2006 USAF Aircraft Structural Integrity Program Conference

C-130 Center Wing MSD/MED Risk Analysis

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Overview

- Background
- Analysis Locations
- MSD/MED Risk Analysis of the Lower Surface Panel
- MSD Risk Analysis of the Wing Joint Fitting
- Structural Integrity Management Strategies
- Conclusions and Lessons Learned

Background

Background

- 1995-2000 Service Life Analysis (SLA) projected fatigue cracking occurrence rates:
  - *Cumulative Fatigue Damage Methodology*
  - *Full Scale Durability Test Results used to estimate the mean time to cracking and determine K_t*
  - *Fatigue Test relative severity to the C-130E Baseline Usage determined to be 3.3*

- 2001-2004 Inspections identified numerous USAF C-130E/H Center Wings with significant fatigue cracking
  - *123 aircraft found with cracks at FCL's*
  - *Service cracking occurring earlier than projected based on SLA*
  - *Prevalence of Multi-Site Damage (MSD) & Multi-Element Damage (MED)*
  - *Service Crack Correlation analysis determined Fatigue Test relative severity to the C-130E Baseline Usage is 2.0*

Background

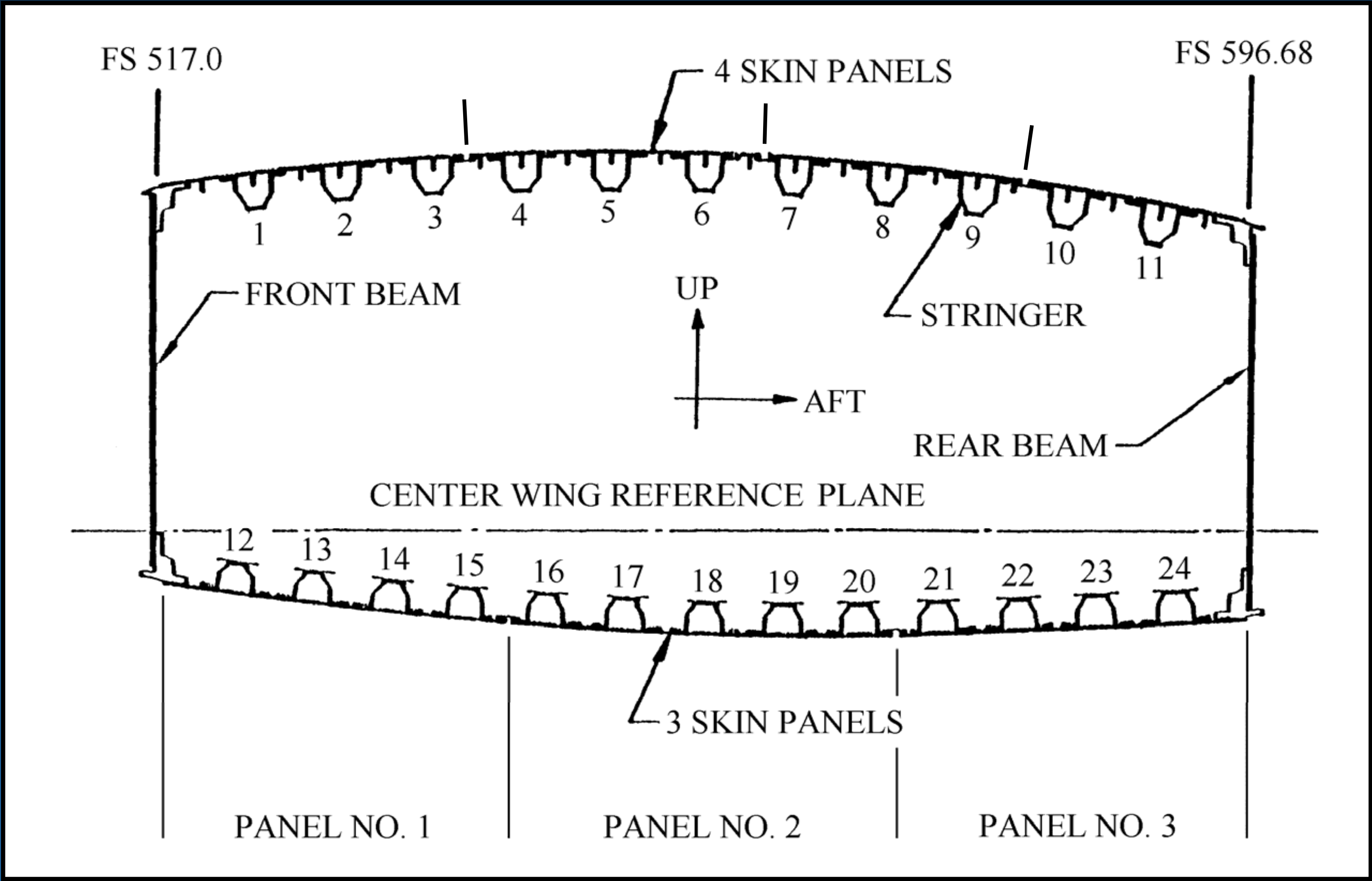
- **2004** USAF Center Wing Service Life Independent Review Team (IRT) Formed:
  - *Lead by Dr. Gallagher*
  - *To validate C-130 Service Life*
  - *To provide guidance on determining Risk*
  - *Focused on 3 Center Wing Zones*
  - *Concern over un-inspected area (95% of lower surface)*
- **2005** Risk Analysis Performed:
  - *Discrete Source Damage – a severed skin panel with cracked stringers*
  - *Fatigue Crack Propagating across an intact panel*
  - *Results presented at 2005 ASIP Conference*
  - *Concluded that a Single Panel Failure must be prevented*

C-130

Background
C-130 Center Wing Box

Background

Center Wing Section View (Typical)

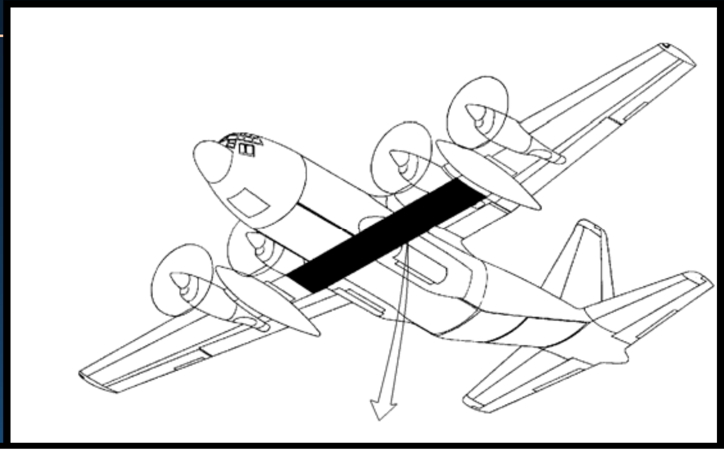


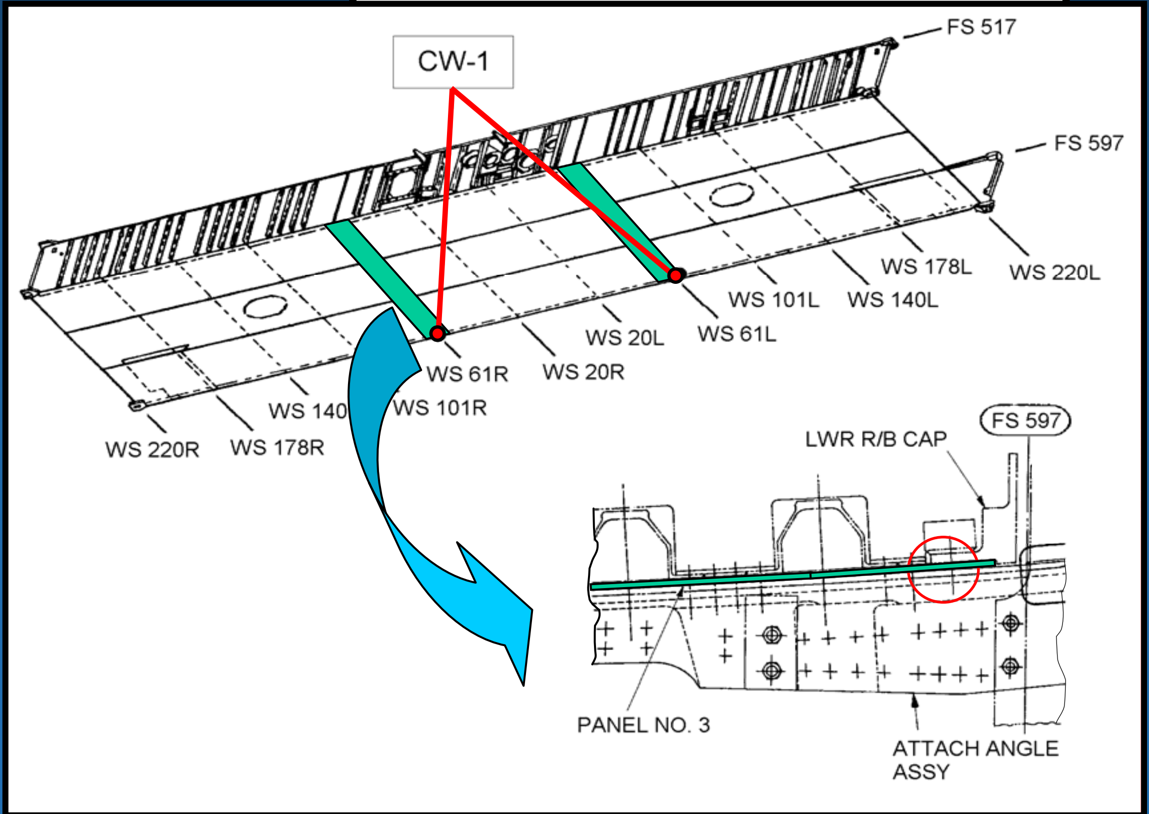
Analysis Locations

Analysis Locations – Zone 1

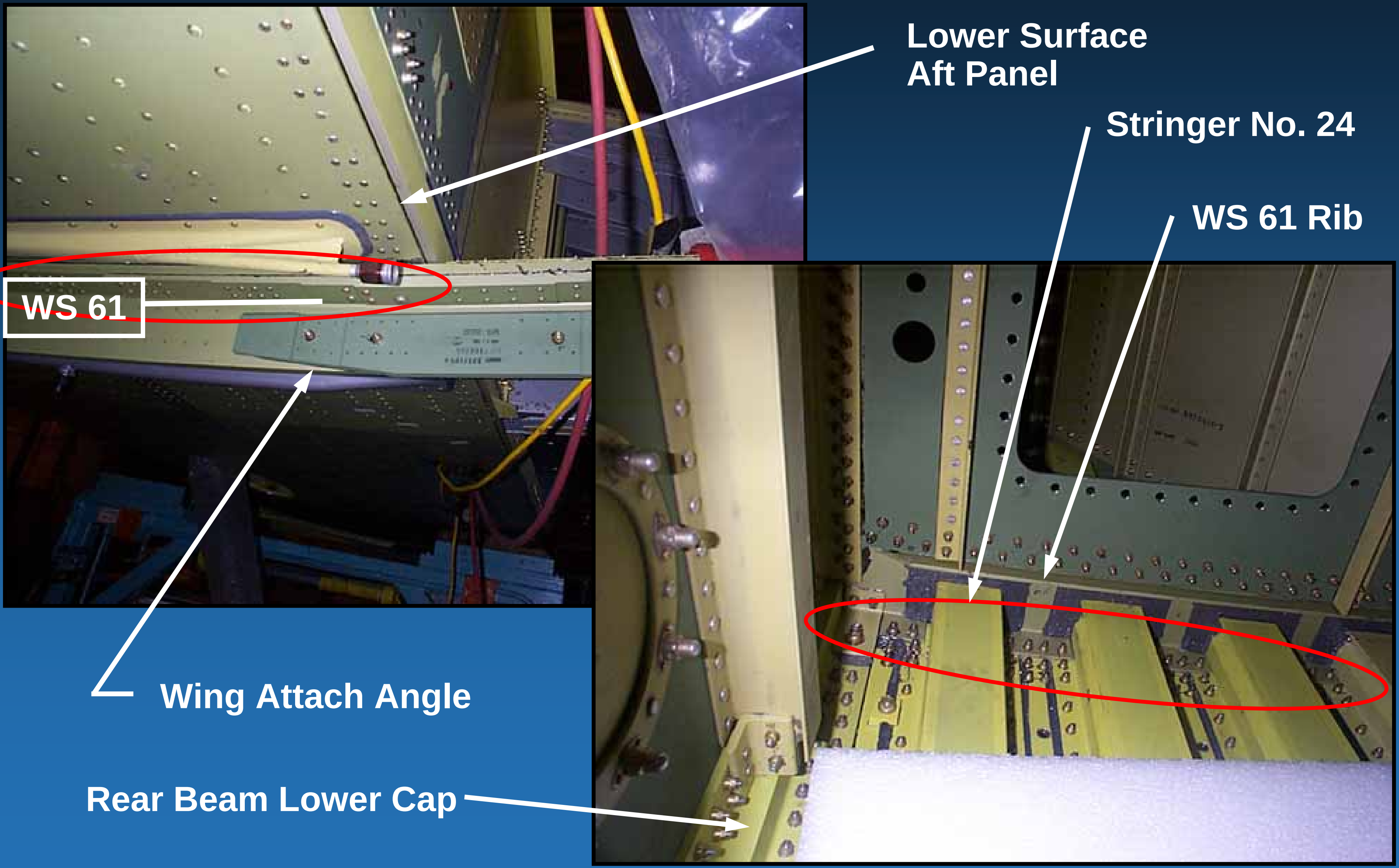
Zone 1 (WS 61):

- Wing to Fuselage Attachment
- Susceptible to MSD and MED
- Difficult to Inspect (requires Bolt Hole Eddy Current) approx 300 Fasteners
- Jan ’05 - 44 USAF A/C found with in-service cracking
  - *Current total – 102 Cracks on 71 A/C*
- Longest Service Cracks Discovered:
  - *USAF 2.0 in.*
  - *Commercial 12.0 in.*
- Critical Crack Size at Design Limit Stress = 6.5 in.





Analysis Locations – Zone 1



Analysis Locations – Zone 1

- **12 inch Fatigue Crack on L382 Commercial Aircraft:**
  - MSD and MED
  - 2 Internal Stringers also cracked at this location

View Looking Up on Center Wing Lower Surface

Panel No. 2

MSD Link-up

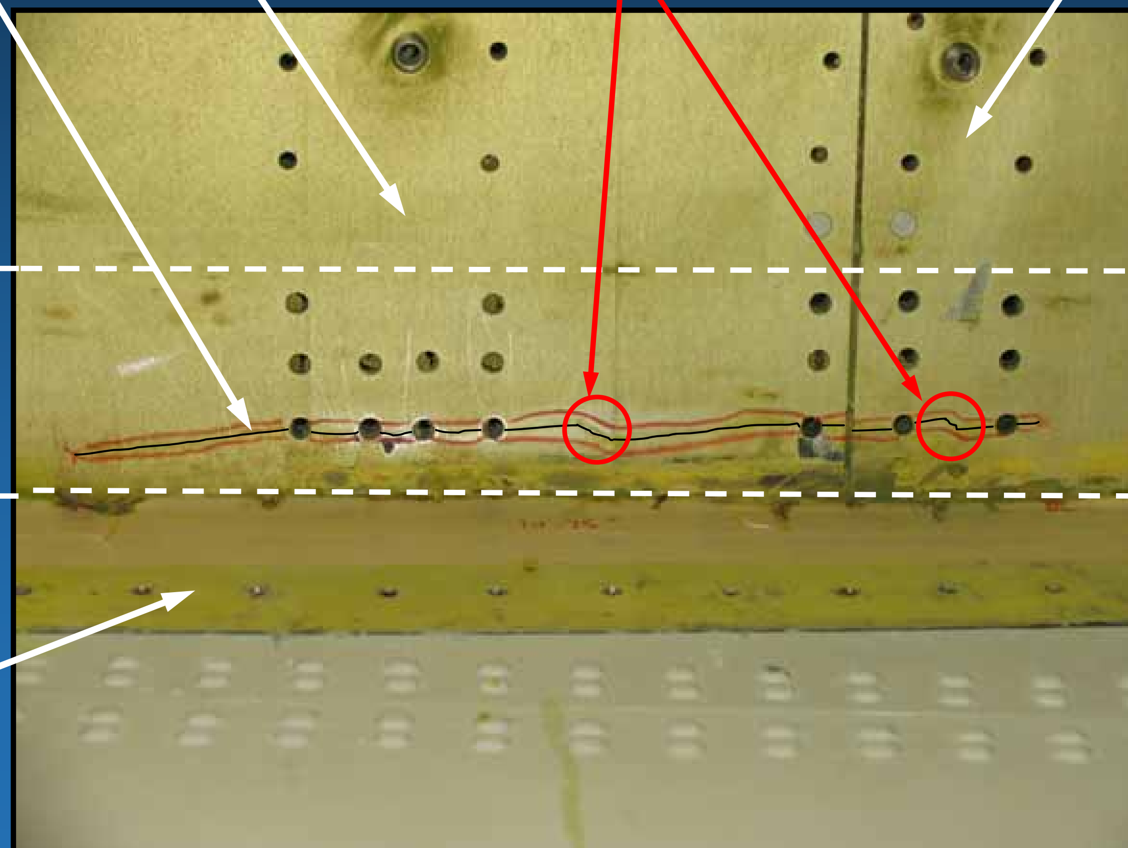
Panel No. 1

Wing Attach Angle Removed

WS 58

WS 61

Fuselage Side Wall Panel

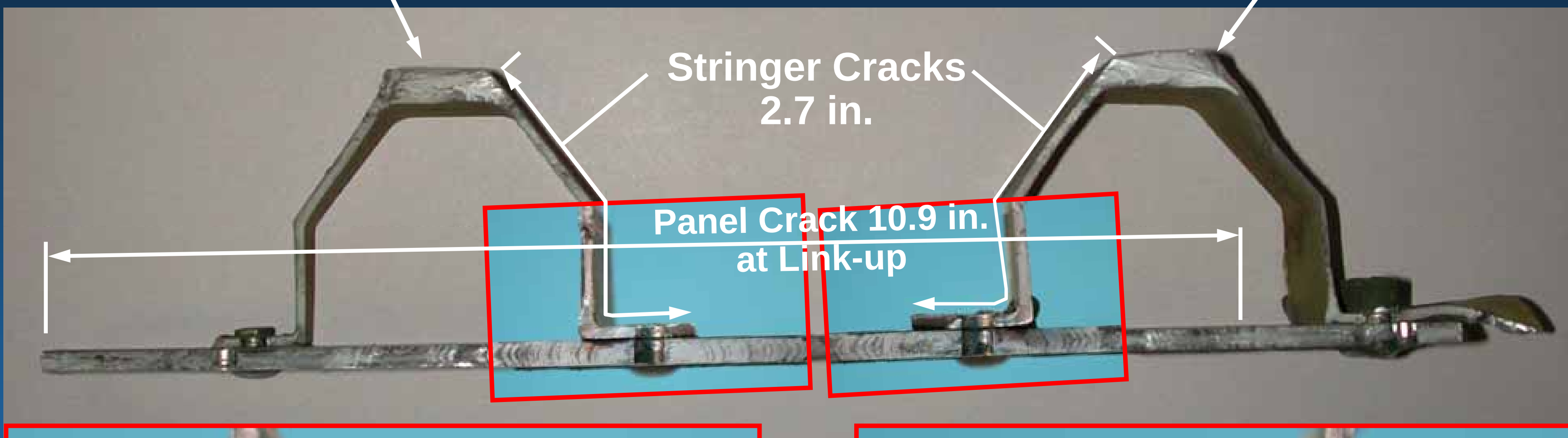


This Wing Could Not Sustain Design Limit Load

Analysis Locations – Zone 1

Zone 1 MSD and MED Cracking

Skin Panel No. 2



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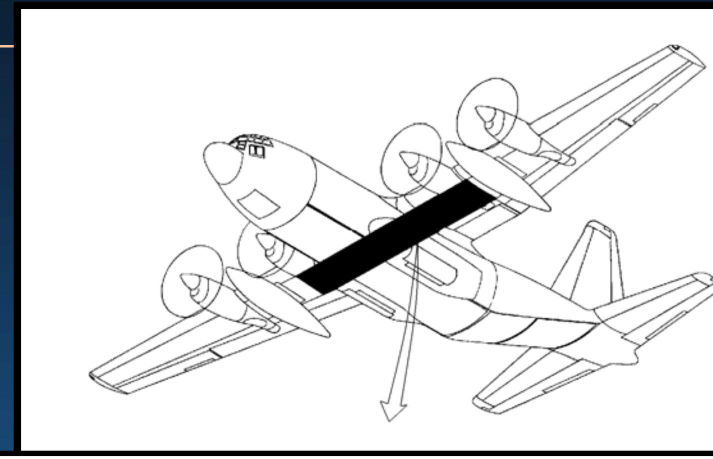
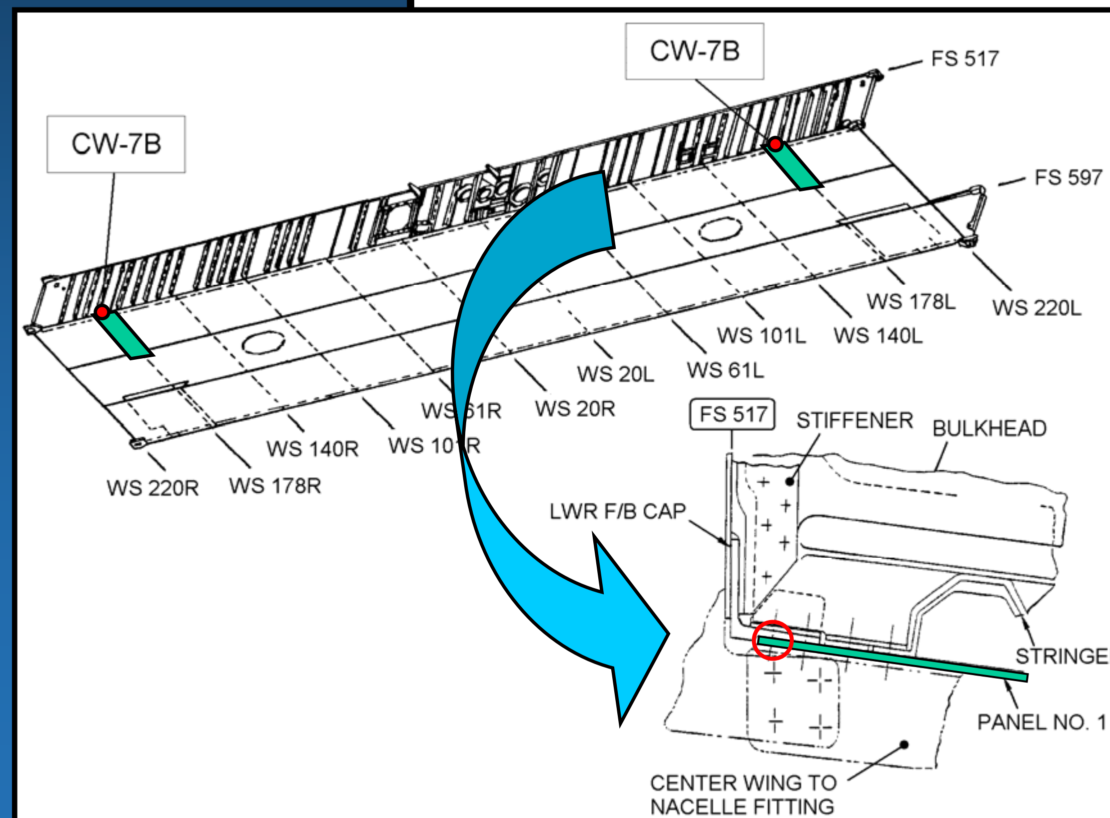
Analysis Locations – Zone 2

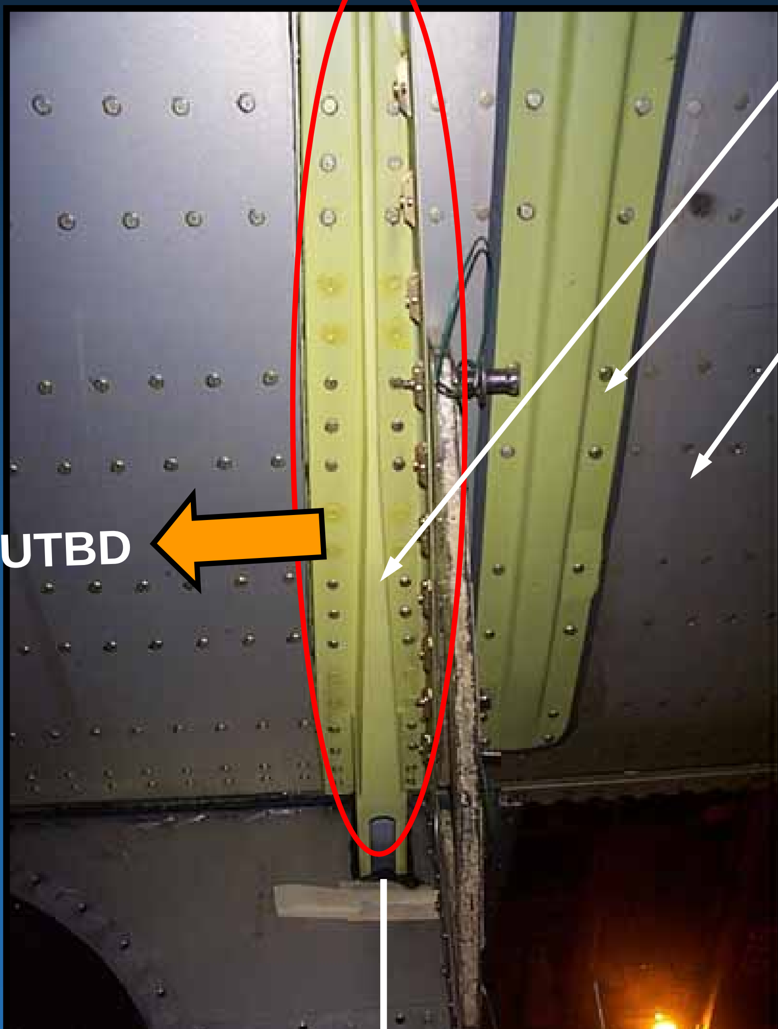


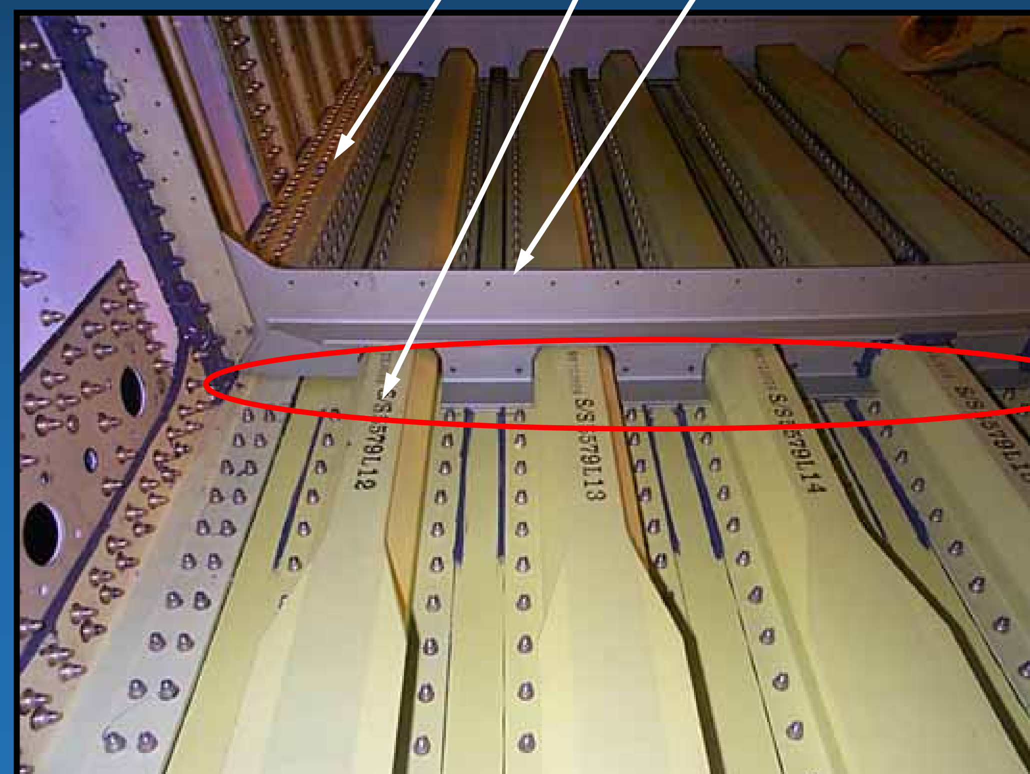
Zone 2 (WS 178):

- Engine Nacelle Attachment to the Wing (WS 213 Similar)
- Requires Bolt Hole Eddy Current Inspection of approx 160 Fastener Holes
- Location of Center Wing Residual Strength Test MSD/MED Failure
- 28 A/C found with in-service MSD/MED cracking:
  - *Front Beam Cap*
  - *Skin Panel*
  - *Stringer*



Analysis Locations – Zone 2

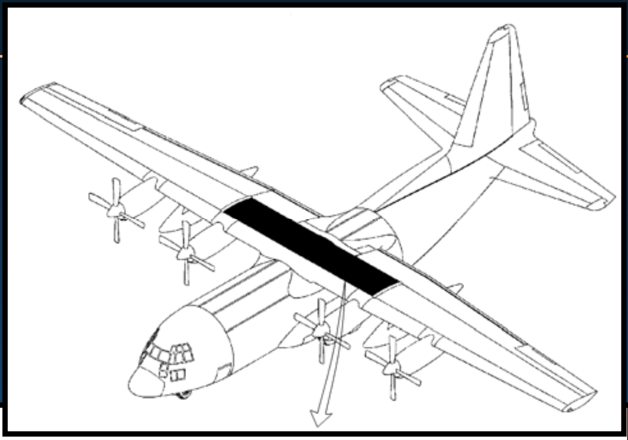


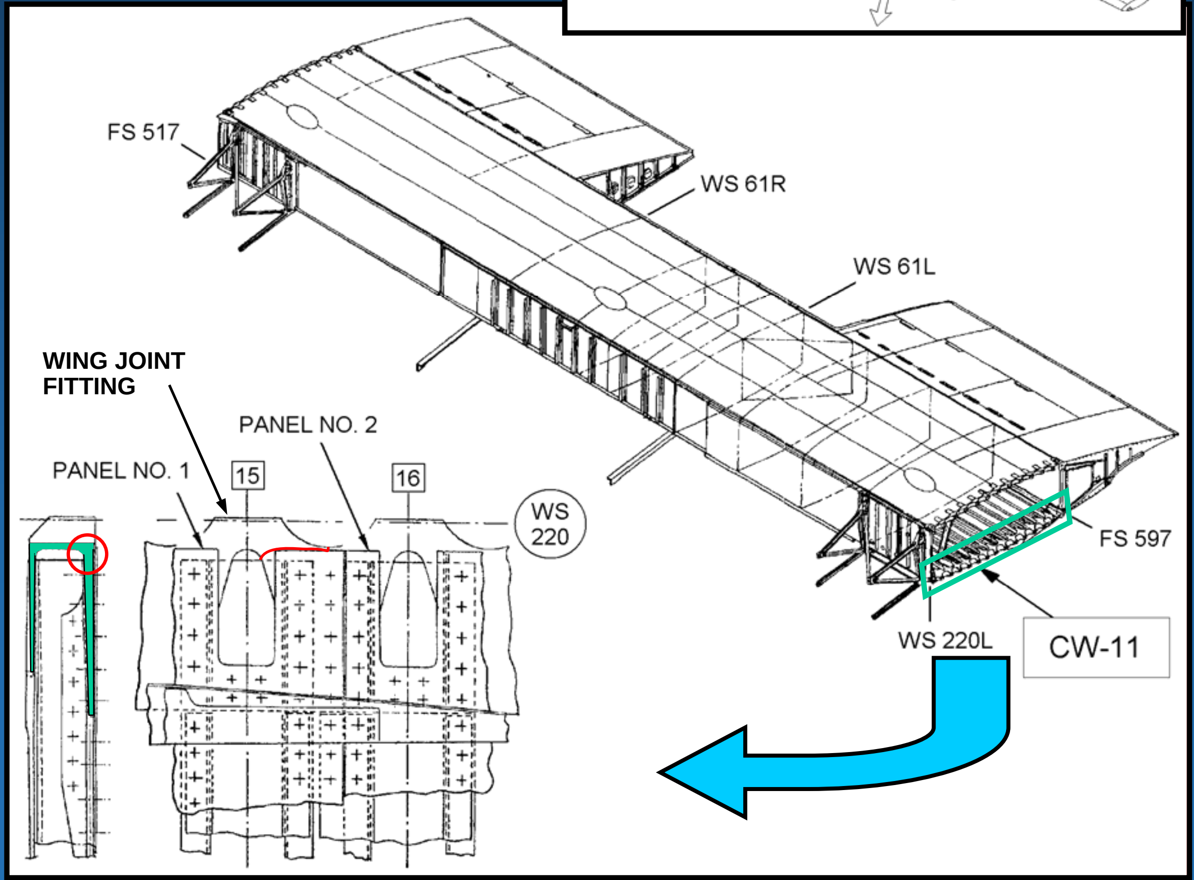


Analysis Locations – Zone 3

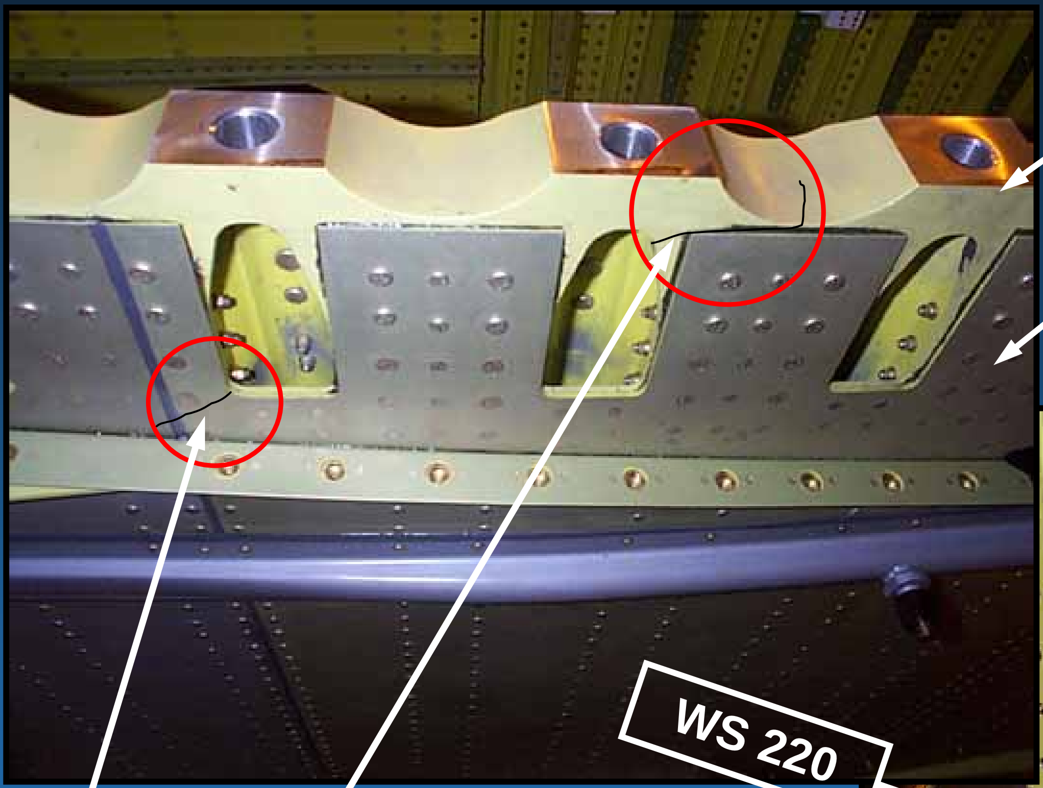
Zone 3 (WS 220):

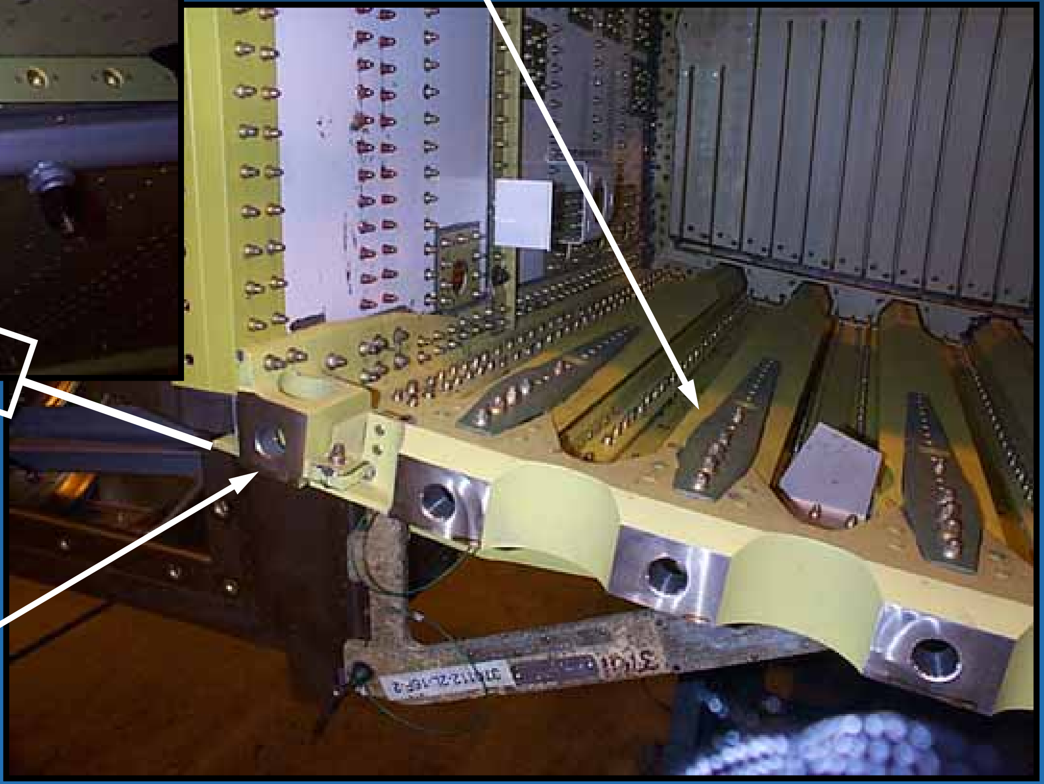
- Center Wing to Outer Wing Production Joint
- Wing Joint Fitting has 13 "Nodes":
  - *Prone to MSD Cracking*
  - *Short "critical" crack length (0.07 in.)*
- 35 A/C documented with in-service MSD/MED cracking:
  - *Multiple Node Cracks*
  - *Adjacent Panel Cracks*
- Three adjacent Node cracks reduce strength to below Design Limit





Analysis Locations – Zone 3





Wing Joint Fitting

Lower Surface Panel

Stringer

WS 220

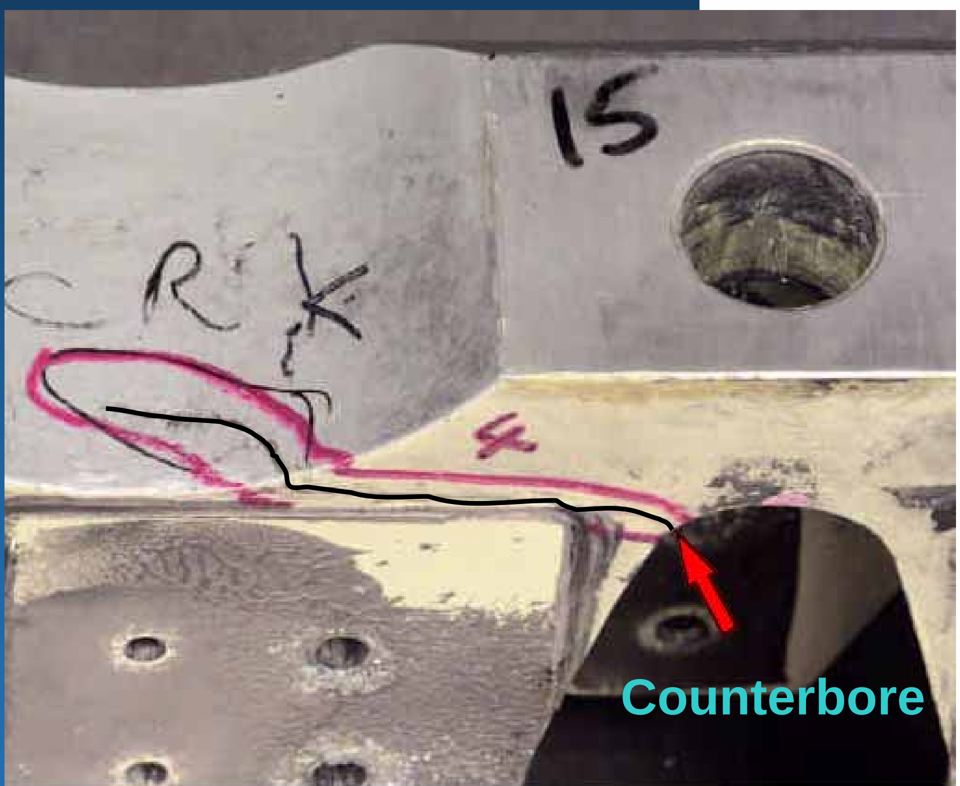
Typical
Panel Crack

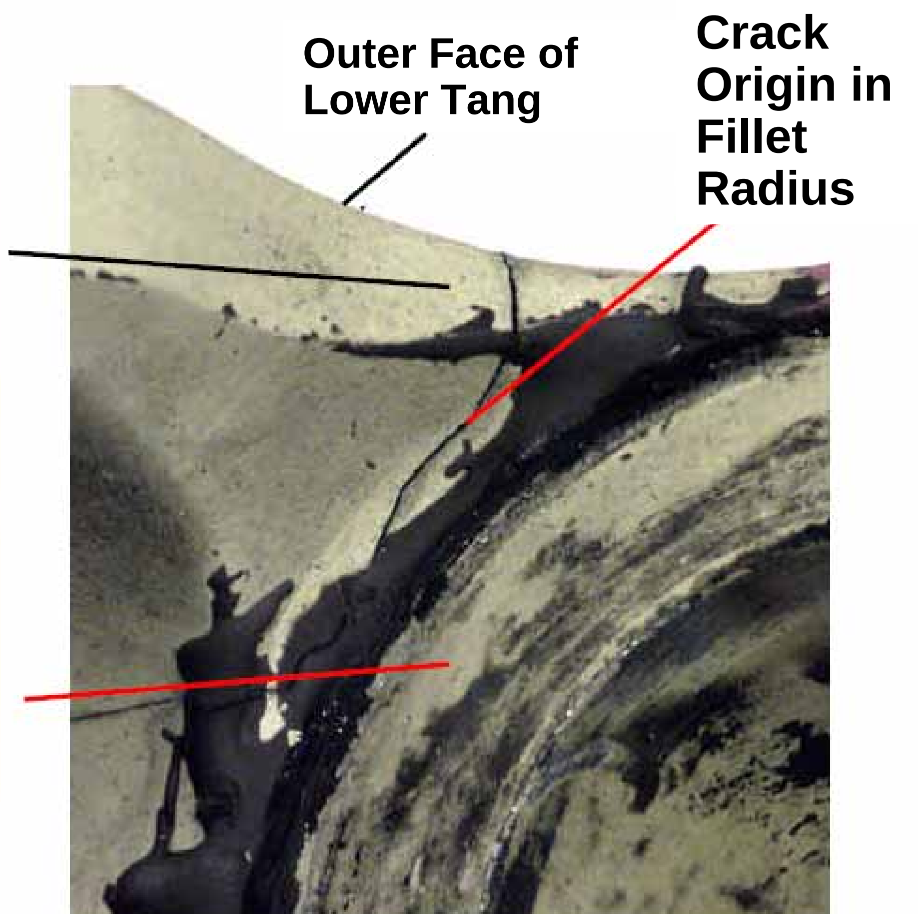
Typical
Fitting Crack

Forward Corner Fitting

Analysis Locations – Zone 3

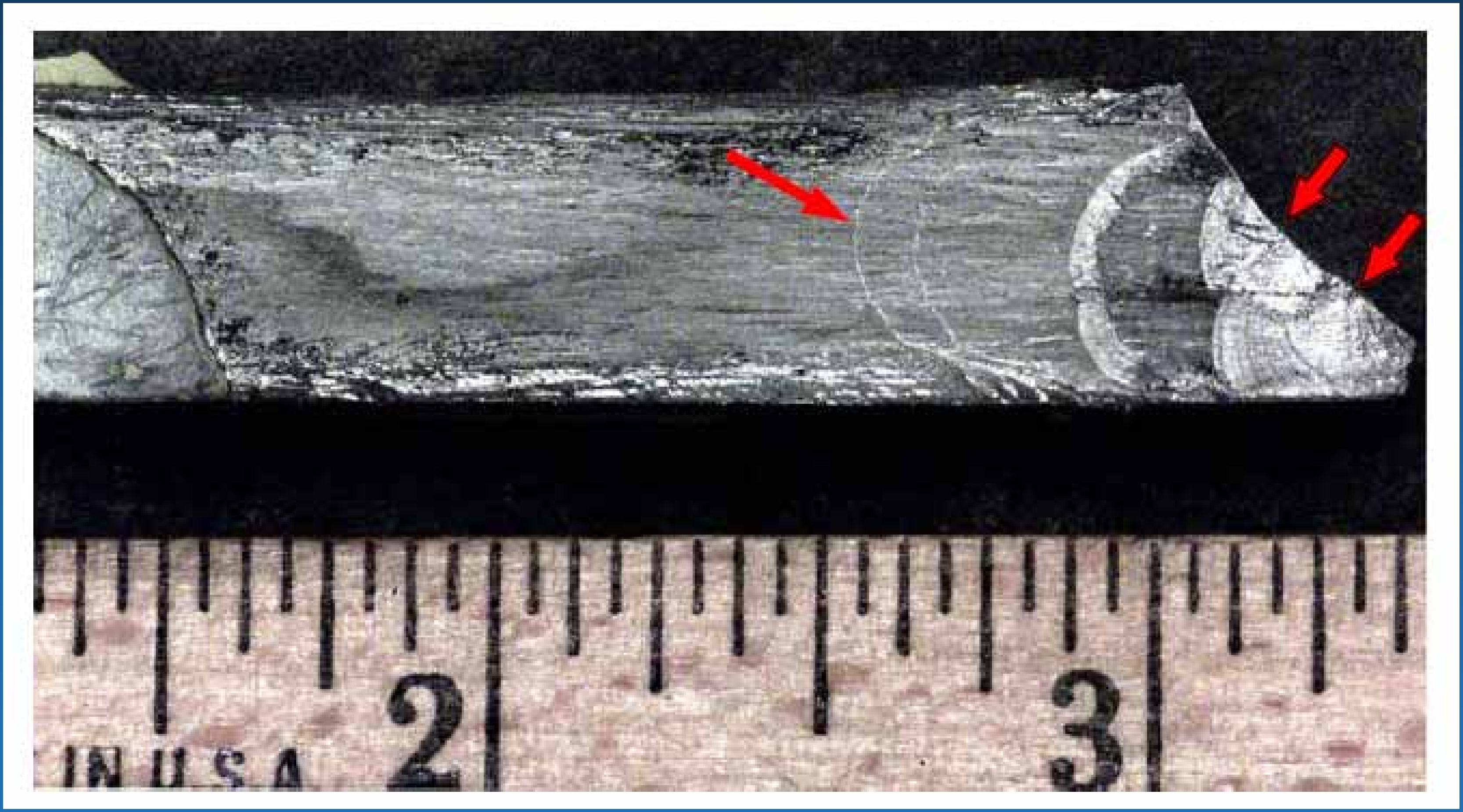
Crack Initiation at Node Bolt Hole Counterbore





Analysis Locations – Zone 3

Typical Node Crack Fracture Surface



MSD/MED Risk Analysis

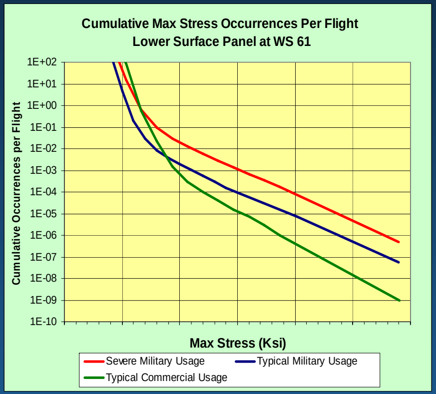
Zone 1 & 2 - Lower Surface Panels

MSD/MED Risk Analysis Zone 1 & 2

- **Test and In-Service Cracking has shown that Zones 1 and 2 experience both MSD and MED Cracking that affect Residual Strength:**
  - ***"Standard" Crack Growth Analysis with Continuing Damage does not adequately model the cracking behavior***
  - ***Single Flight Probability of Failure (SFPoF) is underestimated by the single dominant fatigue crack scenario***
  - ***Discrete Source Damage Risk Analysis (presented at 2005 ASIP Conference) showed that the Risk is unacceptable should a single skin panel fail due to undetected MSD cracking***

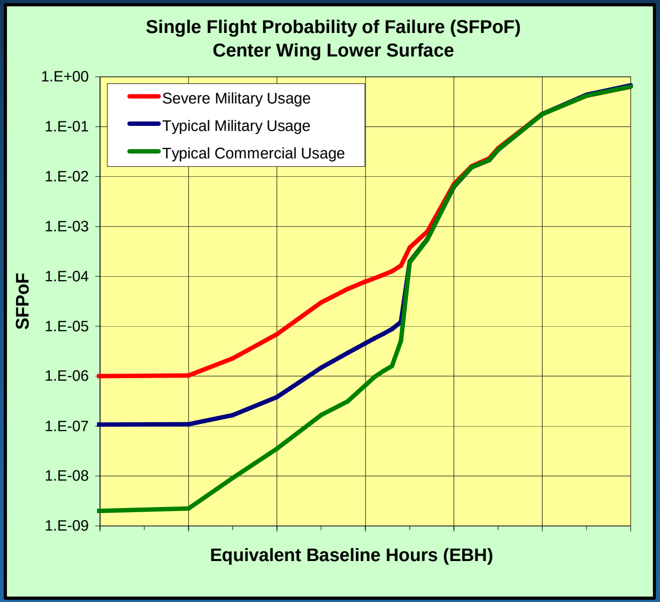
MSD/MED Risk Analysis
Zone 1 & 2

Stress Occurrences

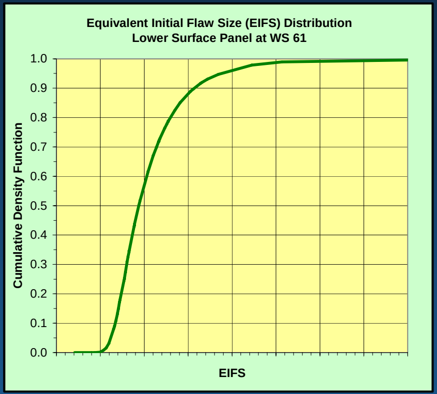


Single Flight

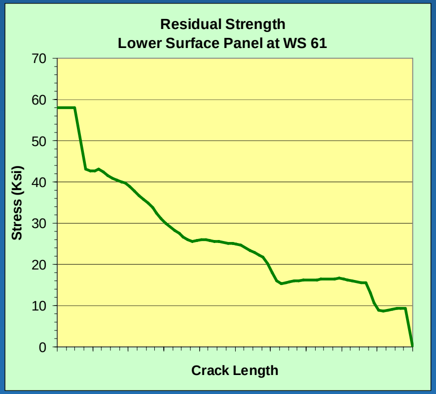
Probability of Failure



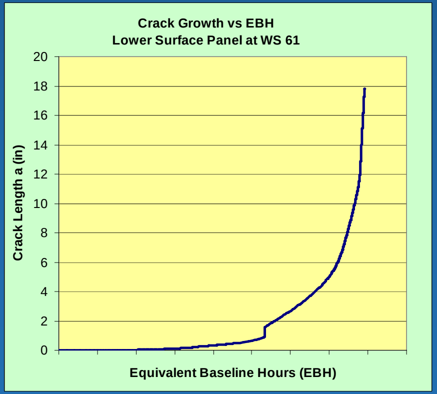
EIFS Distributions



Residual Strength



Crack Growth Rates



Single Dominant Crack Scenario

MSD/MED Risk Analysis Zone 1 & 2

- **LM Aero MSD Crack Growth Analysis Program:**
  - ***Runs from 0 EBH to EBH at MSD Crack "Link-up"***
  - ***Random application of EIFS at multiple locations***
  - ***Analytically grows MSD Cracks (Includes stress intensity interaction effects)***
  - ***Non-Destructive Inspections (NDI) Probabilistic Detection:***
    - "Reset" of discovered cracks to random EIFS following inspection and repair
  - ***Records the MSD maximum crack size at regular intervals of EBH***
  - ***Provides a probabilistic solution to determine time to MSD "link-up" via a Monte-Carlo Simulation***
    - Simulation is repeated 100,000 times to obtain statistical results
    - The probability distribution of MSD Crack Sizes as a function of EBH

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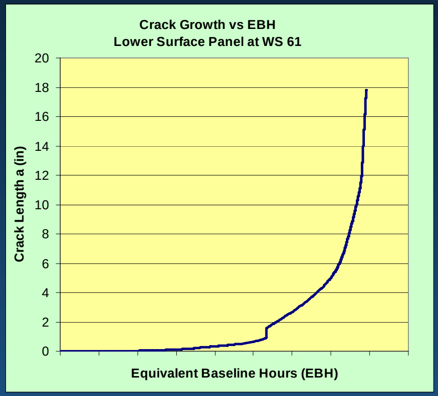
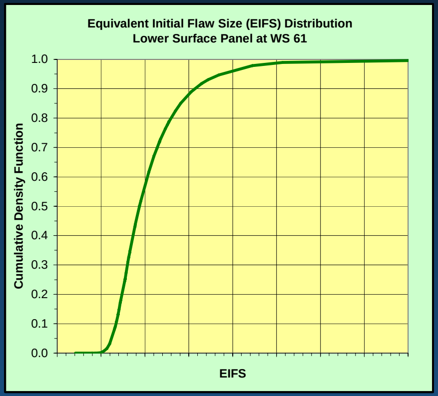
MSD/MED Risk Analysis
Zone 1 & 2

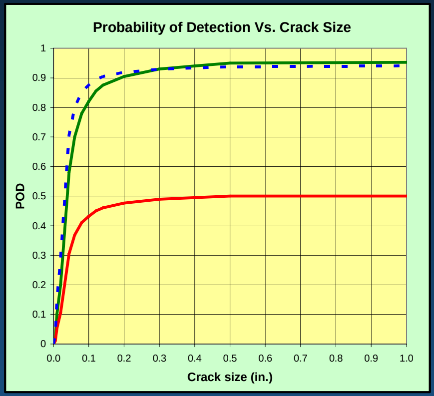
Crack Growth Rates



EIFS Distributions

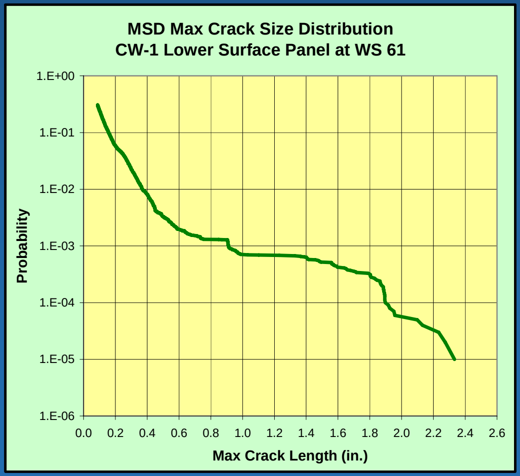


Probability of Detection

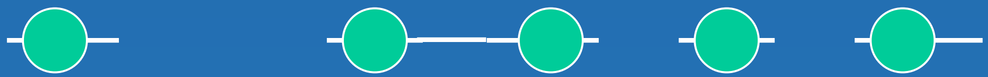


MSD Crack Growth Program

MSD Crack Probability



MSD Crack Scenario



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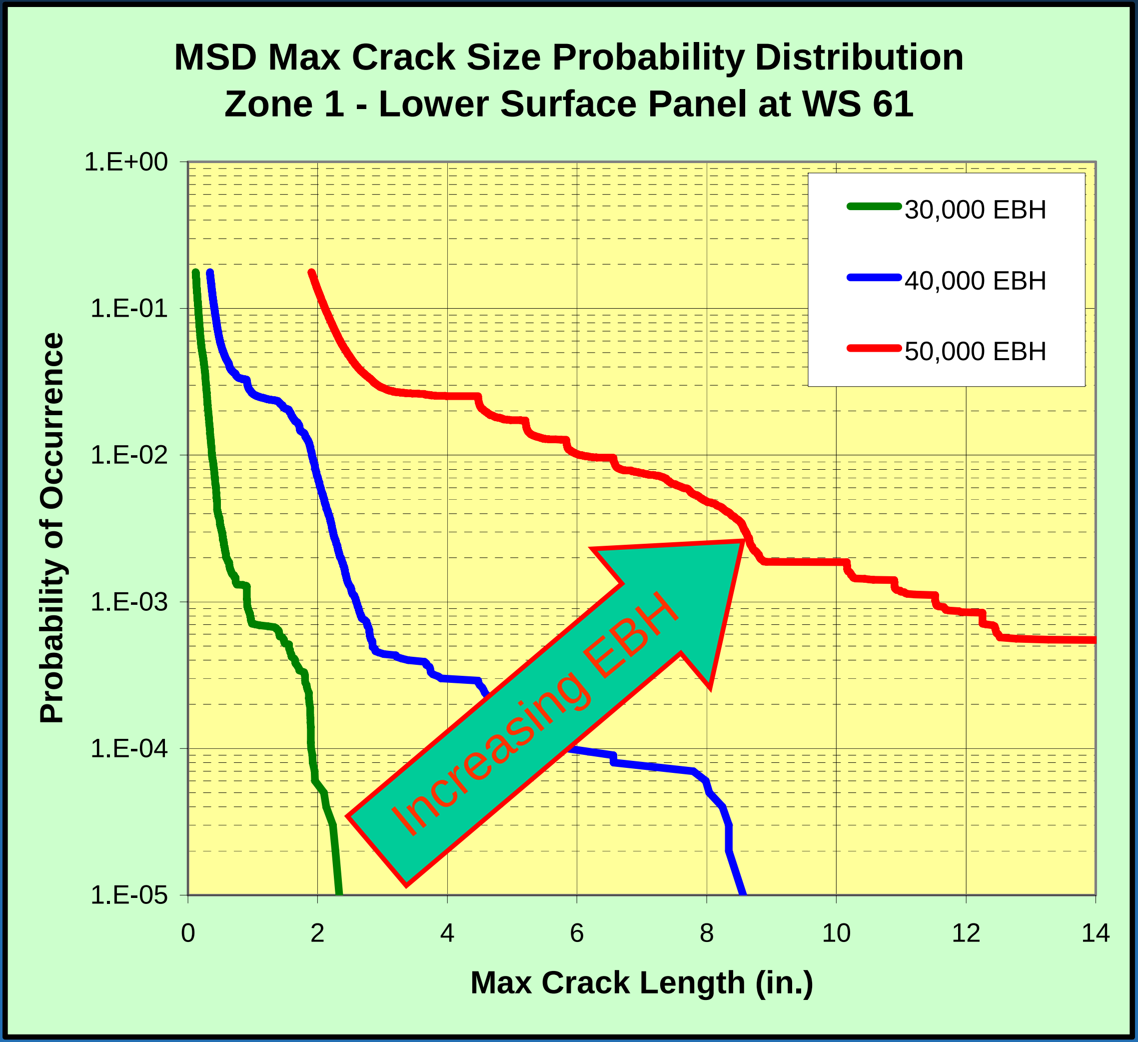
MSD/MED Risk Analysis
Zone 1 & 2



- **Results of MSD Crack Growth Analysis**
- **Determines the probability of a MSD Crack of a given size in increments of approx 350 EBH**
- **Probability Distributions determined for No Inspection and Including Inspection**

MSD/MED Risk Analysis Zone 1 & 2

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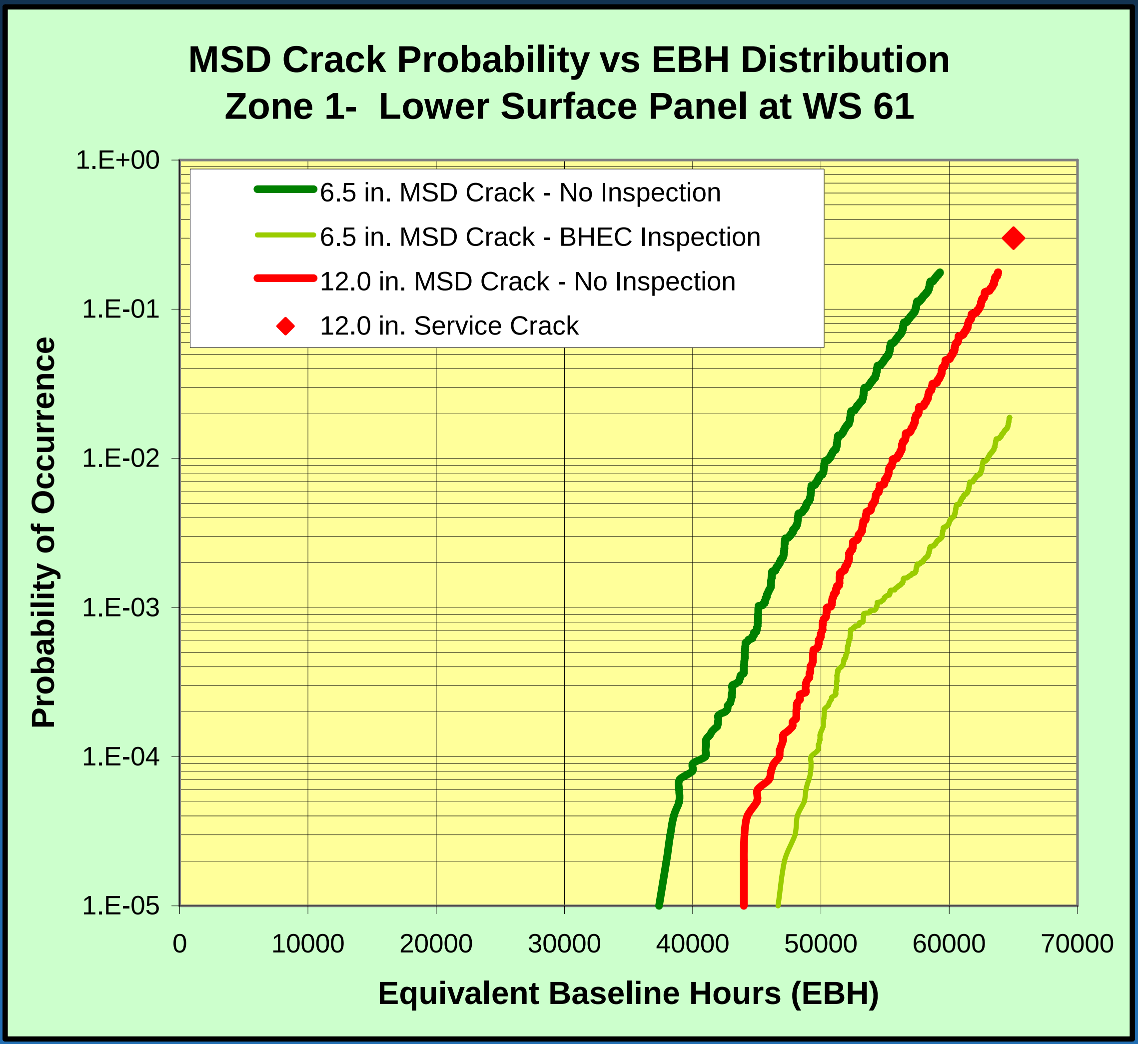


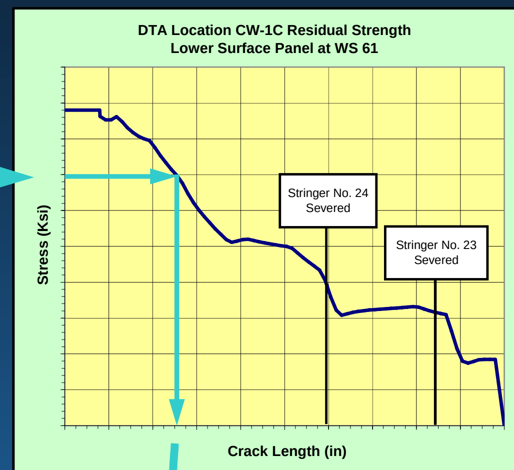
- Results of MSD Crack Growth Program
- Probabilities of a given crack size vs EBH
- Probability of MSD Link-up rises rapidly beyond 40,000 EBH without inspection

MSD/MED Risk Analysis
Zone 1 & 2

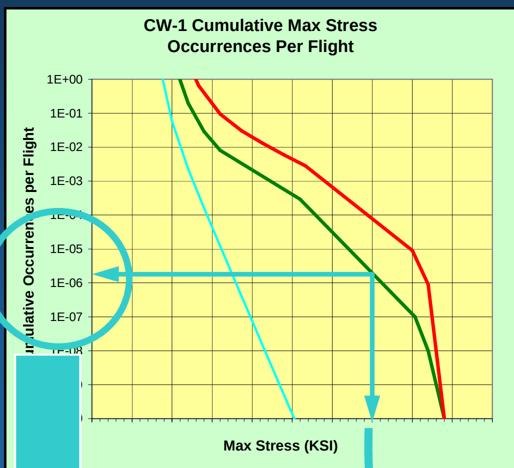
- **Single Flight Probability of Failure Risk Analysis Methodology:**
  - ***For each increment of EBH:***
    - Numerical Integration of Max Stress Probability of Exceedance Curve
    - Max Stress "Layer" value interpolated on Residual Strength Curve to determine Crack Length to cause Fracture (a_{CR})
    - Crack Length a_{CR} value interpolated on MSD Crack Probability Distribution at the given EBH
    - SFPoF is Numerical Product of Probability of Max Stress and Probability of MSD Crack Present
    - Repeat process for all "Layers" of Max stress to the once per flight stress level
  - ***Repeat process for all increments of EBH***

MSD/MED Risk Analysis Zone 1 & 2

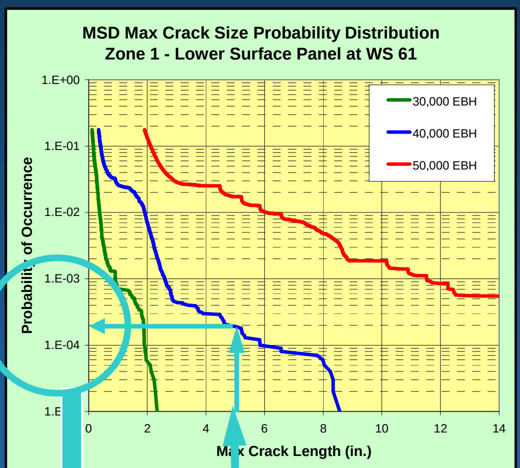
Residual Strength

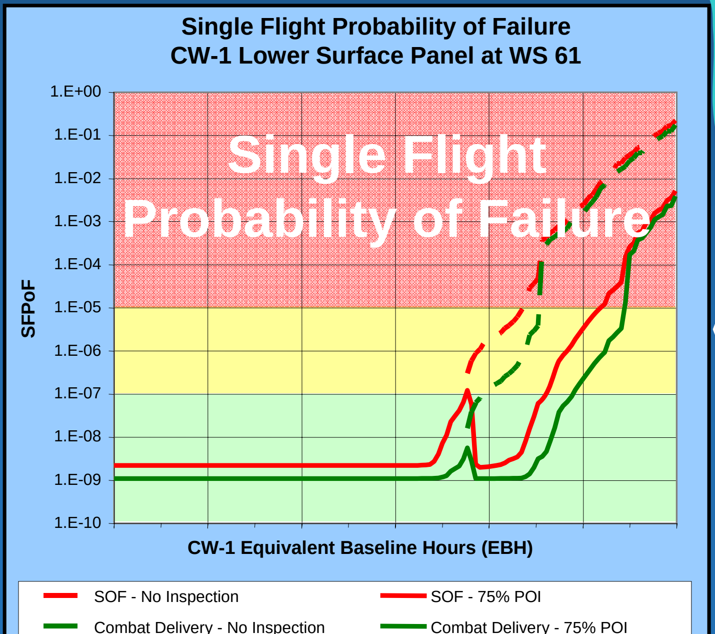


Stress Occurrence Probability



MSD Crack Probability





MSD/MED Risk Analysis
Zone 1 & 2

- **Conclusions of the Lower Surface Panel Risk Analysis:**
  - *MSD Cracking Scenario results in higher Risk probabilities than the single dominant fatigue crack*
  - *Mitigation by inspection is possible, but much uncertainly remains in the Probability of Detection (POD) and Probability of Inspection (POI) due to the large number of fastener holes requiring inspection*
  - *Previous discrete source damage analysis has shown that the Probability of Failure is unacceptable should a single panel fail at 35,000 EBH or higher*

Risk Mitigation Strategy Must Ensure A Panel Failure Does Not Occur

MSD/MED Risk Analysis

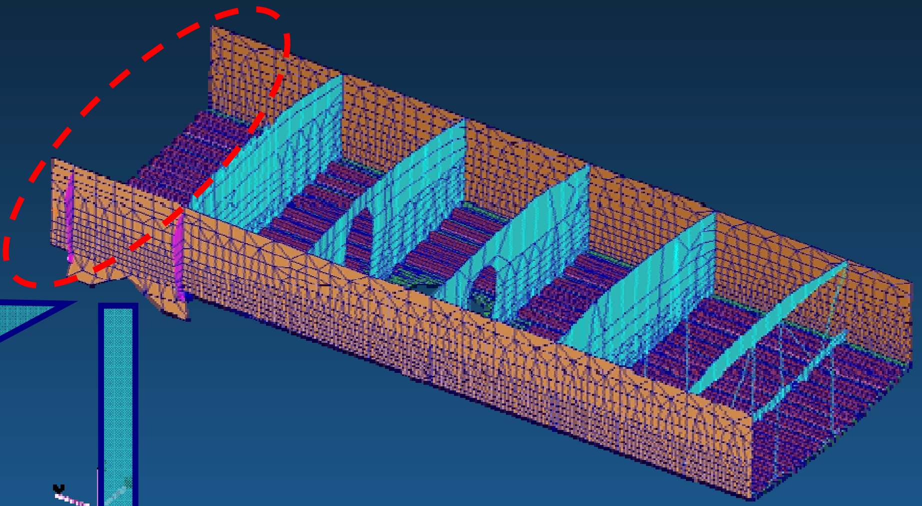
Zone 3 - Lower Wing Joint Fitting

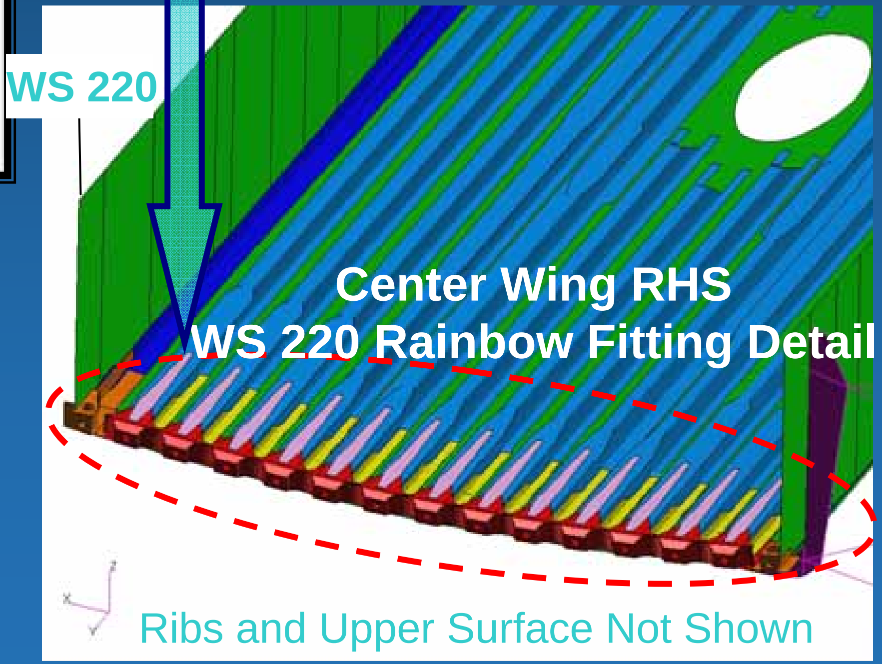
MSD/MED Risk Analysis
Zone 3

- **Test and Service Cracking Data Show that the Wing Joint Fitting Area Experiences MSD/MED Cracking:**
  - ***"Standard" Slow Crack Growth DTA Methodology cannot be applied to determine inspection intervals:***
    - Critical crack length is less than detectable ($a_{CR} < a_{NDI}$)
    - Once per flight max stress "critical" crack size approx 0.5 in.
  - ***Is a single part, with crack arrest features***
  - ***Fitting consists of 13 similar details at similar stress levels where cracking initiates***
  - ***Also, adjacent skin panel (MED) cracking at the fitting outer tang attachment***

How Do we Analyze This?

MSD/MED Risk Analysis
Zone 3





Wing Joint Area FEM

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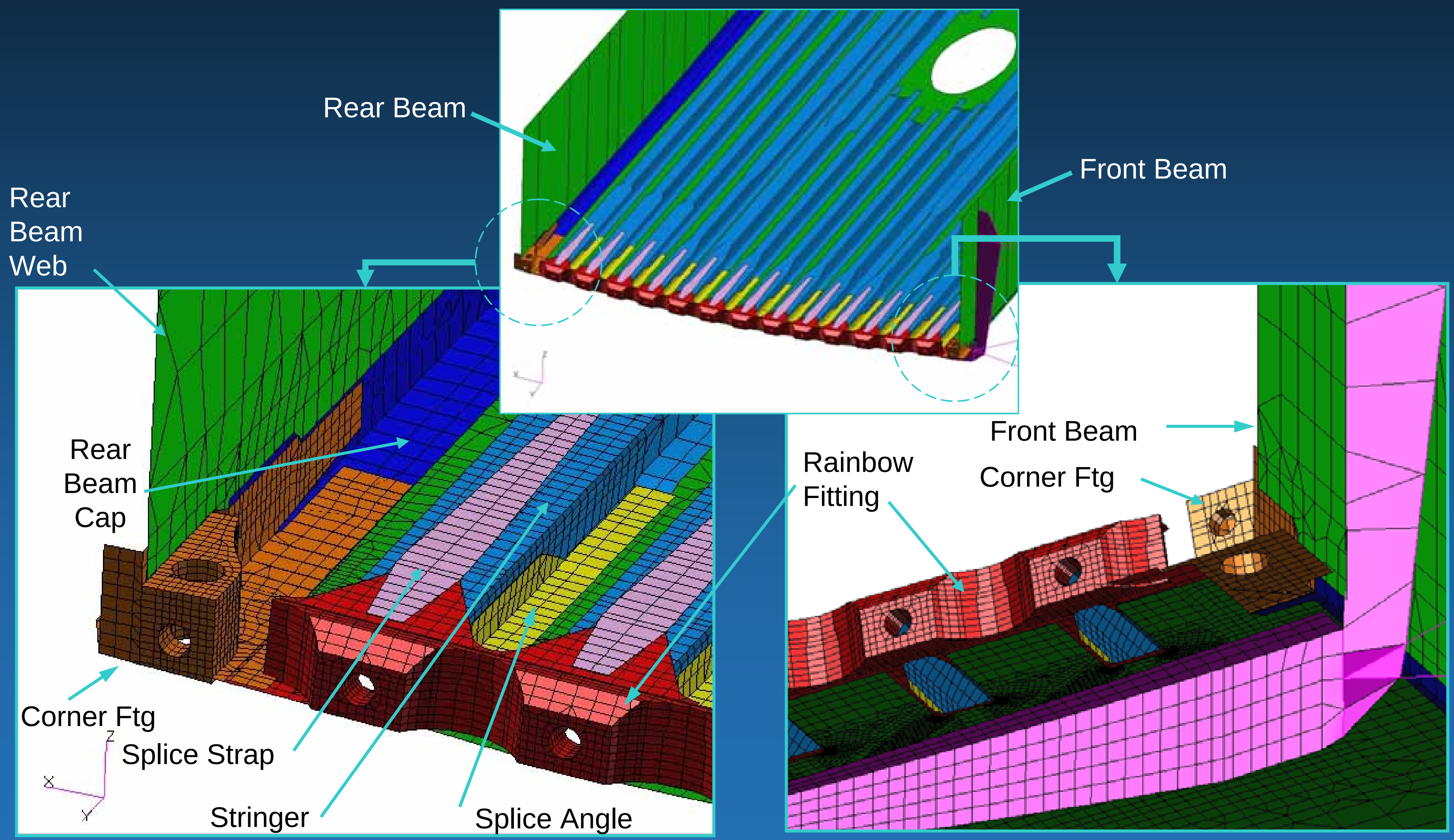
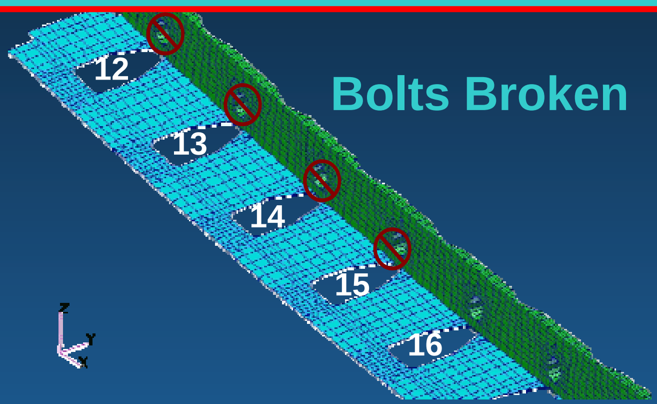
MSD/MED Risk Analysis
Zone 3

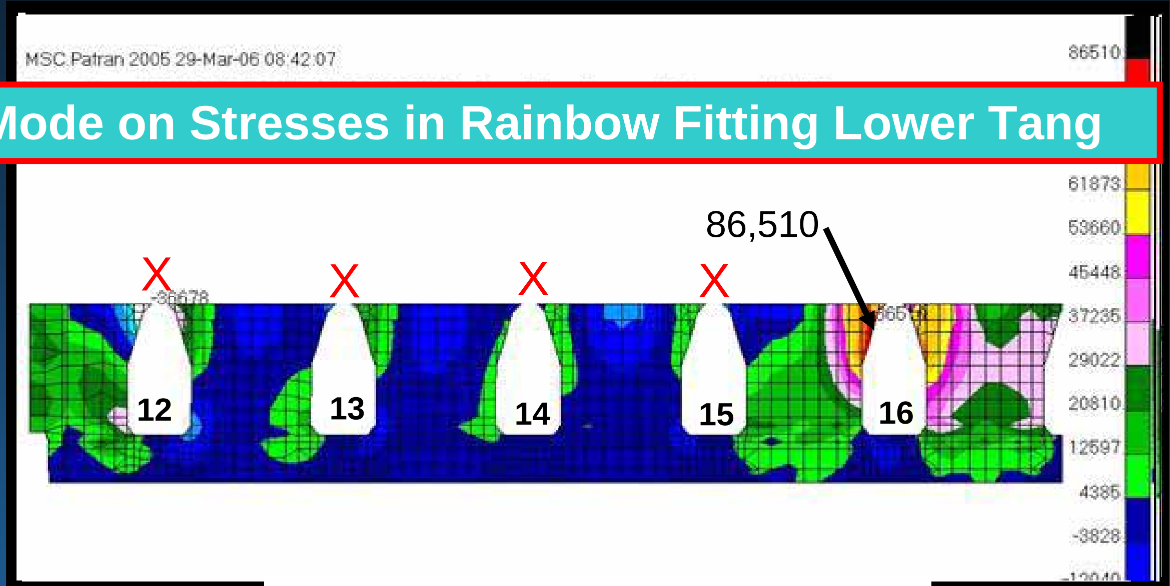


Ribs and Upper Surface Not Shown

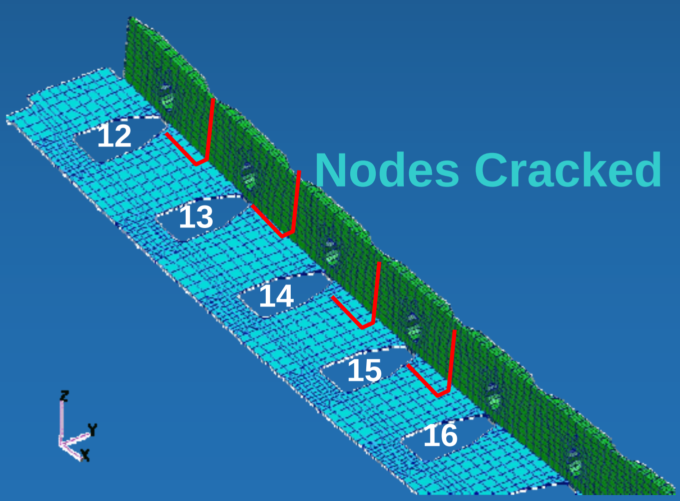
MSD/MED Risk Analysis
Zone 3

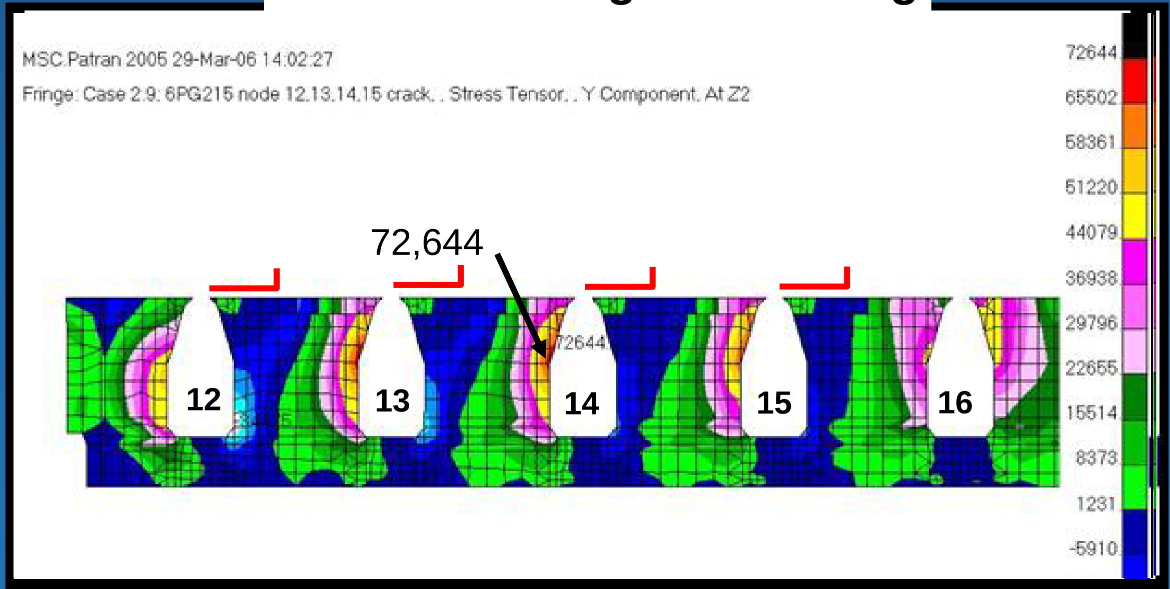
Comparison of Fitting Failure Mode on Stresses in Rainbow Fitting Lower Tang





Rainbow Fitting Lower Tang





MSD/MED Risk Analysis Zone 3

- **Conclusions of Finite Element Model Analysis:**
  - ***"Critical" Crack Length in Node is short (0.07 in.)***
  - ***Crack arrests up vertical face between nodes at 2.5 in.***
  - ***No effect on Bolt Load Distributions until the fatigue crack fractures across the Node (i.e. is 2.5 in. in length)***
  - ***At Design Limit Load, Structure can tolerate:***
    - up to 2 adjacent Nodes fractured
    - up to 5 Nodes fractured, as long as none are adjacent

Presence of adjacent Skin cracks do not affect Wing Joint Fitting Residual Strength

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MSD/MED Risk Analysis Zone 3

- **Wing Joint Fitting MSD Crack Growth Program:**
  - ***Runs from 0 EBH to "T" EBH when all Nodes have Fractured***
  - ***Random application of EIFS at each Node location***
  - ***Analytically grows MSD Cracks (interaction when node fractures)***
  - ***Non-Destructive Inspections (NDI) Probabilistic Detection:***
    - Only fractured nodes can be detected (i.e. 2.5 in. crack)
    - Fitting is "replaced" when one or more node fracture is detected
  - ***Records the Number of Fractured Nodes (adjacent and not-adjacent) at each increment of EBH***
  - ***Provides a probabilistic solution to determine time to "n" fractured Nodes via a Monte-Carlo Simulation***
    - Simulation is repeated 5,000 times to obtain statistical results

The Probability Distribution of "n" number of fractured Nodes as a function of EBH

MSD/MED Risk Analysis
Zone 3

- **Single Flight Probability of Failure (SFPoF) MSD Risk Analysis Methodology:**
  - ***Similar to the Wing Panel MSD Risk Analysis***
  - ***For each increment of EBH:***
    - Numerical Integration of Max Stress Probability of Exceedance Curve
    - Max Stress “Layer” value interpolated on Residual Strength Curve to determine “n” Number of Fractured (Adjacent and Non-Adjacent) Nodes
    - Number of Fractured Nodes interpolated on MSD Cracking Probability Distribution at the given EBH
    - SFPoF is Numerical Product of Probability of Max Stress and Probability of “n” Number of Fractured Nodes
    - Repeat process for all “Layers” of Max stress to the once per flight stress level
  - ***Repeat process for all increments of EBH***

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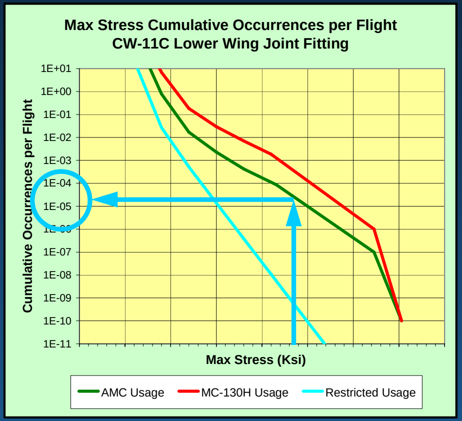
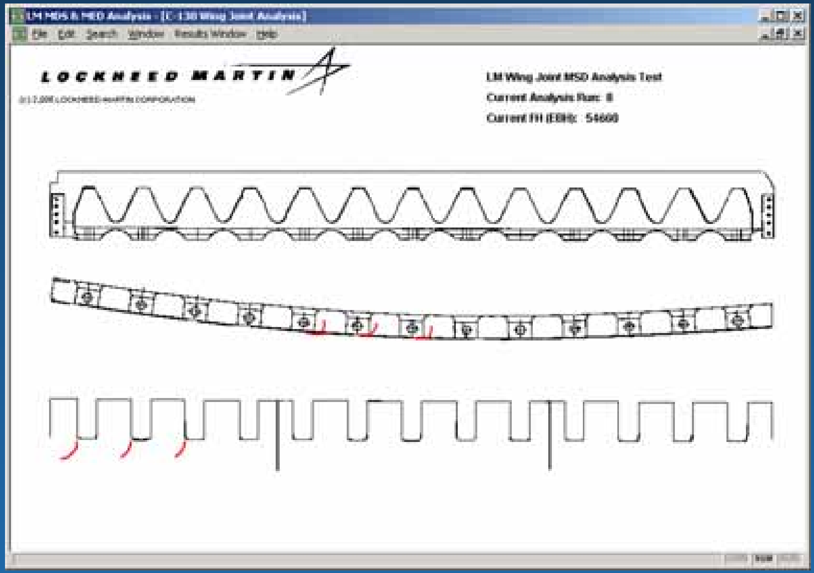
MSD/MED Risk Analysis
Zone 3

Stress Occurrences

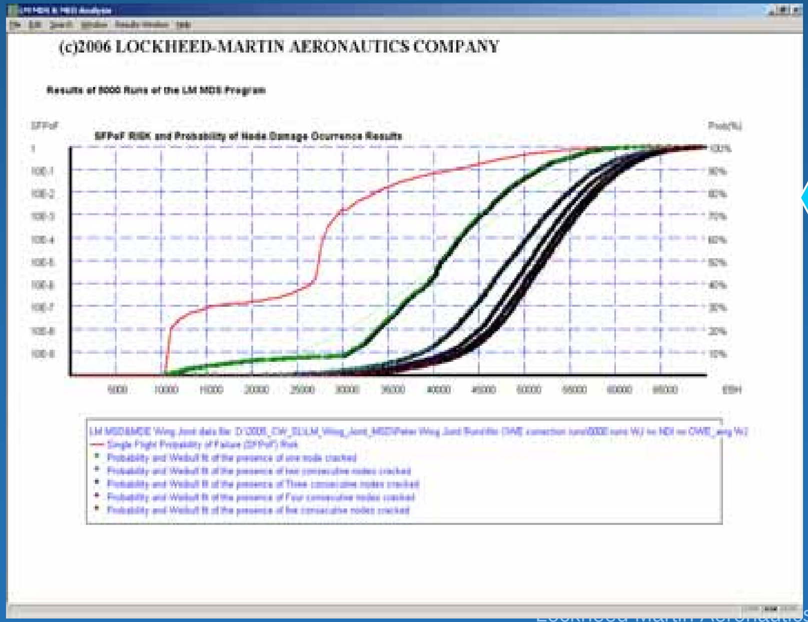


Residual Strength

MSD Crack Growth Analysis



MSD Risk Analysis



Probability of "n" nodes fractured as a function of EBH

MSD/MED Risk Analysis
Zone 3

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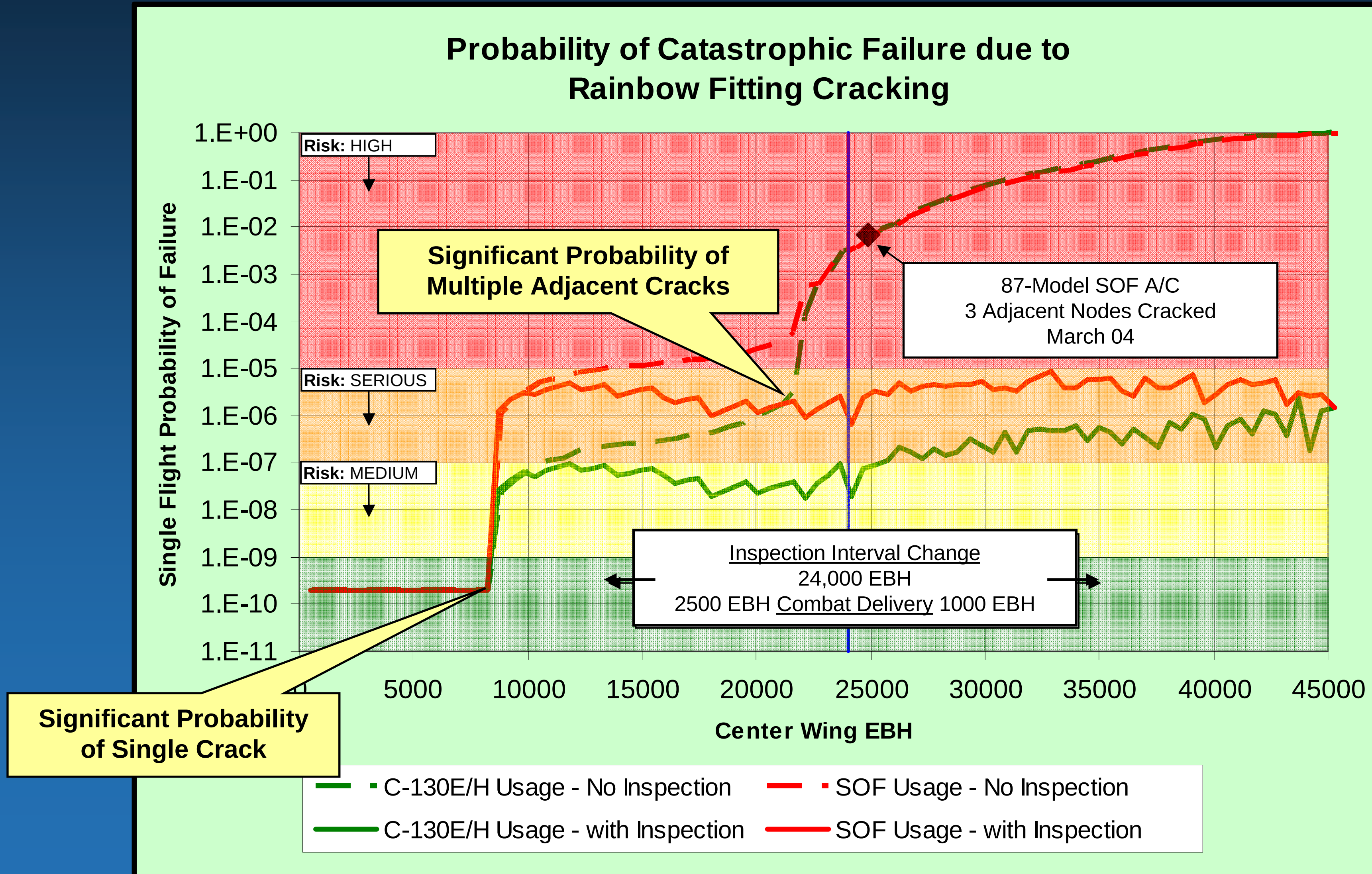

MSD/MED Risk Analysis
Zone 3

- **Conclusions of Wing Joint Fitting Risk Analysis:**
  - ***Substantial increase in SFPoF when one node fractures***
  - ***Risk is Unacceptable if two adjacent nodes fracture***
  - ***Risk can be Mitigated by continued Inspection, but replacement before 25,000 EBH is the preferred option:***
    - Short Inspection Interval Required beyond 24,000 EBH raises concern for NDI complacency
    - 20% Probability of at least one node fractured at 24,000 EBH

Risk Mitigation Strategy Must Include Inspection and Replacement

Structural Integrity Risk Management Strategies

Structural Integrity Risk Management Strategies

- Numerous Risk Mitigation Strategies have been employed by the USAF C-130 ASIP Manager:
  - *Operational Flight Restrictions Imposed on USAF aircraft at 38,000 EBH to reduce maximum wing up-bending load to below 60% of Design Limit*
  - *TCTOs released to inspect for fatigue cracking in wing joint fitting*
  - *Wing Joint Fitting Replacements at PDM*
  - *TCTO released to inspect for generalized cracking of Lower Surface of Center Wings with > 38,000 EBH*
  - *Established Service Life Limit of 45,000 EBH - grounding of high time C-130 aircraft*

- Additional Actions Underway:
  - *Teardown Inspections*
  - *Redesign of Wing Joint Fittings*

Structural Integrity Risk Management Strategies

- **For non-USAF operators, LM Aero has released two major Service Bulletins:**
  - ***82-788/382-57-84 Operational Usage Evaluation and Service Life Assessment***
  - ***82-790/382-57-85 Lower Surface Generalized Cracking and Widespread Fatigue Damage Inspection Requirements***

- **LM Aero is assessing the need to recommend an Operating Limit for the Center Wing:**
  - ***FAA Notice of Proposed Rulemaking (NPRM) issued in April 2006 to establish Operating Limits to prevent Widespread Fatigue Damage***
    - LM Aero has commented on this NPRM and concurs with the need for Operating Limits

Conclusions and Lessons Learned

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- USAF C-130E/H Center Wings have experienced significant fatigue cracking characterized by MSD and MED
- Advanced analytical techniques are required to evaluate the crack propagation rates and residual strength of structure with MSD/MED cracking
- Uncertainty in NDI capability (POD and POI) is significantly reducing the risk mitigation benefit of continued inspection:
  - *Resulted in 2 USAF C-130E Outer Wing Failures in the 1980's prior to Outer Wing Replacement*

INSPECTIONS CANNOT PROTECT SAFETY AFTER ON-SET OF WFD