Some Experiences from 32 years of ICAF Attendance and some Thoughts for the Future

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Anders Blom

ICAF General Secretary

Acknowledgements

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- In particular, thanks are due to Börje Andersson, Pavel Sindelar, Björn Palmberg, Geng-Sheng Wang, and also Hans Ansell from Saab.
- I am also grateful to all present and former ICAF National Delegates I have worked with, as well as for the contacts with other international experts, be they from industry, institutes or academia.
- Here, I am particularly indebted to Jaap Schijve, Jack Lincoln, Tom Swift, and Ulf Goransson for generous help and discussions.

History - 1

- 1829 - Albert, Repeated Load Tests
- 1839 - Poncelet Coins the Word “Fatigue”
- 1851 - Wöhler, First Systematic Fatigue Studies: Fatigue Limit & Stress Range
- Late 1800:s - Train Crash of the Week, UK
- 1903 - Wright Brothers First Flight Delayed due to a Hollow Propeller Shaft Developing a Fatigue Crack. New Solid Spring Shaft from Dayton, OH, brought in to Test Site in North Carolina

History -2

- 1927 - First In-Flight Structural Fatigue Failure: Wing to Strut Fitting, Dornier Merkur Monoplane, Lufthansa, Germany, 6 killed
- 1929- Imperial Airways Handley-Page Crash into English Channel, Engine Connecting Rod, 7 killed
- 1934 - Swissair Curtiss Condor Biplane Failure, Wing Strut, Near Tuttelingen, Germany, 11 killed
- 1944 - US Air Force First Fatigue Test, B-24 Nose Landing Gear

FOUNDATION OF ICAF

- 1949 - Dr. Frederik J. Plantema publishes “Fatigue of Structures and Structural Components” - Idea of ICAF born
- 1951 - Birth of ICAF: Meeting at College of Aeronautics, Cranfield on Sept. 14. Dr. Plantema (NLL), Mr. E.J. van Beck (Fokker), Prof. W.S. Hemp (College of Aeronautics) & Mr. Bo Lundberg (FFA)
- 1952 - First ICAF Conference, Amsterdam. Nine people from The Netherlands, UK, Sweden, Switzerland & Belgium

GROWTH OF ICAF - 1

- 1953 - 2nd Conf., Stockholm, 24 attendants
- 1955 - 3rd, Cranfield, 40 people
- 1956 - 4th, Zurich, 33 people, France and Germany new
- 1957 - 5th, Brussels, 35 people, Italy new
- 1959 - 6th Conf., Amsterdam, 30 people
- 1959 - 1st Symp., Amsterdam, 121 people
- Biannual meetings after 1959 meeting, with 2 day Conference & 3 day Symposium

GROWTH OF ICAF - 2

- Quick increase in no. of attendants, some 200 people in Symposium, Rome, 1963
- 1963, USA presents National Review
- 1959 - 1963, Meetings held with AGARD SMP
- 1966 - Dr. Plantema died. Dr. Jaap Schijve acts as secretary ad interim until Mr Jurg Branger elected new General Secretary in 1967
- 1967 - First Plantema memorial lecture given by J. Branger on the birth and growth of ICAF

May 2, 1952, 1st Flight deHavilland DH-106 Comet (Yoke Peter)

Wreckage recovered of crashed Comet (Yoke Peter)

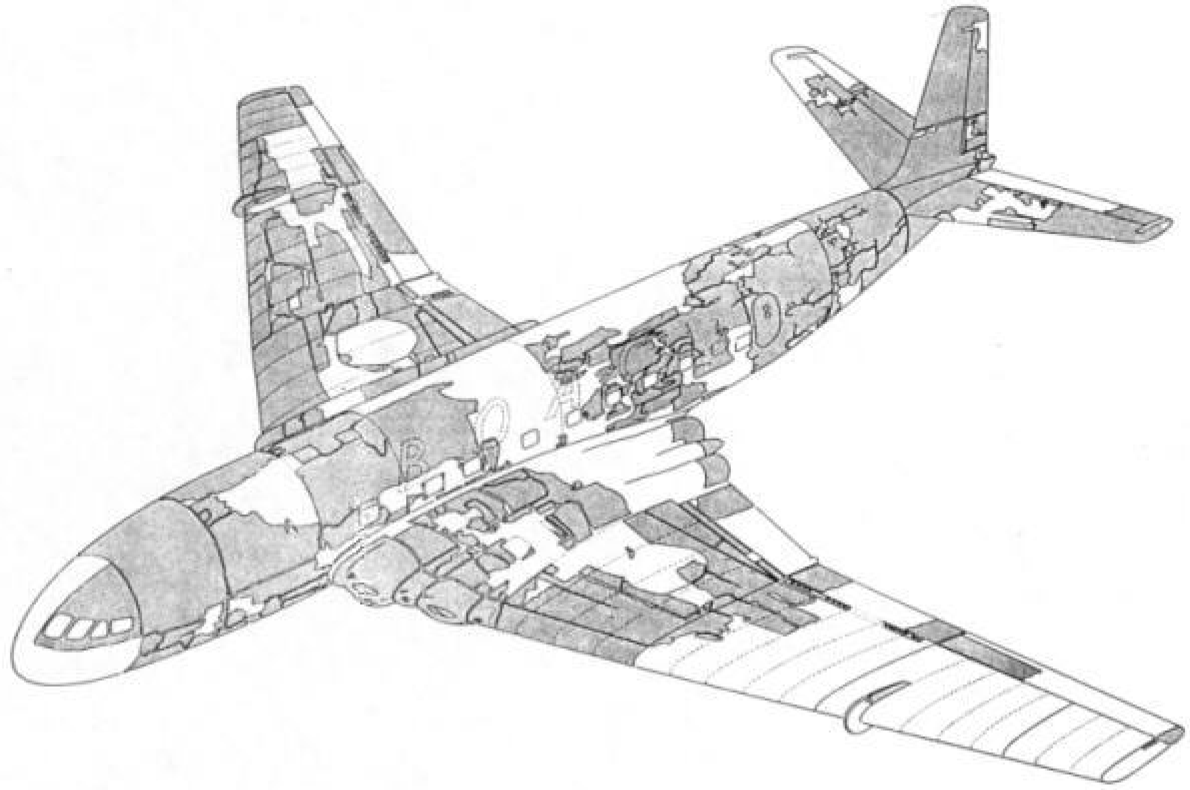
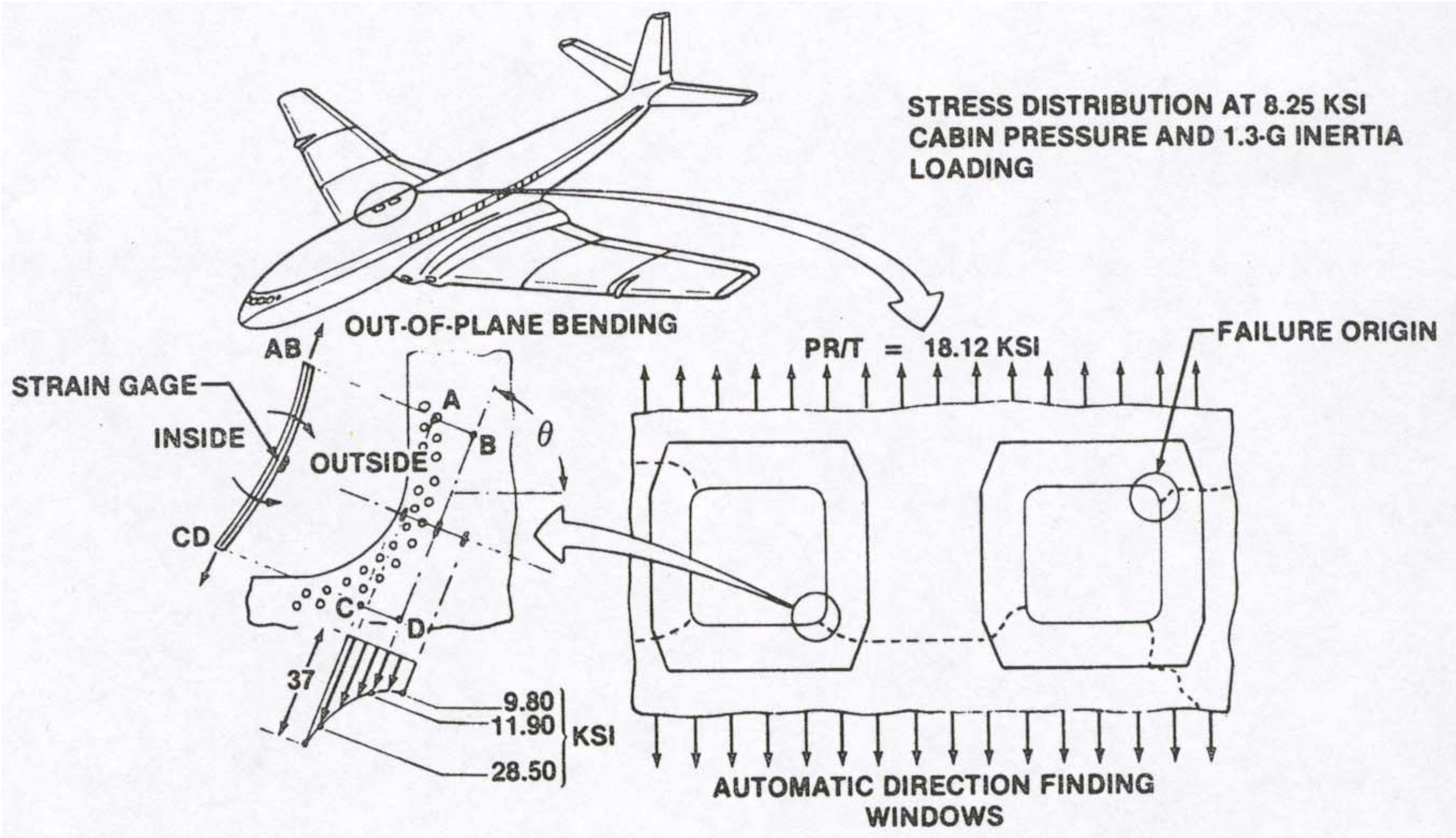


FIG. 2. DIAGRAM SHOWING AMOUNT OF WRECKAGE RECOVERED—G-ALYP.

Probable failure origin in Comet (Yoke Peter)



SOME IMPORTANT CONTRIBUTIONS

- 1939: W. Weibull derives his famous distribution ad hoc (weakest link). One of 3 possible types of extreme value distributions
- Late 50-ies: H.C. Johnson, Closed Loop Servohydraulic Test System
- 1961: P.C. Paris, Fracture Mechanics Approach to FCG, Rejected in 3 leading journals
- Late 60-ies: W. Elber, Fatigue Crack Closure
- 1967: T. Endo, Rainflow Cycle Counting Method
- Early 70-ies: Finite Element Method introduced in teaching at technical universities
- 1974: USAF Damage Tolerance following failure of F-111 in 1969 & fatigue problems of C5-A Cargo aircraft

General Dynamics F-111A Aardvark

Design Service Life: 4,000 hours
4,000 flights

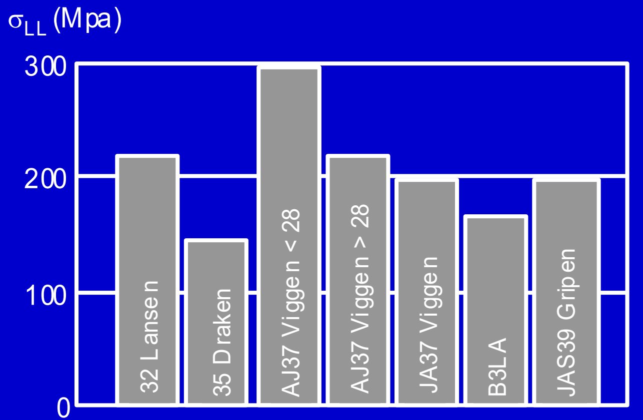
Dec. 22 1969

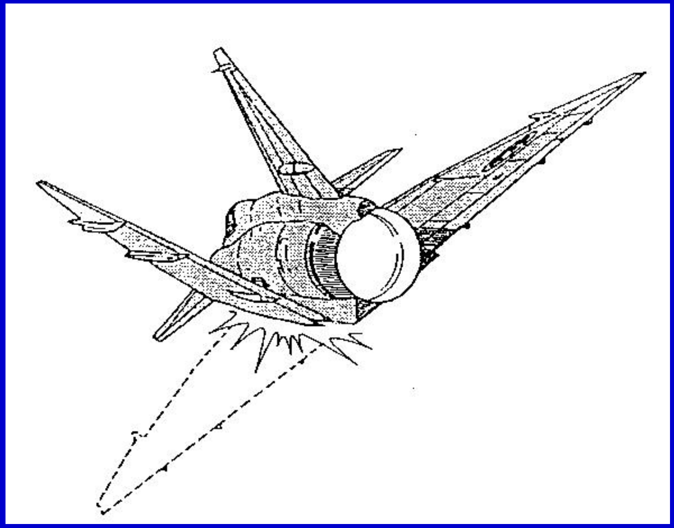
USAF F111 #94 - New Mexico

105 hours & 107 flights

July 1974 - Oct. 1975

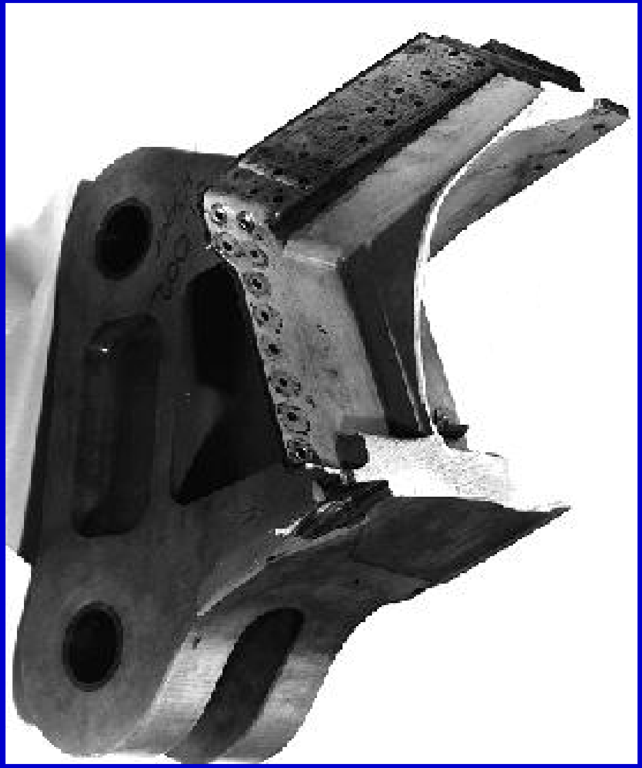
Saab AJ37 Viggen - Main Wing Spar Failure





- 37.011 152 hours
- 37.005 286 hours
- 37.014 275 hours

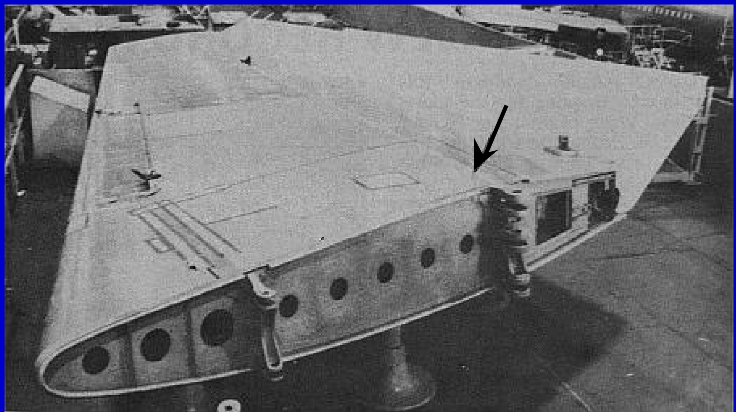
Design Service Life: 2,000 h



May 14 1977

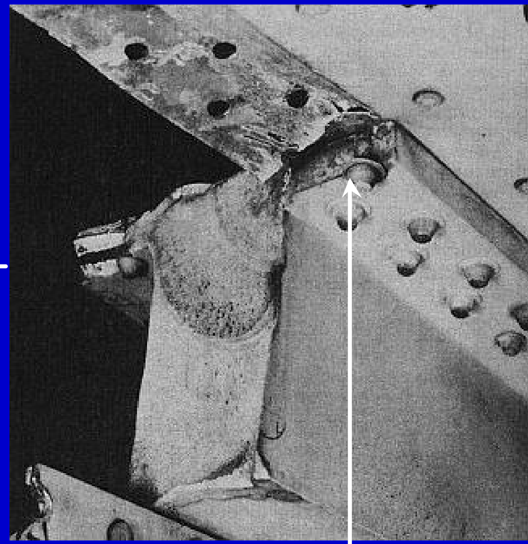
Dan Air G-BEBP - Lusaka Airport

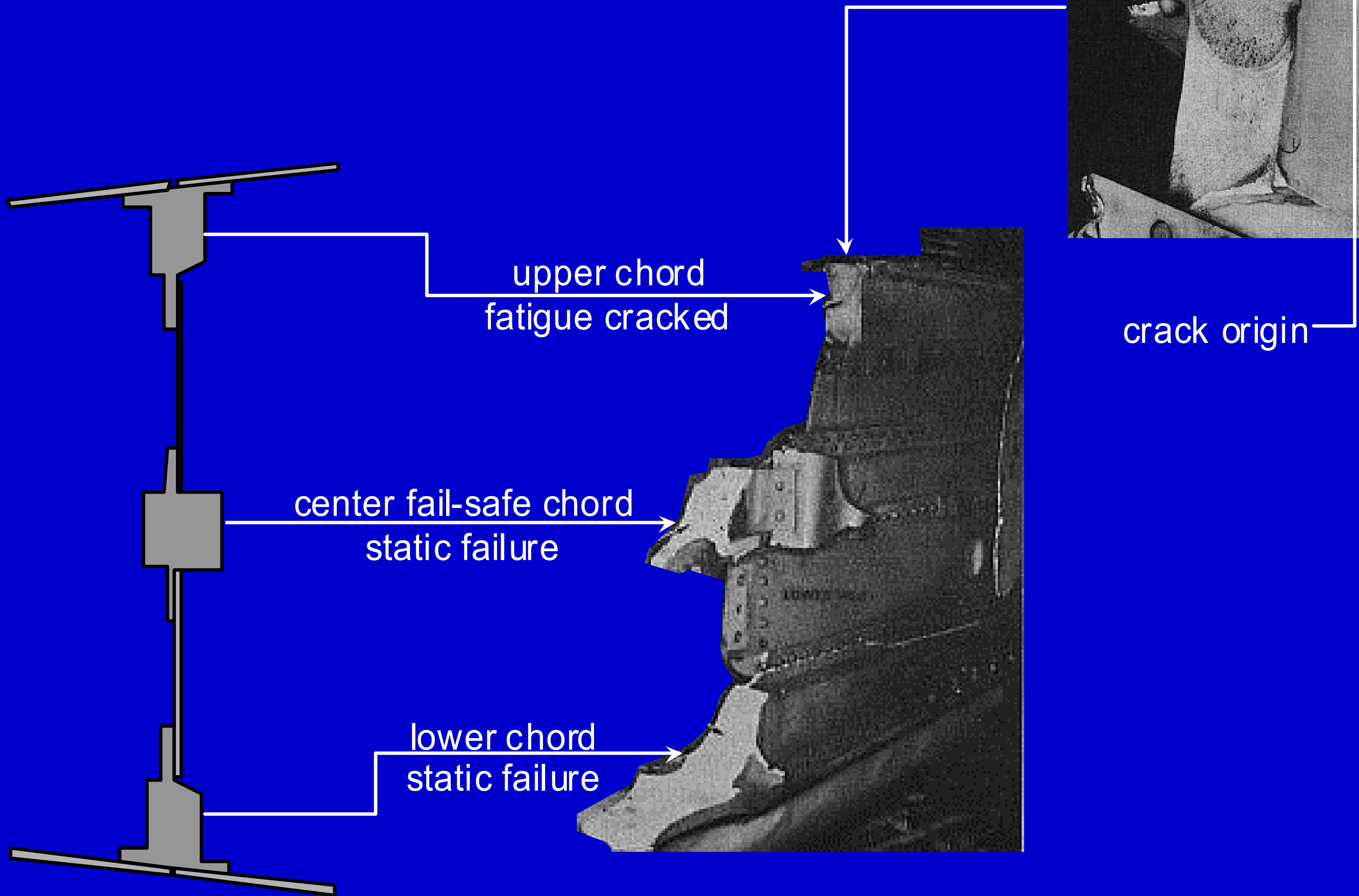
47,621 hours & 16,723 flights



Boeing 707-321C
Design Service Life: 60,000 h

Failed Tailplane Spar

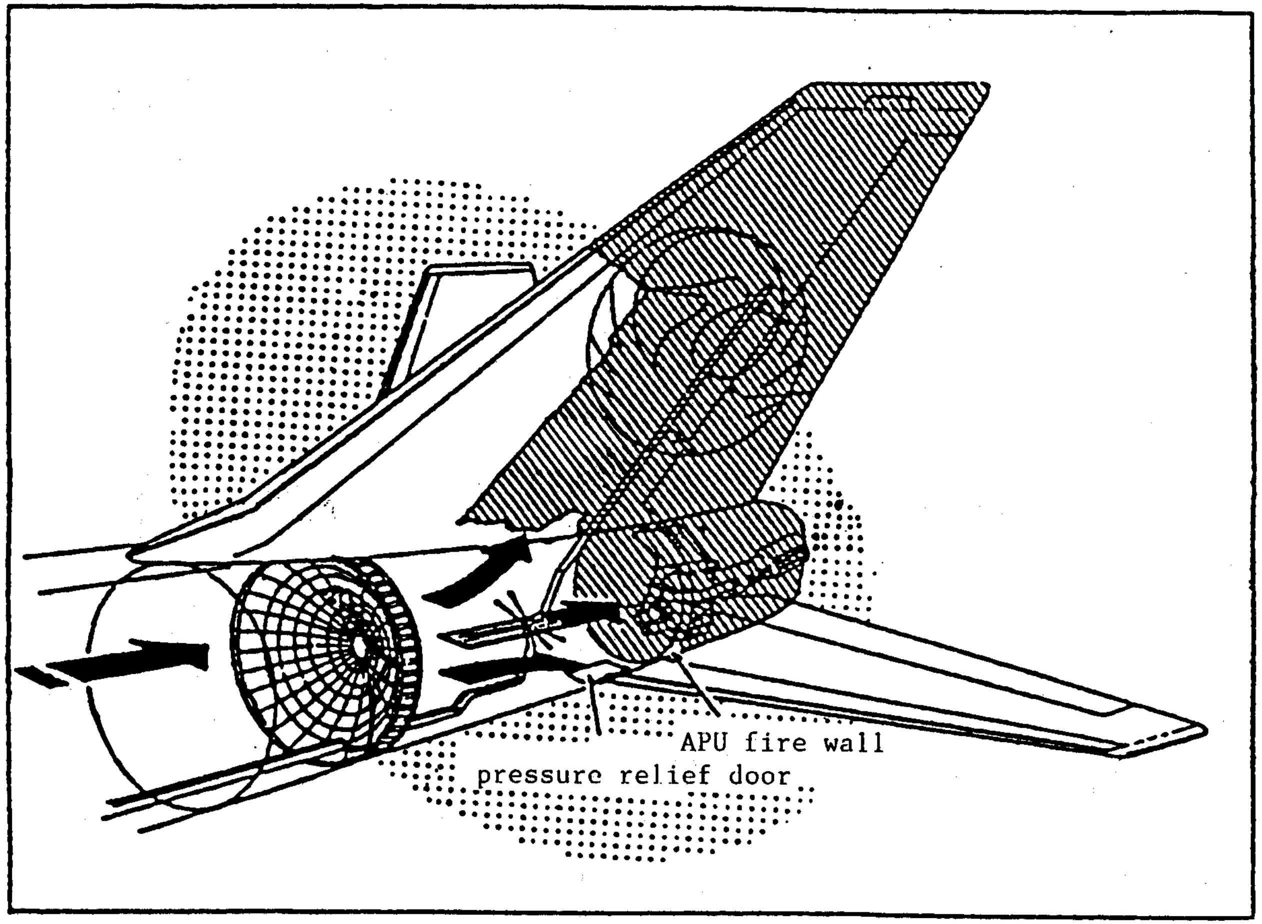




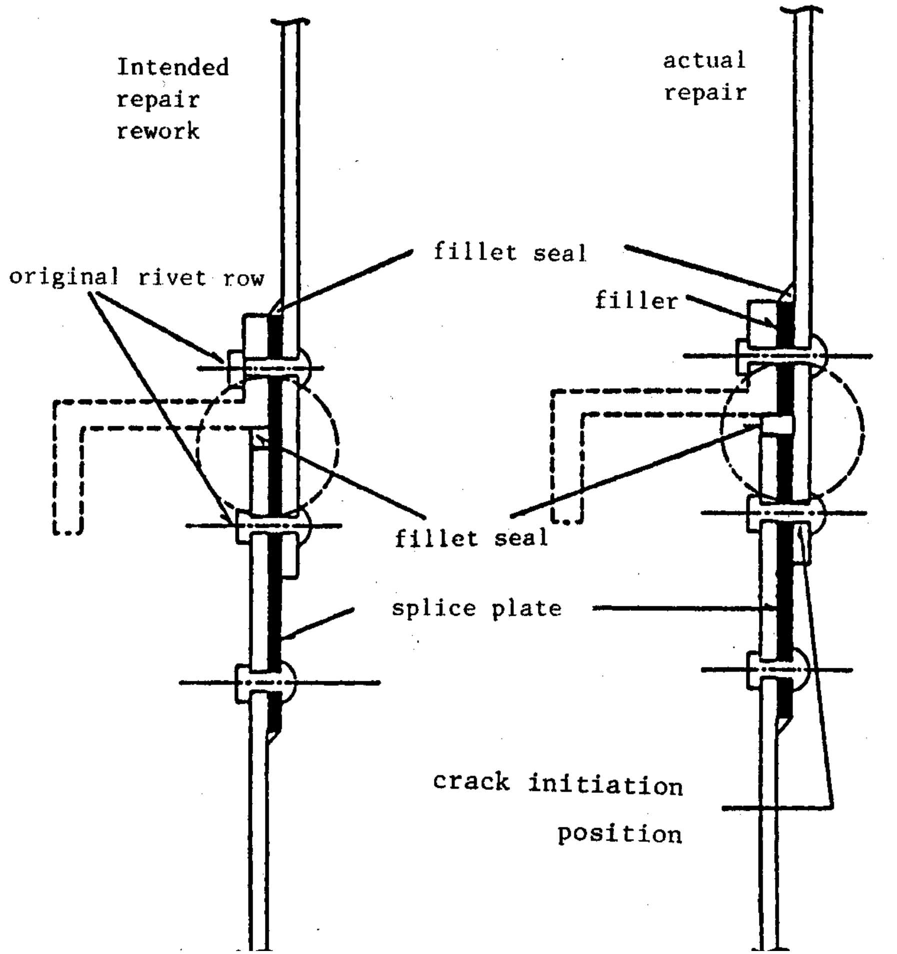
ICAF in the 80-ies

- Good funding available in most countries
- Basic research in fracture mechanics (K-solutions, failure criteria)
- FCG studies on mechanisms, closure, thresholds, aging effects (planar slip/wavy slip), overloads, compression loading, spectrum loading etc
- Standardized load sequences (Falstaff, Twist, Helix, Felix, Enstaff, Carlos etc) used for data exchange
- Basic work on Composites, focus on basics (humidity, temp)
- Joints (load transfer, secondary bending, fastener systems, cold working, fretting etc)
- Exchange of documents between member countries
- Close links to AGARD

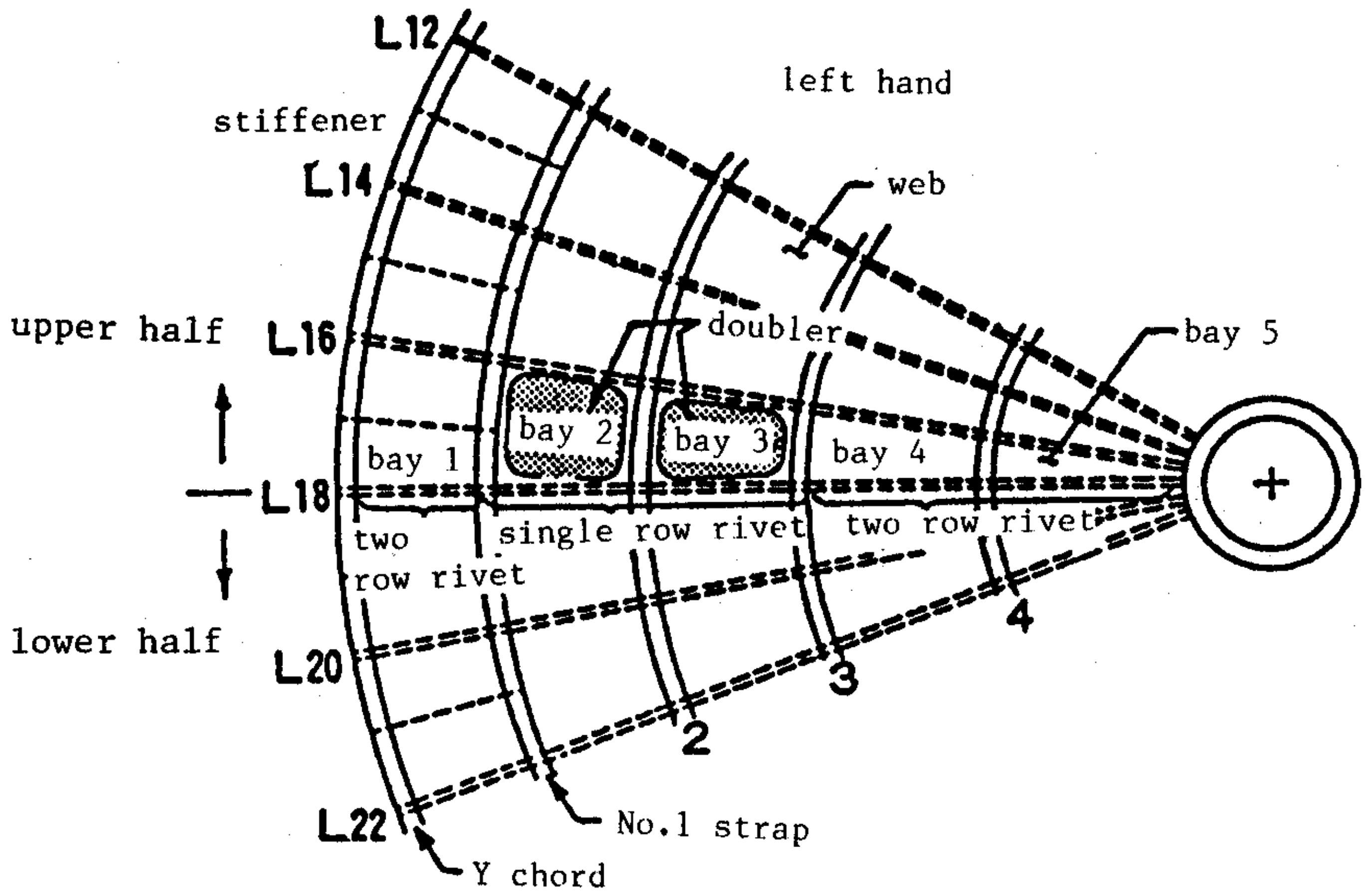
Estimated fracture of rear section of JA 8119 Boeing 747 SR-100 crashed in Japan
August 12, 1985



L18 splice section. Intended repair and actual incorrect repair



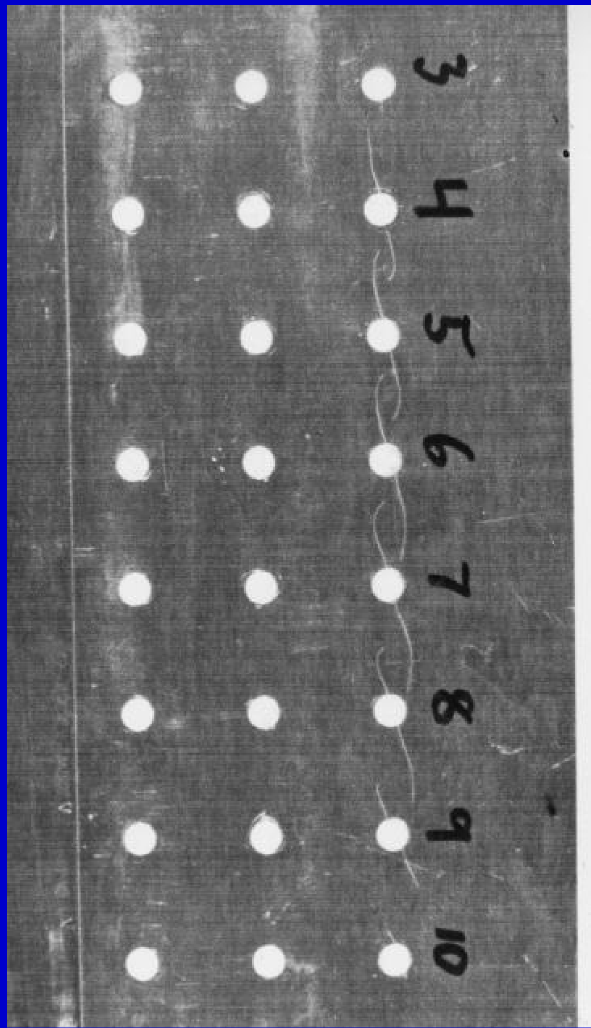
Aft pressure bulkhead of JA 8119 Boeing 747 SR-100 crashed in Japan, 1985



April 28 1988

Aloha Airlines - Flight 243

35,493 hours & 89,090 flights



Boeing 737-200

Design Service Life: 51,000 hours

75,000 flights

Personal 1980-ies

- Damage Tolerance was introduced in Sweden by reanalyzing the two existing 37 Viggen fighter/attack versions
- Composite materials were introduced, firstly in a replacement fin of the Viggen aircraft
- Design of 39 Gripen, based on damage tolerance requirements, with high portion of primary composite structure
- Personal interaction with European and US scientists through academia (MIT, UC Berkeley and Brown Univ), organizations like ASTM E9 and E24, and AGARD.
- Got to know persons like Paul Paris, George Irwin, Rob Ritchie, Subra Suresh, Jim Newman, Wolf Elber, and many others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FARA

Damage Tolerance Assessment of 37 Viggen

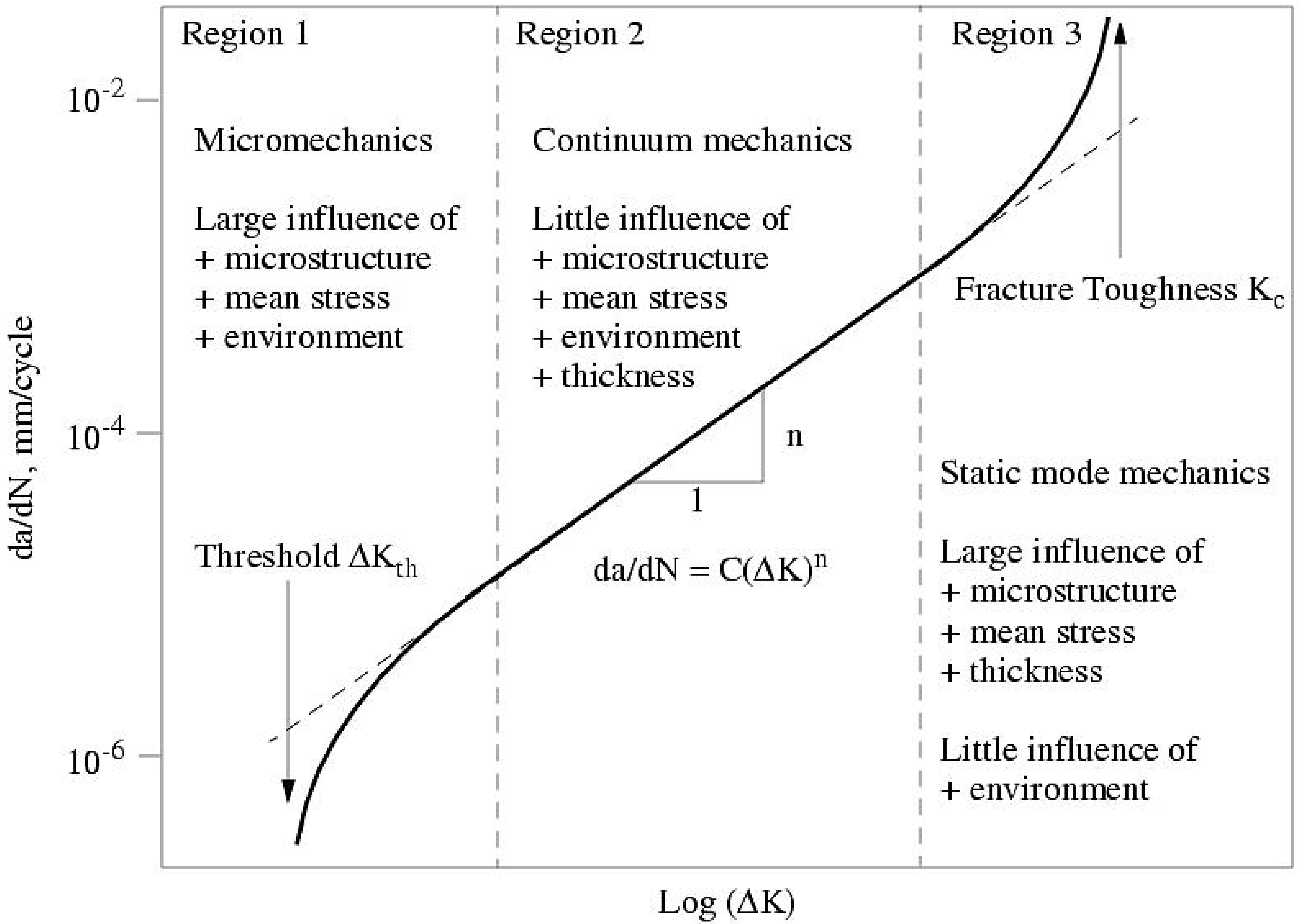
- Original safe life design of 2800 flight hours
- Verification of methodology by verifying calculation of stress intensity factors on stiffened structures and correlating with experiments
- K-factors obtained by weight function techniques and 3D p-version FEM
- Stress analysis by FEM (75000 dof:s or more by substructuring)
- Focus on main wing attachment and fin attachments
- Wing attachment - Four spectrum fatigue lives tested followed by four more fatigue lives including artificial damage (22 flaws, crack tip radius less than 0.02mm)
- Crack growth from fuel pipe holes and wing bolt holes
- Fin testing with symmetric spectrum (largest overloads occurred in pairs of plus/minus a certain percentage of limit load) caused retardation on the side seeing compression/tension and rapid growth on the other side)

Lessons learned Dam Tol 37 Viggen

- Difference in local monitored strains in real structure compared to stress analysis. Up to 10% can be expected due to incorrect boundary conditions, friction, and load introductions.
- Not easy to obtain flaw growth at artificial flaws despite careful EDM
- Do not use spectrum with paired tension/compression loads. A real fin will have crack growth between the two obtained test results on each side of the fin
- For the new version of the JA 37 Viggen (fighter version) both experiments and calculations showed that extended usage may be possible
- For the older version of the AJ 37 Viggen (attack version) we obtained contrary results which could not be shown at the time. However, all versions of the 37 Viggen were taken out of service before any critical fatigue life due to introduction of the 39 Gripen aircraft

Early work on Composites and some thoughts

- Initially, experience from metals used to plan and perform tests. This was quickly understood as incorrect
- Very much work on effects of humidity and temperature. The latter still holds whereas environmental testing is scarce
- Laminated plate theory works unecpectedly well, possibly because temperature and humidity effects partly cancel each other out
- Free edge induced delamination studied in detail together with stress analyses of singularities. Today largely ignored
- All originators of damage tolerance negative to pressurized fuselage of composite. Today we fly the Dreamliner
- All universities teach students about weight savings with composites. However, real benefit has been reduced inspection and maintenance costs
- Design and certification of composites largely empirical with unclear safety margins if strain levels will be increased in future



Region 1
Region 2
Region 3
10^{-2}
10^{-4}
10^{-6}
da/dN, mm/cycle
Micromechanics
Large influence of
+ microstructure
+ mean stress
+ environment
Threshold ΔK_{th}
Continuum mechanics
Little influence of
+ microstructure
+ mean stress
+ environment
+ thickness
n
1
$da/dN = C(\Delta K)^n$
Fracture Toughness K_c
Static mode mechanics
Large influence of
+ microstructure
+ mean stress
+ thickness
Little influence of
+ environment
Log (ΔK)

ICAF in the 90-ies

- Still decent funding, but less than during 80-ies
- Damage tolerance of structures become required for all civil aircraft. Military aircraft only damage tolerant design in the USA and Sweden
- Aging aircraft issues become largest research topic ever
- Composites gradually introduced even more, focus is on low energy impact damage and BVID
- Numerical modelling advanced (Dofs, p-version FEM, convergence rates, error control)


70105

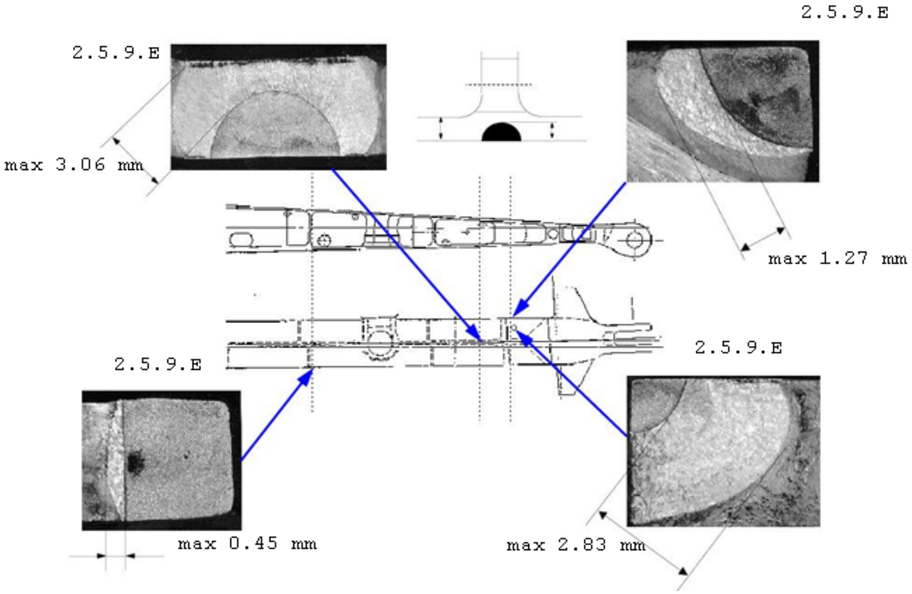
39 Gripen

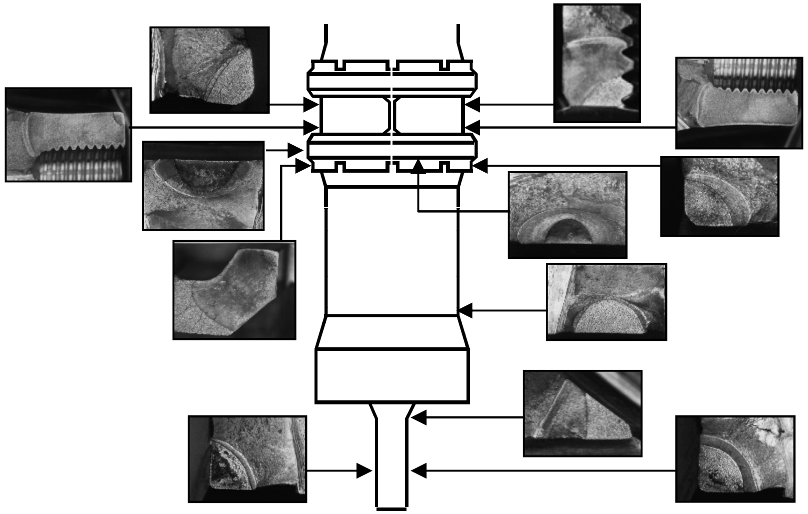
- First (and still only) fighter designed for damage tolerance outside the USA
- This approach resulted in substantially lower stresses than in 37 Viggen
- Multi-role aircraft
- Original analysis goal: 3000 hrs inspection-free service life
- Original verification goal: 4000 hrs inspection-free service life
- No detail to have shorter inspection interval than 400 hrs
- Fatigue test of minimum four life times
- Damage tolerance test of minimum two life times
- Residual strength requirement always 120% limit load
- No buckling allowed of composite parts below 150% limit load
- Today upgraded into a generation 4.5 fighter with AESA radar, (supercruise), longer range, updated sensor suites and communication systems (Gripen E)

Full-scale fatigue and damage tolerance testing

All structure of airframe and systems

Abt. 800 initial flaws installed in full-scale component testing





Experience from certification

- Personally responsible for static strength, fatigue and damage tolerance on contract from FMV
- For a person with research background this was a fantastic experience. Walking on the several first aircraft with drawings in hand and checking both calculations and test programs yielded a very important understanding of structural behaviour and various types of real problems
- Unusal examples included, e.g.: Critical crack length in the area between integral tanks in the wing and the air inlet, in order not to get enough fuel into the engine to cause explosion; the probability of failure on the second tire in the main landing gear if one tire explodes on landing; critical deformations of the automatic gun to avoid hitting the aircraft itself
- The test program has been reported over the years and has been largely very successful
- The same goes for actual service experience of the aircraft
- Mechanical systems also damage tolerant verified

ICAF in the 00-ies until now

- Significantly less funding for military purposes
- Significantly fewer aircraft projects
- Risk for losing experience and repeating mistakes from the past
- Need for knowledge transfer to young generation
- Risk for trust in huge calculations without substantiated input data, load cases, boundary conditions, and structural testing
- Aeronautics cost driven but safety should come first
- More focus on Helicopters and Systems

Trends in Civil Aeronautics

- Present fleet will multiply within next 20 years. Some 30.000 new A/C at a cost of some 5.000 billion USD needed world wide
- Main drivers are reduced emissions and noise. ACARE goals, with year 2000 as base line, for 2050 are 75% less CO_2, 90% less NO_X, and 65% less perceived noise
- Industry work on reduced production costs, passenger comfort
- Safety still priority
- Cyber security must be developed further

Fighter Generations

1st generation

- Subsonic gun fighters

2nd generation

- Supersonic
- Visual range combat capability

3rd generation

- Digital avionics systems
- Beyond visual range capability
- Role optimized variants

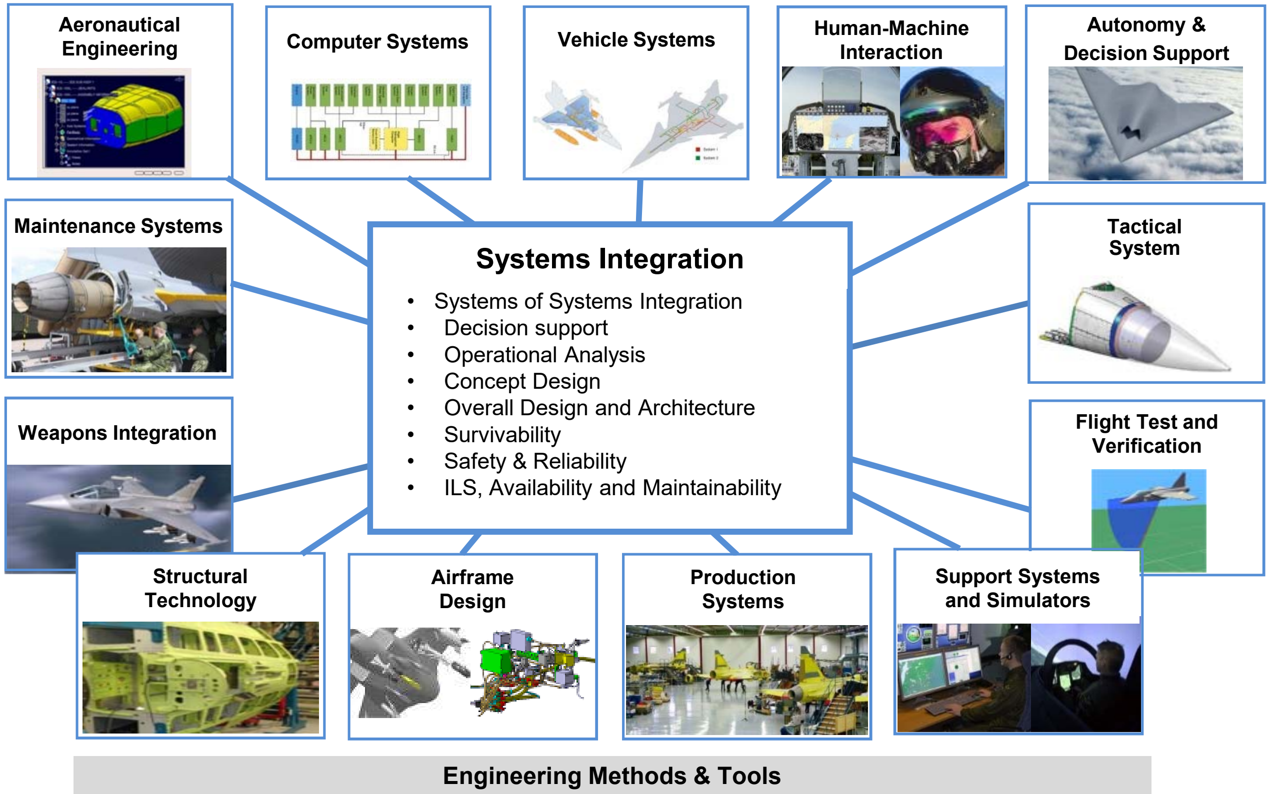
4th generation

- Integrated digital avionics systems
- Datalink and data fusion for unrivalled situation awareness
- Digital fly-by-wire - relaxed stability
- Signature reduction incorporated in design
- Design for low life cycle costs
- Growth potential for next generation of weapons
- Multi-role capability

5th generation

- Internal weapons bays
- Designed for low signature

WHAT DOES AERONAUTICS CONTAIN ?



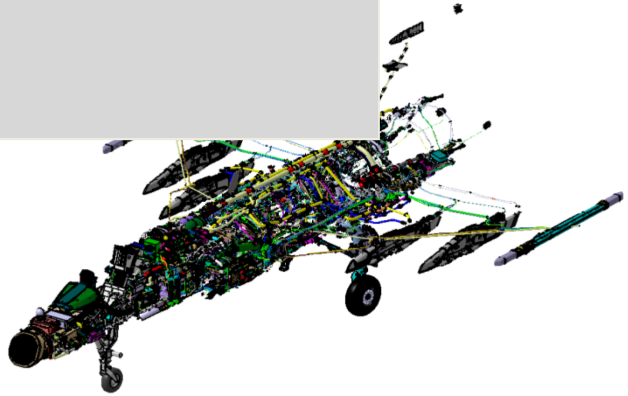
Operational ability → Systems complexity → Cost

Fleet size diminish and required operational life raise

A/C35 Draken
Number of aircraft: ~600
Design service life: 1500 h

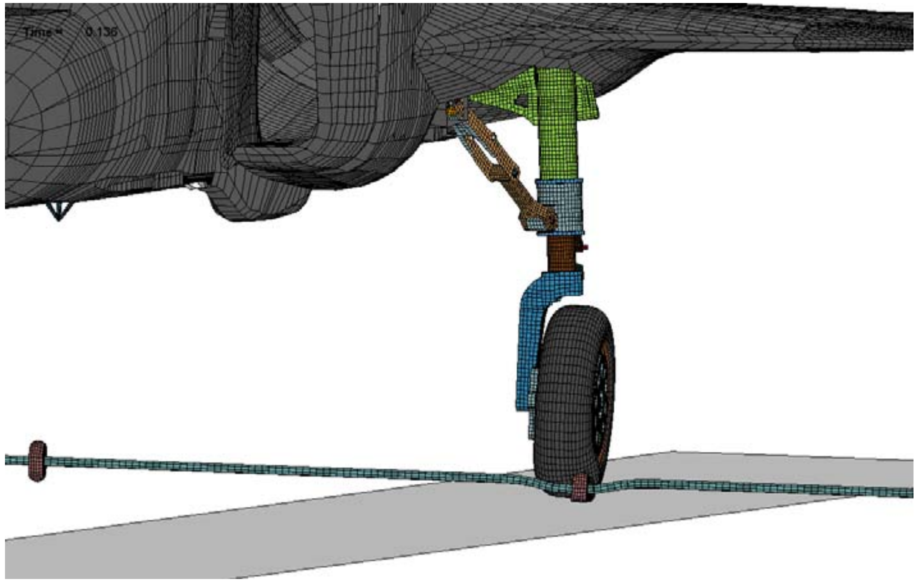
- Smaller production series
- Longer duration
- Design for future systems and tactical changes
- High demands on availability
- Increased demands on survivability

A/C39 Gripen
Number of aircraft: ~200
Design service life: 4000 h



Trend: **Increasing computational resources**

- Faster computers
- Larger and cheaper data storage
- Increasing number of available commercial software tools



Possibilities:

- Faster and more complex calculations.
- Enables Model-Based-Design.
- New types of simulations become feasible (productions processes, multi-body-dynamics, multi-physics, non-linear analysis, etc)
- Parametric studies and optimization.

Challenges:

- Validation. Fast and advanced calculations are not necessarily reliable.
- Finding right balance between accuracy and rapid response in different project stages.
- A large number of different analyses tools may lead to a very complex process which can be difficult to maintain over time.

Trend: More multidisciplinary analysis processes

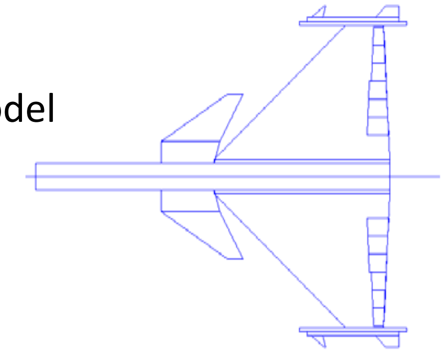
Example: Static aeroelastic analysis

Possibilities:

- Better designs can often be found by avoiding to separate the overall design problem into a number of problems for each discipline at an early stage.
- More global view of the engineering task by solving coupled problems.
- The same models can be used by several disciplines.

Structural model

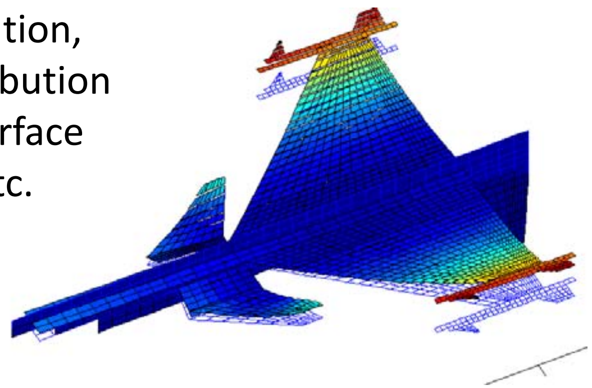
\+ Aerodynamic model



Challenges:

- Development of analyses tools and practical applications will be more complex to perform with several technical disciplines closely involved in the same process.

Static deformation,
Pressure distribution
and control surface
effectivenes etc.



Trend:

Closer integration between structural design (CAD), production and structural analysis (FEM)

Possibilities:

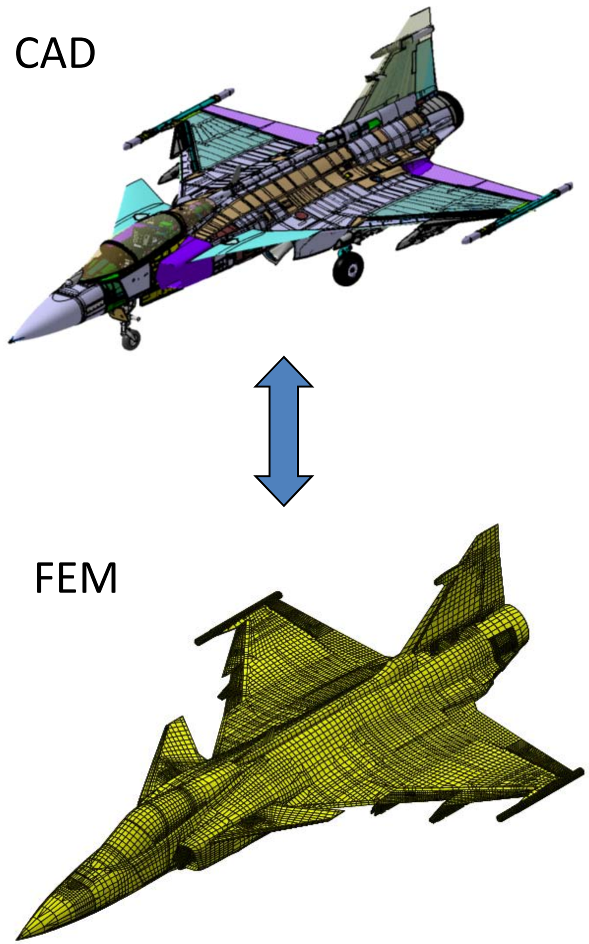
- CAD models (Catia) contain a more complete set of product data. This gives a better possibility to generate analysis models.

  Information can be communicated i both directions, CAD <=> FEM.

- Better opportunities to simulate production processes, e.g. forming/draping, shape distortion, tolerances, autoclave simulation.

Challenges:

- Modeling of external loads on a complete aircraft will still require in-house software for a long time ahead.



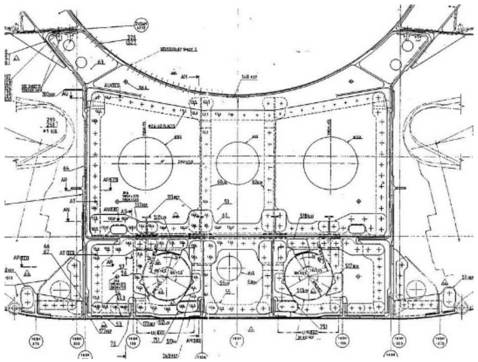
Evolution of Design Principles

Static
Safety-by-margin → **Safe-life**
Safety-by-retirement

↓ ↓(↑)

- Design for inspectability
- Attention to robustness and fail safe
- Lessen the inspection burden
- Keep track on actual structural conditions - CBM
- Design for reparability

Parts count reduction → integral design solutions



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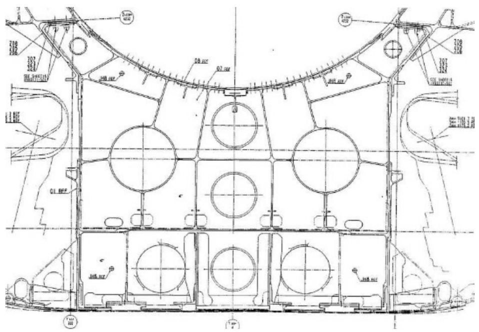
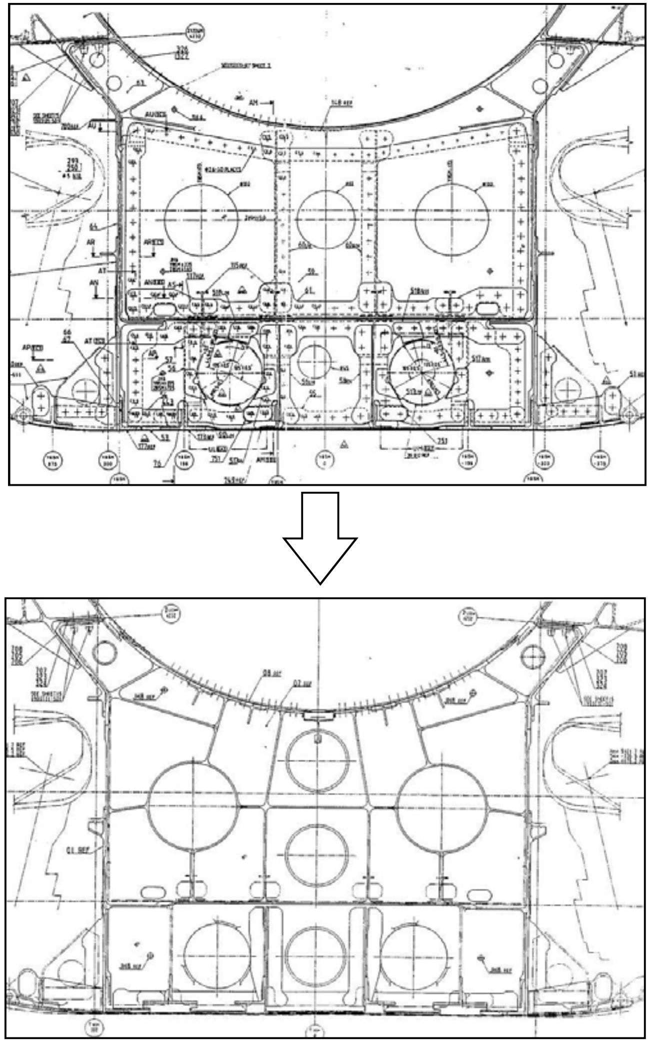


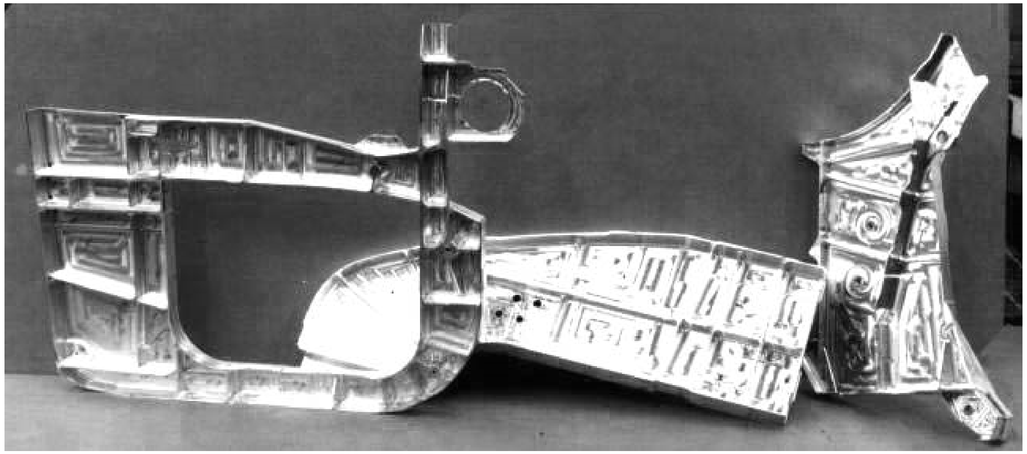
PARTS COUNT REDUCTION

1,500 parts in 44 areas considered

- 1,000 parts to be integrated
- 9,000 fasteners removed
- 1,600 detail tools removed
- 500 assembly tools removed

abt. 70% implemented into 39C/D versions



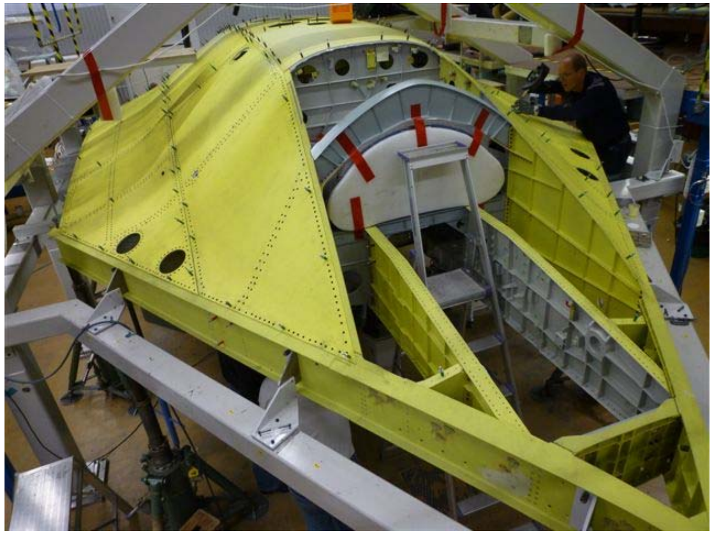


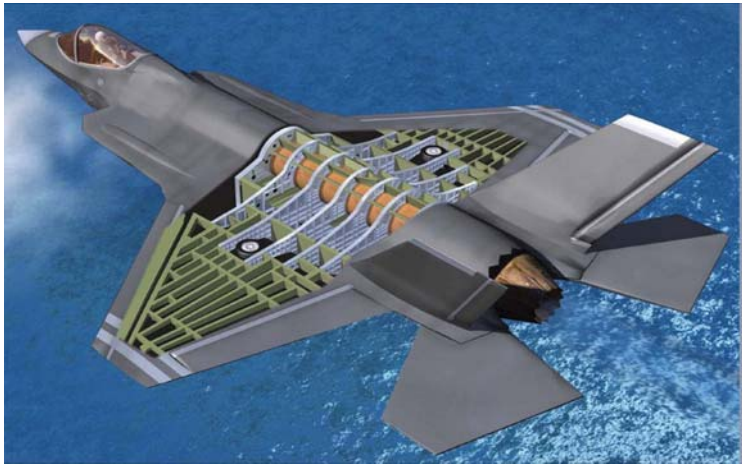
Structural concepts - present

- Detachable half wings mounted on a wing carry through box
- Constant wing aspect ratio optimized against speed requirements of the principal designed role
- Separated tail planes (US) or
- Full delta configuration and additional control by fully active canards (EU)
- Single fin (EU) or
- Twin fins (US)
- Single or twin low bypass turbofan engines
- Weapons wing and fuselage mounted mostly external
- In flight refueling
- Internal weapon bays (US)

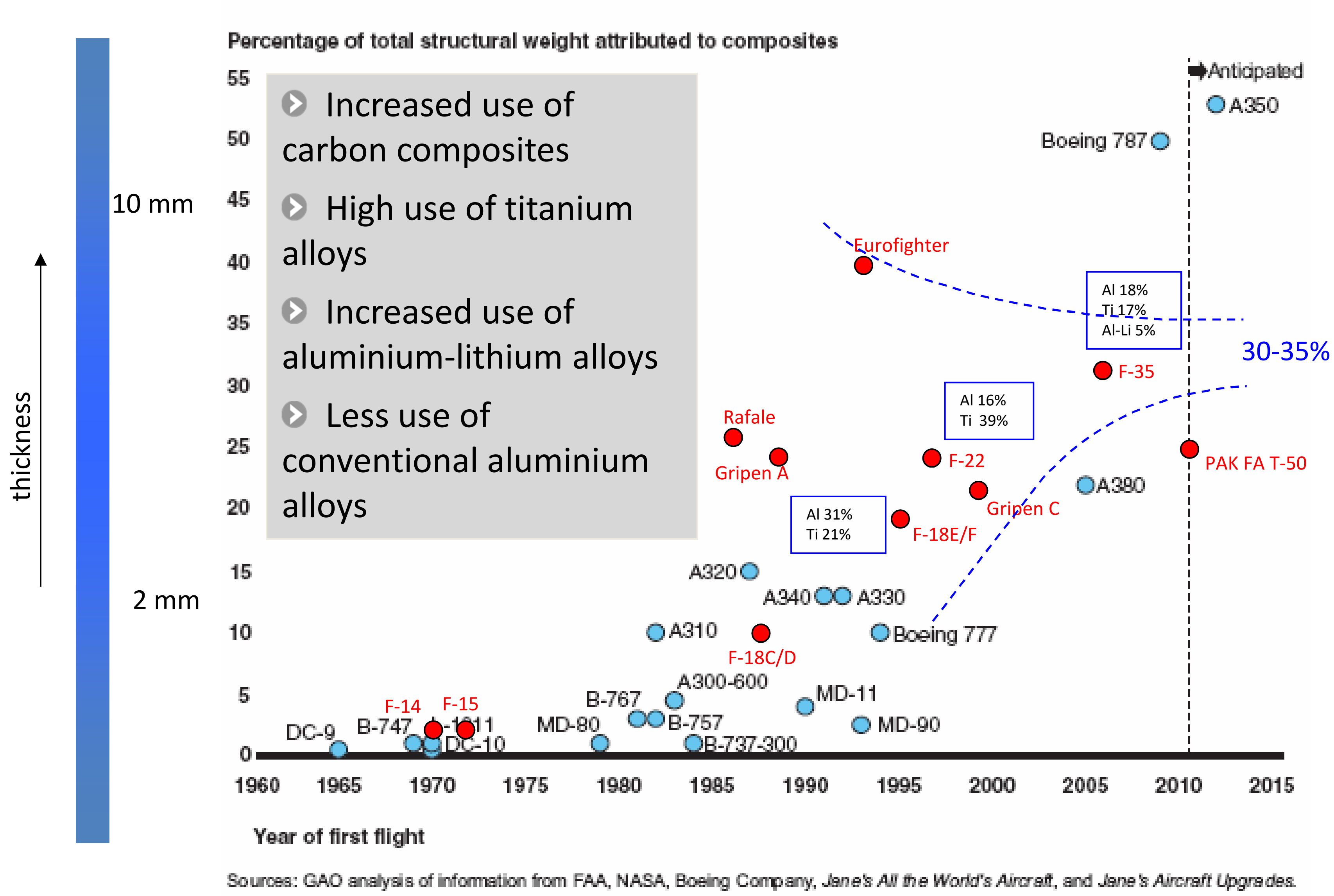
Material selection issues

- Composites show most advantage at intermediate thicknesses, e.g. combat aircraft wing skin - tough with in-plane strength
- Anisotropic nature of composites allow for optimization of stiffness and strength, e.g. flutter alleviation
- Composite constructions allows for incorporation of sensors and properties for signature control
- Thinner sections: weight advantage for metals and particularly where there is a thermal requirement, e.g. fuselage skin
- Heavier structures requiring three-dimensional load capability are preferably machined from metals
- Metal structure perform better than composite structure under impact conditions including battle damage
- Metal structure suffers from fatigue and are prone to corrosion





Structural Materials



Some dos and some do nots

- Do realise that growth rates near threshold are less than the lattice spacing. Hence, not a through the thickness continuous process
- Do not write papers on correlation between C and m in Paris law – meaningless work already done
- Do not take old experimental data and fit a polynomial correction to existing models claiming improvement – new experiments may yield other results
- Do not extend LEFM (or other theories) outside their limits and then claim that the theory does not work
- Do not fit an exponential equation to data points, backintegrate and claim the theory works
- Do not use single overlap joints – secondary bending worse than any acceptable design makes all data useless
- Do not ask for the smallest detectable flaw with NDI – ask for the largest flaw that cannot be missed
- Do realise that many material effects do not transfer to structural levels, eg fatigue limit is proportional to yield strength (and therefore inversely prop to grain size) but after welding, cutting, or operation flaws exist and they scale with Young's modulus not strength
- Always use simple models to check that advanced FEM or similar results are reasonable
- Understand the physics such that you understand the possible implications of your results, i.e. are they meaningful compared to other issues
- Any modeling without understanding of usage and loading seems pointless

New Developments and Potential Problems: 1

- Production costs
- Manufacturing techniques (laser welding, friction stir welding, casting, High Speed Machining)
- Passenger comfort (cabin noise)
- Environmental issues (engine &noise emissions)
- Fewer but larger aircraft companies
- How to maintain development with less military efforts at reasonable costs?

New Developments and Potential Problems: 2

- High speed machining - Worse fatigue properties, Residual stress fields and their relaxation, Integral (Monolithic) structures with hazardous damage tolerance properties
- Resin transfer moulding - Composites in general (and sandwich structures) likely to allow higher applied strains to compete with metals - Fatigue may result
- Personal opinion is that composite design is empirical and not science based. Future developments can either solve that problem (too expensive) or incorporate 3D reinforcements for locations with out of plane loading
- Hybrid Composites (Metal / Composites) create certification problems
- New large transport aircraft suffer weight problems, High strength materials, Higher stresses
- To prevent ageing aircraft problems, lower stresses are needed
- Aging aircraft problem well understood but not solved. Corrosion models are typically of micro-mechanics type, i.e. dependent on planar geometry

New Developments and Potential Problems: 3

- Decline in military spending, no longer technology leader
- Less interest in higher education
- Young generation, in the west, less educated than parents for first time since beginning of last century
- Industry must fight to stimulate very young persons, increase salaries, compete with sexy new technical fields
- The best engineers/scientists/workers need to be motivated to apply for the aeronautical sector
- Future competence problem may become a major problem
- These are all valid points for Europe and USA. However, the aeronautics industry is changing fast.