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
**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**
• **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
Center Wing Section View (Typical)

- Front Beam
- Stringer
- Rear Beam
- Center Wing Reference Plane
- 4 Skin Panels
- 3 Skin Panels
- Panel No. 1
- Panel No. 2
- Panel No. 3

Legend:
- FS 517.0
- FS 596.68
- Up
- Aft
C-130 Center Wing
MSD/MED Risk Analysis

Analysis Locations
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

- Lower Surface Aft Panel
- Stringer No. 24
- WS 61 Rib
- Wing Attach Angle
- Rear Beam Lower Cap
**C-130**

**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  Panel No. 1

WS 58  MSD Link-up

WS 61

Wing Attach Angle Removed

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

Stringer 16

Stringer 17

Stringer Cracks 2.7 in.

Panel Crack 10.9 in. at Link-up

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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

- Nacelle Attach Fitting
- Drain Trough
- Lower Surface Fwd Panel
- Front Beam Lower Cap
- Stringer No. 12
- WS 178 Rib

OUTBD

WS 178
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
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Analysis Locations – Zone 3

Wing Joint Fitting
Lower Surface Panel
Stringer

Typical Panel Crack
Typical Fitting Crack
Forward Corner Fitting

WS 220
Crack Initiation at Node Bolt Hole Counterbore

Analysis Locations – Zone 3

Outer Face of Lower Tang
Crack Origin in Fillet Radius

Counterbore

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Analysis Locations – Zone 3

Typical Node Crack Fracture Surface
C-130 Center Wing
MSD/MED Risk Analysis

MSD/MED Risk Analysis
Zone 1 & 2 - Lower Surface Panels
• 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
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MSD/MED Risk Analysis
Zone 1 & 2

Stress Occurrences

Single Flight
Probability of Failure

Cumulative Max Stress Occurrences Per Flight
Lower Surface Panel at WS 61

SFPoF

Equivalent Initial Flaw Size (EIFS) Distribution
Lower Surface Panel at WS 61

Residual Strength

Crack Growth Rates

Single Dominant Crack Scenario
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
**C-130**

**MSD/MED Risk Analysis**

**Zone 1 & 2**

### Crack Growth Rates

Crack Growth vs EBH
Lower Surface Panel at WS 61

### EIFS Distributions

Equivalent Initial Flaw Size (EIFS) Distribution
Lower Surface Panel at WS 61

### Probability of Detection

Probability of Detection Vs. Crack Size

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**MSD Crack Growth Program**

**MSD Crack Probability**

**MSD Crack Scenario**

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**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**
- 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
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**

### Stress Occurrence Probability

**CW-1 Cumulative Max Stress Occurrences Per Flight**

- **Max Stress (KSI)**
  - **1E-10**
  - **1E-09**
  - **1E-08**
  - **1E-07**
  - **1E-06**
  - **1E-05**
  - **1E-04**
  - **1E-03**
  - **1E-02**
  - **1E-01**
  - **1E+00**

### MSD Crack Probability

**MSD Max Crack Size Probability Distribution**

- **Zone 1 - Lower Surface Panel at WS 61**
  - **Max Crack Length (in.)**
    - **1E-05**
    - **1E-04**
    - **1E-03**
    - **1E-02**
    - **1E-01**
    - **1E+00**

### Residual Strength

**DTA Location CW-1C Residual Strength**

- **Lower Surface Panel at WS 61**

### Single Flight Probability of Failure

**CW-1 Lower Surface Panel at WS 61**

- **CW-1 Equivalent Baseline Hours (EBH)**
  - **1E+00**
  - **1E+01**
  - **1E+02**
  - **1E+03**
  - **1E+04**
  - **1E+05**
  - **1E+06**
  - **1E+07**
  - **1E+08**
  - **1E+09**
  - **1E+10**

- **SFPof**
  - **SOF - No Inspection**
  - **SOF - 75% POI**
  - **Combat Delivery - No Inspection**
  - **Combat Delivery - 75% POI**

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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 uncertainty 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**
C-130 Center Wing
MSD/MED Risk Analysis

MSD/MED Risk Analysis
Zone 3 - Lower Wing Joint Fitting
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?
C-130

MSD/MED Risk Analysis
Zone 3

RHS Center Wing Residual Strength FEM (in red)

LM Aero C-130 Baseline Airframe FEM

Wing Joint Area FEM

Center Wing RHS
WS 220 Rainbow Fitting Detail

Ribs and Upper Surface Not Shown
Ribs and Upper Surface Not Shown

Rear Beam
Front Beam
Rear Beam Web
Rear Beam Cap
Corner Ftg
Splice Strap
Stringer
Splice Angle
Rainbow Fitting
Corner Ftg
Comparison of Fitting Failure Mode on Stresses in Rainbow Fitting Lower Tang

Bolts Broken

Nodes Cracked
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
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

The Probability Distribution of “n” number of fractured Nodes as a function of EBH
**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*
MSD Crack Growth Analysis

MSD/MED Risk Analysis
Zone 3

Probability of “n” nodes fractured as a function of EBH

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**Probability of Catastrophic Failure due to Rainbow Fitting Cracking**

![Graph showing probability of failure over center wing EBH with risk levels and inspection intervals.]

- **Significant Probability of Single Crack**
- **Significant Probability of Multiple Adjacent Cracks**
- **87-Model SOF A/C 3 Adjacent Nodes Cracked March 04**
- **Inspection Interval Change**
  - 24,000 EBH
  - 2500 EBH Combat Delivery
  - 1000 EBH

**Risk Levels:**
- High
- Medium
- Serious

**Legend:**
- C-130E/H Usage - No Inspection
- SOF Usage - No Inspection
- C-130E/H Usage - with Inspection
- SOF Usage - with Inspection
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

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Risk Mitigation Strategy Must Include Inspection and Replacement
C-130 Center Wing
MSD/MED Risk Analysis

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
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
• 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