Aeronautics & Astronautics

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Fatigue and Damage Tolerance Requirements of Civil Aviation

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Parts of the material for this presentation is taken from presentation material by Mr. Dan Cheney, Mr. Walter Sippel, Mr. Greg Schneider and Mr. Robert Eastin of FAA. Major parts of the material in these presentations are taken from the AA531 course textbook, 'Fatigue of Structures and Materials' by Prof Jaap Schijve, Springer, 2009. Professor Schijve is currently affiliated with Delft University of Technology. This material cannot be reproduced in whole or part without written permission of the author and/or the publisher.

Mechanical Failure Modes of Metals

Common Examples

- Overload, ductile, or brittle fracture
- Environmentally assisted fractures:
  - Corrosion, Fretting, Hydrogen Embrittlement
- Creep
- Wear
- Impact
- Dynamic loading
- High Temperature
- Buckling
- Fatigue

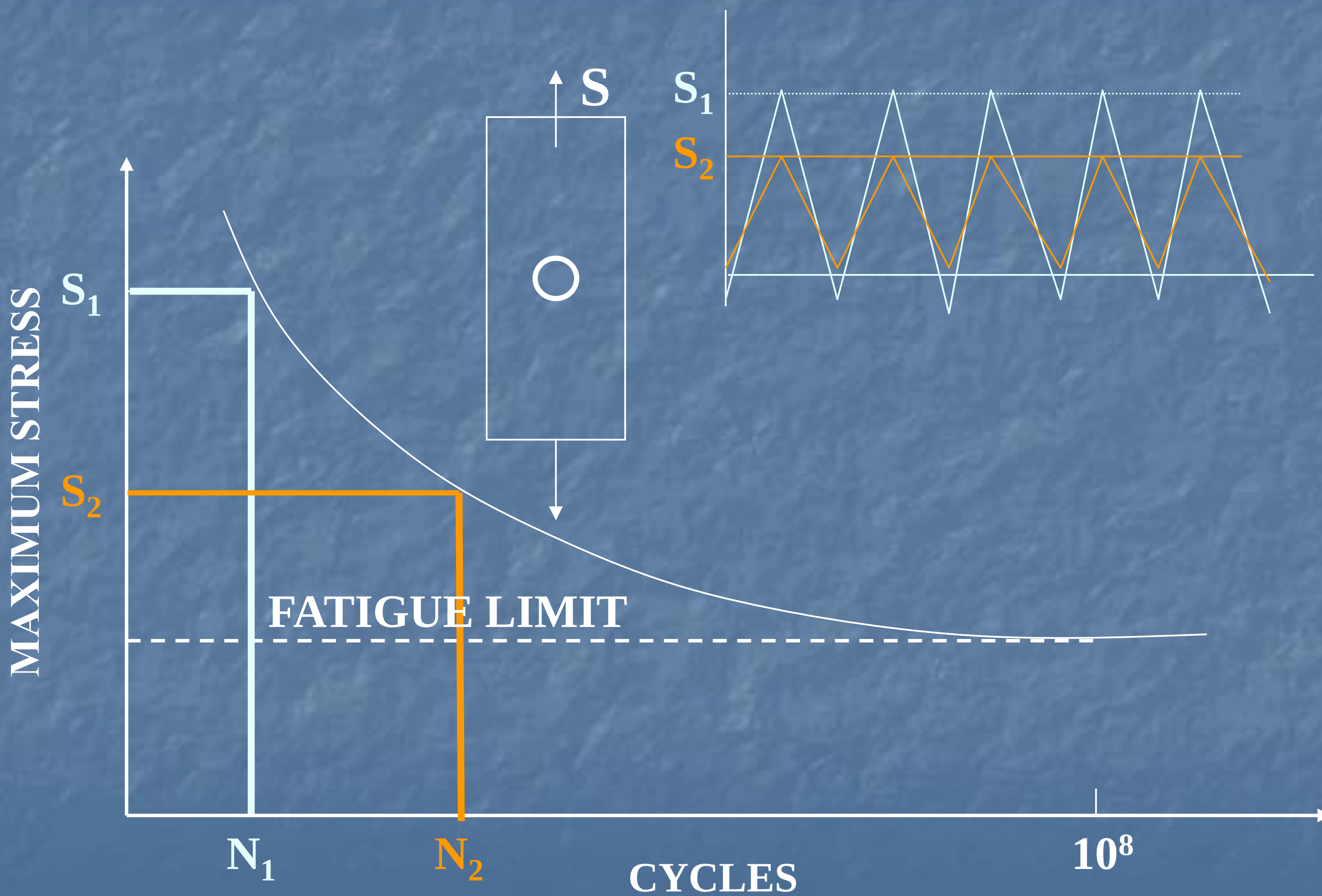
Mechanical Failure Modes of Metals

What is Fatigue?

- Failure mode in metals subjected to repeated loads
- More than half due to fatigue
  - Reports vary between 50 to 90 percent
- US costs: $\underline{+}$ $119 billion/year
  - 4% of national gross income
- Can be minimized by
  - Proper Design
  - Good Material Selection
  - Alternative Joints
  - Lower Working Stress Levels
  - Improved Material Surface Treatment
  - Improved Service Environment
- Predicted using Test and Analysis

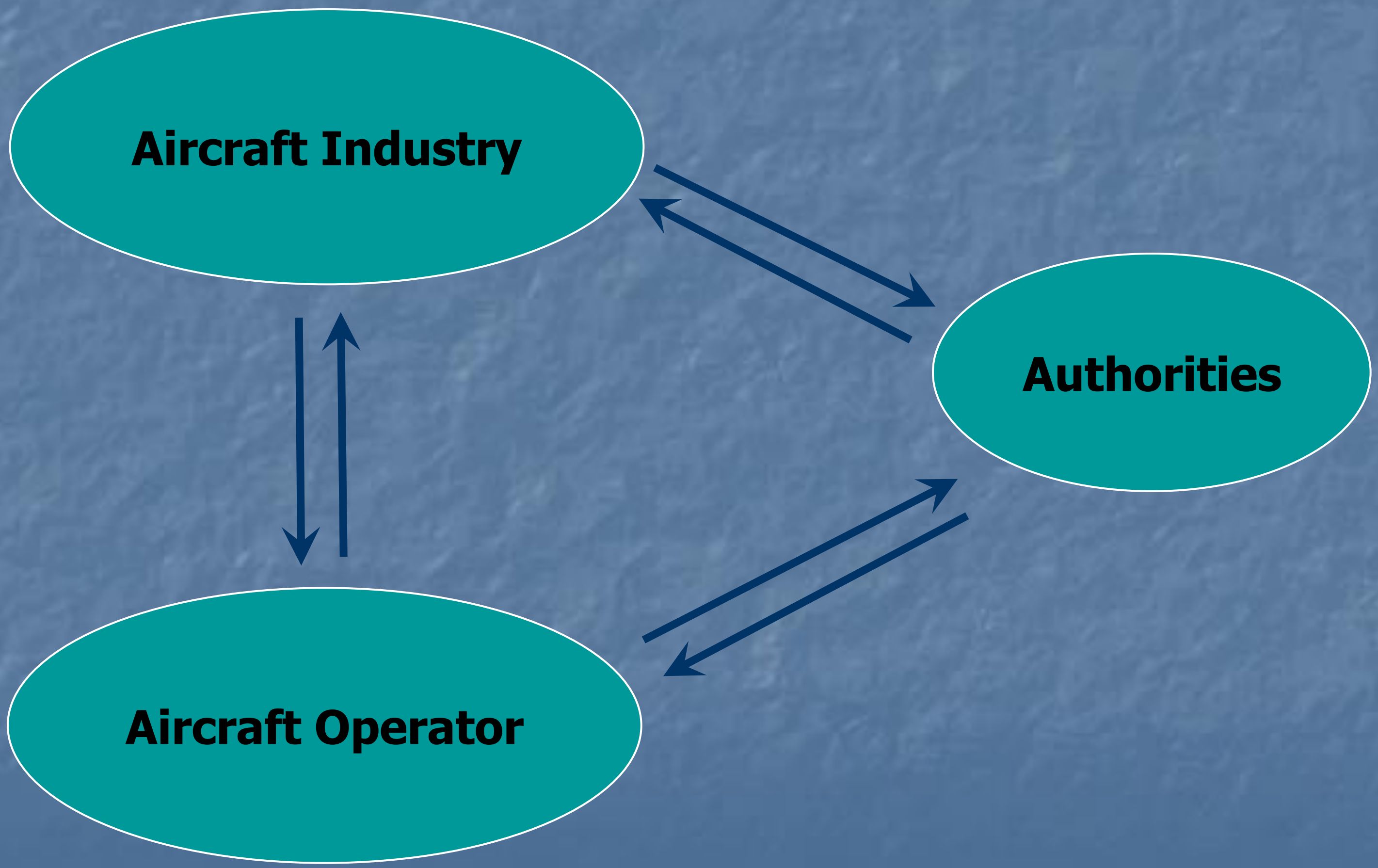
Fatigue (S-N) Curve

a.k.a. Wöhler Curve



The Famous Three Legged Stool

Balancing Issues



Designing a Structure

Against Fatigue and For Damage Tolerance

Aircraft Industry	Good Selling Properties Low Weight Economic Production	Controversial Issues
Aircraft Operator	Low Price Low Operational Costs Low Maintenance Costs	
Authorities	Regulations, Certification, Safe Aircraft, Damage Tolerant	

University of Washington

Course Purpose

This Course Will:

- Survey topics associated with fatigue and damage tolerance analyses of aircraft structures
- Discuss:
  - Civil and military aviation requirements
  - The possibilities for predictions
  - Designing against fatigue
  - How to deal with damage tolerance

Damage Tolerance Requirements

- Civil authorities and USAF DT requirements use similar words but have significant difference
  - FAA safety requirements - leaves room for interpretation
  - USAF design requirements - not much room for interpretation
- Prevent fatigue damage in different manner
- Mainly because of different experiences, utilizations, and performance expectations

See "Contrasting FAA and USAF Damage Tolerance Requirements", by Robert Eastin

USAF Damage Tolerance Requirements

- Up to 1958:
  - No formal fatigue requirements- designs based on static strength considerations plus safety factors expected to preclude fatigue damage
- Crashes of six B-47 in 1958
  - Adoption of formal fatigue requirements in the design to prevent fatigue damage – Safe-Life
    - Development of MIL-8866 & MIL-8867
- Crash of F-111 in Dec. 1969 after 107 hours
  - Adoption of damage tolerance as a formal design requirement – Damage Tolerant
    - Development of MIL-83444

USAF Damage Tolerance Requirements

- The Air Force DT criteria were first published in MIL-A-83444.
  - served as a fundamental reference for initial flaw sizes and the development of inspection requirements from the crack growth analysis.
- In the late 1980's, MIL-A-87221 superseded 83444.
  - This document was written in a "Lessons Learned" format and was considerably more difficult to use. This maybe the reason that so many people continued to reference 83444.
- In the mid 2000's, JSG-2006 superseded 87221.
  - As the report number suggests, this is a Joint Services Group document rather than strictly Air Force as were the predecessors. See the course DVD

USAF Damage Tolerance Requirements

- The latest significant changes came in the 2008-2009 time frame when the aging aircraft concepts were rolled into the DT methods.
- Up to that point, the rogue flaw methodology was used to establish inspection requirement along with Durability analyses.
- The Durability component is comprised of crack growth from a typical 0.005" initial flaw as well as a crack initiation (nucleation) analysis.
- This methodology shift is documented in an Engineering Service Bulletin. This document also contains a historical summary of the DT methodology.

USAF Damage Tolerance Requirements

- The DT analysis and test requirements fall under ASIP (Airframe Structural Integrity Program).
  - The ASIP program requirements are documented in MIL-STD-1530.
    - An analogous document to CFR Part 25.
- There are other documents dating back to 1960 - analogous to FAA Advisor Circulars
  - Share the title Airplane Strength and Rigidity General Specification.
  - Here is a brief summary of the ones relative to Damage Tolerance analysis:
    - MIL-A-8860 – General Specification
    - MIL-A-8861 – Flight Loads
    - MIL-A-8866 – Repeated Loads, Fatigue and DT
    - MIL-A-8867 – Ground Test

Civil Aviation Damage Tolerance Requirements

- Up to 1956:
  - CAR 4b.316: required fatigue evaluations and retirement– Safe-Life
- Crashes of two Comet 1 in 1954
  - Adoption CAR 4b.270 (1956)- Fail-Safety supplementing safe-life as an option
- Crash of 707-300 in May 1977 in Lusaka
  - Adoption FAR 25.571 Amendment 45 (1978): dropping fail-safety and adopting Damage Tolerance requirements while maintaining safe-life
- Aloha 737-200 incident in May 1988 in Maui
  - New rulemaking to adopt Limit Of Validity

Boeing B-47

Fatigue problems led to USAF adoption of fatigue requirements in the design considerations

UNIVERSITY OF WASHINGTON

Lockheed C-5A Galaxy

Wing fatigue issues led to major redesign…

Metal Fatigue

- Before we turn the crank we should get familiar with a brief history of fatigue in aviation, meaning of terms and reason for doing what we are doing
  - A brief history of fatigue in general and in aviation will follow in next several slides
  - Meaning of terms will be discussed as introduced
- Keep in mind that typical fatigue analysis of aircraft structures is performed during the design phase for economical reasons, while the damage tolerance assessment of structures is performed for safety.
    - There are company requirements that need to be met with these analysis as well as the regulatory agency requirements, which are used to certify, operate and maintain the airplane
- Let's first get familiar with types of fatigue in general

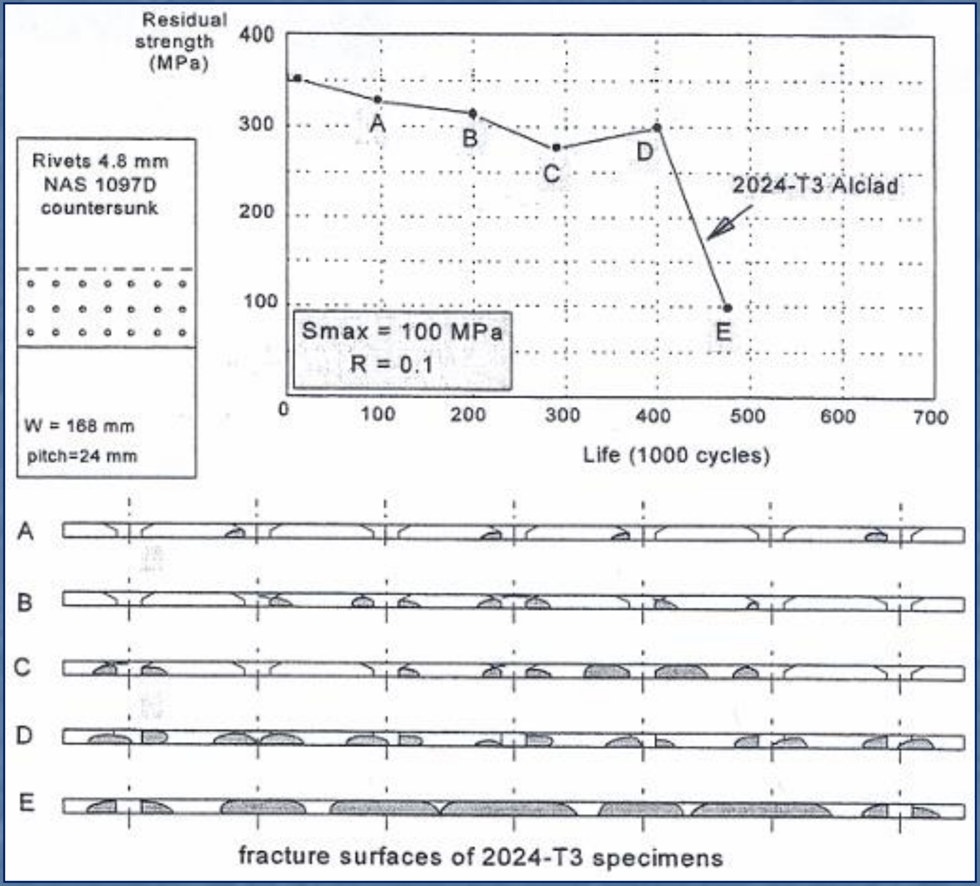
Fatigue Types

Three Fatigue Types

- **Normal Fatigue**
  - Nominal: no "surprises"
  - An inherent characteristic
  - Expected, inevitable, predictable
  - Probability increases steadily with time
- **Anomalous Fatigue**
  - Off nominal physical condition
  - Unexpected and unpredictable
  - Some designs more vulnerable than others
- **Unexpected Normal Fatigue**
  - Incorrect load analysis- external/internal loads
  - Unexpected usage of aircraft

Fatigue Types

Normal Fatigue



This is the type of fatigue damage that is the subject of this course

Ref. *J. Schijve. Fatigue of Structures and Materials, 2nd Edition, Springer, (2009) Page 605.*

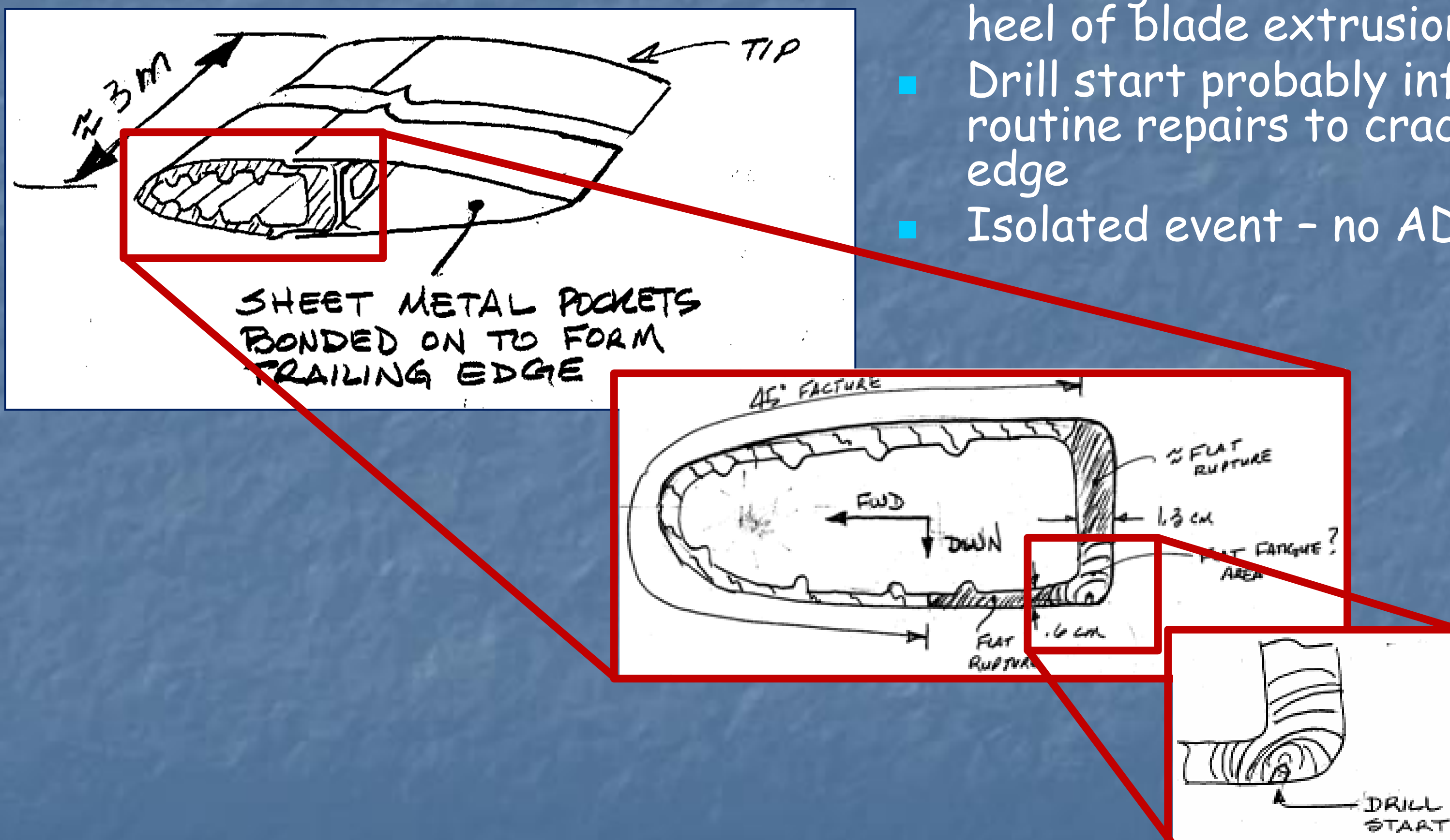
Fatigue Types

Anomalous Fatigue

- Catastrophic loss outer 3 meters of CH54A main rotor blade on July 18, 1998.

Fatigue Types

Anomalous Fatigue (continued)



- Cracking initiated at drill start in heel of blade extrusion
- Drill start probably inflicted during routine repairs to cracks in trailing edge
- Isolated event – no AD issued

Fatigue Types

Unexpected Normal Fatigue

- Chem-milled cracking of solid skins in narrow body airplanes

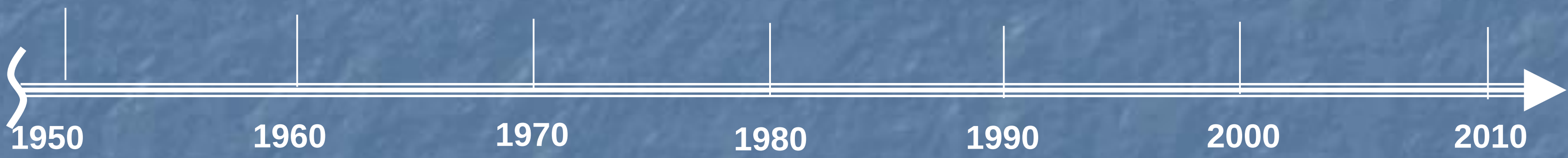
Review

Fatigue

- Failure mode in metals
- S-N Curve
- Balancing Priorities
- Best design practices
- Types of Fatigue:
  - Normal
  - Unexpected Normal
  - Anomalous Fatigue

Evolution of Fatigue Requirements

Timeline



CAR 4b.316

Fatigue (Safe-Life)

CAR 46.316 *Fatigue strength*. The structure shall be designed in so far as practicable, to avoid points of stress concentration where variable stresses above the fatigue limit are likely to occur in normal service. (Sept. 1, 1949)

This was achieved by:

1. Design to stress levels below the endurance limit.
2. Retire the structure prior to the fatigue life.

Military Requirement

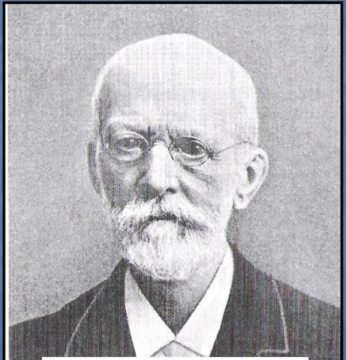
Designs based on static strength considerations plus safety factors expected to preclude fatigue damage.

History of Metal Fatigue

1800's

- Only partly understood
- Historically slow & expensive
- 1837: First article by W.A.J. Albert in 1837 about results of fatigue test of chains
- 1840's: railroad axles failed
- 1840's & 1850's: "fatigue" is coined
  - Braithwaite coined the term for common service failures in 1854

Versailles rail accident (May 8, 1842)



August Wöhler

Father of systematic fatigue testing

History of Metal Fatigue

1800's & Early 1900's

- 1850's: August Wöhler & systematic fatigue testing
  - S-N diagram & fatigue limit
  - Range of stress over maximum stress
- 1870's & 1890's: Gerber and mean stress; Goodman & simplified theory
- 1886: Bauschinger and yield strength in tension and compression
- Early 1900: Erwing and Humfrey and the optical microscope
- 1910: Basquin and alternating stress vs. life (S-N)

History of Metal Fatigue

1920's & 1930

- 1920: Gough and bending and tension.
- 1920: Griffith publishes on brittle fracture of glass
  - He discovered that $S\sqrt{a}$= constant
- 1924: Palmgren and a linear cumulative damage model
- 1920's: McAdam and corrosion fatigue studies
- 1930: Haigh and steel strength in presence of notches

History of Metal Fatigue

1930's to 1950's

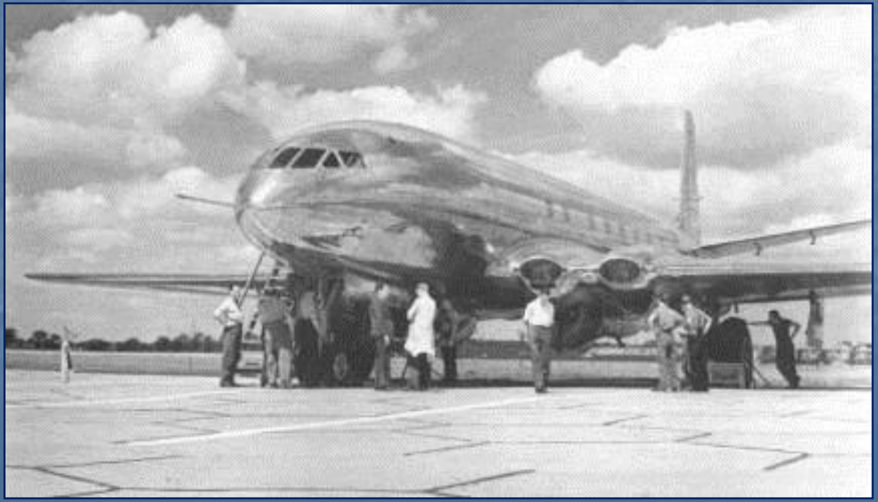
- 1930's: shot-peening in automotive industry
- 1945: Miner and a linear cumulative fatigue damage criterion suggested by Palmgren in 1924
  - Palmgren-Miner rule
  - An important tool in fatigue life prediction despite shortcomings
- 1953: Peterson's book on K_t
- 1952: first jet-propelled passenger jet, Comet
  - http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=28

History of Metal Fatigue

Fact or Fiction?

History of Metal Fatigue

De Havilland Comet 1[1]



Comet 1 Accidents – Circa 1950'S

First commercial flight in January 22, 1952

First sign of problem in May 2, 1953; 2 more crashes to follow within a year!

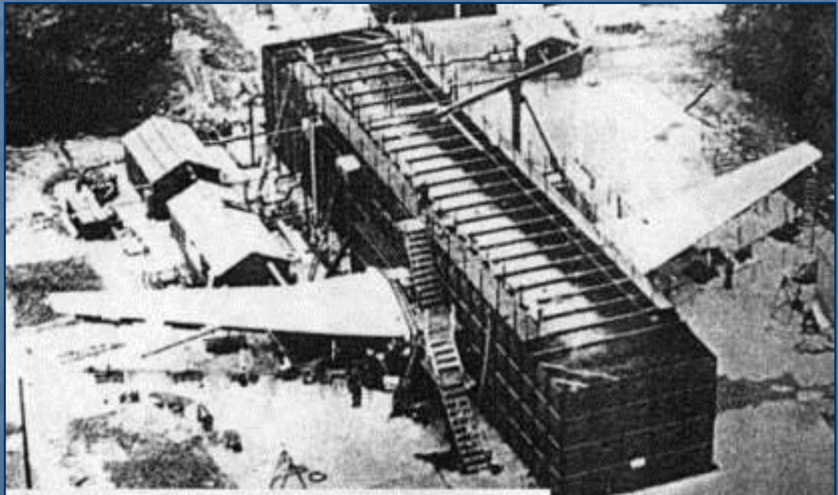
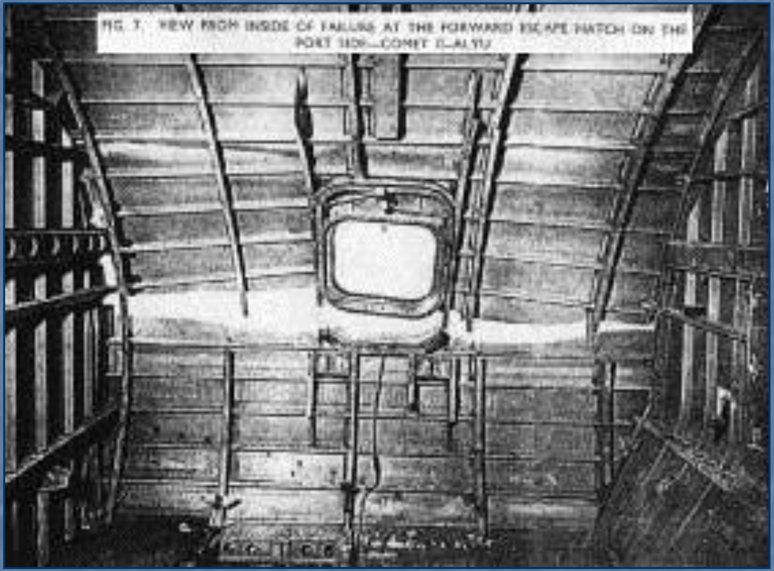


FIG. 6. AERIAL VIEW OF COMET G-ALYU IN TESTING TANK.

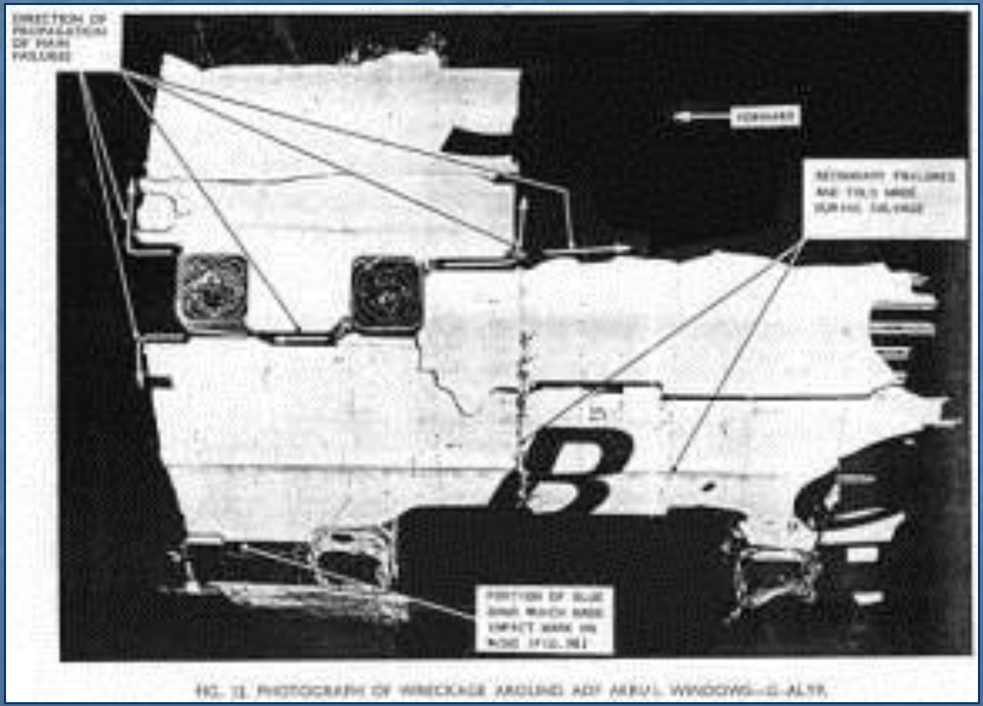
G-ALYU, was subjected to full-scale hydro-fatigue testing.

Comet 1 Accidents

Known Issues, Tragic Result

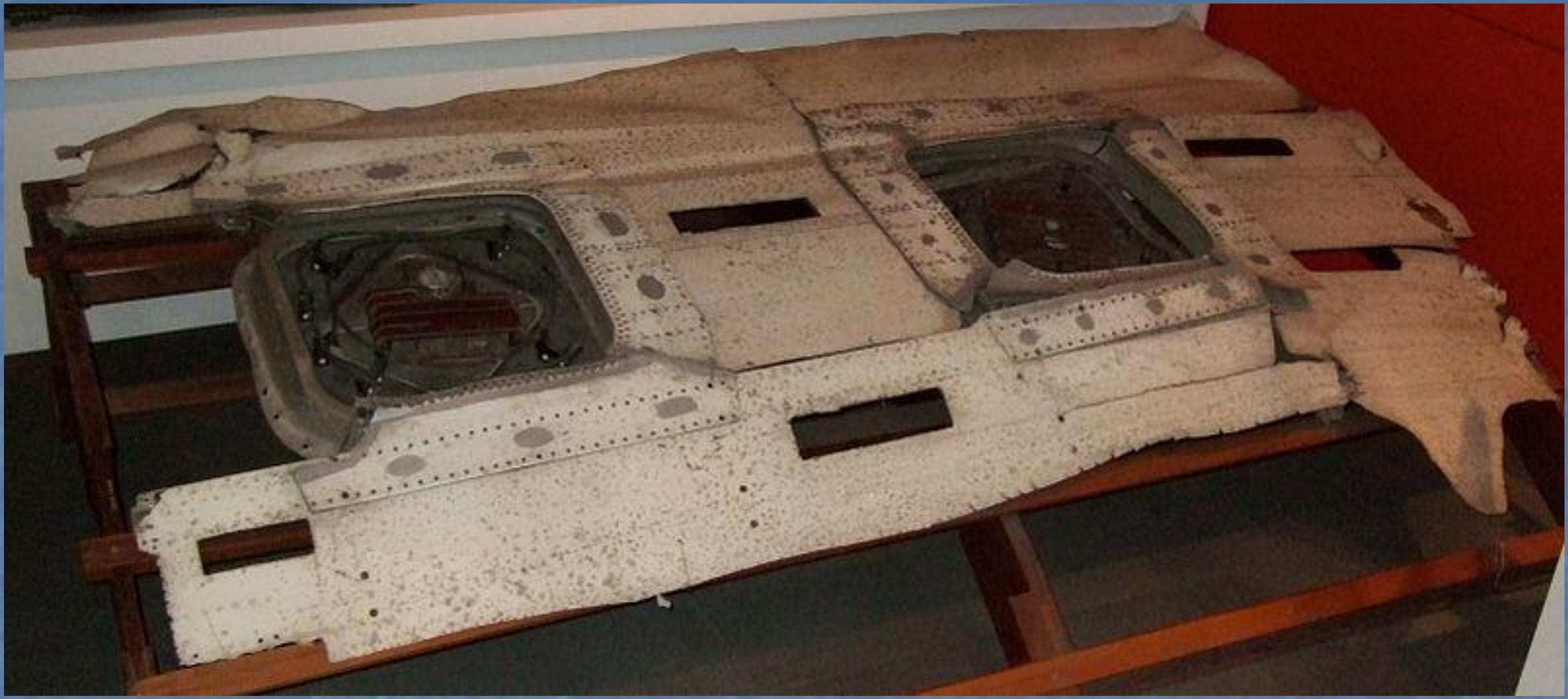


In the test ~3,600 flight cycles 4.5m section of the fuselage at Escape Hatch the ruptured



G-ALYP sections recovered from the sea confirmed the test results; in this airplane the crack was at the ADF Aerial Window

Comet 1 Accidents



The fuselage fragment of *G-ALYP* on display in the Science Museum in London. Fuselage fragment of de Havilland Comet G-ALYP which crashed January 10, 1954. This fragment, retrieved from the bottom of the Mediterranean Sea, was determined to be the original cause of the crash as it tore lose.
Ref: ObjectWiki- Science Museum. 24 September 2009

Comet 1 Accidents- What Went Wrong?

- Airplane was certified as safe-life for 16,000 flights and 10 years of utilization.
- Operational Pressure higher than existing airplane models of the time
  - P=8.25 psi compare to ~5 psi
- Full scale test to 30 times up to or near 2P plus 2000 times higher than P
  - Designed for 2.5P
- As a result of high applied P many fatigue critical details were plastically deformed
  - Caused an artificially long fatigue life

Comet 1 Accidents- Accident Impact

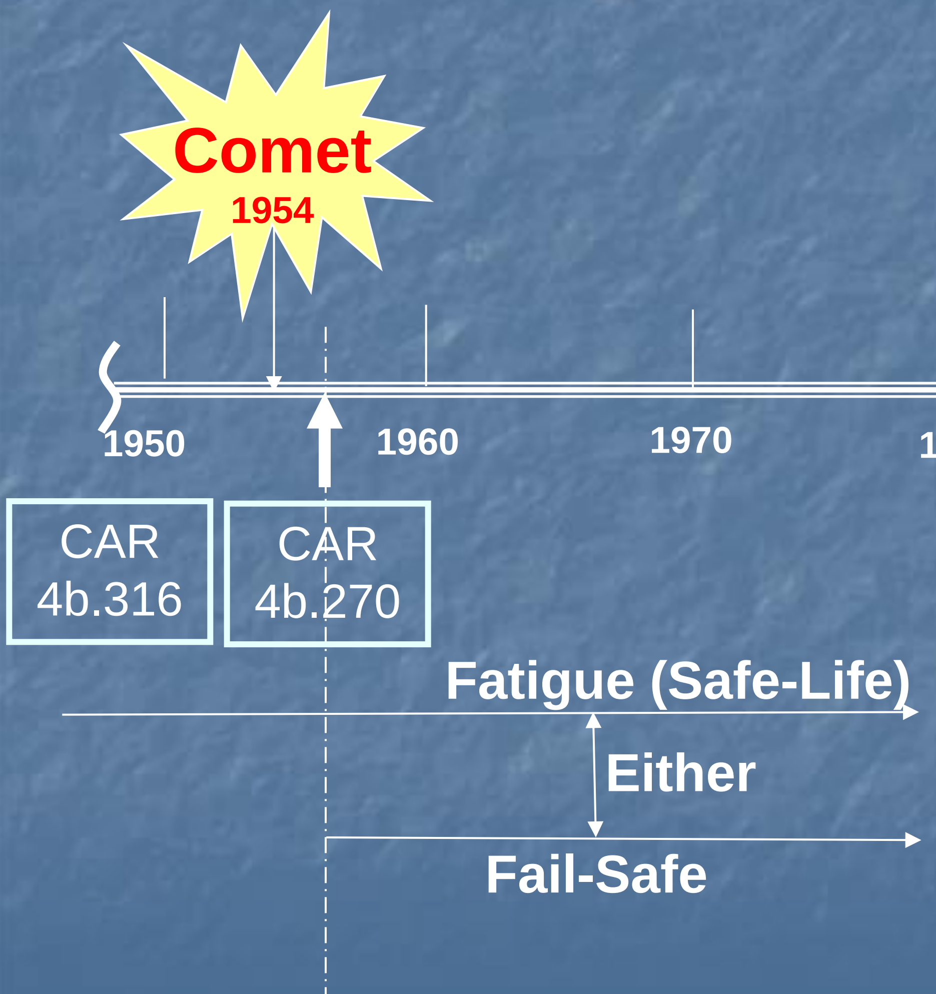
- Increased concern with respect to pressurized fuselage design including
  - Allowable 1 P stress levels
  - Detail design features
  - Crack arrest capability
- Increase concern relative to fatigue
- Highlighted need for representative full-scale fatigue testing to understand fatigue performance
- Increased merit of fail-safe design

CAR 4b.270 Fatigue Evaluation

- Adopted fail-safety as an option to safe-life design philosophy
- Adopted requirements for formal evaluation of structure susceptible to fatigue
- Introduced the concept of Principal Structural Elements (PSE)

Evolution of Fatigue Requirements

Timeline



<u>CAR 4b.270</u> *Fail Safe Strength.* It shall be shown by analysis/test that catastrophic failure or excessive structural deformation … are not probable after fatigue failure or obvious partial failure of a single PSE. After such failure, the remaining structure shall be capable of withstanding static loads corresponding with the flight loading conditions in paragraph (1) and (2)…

CAR 4b.270 Fatigue Evaluation- Civil

- Certification bases for many aircrafts during 1950's to 1970's:
  - Airbus: A300
  - Boeing: 707/720, 727, 737, 747
  - British Aircraft Corporation: BAC 1-11
  - Fokker: F-28
  - Lockheed: L-1011
  - McDonnell Douglas: DC-8, DC-9/MD-80, DC-10

What was happening in the military world during this time?

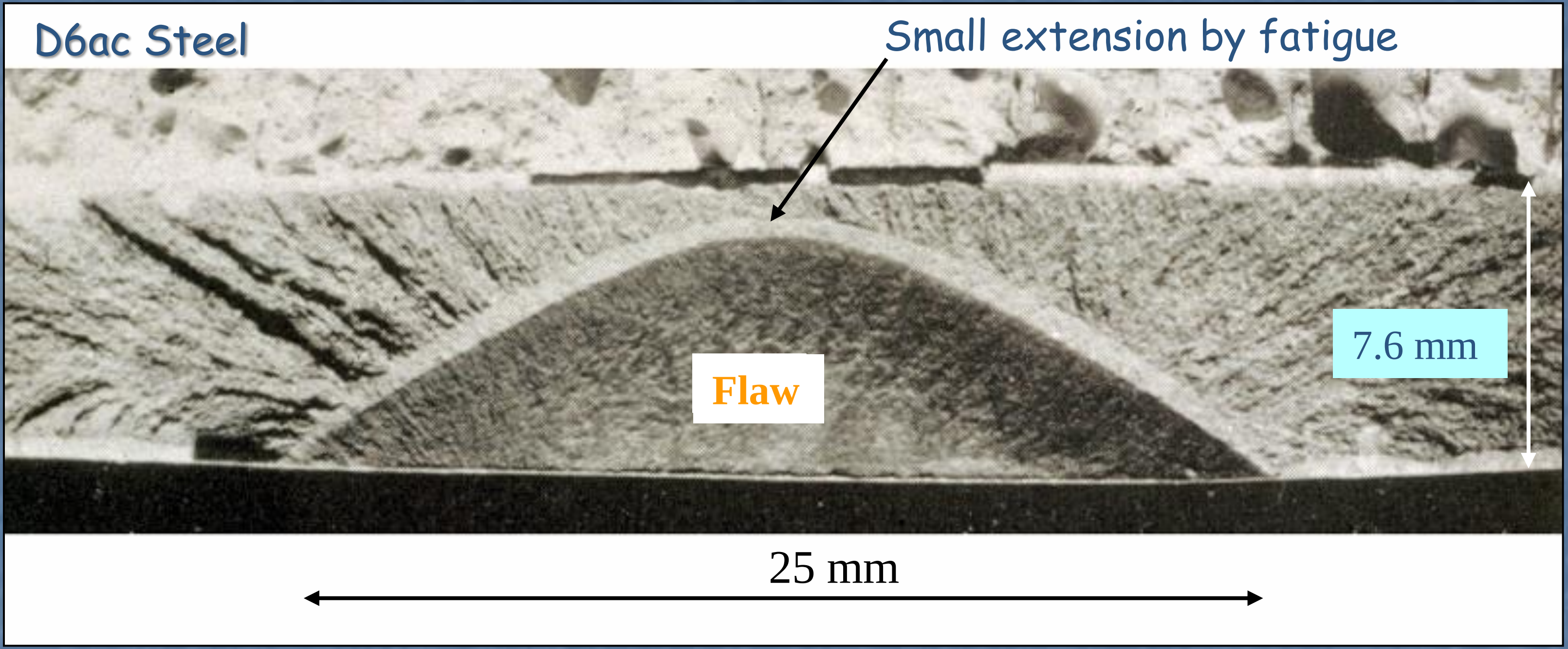
History of Metal Fatigue

General Dynamics F-111 –

Designed based on safe-life concept

History of Metal Fatigue

F-111: 22 December 1969 – Nellis AFB, NV

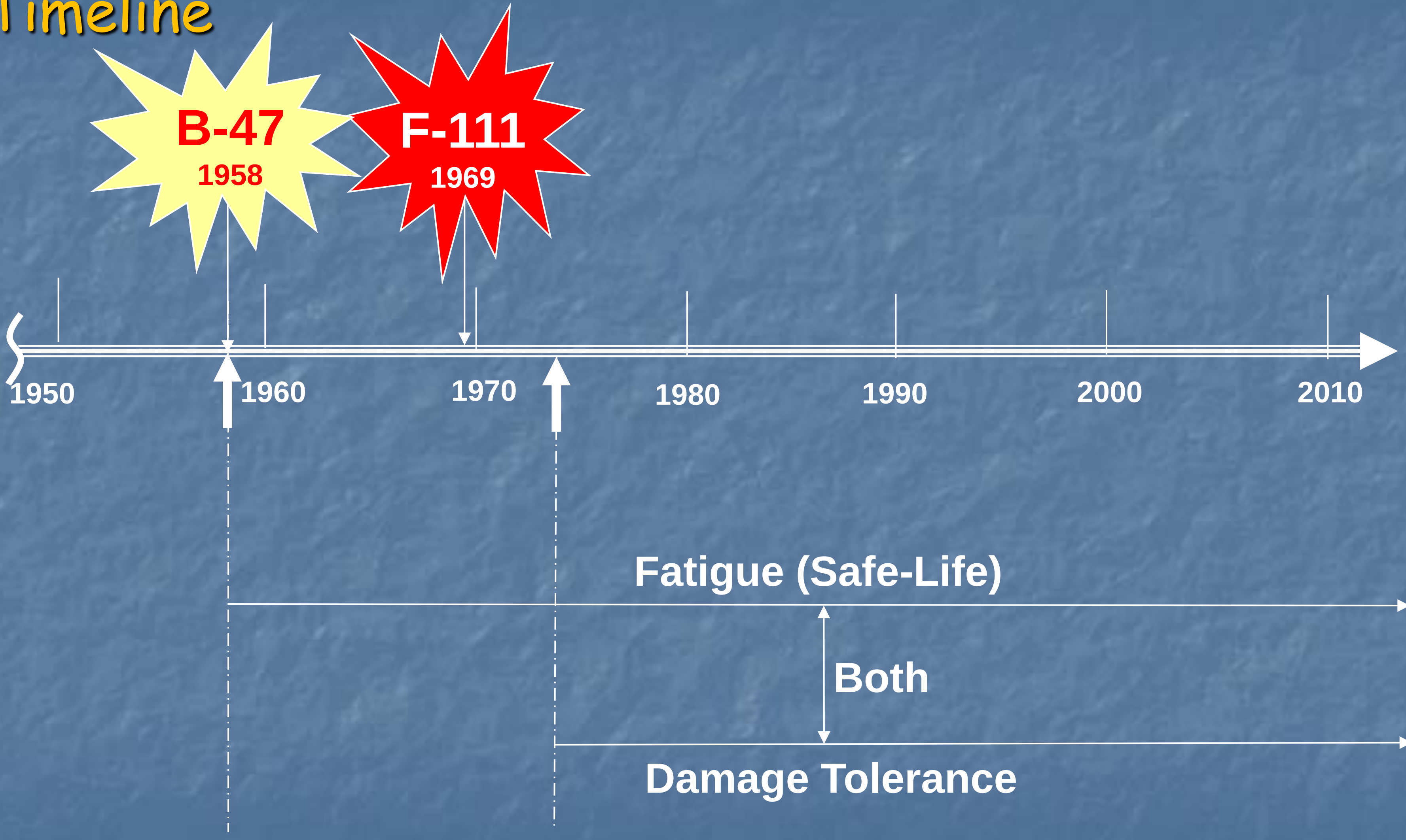


D6ac Steel
S_U = 1600 MPa√m
K_{IC} = 40-100 MPa
(different lots)

Failure of F-111 wing due to initial flaw in the steel plate and some limited extension by fatigue crack growth.

Evolution of Fatigue Requirements- USAF

Timeline

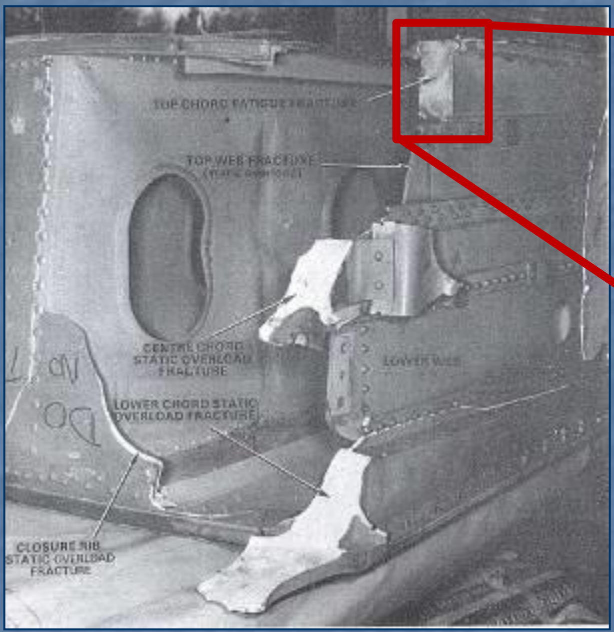


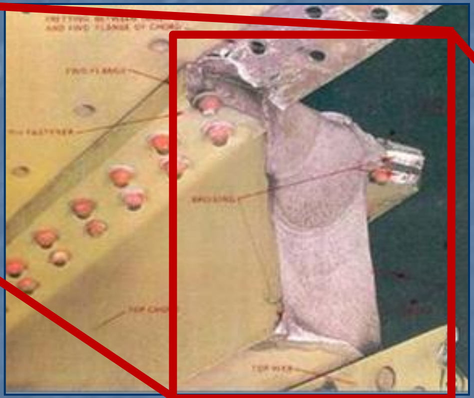
History of Metal Fatigue

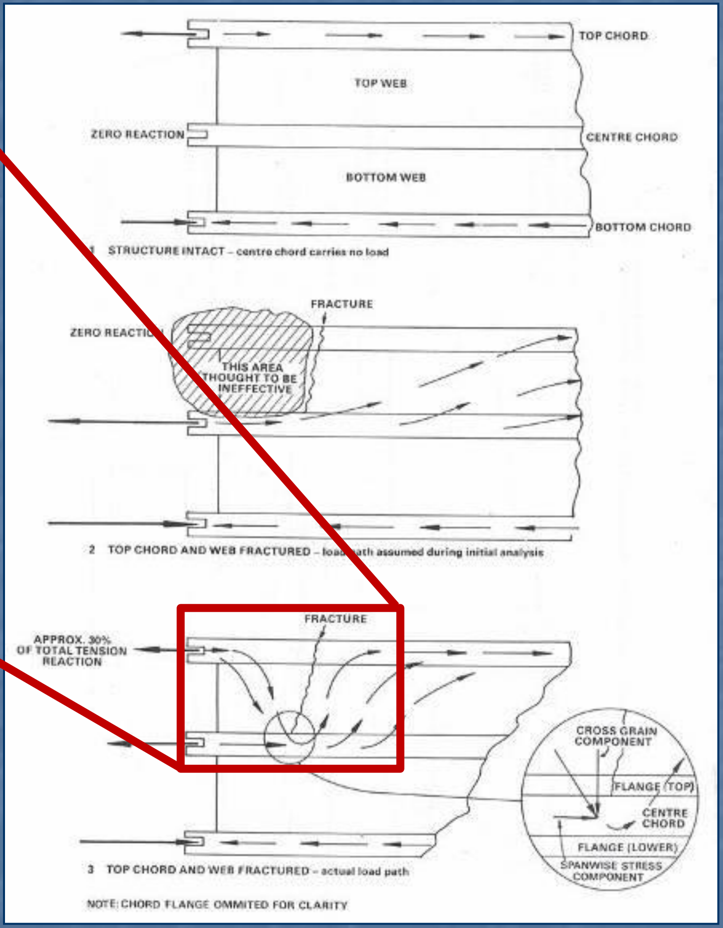
Dan Air Boeing 707 – 14 May 1977

History of Metal Fatigue- What Went Wrong?

B-707-300 Horizontal Stabilizer



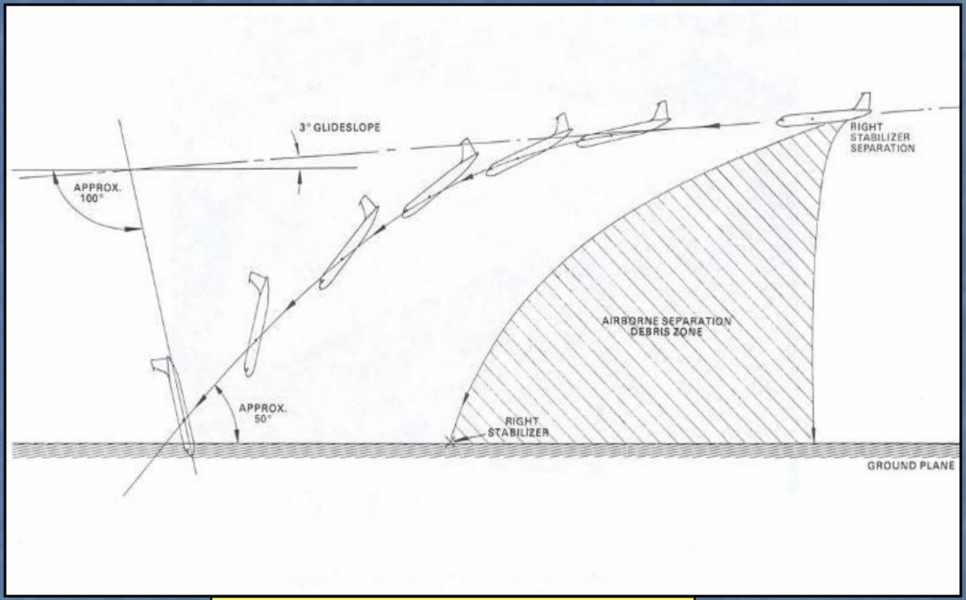




Fatigue Crack in the Rear Spar Upper Chord

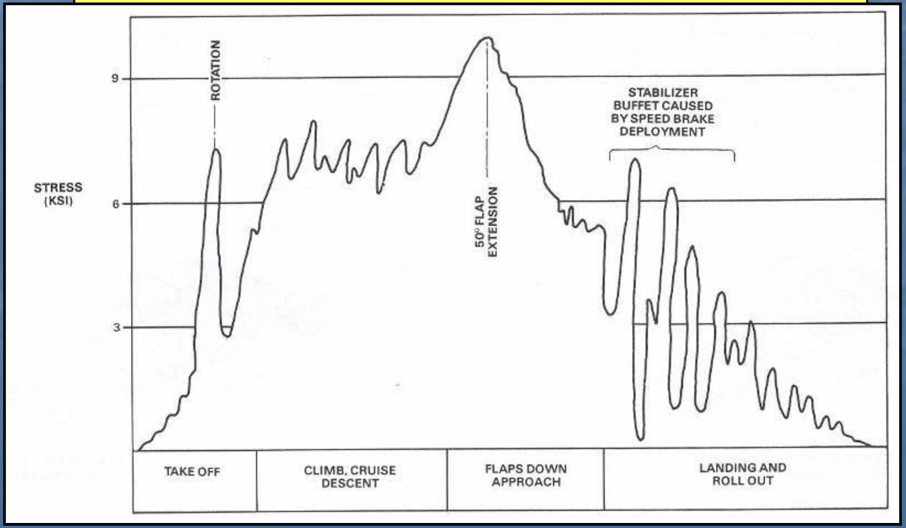
Dan Air Accidents- What Went Wrong?

Accident trajectory and stress profile



G-BEBP Estimated Trajectory Following Stabilizer Separation

Typical Flight Stress Profile - 707-300 Series Horizontal Stabilizer Stress in Rear Spar Upper Chord



For complete accident discussions refer to: http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=39

History of Metal Fatigue- Accident Impact

Dan Air accident aftermath

- Following the Dan-Air accident (and partly due to F-111 accident), FAR 25.571 was re-titled in 1978 with Amdt 25-45: "Damage Tolerance and Fatigue Evaluation of Structure"
  "(b) Damage Tolerance (Fail-Safe) Evaluation"
  - Emphasized damage delectability and growth rates
  "(c) Fatigue (Safe-Life) Evaluation" remained as option - e.g. main landing gear post
  "(e) Damage tolerance (Discrete Source) Evaluation"
  - Specified certain types of damage (e.g., birds, engine debris)
- Referenced Advisory Circular 25.571-1 for guidance
- Consideration for "damage at multiple site" was stated in (b) Amdt 25-45
  - Due to events in past 30 years this type of cracking has received special consideration.

History of Metal Fatigue- Accident Impact

Dan Air accident aftermath (cont.)

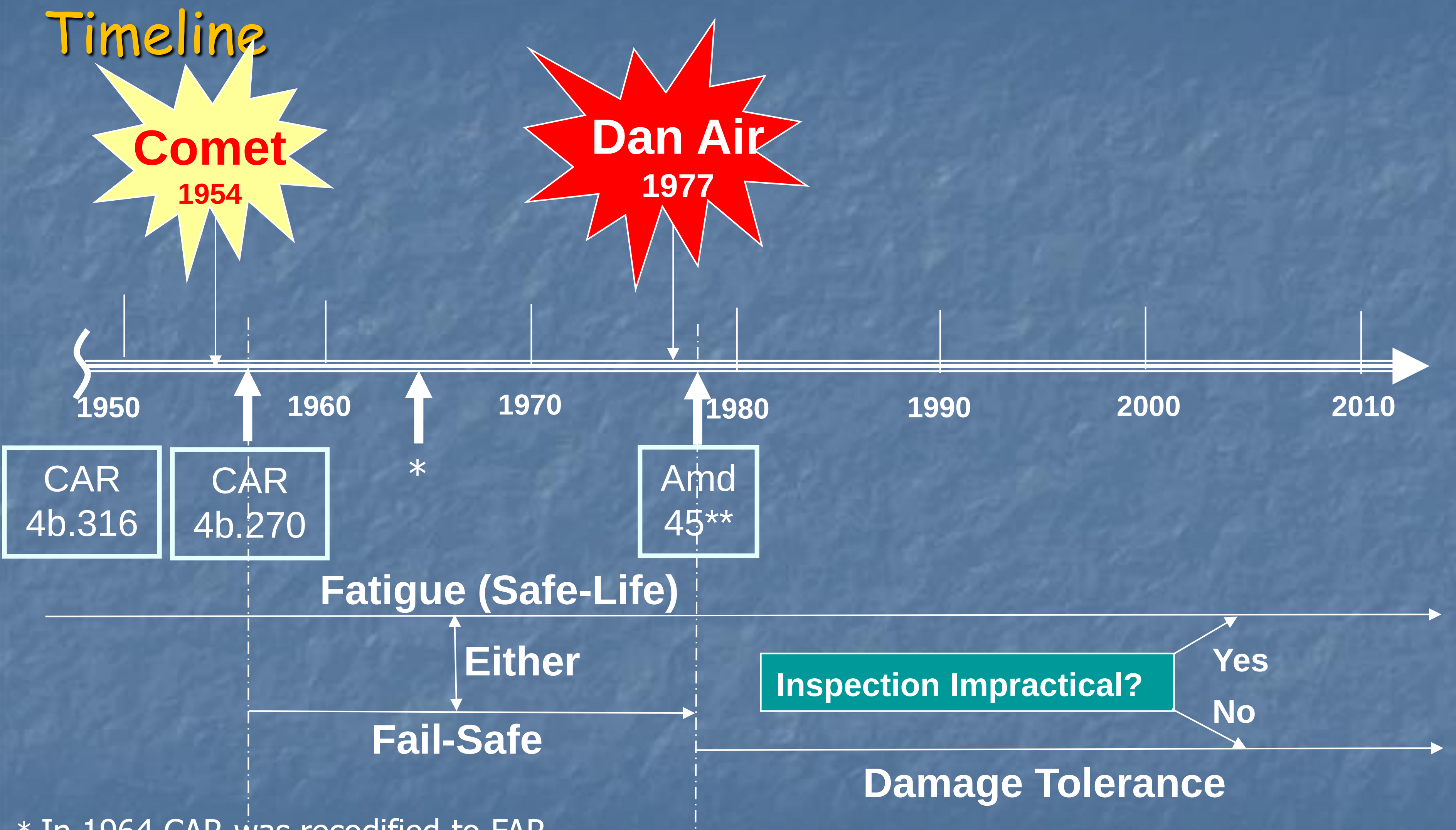
- Regulatory changes to consider: Mr. Eastin, FAA, and Prof. Bristow, UK-CAA
  - Required fatigue life assessment including full-scale fatigue testing to demonstrate the fatigue performance of all primary structure
  - Develop guidance on flight test validation of fatigue loads used for analyses and tests
  - Set upper limits on inspection thresholds regardless of analysis results
  - Require full scale damage tolerance testing
  - Developed guidance on assessing significance of design changes within same certification bases (c.f. CPR)

History of Metal Fatigue

Dan Air 707-300 – Lessons Learned

- Importance of identifying fatigue critical locations and areas
- Importance of having correct fatigue spectrum loading
- Fatigue & residual strength behavior: complex & difficult to predict
- Total reliance on "Fail safety" may not meet safety objective

Evolution of Fatigue Requirements



* In 1964 CAR was recodified to FAR

** AC 91-56 was also issued; set policy for OEMs to develop Supplemental Inspection Programs (SID) for pre-45 models

§ 25.571 Amendment 45

- Adopted Damage Tolerance as replacement for Fail-Safe structures:
  - Required inspection or other procedure to detect the crack prior to failure
  - Retained Safe-Life as option if DT impractical
- Required special consideration for damage at multiple sites
- Required evaluation for accidental damage and environmental damage

Advisory Circular 91-56

- AC Subject: Supplemental Structural Inspection (SID) Program for Large Transport Category Airplanes
  - Required the OEM in conjunction with operators to develop SID on a timely manner
  - Develop inspections and/or modifications in accordance to damage tolerance principles of 25.571 Amnd 45
  - Subject airplane models - 11 Elite:

A300	707/720	DC-8
BAC 1-11	727	DC-9/MD-80
F-28	737 Classics	DC-10
L-1011	747	

  - Equivalent to AC 91-56 was UK airworthiness Notice 89

Advisory Circular 91-56 (cont.)

- The continuing assessment of structural integrity may involve more extensive damage than might have been considered in the original fail-safe evaluation of the airplane
  - A number of small adjacent cracks, each of which may be less than the typically detectable length, developing suddenly into a long crack
  - Failures or partial failures in other locations following an initial failure due to redistribution of the loading causing a more rapid spread of fatigue; and
  - Concurrent failure or partial failure of multiple load path elements (e.g. lugs, planks or cracks arrest features) working at similar stress levels.
- All the SID are mandated by Airworthiness Directives

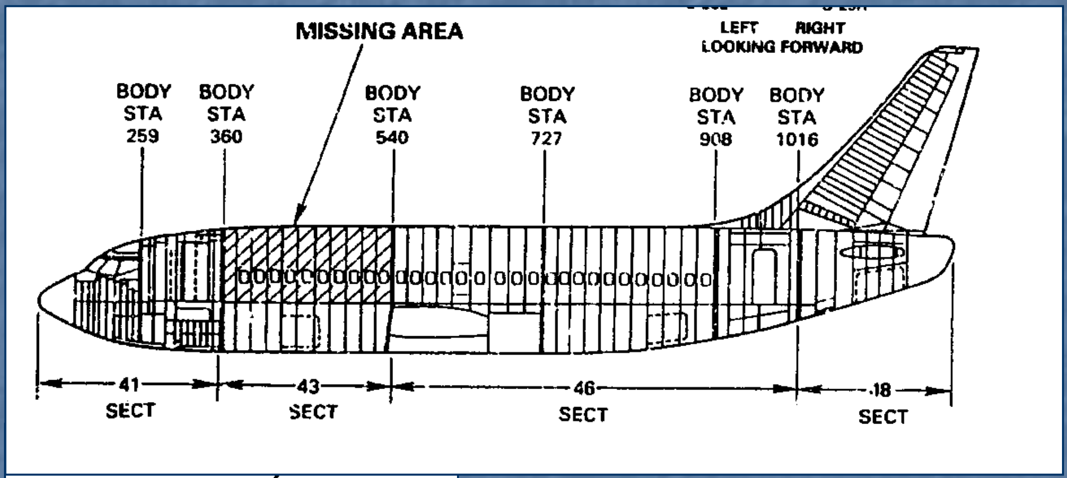
History of Metal Fatigue

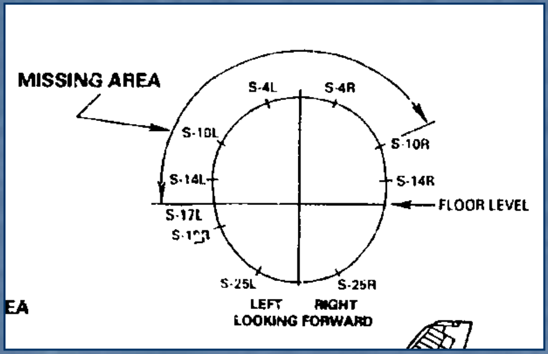
Boeing 737-200 Aloha Incident - 28 April 1988

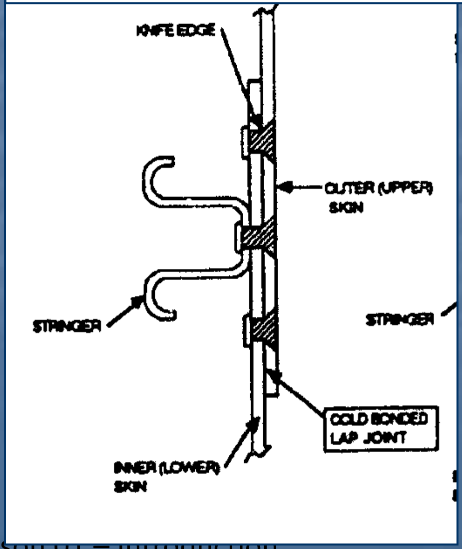
For complete accident discussions refer to:
http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=20

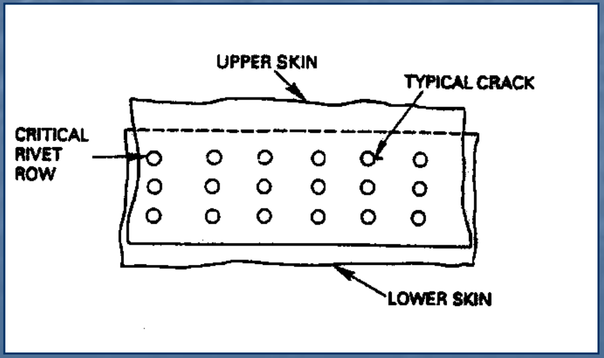
History of Metal Fatigue

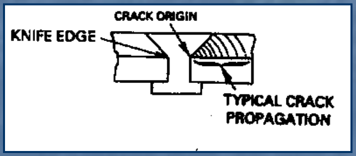
Boeing 737-200 Aloha Incident - 28 April 1988



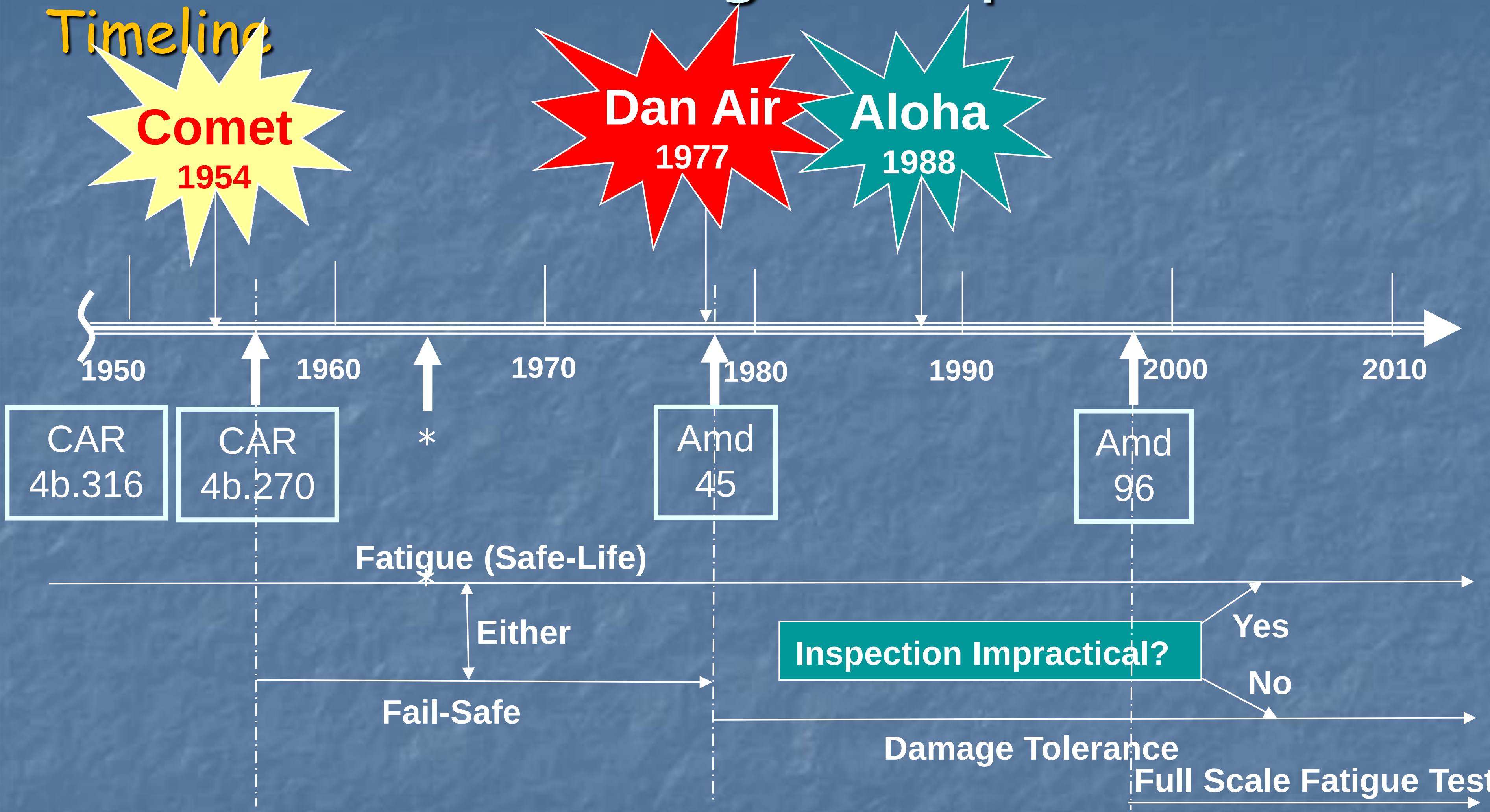








Evolution of Fatigue Requirements



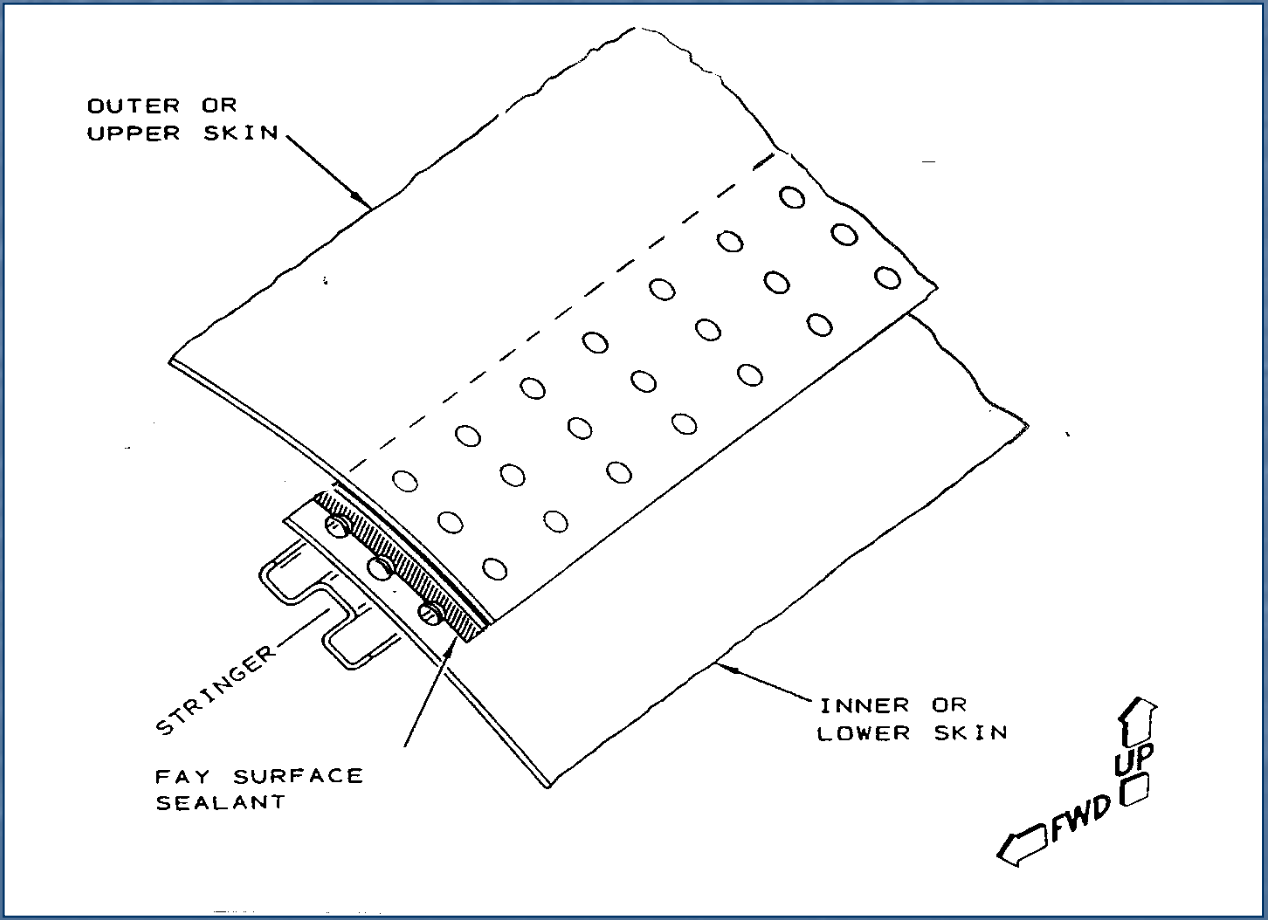
* In 1964 CAR was recodified to FAR

** AC 91-56 was also issued; set policy for OEMs to develop SID for pre-45 models

History of Metal Fatigue

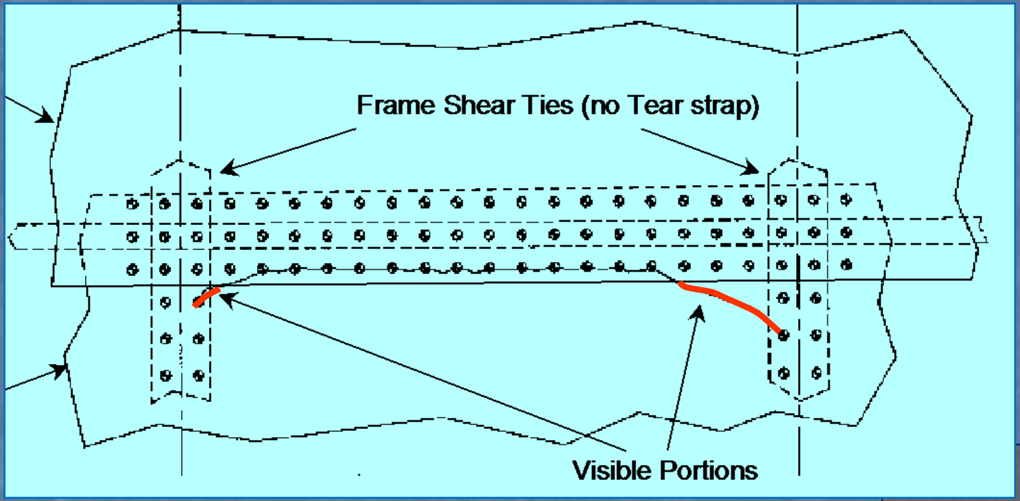
727-200 Lap Splice Cracking- Dec 1998

Line number 850 and on

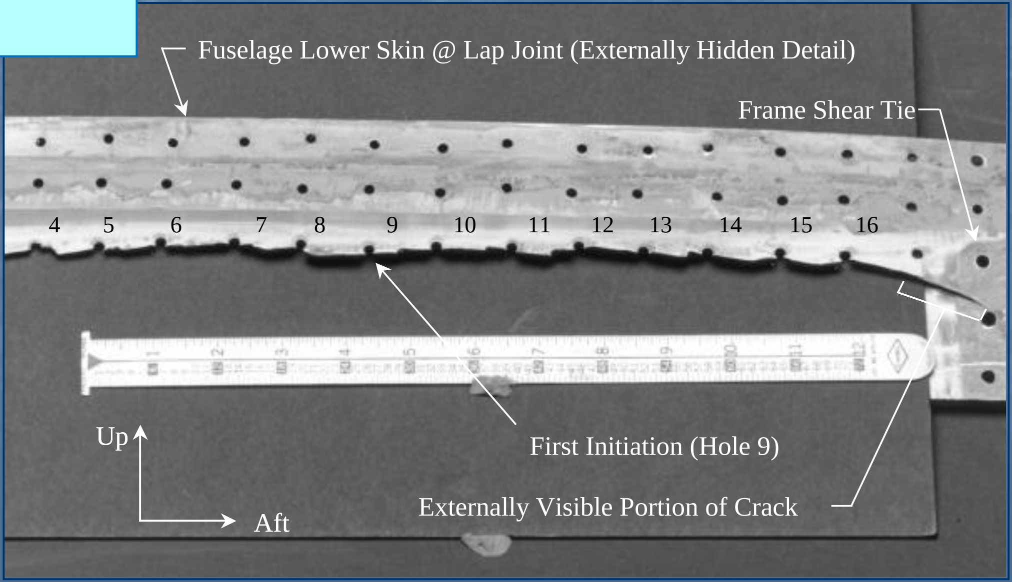


History of Metal Fatigue

MSD: Fuselage Lap Slice Cracking



- Delta Air Lines, Boeing 727-200, 1998
- During preflight walk around, two cracks found growing out from underneath lap joint
- Disassembly of joint revealed 20" crack due to linkup and growth of multiple cracks at fastener holes

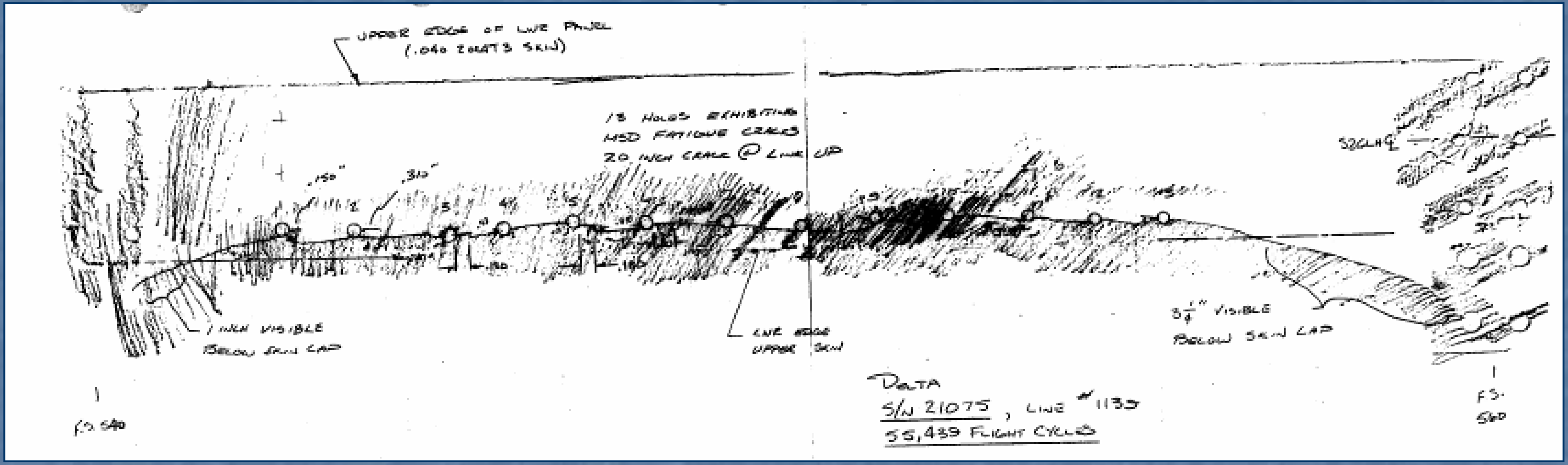


- Fleet inspections found similar condition on other airplanes
- Determined to be an unsafe condition likely to occur on other aircraft:

  AD 99-04-22 was issued

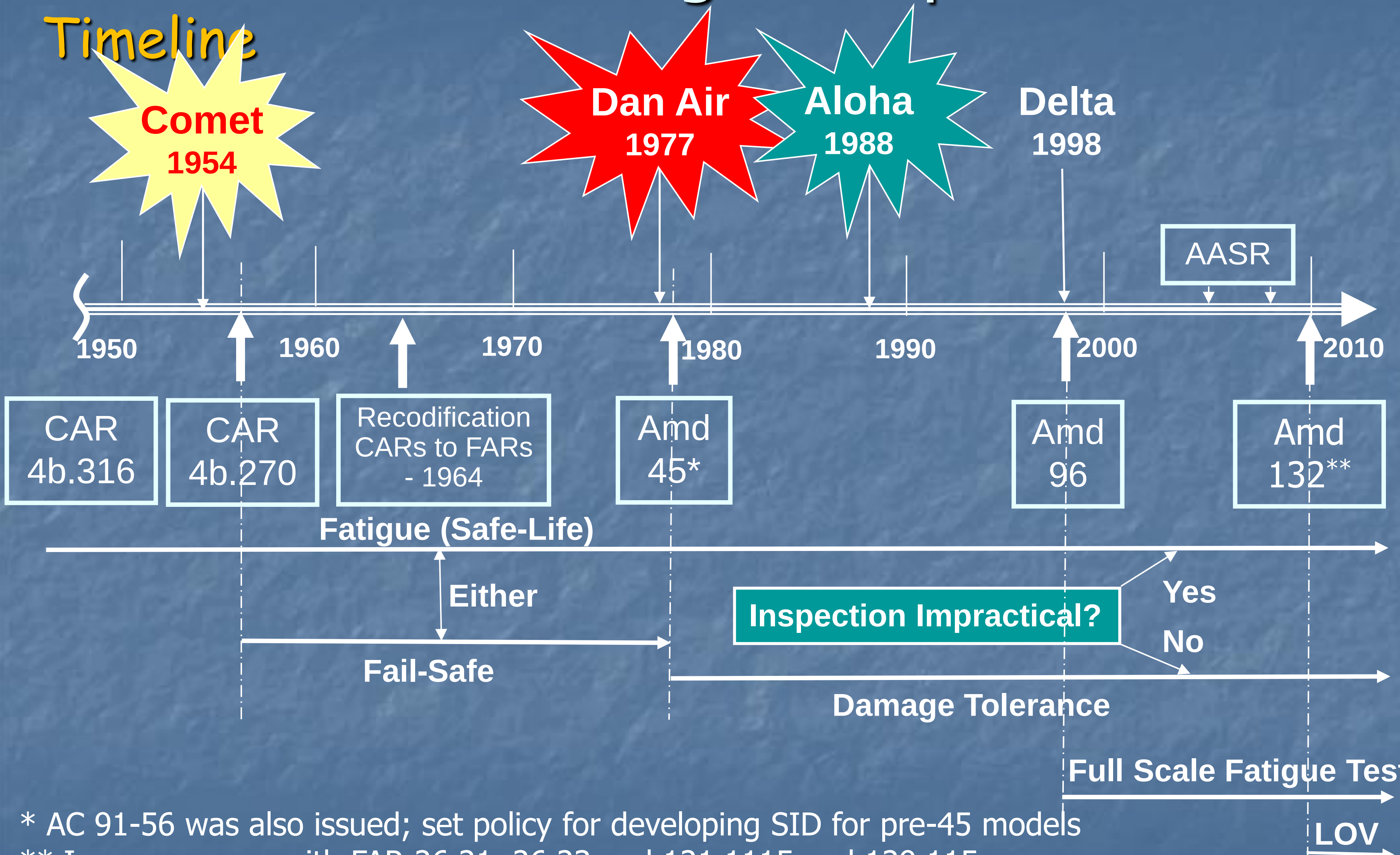
History of Metal Fatigue

Boeing 727 MSD Finding- Pencil rubbing of the skin



- Exposed 3 1/4" end found during pilot preflight walk around
- 20" long MSD link-up
- *A/C* had accumulated 55,439 cycles

Evolution of Fatigue Requirements

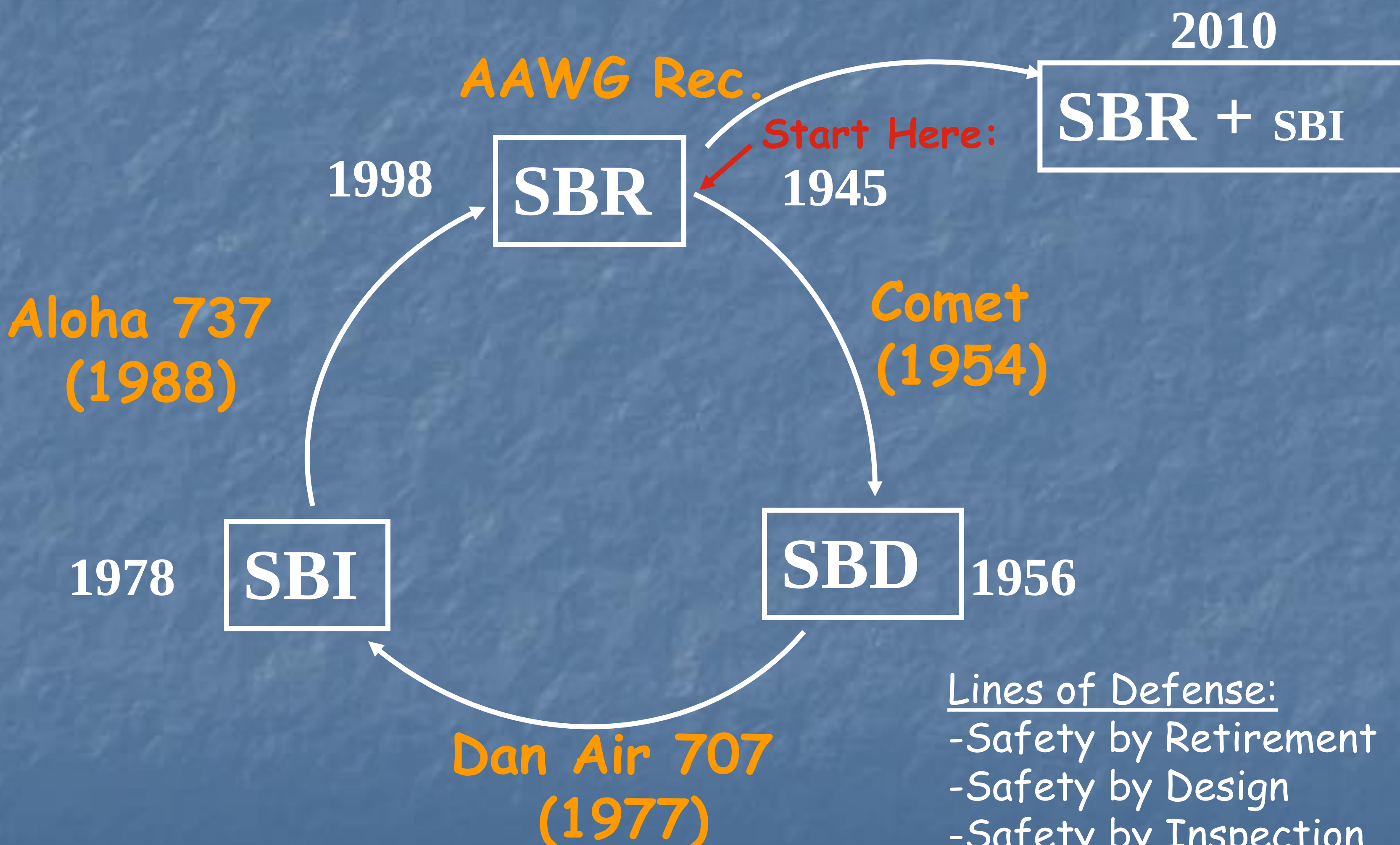


* AC 91-56 was also issued; set policy for developing SID for pre-45 models

** In concurrence with FAR 26.21, 26.23 and 121.1115 and 129.115 (AC 25.571-1D and AC 120-104)

History of Metal Fatigue- Civil Aviation

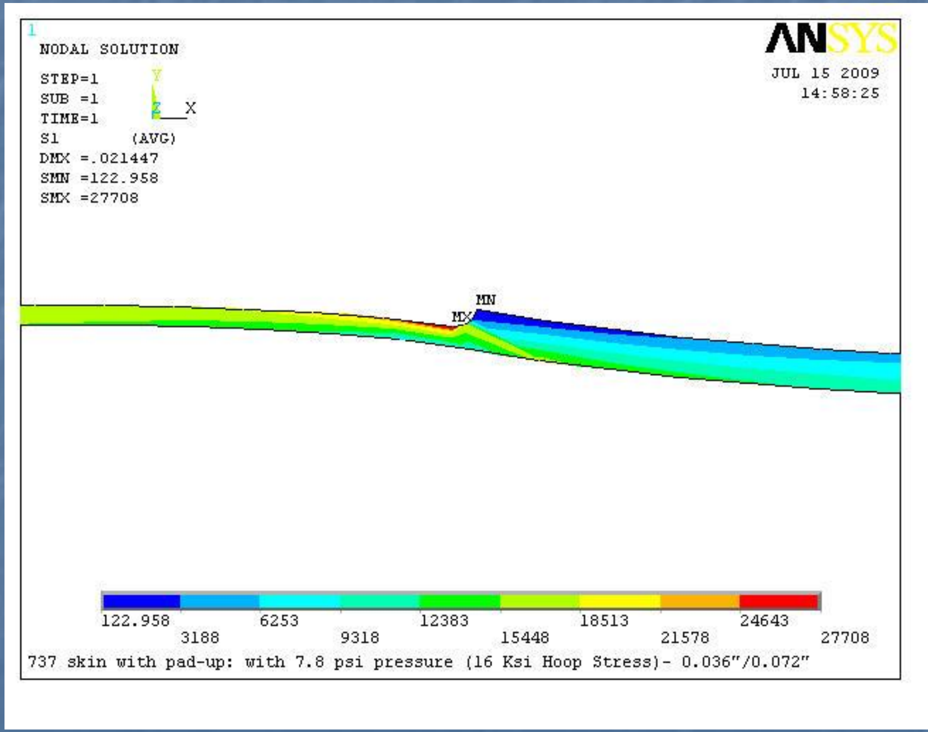
Has WFD Mitigation Come Full Circle?



Lines of Defense:
- Safety by Retirement
- Safety by Design
- Safety by Inspection

History of Metal Fatigue

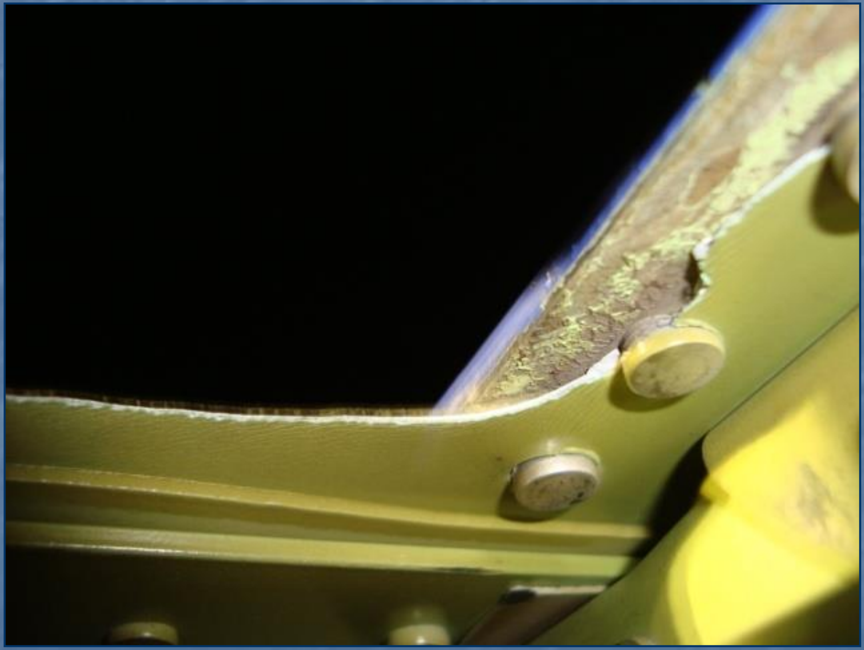
- Chem-mill pockets in fuselage skin cause eccentricity, which is a source of additional bending stress that can lead to early cracking.



History of Metal Fatigue

Lap Splice Cracking - April 1, 2011

- 737-300 Lower skin multiple bay cracking and subsequent decompression led to an emergency AD



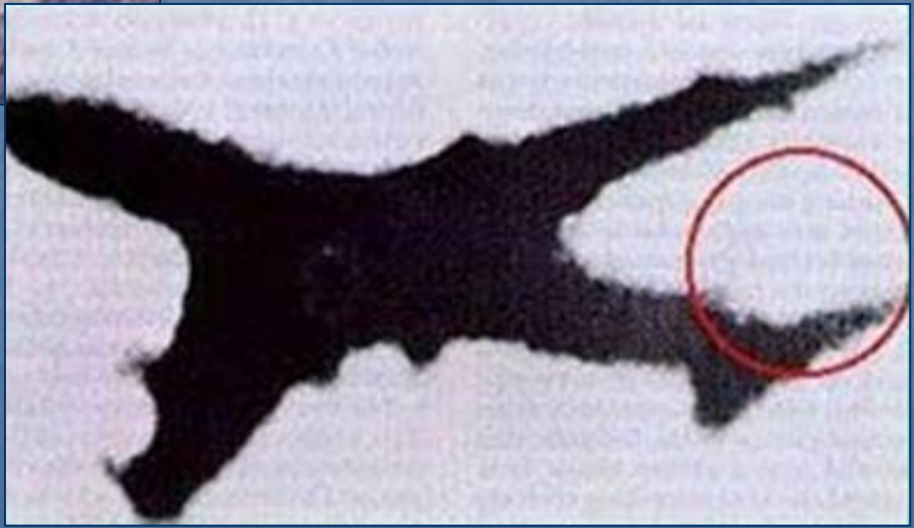
Accidents

Improperly Installed Repairs

- Two major accidents attributed to improperly installed repairs:
  - Japan Airlines Flight 123
  - China Airlines Flight CI611

Examples of Anomalous Fatigue- JAL 123

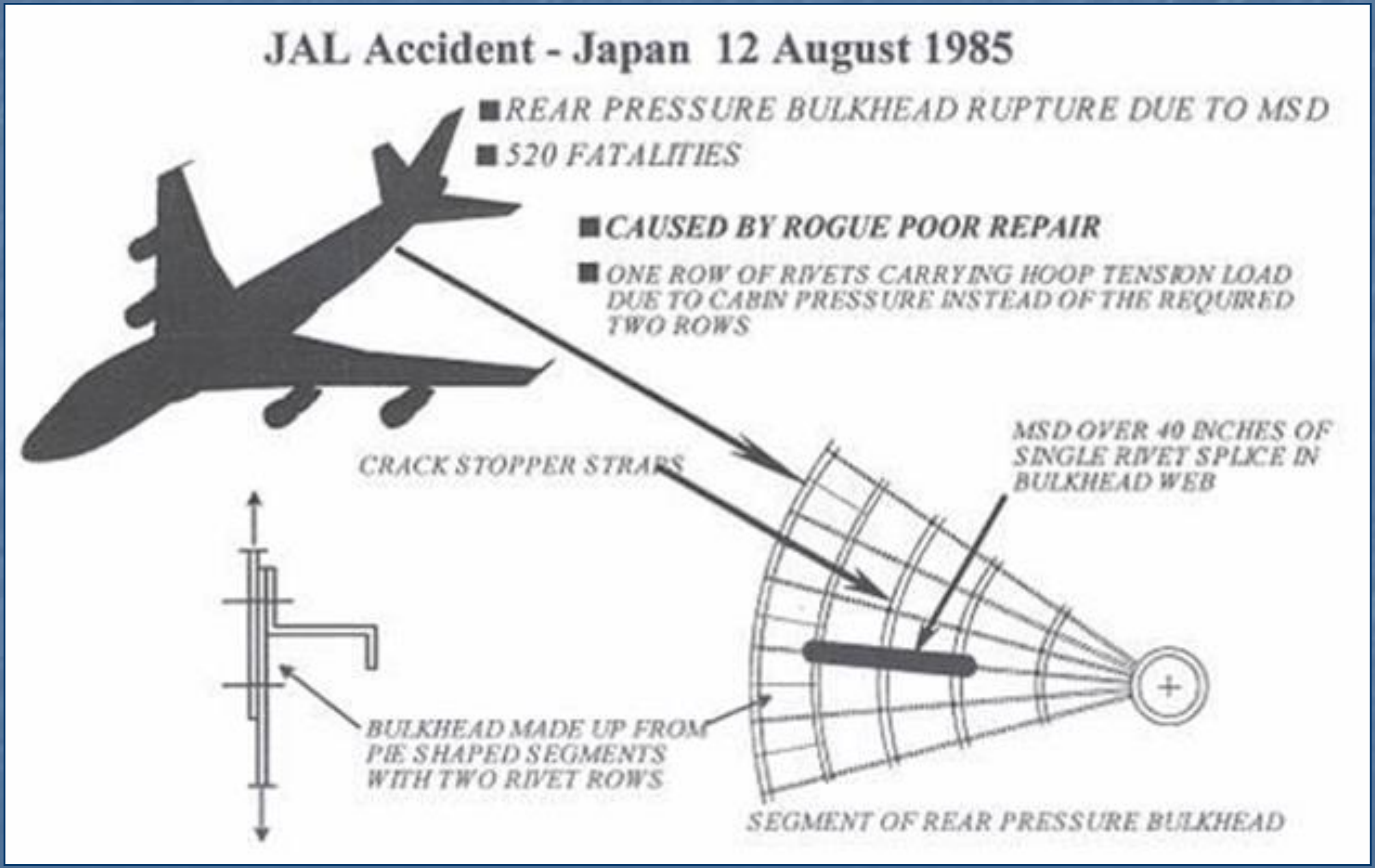
Japan Airlines, Flight 123, Boeing 747



For complete accident discussions refer to: http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=16

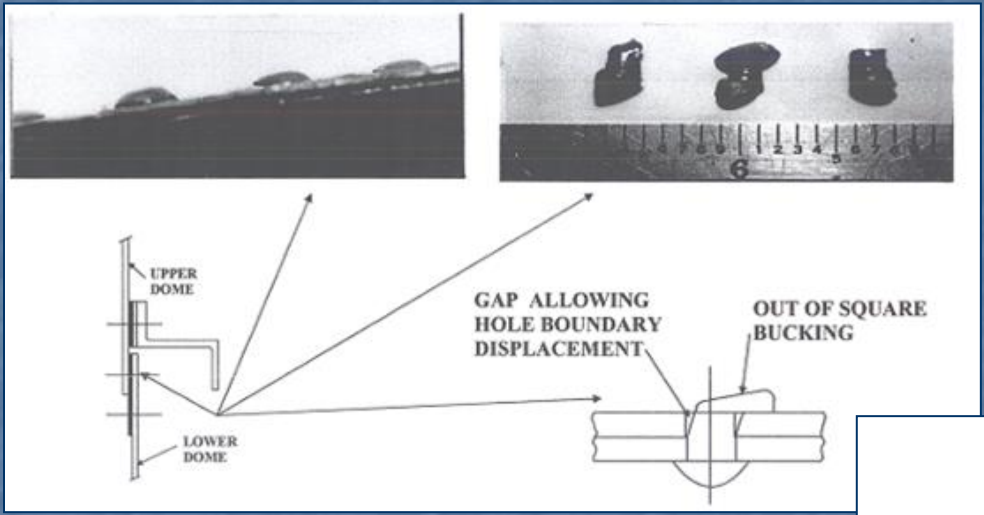
Examples of Anomalous Fatigue- JAL 123

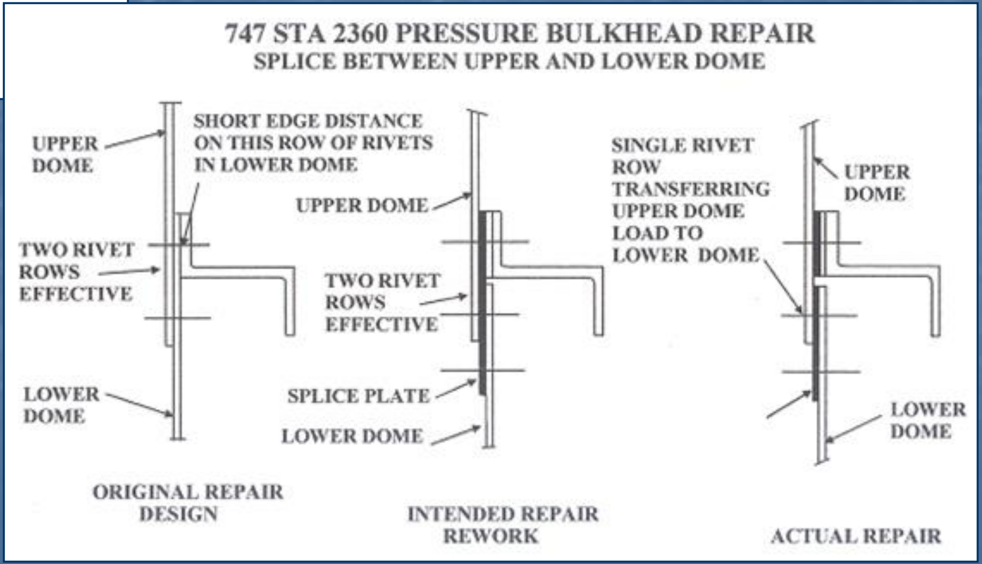
Gunma Prefecture, Japan (August 12, 1985)



Examples of Anomalous Fatigue- JAL 123

JAL Flight 123, Gunma Prefecture, Japan





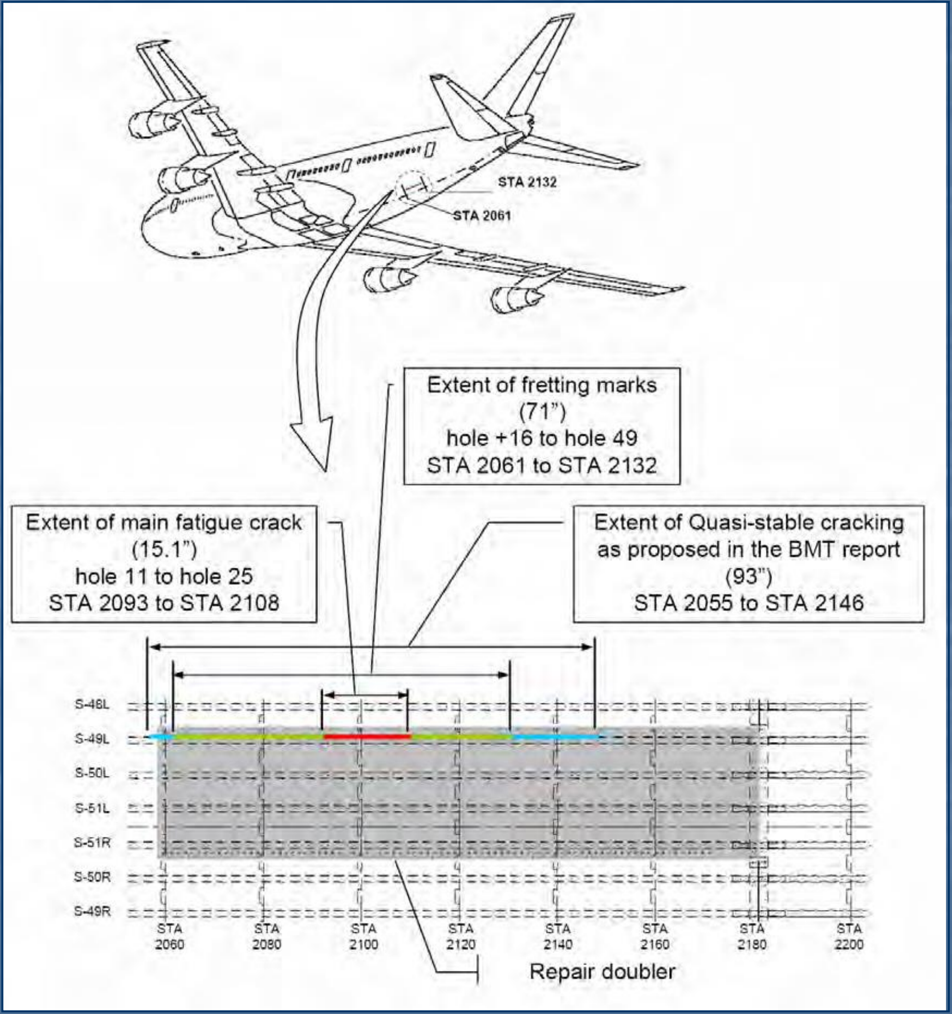
Filler!
Left with one row joint!

Examples of Anomalous Fatigue- China Airlines

China Airlines, Boeing 747, Flight CI611

- Near Taiwan Strait, Penghu Island (May 25, 2002)
- In-flight break up at 34,900' due to improperly installed repair.

For complete accident discussions refer to: http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=6



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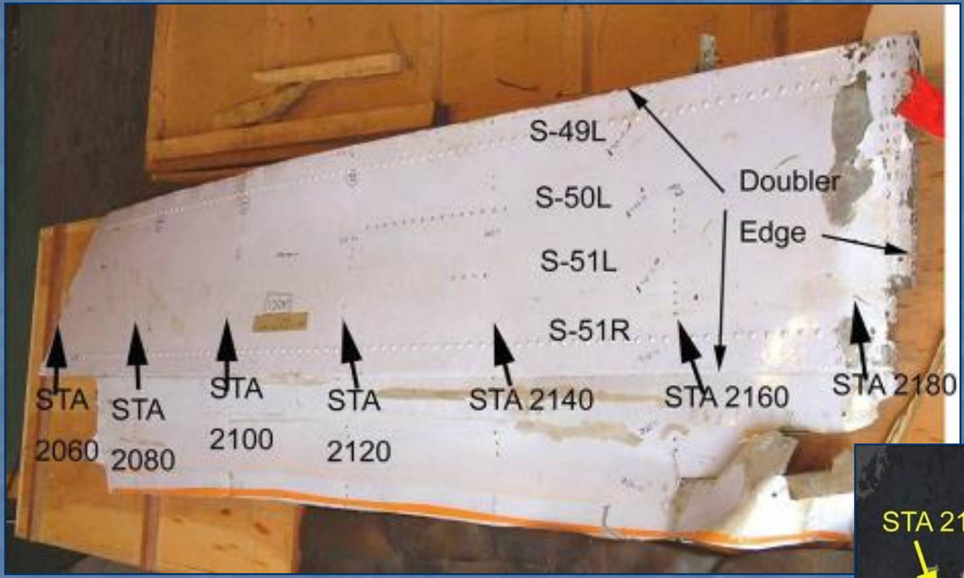
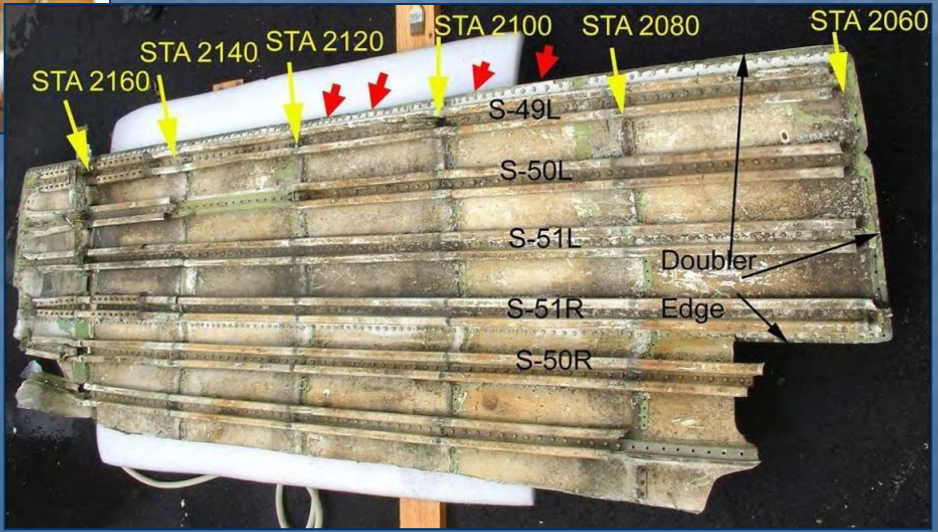
Examples of Anomalous Fatigue- China Airlines

China Airlines, 747, Flight CI611





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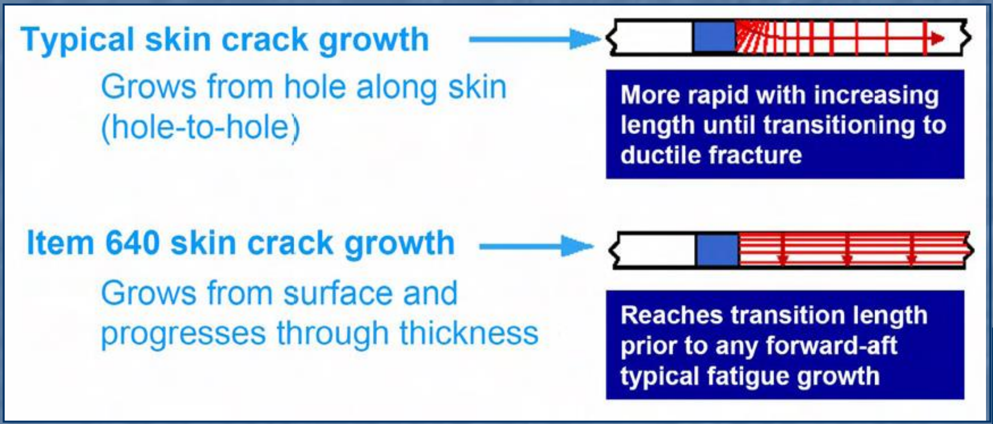
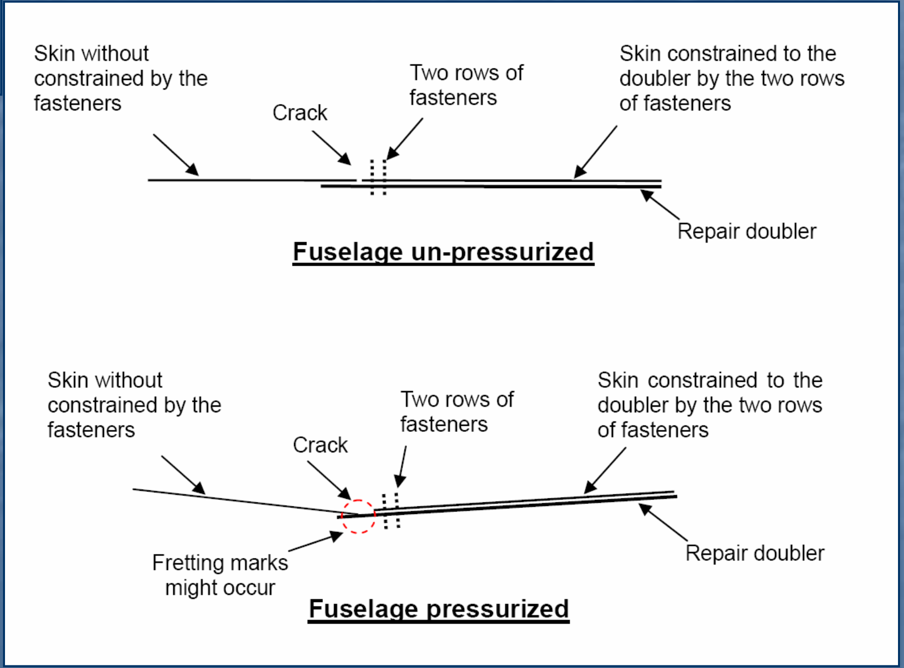
Examples of Anomalous Fatigue- China Airlines

China Airlines, 747, Flight CI611



Per SRM the scratches should be removed if the damage is within the limit. Otherwise the damaged area should be removed before the installation of a doubler.



The scratches were not removed. The doubler was installed to cover the scratches but could not covered the whole damaged area. Some scratches still existed beyond the peripheral fasteners of the doubler.

The Safety Council believed that the repair did not executed in accordance with Boeing SRM.

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Course Introduction

FAR 25.571

The next few slides introduce the course outline as it relates to the requirements of the FAR 25.571 Amendment 25-45, 25-96 and 25-132.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (a) *General.* An **evaluation** of the strength, detail design and fabrication must show that catastrophic failure due to fatigue, corrosion, or accidental damage, will be avoided throughout the operational life of the airplane.
  - Amndt 25-96 added: evaluation to include "manufacturing defects" as a source of failure.

Discuss: What does "operational life of the airplane" mean?

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- This evaluation must be conducted in accordance with the provisions of paragraphs (b) and (e) of this section, except as specified in paragraph (c) of this section, for each part of the structure which could contribute to a catastrophic failure (such as wing, empennage, control surfaces and their systems, the fuselage, engine mounting, landing gear and their related primary attachments).

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- Advisory Circular AC No. 25.571-1A contains guidance information relating to the requirements of this section (copies of the Advisory Circular may be obtained from --U.S. Department of Transportation, Publications Section M443.1, Washington, D.C. 20590). For turbojet powered airplanes, those parts which could contribute to a catastrophic failure must also be evaluated under paragraph (d) of this section. In addition, the following apply:

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (1) Each evaluation required by this section must include-
- (i) The typical **loading spectra**, temperatures, and humidities expected in service;
- (ii) The identification of **principal structural elements and detail design points**, the failure of which could cause catastrophic failure of the airplane; and
- (iii) **An analysis, supported by test evidence, of the principal structural elements and detail design points identified in paragraph (a) (1) (ii) of this section.**

Discuss: What do "principal structural elements" and "detail design points" mean?

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (2) The service history of airplanes of **similar structural design, taking due account of differences in operating conditions and procedures, may be used in the evaluations required by this section.**
- (3) Based on the evaluations required by this section, **inspections or other procedures must be established** as necessary to prevent catastrophic failure, and must be included in the maintenance manual required by §25.1529.

Added Words in Amendment 25-96

- (3) Inspection thresholds for the following types of structure must be established based on crack growth analyses and/or tests, assuming the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing or service-induced damage:
  - (i) Single load path structure, and
  - (ii) Multiple load path "fail-safe" structure and crack arrest "fail-safe" structure, where it cannot be demonstrated that load path failure, partial failure, or crack arrest will be detected and repaired during normal maintenance, inspection, or operation of an airplane prior to failure of the remaining structure.

Added Words in Amendment 25-132

- (3) … Continnued Airworthiness required by §25.1529. the limit of validity of the engineering data that supports the structural maitenance perogram (LOV), stated as a number of total accumulated flight cycles or flight hours or both, established by this section must also be included in the Airworthiness Limitation Section of ICAW required by § 25.1529. Inspection thresholds for the …

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

(b) *Damage-tolerance (fail-safe) evaluation.* The evaluation must include a **determination** of the **probable locations and modes of damage due to fatigue**, corrosion, or accidental damage. The determination must be by analysis supported by test evidence and (if available) service experience. Damage at multiple sites due to prior fatigue exposure must be included where the design is such that this type of damage can be expected to occur.

How was "dame at multiple sites" handled in the past?

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New Words in Amendment 25-132

- (b) … due to fatigue, corrosion, or accidental damage. Repeated load and static analyses supported by test evidence and (if available) service expereince must also be incorporated in the evaluation. Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. An LOV must be established that corresponds to the period of time, stated as number of total accumulated flighht cycles or flight hours or both, during which it is demonstrted that wuidespred fatigue damage will not accou in the aierplane structure. This demonstration must be by full-scale fatigue test evidence. The type

New Words in Amendment 25-132

certificate may be issues prior to completion of full-sacle fatigue testing, provided the Administrator has approved a plan for completing the required tests. In that case, the Airworthiness Limitation section of the ICAW required by § 25.1529 must specify that no airplane may be operated beyond a number of cycles equal to ½ the number of cycles accumulated on the fatigue test article, until such testing is completed. The extend of damage for …

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

The evaluation must incorporate **repeated load** and **static analyses** supported by test evidence. The extent of damage for residual strength evaluation at any time within the operational life of the airplane must be consistent with the initial detectability and subsequent growth under repeated loads. **The residual strength evaluation must show that the remaining structure is able to withstand loads (considered as static ultimate loads) corresponding to the following conditions**

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (1) The limit symmetrical maneuvering conditions specified in §25.337 at VC and in §25.345.
- (2) The limit gust conditions specified in §§ 25.341 and 25.351(b) at the specified speeds up to VC and in §25.345.
- (3) The limit rolling conditions specified in § 25.349 and the limit unsymmetrical conditions specified in §§ 25.367 and 25.427, at speeds up to VC.
- (4) The limit yaw maneuvering conditions specified in § 25.351(a) at the specified speeds up to VC.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (5) For pressurized cabins, the following conditions:
- (i) The normal operating differential pressure combined with the expected external aerodynamic pressures applied simultaneously with the flight loading conditions specified in paragraphs (b)(1) through (4) of this section, if they have a significant effect.
- (ii) The expected external aerodynamic pressure in 1g flight combined with a cabin differential pressure equal to 1.1 times the normal operating differential pressure without any other load.
  - The maximum value of normal operating differential pressure (including the expected external aerodynamic pressure during 1g level flight) multiplies by a factor of 1.15, ommiting other loads.
- (6)For landing gear and directly affected airframe structure, the limit ground loading conditions specified in §§ 25.473, 25.491, and 25.493.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- If significant changes in structural stiffness or geometry, or both, follow from a structural failure, or partial failure, the effect on damage tolerance must be further investigated.
- (c) *Fatigue (safe-life) evaluation.* Compliance with the damage-tolerance requirements of paragraph (b) of this section is not required if the applicant establishes that their application for particular structure is impractical. This structure must be shown by analysis, tests, or both, to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (d) *Sonic fatigue strength.* It must be shown by analysis supported by test evidence, or by the service history of airplanes of similar structural design and sonic excitation environment, that -
- (1) Sonic fatigue cracks are not probable in any part of the flight structure to sonic excitation; or
- (2) Catastrophic failure caused by sonic cracks is not probable assuming that the loads prescribed in paragraph (b) of this section are applied to all areas affected by those cracks.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- (e) *Damage-tolerance (discrete source) evaluation.* The airplane must be capable of successfully completing a flight during which likely structural damage occurs as a result of--
- (1) Impact with a 4-pound bird at likely operational speeds at altitudes up to 8,000 feet;
- (2) Propeller and uncontained fan blade impact;
- (3) Uncontained engine failure; or
- (4) Uncontained high energy rotating machinery failure.

§ 25.571 Damage-Tolerance and Fatigue Evaluation of Structure

- The damaged structure must be able to withstand the static loads (considered as ultimate loads) which are reasonably expected to occur on the flight. Dynamic effects on these static loads need not be considered. Corrective action to be taken by the pilot following the incident, such as limiting maneuvers, avoiding turbulence, and reducing speed, must be considered. If significant changes in structural stiffness or geometry, or both, follow from a structural failure, the effect or damage tolerance must be further investigated.

(Amendment 25-45 Eff. 12/1/78)

Evolution of Fatigue Requirement- **Wrap-up**

- Fatigue is a major failure modes for metals
- Fatigue has different types
- Requirements have been adopted to provide acceptable level of safety
- These requirements have evolved since 1940's
  - Civil aviation and Military aviation requirements have taken a different paths, but they have merged to similar requirements
- Current requirements to ensure safety for:
  - areas susceptible to WFD is a combination of inspection or other procedures plus modification, and for
  - areas not susceptible to WFD inspection or other procedures is used.