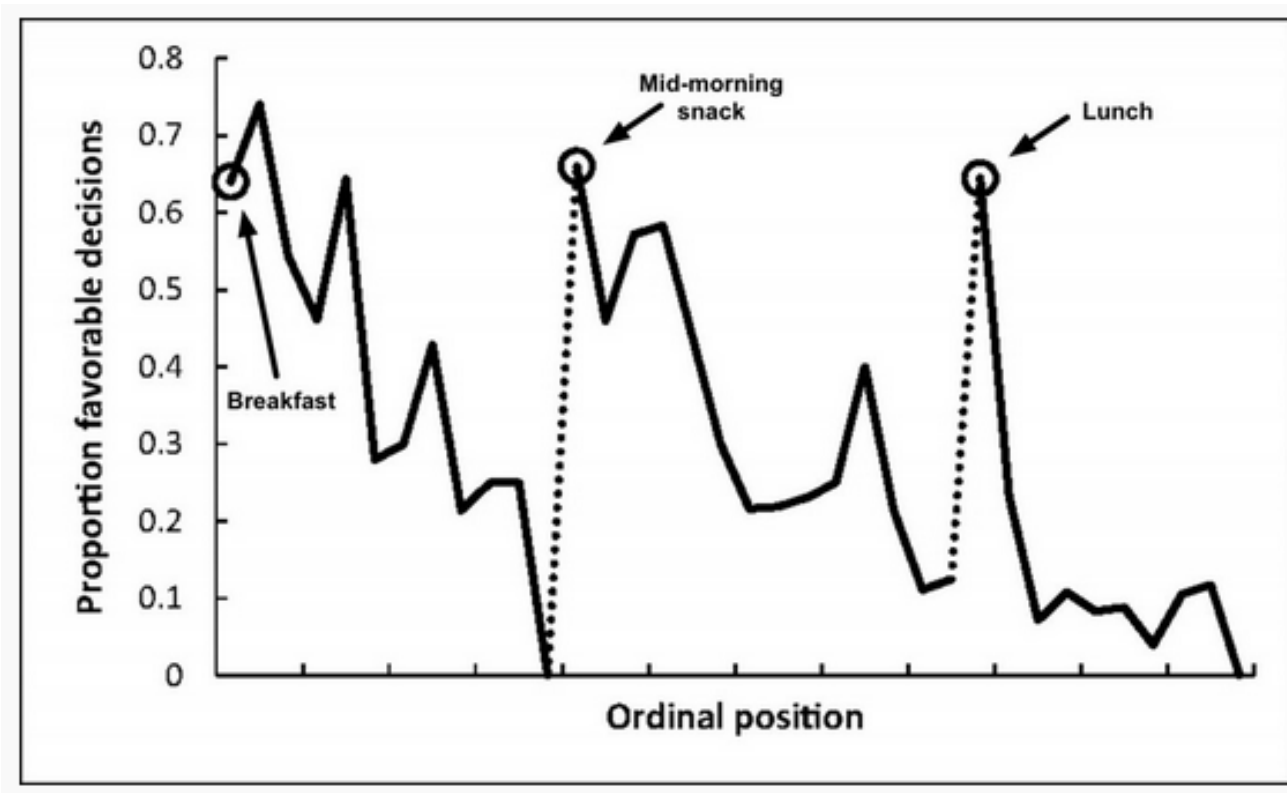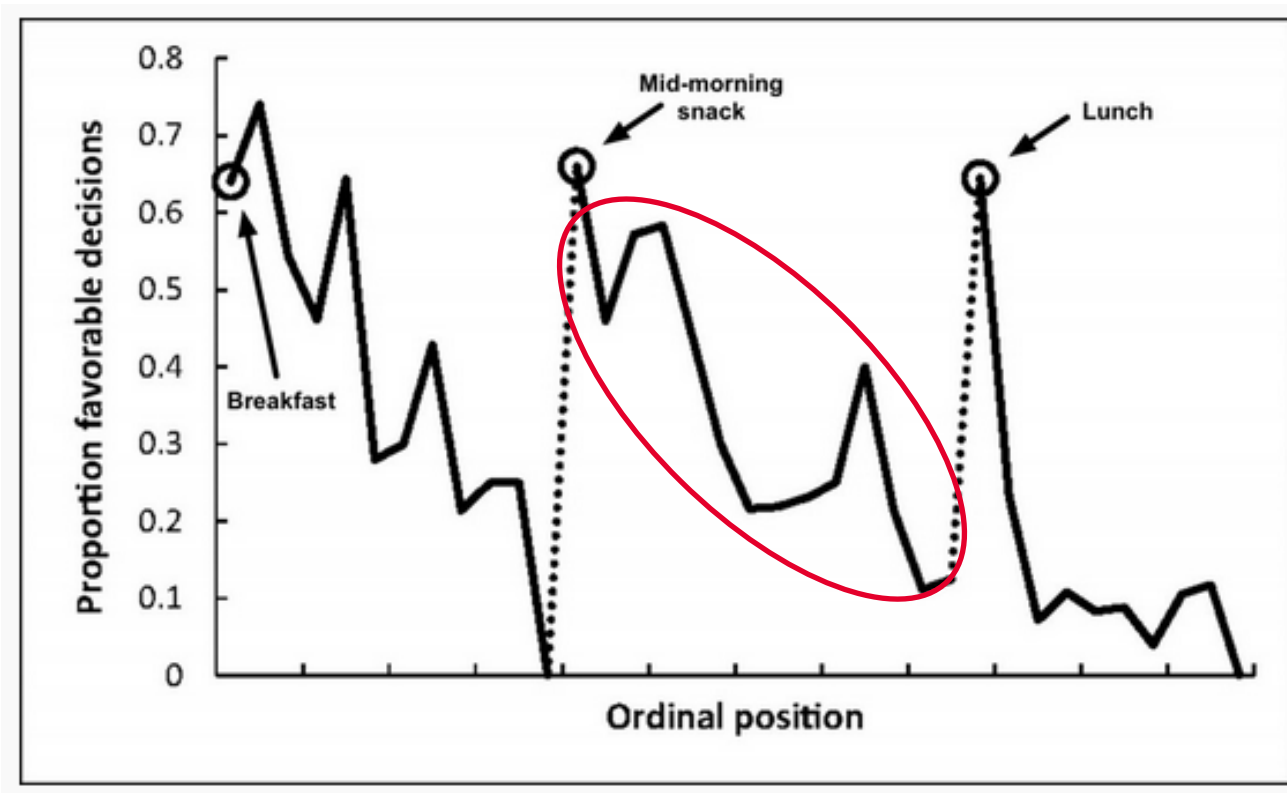# OEM's Approach to Widespread Fatigue Damage

Steve Perry, Principal Engineering Specialist, CSALP
15 November 2018

AIRBUS

BOMBARDIER

Contents

- Some definitions

- Brief history

- WFD Rule

- Implementation at Bombardier and CSALP

  - FAR 26 CRJ900/1000

  - FAR 25 A220-100/300

- Closing remarks

AIRBUS

BOMBARDIER

AIRBUS

BOMBARDIER

AIRBUS

BOMBARDIER

Some definitions

- Widespread Fatigue Damage (WFD) is the simultaneous presence of cracks at multiple structural locations that are of sufficient size and density that the structure will no longer meet the residual strength requirement of FAR 25.571

- $WFD_{(average\ behavior)}$ — The point in time, without intervention, when 50% of the fleet is expected to develop WFD for a particular structure.

- There are two sources of WFD: Multiple Site Damage and Multiple Element Damage.
  - Multiple Site Damage (MSD) is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural element
  - Multiple Element Damage (MED) is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in adjacent structural elements.

AIRBUS

BOMBARDIER

Simplified definitions

WFD = fatigue

MSD = fatigue

MED = fatigue

(R G Eastin, Delft 2007)

AIRBUS

BOMBARDIER
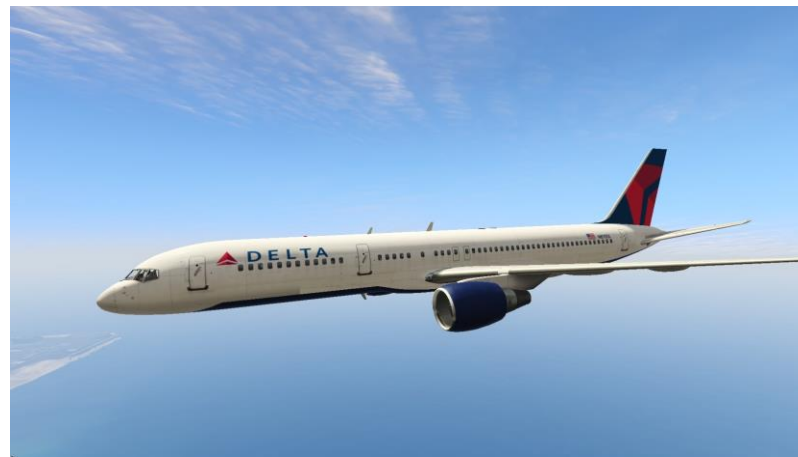
History

- Safe Life
  - Oldest form of designing against fatigue
    - Replacement of coach axles after 60,000 km in 1850s France (Schutz, 1993.)
    - de Havilland Comet

- Fail-Safe
  - Boeing 707, DC8, Airbus A300

- Damage Tolerant
  - Since 1978
    - Challenger CL-600, Boeing 757/767.
  - Limit of Validity
    - C Series (A220), Boeing 787

AIRBUS

BOMBARDIER

History

AIRBUS

BOMBARDIER

History

- 28 April 28, 1988, Aloha Airlines flight Hilo to Honolulu
- Lost area of cabin at 24000 feet
- Landed at Kahului
- One crew member died, one crew member and seven passengers seriously injured
- NTSB/AAR-89-03:
  - probable cause was the failure of the maintenance program to detect significant disbonding and fatigue damage
  - Contributing factors:
    - failure of Aloha Airlines management to supervise properly its maintenance force
    - failure of the FAA to require inspection of all the lap joints proposed by Boeing
    - lack of a complete terminating action after discovery of early production difficulties in the lap joint which resulted in low bond durability, corrosion, and premature fatigue cracking

AIRBUS

BOMBARDIER
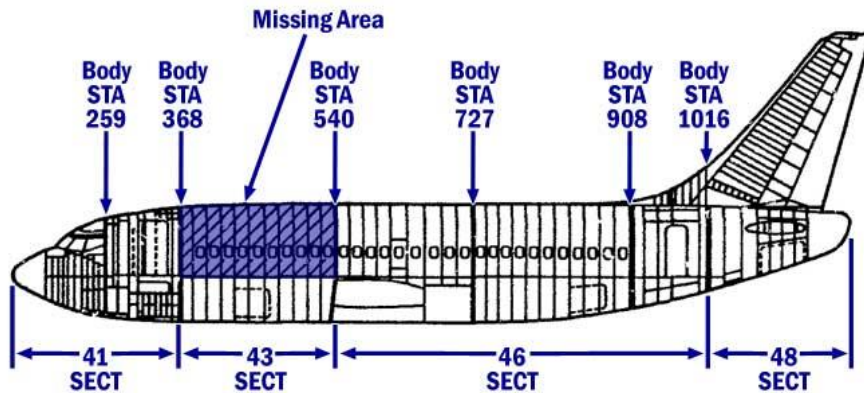
Problem - Widespread Fatigue Damage

- Fatigue Damage inspections are based on damage tolerance analysis, assuming a single hypothetical rogue flaw ("anomalous"[1] or "incidental"[2] fatigue)

- *Real* fatigue cracks will eventually develop at multiple locations (undermining fail-safe features) as the airframe approaches the end of its design life ("normal"[1] or "symptomatic"[2] fatigue) .

- Regular inspections will be unable to provide adequate protection against WFD.

1. Eastin
2. Schijve

AIRBUS

BOMBARDIER

Solution - Widespread Fatigue Damage rule

- WFD can be precluded if an operational limit is mandated

- The Limit of Validity (LOV) is the period of time in flight cycles and flight hours, up to which it has been demonstrated by test evidence, analysis and, if available, service experience and teardown inspection results of high-time airplanes that WFD will not occur in the airplane structure. The LOV refers to the engineering data that support the structural maintenance program and addresses WFD at an aircraft level and not at a detail or component level.

AIRBUS

BOMBARDIER

WFD rule

<u>FAR 26.21</u>

- Issued on Oct. 28, 2010
  - Publication date Nov. 15, 2010
  - Effective date Jan. 14, 2011
  - Existing airplanes subject to the rule are turbine-powered airplanes with a type certificate issued after January 1, 1958, which have a maximum takeoff gross weight greater than 75,000 pounds and are operated under part 121 or 129.

- <u>FAR 25.571 Amdt 132</u>
  - Airplanes whose type certificate was applied for after January 14, 2011

- <u>Advisory Material</u>
  - AC 120-104
  - AC 25.571-1D

AIRBUS

BOMBARDIER

WFD rule

- FAR 25 Amdt 96, 1998
  - WFD must be considered
  - Full-scale test mandated
  - Aircraft operation limited by fatigue test progress

- FAR 26.21 and FAR 25 Amdt 132, 2010
  - Must establish LOV

AIRBUS

BOMBARDIER

Implementation - WFD (average behavior), ISP, SMP

Figure 6-3
MSD/MED Residual Strength Curve
(Including WFD Inspections)
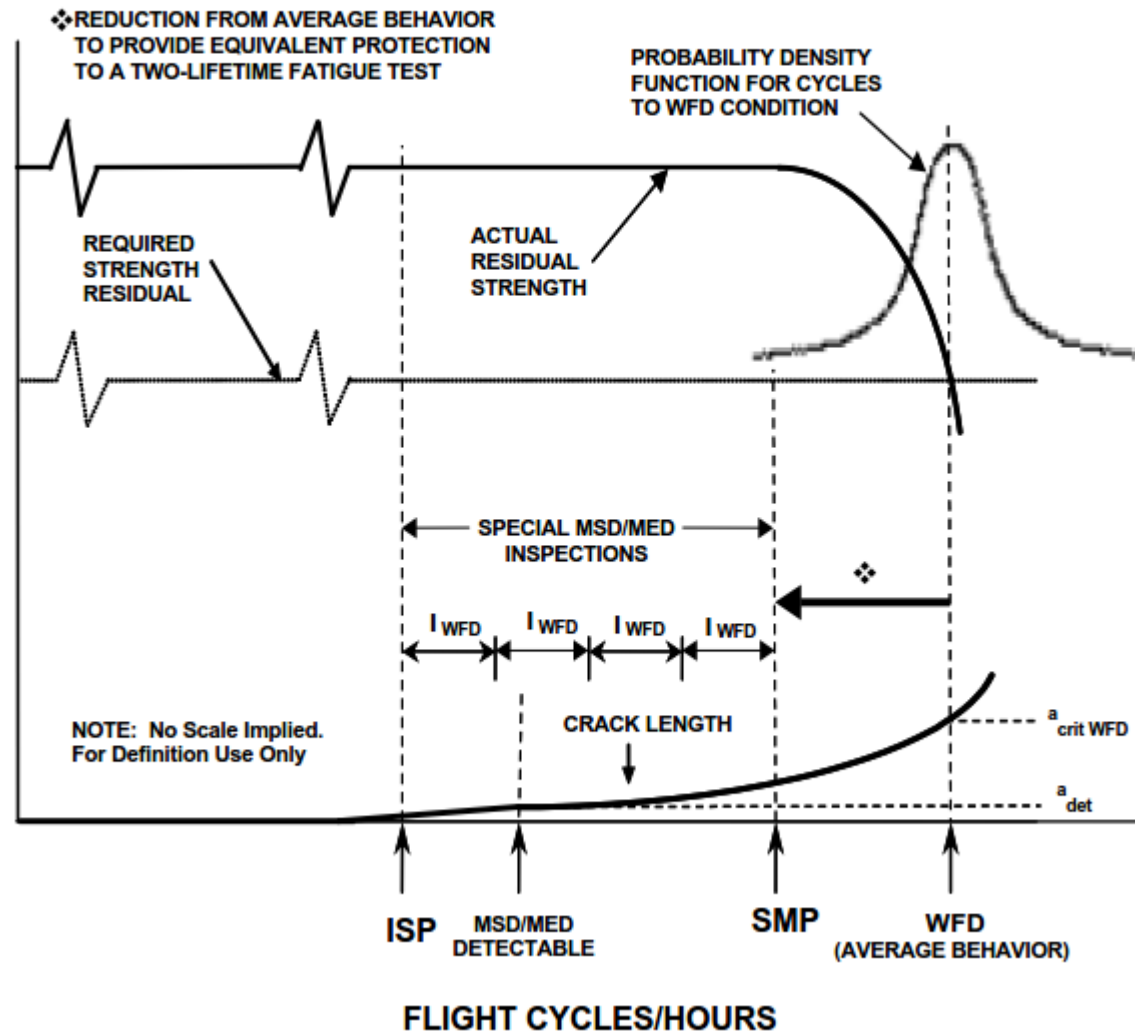
Implementation - test duration

AC25.571-1D

- Assuming inspection for MSD/MED is impractical, replacement or modification would be required at [the test duration] divided by 3 per the guidance in AC 120-104. For areas where inspections for MSD/MED are practical, the applicant may defer replacement or modification until X divided by 2, provided inspections for MSD/MED start at X divided by 3. The applicant should consider these factors when deciding on the duration of a full-scale fatigue test.

- CRJ900 (and CRJ700) test duration was twice Design Service Goal = 2 x 80,000 FC (110,000 FH)

- Selected LOV (applicable at aircraft level) = DSG

AIRBUS

BOMBARDIER

Implementation – WFD evaluation

- Identify WFD-susceptible structure
- for each:
  - Establish WFD(average behavior)
  - Define ISP and SMP

Figure 7-2

Airplane Maintenance Actions
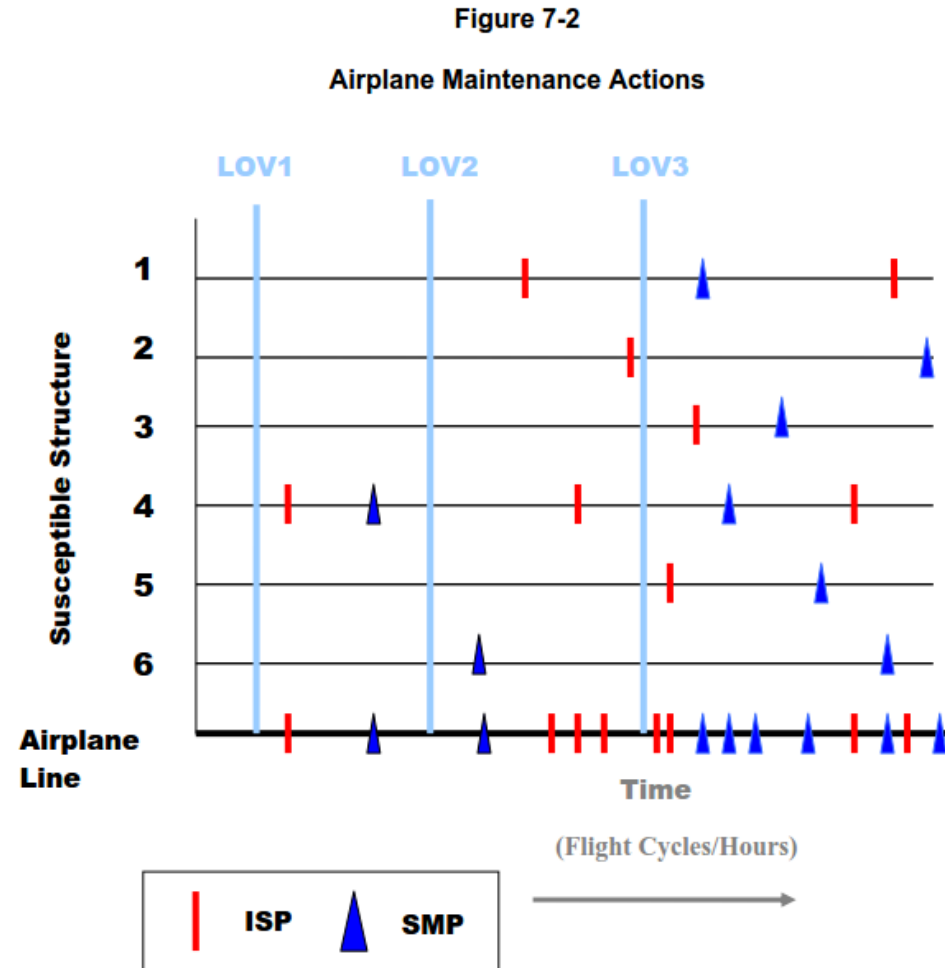
Implementation – WFD evaluation

- In essence, freedom from WFD is shown by:
  - Completion of a full-scale fatigue test of minimum duration 2 x LOV
  - Completion of residual strength tests of WFD-susceptible areas
  - Teardown inspections, while not essential, are necessary if WFD$_{(average\ behavior)}$ is to be established beyond test duration x 2

- Analysis of MED is possible through conventional durability and damage tolerance methods

- Analysis of MSD, must consider interaction between crack tips
  - In principle, sophisticated procedures can be produced to model initiation, propagation and interaction of multiple fatigue cracks. However, due to environmental effects, manufacturing variability and the fundamentally random nature of fatigue, increasing levels of analysis complexity may not lead to an appreciable improvement in calculated crack growth life. A typical approach is to perform relatively simple calculations with robust conservatism built-in to complete the WFD evaluation.

AIRBUS

BOMBARDIER

Implementation – WFD evaluation

Determination of SMP and ISP

WFD damage tolerance analysis considers the period of time between the detectable crack length until failure due to crack link up or net section yield.

For WFD damage tolerance analysis, the same initial flaw size is considered to exist on diametrically opposed sides of every hole and aligned perpendicular to the maximum tensile stress
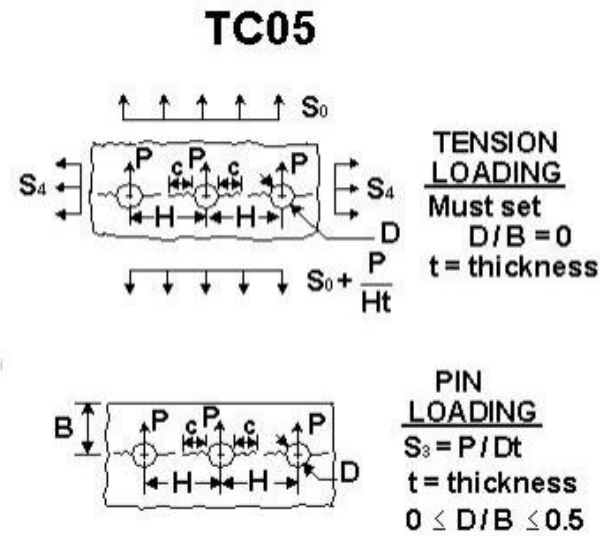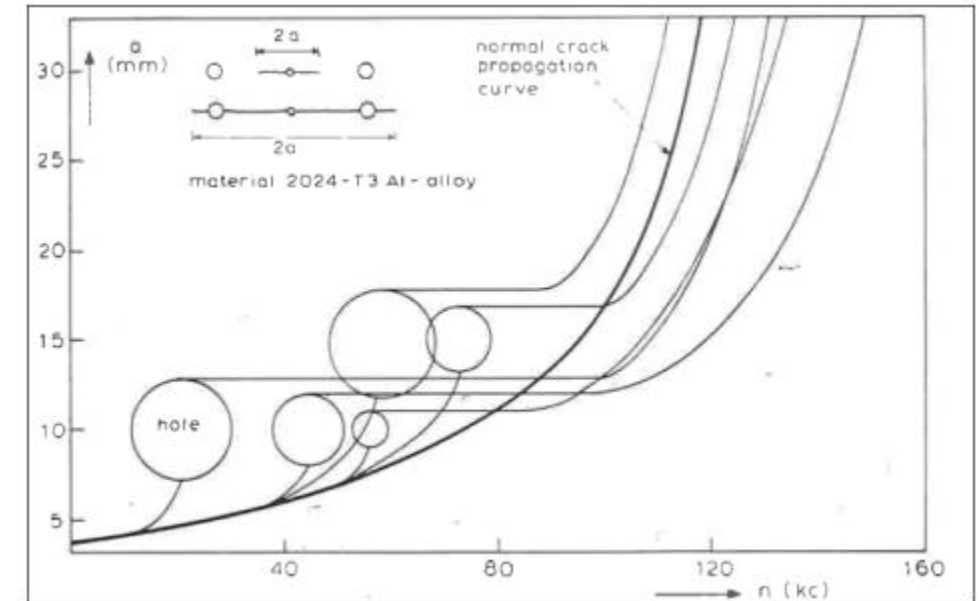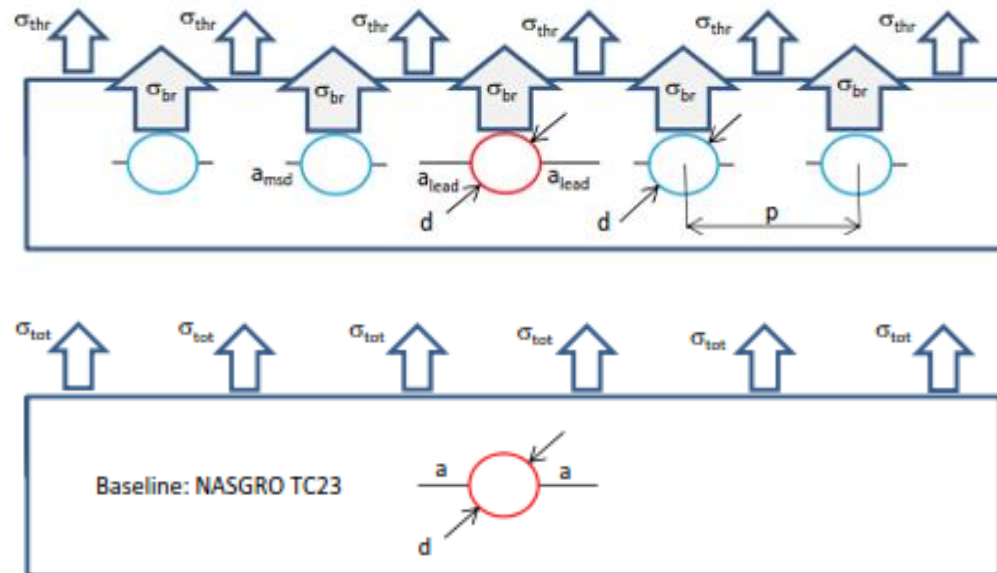

FIGURE 3 MODEL FOR MSD CRACK GROWTH (REF. NASGRO® MODEL TC05)

Implementation – WFD evaluation

- Where there are findings in a lap joint, say, a more complex approach may be required
- A tool has been developed to model a lead crack growing in a row of holes in the presence of damage at each hole

MULTI-SITE DAMAGE CRACK GROWTH AND RESIDUAL STRENGTH ANALYSIS
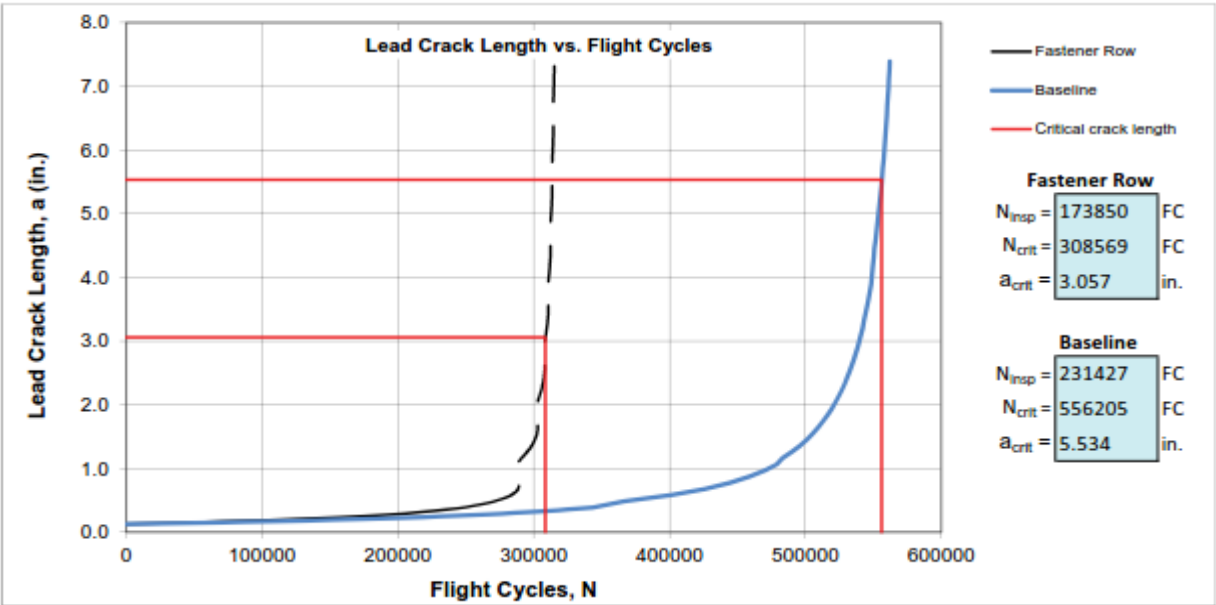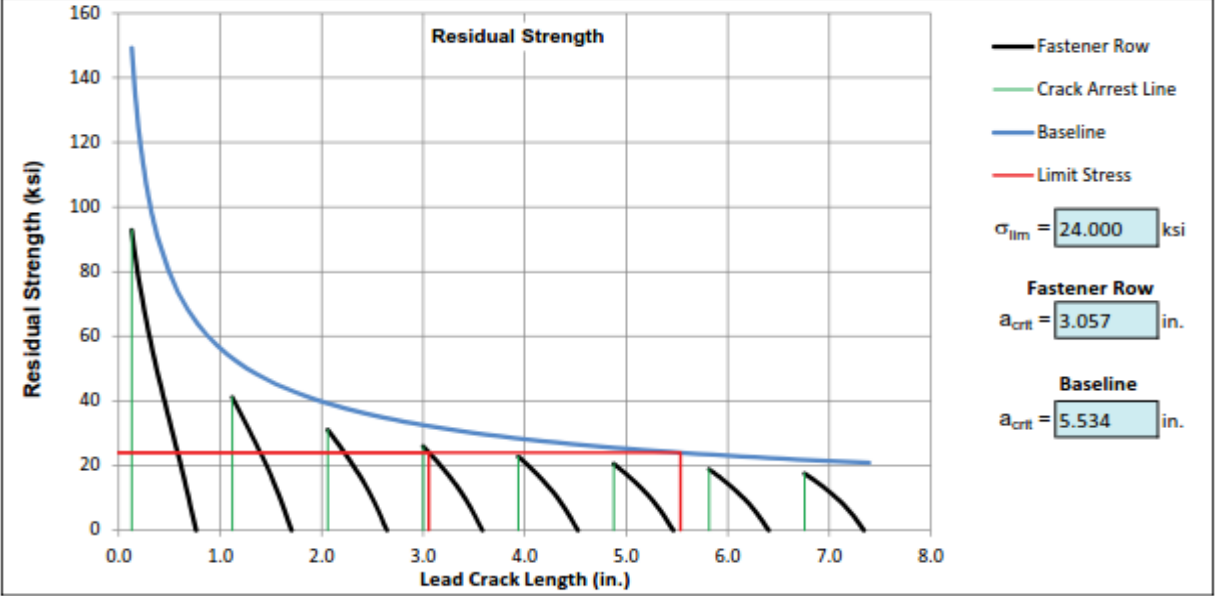
AIRBUS

BOMBARDIER

Implementation – WFD evaluation

Baseline scenario is a two-tip crack growing from an open hole in an infinite panel provided by NASGRO TC23

This is compared with the same crack growing in the presence of MSD

Factors derived to apply to threshold and repeat interval to account for test findings

AIRBUS

BOMBARDIER

Implementation – WFD evaluation

- MSD
  - effectively eliminates the re-nucleation retardation that allows the baseline model to ignore the presence of holes ahead of the lead crack
  - Accelerates lead crack growth by link-up and interaction with crack tip stress fields
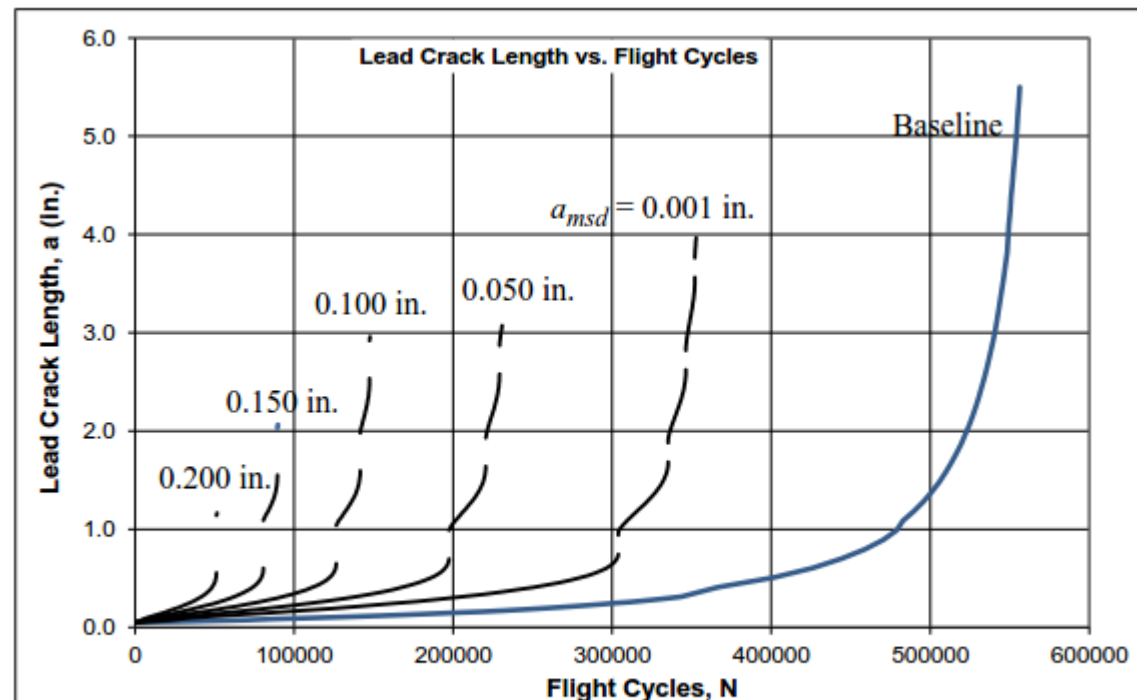 - Reduces critical crack length

FIGURE 7 *Effect of a_{msd} on Crack Growth and a_{crit}*

CRJ900 Implementation – WFD-susceptible structure
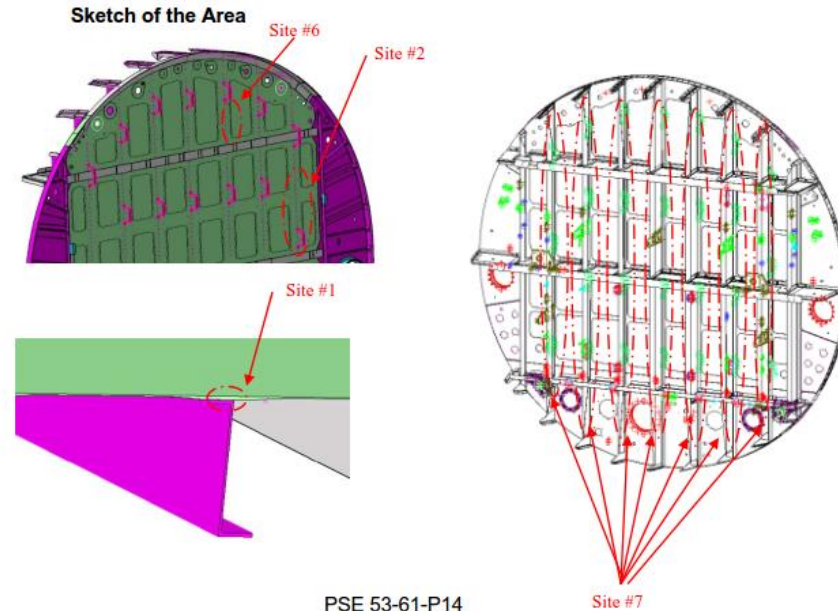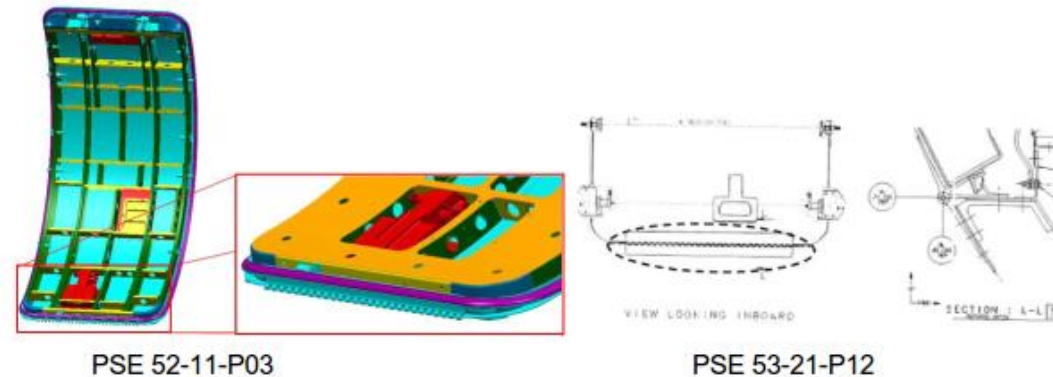
- Identify WFD-susceptible structure

Fuselage

- Longitudinal and circumferential skin joints;
- Frames and stringers;
- Pressure bulkhead cap angles;
- Stringer to frame attachments;
- Window surround structure;
- Wing to fuselage attachments;
- Door hinges and latches;
- Skin at doubler run-out.
- Pressure floor

Wing/Empennage

- Skin joints;
- Rib to skin attachments;
- Skin at doubler run-out;
- Stringer run-out.
- Wing trunnion

Sketch of the Area

Site #6
Site #2
Site #1

PSE 53-61-P14
Site #7

Sketch of the Area

PSE 52-11-P03
PSE 53-21-P12

AIRBUS

BOMBARDIER

Implementation – Evaluation

- The compliance against FAR 26.21 is based on the original certification full scale fatigue testing
  - 2 x LOV or 2 x 80,000 FC

- Evaluation is based on:
  - certification test data
  - tear down inspections
  - service history
  - damage tolerance analyses

AIRBUS

BOMBARDIER

Implementation – Evaluation

- WFD(average behavior) is derived from test results, supplemented with damage tolerance analysis. Two categories of result following teardown:

  1) no MSD/MED findings
  2) with MSD/MED findings

- Non-destructive inspection of all WFD-susceptible areas

  – Detectable cracks lengths with high POD:

    – Rotor probe inspection of fastener hole   0.040"
    – MOI of area outside countersink   0.015" to 0.020"

AIRBUS

BOMBARDIER

Implementation – Evaluation

- For structures with no findings:

$$WFD_{average\ behavior} = N_{test} + (N_{crit} - N_{det})_{DTA}$$

  – effective inspection

$$ISP = \frac{WFD_{average\ behavior}}{3}$$

$$SMP = \frac{WFD_{average\ behavior}}{2}$$

  – Non-effective inspection

$$SMP = \frac{WFD_{average\ behavior}}{3}$$

AIRBUS

BOMBARDIER

Implementation – example

- PSE 52-11-P03, Passenger Door Piano Hinge

No cracks found at end of 160,000FC

Detectable crack in hole = 0.040"

Assume $c_{initial}$ = 0.040"

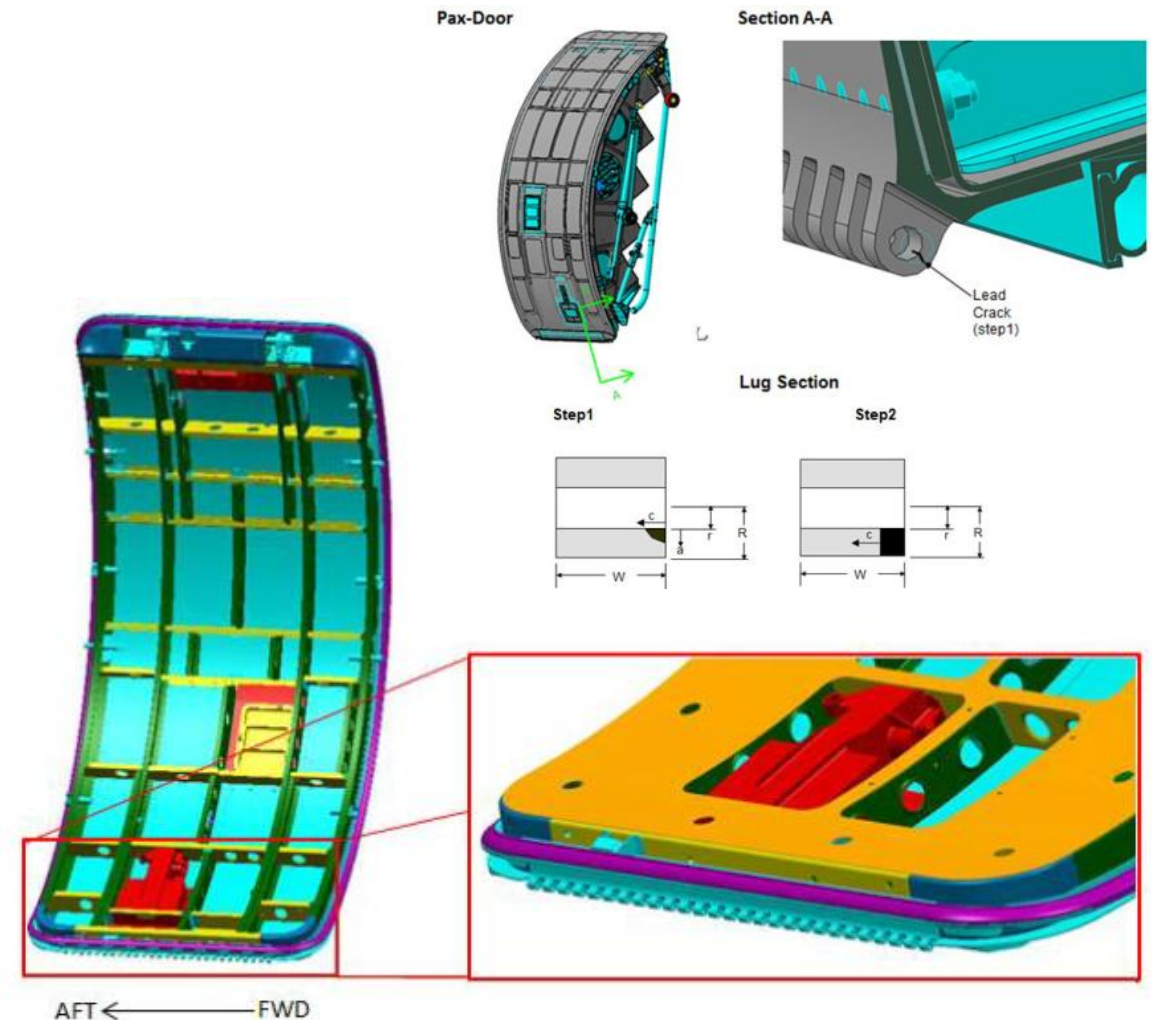Ncrit = 46,200 FC by DTA

Ndet = 0

$WFD_{average\ behavior}$ = 160,000 + (46,200 – 0) = 206,200 FC

ISP =   206,200 / 3 = 68,700 FC

SMP =   206,200 / 2 = 103,100 FC > LOV

AIRBUS

BOMBARDIER

Implementation – example

- PSE 53-41-P14, Aft pressure Bulkhead – Beam to Web Structure

Bulkhead was replaced on test at 60,000 FC, so only 100,000 FC accumulated – no cracks found

Assume $c_{initial}$ = 0.025"

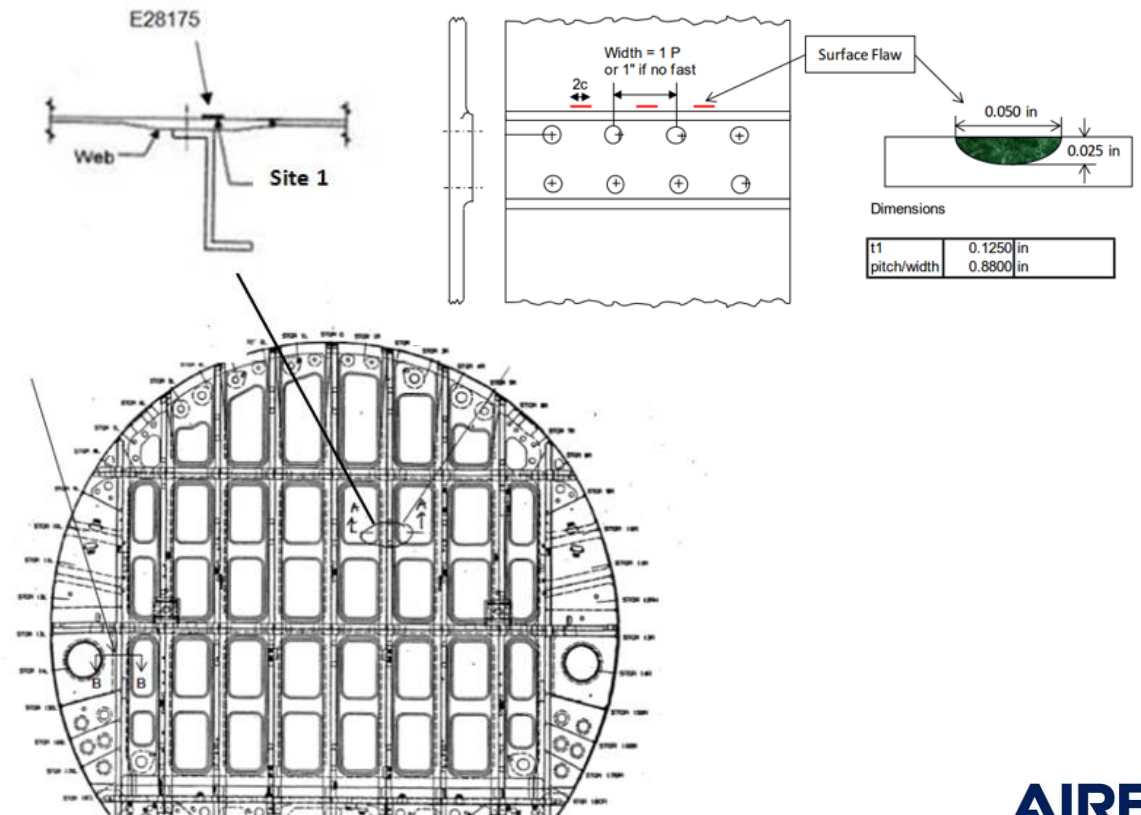Ncrit = 190,182 FC by DTA

Ndet = 0 FC

$WFD_{average\ behavior}$ = 100,000 + (190,182 − 0) = 290,182 FC

ISP =   290,182 / 3 = 96,700 FC > LOV

SMP =   290,182 / 2 = 145,000 FC > LOV

AIRBUS

BOMBARDIER

Implementation – example

- Longitudinal fuselage joint – teardown with findings

- Lead crack in presence of MSD

$$WFD_{average\ behavior} = N_{test} + C_{rep} \times (N_{crit} - N_{test})_{DTA}$$

- a_{MSD} = 0.04" (minimum detectable by rotor probe)

- a_{lead} = crack length corresponding to test finding

- N_{test} = flight cycles accumulated at teardown

- N_{crit} = flight cycles for 2-tip crack (a_{lead}) from a hole to grow to critical

- C_{rep} = knockdown factor calculated for interaction with MSD

AIRBUS

BOMBARDIER

Implementation – C Series / A220

- WFD-susceptible structure identified

- Full-scale fatigue test started in August 2014

- 180,000 flight cycles completed in January 2018

- Residual strength testing completed in May 2018

- Teardown underway

AIRBUS

BOMBARDIER

Implementation – C Series / A220

- In contrast to most previous full-scale tests, this being the first commissioned following introduction of the WFD rule, objectives were to:

  - focus on basic fatigue resistance of structure

  - minimize the number of artificial damages introduced during cycling

  - avoid "contamination" of WFD-susceptible structures

  - for residual strength tests -
    - select load cases that were critical for WFD-susceptible structures (eg 1.15 x DP)
    - demonstrate multi-load path capability

  - Carry out systematic and rigorous teardown inspections

AIRBUS

BOMBARDIER

Implementation – C Series / A220

- Design against fatigue aided by introduction of fatigue methodology
- Areas prone to MSD/MED designed with healthy fatigue margins
- Particular attention paid to Al-Li pressure shell – longitudinal and circumferential joints and frame attachments
- Also used in extensive redesign of forward pressure bulkhead. Zero cracks found at end of test.
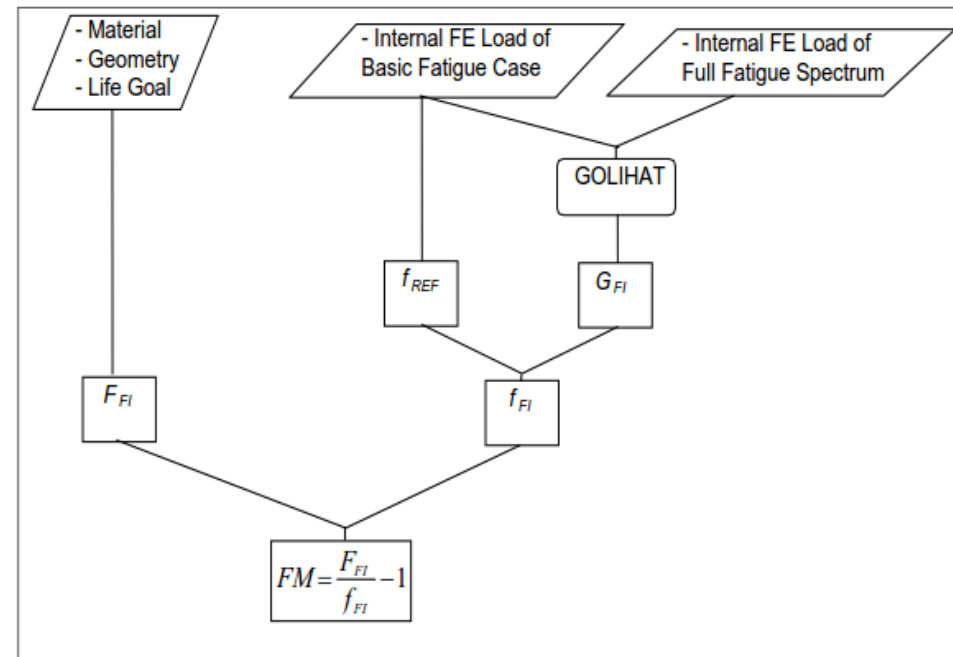

FIGURE 1 – PROCESS CHART FOR FATIGUE ANALYSIS

AIRBUS

BOMBARDIER

Implementation – C Series / A220

• DADT at IABG in Dresden, Germany

AIRBUS

BOMBARDIER

Implementation – C Series / A220

- DSG = 60,000 FC

- Candidate LOV = 80,000 FC

- Test duration < 3 x LOV

- Similar procedure to that adopted on CRJ900 will be used to define ISP and SMP for each area of WFD-susceptible structure

AIRBUS

BOMBARDIER

Concluding Remarks

- WFD is the inevitable and familiar consequence of an aging airframe
- It undermines fail-safe features and lead crack growth scenarios
- Establishing a limit on the operation of the fleet defined by the point at which DTA-based AWLs are no longer reliable is a prudent measure
- The LOV is primarily based on the outcome of full-scale fatigue testing supplemented by DTA, taking into account crack-tip interaction
- Full-scale testing should focus on exploration of fatigue resistance of structure (including fail-safe capability) and move away from substantiation of damage tolerance analysis, which is better achieved through historical comparisons and dedicated coupon testing

AIRBUS

BOMBARDIER

Thank you

AIRBUS

BOMBARDIER