Residual Strength of Bonded Repairs After 10 Years of Service

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Aircraft Structural Integrity Program Conference

U.S. AIR FORCE

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- **Industry Partner** LOCKHEED MARTIN
  - **Surendra Shah, J.T. Huang, & Lew Zion**

- **… and many others** (you know who you are)

Overview

- Background on bonded repairs
- Repairs to C-141 wing planks
  - "Weephole" repairs
- USAF policy & issues
- Bonded Repair Evaluation Program
  - Mechanical testing
  - Results
- Concluding remarks

Advantages Offered by Bonded Repairs

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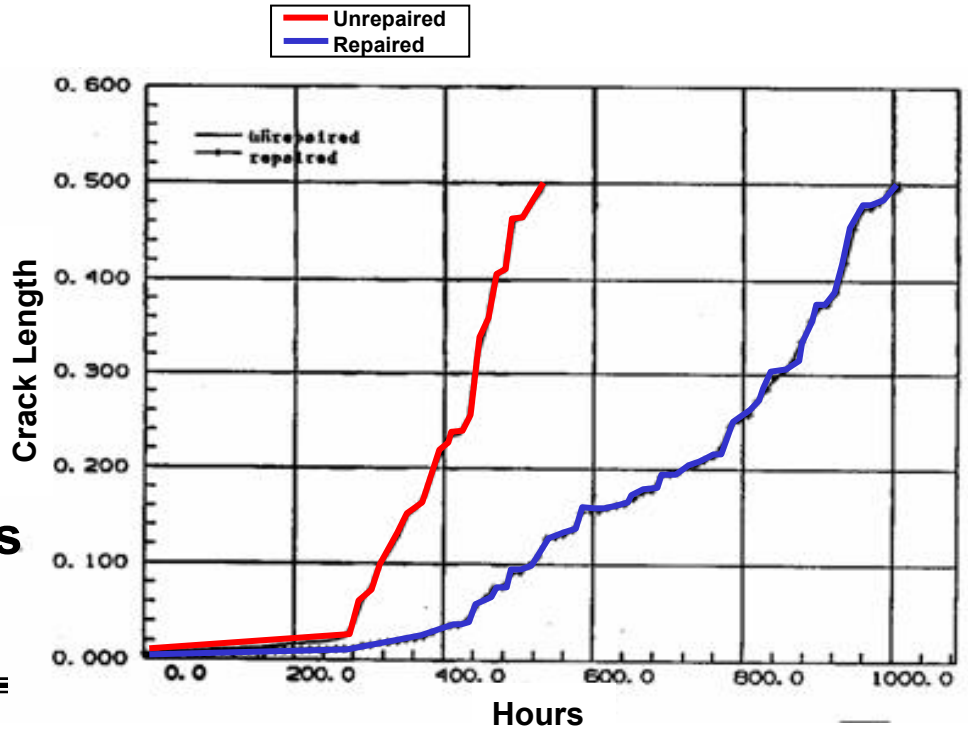
- **Tailorability**
  - Strength
  - Stiffness
  - "Directionality"
- **Ease of application**
  - With correct equipment
- **Crack "Slowing" Capability**
- **Lack of additional stress raisers**
  - i.e. no additional holes



- **Disadvantages**
  - Material
  - Initial Cost
  - Training & tech orders
  - Experience & confidence in durability

USAF Experience in Bonded Repairs

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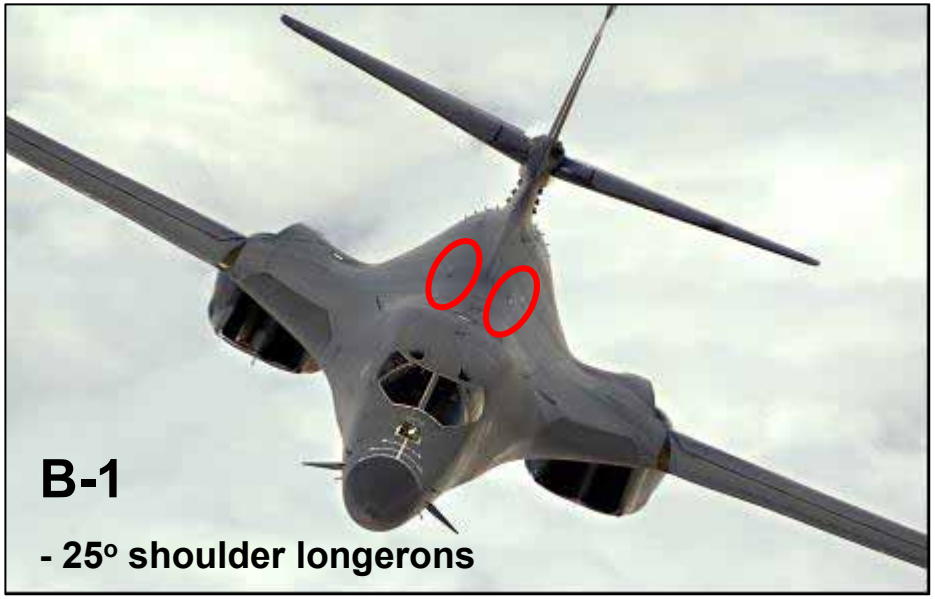

USAF C-141 Bonded Repairs

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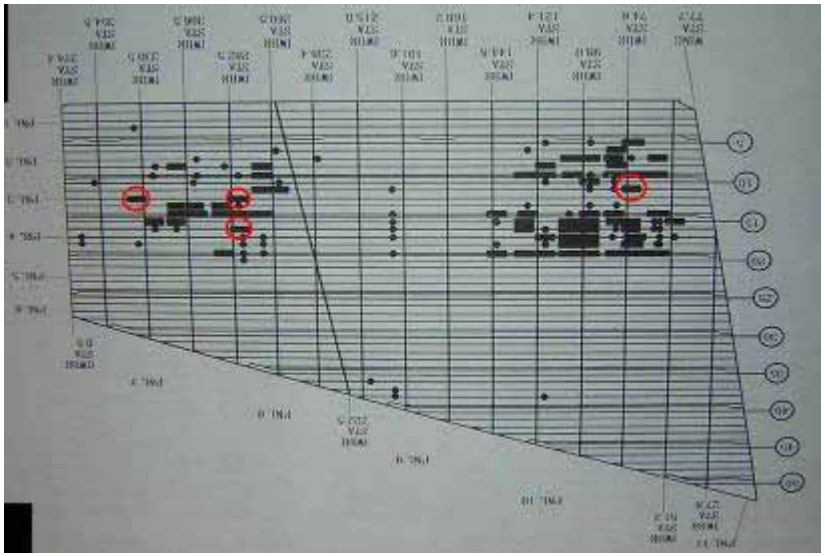
- **1991- , post - Gulf War I**
- **Weephole cracking**
  - Lower wing skins



- **120 aircraft repaired**
  - Usually 3 patches per repair
  - ~ 770 bonded repairs installed
  - ~ 2300 bonded patches

USAF C-141 Bonded Repairs

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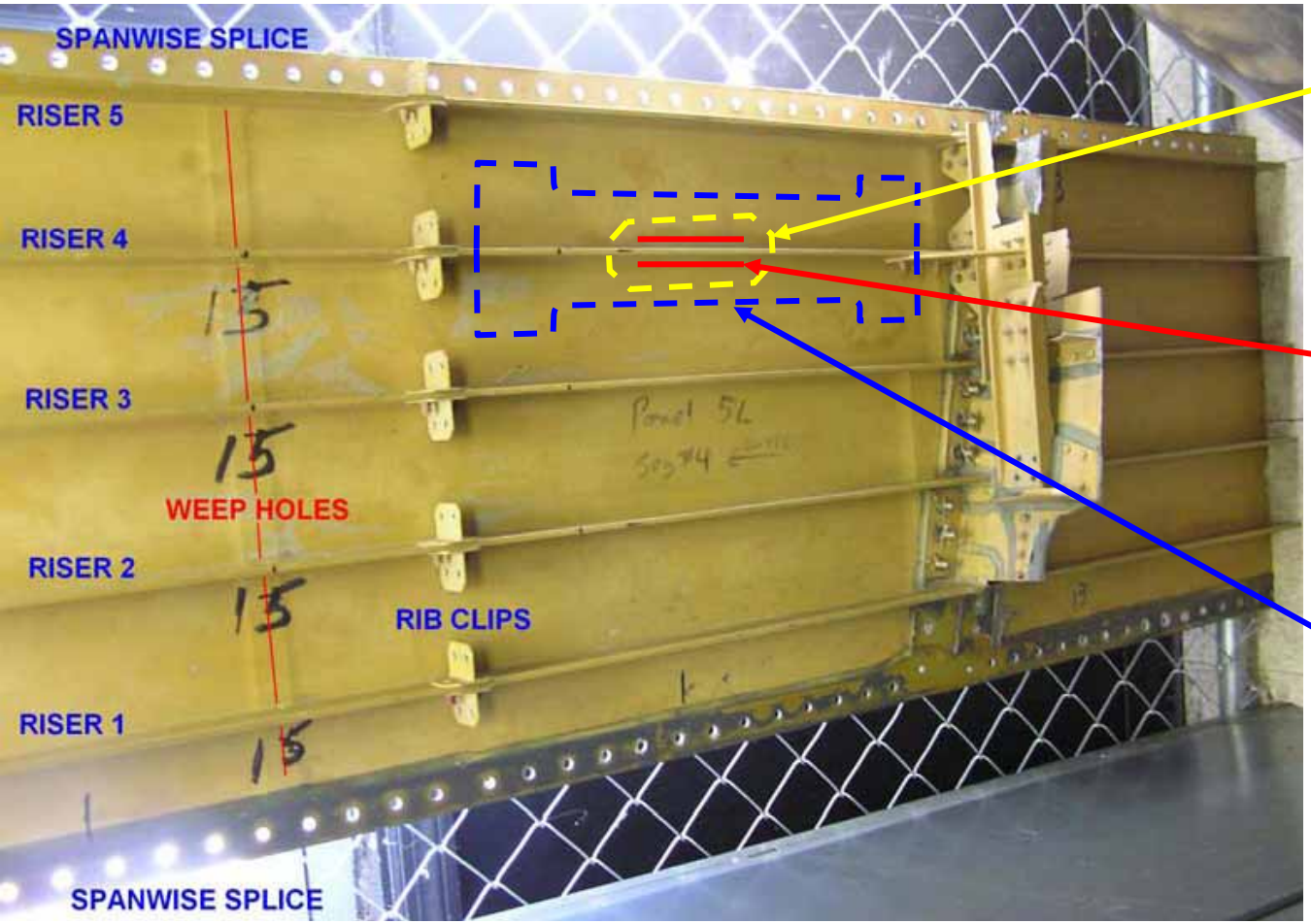

1 outer moldline (OML) patch

2 riser patches (installed inside wing)

Test Specimen

- **C-141 Wing Plank**
  - View from the inside looking out
  - ~ 20 feet long and ~4.5 feet wide

Repair Materials & Processes

- **Boron-epoxy repair patches**
  - Textron/Specialty Materials 5521
  - pre-cured & inspected
- **Standard installation procedures were used on all tested specimens**
  - Grit-blast silane surface prep
  - Pre-cured BR127 epoxy primer
  - 250°F curing epoxy film adhesive
  - Controlled heater blankets & vacuum bagging

These M&P will serve as the baseline for all future USAF bonded repairs

USAF Policy on Bonded Repairs

Bonded repairs to safety-of-flight (S-o-F) structure are permitted if:

1. **Unrepaired structure can withstand design limit**

2. **Repaired structure will be inspected using a schedule based upon the unrepaired structure**

Unresolved Issues for the USAF

Confidence in bond line integrity and durability

Ability to repair complex geometries

Standardized, user-friendly design & analysis tools

Part of the "solution":

A USAF-sponsored program to assess the residual strength of bonded repairs that experienced over a decade of operational service

Bonded Repair Evaluation Program

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General Approach

- **Harvest C-141 wing plank repairs from Davis-Monthan AFB, AZ (AMARC)**
- **Perform residual strength testing**
- **Revisit USAF policy using test results**

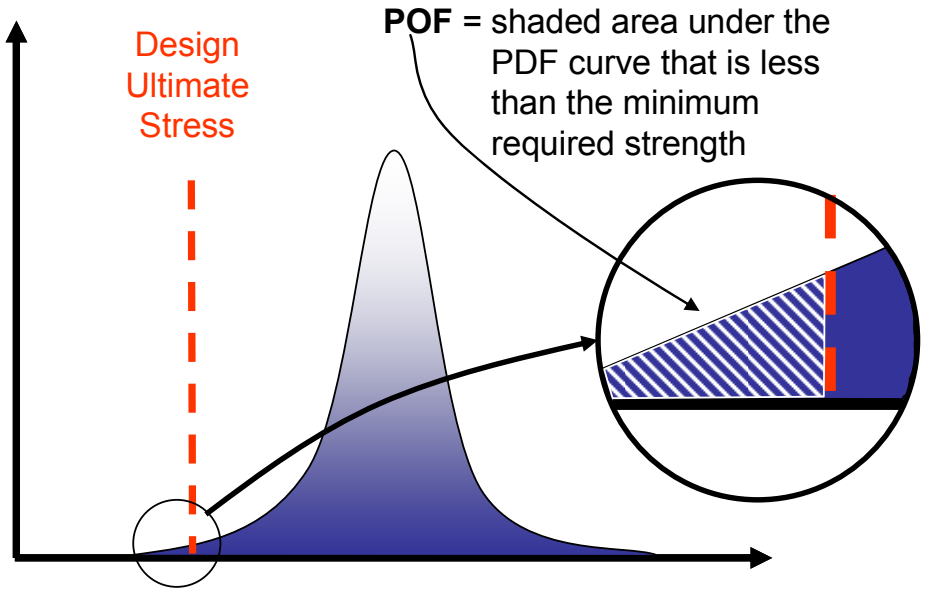
- **Test Success Criterion**
  - Achieve req'd residual strength
  - P(DUS) > 99.9999999%
  - POF < 10^{-7}
- **Test Program Goal:**
  - Increase confidence to:
    - support permanence of repairs
    - reduce inspection burden

C-141 Repair Inspection Req'ts

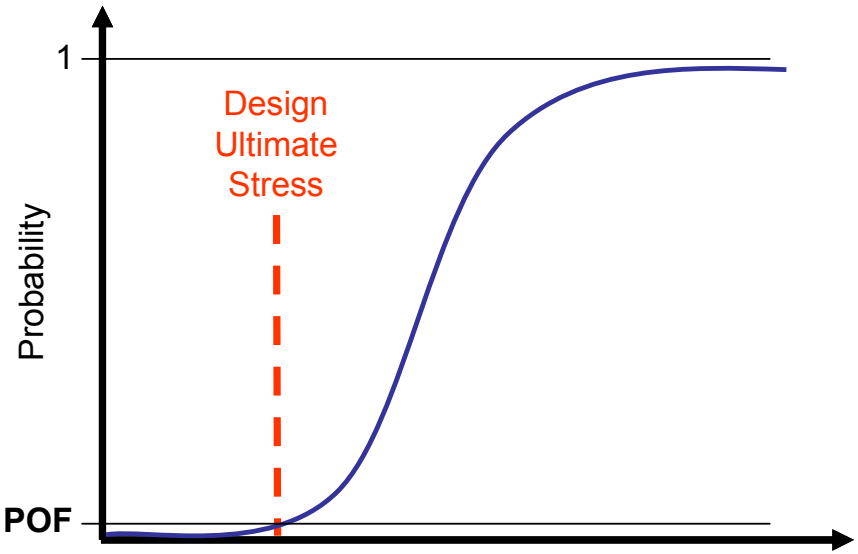
- **Every ISO inspection**
  - Visual
  - Coin tap
  - Eddy current - of metal structure surrounding patch
- **Every PDM (or 6 years, whichever is earlier)**
  - All ISO inspections + thermography
- **Inspections performed on OML patch only**

Test Success Criterion

- **Probability (strength < DUS) [“POF”] must be < 10^{-7}**
  - Where “failure” is defined as a loss of bonded repair



Probability Density Function (PDF) of the Residual Strength of Repaired Specimens



Cumulative Density Function (CDF) of the Residual Strength of Repaired Specimens

Definitions:

Design Limit Stress (DLS)
highest stress encountered during service life of aircraft

Design Ultimate Stress (DUS)
1.5 x Design Limit Stress

Age Characteristics of Tested Repairs

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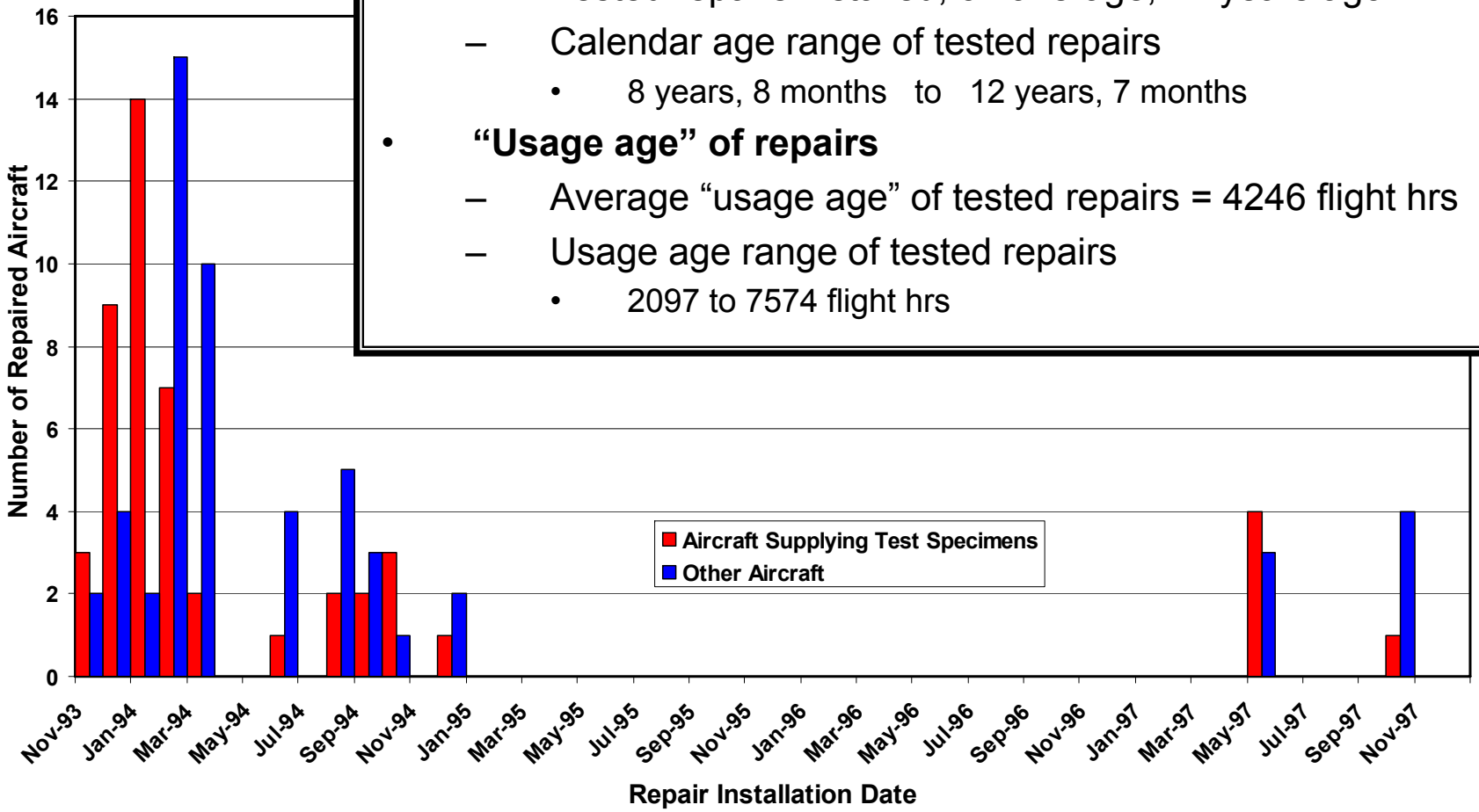
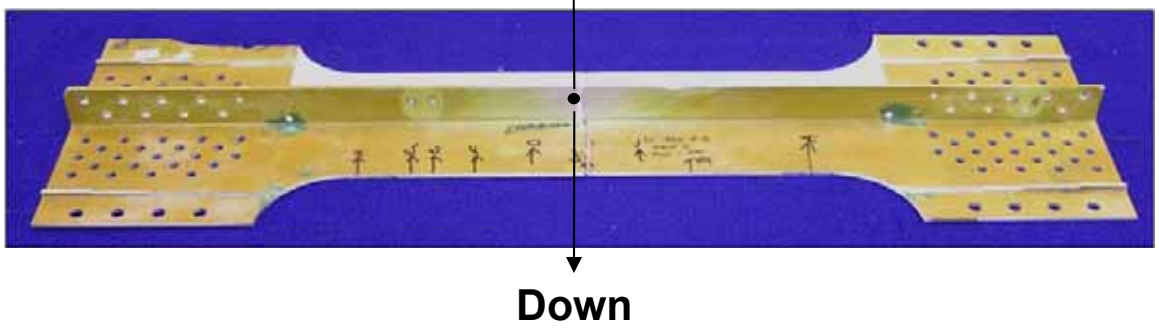
- **"Calendar" age of repairs**
  - Tested repairs installed, on average, 12 years ago
  - Calendar age range of tested repairs
    - 8 years, 8 months to 12 years, 7 months
- **"Usage age" of repairs**
  - Average "usage age" of tested repairs = 4246 flight hrs
  - Usage age range of tested repairs
    - 2097 to 7574 flight hrs



Tested repair population ~ Total repair population

Crack Characteristics of Tested Specimens

- **47 of 52 specimens had detectable cracks originating at weepholes**
  - 19 extended downwards
  - 27 extended upwards
  - 1 extended in both directions



- **Average crack length: 0.105”**
- **No discernable crack growth occurred in service**

Mechanical Testing

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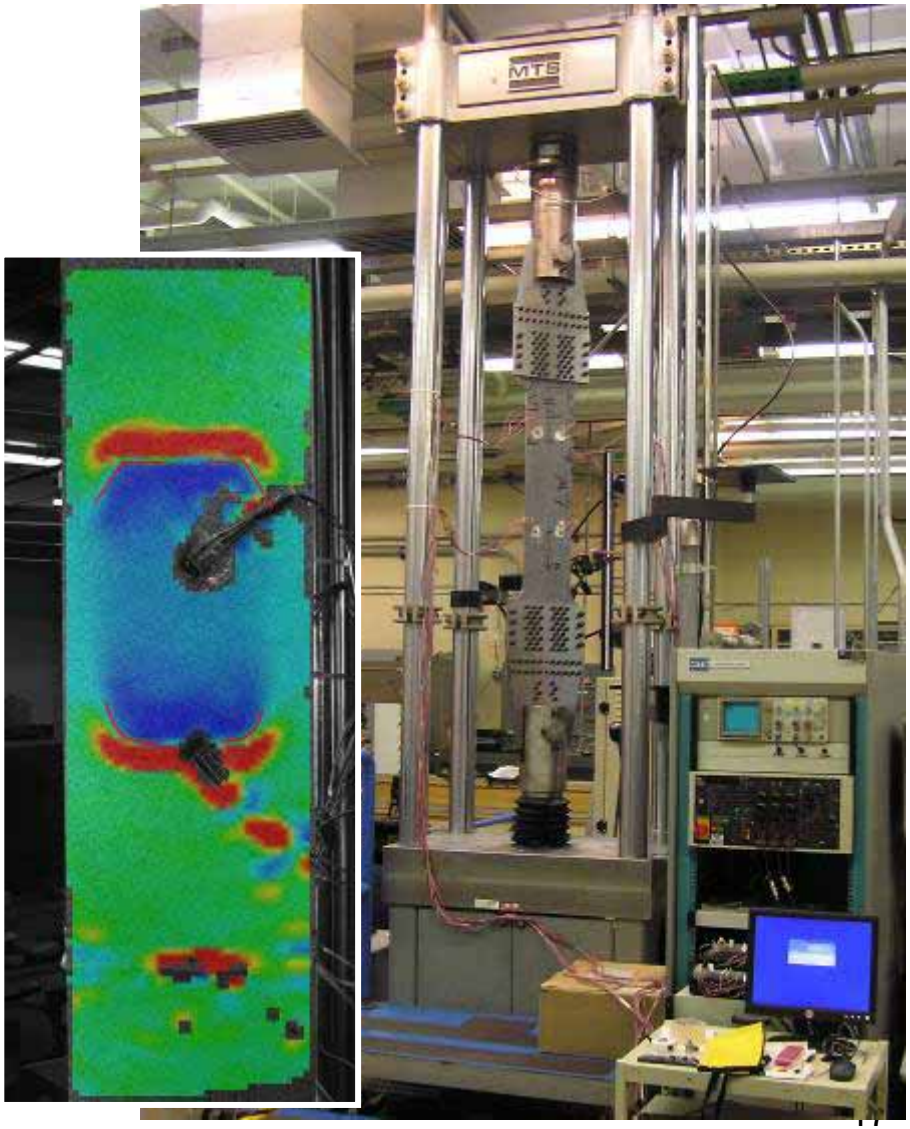
- Servohydraulic test frame
- Computer-controlled data acquisition
- Full-field stereo-optical (SO) speckle pattern strain measurement
  - Video strain mapping



Mechanical Testing

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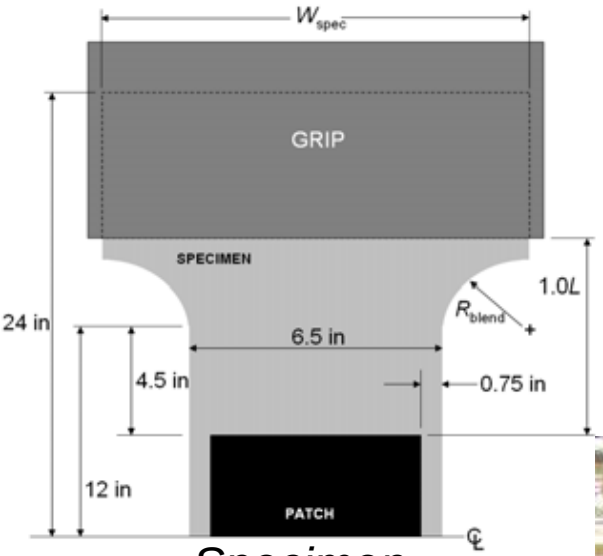
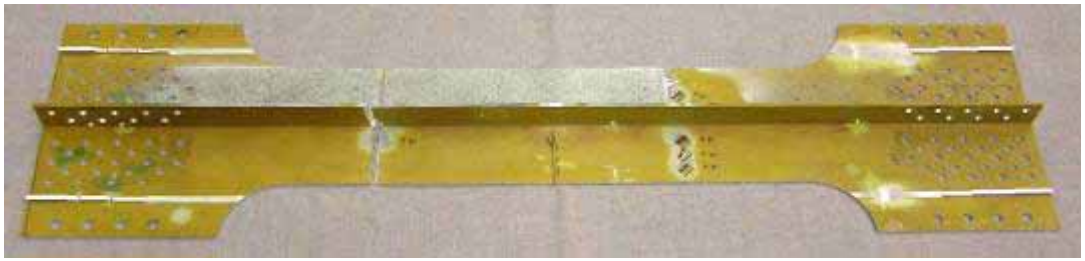


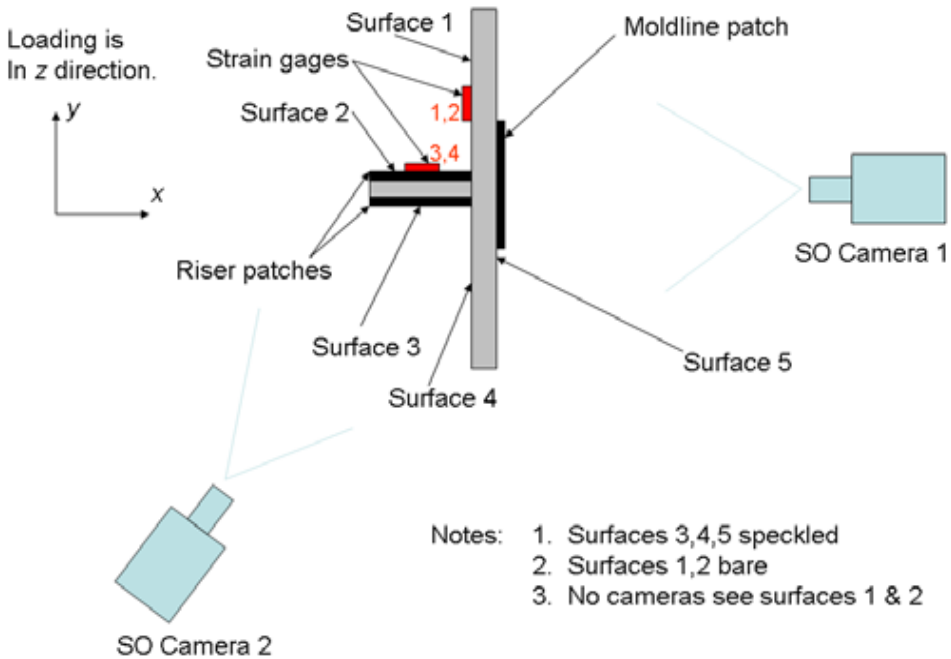
Specimen Dimensions



Specimen Geometry

Grip Design

Test Instrumentation



Mechanical Testing

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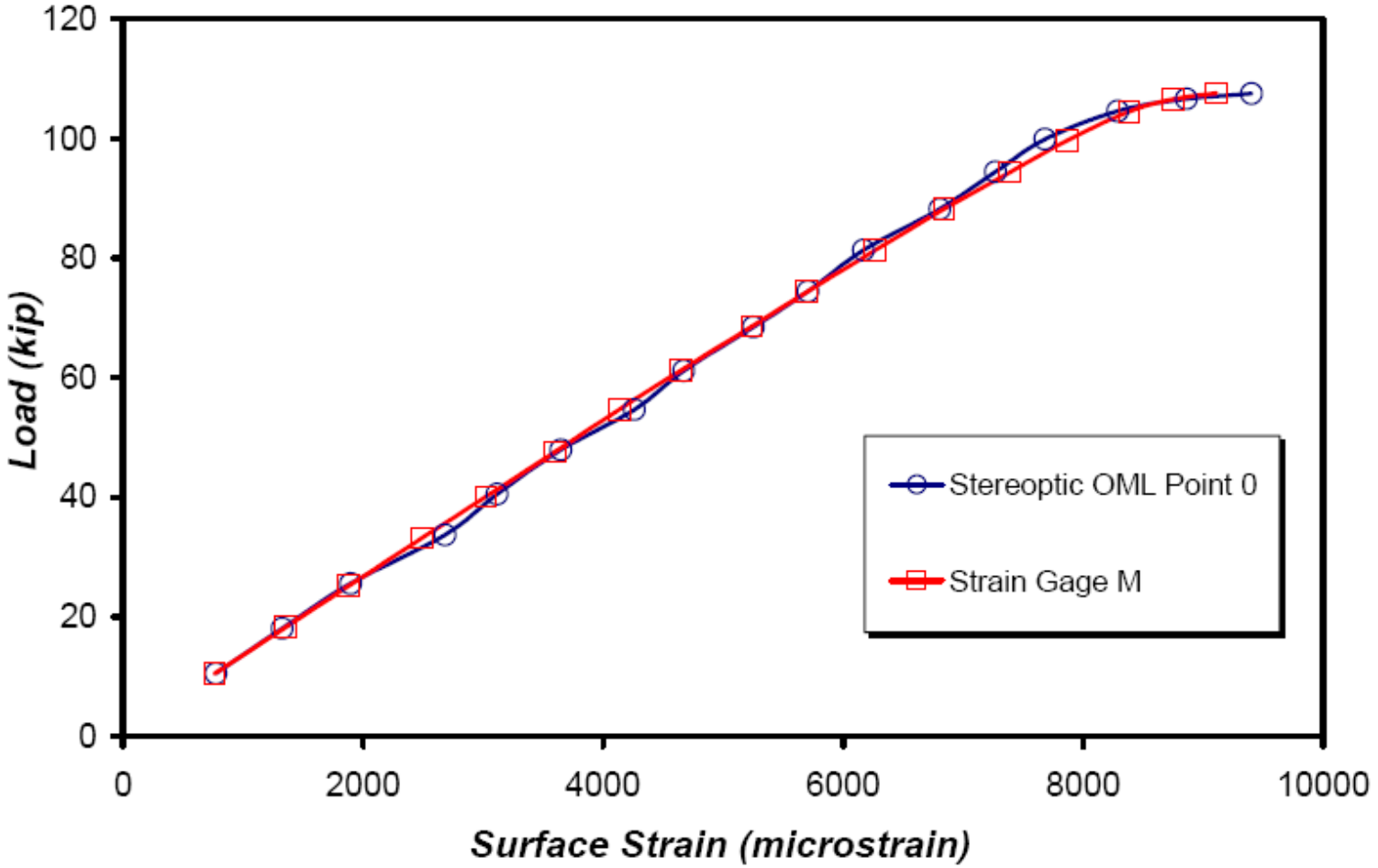
Strain Measurement Correlation



Very good correlation between strain gages & SO system

Mechanical Testing

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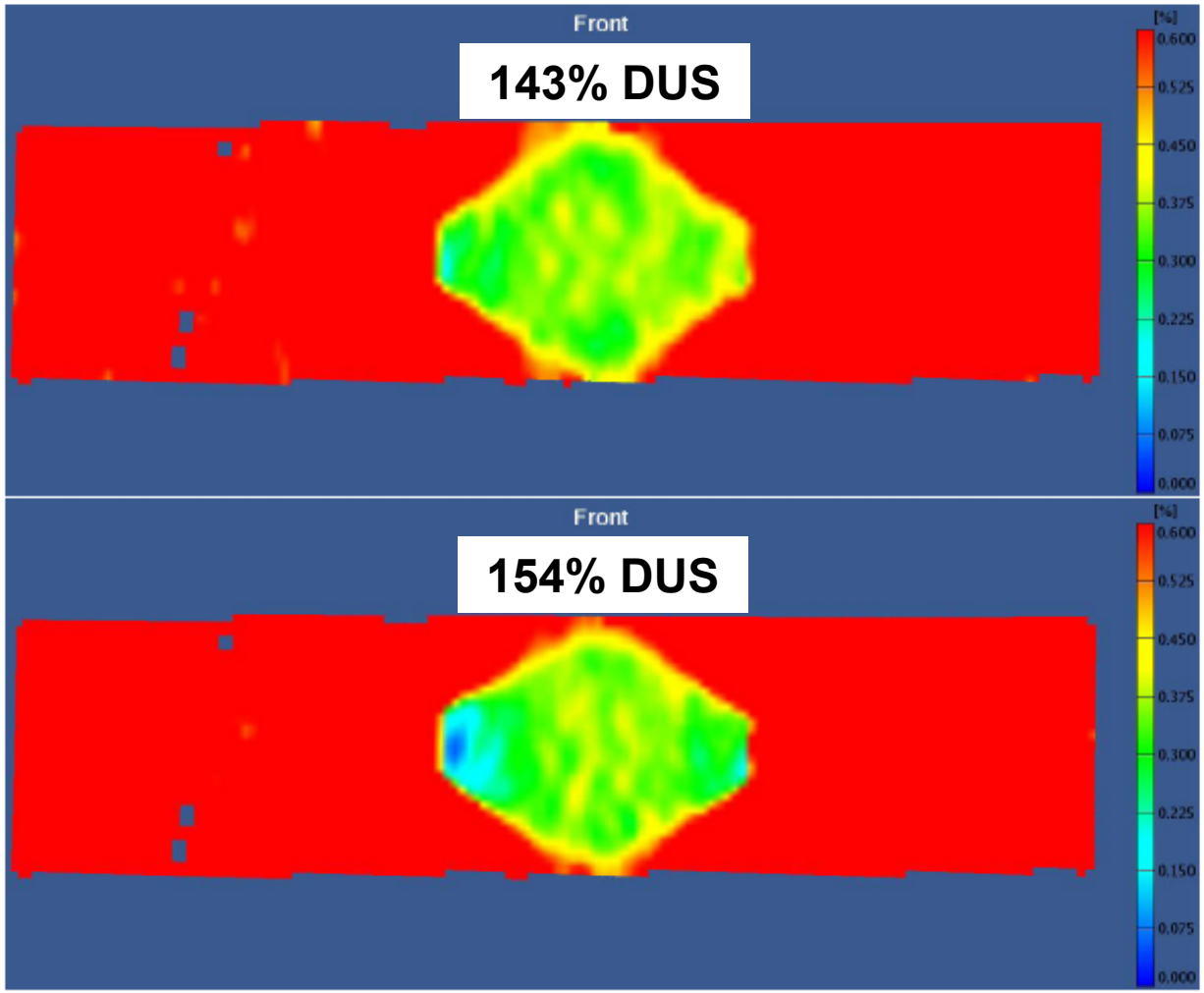
Typical Stereo-Optical Strain Measurements



Test Results

- **Specimens tested: 52** (valid tests)
  - All specimens achieved DLS
  - All specimens achieved DUS
  - Average residual specimen strength achieved:
    - > 225% DLS > 150% of DUS
- **Patches tested: 156** (3 per specimen)
  - 154 patches remained intact thru DUS
  - 7 patches (all OML) failed above DUS but before specimen failed
  - 2 patches (both OML) failed before reaching DUS
    1. Outer ply disbonded due to presence of release film
       - Disbond occurred at ~146% DLS or ~97% DUS
       - Specimen achieved ~237% DLS or ~158% DUS
    2. Patch disbonded from primed substrate; unknown cause
       - Disbond occurred at ~139% DLS or ~93% DUS
       - Specimen achieved ~239% DLS or ~159% DUS

No evidence of environmental degradation to critical metal-primer interface

Test Results

Each Repair = 1 "Entity"

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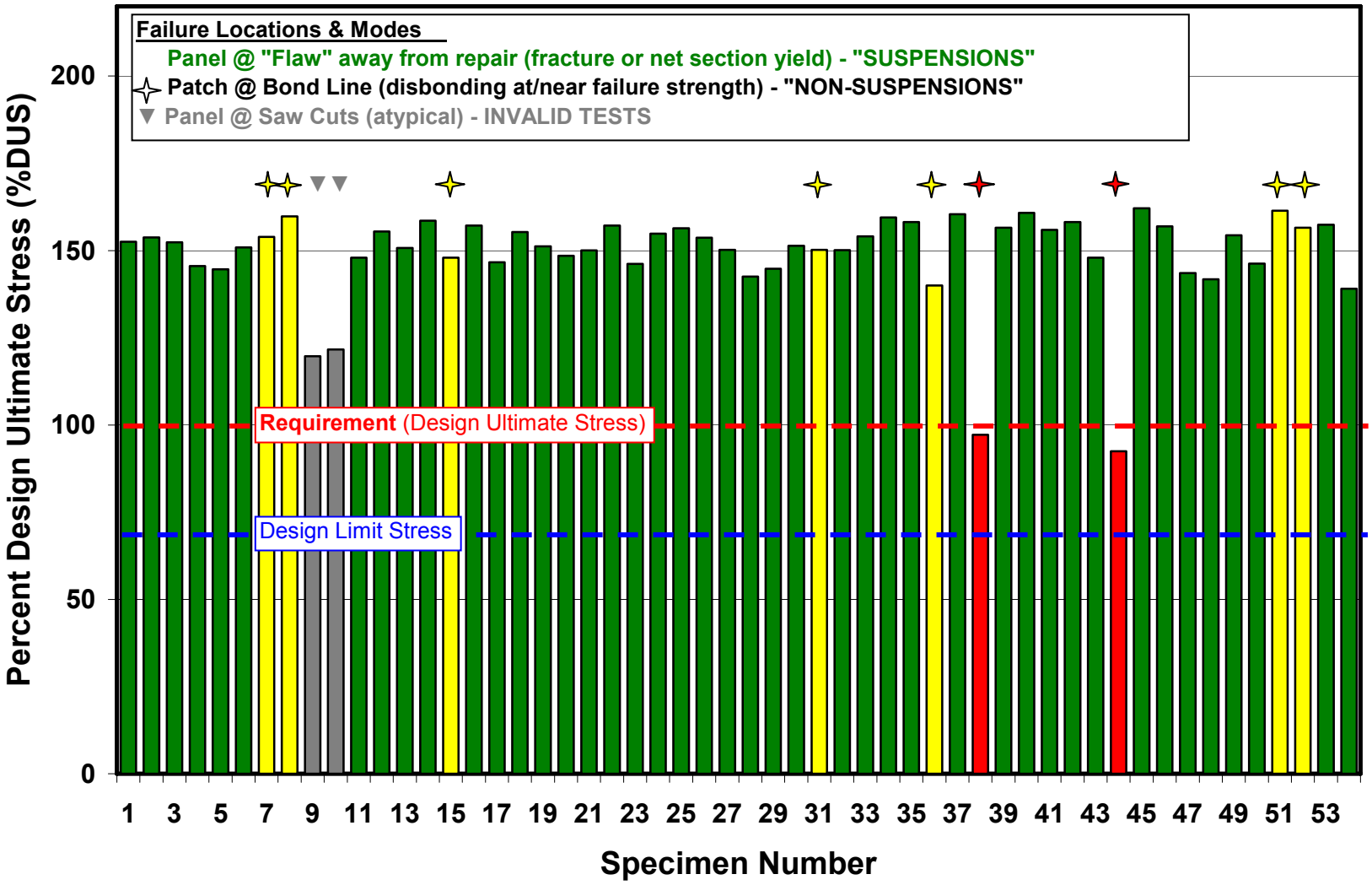
C-141 Bonded Repair Residual Strength



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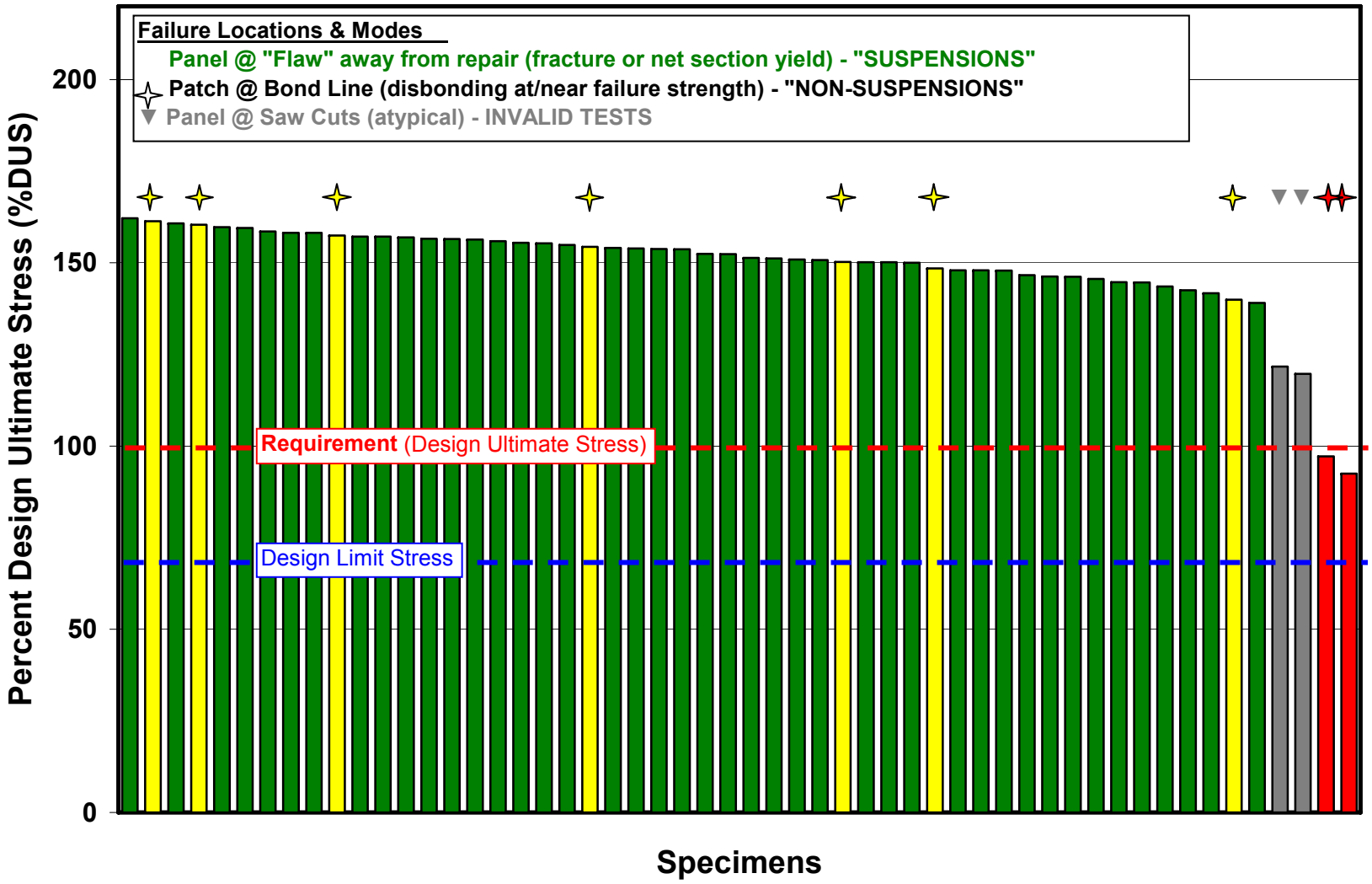

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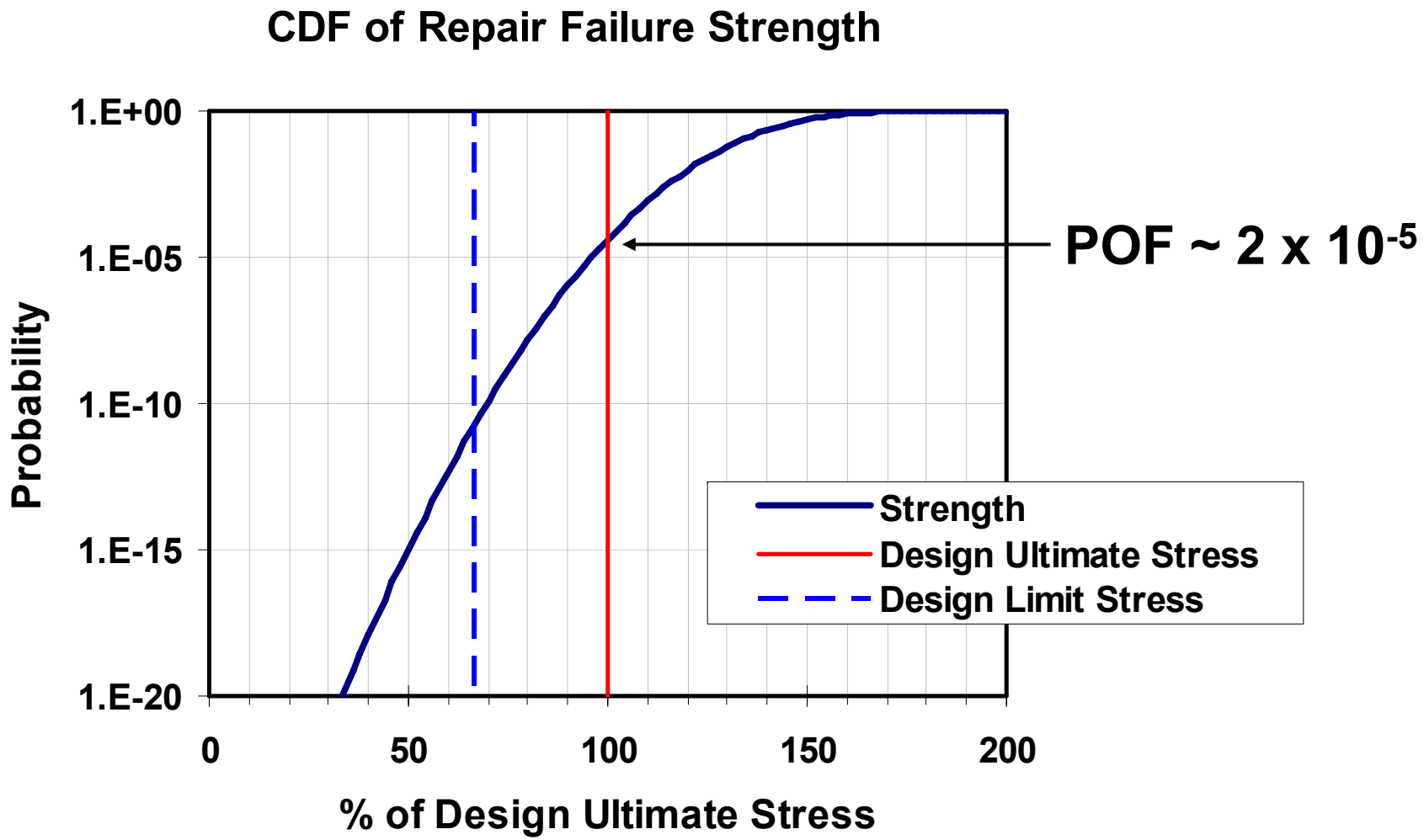

Test Results

Each Repair = 3 "Entities"

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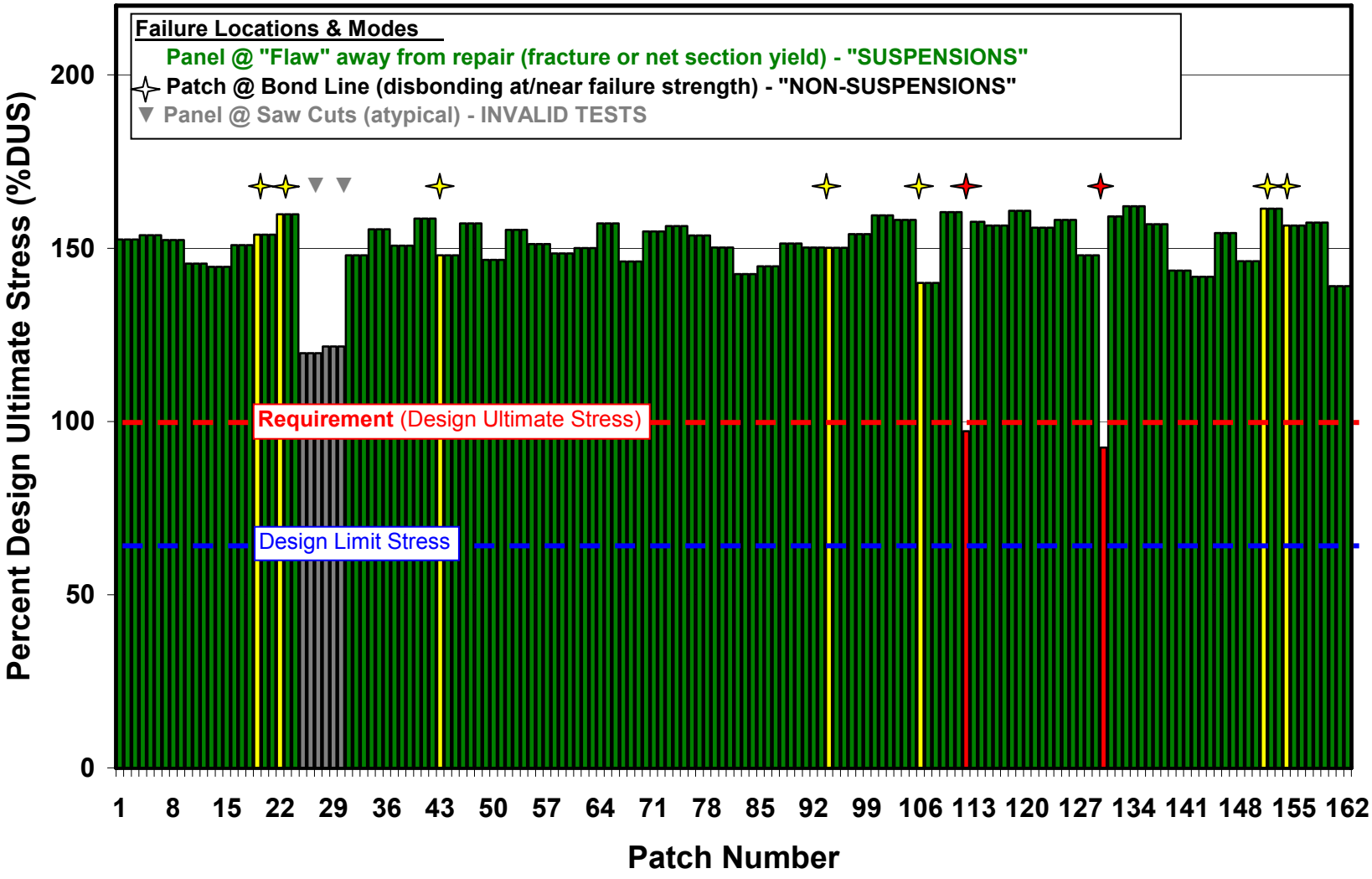
C-141 Bonded Repair Residual Strength



Test Results

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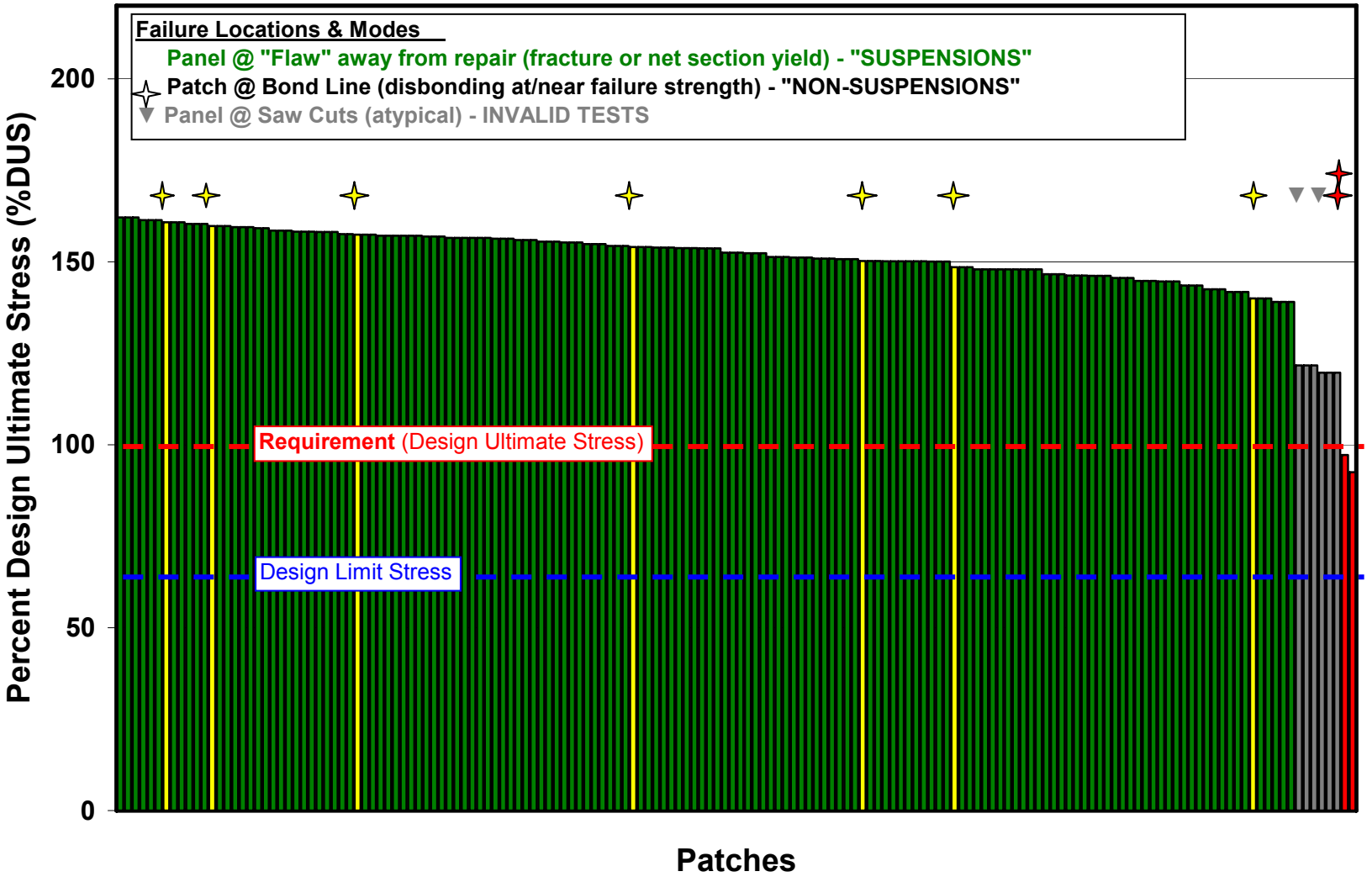
C-141 Bonded Repair Residual Strength



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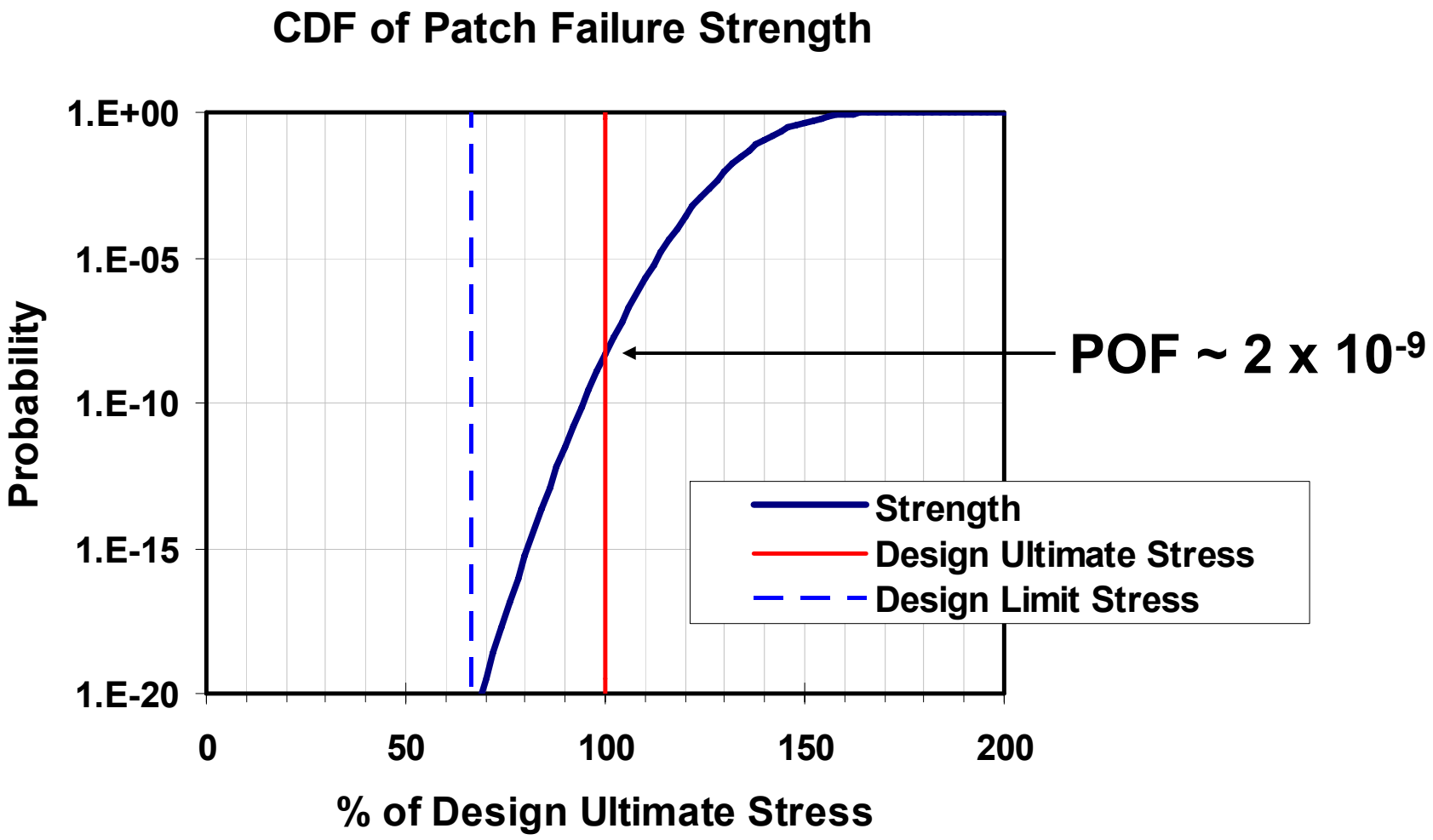

Analysis

- **Probability of Failure (POF) depends on analysis**
  - Treating each 3-patch repair treated as a single entity (i.e. repair is redundant)
    - 50 successful repairs out of 52: POF ~ 4×10^{-2}
    - Statistical analysis of repair failure strengths: POF ~ 2×10^{-5}
  - Treating each 3-patch repair treated as a three entities (i.e. repair is not redundant)
    - 154 successful patches out of 156: POF ~ 1×10^{-2}
    - Statistical analysis of patch failure strengths: POF ~ 2×10^{-9}
- **Probability of reaching DUS in structure was not accounted for in this analysis**
  - For the C-141: P(structural stress $\geq$ DUS) ~ 3×10^{-12} per flight hour

Analysis of results suggests that a risk-based approach is possible and appropriate

Concluding Remarks

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- No specimens failed below DUS
- Probability of Failure range: 4×10^{-2} to 2×10^{-9} (or less)
- No evidence of long-term environmental degradation
- Design criteria and materials & processes appear robust
- Proper infrastructure & technician training are crucial
- Redundancy may be necessary to reduce risk
- Longer inspection intervals appear possible
- Results are being reviewed by USAF ASIP Manager

In light of the results of this test program, the USAF plans to revise its policy on bonded repairs to reduce the inspection burden and permit "credit" to be taken for bonded repairs to safety-of-flight structures

Problems Bonded Repairs Will Probably Not Solve

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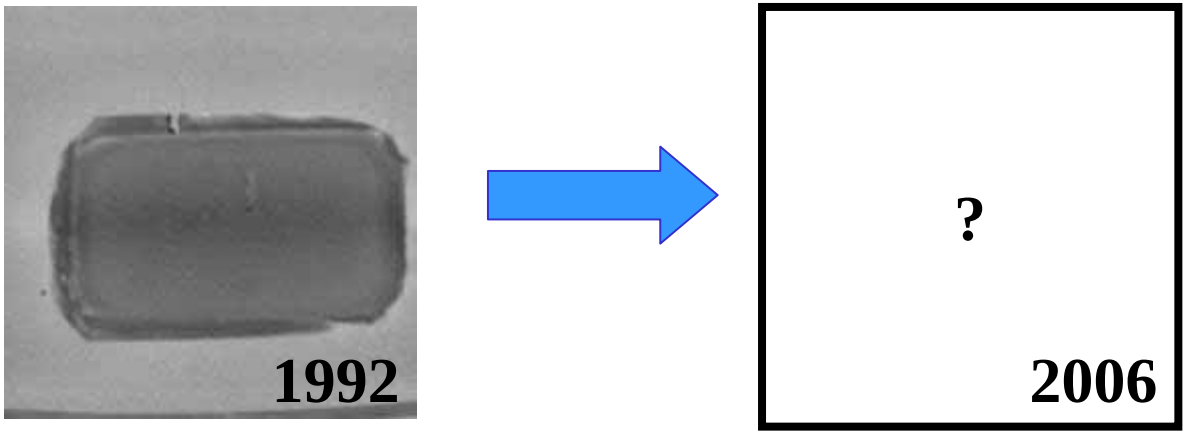
Pre-Test Elements of the Test Program

- **Pre-test thermal imaging NDI ("thermography")**
  - Compare with original images, circa 1990
  - Check for crack growth or disbonds



- **Pre-test prediction of failure load (stress) & location**
  - Evaluate current structural analysis tools
- **Extensive use of original documentation**
  - Selected only repairs made using standard procedures