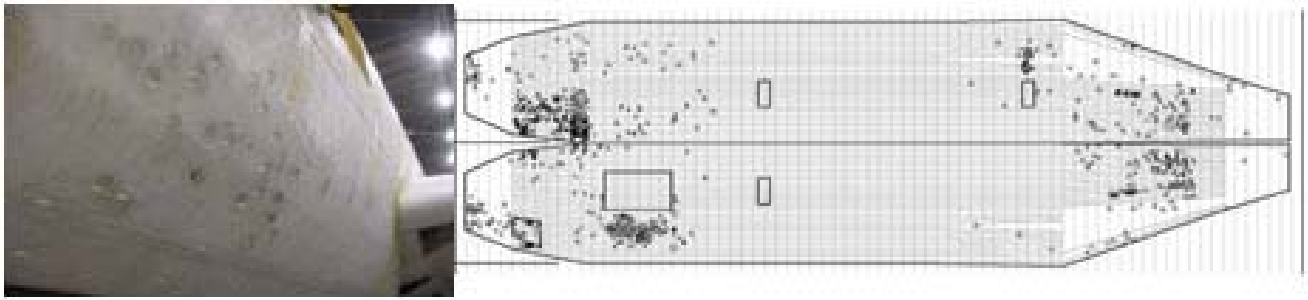
New Structural Guidelines for Dent Allowables on Fuselages



Cornelis Guijt

USAF Academy Department of Engineering Mechanics
Center for Aircraft Structural Life Extension

Oklahoma City Air Logistics Center

CONTENTS

- Overview
- Research objectives
- Field survey
- T.O. overview and dent definitions
- Fatigue considerations
- Static stability
- Summary
- Recommendations
- Future work

OVERVIEW

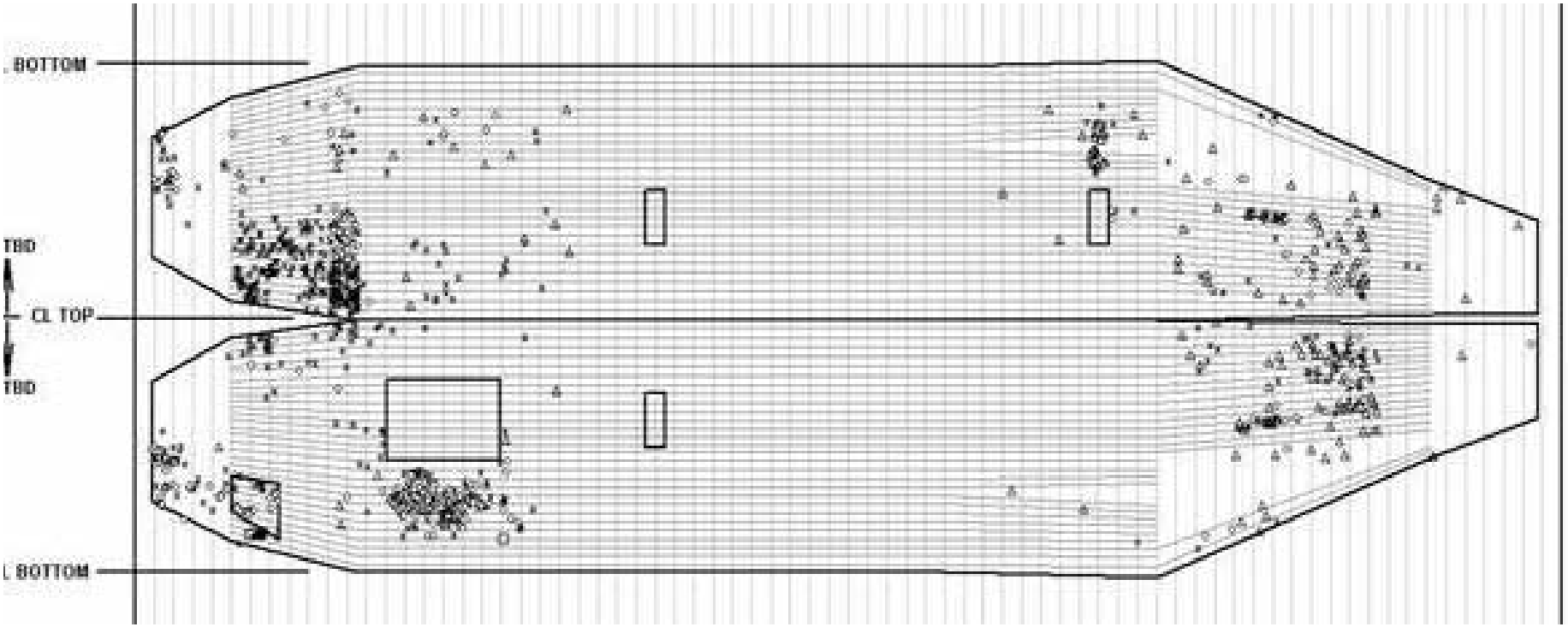
- Dented fuselage structure
- Heavy maintenance burden
- Oklahoma City ALC has requested research effort to reduce maintenance burden
- Boeing Field survey
- Tech Order (T.O.) guidelines, proprietary OEM information
- Prevent unnecessary maintenance by developing better guidelines based on research
- Current allowables depend on zones on the aircraft:
  - Some zones no dents allowed
  - > 3” away from stiffener
  - 0.03”- 0.25” depth limit

RESEARCH OBJECTIVES

- Are dents a fatigue concern?
  - Effect of re-forming?
- Do dents affect static stability?
  - Effect on compression loading
  - Effect on shear loading
- Provide experimental data for future analysis
- Recommendations for ALC and T.O.

FIELD SURVEY

- Field survey of 27 aircraft
  - 1127 dents
    - 664 unfilled
    - 298 filled
    - 156 repairs
  - Maintenance
  - Stands
  - Hail/strikes

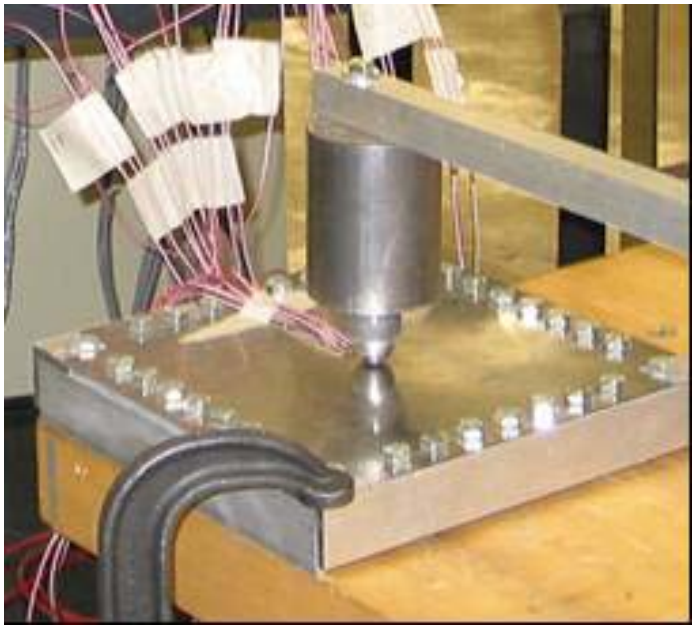


OVERVIEW of typical T.O. LIMITS

- *Hand forming not allowed*
- Fuselage zones
  - 2024-T3 skins
    - *<3” stringer, <0.03”, rest <0.25”*
    - Fill for aero
  - 7075-T6 skins
    - Must be repaired
- *Multiple dents in one bay must be repaired*
- Dent on stringer must be repaired

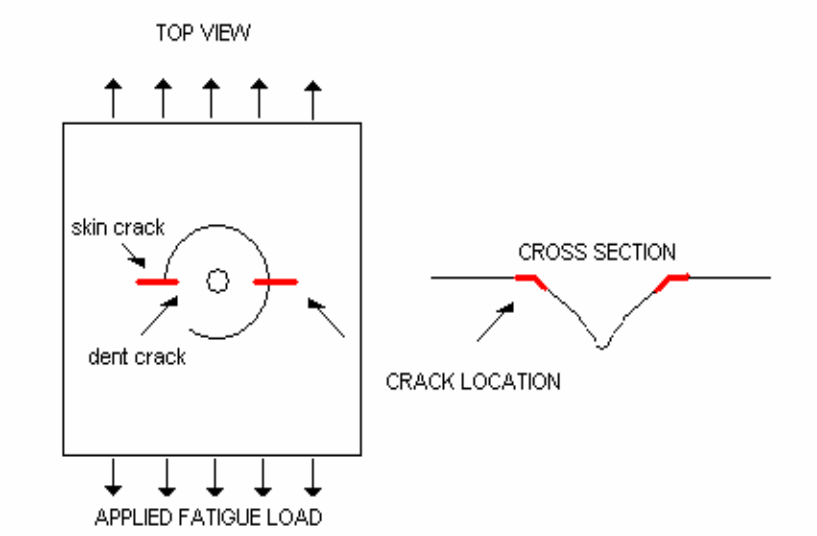
Dent forming

- Ring support for diameter control
- Potential energy for depth
  - Weight
  - Height



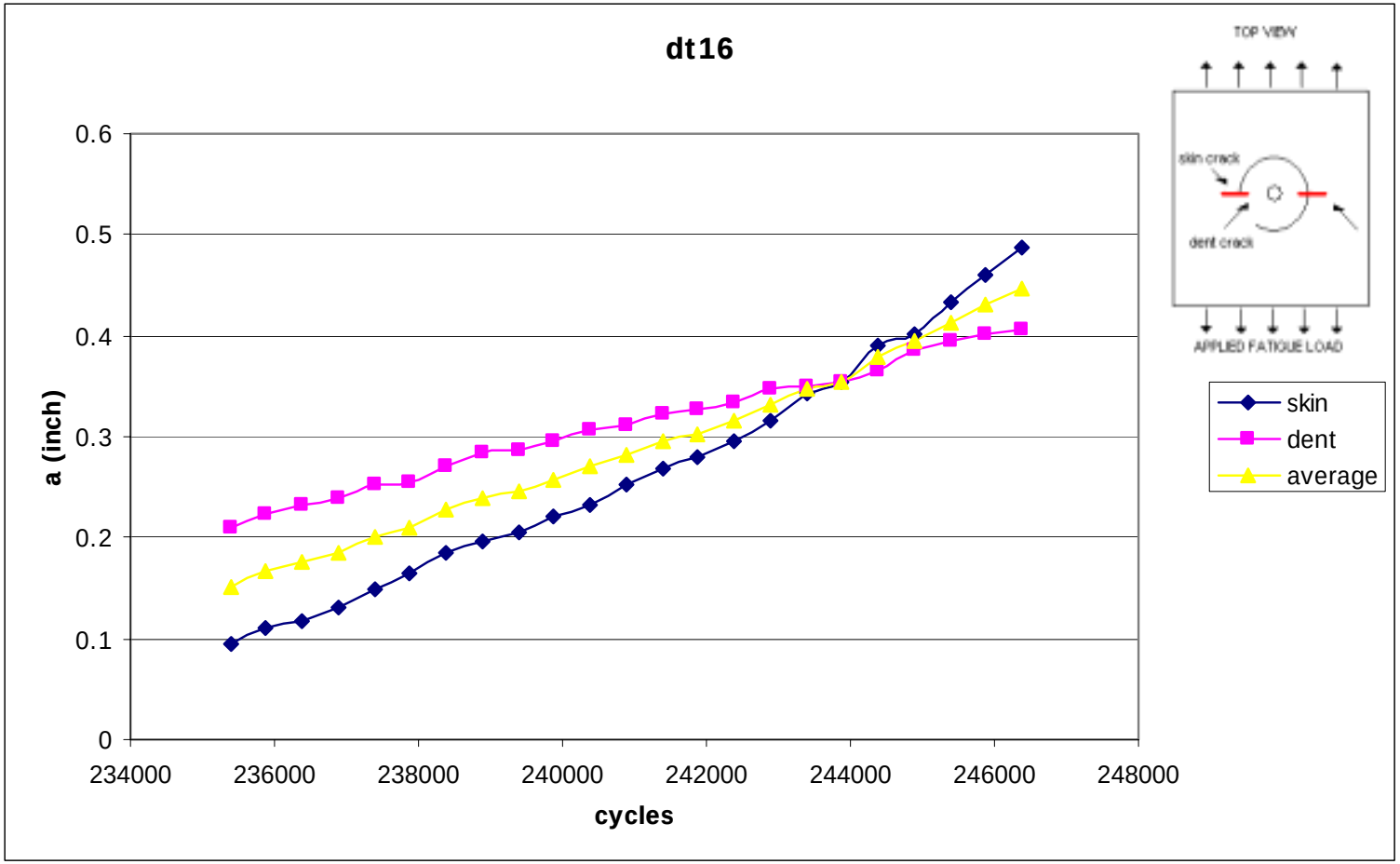
FATIGUE CONSIDERATIONS

- Critical Fatigue location
  - Not in bottom of dent
  - Ring support at critical location
  - Dent behaves like an open hole
  - Secondary bending due to shift in neutral axis



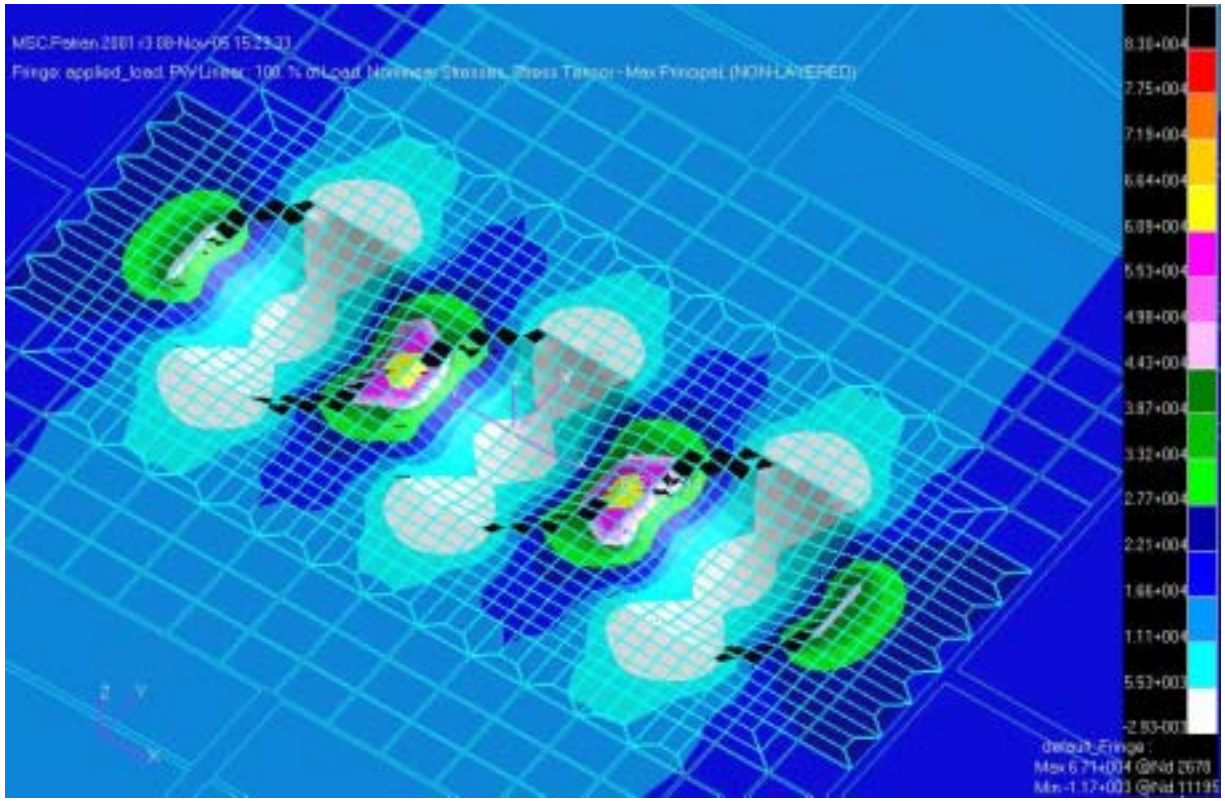
- Unstiffened panels
  - 0.04” thick, 2024-T3 Clad
  - Variations:
    - Bare
    - 0.06”

Load bypass around dent



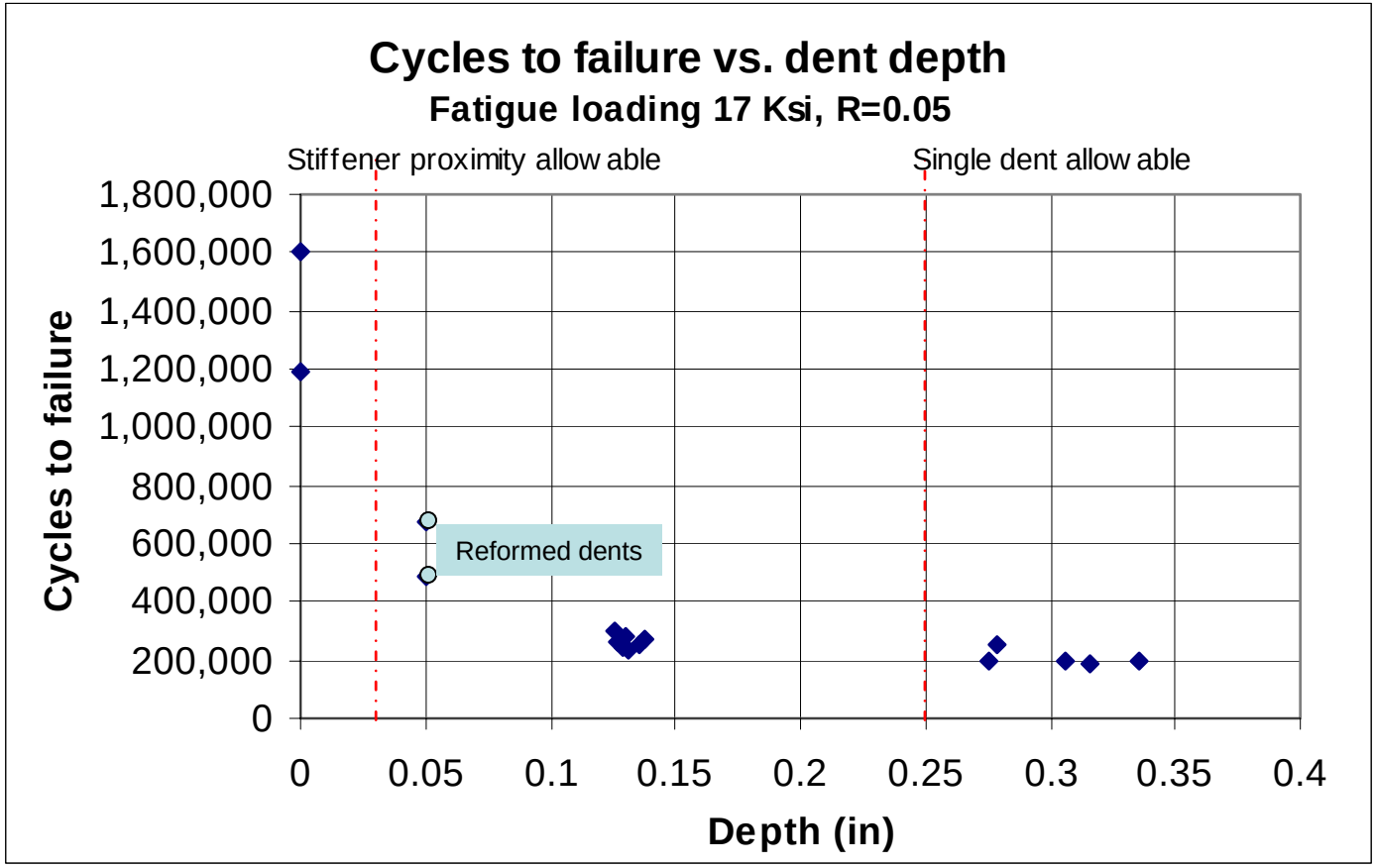
Multiple Dents (analysis)

- Up to ½ dent diameter, negligible effect
- At 1/8 dent diameter, Kt increases 1.6 times compared to single dent
- Aspect ratio of dent/gouges do affect Kt



Standardized fatigue testing

- Limited dent depth effect
- Reforming dents improves fatigue life
- Life well above service life (est. <100,000 cycles)



Fatigue Conclusions

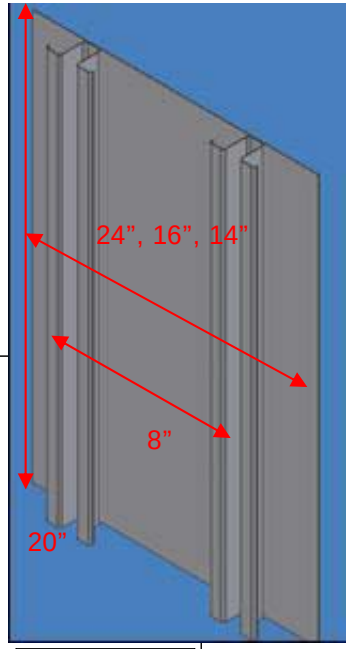
- Limited effect of dent depth
- Use of ring support and sharp transition yields conservative results
- Reforming improves but does not completely restore fatigue life
  - Reduce secondary bending
  - Cold working
- Worst dent still has sufficient fatigue life
- Dents do affect fatigue, but do not decrease the required fatigue life (~100,000 cycles)

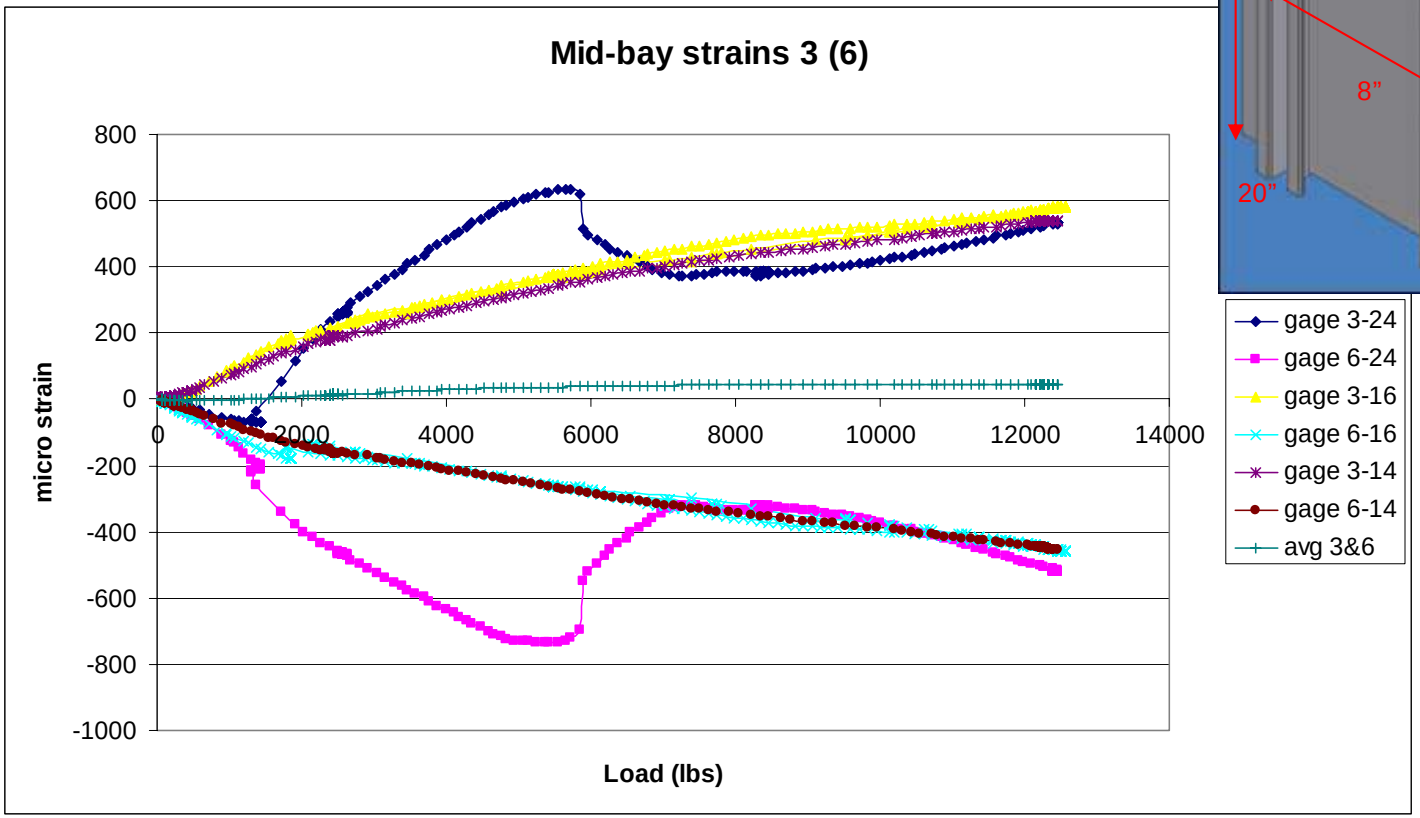
STATIC STABILITY; COMPRESSION

- Proper compression loading
- Analysis of compression loaded panels
- Stiffened panels
  - 0.04” 2024-T3 skin
  - 8” stiffener spacing
    - 100^0 countersunk fasteners
    - 7075-T6 stiffeners
  - 20” panel length/frame spacing
- Single dent (2” and 5”), Multiple 2” dents

Compression panel

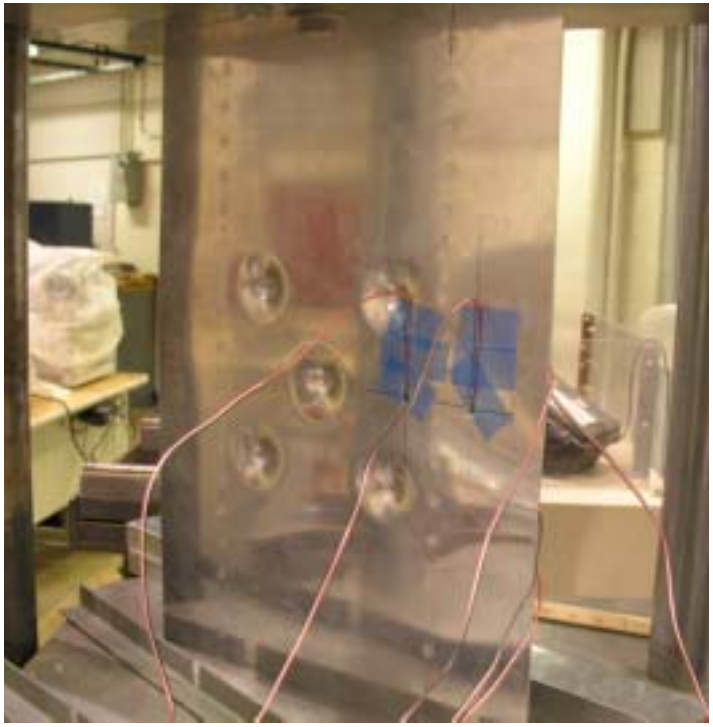
- Verify proper loading
- Effect of panel width
- Non-effective skin (avg. stress)





Effect of multiple dents

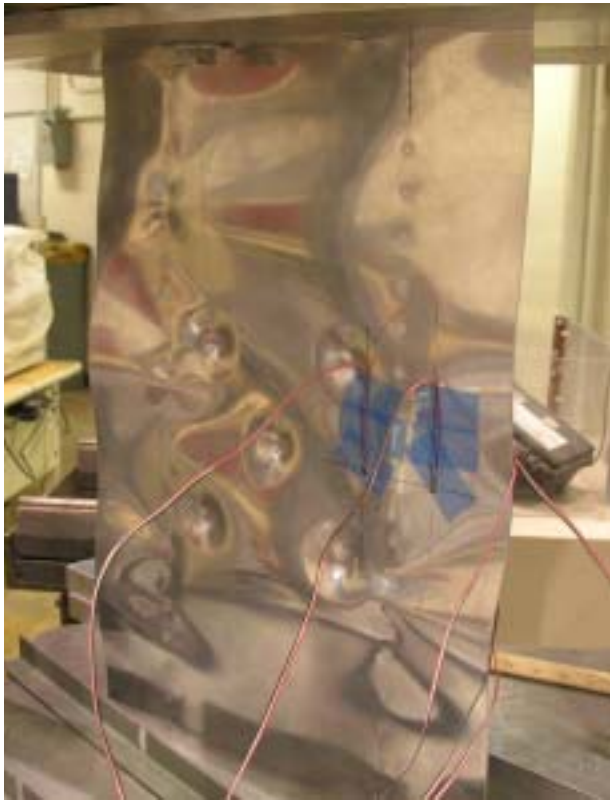
- Relief from multiple dent limitation
- Effect of dents close to stiffener
- Close to effective width area



Typical compression behavior

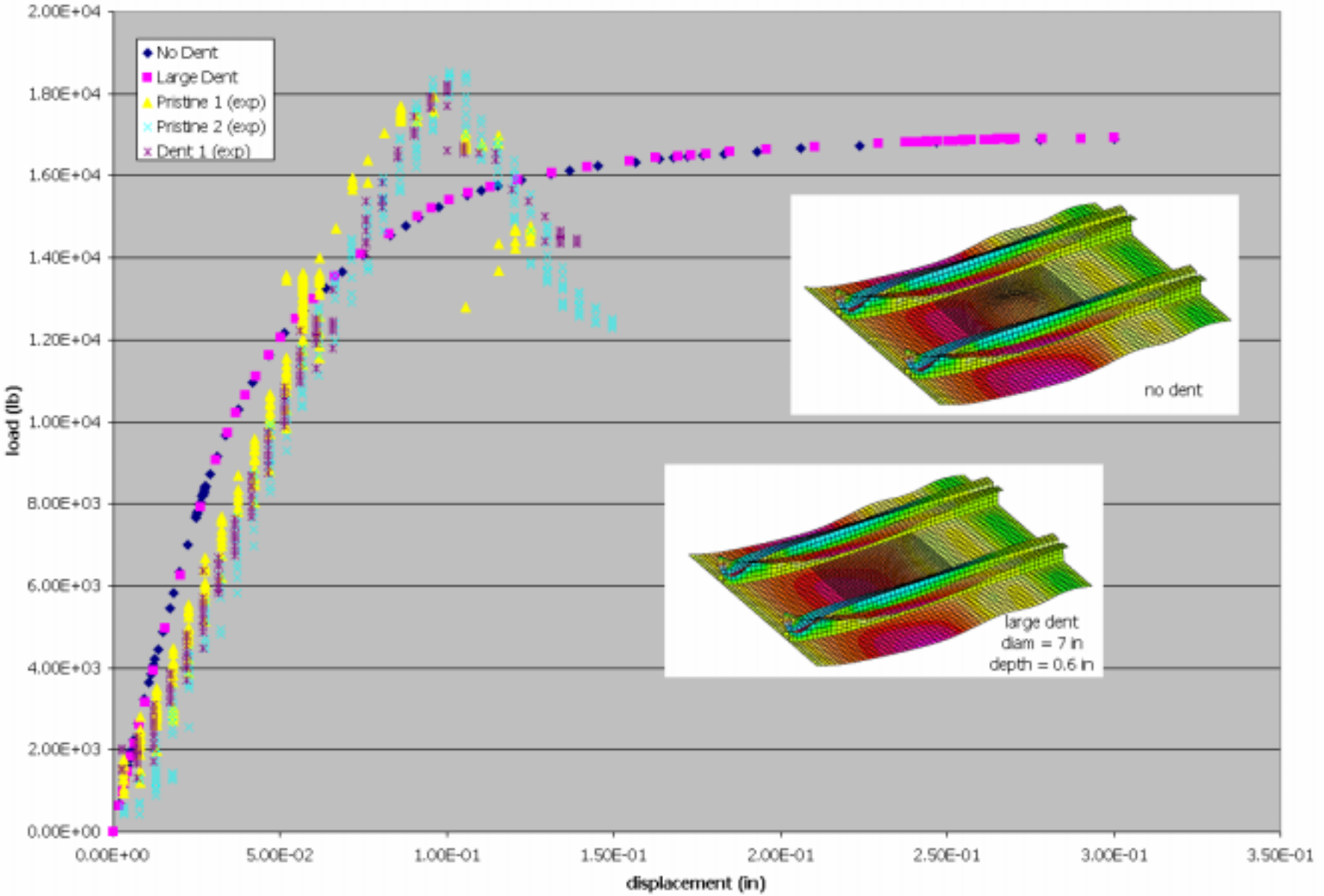
- Inter-rivet buckling
- Local stiffener crippling
- Skin wrinkling
- Torsional instability





FEM RESULTS: Compression

Analysis by Jim Greer, CAStLE



Compression testing conclusions

- Failure loads of panels;

Panel	avg Max Load	+/-
	Kip	Kip
Pristine	18.3	0.3
Large dent	18.6	0.3
5-dents	20.2	0.6

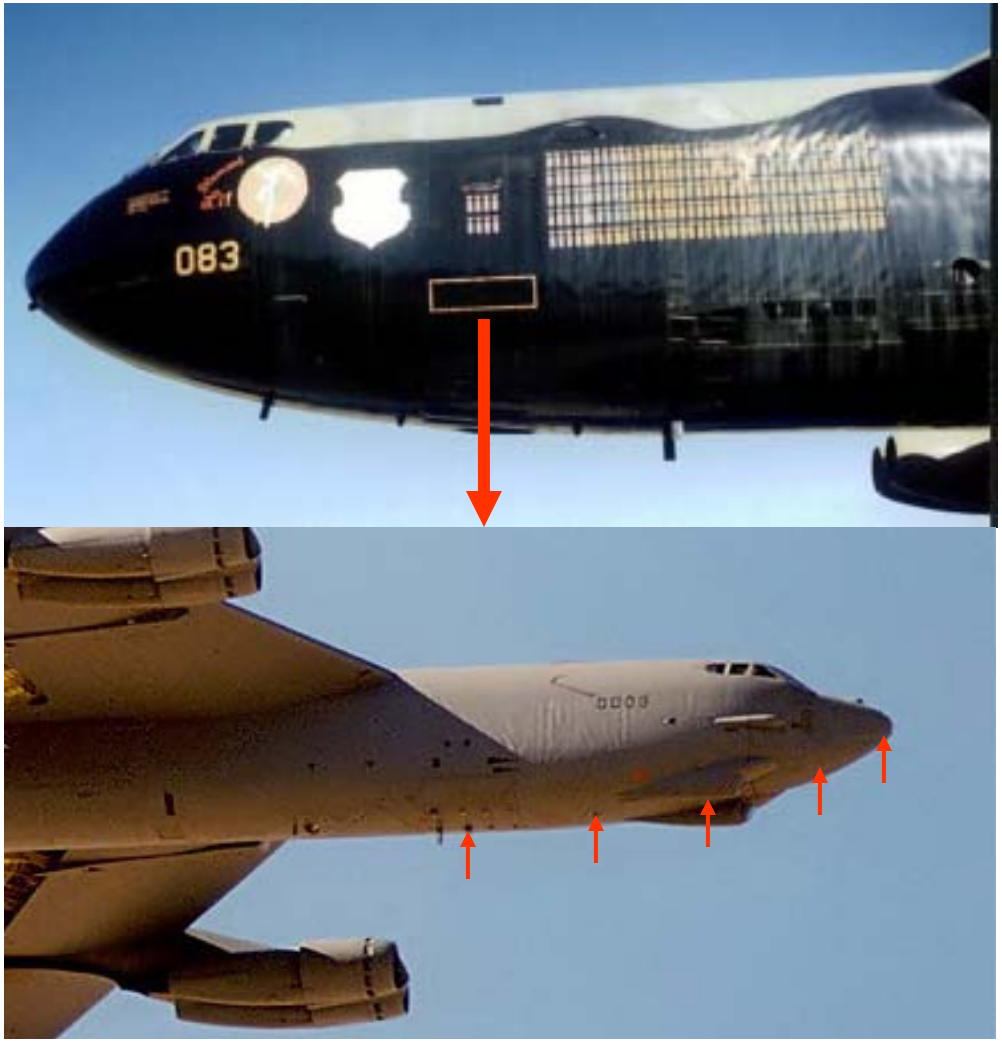
- No significant effect of dents
- No effect of multiple dents
- Dents seem to stiffen/strengthen the panel slightly

STATIC STABILITY; SHEAR

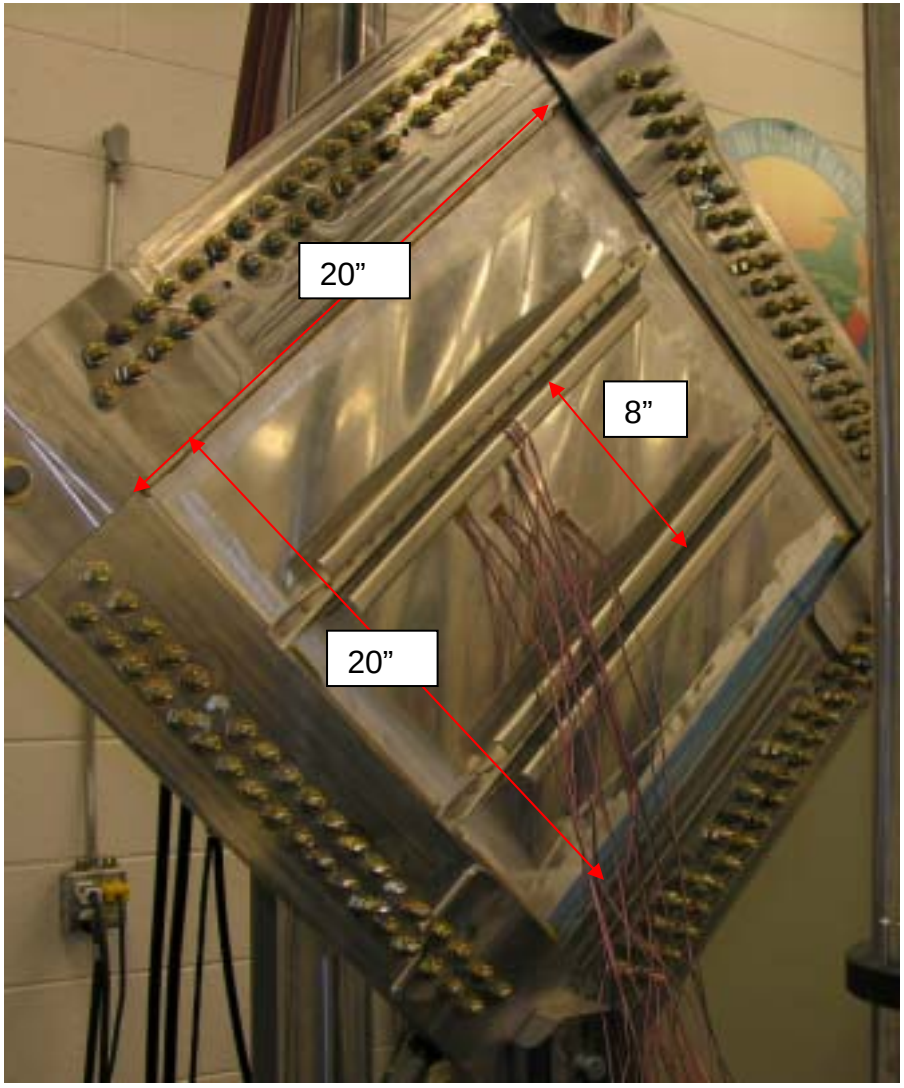
- Bi-axial shear loading more complex
- Shear:
  - Tension in one direction, equal compression perpendicular to tension
  - Tension: no stability concern
  - Compression: possibly same behavior as earlier in the compression test
- Single dent (2” and 5”), Multiple dents (2”)

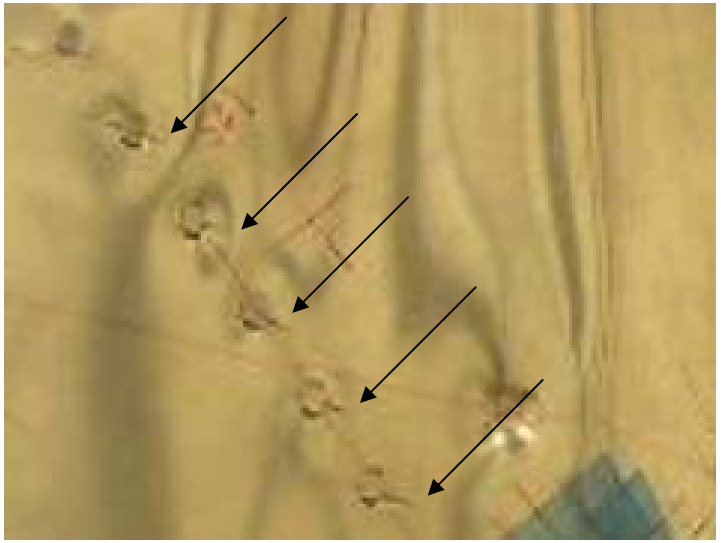
Shear loading

- B-52 example
- Shear buckling apparent on static display/ground loading
- Shear buckles disappear in flight due to lift of fuselage



Large shear frame





Shear conclusions

- Shear failure loads:

Panel	avg Max Load	+/-
	Kip	Kip
Pristine	34.0	0.8
Dented	34.6	0.4
5-dents	36.4	0.7

- No detrimental effect of dents
  - Slight increase of failure loads with dents

Summary

- Dents do affect fatigue
- Dents do not diminish the life under the required fatigue life

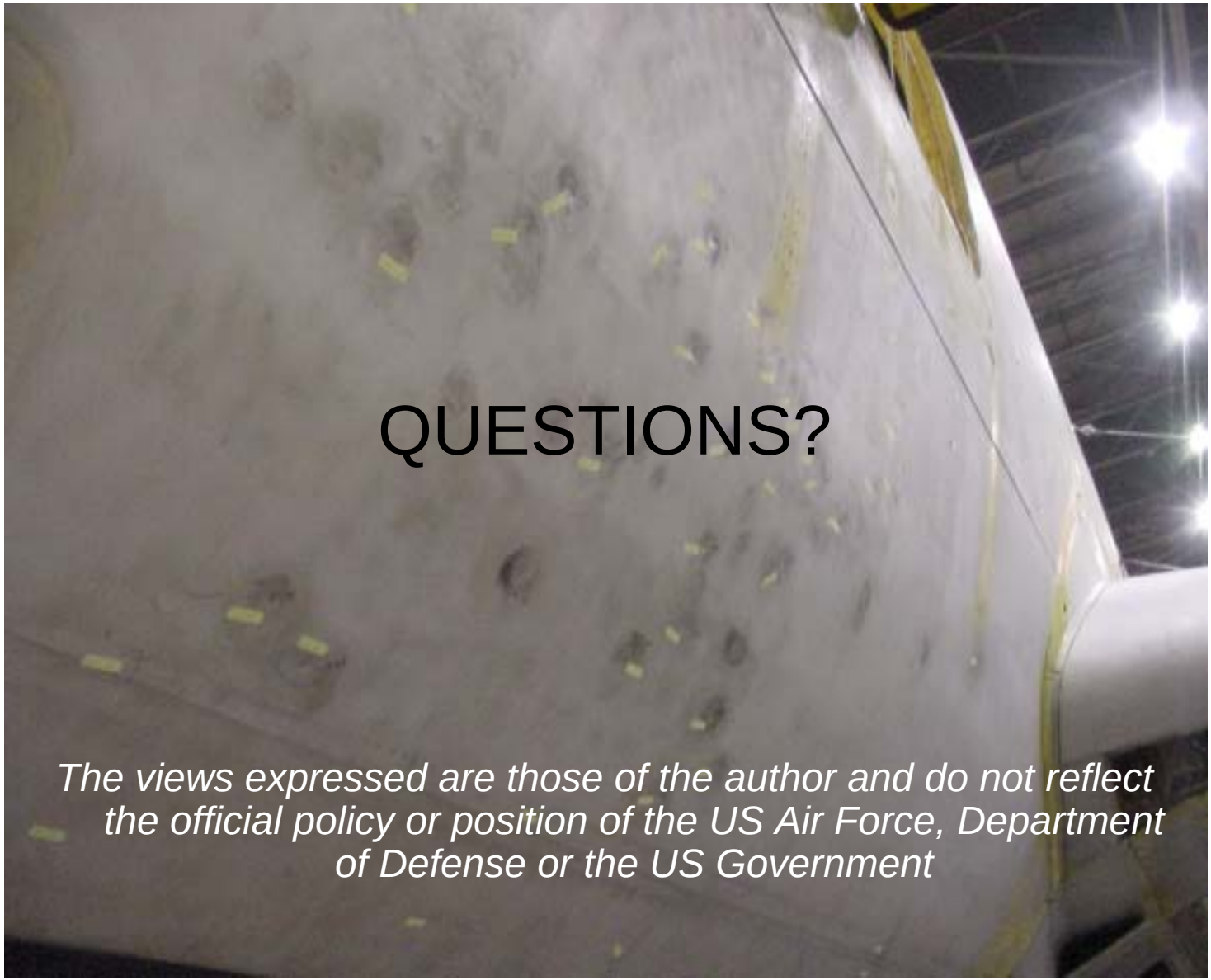
- Damage in the non-effective skin area will not affect panel strength in compression
- Most of skin is ineffective in shear/compression
- Only damage in the effective width of the skin might possibly affect panel strength
- Very limited analysis needed; effective/non-effective skin

Recommendations

- Favorable T.O. recommendation: dents outside the effective width of a panel are not an issue for static stability, *no maintenance actions required*
- A typical transport fuselage structure was tested, these results should be applicable for similar types of shell structures/aircraft

FUTURE WORK

Dents in 7XXX aluminum
  - Especially regarding fatigue concerns
- Expand to configurations with more effective skin
  - Thicker skins
    - Less likely to dent?
    - Larger effective areas
  - Effect of dents inside effective skin
- Analyze effective zones on aircraft
- Evaluate alternative repair options for dents
  - Reforming techniques
  - Traditional repairs/cut-outs
    - Bonded repairs at critical positions around dent
- Cross-cutting solution
- Results already applied on 2 platforms
- Return on investment 20 - 600



QUESTIONS?

The views expressed are those of the author and do not reflect the official policy or position of the US Air Force, Department of Defense or the US Government

Aging Aircraft Repair Strategies Utilizing Cold Expansion Technologies

by:
Len Reid
Vice President,
Research & Development

29 November – 1 December 2005

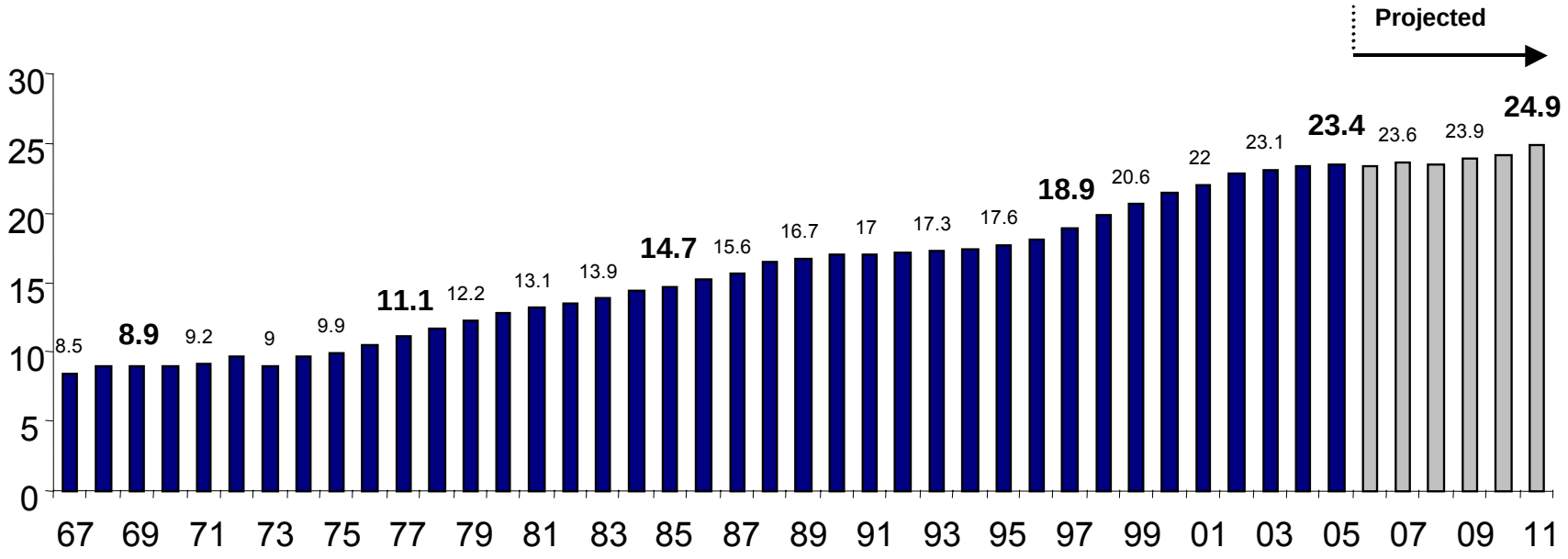
Memphis Tennessee

Objective

Present an overview of the various cold expansion processes to show how these may be utilized to effect economical repair strategies on aging military aircraft and reduce maintenance cost

Aging Aircraft

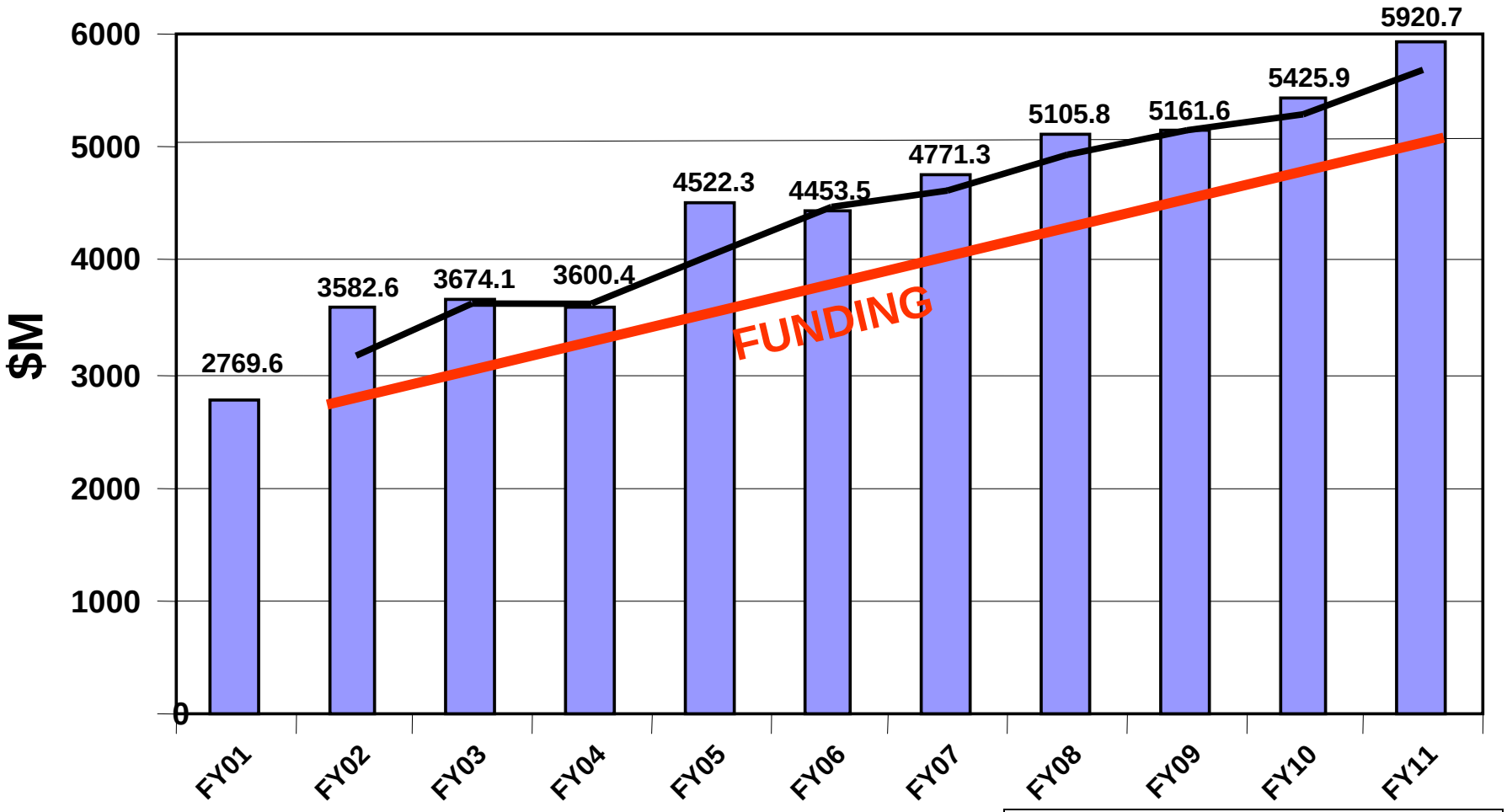
Average USAF Fleet Age



MXG Briefing; Gen (Select) Cameron

OO-ALC Nov 2005

Maintenance Costs Growth (projected)

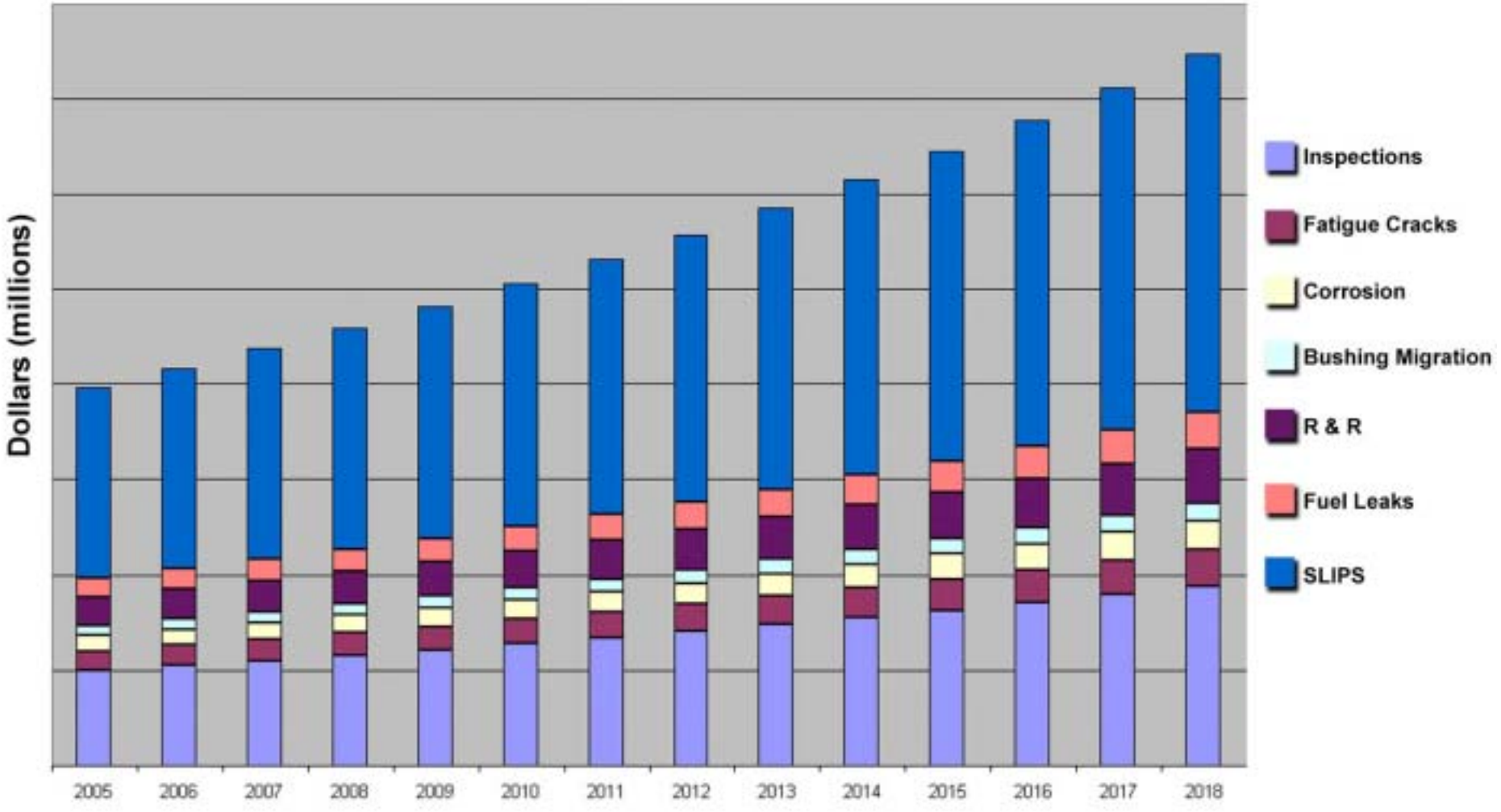


MXG Briefing; Gen (Select) Cameron
OO-ALC Nov 2005

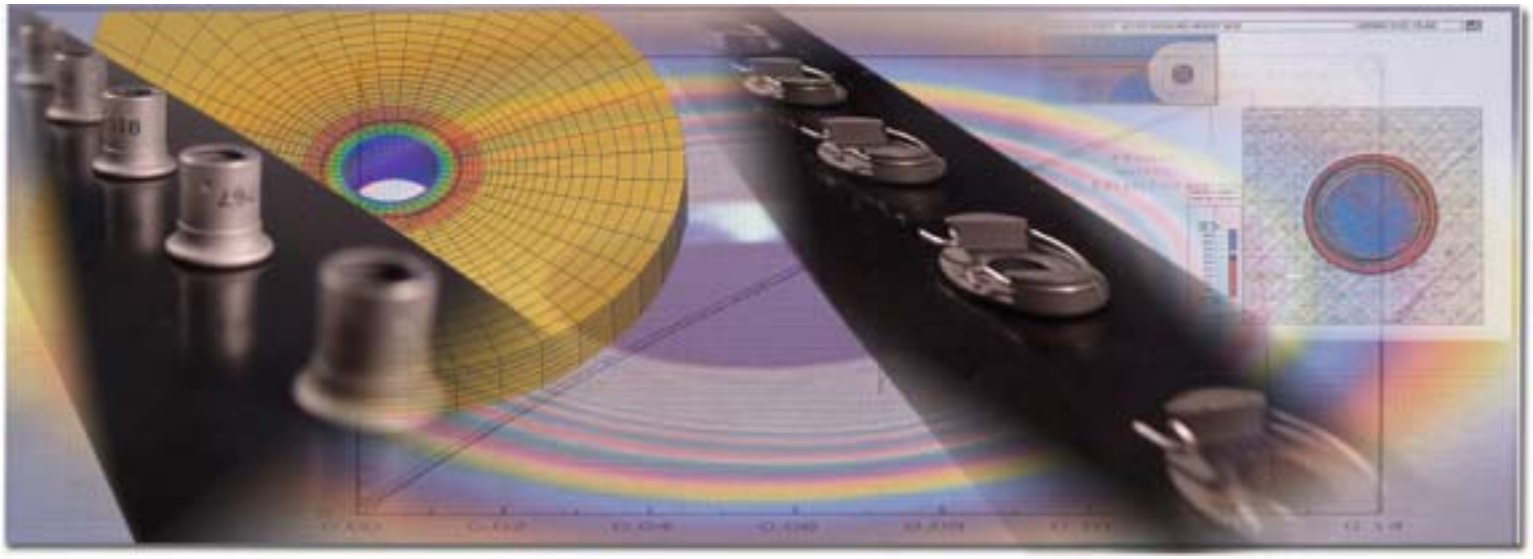
What are the structural maintenance cost drivers

- Structural inspections
- Fatigue crack abatement
- Corrosion abatement
- Lug durability/bushing migration
- Fuel leaks
- Component replacement
- Major Structural Life Improvement Programs (SLIP)

Maintenance cost elements



Today's Maintenance Challenges Require New Solutions



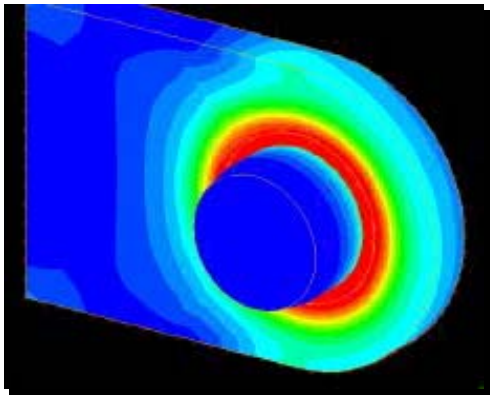
Structural Problems Solved By Residual Compressive Stress Initiatives

- Structural fatigue life and damage tolerance enhancement
- Hole resizing, bushing retention, life and damage tolerance enhancement of lugs
- Elimination of nut plate fatigue, fastener hole resizing
- Blind access and improved sealing of blind threaded nuts and inserts
- Improved structural modifications, design and repairs

Cold Expansion Solution

Cold Expansion (cold working) **induces a zone of residual compressive stress** around and through a hole, typically extending radially at least one radius around hole.

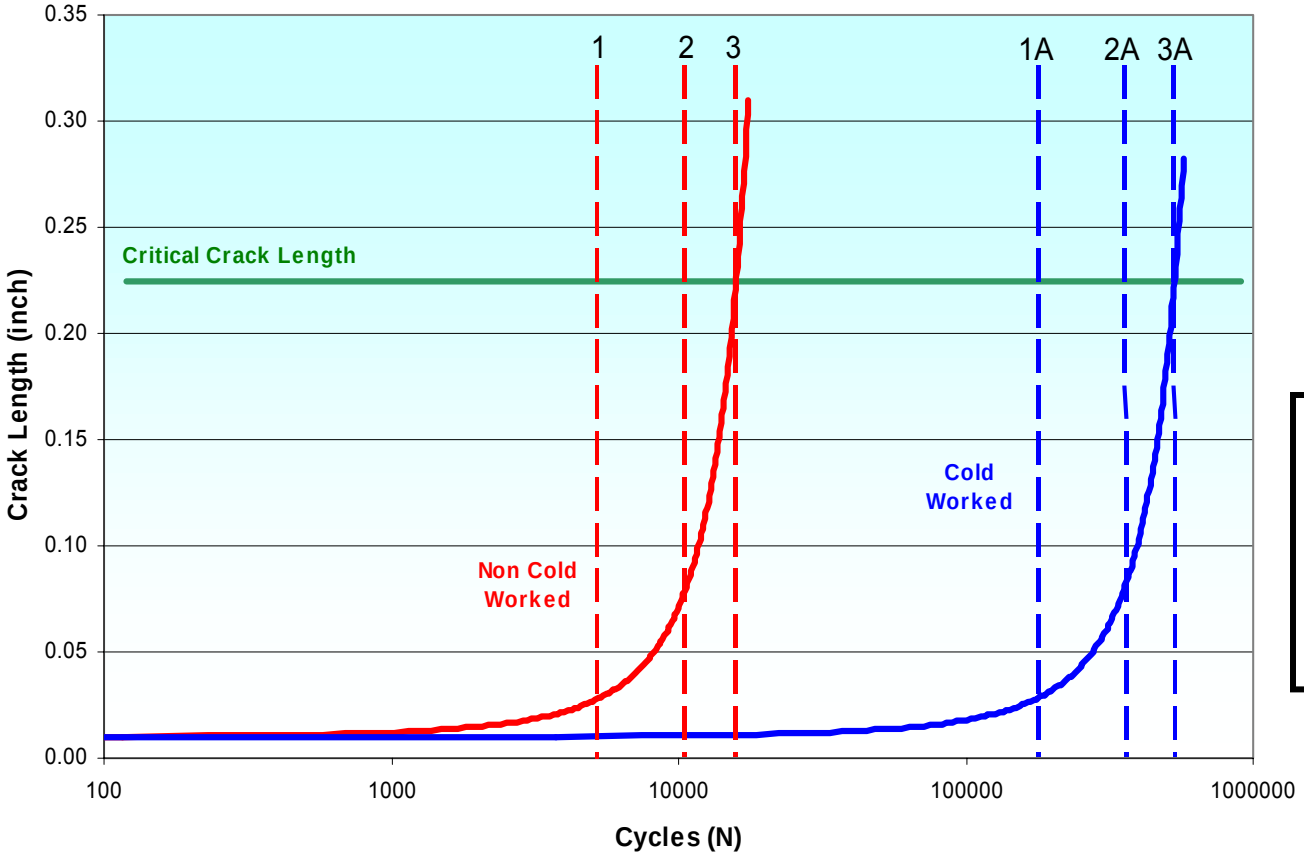
Hole is effectively "shielded," reducing effective stress intensity factor and therefore the propagation fatigue cracks.



Radial expansion of bushings is also effective in inducing beneficial residual stresses in attachment lugs and fittings to enhance durability and fatigue life

Improves fatigue life and durability and damage tolerance of structure.

Extended Inspection Interval with Cold Expansion



Cold expansion will often extend initial inspection threshold beyond the original economic life of the structure

Constant amplitude fatigue test

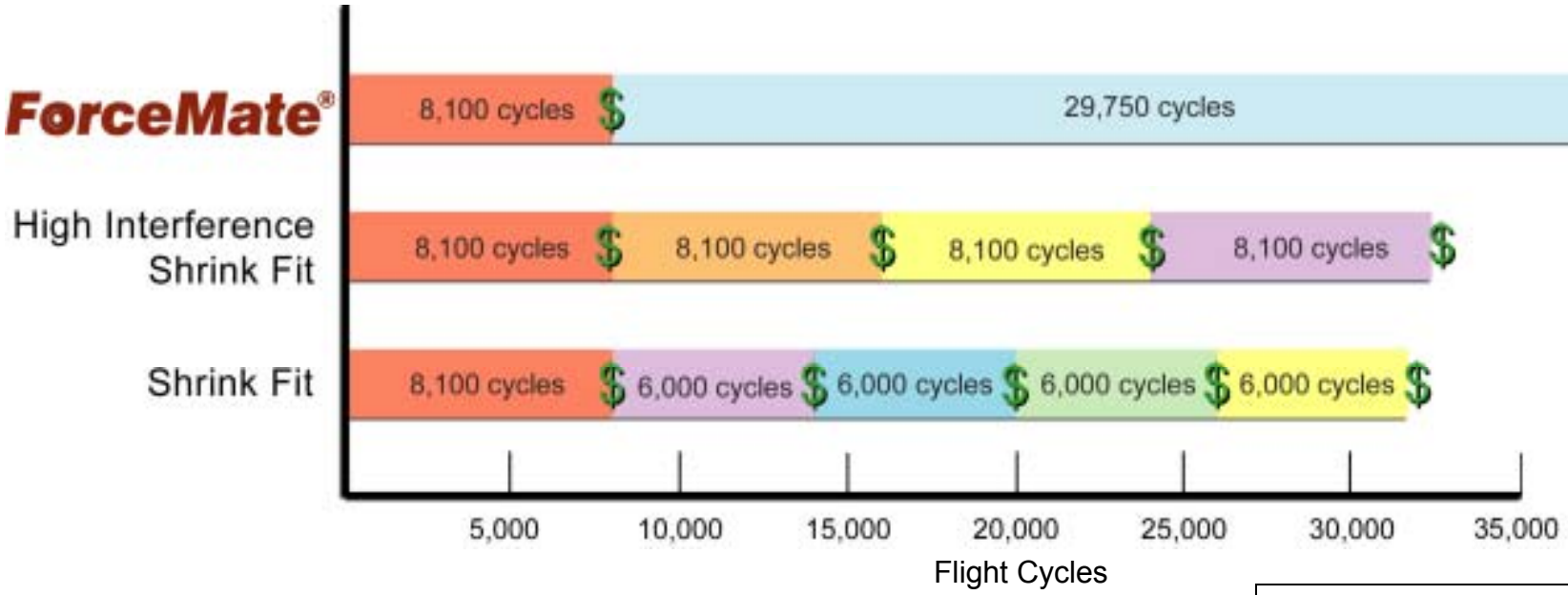
Material: 2024 T3

Hole Dia: 0.312 in

Stress: 25 ksi net, R-Ratio: 0.05

Environment: Ambient air

Reduced Inspections
Engine Pylon Example



- ForceMate bushings replaced shrink fit plus roller-swage bush
- Rework time cut to hours rather than days
- Most significant was extended inspection intervals

ForceMate eliminates costly inspections

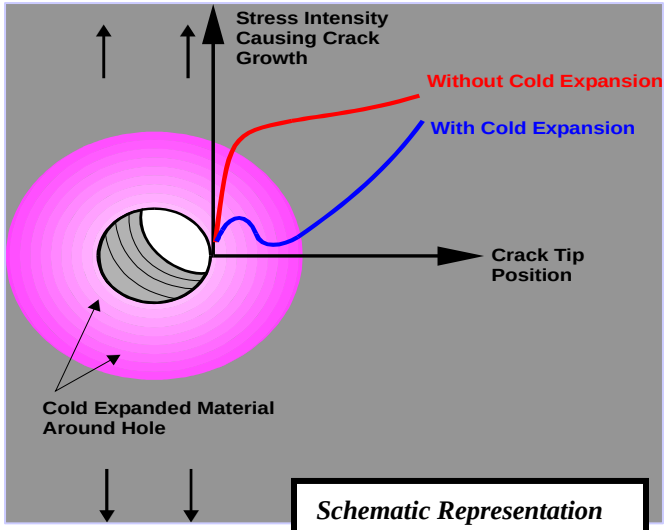
AH-1W COBRA

Stub Wing Lug Attachment

- Production and overhaul retrofit to increase fatigue life of wing from 1500 to 4000 hours
- Use of ForceMate bushings realized operating and support cost savings of $24.1 to $44.3 million

Fatigue Crack Abatement

Reduction in Crack Tip Stress Intensity



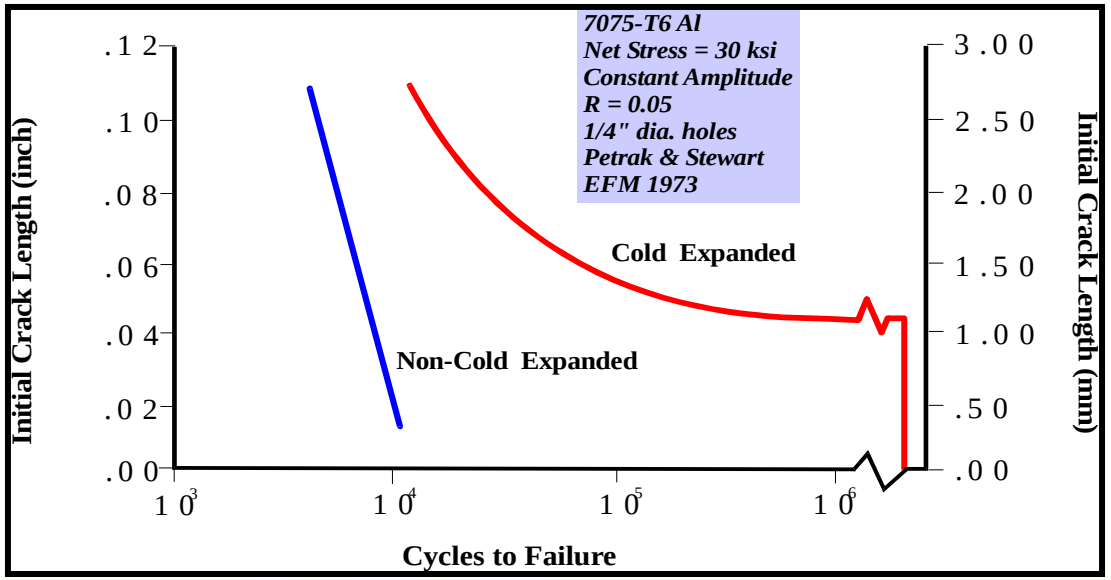
Schematic Representation

Report G. Clark, DSTO ARL, AUST.

1991 Fatigue of Engineering Materials

The large zone of residual compressive stress

- Improves damage tolerance
- Reduces stress intensity factor range (ΔK)
- Retards or arrests crack growth



Durability and Damage Tolerance (DADTA) Benefit

- **USAF DADTA* Approach**

  – **Assume 0.050-inch initial flaw**

When hole cold expansion used

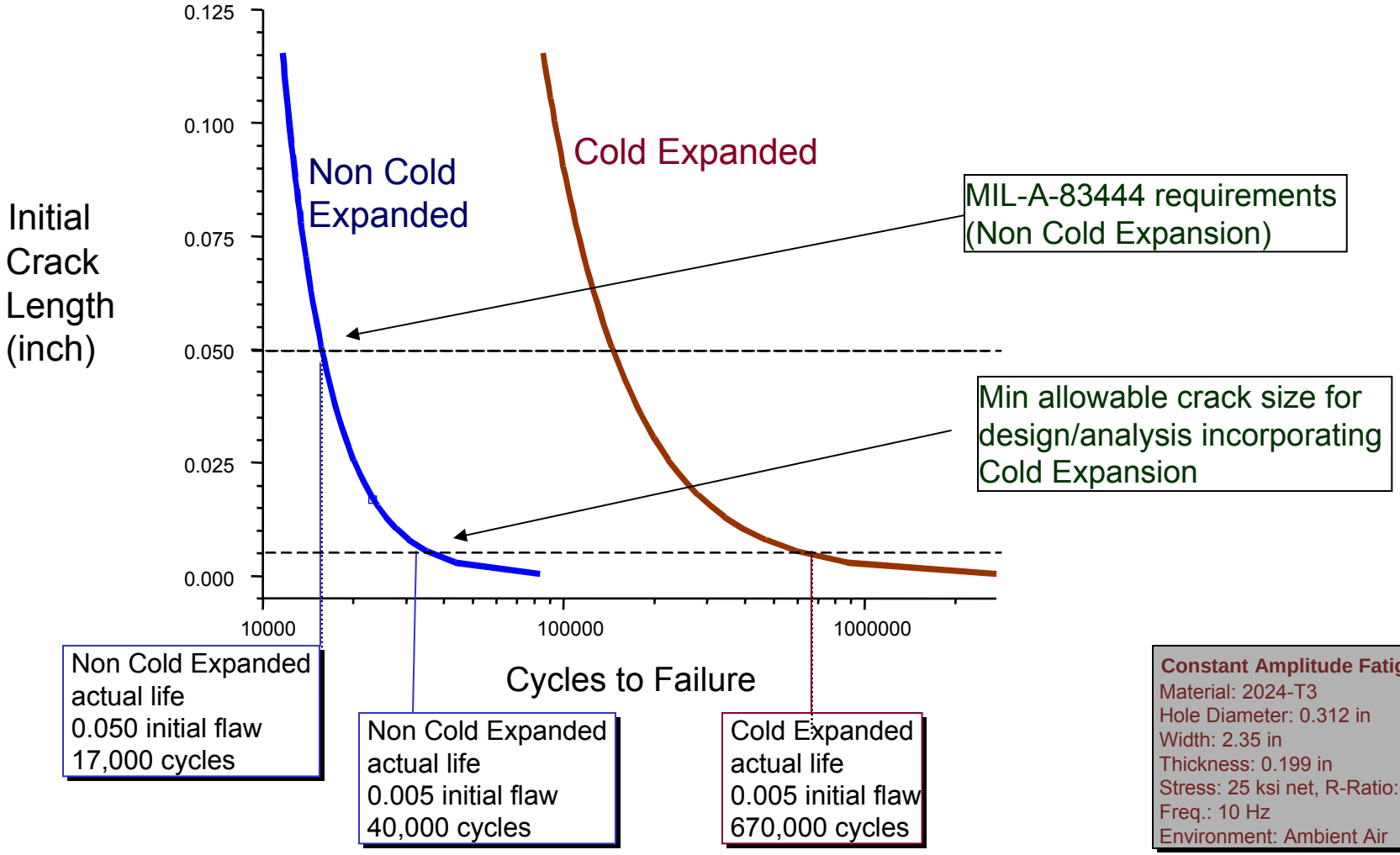
– **Allow smaller initial flaw**

– **Typically 0.005 inch**

Very conservative analysis method

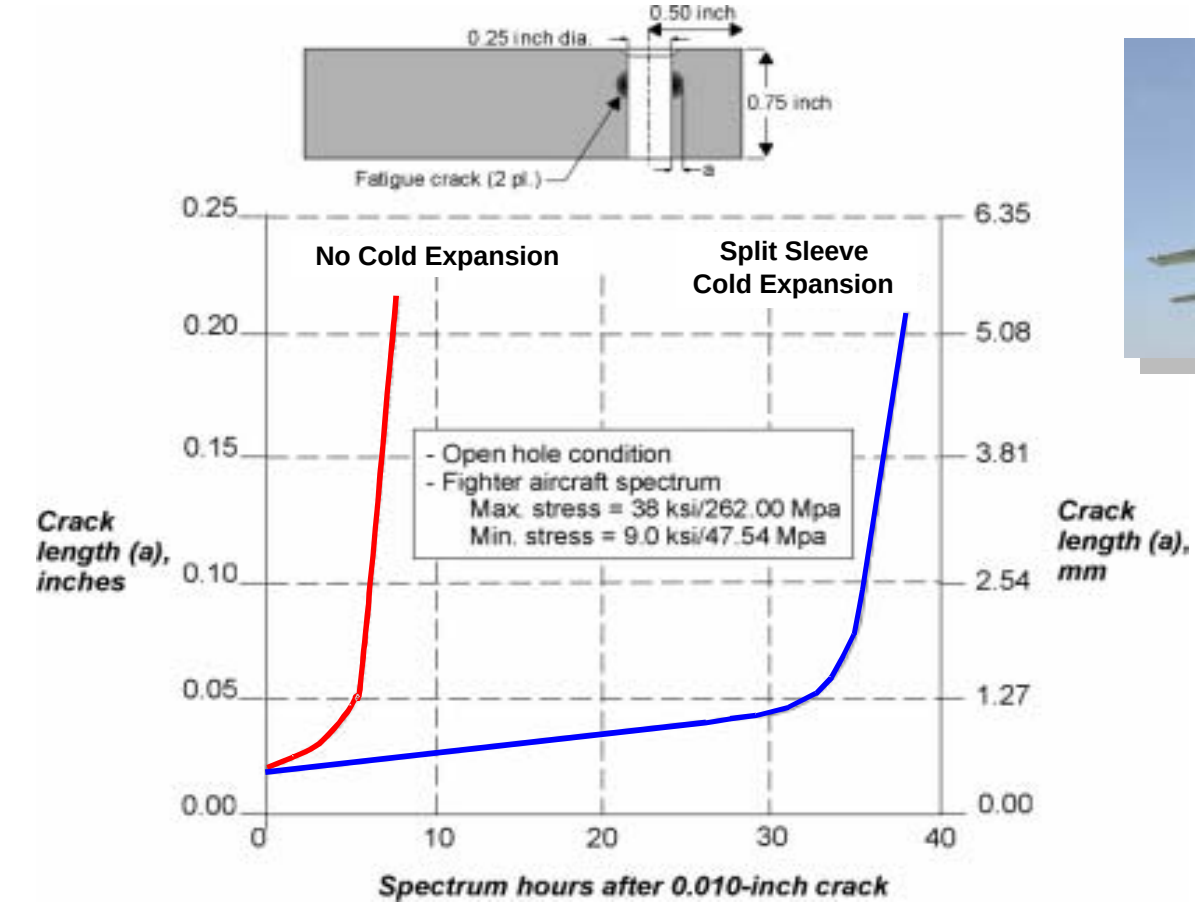
*MIL-A-83444, MIL-STD-1530

Conservatism of USAF DADTA Approach



Constant Amplitude Fatigue Test
Material: 2024-T3
Hole Diameter: 0.312 in
Width: 2.35 in
Thickness: 0.199 in
Stress: 25 ksi net, R-Ratio: 0.05
Freq.: 10 Hz
Environment: Ambient Air

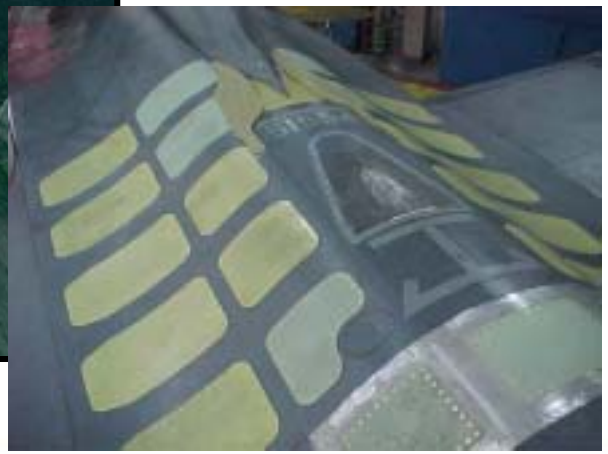
Damage Tolerance Benefits; Fighter Aircraft Study



Ref: Rich, D. L. and Impellizzeri, L. F., "Fatigue Analysis of Cold Worked and Interference Fit Fastener Holes," ASTM STP 637 1977

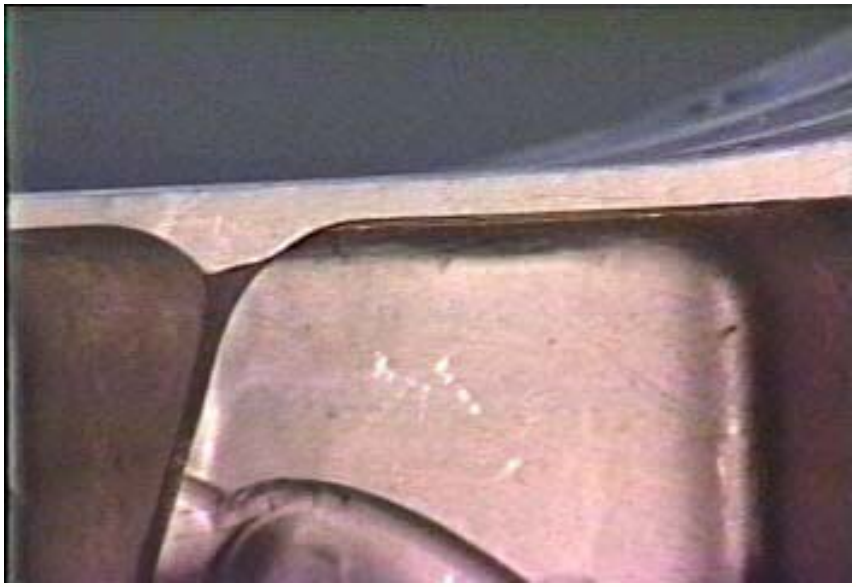
Repair of F-16 Fuselage Access Panel Riveted Nut Plates

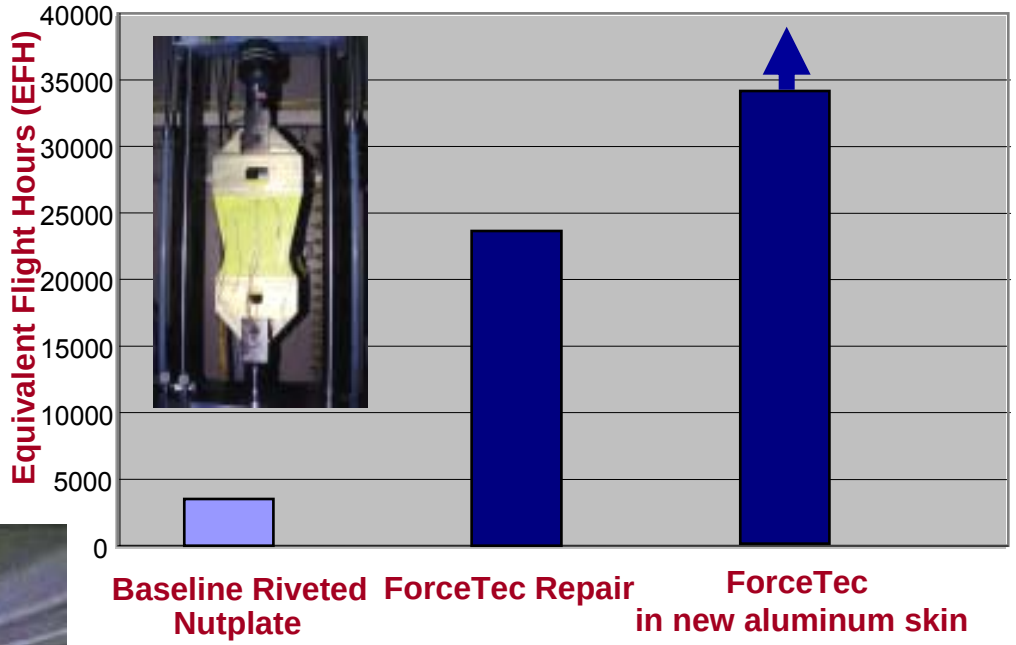
Fighter Doors Program



Fatigue Test Results

Sealed ForceTec Rivetless Nutplate Installation





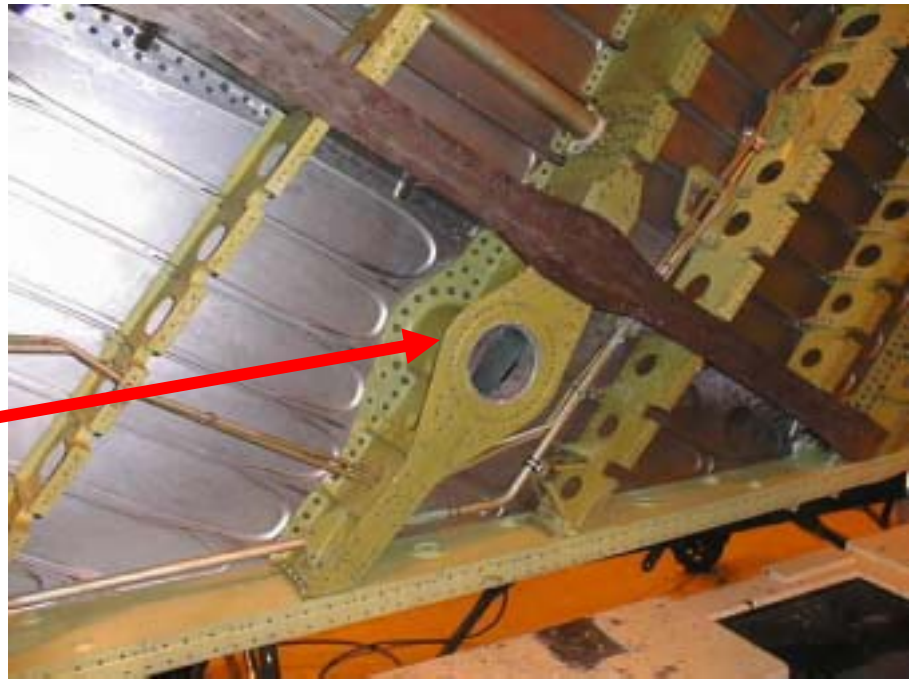
Home Plate Specimen

Corrosion Abatement

- Cold expansion does not stop corrosion however, it can mitigate the damage in holes if not too severe by allowing removal of damage and installation of oversize fasteners
- ForceMate bushings can repair/resize the hole to nominal size

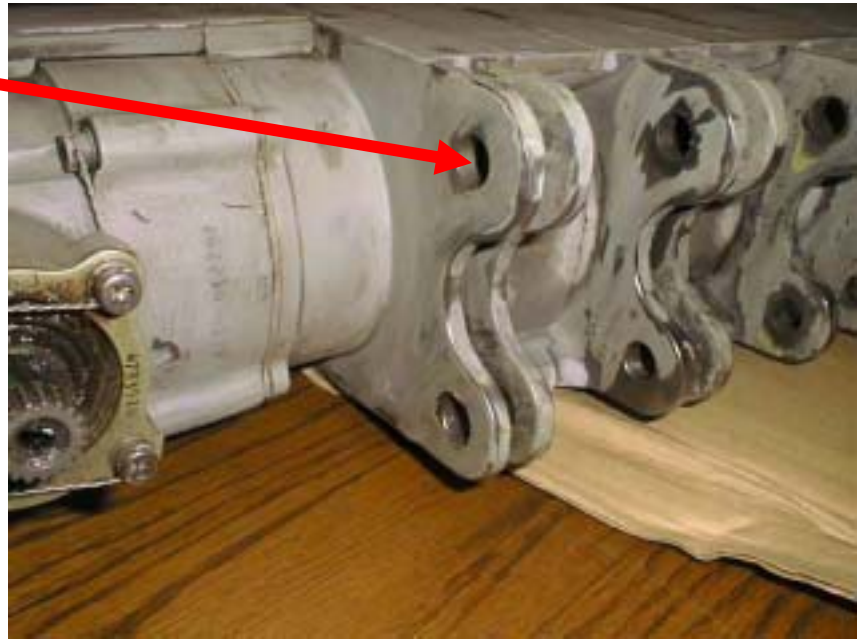
ForceMate Solution
Wing Weapon Pylon

- FTI ForceMate solves bushing corrosion problems
  - Large 5 ½” bushing
  - “BlueCoated” for anti-fretting



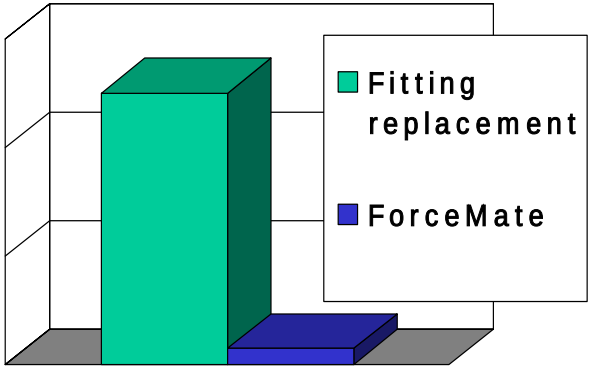
F-18 Wing Fold Transmission ForceMate Repair Solution

- Wing fold transmission repair using FTI ForceMate bushings
- ForceMate allows repair of corrosion problems without removal of “slices”



ForceMate Bushing to Repair Rainbow Fitting Corrosion

Most common cause of fitting replacement is corrosion. USAF ForceMate allows fittings to be repaired on aircraft versus being scrapped



Graph represents cost per aircraft difference

Cost of tooling recovered on first aircraft completed

C-130 Cargo Ramp Corrosion

- **Problem:** Corrosion in attachment of sloping longeron typically requires longeron replacement
- **Solution:** Corrosion in holes removed and holes restored using expanded bushings
- **Savings** exceed $75,000 per fitting restored

Corroded fitting

Repaired fitting

Lug Durability/Bushing migration

- **ForceMate® Induces beneficial residual stresses in parent material**
  - **Increased fatigue life & damage tolerance**
- **Consistent high interference fit**
  - **Provides greater resistance to rotation, fretting and push-out**

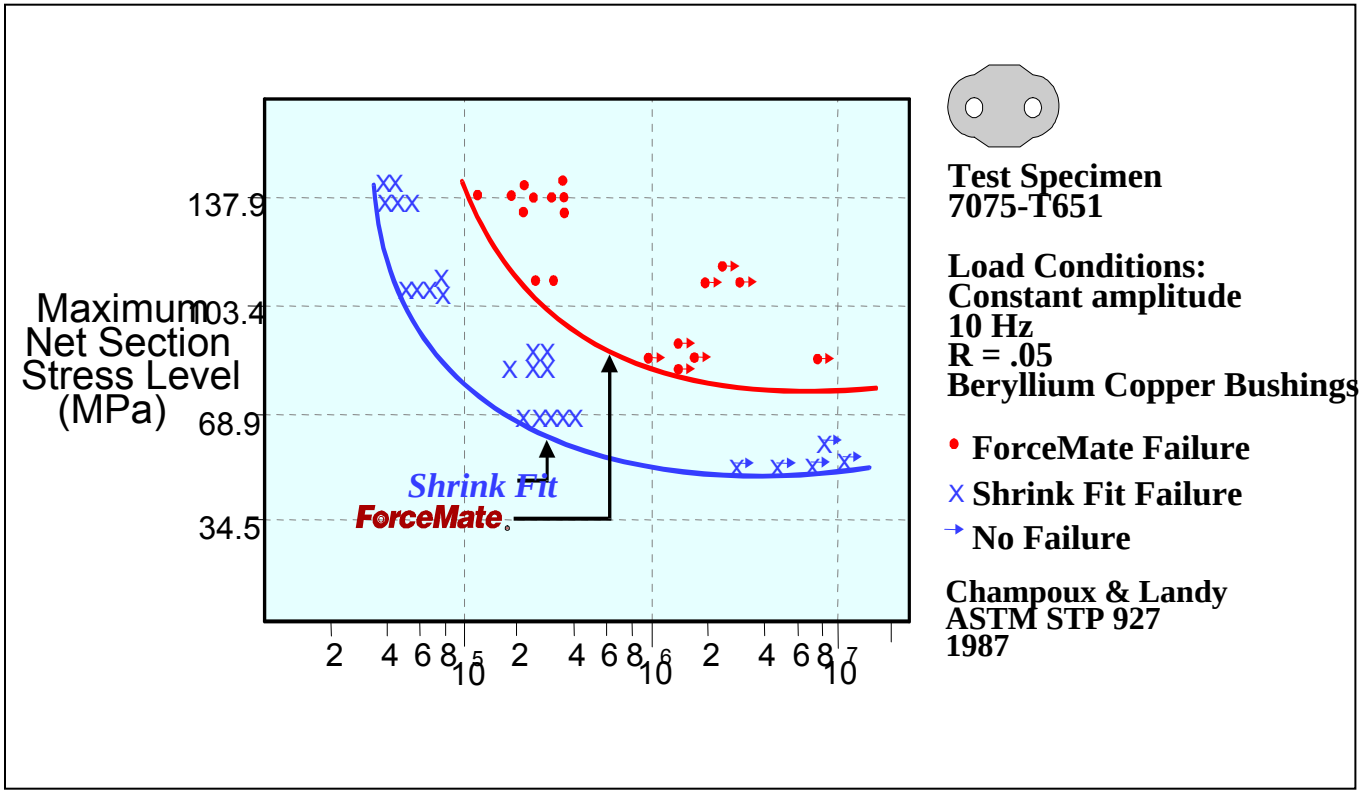
Typical lug failure from fretting induced fatigue

100,000cycles @ 17 KSI

Same bushing installed using ForceMate

1,000,000 cycles @ 21 KSI

Typical Fatigue Life Comparison Shrink Fit and ForceMate Bushings



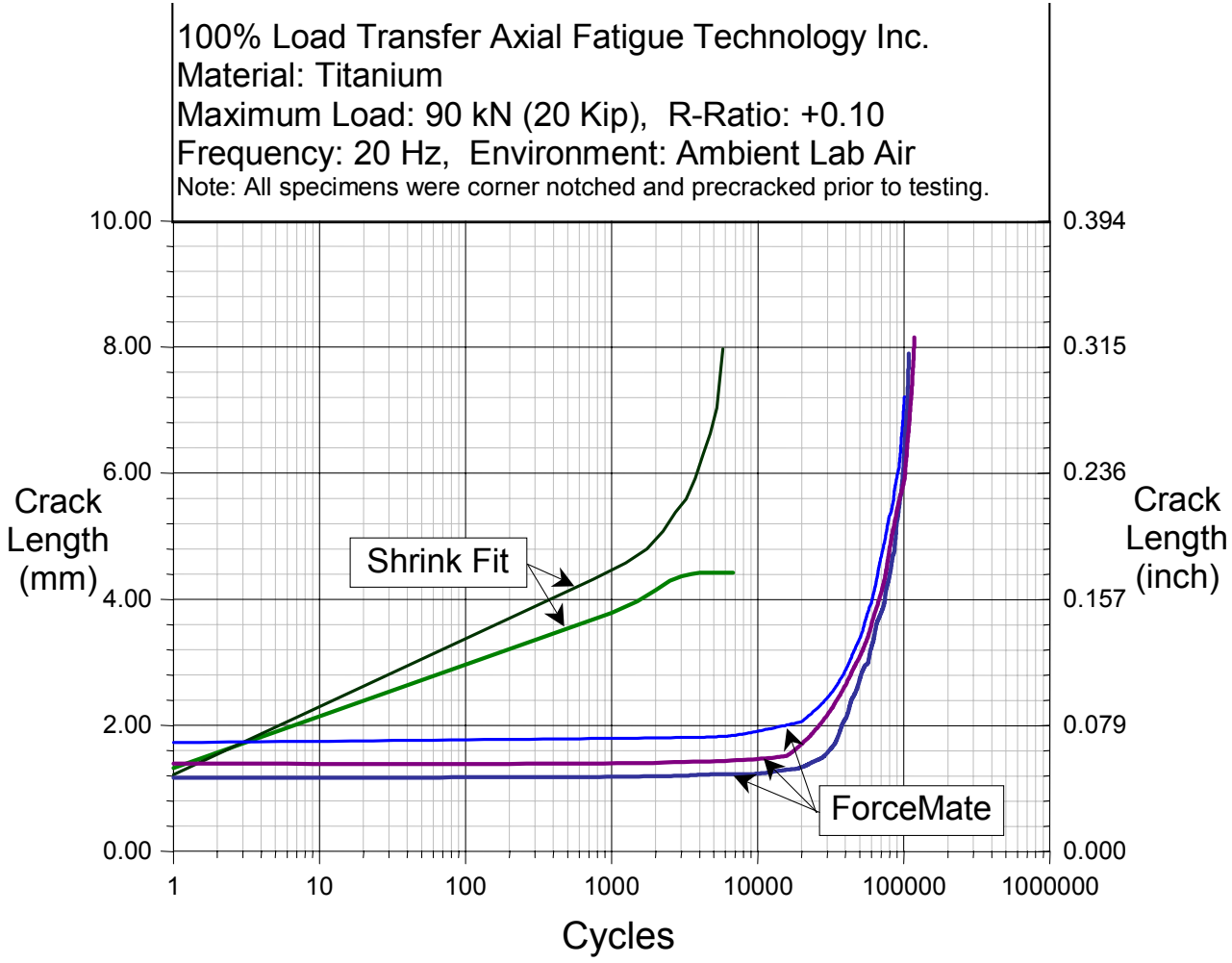
Test Specimen
7075-T651

Load Conditions:
Constant amplitude
10 Hz
R = .05
Beryllium Copper Bushings

- **ForceMate Failure**
- **Shrink Fit Failure**
- **No Failure**

Champoux & Landy
ASTM STP 927
1987

ForceMate Bushing Damage Tolerance



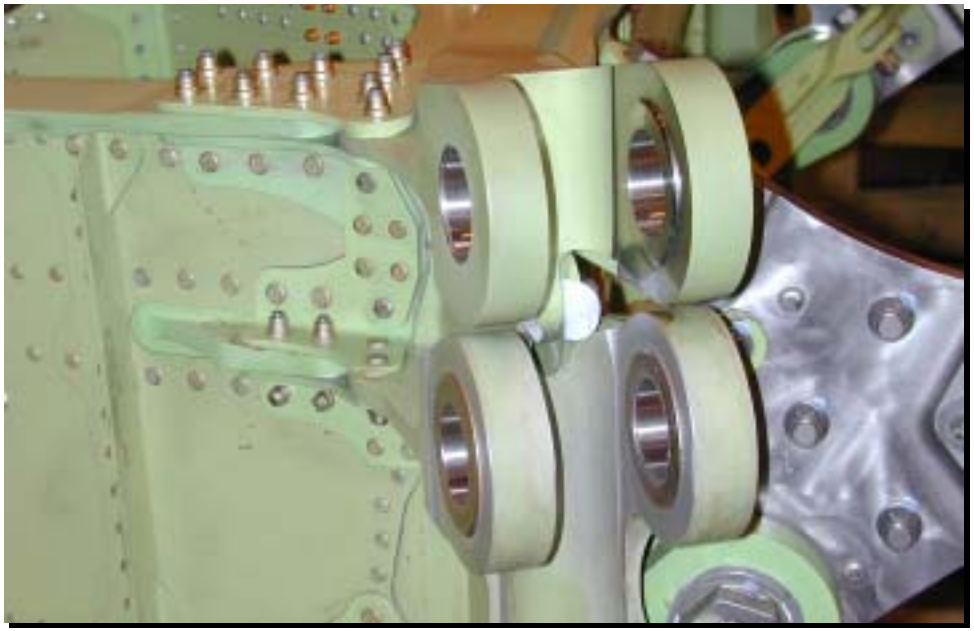
- **17-4 stainless steel ForceMate bushings**
  - –28.5 mm (1-1/8 inch) pin diameter
- **Titanium lug specimens**
  - –Pre-cracked with corner flaw in hole
  - –Two lugs with outer edge cracks

ForceMate crack growth life improvement - 20:1

Horizontal Tail Attachment Lugs

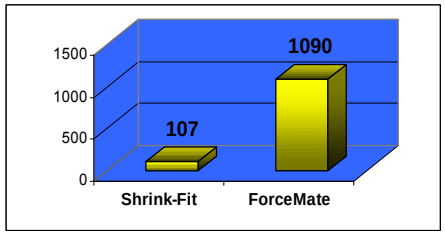
Bushing migration and subsequent corrosion

- Migrating bushings
  - Sealant bond breaks
  - Corrosion results
  - Old process was recurring inspections, and fitting replacement when beyond limits
- ForceMate repair
  - Migration is eliminated
  - Sealant bond remains
  - Corrosion in lug bore is eliminated



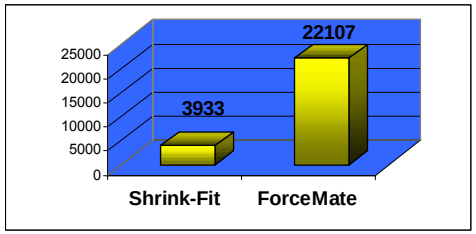
Comparative Performance to Shrink-Fit Bushings

Torque



10.2 : 1 Improvement

Pushout

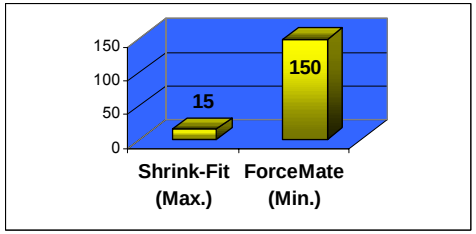


5.6 : 1 Improvement

Fatigue

> 10:1
at 25% increase in stress level

Vibration



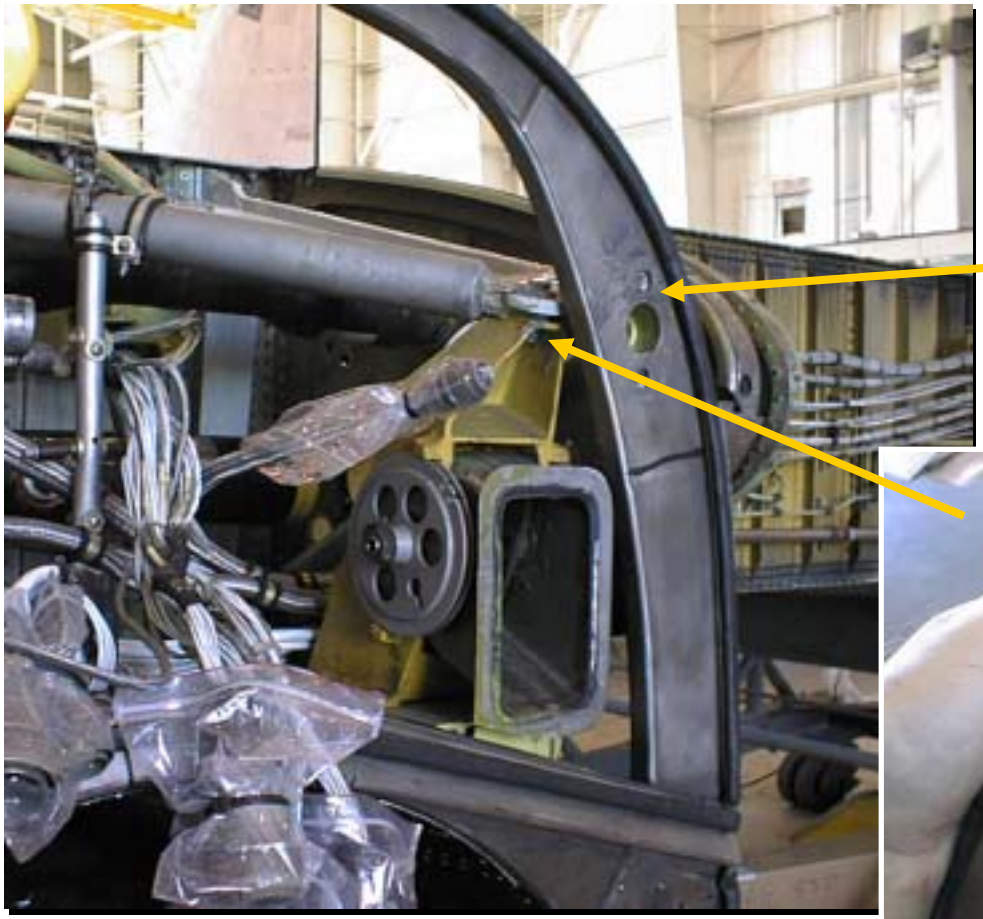
10 : 1 Improvement

Engine Strut ForceMate Modification

- B-52 fleet has been modified
- KC-135 modification in-work

•Modification eliminates fatigue inspection of strut attach locations

C-130 Truss Mount Cone Bushing Hole and Sway Brace Attachment



ForceMate Bushings saved 150 maintenance man-hours per truss

Component Replacement
USAF Savings

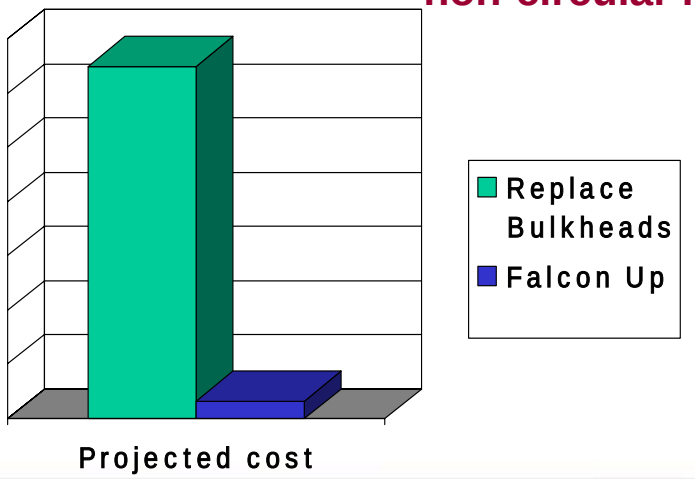
- C-130 Rainbow Fitting
- F-16
  - Upper Fuselage skins
  - Pylon Rib
  - Falcon Up – bulkhead replacement
- KC-135 Wing skin replacement
- Vertical tail LE spar

F-16 Falcon UP

- F-16 Wing carry through bulkheads
- Fatigue cracks found in the durability test, and in the field

Cold expansion of non-circular holes

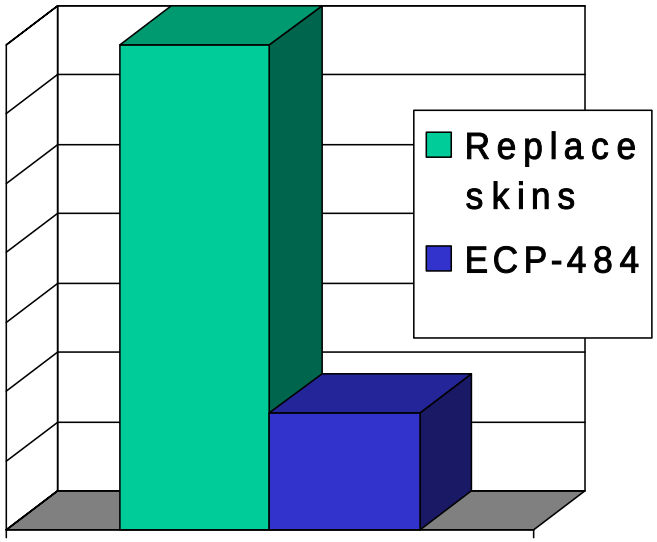
- Next Best Alternative – replace bulkheads
- Falcon UP = Split Sleeve Cold Expansion to size, less than 10% of the cost



KC-135 – ECP-484

- Lower wing skin cracking in the outboard wings

- **Option**: Skin or wing replacement
- **Solution** – Split Sleeve Cold Expansion to size – Less than 1/4 of the cost to implement



Projected cost

ForceTec Riveted Nut Plate Replacement

Leading Edge attach holes damaged and ovalized

- Need to install new LE
  - Current method would require over sizing holes to match damaged holes in LE spar
- ForceTec repairs and resizes holes in one operation
- Solves Edge Margin concerns in repair

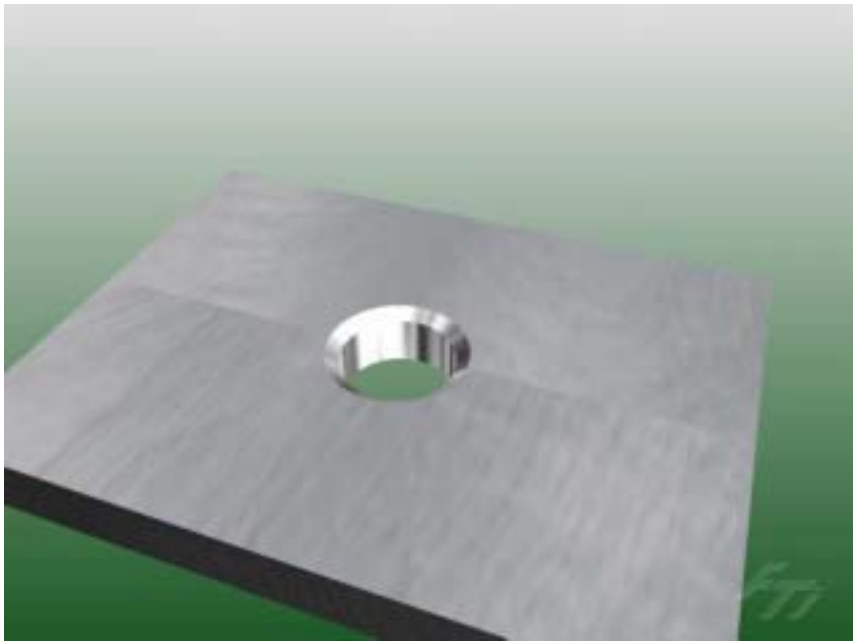
F-16 Wing Fuel Leak Problems

- In 2003 78 USAF aircraft in depot for SLIP mods
- 862 extra days unplanned downtime due to fuel leaks from wing fasteners
  - (ten days per aircraft)

- In addition, operators report fuel leaking as top driver for maintenance effort and reduced mission capability rates.

The Solution - TukLoc

- Advanced blind fastening system with the advantages of a high interference fit from FTI's cold-expansion technology.
- Direct replacement for NAS1734 nuts



Results of Rework

- Sample 8 jets 16 months prior to TukLoc
  - –66 leak occurrences
  - –~3 days downtime/jet
    - Includes sealant cure time
  - –238.4 maintenance man-hours
- **Since TukLoc – zero leaks reported**

Joe Smith, Analyst

OO-ALC 508th Fighter Support Wing

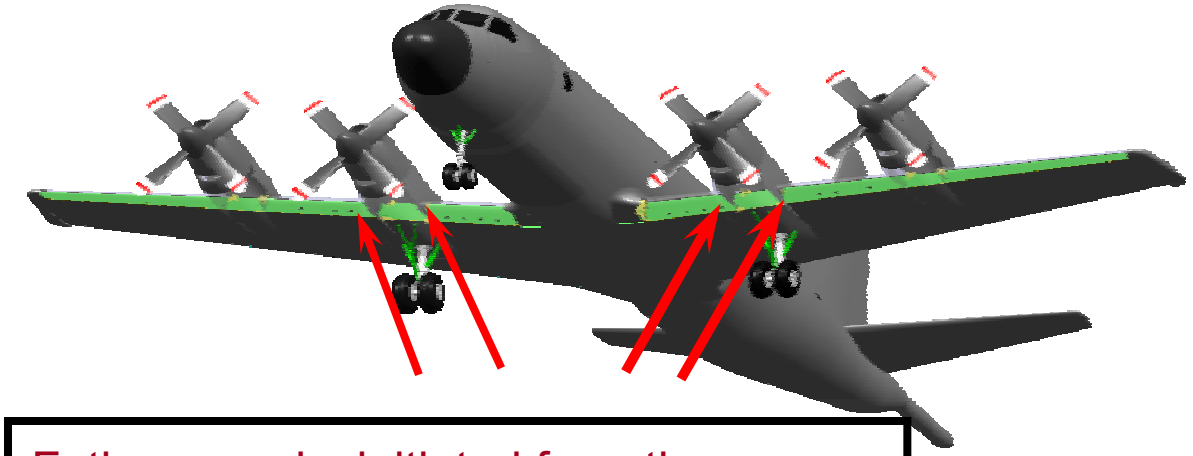
Major Structural Life improvement programs

- Wing structural life extensions
  - KC-135 Wing (ECP-484)
  - T-38 Wing enhancement
  - A-10 Hog-up
  - USN P-3 Orion
  - F-4

T-38 Lower wing skin Countersink Cold Expansion of 200 fatigue critical holes

ForceMate repair of D-panel existing riveted nut plate holes

Life extension mod to P-3 Fleet



Fatigue cracks initiated from the fastener and nutplate satellite rivet holes in the under wing fillet fairing.

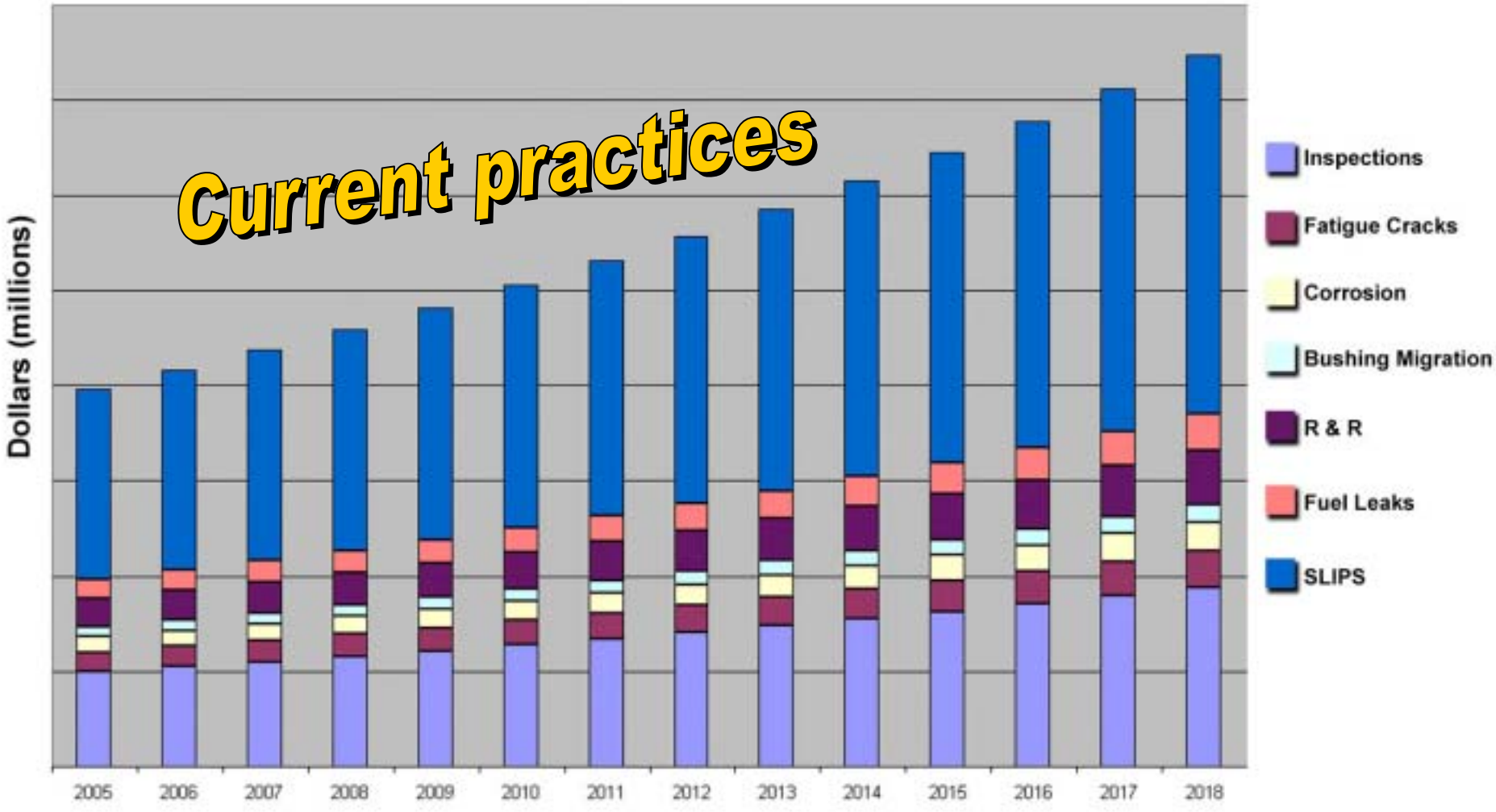
Wing life extended by cold working satellite rivet holes and installing ForceTec Rivetless Nutplates.

Alternative is inner wing box replacement

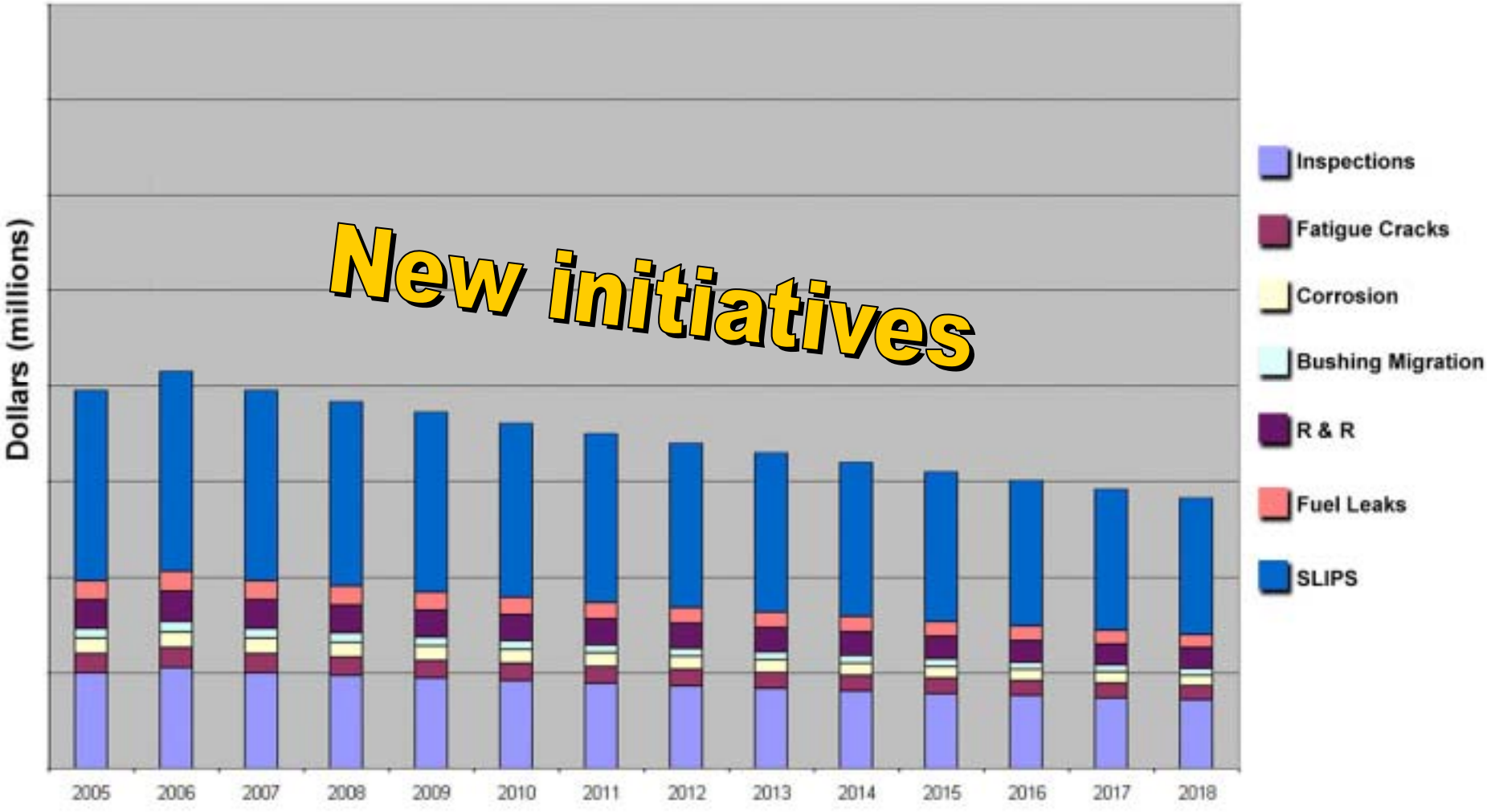
Wing FSFT experienced cracking at 16,785 test hours

<u>Repair Test Demonstrated Life</u>
84,000 Hours

Spiraling Maintenance Costs can be constrained or reduced



Spiraling Maintenance Costs can be constrained or reduced



New Challenges require New Solutions

Exploit the advantages of innovative technologies

Summary

- Innovative thinking needed to reduce the total operating cost of our aging fleet
- Don’t accept “that’s the way things are.”
- New technology is available to reduce costs
  - In all cases, the applications addressed in this briefing were paid for in reduced cost of the maintenance activity.

“Cold expansion technologies can be directly credited with keeping the fleet of military aircraft flying and saving millions of dollars in the process”

Dr. Jack Lincoln

Thank You!

Questions?

Ogden Air Logistics Center

U.S. AIR FORCE

Development of an Inspectable Repair for A-10 Fuel Vent Hole Cracking in Integrally Stiffened Wing Skins and Extruded Spar Caps

Aircraft Structural Integrity Conference

01 Dec 2005

1Lt Larry Ware
A-10 System Program Office
lawrence.ware@hill.af.mil

Co-Authors

- Ms. Kristi Xidas- A-10 Test Engineer, NGC
- Dr. Paul Clark- A-10 Analysis Lead Engineer, USAF
- Dr. Mark Thomsen- A-10 ASIP Manager, USAF

- **Special Acknowledgements**
  - Ken Grube- A-10 Program Manager, NGC
  - Ken Eaton- Regional Manager, FTI

U.S. AIR FORCE

FATIGUE TECHNOLOGY INC.

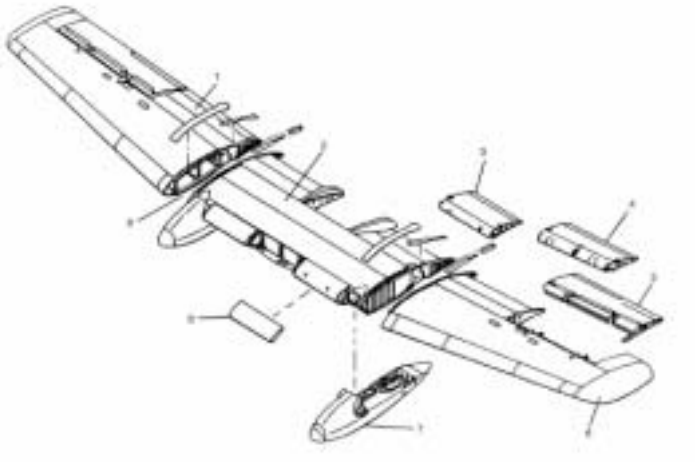
NORTHROP GRUMMAN

Overview

- A-10 Wing Construction
- Repair Development
- Validation Process
- Repair Process
- Cost Benefit
- Other Applications

A-10 Wing

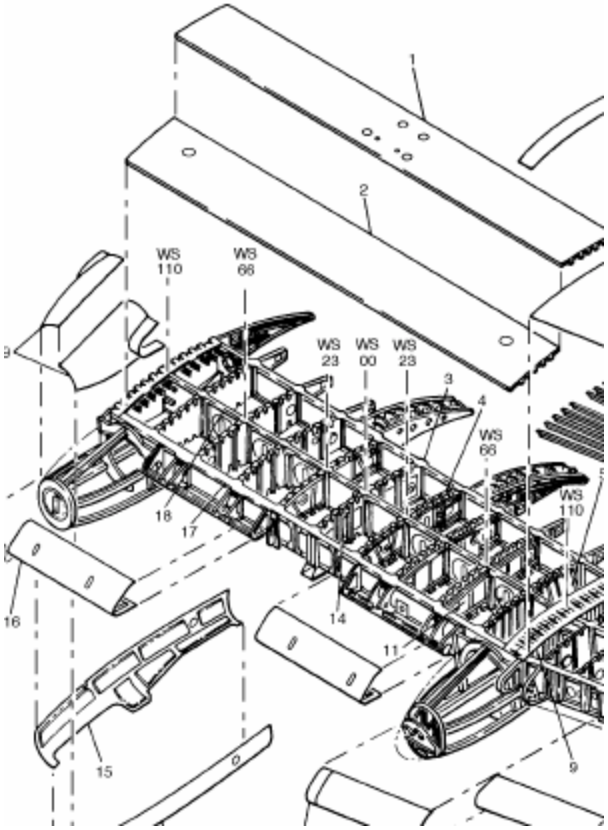
- The A-10 has met its original service requirement and must now serve at least a second
- A-10 wing consists of 3 sections
  - Wing Center Panel (WCP)
  - 2 Wing Outer Panels (WOP)



- Wing Center Panel
  - Approximately 18 ft long
  - Integral fuel cell
  - 2 configurations- thin lower skin and thick lower skin
  - Service Life Extension Program (SLEP 1)

Wing Construction

- **WCP Upper Skin**
  - **2 integrally stiffened machined 7075-T76511 extruded planks**
  - **80 vent holes per wing**
- **Mid-Spar Upper Cap**
  - **T-section 7075-T76511 extrusion**
  - **8 vent holes per wing**

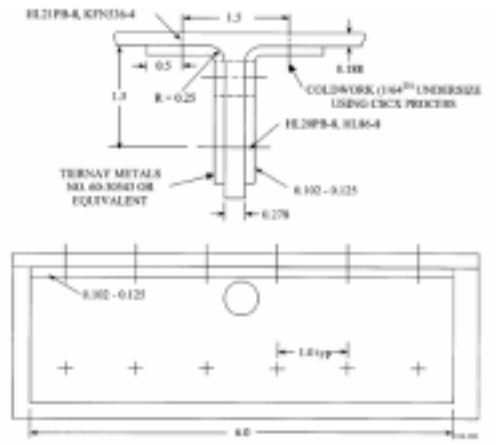


Upper Cover Cracking

- Cracks form on upper and lower sides of holes
- Average of 16 holes per aircraft are found cracked
- Maximum of 64 holes found cracked on one aircraft

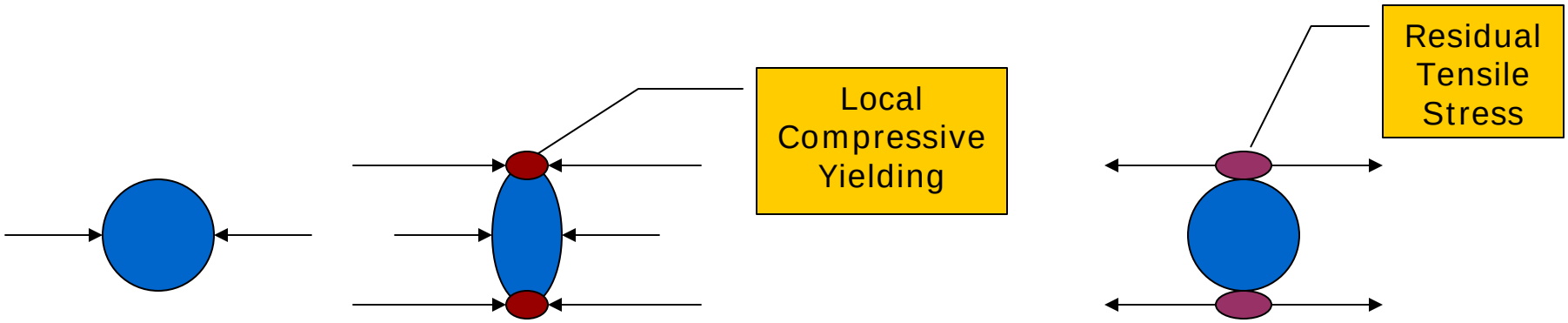
Original Repair

- 2 nested back to back L-angles
- 18 new fastener holes
- 9.5 hours labor and fabrication



Damage Evolution

- **Residual Tensile Stresses around the open hole were the root cause of the cracking**
  - **Initial compressive loading produces localized yielding around vent holes**
  - **Compression cycles combined with residual stresses on top and bottom of holes develop cracks**



Damage Evolution

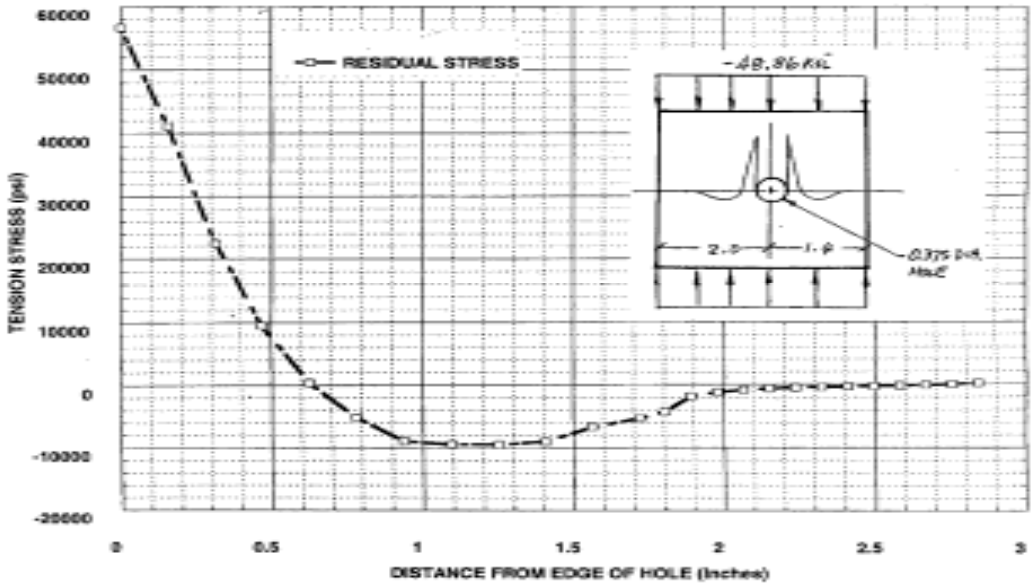


Figure 6-2 Northrop Grumman Report SA220R0438

- **Compression dominated spectrum which also includes some tension loads due to negative bending increases stresses amplitude**

Improved Repair

- New Repair Concept
  - Install steel bushing or plug to prop hole open and still transfer compressive loads
    - Bushing Migration?????
    - Hole Fit????
  - Fatigue Technology Inc. (FTI) ForceMate Bushing Installation
    - Mandrel to expands bushing in the hole
    - Similar to BushLoc
    - No split sleeve required
    - Restrains hole from elongating
    - Better hole fill improves durability

ForceMate® Bushing Installation

Validation Testing

- Installation test

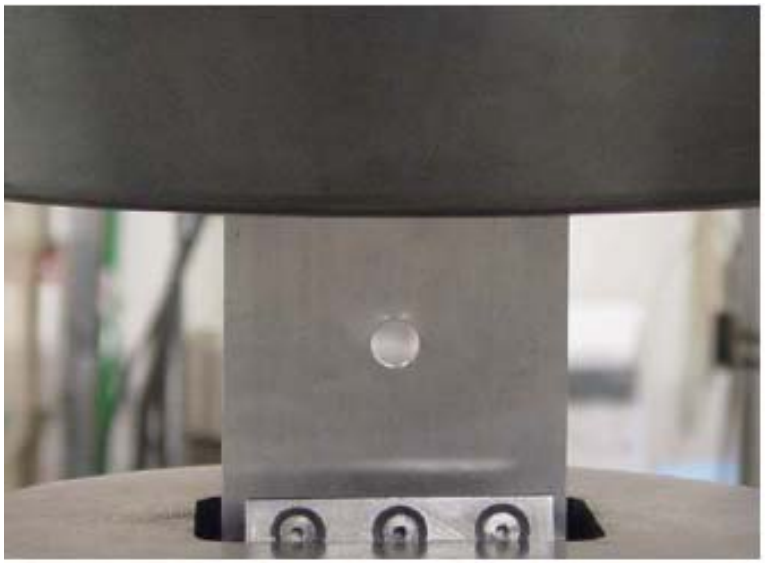
ForceMate® Bushing Installation

- A-10 spectrum fatigue test
  - Flat plate coupon test
  - Semi Component test
- Static Testing
  - Semi Component test

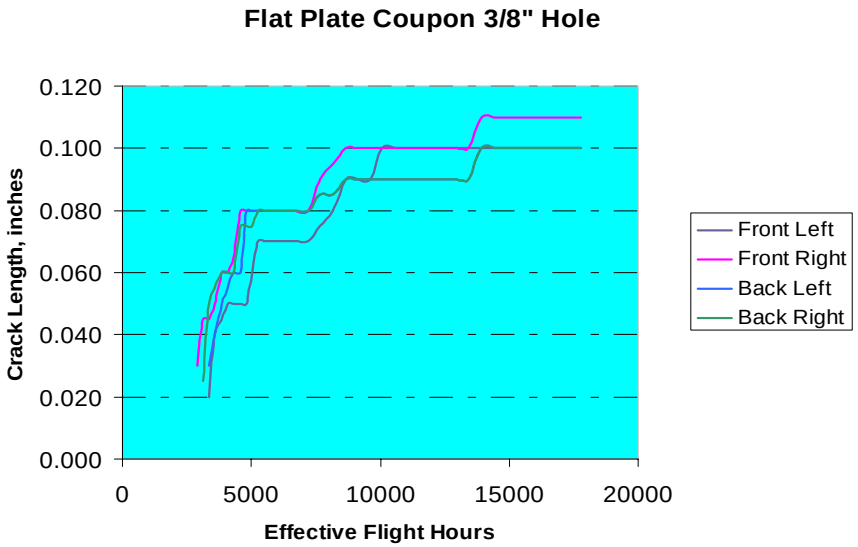
NORTHROP GRUMMAN

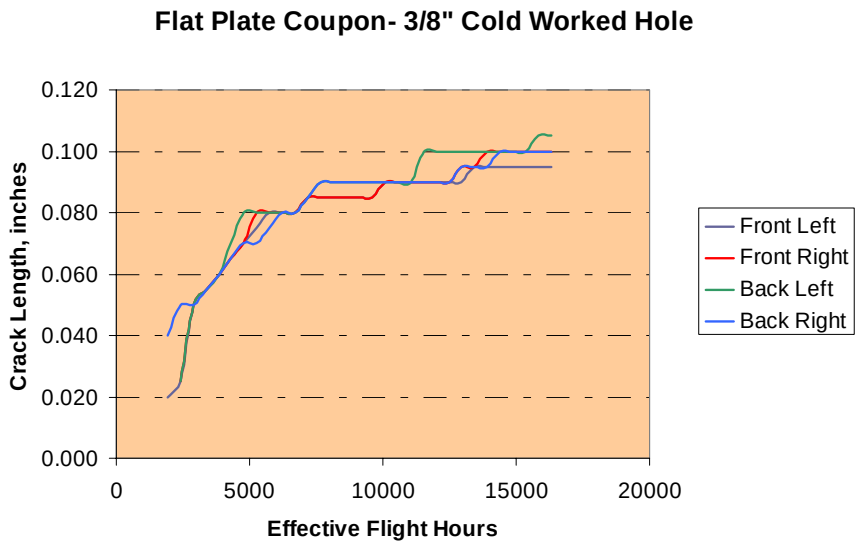
Flat Plate Coupon Testing

- Flat plate coupon testing
  - 3- original .375” baseline holes
  - 3- 3/8” cold worked holes
  - 3- .500” ForceMate bushed holes



Flat Plate Coupon Testing

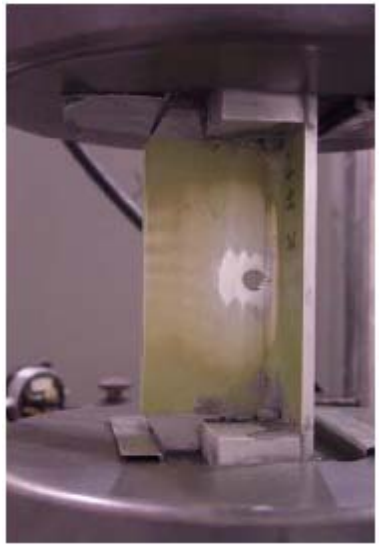




- Cold Worked 3/8” hole showed similar crack growth to Original 3/8” hole configuration. No benefit in compression dominated spectrum
- .500” ForceMate coupon showed no cracks

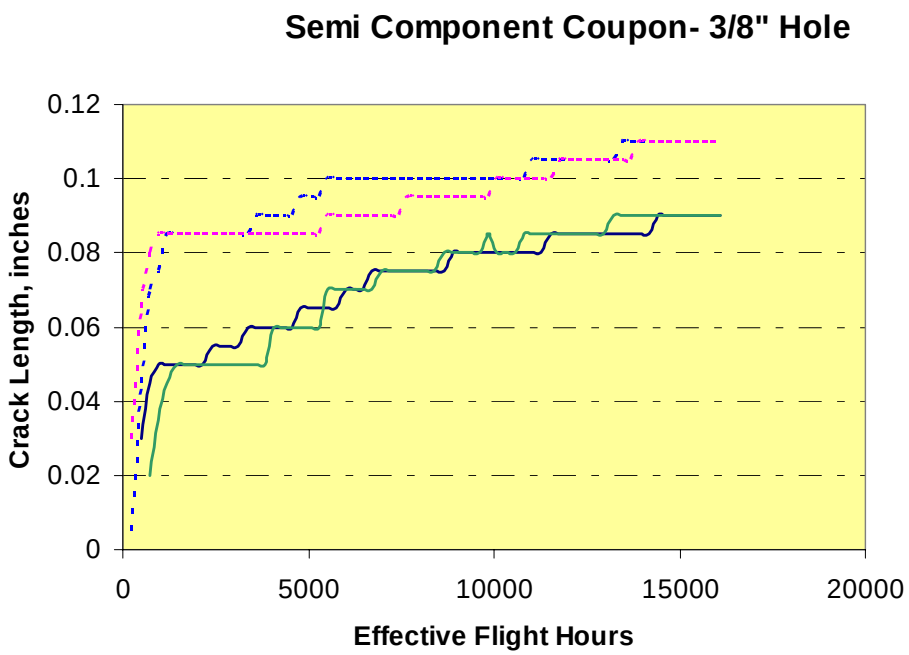
Semi Component Testing

- A-10 loads spectrum testing
  - Semi-component coupons
    - Components came from actual aircraft wing with 5832 flt hrs
    - 3- original .375” baseline holes
    - 3- .500” ForceMate bushed holes
    - 3- 1.000” ForceMate bushed holes



NORTHROP GRUMMAN

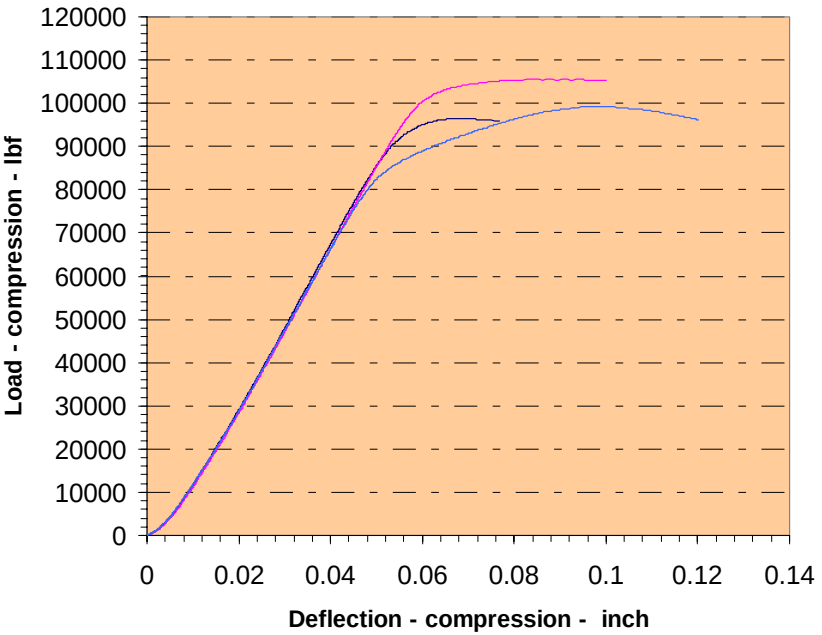
Semi Component Testing

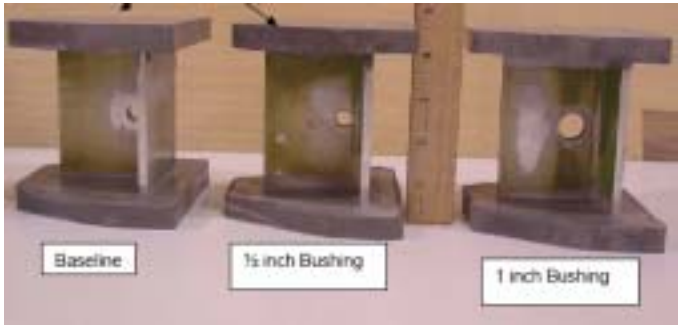


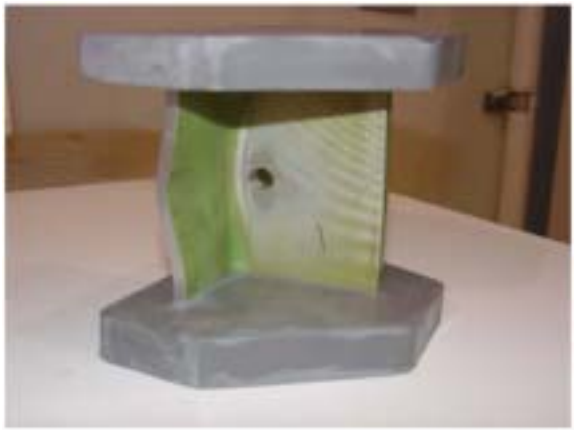
- Solid lines indicate the cracks that are on the side of the hole closest to the skin
- Dashed lines indicate the cracks that are on the side of the hole furthest from the skin

- No cracks were found in either the .500” or the 1.00” ForceMate bushed holes

Semi Component Static Testing







NORTHROP GRUMMAN

Testing Summary

- Flat Plate Coupons
  - Original 3/8” hole- 25,916 EFH=0.122” crack
  - Cold Worked 3/8” hole- 18,480 EFH=0.112” crack
  - ½” ForceMate Bushing- 39,990 EFH= no crack
- Semi-Component Coupons
  - Original 3/8” hole- 24,480 EFH=0.115” crack
  - ½” ForceMate Bushing- 16,800 EFH= no crack
  - 1” ForceMate Bushing- 22,254 EFH= no crack
  - All cracks verified at 35x magnification

NORTHROP GRUMMAN

Testing Summary con't

- Wing Fatigue Test showed similar cracking to semi component tests
  - Fleet cracking has shown larger crack sizes
- Semi Component Static Compression Test
  - Original 3/8" hole configuration
    - Baseline data
  - ½" ForceMate Bushing Installation
    - No loss in crippling strength
  - 1" ForceMate Bushing Installation
    - No loss in crippling strength

NORTHROP GRUMMAN

Repair Process

- **Tooling Requirements**
  - Pre-Reamer
  - Starting Reamer
  - Mandrel
  - Offset Puller
  - Hand Pump
  - Bushing

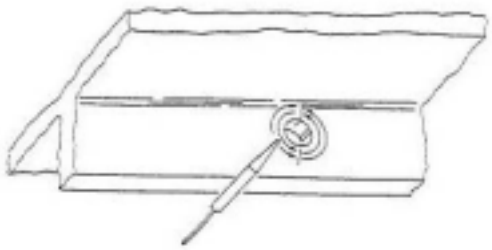
ForceMate® Bushing Installation

- **Repair Steps**
  1. Ream hole with pre-reamer
  2. Ream hole with starting reamer
  3. NDI to ensure no cracks
  4. Install bushing using offset puller and hand pump

Installation

Inspection Capability

- Repair can still be inspected by the current inspection method with the bushing installed
- Due to the success of the tests, inspection interval is now 8000 hrs for the A-10



$ Cost Benefit $

- Original Repair
  - 9.5 hours labor = $937.00
  - Repair components = $48.00
  - Total cost = $985.00
- ForceMate Bushing Repair
  - 1 hour labor = $98.00
  - Bushing cost = $38.00
  - Total cost = $136.00
- Total Savings
  - Per repair- $849.00
  - Per Aircraft (avg. 16 repairs)- $13584.00
  - Remaining SLEP1 aircraft- $3 MIL

Other Applications

- Lower Skin Integral Stringer Fuel Transfer Holes
- Pylon Stud Holes
- Wing Attach Fitting Holes
- Upper Spar Cap Fastener Holes

Summary

- A-10 Wing Construction
- Repair Development
- Validation Process
- Repair Process
- Cost Benefit
- Other Applications

Questions ?

lawrence.ware@hill.af.mil