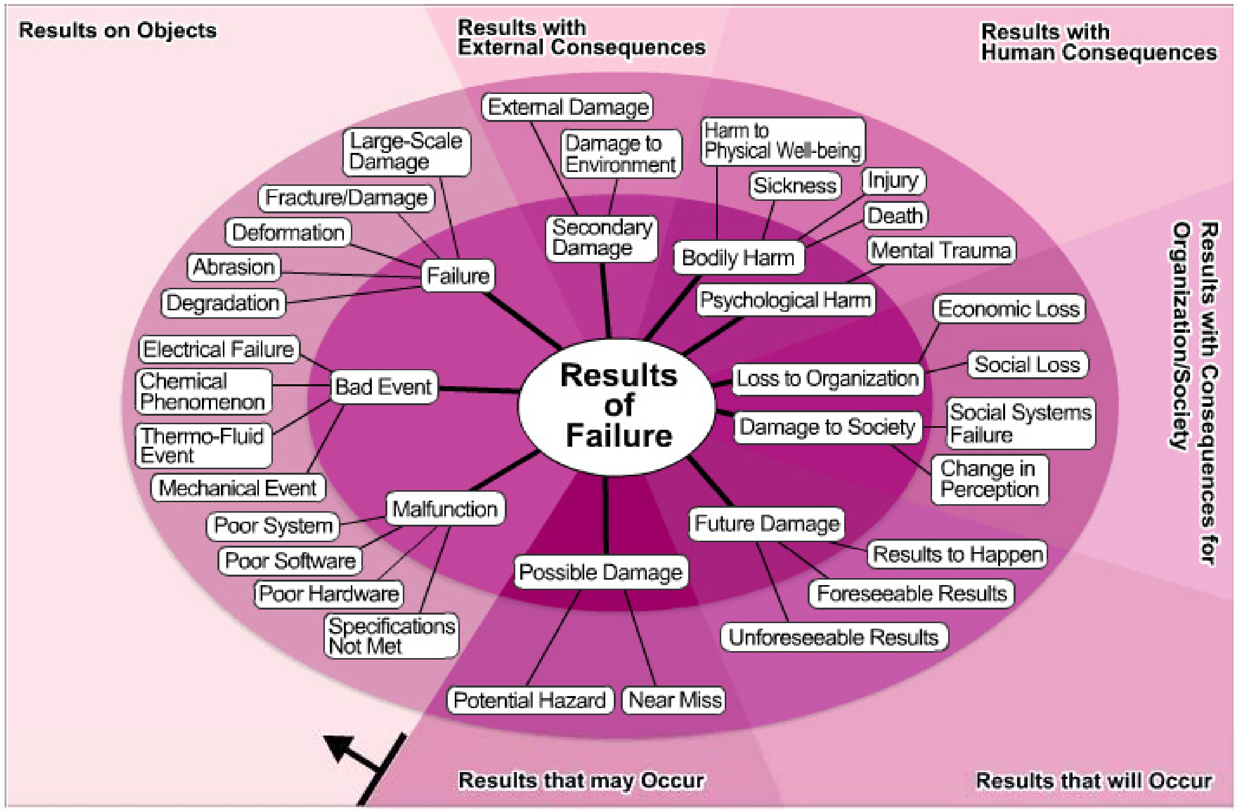

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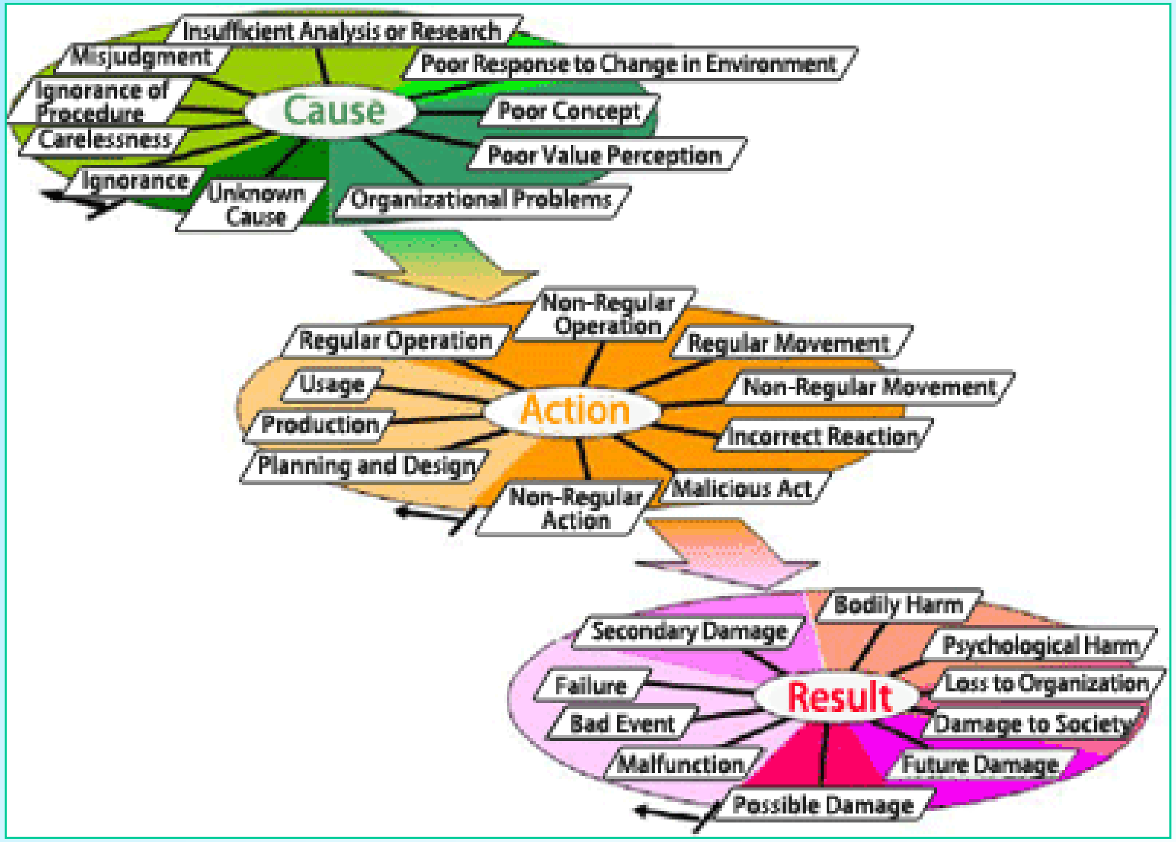
Systems Analysis and Characterisation



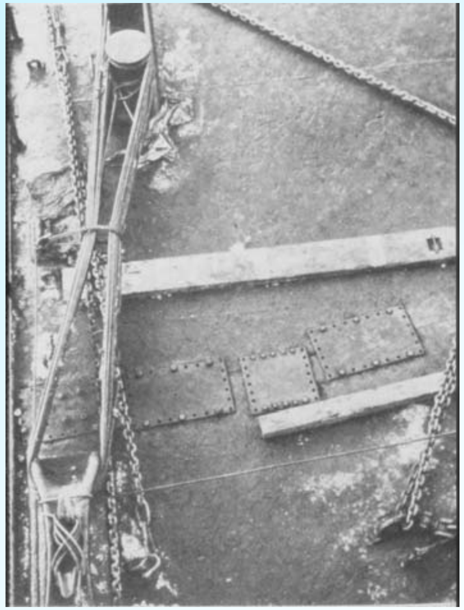
The "flow" down from Cause through Action to Result for any particular scenario can be easily understood and communicated

Causes of Failure

Include:

- Inappropriate design, fabrication or manufacture
- Inadequate management of the design process
- Human-system interactions which are not fail-safe
  - Flawed operational decision support systems
  - Dangerous sequences of actions
  - Inappropriate inspection or maintenance procedures
- Software and firmware problems
- System and structural complexity
  - New technology
- Human error

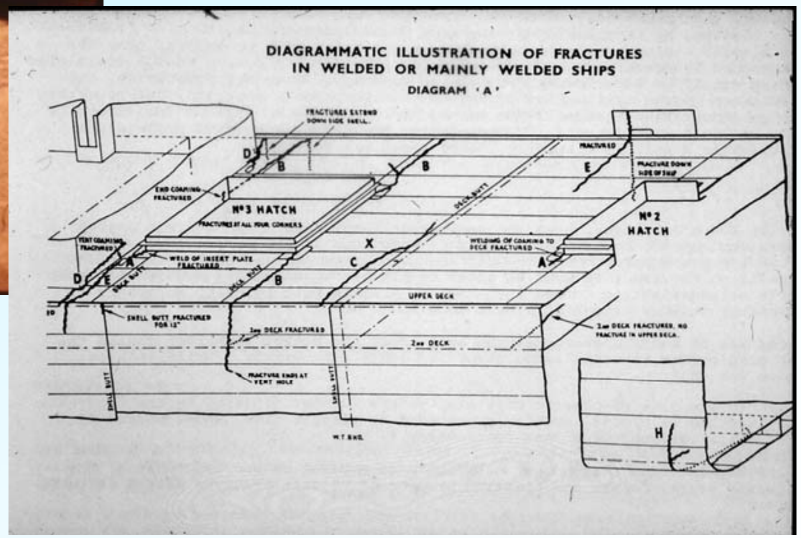
Causes of Failure



Inappropriate design, fabrication or manufacture

- Liberty ships - 1942

New fabrication technology (welding) for traditional design (rivets)



Causes of Failure

Inadequate management of the design process

- Alexander Kielland oil accommodation platform – delivered July 1976, failed March 1980
  - Uncontrolled design changes late in partitioning or integration stages

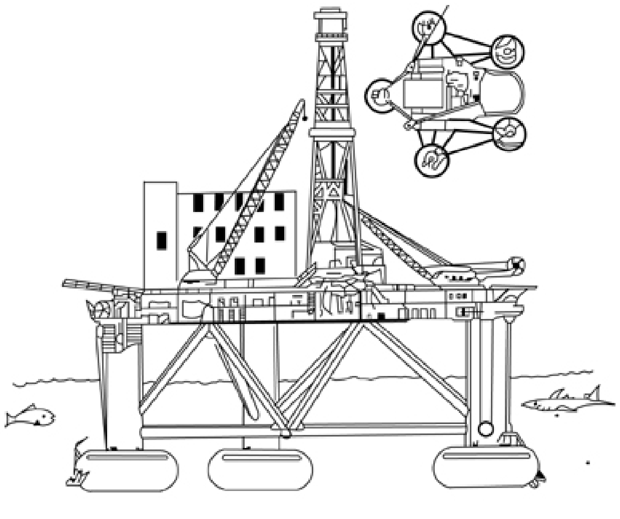
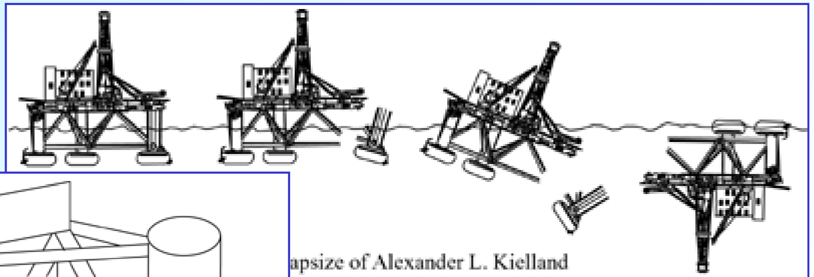


Fig. 2 Alexander L. Kielland



apsize of Alexander L. Kielland

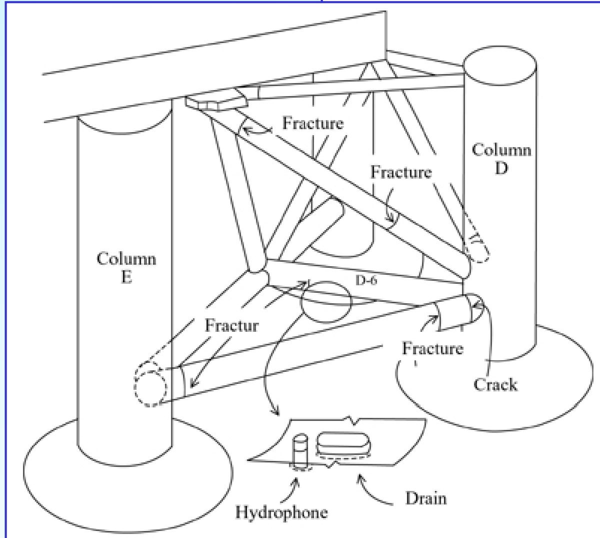
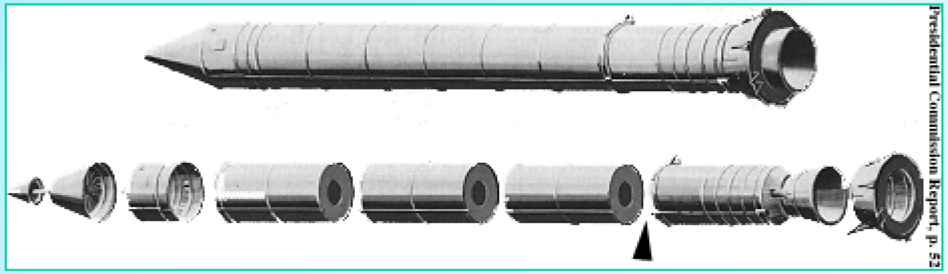


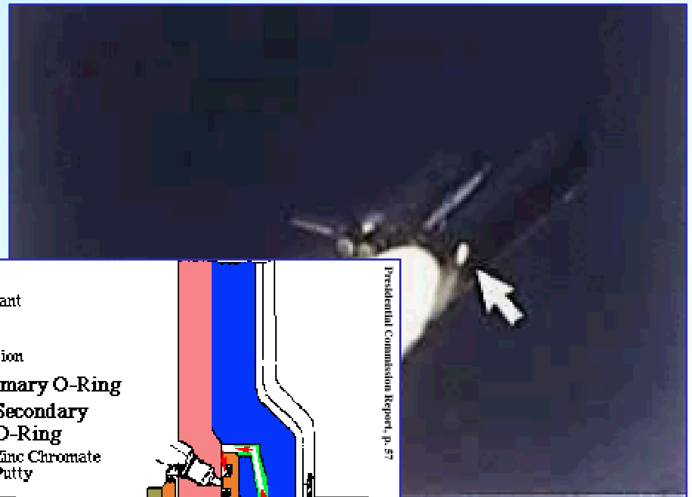
Fig.5 Position of hydrophone and bracings connected columns

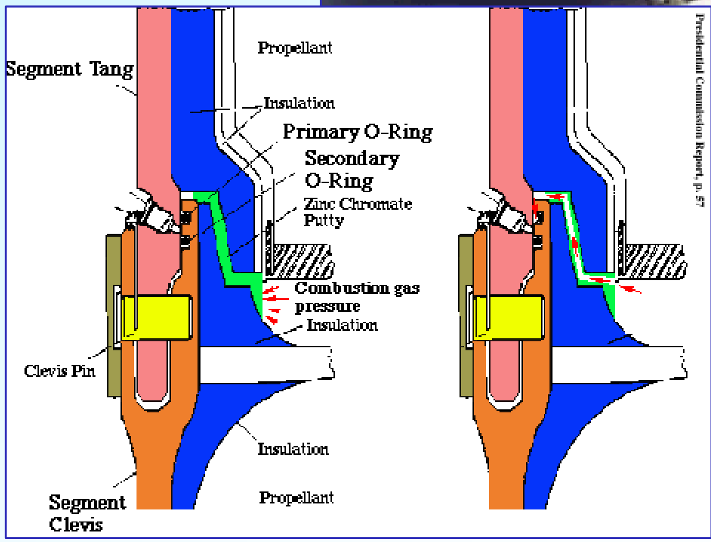
Causes of Failure



Human-system interactions which are not fail-safe

- Flawed operational decision support systems
  - Challenger space shuttle

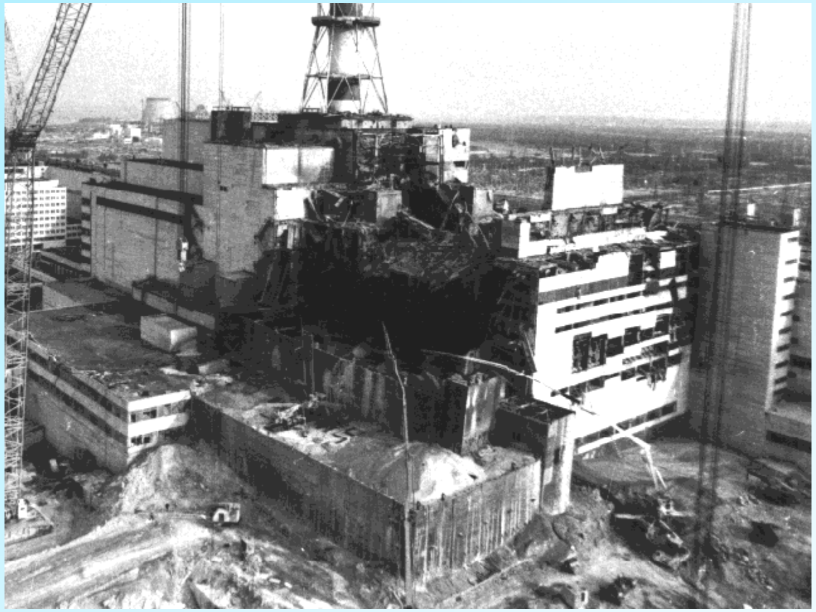




Causes of Failure

Human-system interactions which are not fail-safe

- Dangerous sequences of actions
  - Chernobyl Nuclear Reactor



Non-routine test operation:

- Isolation of the emergency core cooling system – had this been operational it might have reduced the impact of the accident
- Operation at low power levels (<< 700 MW) led to known reactor control rod instability
- Operation of additional core cooling pumps, which reduced the level of water in the steam separator

Test performed by night shift

Poor knowledge of characteristics

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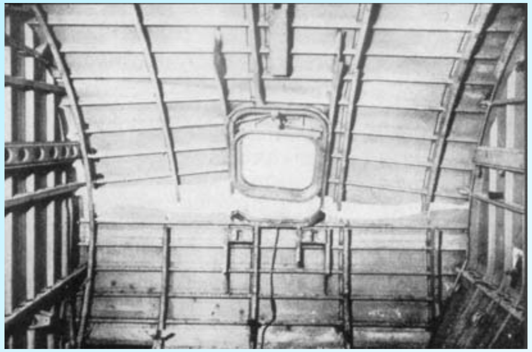
Causes of Failure



System and structural complexity

- New technology
  - Comet airliner - entered service in 1952 flying from London to Johannesburg
  - Between May 1953 and April 1954 3 aircraft broke up in the air
  - Withdrawn from service and extensive investigation undertaken
    - Full-scale structural testing (for first time)
    - Retrieval of pieces from bottom of Mediterranean
  - New technology introducing new load cases - high altitude flight for turbojet engines requiring cabin pressurisation giving out-of-plane bending
  - Mismatch between service loads and fatigue test procedure
  - Comet Video.VOB

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Achieving Reliability

How do we achieve success?

- Integrated and concurrent systems design
- Advanced modelling and expert systems
- In-service monitoring of loads, strains and damage
- Sophisticated testing and materials characterisation
- Detailed understanding of behaviour of cracked bodies
    - Fracture mechanics
    - Crack growth mechanisms
        - Fatigue
        - Environmentally assisted cracking; SCC, LMAC etc
        - Creep
- Fracture control plans

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Achieving Reliability

Integrated and concurrent systems design

- Evolution of military aircraft engine development process

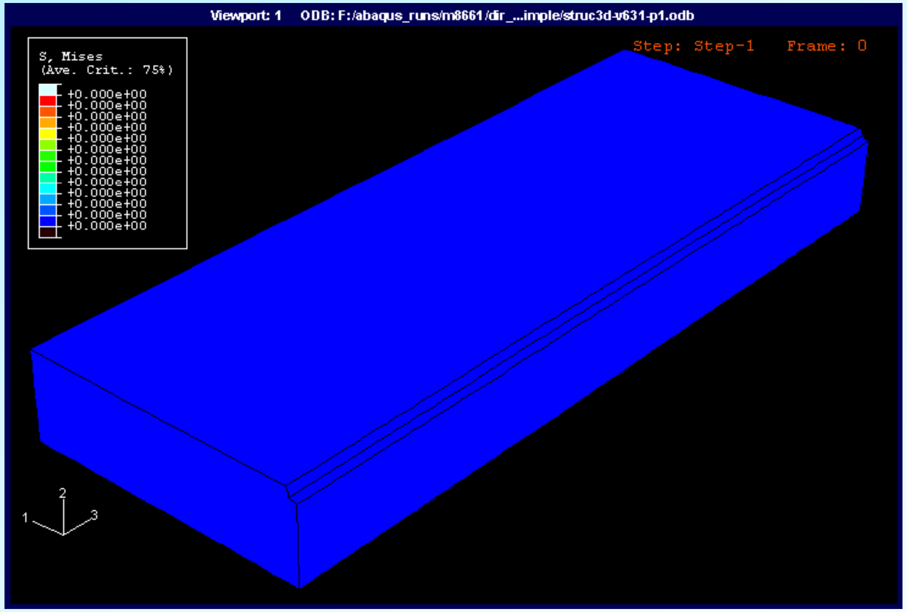
F100-100 (CIRCA 1970)	F100-220 (CIRCA 1980)	F119-100 (CIRCA 1990)
• PERFORMANCE FOCUS	• BALANCED FOCUS BETWEEN PERF. & DURABILITY	• APPLICATION TO ALL SUBSYSTEMS/COMPONENTS
• MINIMAL ANALYTICAL UNDERPINNING	• MATERIAL CHARACTERIZATION	• EXPANSION OF PROCESS TO ALL FUNCTIONAL DISCIPLINES (PERF, OPER, ETC)
• ITERATIVE TAAF APPROACH (Test, Analyze and Fix)	• INCREASED EMPHASIS ON ANALYSIS	• EXTENSIVE ANALYTICAL RIGOR IN DESIGN
• LIMITED INSTRUMENTED TESTING	• ATTENTION TO ACTUAL ENVIRONMENT/USAGE	• COMPREHENSIVE ENVIRONMENT/RESPONSE CHARACTERIZATION
• NON-REPRESENTATIVE ENDURANCE TESTING (QT)	• REPRESENTATIVE ENDURANCE TESTING (AMT)	• PROOF/MARGIN TESTING
• INSUFFICIENT ANALYTICAL & EMPIRICAL TOOL SET	• DAMAGE TOLERANCE DESIGN APPROACH FOR SAFETY CRITICAL COMPONENTS	• DAMAGE TOLERANCE EXTENDED TO MISSION CRITICAL COMPONENTS
• LITTLE ATTENTION TO LIFE MANAGEMENT	• FULL LIFE TESTING OF MAJOR STRUCTURAL COMPONENTS	• EXTENSIVE COMPONENT, SUBSYSTEM, & SYSTEM LEVEL "SMART" TESTING
		• PROCESS DEVELOPMENT & MATURATION IN EMD

EMD = Engineering and Manufacturing Development

Achieving Reliability

Advanced modelling and expert systems

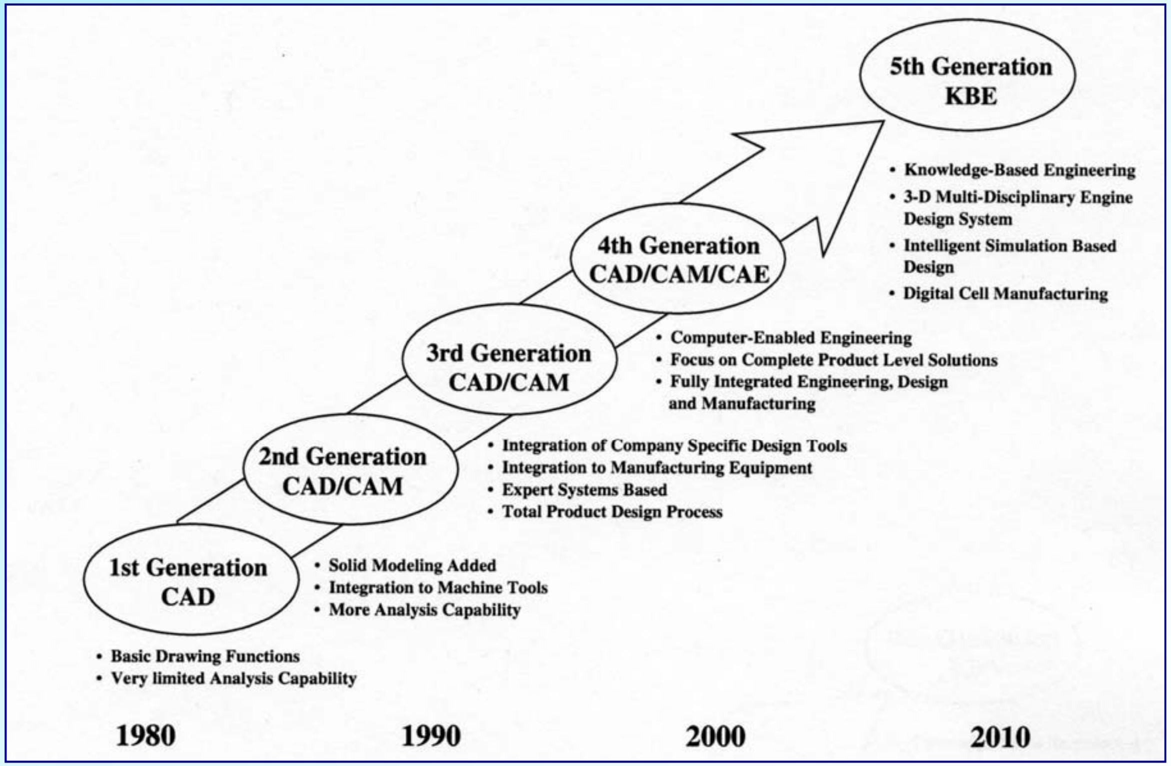
- Finite element modelling, e.g. of heat flow during welding – can calculate residual stresses and predict performance (Corus)



Achieving Reliability

Advanced modelling and expert systems

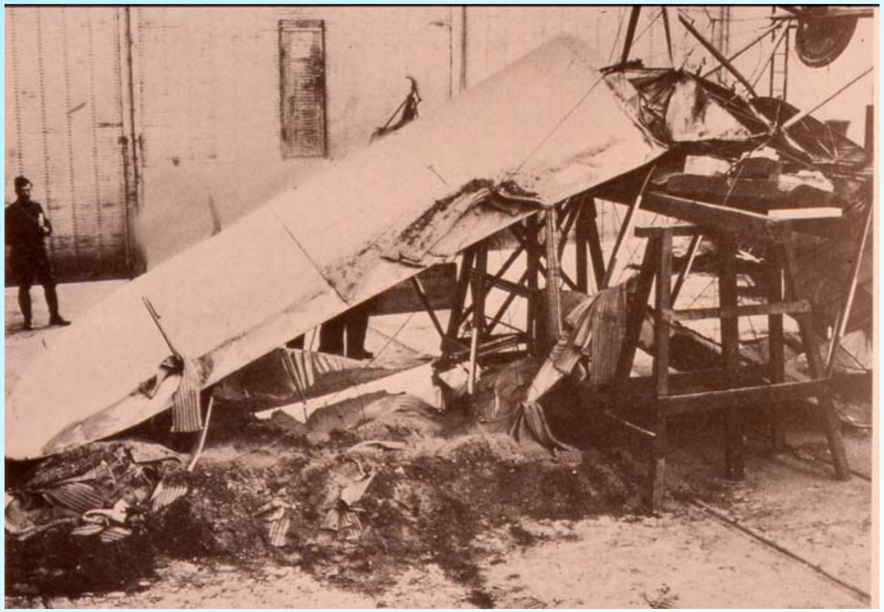
- Evolution of CAD/CAM in military aricraft engine development



Achieving Reliability

Sophisticated testing and materials characterisation

- Comet was first example of full scale testing of aircraft
- Early testing was based on 'limit-load' with 'factor of safety'



Wing testing on a BE2 biplane in 1912 using bags of lead shot

Fokker states "wood is a fatigue conditioned material"

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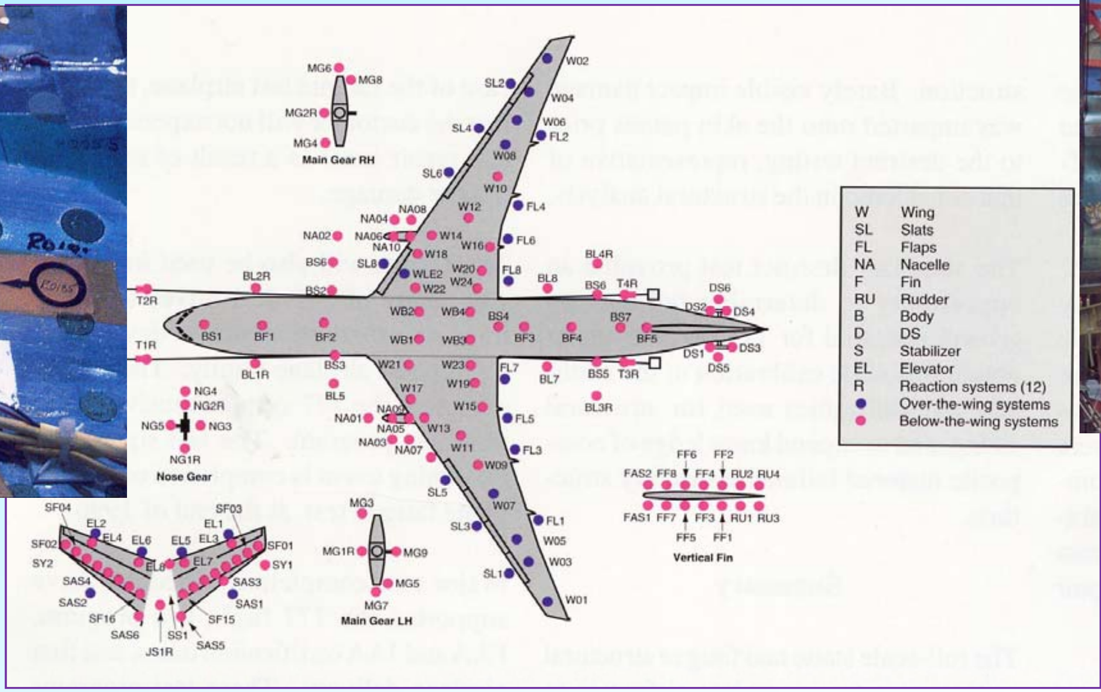
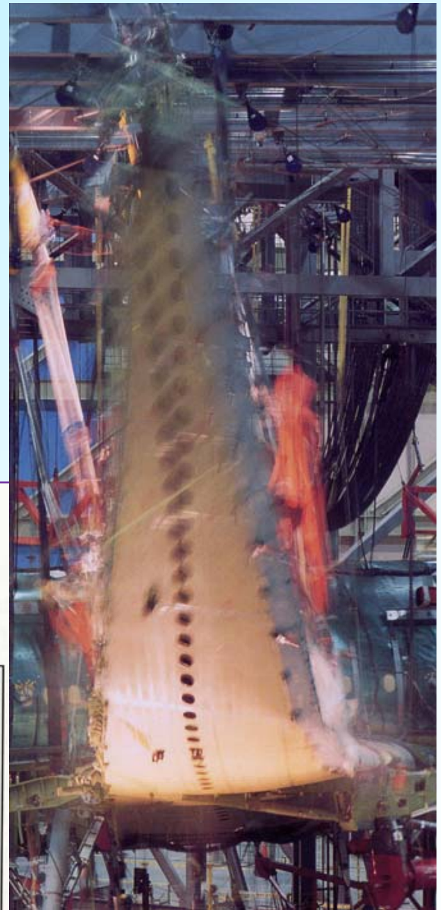
Achieving Reliability

Sophisticated testing and materials characterisation

- Structural testing of Boeing 777

3 of 4,300 strain gauges – these are near a passenger door cut-out



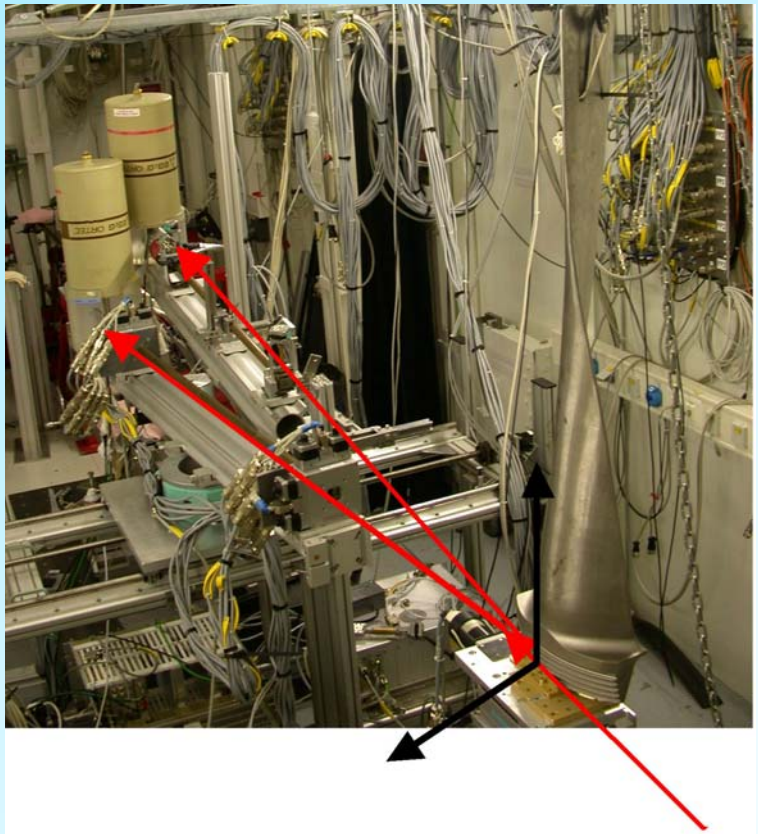


100 hydraulic actuators apply fatigue and static loads to the aircraft

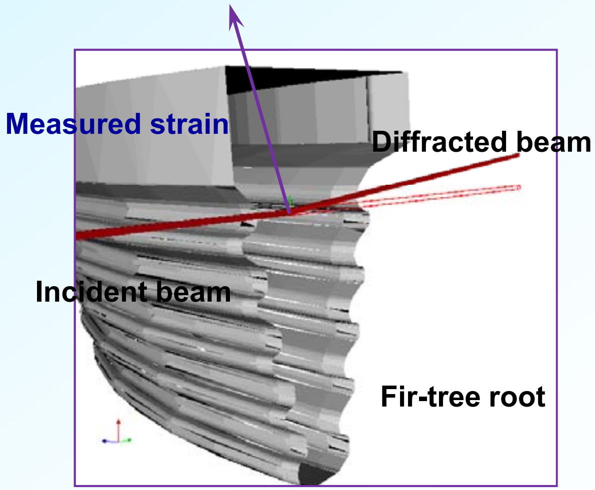
Achieving Reliability

Sophisticated testing and materials characterisation

- Synchrotron diffraction measurement of residual strains



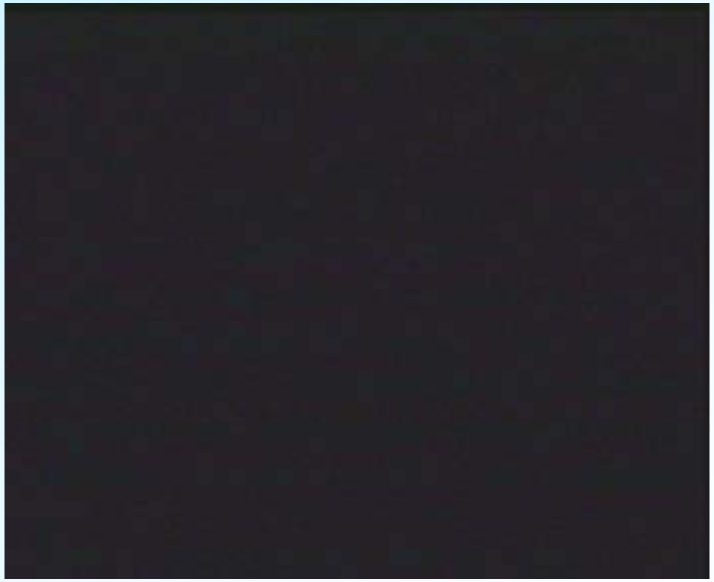
Measuring bi-axial residual strains in the fir tree root of an ESKOM steam turbine blade at the European Synchrotron Radiation Facility in Grenoble, France



Achieving Reliability

Sophisticated testing and materials characterisation

- Aero-engine turbine blades
  - Impact damage – bird strike



Rolls Royce Trent engine – titanium fan blades

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Achieving Reliability

Sophisticated testing and materials characterisation

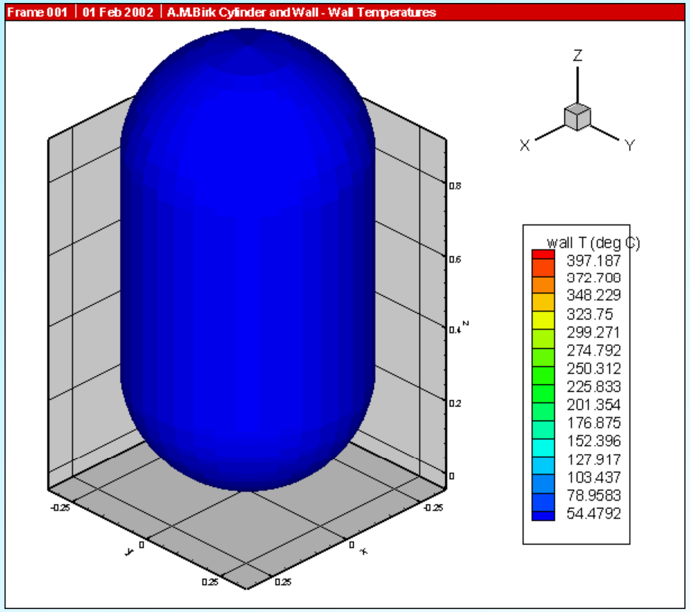
- Aero-engine turbine blades
  - Fretting fatigue of blade root

Rolls Royce Trent engine – titanium fan blades

Achieving Reliability

Sophisticated testing and materials characterisation

- Propane rail wagons subject to heating from fires
  - If a tank holding a pressure liquefied gas (such as propane) fails suddenly, then part of the contained liquid can boil violently producing an explosive effect
  - Interested in factors affecting length of time tank will resist fire – FE modelling confirmed with full-scale testing



Work by AM Birk at Queen's University, Ontario

Achieving Reliability

Want fracture-safe and fatigue-reliable structures

- ***Fatigue***: Process of crack initiation and growth by microplasticity in metal - (generally, a nonlinear constitutive response in a material leading to hysteretic energy loss)
- ***Fracture***: Sudden, catastrophic collapse under a static load (certain cases), a steadily rising load, or as the final stage in fatigue

- **Ongoing problem areas**:
  - Single parameter K-characterisation of crack tip stresses
  - Material/environment-induced crack tip shielding
  - Incorporation of residual stresses into life prediction
  - Global manufacturing and supply chain

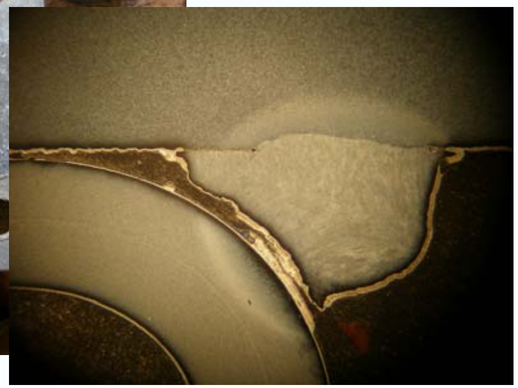
Achieving Reliability


LMAC

Detailed understanding of behaviour of cracked bodies

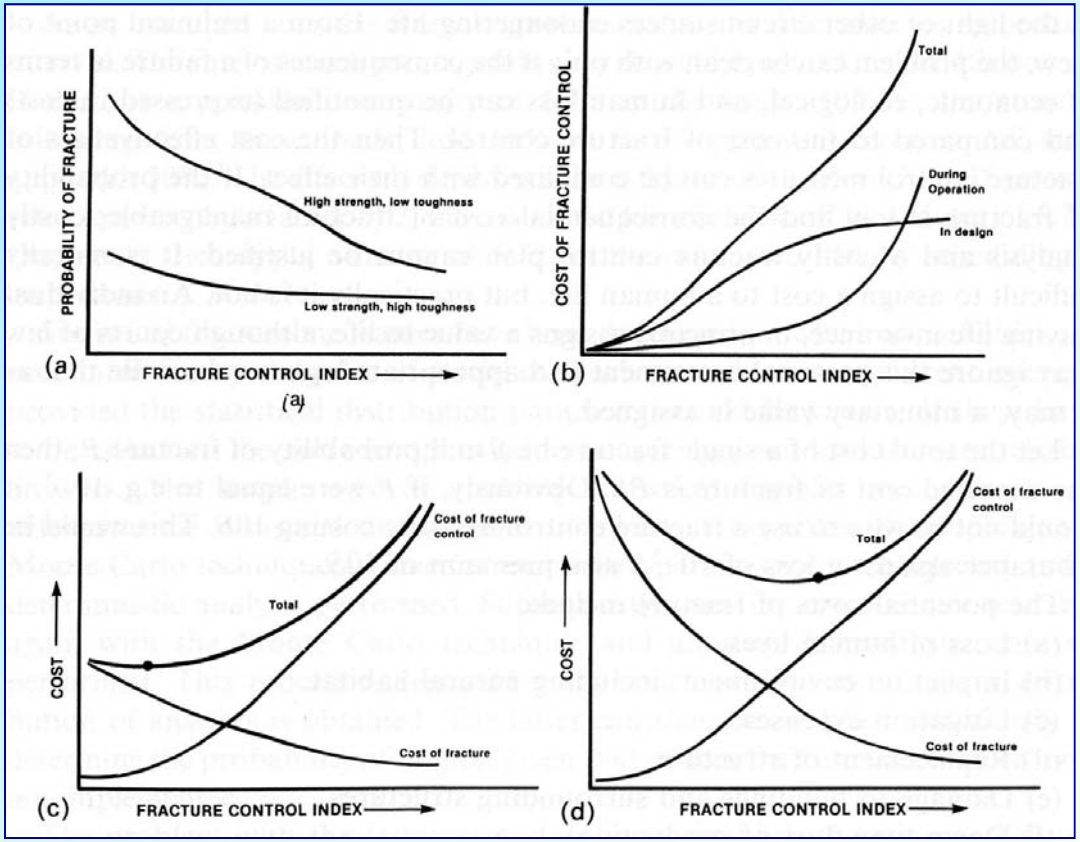
- Fracture mechanics
- Crack growth mechanisms
  - Fatigue
  - Environmentally assisted cracking; SCC, LMAC etc
  - Creep
- Joint problems (welds)
- FM-based fatigue design
  - BS 7608 (Eurocode 3)
  - BS 8118 (Eurocode 9)
  - BS 7910 (PD 6493)


Boat Cradle



Achieving Reliability

Assessing fracture control plan viability



- Probability of failure decreases as FCI increases (a)
- Fracture control cost increases with FCI both for design and in operation (b)
- Can plot a total cost curve (c)
- Higher cost structures justify a higher FCI

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Conclusions

- Our ability to design and build very complex and statistically reliable structures and products has increased dramatically over the last 30 years
- Driven by:
  - Advances in computing power and sophistication of electronics
  - Development of fracture mechanics and its application to fatigue crack growth
  - Systems engineering approaches and life cycle analysis
  - Integrated, concurrent design
  - Progress in materials science and engineering
- Mechanical engineers have been at the heart of many of these developments

Conclusions

Case Studies in Failure Analysis