OVERVIEW OF SELECTED STRUCTURAL FAILURES

Ric Leist, PE

15 June, 2023

© R Leist Engineering, PLLC 2023

TOP LEVEL UP FRONT

Focus is on the Engineering Process Lessons Learned

- Static Failure Cases
  - Tacoma Narrows, Washington
  - John Hancock Tower, Boston
  - Hartford Connecticut Civic Center Roof
  - Hyatt Regency Walkway, Kansas City, MO
- Fatigue Cracking Cases
  - Comet Airliner, British Aerospace
  - Aloha Airlines, Boeing
  - Selected Cracking Details Analytical Examples
  - Aircraft Sonic Fatigue Example
  - Surface Finish Effect on Life
- Damage Tolerance Cases
  - Molasses Tank(s)
  - Liberty Ships
  - F-111
  - 707 Horizontal Tail
  - AA Flight 191 Chicago IL
  - UA Flight 232 Sioux City IA
  - Space Shuttles Challenger
  - Space Shuttle Columbia

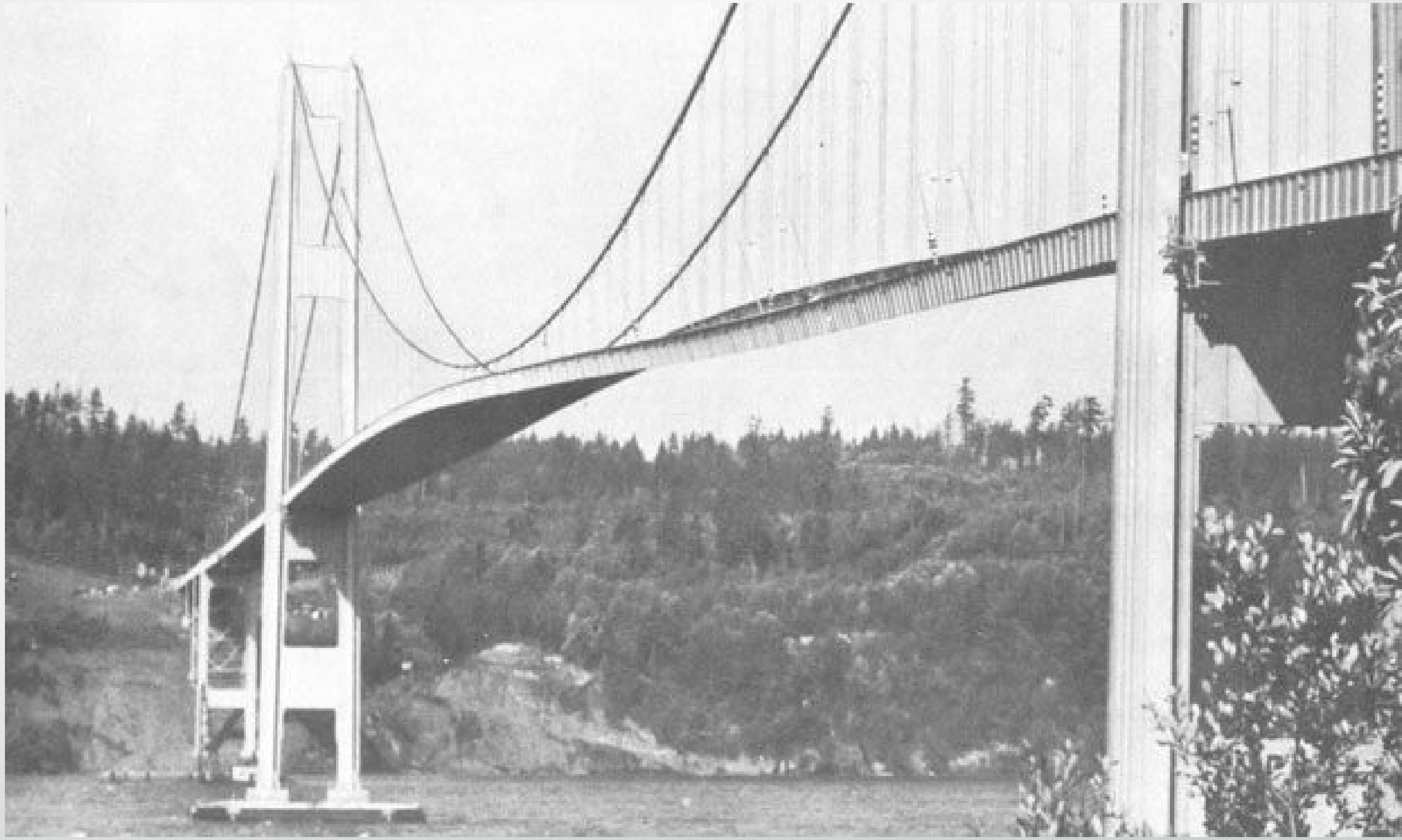
© R Leist Engineering 2023

Static Failure Examples

© R Leist Engineering 2023

Tacoma Narrows Bridge 1940

- **No fatalities / injuries**
- **Lasted quite a while**
- **Relatively new bridge (4 mo)**
- **Causes:**
  - **Did not consider vortex shedding in crosswinds**
  - **Not stiff enough for bending or torsion**
  - **Final cause failed in fatigue**



Courtesy: Timeline / Civil Engineering Portal

© R Leist Engineering 2023

John Hancock Tower, Boston 1973

- Issues since built in 1973
- Windows popped out of structure twice
- No fatalities / injuries
- Causes:
  - Building flexible and sways due to crosswinds
  - Another factor, thermal variation put stress on metal coated windows
  - Solution was interesting
    - Cleared and reinforced 111th floor
    - Strain gauged the building
    - Installed 11 ton lead mass on rollers that is moved by computer guided hydraulic actuator system based on strain gauge inputs to counterbalance the building deflections

Courtesy: The Civil Engineering website

Reference: The Civil Engineering website and an OSU Civil Engineering Professor

© R Leist Engineering 2023

Hartford Connecticut Civic Center Roof 1978

- No fatalities / injuries
- Causes: Many
  - Design used unusual truss configuration
  - Poor torsion section properties (i.e. low rad of gyration)
    - Very buckling sensitive
  - Too much reliance on FEM
  - Some elements were resized but FEM not reanalyzed
  - Miss-estimated structure weight
  - Some details not built as specified
  - Some design features not per AISC code

Reference: ASCE Council on Forensic Engineering / Univ of N. Carolina Case Studies

View of the Hartford Civic Center roof, which collapsed on January 18, 1978 - Connecticut Historical Society

Courtesy: Timeline / Civil Engineering Portal

© R Leist Engineering 2023

Hyatt Regency Hotel Walkways 1981

- **114 fatalities, 200 injured**
- **Causes:**
  - **Poor design**
  - **Redesign overstressed steel support rods**
  - **Fatigue details**
  - **Engineering Firm did not check field redesign**
  - **Overloaded walkways**
  - **Approval of drawings issues**

Courtesy: Timeline / Civil Engineering Portal

Reference: St. Louis Post-Dispatch

© R Leist Engineering 2023

Fatigue Failure Examples

© R Leist Engineering 2023

Comet Airliner – 1954 (2 events)

- Two incidents
- All souls lost
- Britain believed it could be terrorist bomb
- Royal Navy sent divers to retrieve wreckage and reassemble in a warehouse
- Fatigue found in structure
- Lack of damage tolerance caused complete airframe disintegration

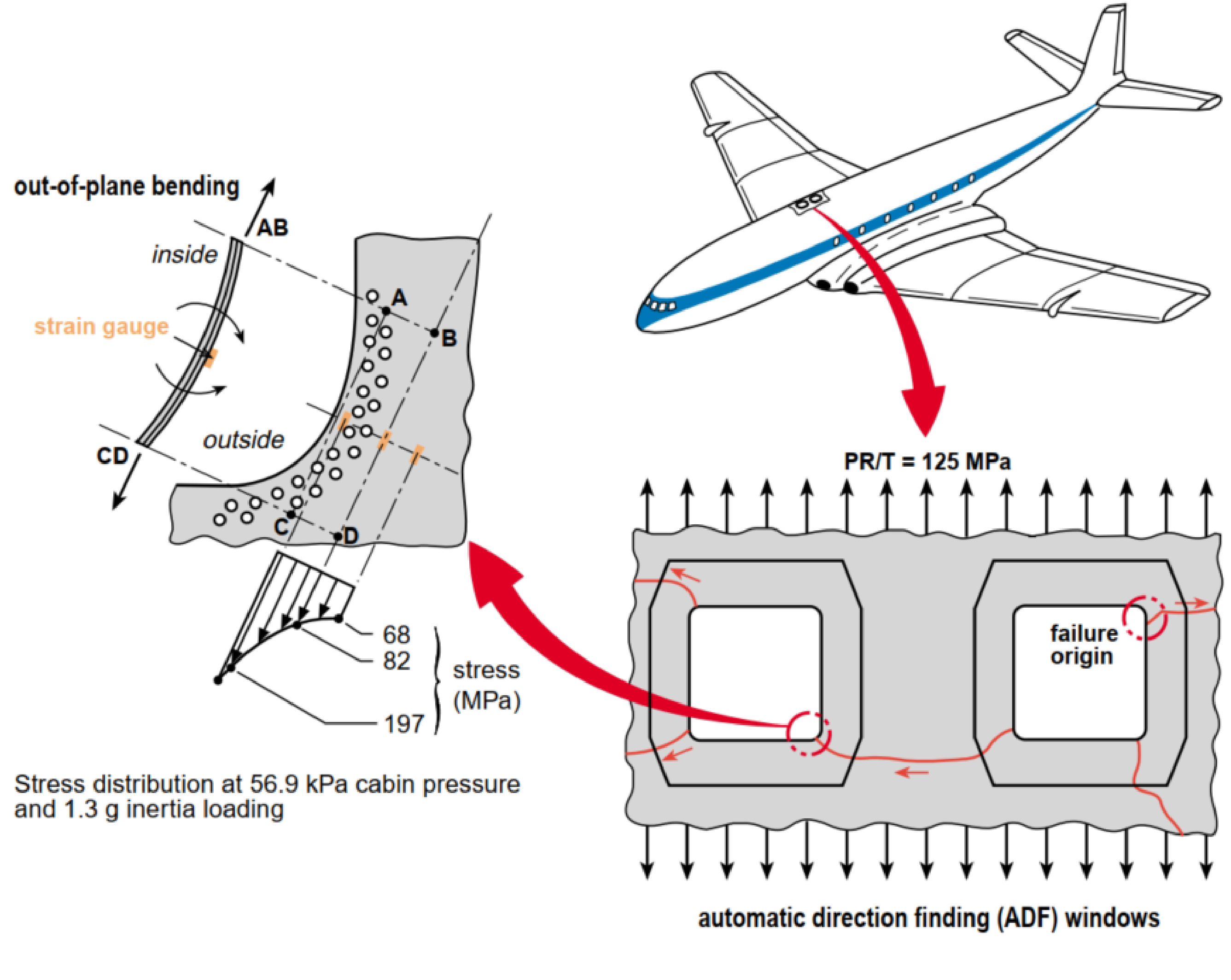


Fig. 4 Probable failure origin of service aircraft Comet G-ALYP: stress distribution obtained from repaired test aircraft, Comet G-ALYU (Swift, 1987)

Reference: R.J.H. Wanhill, NLR-TP-2002-521

© R Leist Engineering 2023

Comet Airliner – 1954 (2 events)

- **Detail showing crack nucleation location**
- **Frame outer flange discontinuity creates high fastener bearing loads / concentration**
- **Causes:**
  - **Higher cabin pressure**
  - **Frame discontinuity raised notch stresses**
  - **Square corner navigation cutouts also raised stresses due to compound Kt superposition**

Reference: R.J.H. Wanhill, NLR-TP-2002-521

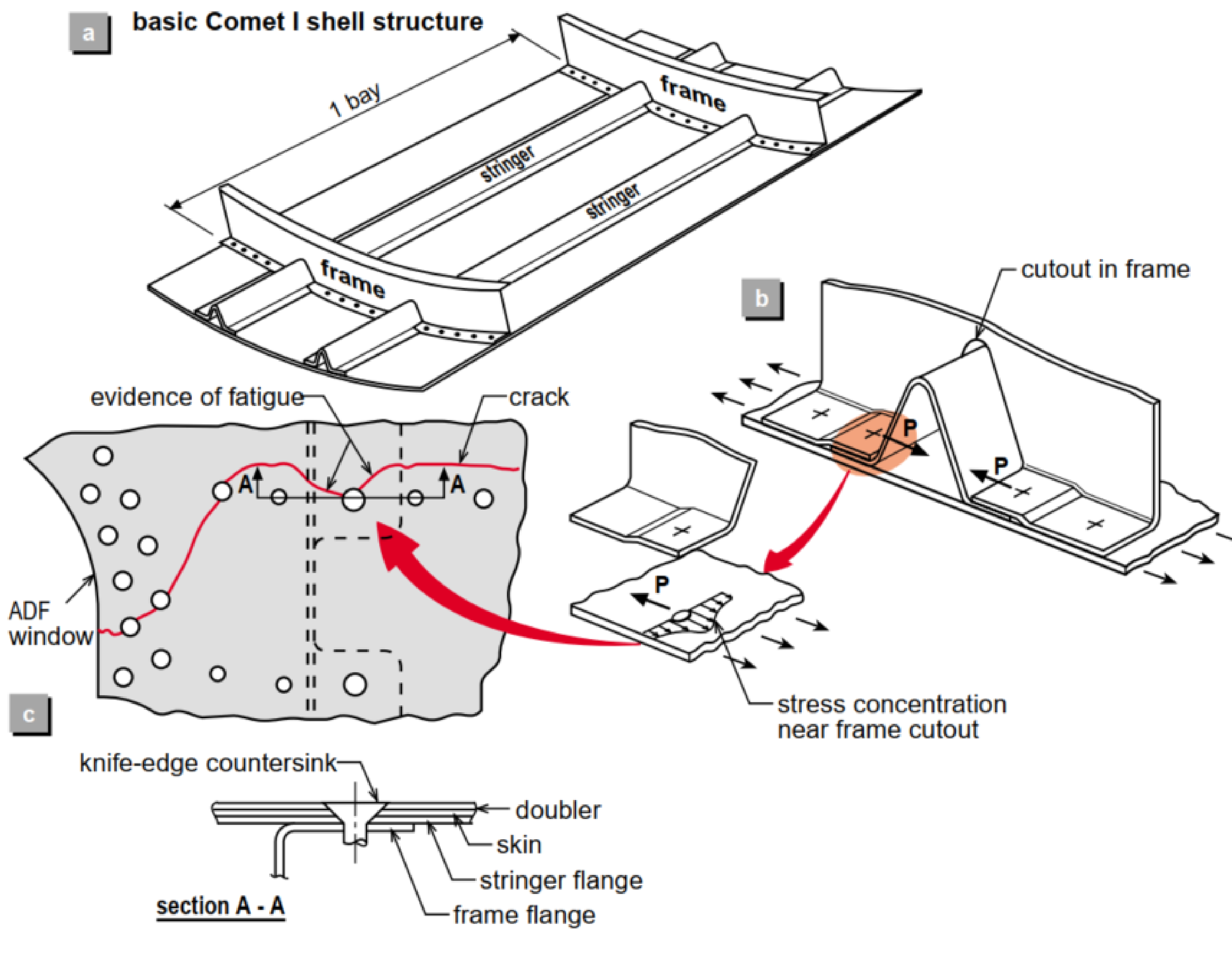


Fig. 5 Details of the probable failure origin of service aircraft Comet G-ALYP (Swift, 1987)

© R Leist Engineering 2023

Comet Airliner – 1954 (2 events)

- Aircraft taken out of service and full scale pressure tested
- Test aircraft showed cracking in different locations
- 1.33 x Press proof loads were applied

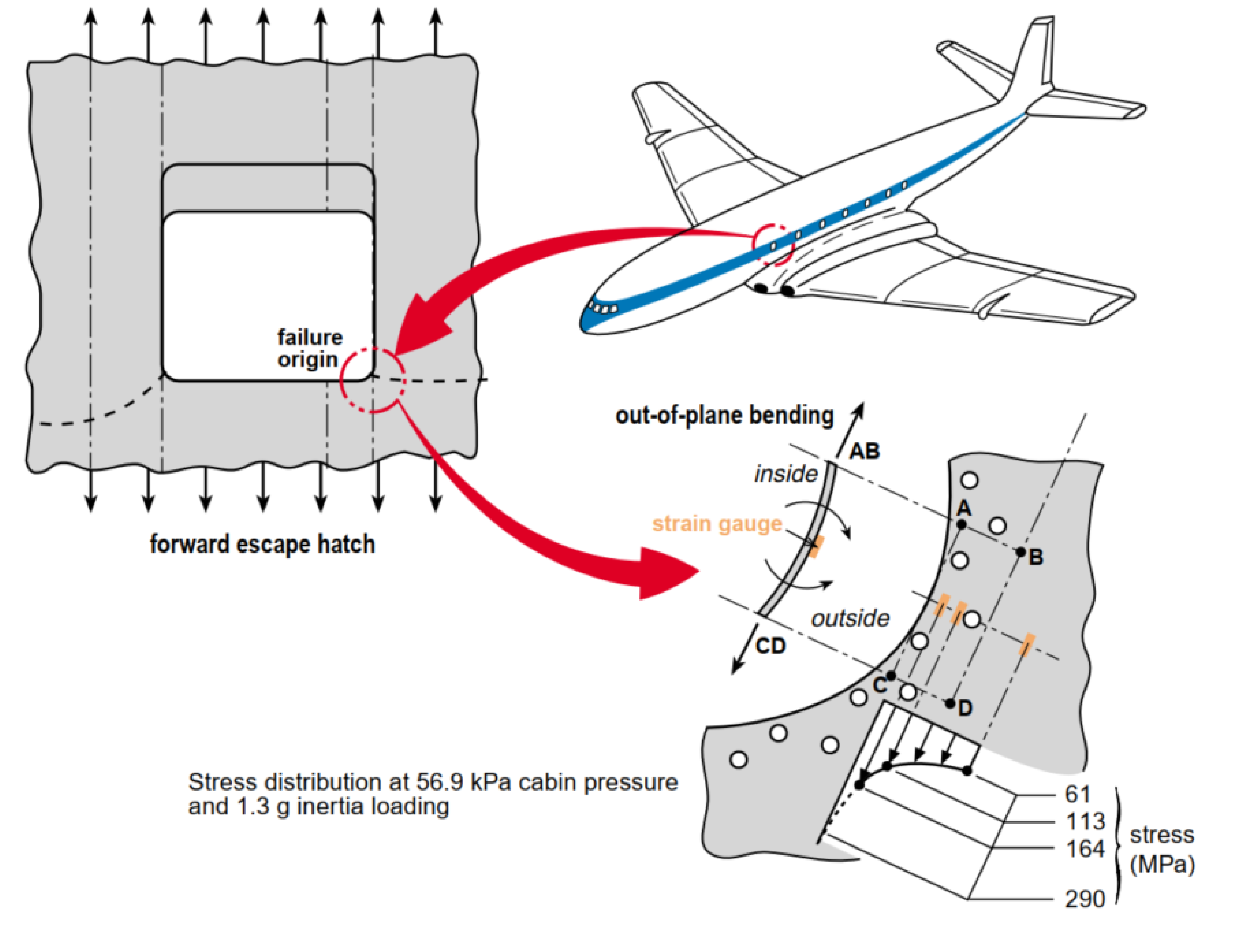


Fig. 3 Probable failure origin of test aircraft Comet G-ALYU: stress distribution obtained after repair (Swift, 1987)

Reference: R.J.H. Wanhill, NLR-TP-2002-521

© R Leist Engineering 2023

Aloha Airlines 737 - 1988

- **Early 737**
- **1 fatality**
- **Miracle landing**
- **Resulted in Aging Aircraft Pgm.**
- **Causes:**
  - **Poor loadpath design**
    - **Knife edge hole**
    - **Failsafe straps not long enough**
  - **Manufacturing difficulty**
  - **Poor Service Bulletin approach / enforcement by FAA**
  - **Poor maintenance program at Aloha**
    - **Corrosion prevention / detection**
    - **NDI training**
      - **Aircraft was inspected prior to failure**
  - **Stress intensity solution inadequate (crack interaction)**

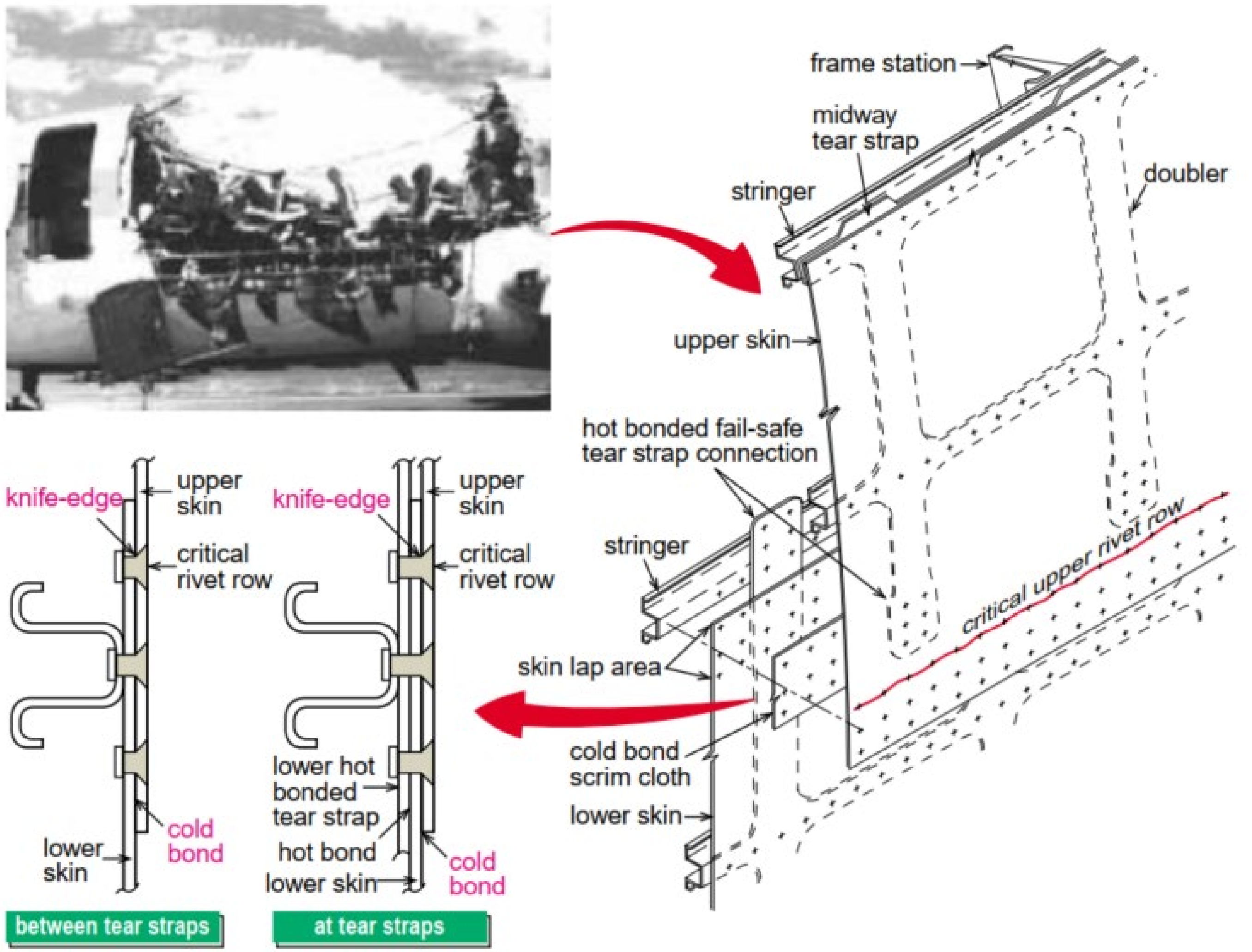


Fig. 8 Structural aspects of the Aloha Airlines Boeing 737 accident: Multiple Site fatigue Damage (MSD) occurred in the outer (upper) skin, commencing from the knife-edges of the rivet holes along the upper rivet row

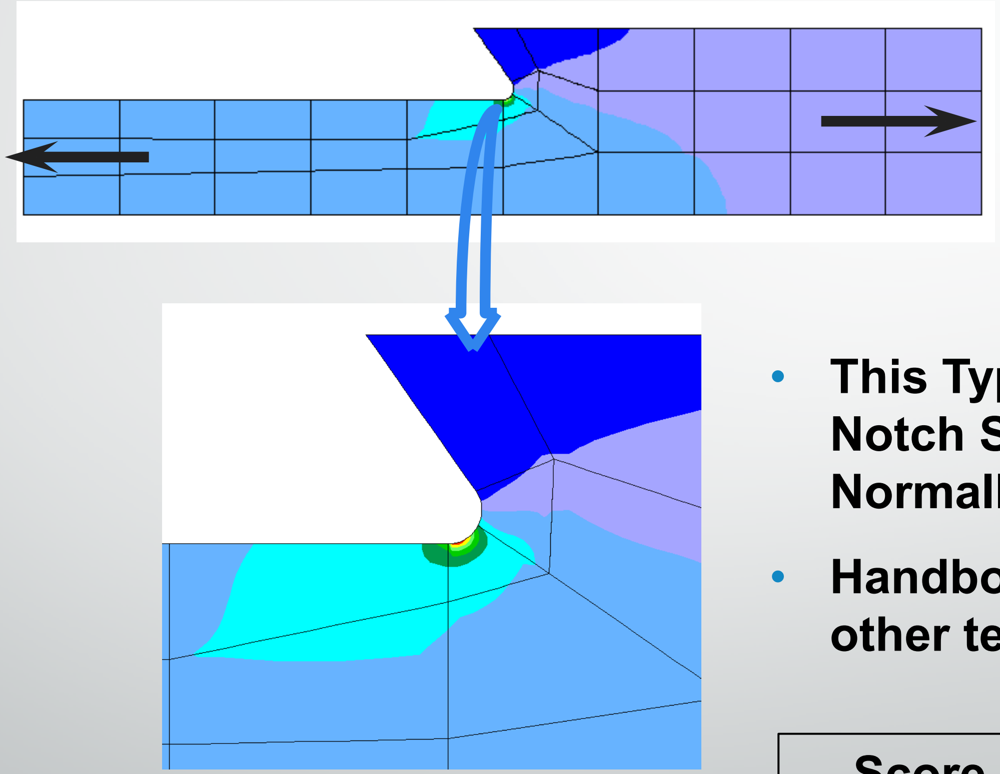
Reference: R.J.H. Wanhill, NLR-TP-2002-521 & NTSB/AAR-89/03

© R Leist Engineering 2023

Example Analyses

© R Leist Engineering 2023

Max Stress Not at Notch Tangency where Crack Originated



- p-Version FEM
- Restrained Against Vertical Displacement

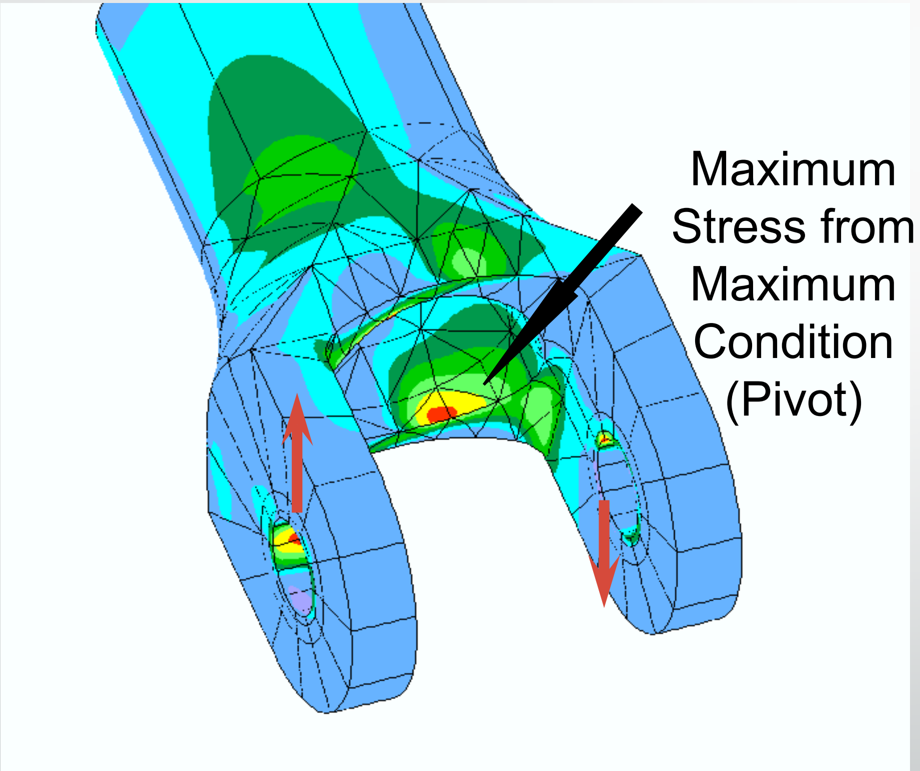
- This Type Geometry Notch Stresses Not Normally in Handbooks
- Handbook is only σ_1 not other terms σ_2, σ_3

Score marks (machining mismatch marks) triggered early cracking

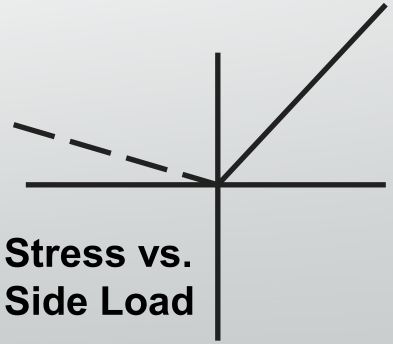
© R Leist Engineering 2023

Unit Load Condition Modeling

Difficult to analyze due to complex loading and stress response



- **Several Unit Load Conditions May Be Required**
- **Stresses May Be Bilinear with Load**

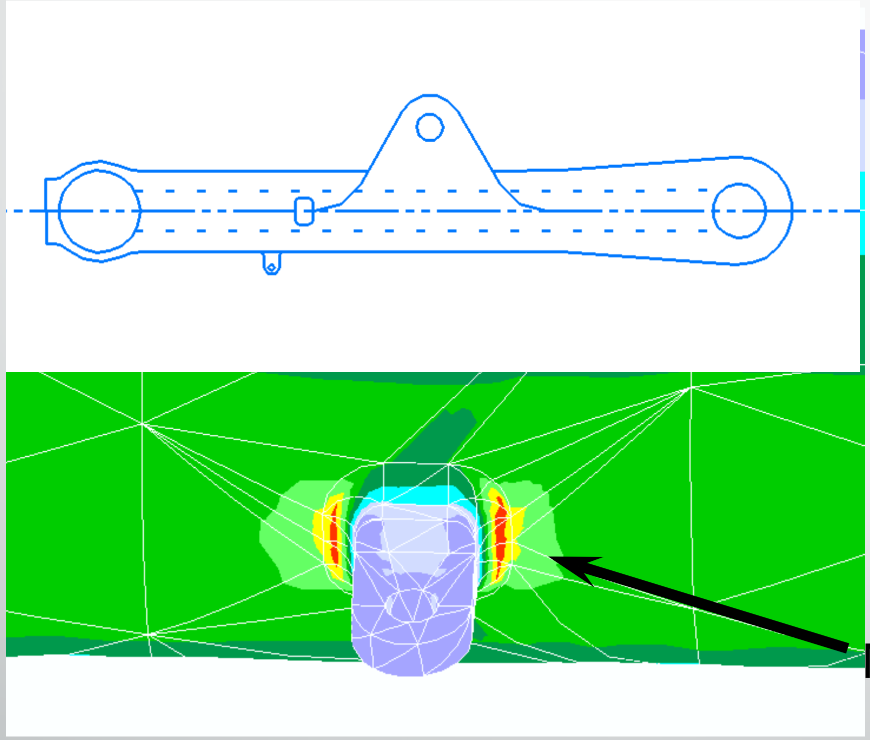


Stress vs. Side Load

© R Leist Engineering 2023

Modeling for Accurate Stress

Design did not need lug in this location



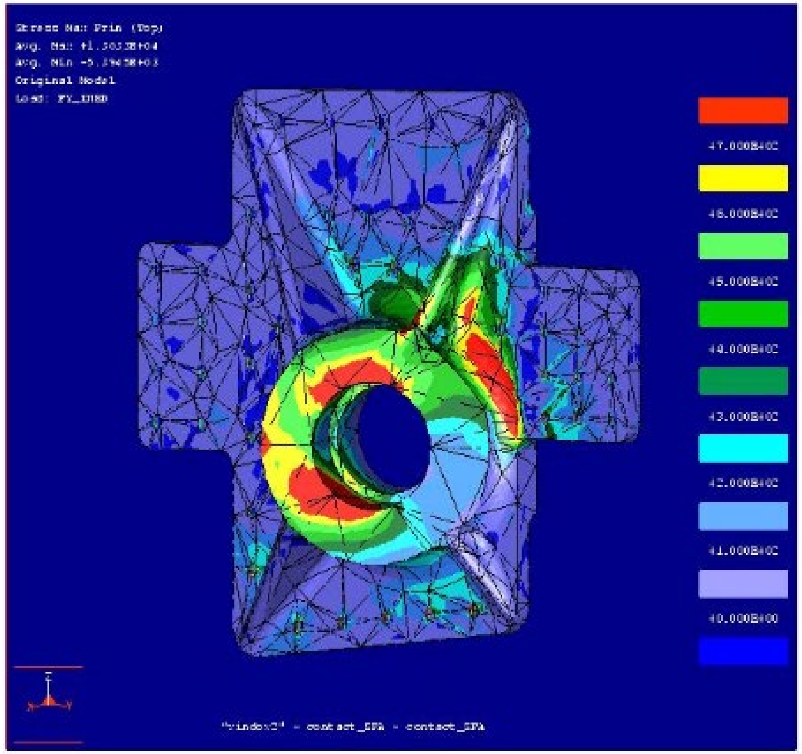
Max Stress

- **Model accuracy is dependent upon type of model and good model practice**
  - **p-element - approx. 4 elements (p = 8)**
  - **h-element approx. 90 elements**

© R Leist Engineering 2023

Stiffness May Be Essential to Solve

Complex part resulted in compound stress concentrations



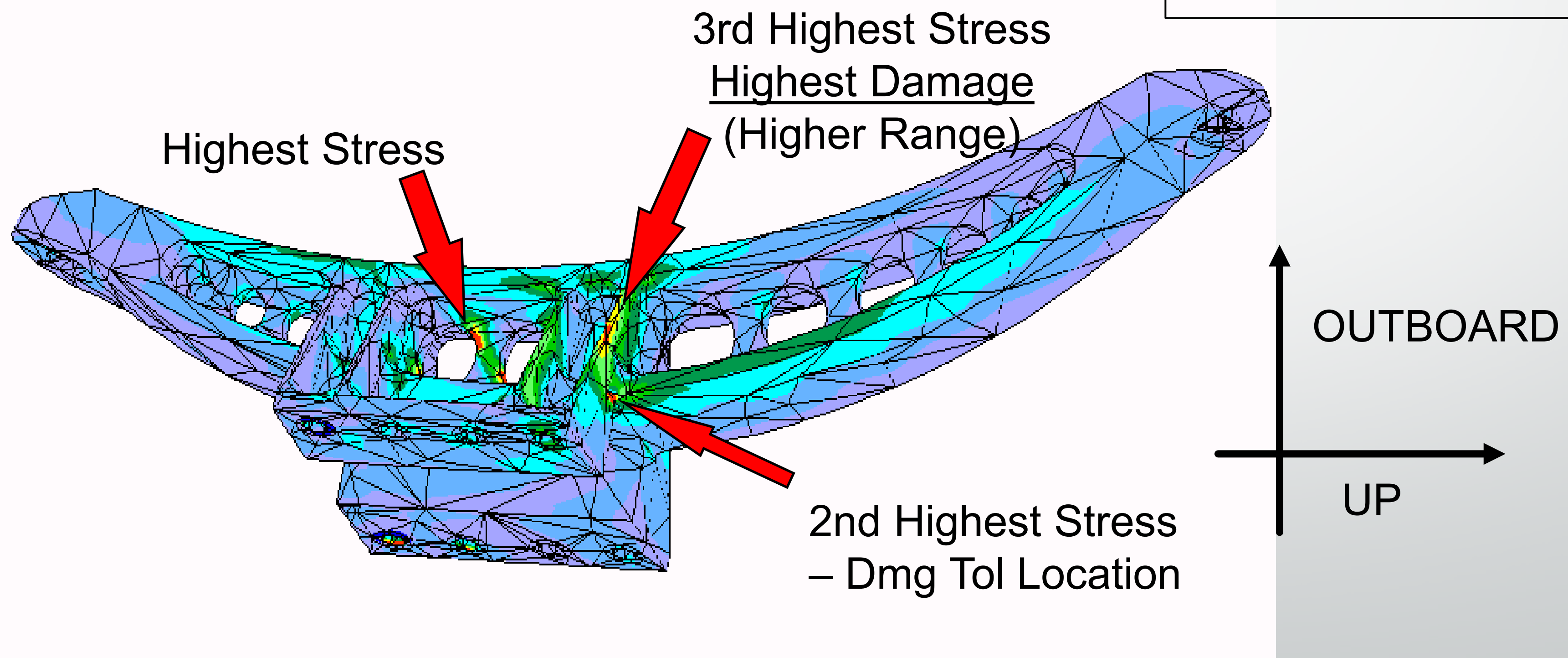
- **Part loaded in bearing**
- **40 bolts modeled in contact**

© R Leist Engineering 2023

Damage is from σ_{max} and R

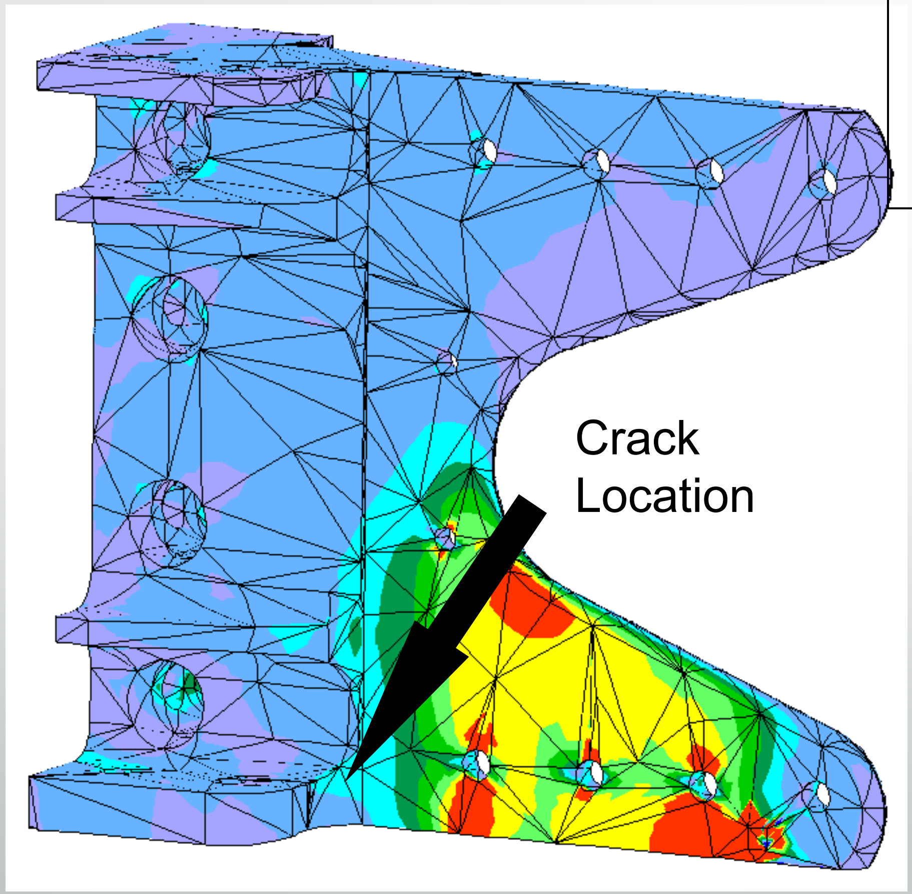
R =$\sigma_{min}/\sigma_{max}$

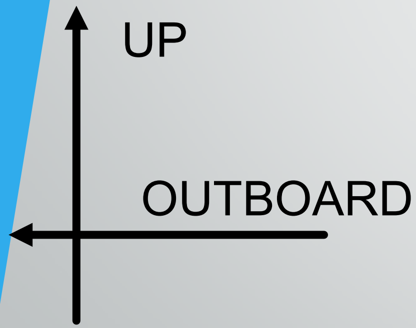
Part did not crack at damage tolerant location. Subsequent analysis showed it was not the most critical detail.



© R Leist Engineering 2023

Modeling Accuracy Important





Part cracked due to test issues

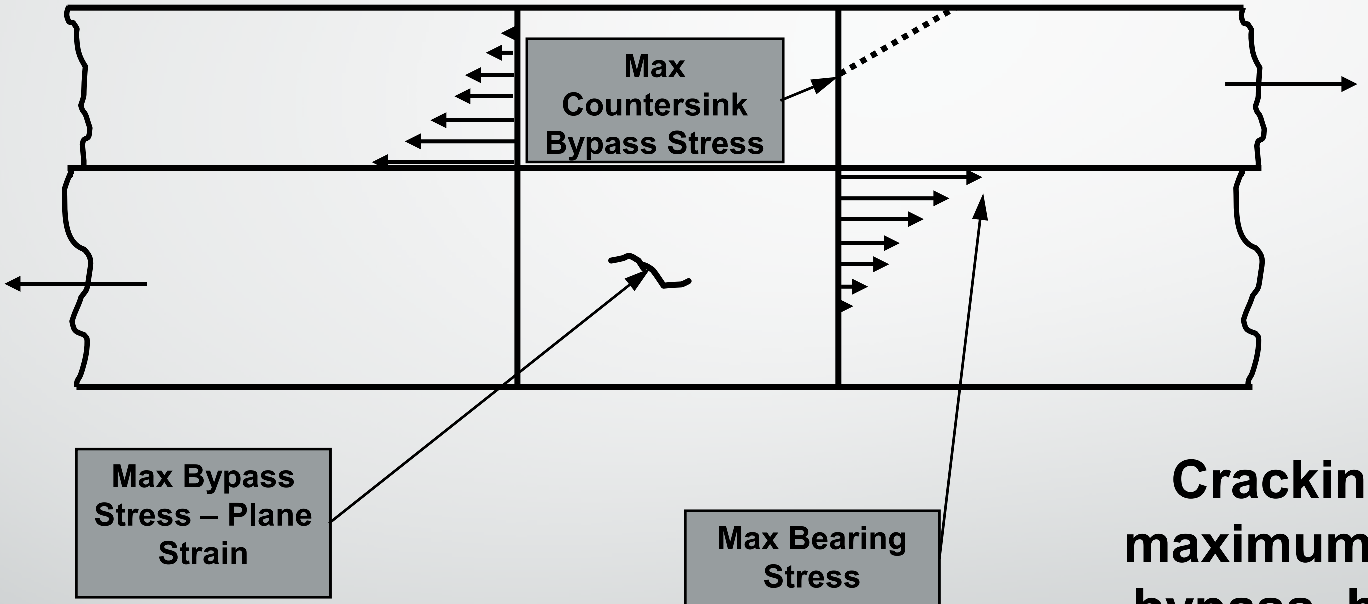
- **Full scale actuator controller failure**
- **Component test fixture design highly preloaded the article**
  - **Resulted in 14 orders of magnitude reduction in life**

Complex loading should be modeled.

Results may be unexpected.

© R Leist Engineering 2023

CRACK INITIATION IS POINT SPECIFIC

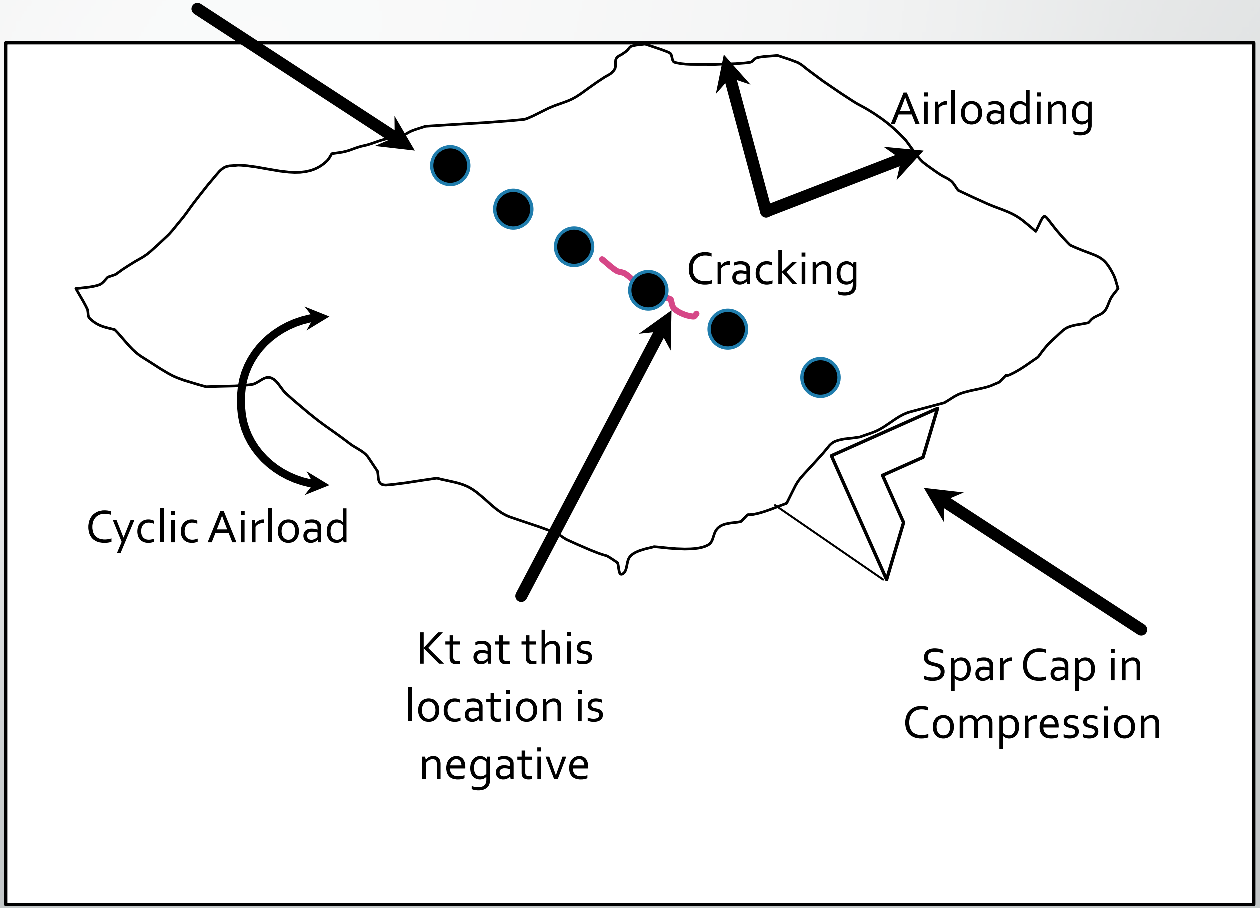


Cracking results from maximum combination of bypass, bearing, and / or bending notch stresses plus manufacturing effects like surface finishes

 © R Leist Engineering 2023

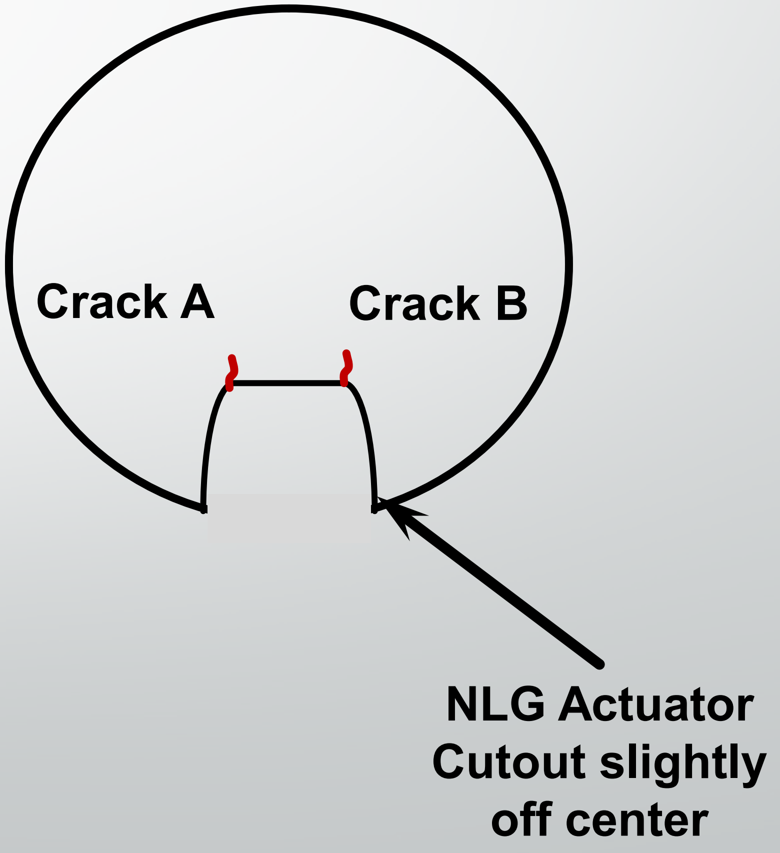
SONIC FATIGUE EXAMPLE
Horizontal Tail Upper Skin Cracking

- **Know all aspects from the environment**
  - **2 mean stresses**
  - **Source of sound loading**
  - **Flight load effect on damage location**
  - **Normal Pilot Operating Procedure**
  - **How does panel preload affect panel response**
- **Know source of data**
  - **Normal sonic fatigue test pressure perpendicular to panels**
    - **This pressure is flowing parallel to skin**
  - **Does the test panel alloy match?**
  - **Does the stiffener attachment / stiffness matter?**
  - **Normally, fatigue panels have straight shanked holes**
    - **These holes have knife edge**



Surface Finish Effect on Life

- Cyclic pressure test did not crack at nose gear actuator cutout
- Fullscale flight load + pressure test cracked in two radii
- Crack A cracked in 1/5 time of Crack B
- Subsequent analysis showed Crack A lower stress; Life should have been 8 times longer
- Surface Finish marks from deburring were different
  - Crack A sanded across thickness and rougher
  - Crack B was parallel to edge



 © R Leist Engineering 2023

Damage Tolerance Failure Examples

MOLASSES TANK(S) - 1919

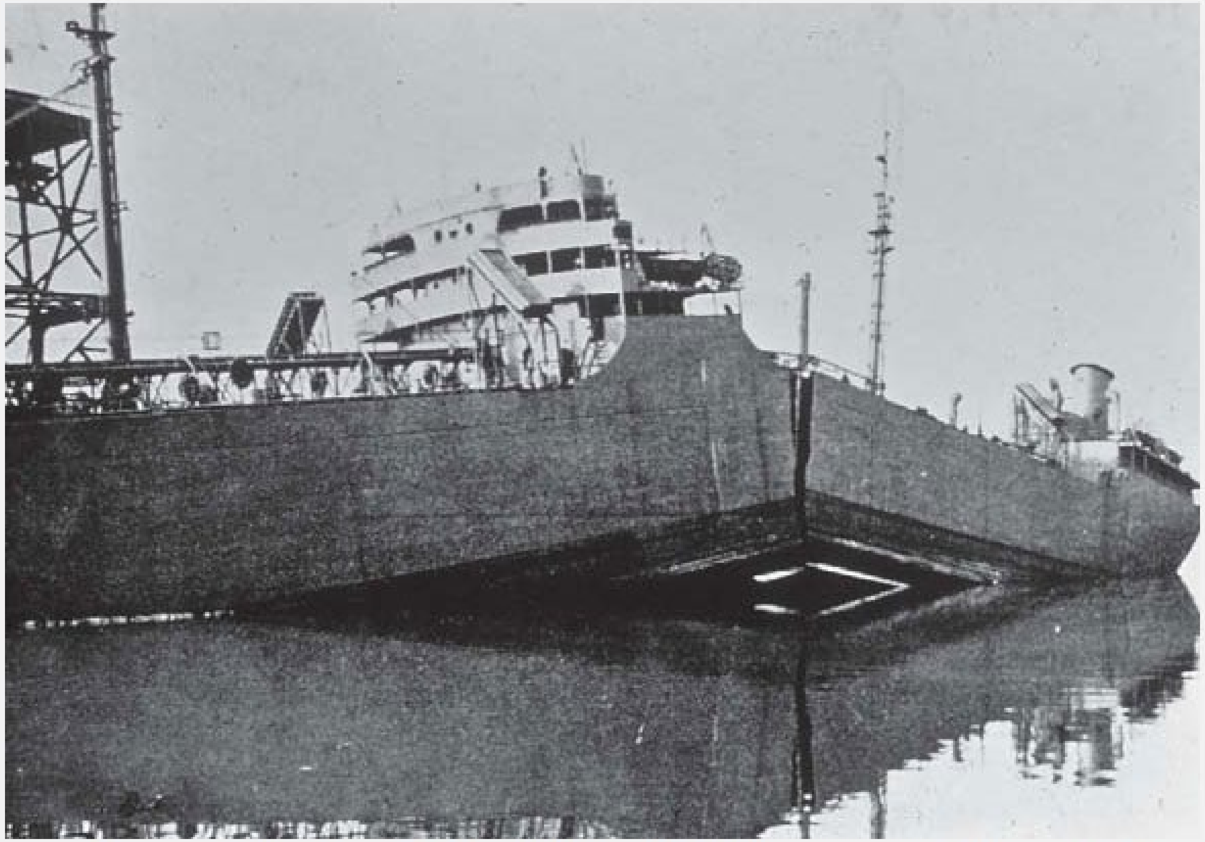
- **2.3M gal molasses tank (50 ft high by 90 ft dia) ruptured, 15 Jan 1919**
- **21 fatalities / 150 injuries plus many horses, buildings, etc.**
- **$628K damages**
- **25ft x 160ft wall moved at 35 MPH**
- **Causes:**
  - **Flaw at rivet hole; Poor quality construction**
  - **Brittle steel**
  - **Cold temperatures**
- **Resulted in birth of Fracture Mechanics - Griffith**

Reference: Encyclopedia Britannica; Hertzberg Deformation and Fracture Mechanics of Engineering Materials

© R Leist Engineering 2023

LIBERTY SHIPS DURING WW II

- 1500 brittle fractures in over 2700 ships; several sunk
- Some fractures were at the dock before fitting
- Causes:
  - Square hatch pass thru hull with sharp corners, not reinforced (until later)
  - Brittle, low toughness steel, very temperature sensitive
    - One ship hull was launched in afternoon and next (cold) morning ship was fractured at dock
  - Inexperienced welders working rapidly to complete ASAP
    - Record was hull launch 5 days after keel laid
  - Uncalibrated welding procedures
  - Residual stresses and lack of fusion flaws in the welds



The Liberty ship S.S. Schenectady, which, in 1943, failed before leaving the shipyard. (Reprinted with permission of Earl R. Parker, Brittle Behavior of Engineering Structures, National Academy of Sciences, National Research Council, John Wiley & Sons, New York, 1957.)

Reference: Hertzberg, Deformation and Fracture Mech of Engr Matls; P. Paris class notes 1981; Science Direct

© R Leist Engineering 2023

F-111 WING PIVOT FITTING - 1969

- **107 airframe hours**
- **Not only one failure; several fatalities**
- **Causes:**
  - **Fold in forging 1” x 0.38”**
  - **D6AC steel not damage tolerant (low toughness)**
- **Directly responsible for USAF ASIP Damage Tolerance Program**

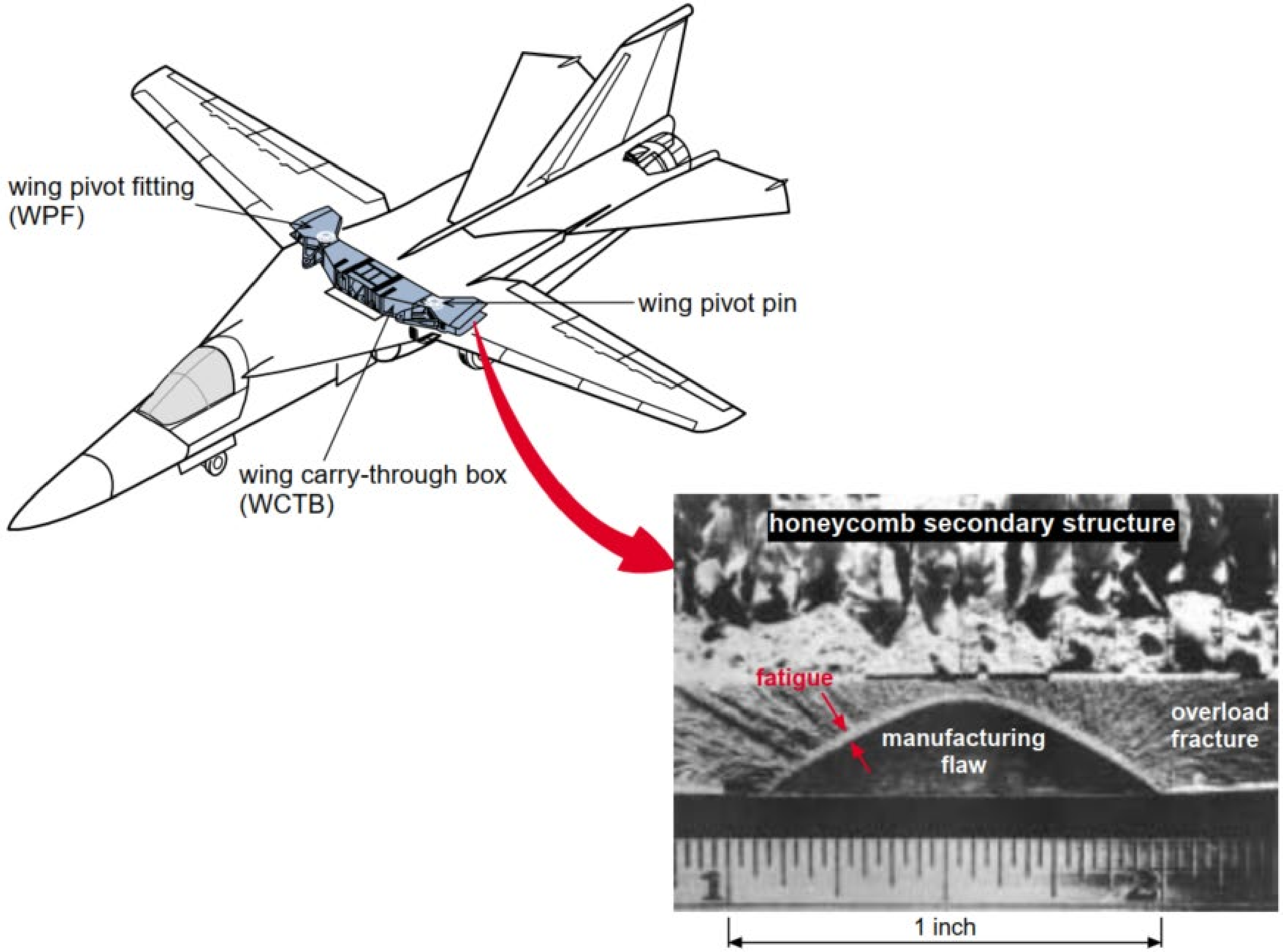


Fig. 6 Failure origin of F-111 #94: a manufacturing flaw in the high-strength steel lower plate of the left-hand wing pivot fitting

Reference: R.J.H. Wanhill, NLR-TP-2002-521

© R Leist Engineering 2023

Dan Air 707 Horizontal Tail - 1977

- 707-300 formerly in service with British Airlines
- Failed on approach Lusaka, Africa; 6 fatalities
- 47K flight hours (Design Goal – 60K)
- Causes:
  - High load transfer skin joint
  - High aft loads to elevator rib
  - High engine buffet loads on landings
  - Failsafe test not sufficient
  - No Damage Tolerance inspection program

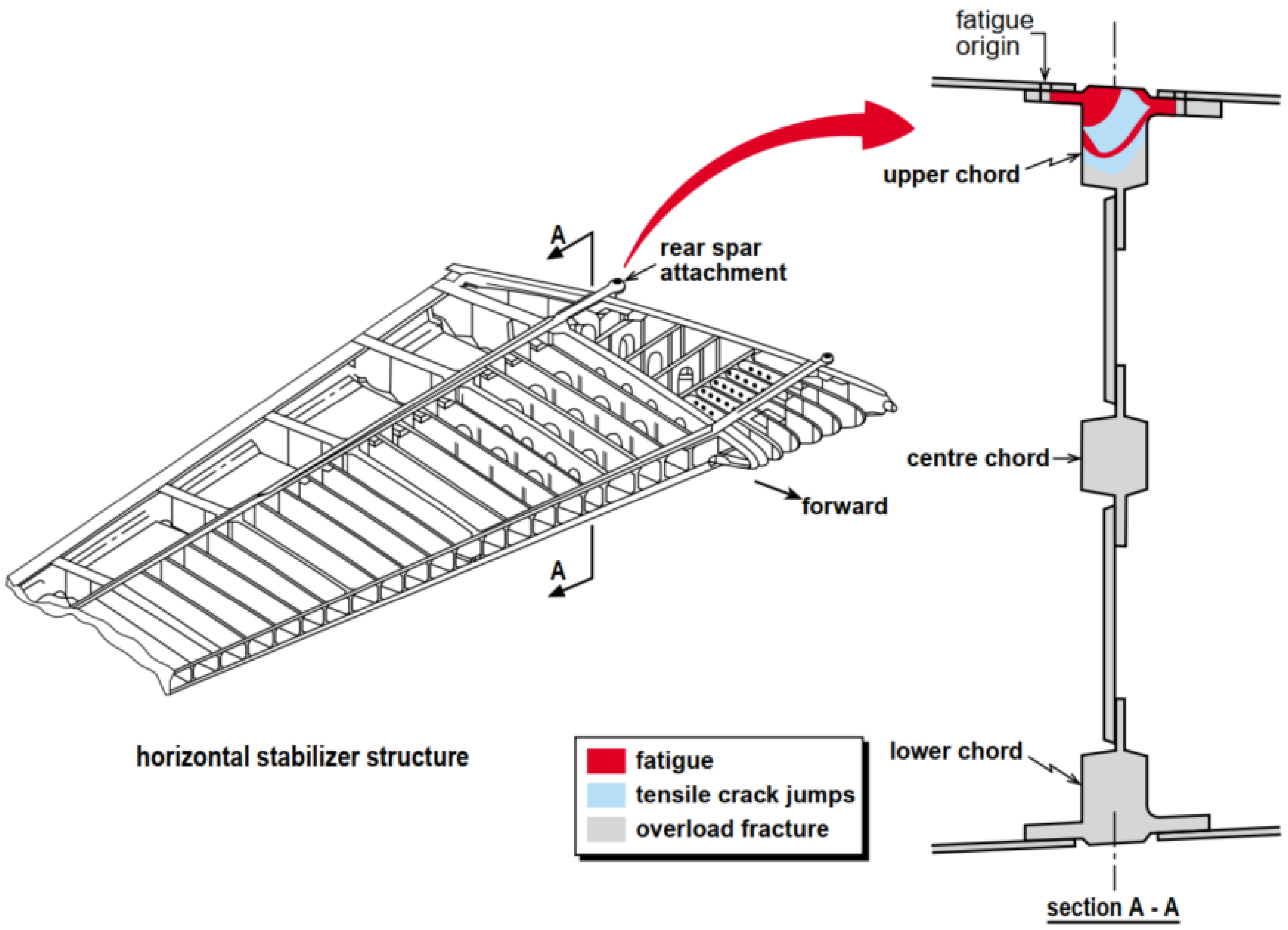


Fig. 7 Failure origin of the Dan Air Boeing 707. After Howard (1986)

Reference: R.J.H. Wanhill, NLR-TP-2002-521

© R Leist Engineering 2023

American Airlines Flight 191 - 1979

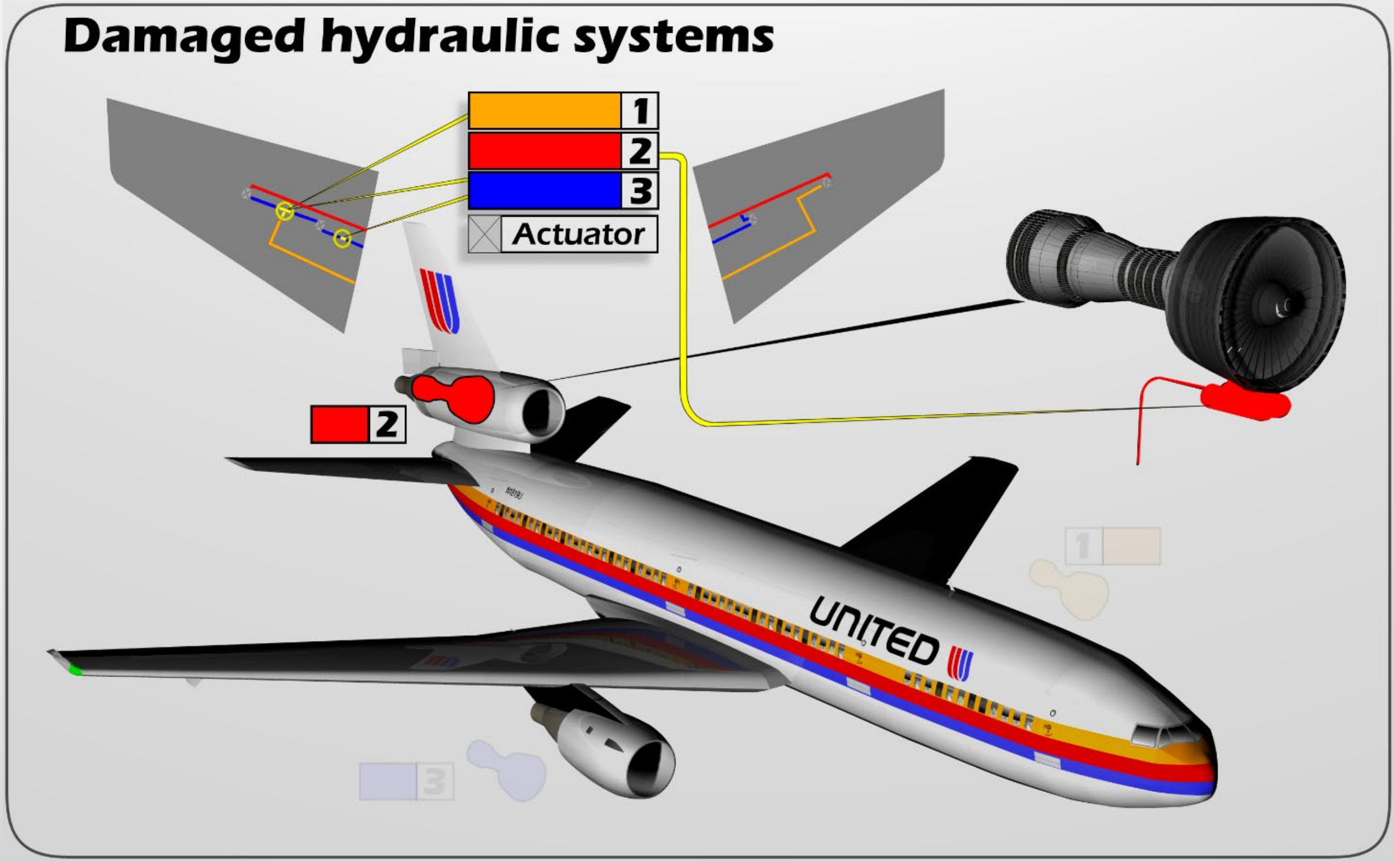
- 271 fatalities; no survivors
- LH Engine separated on takeoff in CHI
- Causes:
  - Maintenance induced crack grew for many flights before failure
    - Inspected 3 times without detection; difficult inspect
  - Design placed hydraulics in front of wing front spar for ease of maintenance
  - Engine/pylon separation was designed to roll over top of wing
    - Fwd pylon held too well, crushing hydraulic lines, retracting all LH wing flight control surfaces

Reference: Wikipedia; NTSP report; McDD Engineering Assessments

© R Leist Engineering 2023

United Airlines Flight 232 - 1989

- **112 fatalities; 171 injured; 184 survived**
- **Failure of Stage 1 tail mounted engine disk**
- **Severed all three hydraulic systems in engine / horizontal tail**
- **Cause:**
  - **Maintenance procedure did not report fatigue crack growing from a manufacturing defect in the disk forging during manufacture**
  - **Damage Tolerance Procedures not followed**

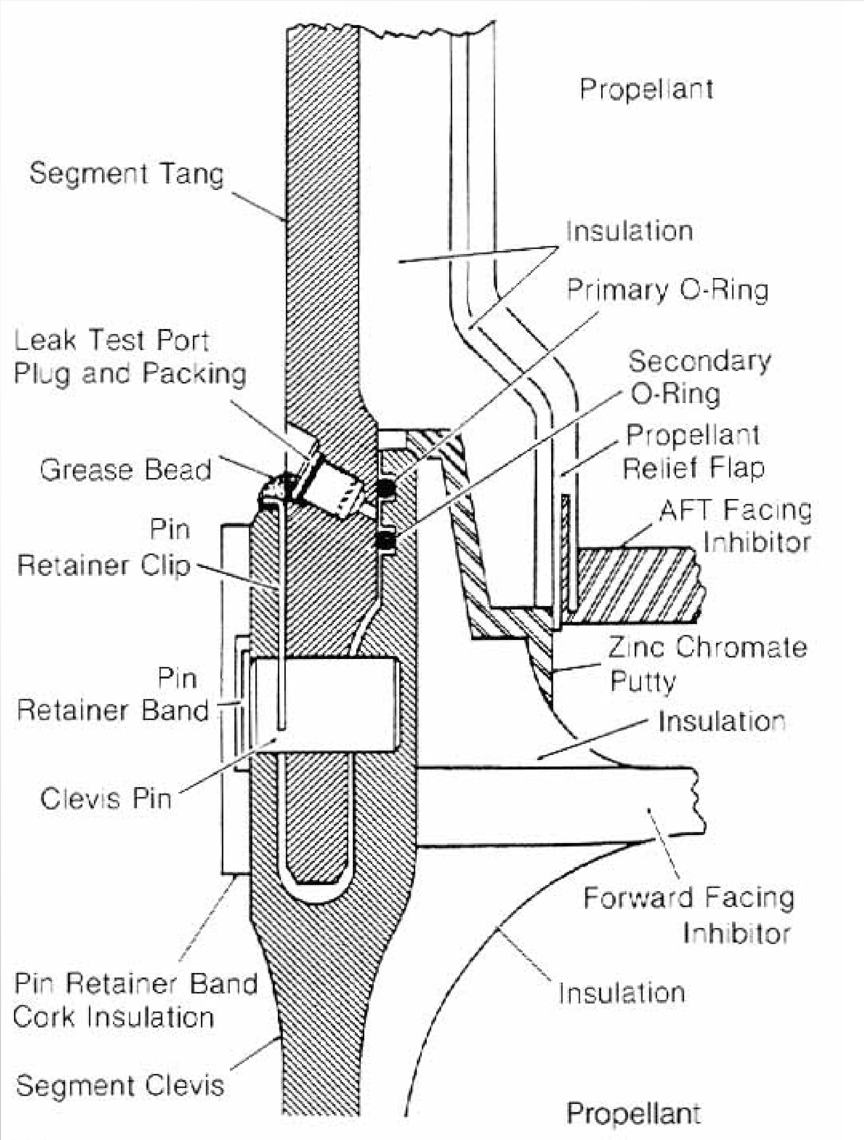


Reference: Wikipedia; NTSP report; News Reports

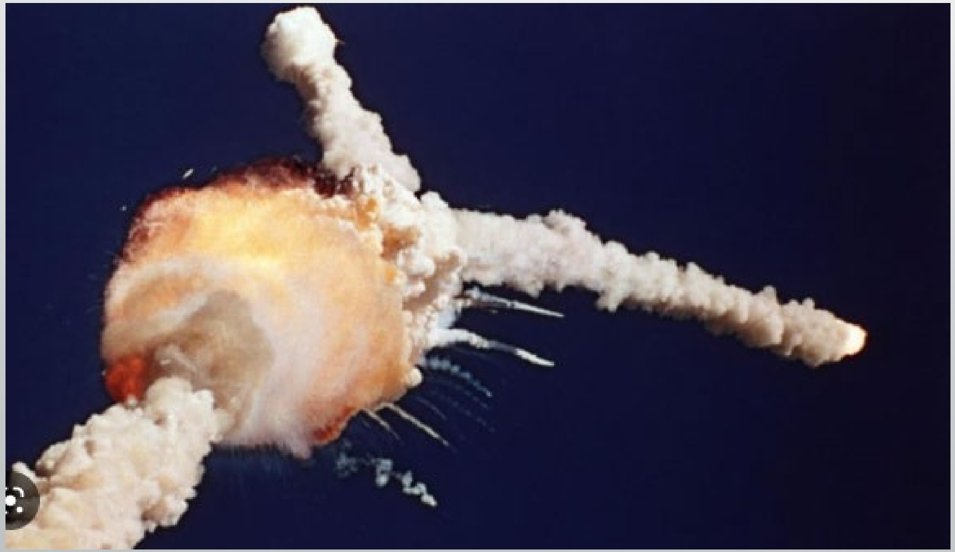
© R Leist Engineering 2023

Challenger Space Shuttle, 1986

- **Excessive tolerance in design allowed O-rings to gap, allowing burning fuel blow-by, O-ring erosion (known for several years)**
- **Failure:**
  - **Morton Thiokol engineers warned about issues as did NASA engineers**
  - **Erosion, design tolerance, and cold weather allowed joint to catastrophically fail on launch**
  - **Another failure was excessive personnel turnover in SRB assembly at Cape Kennedy (low salaries)**



Reference: Wikipedia; NASA investigation briefings; Ency Britannica



© R Leist Engineering 2023

Columbia Space Shuttle, 2003

- **Circled areas show where insulation failed and where it struck the shuttle wing**
- **Failure:**
  - **Disbonded insulation could not be detected.**
  - **No process to repair damage in Mission.**
  - **Impact to LH wing LE damaged heat shield which progressively overheated the substructure on re-entry until wing failure occurred.**

Reference: Wikipedia; Boeing Tech Fellow; NASA investigation briefing; Ency Britannica

© R Leist Engineering 2023

OVERVIEW OF SELECTED STRUCTURAL FAILURES

Questions?
Ric Leist, PE
316-214-3351
ricles@cox.net

 © R Leist Engineering 2023