B-1 Dorsal Longeron Repair Concept Case Study

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BOEING

Outline

B-1 Bomber

- History and Background
- Interim Repair
- Results from an Aircraft Ground Strain Survey
- The Optimization Process used to Develop the Long Term Repair
- Structural and Non-Structural Testing
- Accomplishments and Looking Ahead

Background of Dorsal Longeron Cracks

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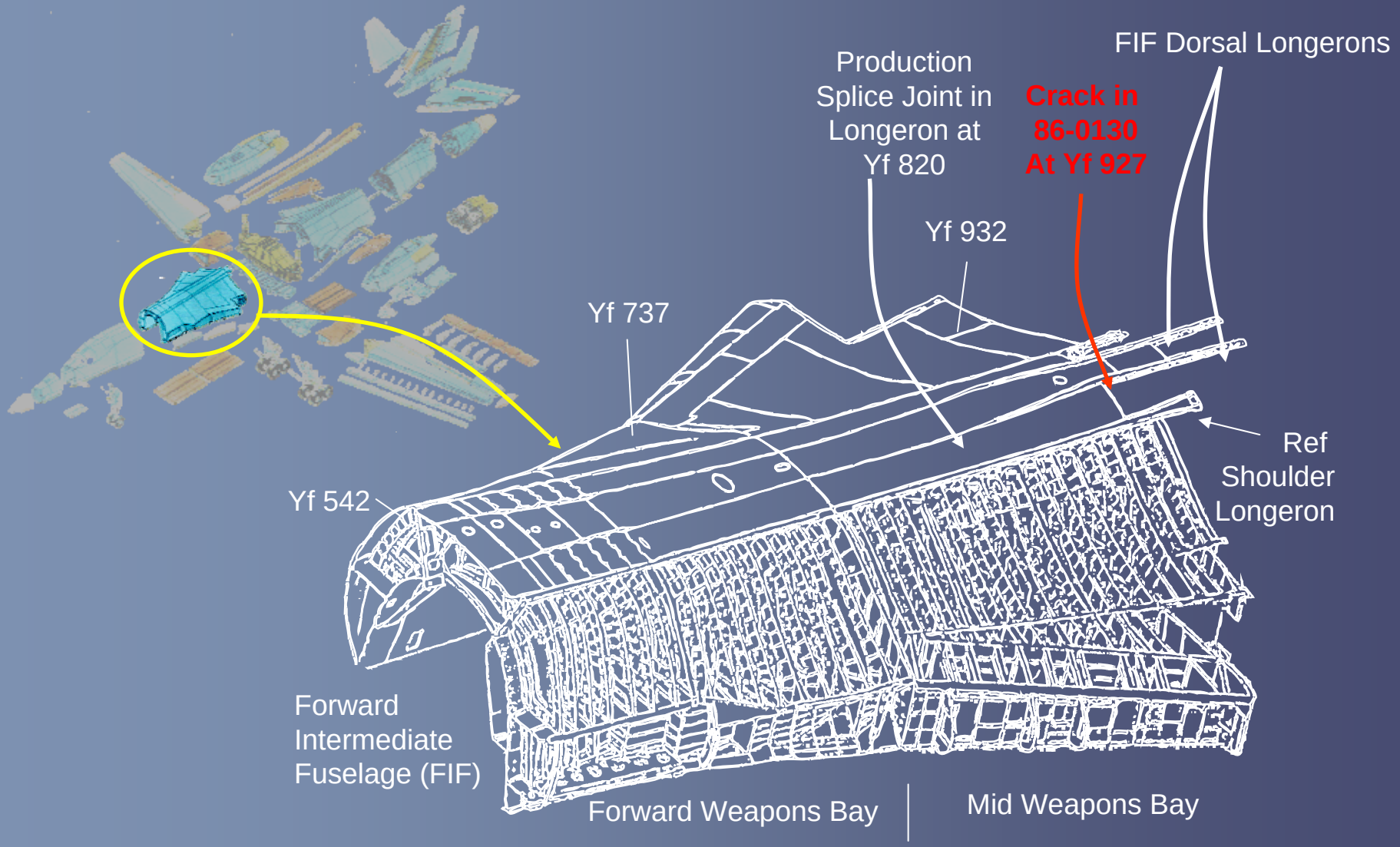
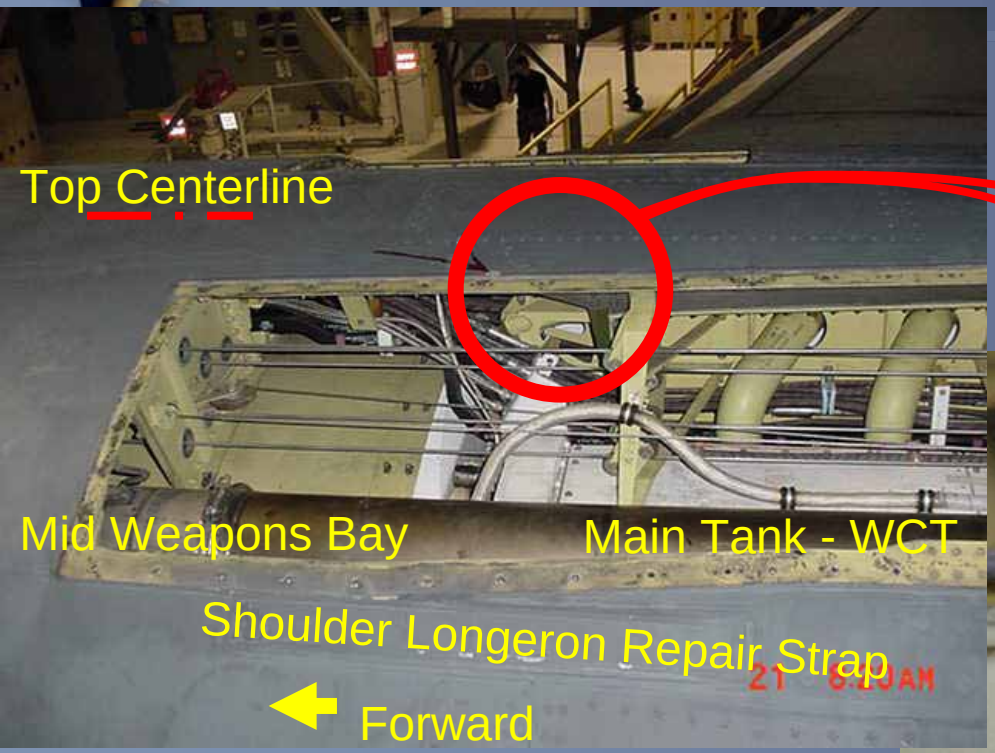
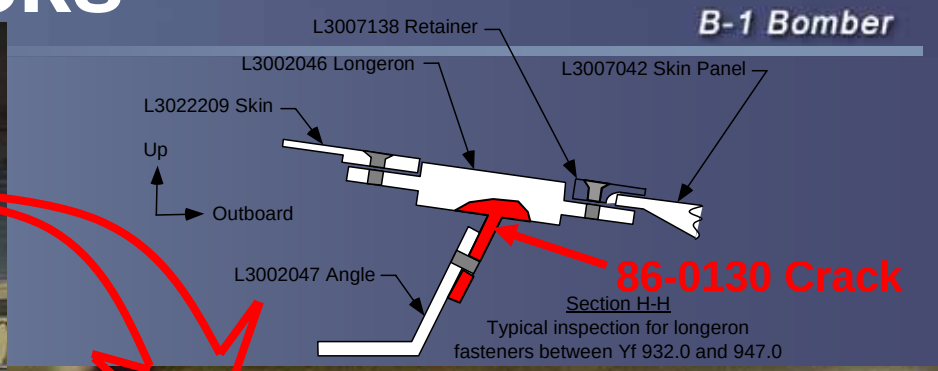


Background of Dorsal Longeron Cracks





Cracks begin at bolt hole and run to bottom of flange. Cracks growing up from bolt hole advance rapidly.

Background of Dorsal Longeron Cracks

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- **Problem:**
  - More than 2/3rds of the B-1 fleet have cracks in the Steel Dorsal Longerons
- **Cause**
  - Aircraft usage more severe than design spectrum
- **Challenges**
  - Permanent repairs urgently needed
    - Cracks growing, numbers increasing
  - Interim bolted strap repairs for cracked caps have limited life

# A/C with…	7/30/2004	8/9/2005
NO Cracks	22	20
1 Crack	20	15
2 Cracks	21	32
Not Insp	4	0
Cracked caps*	2	2

* Aircraft with cracked caps restricted from flight until interim repair performed

Immediate Actions

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- Inspect entire force
- Performed fail safe analysis
- Begin developing interim repair

Safety of Flight Analysis

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- Fail Safe analysis performed to determine what happens if one or both dorsal longerons fail completely
- Analysis concluded that even if both dorsal longerons are failed, shoulder longeron can sustain limit load times dynamic factor provided that the shoulder longeron repair doublers are intact.

Interim Repairs

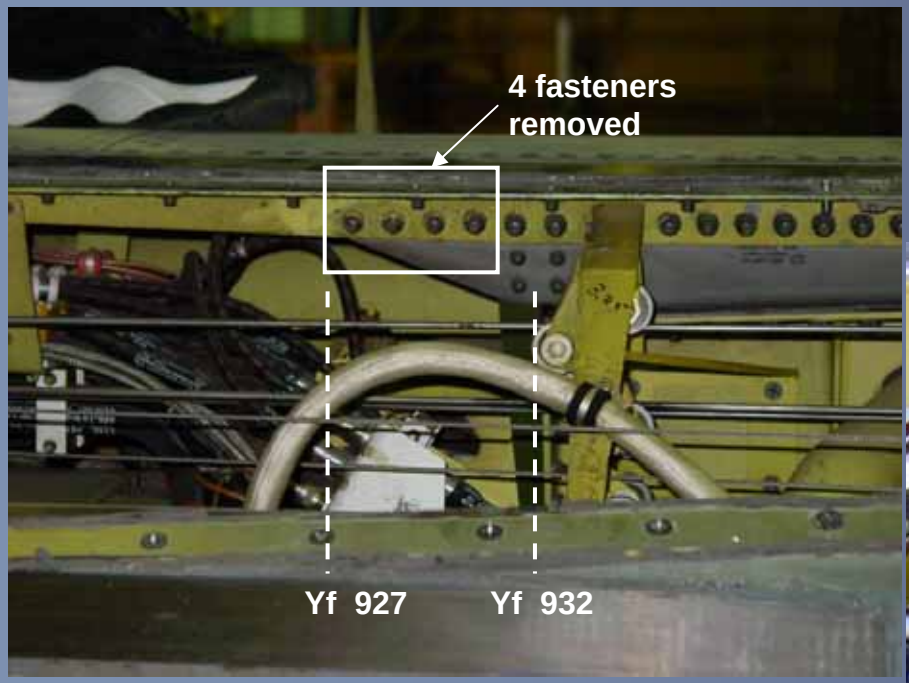
- Various temporary repair options developed depending on condition discovered at inspection
  - Fastener removal / cold working
  - Scallop repair
  - Bolt on doubler repair

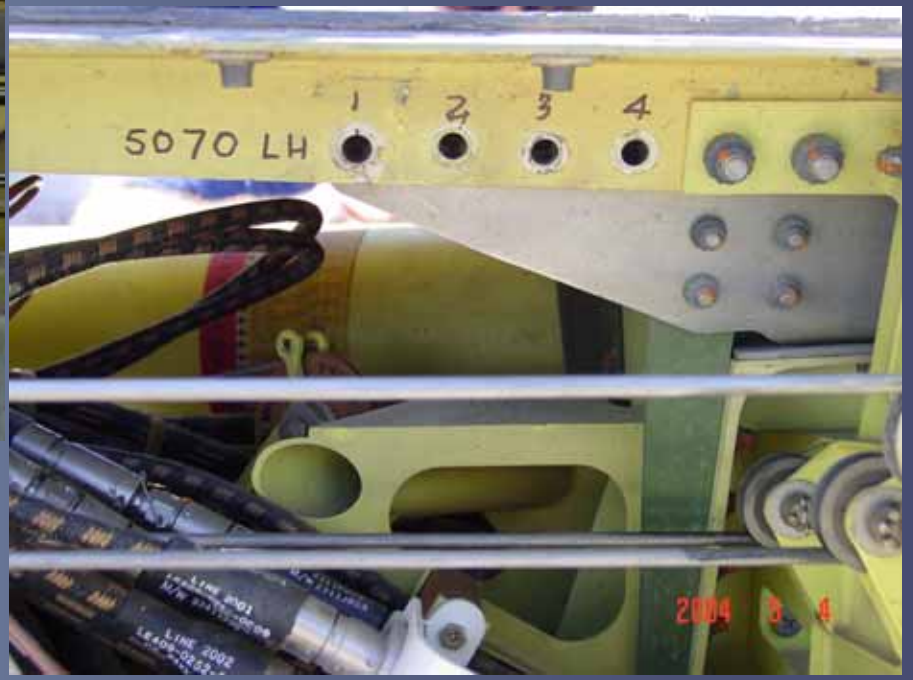
Interim Repairs

- Fastener Removal
  - Full A/C NASTRAN model used to verify concept and effectiveness
  - Local load distribution only
  - No global effect on rest of A/C
  - Fasteners not reinstalled
  - Currently all A/C in force have fasteners removed
- Cold Working 4 holes (TCTO 1B-1B-1337)
  - Remove 5-7 o'clock crack by reaming up to .50" Dia if E.D. is sufficient prior to cold working
  - Fasteners not reinstalled
  - To date three A/C have been cold worked

Interim Repairs

- **Fastener Removal**





Interim Repairs

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- **Scallop Repair**
  - **Mechanica model shows large reduction in stress concentration**
  - **Crack growth analysis demonstrated sufficient life**
  - **Used when crack length beyond that which can be removed by over-sizing hole but no exit crack growing up**
  - **Three A/C have this repair**

Interim Repairs

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Scallop Repair (A/C 85-0065 RHS)

Interim Repairs

Scallop Repair (A/C 85-0073 LHS)

Interim Repairs

- **Bolt on doubler**
  - **Used when exit crack exists**
  - **Extensive Mechanica modeling to verify repair**
  - **Sufficiently restores strength of longeron**
  - **Relatively low predicted life for doublers**
  - **Two A/C have this repair**

Interim Longeron Repair

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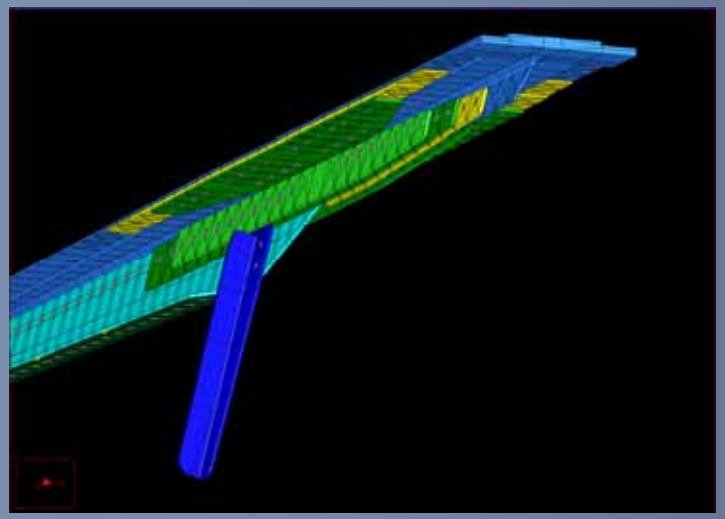

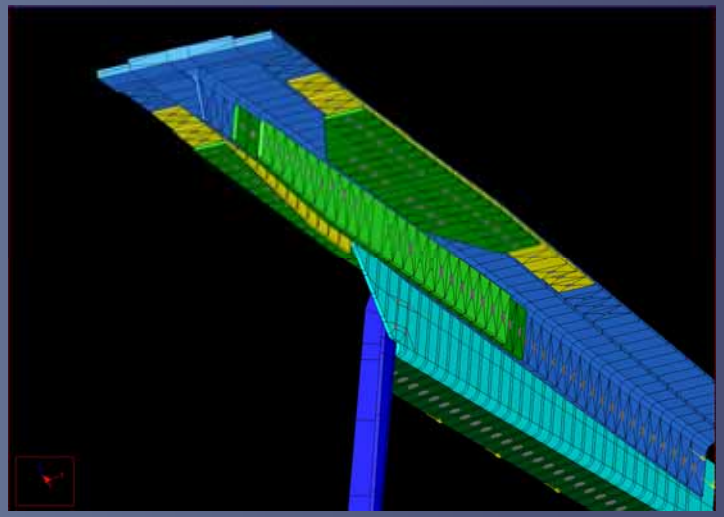

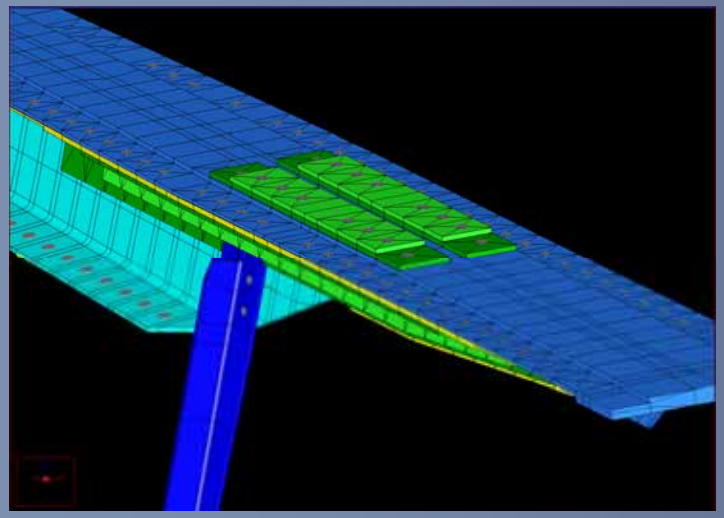

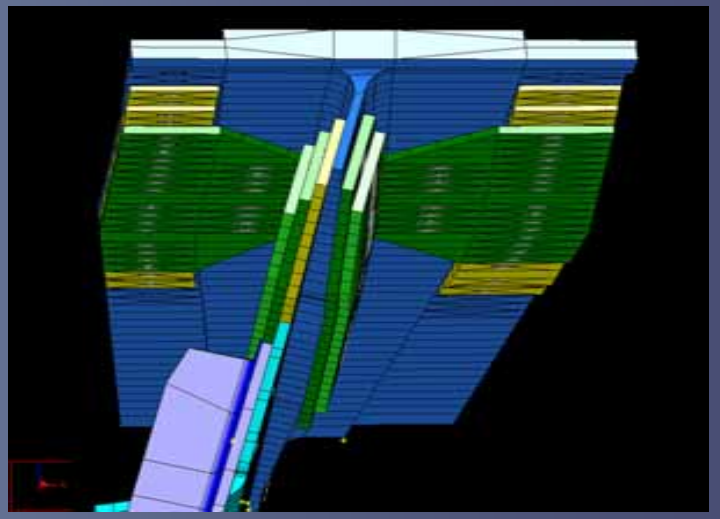

Ground Strain Survey Test

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- Most efficient way to verify loads
  - Known conditions can be reproduced on analysis models
- Results used to fine tune analysis models
- Help to understand cause of cracking

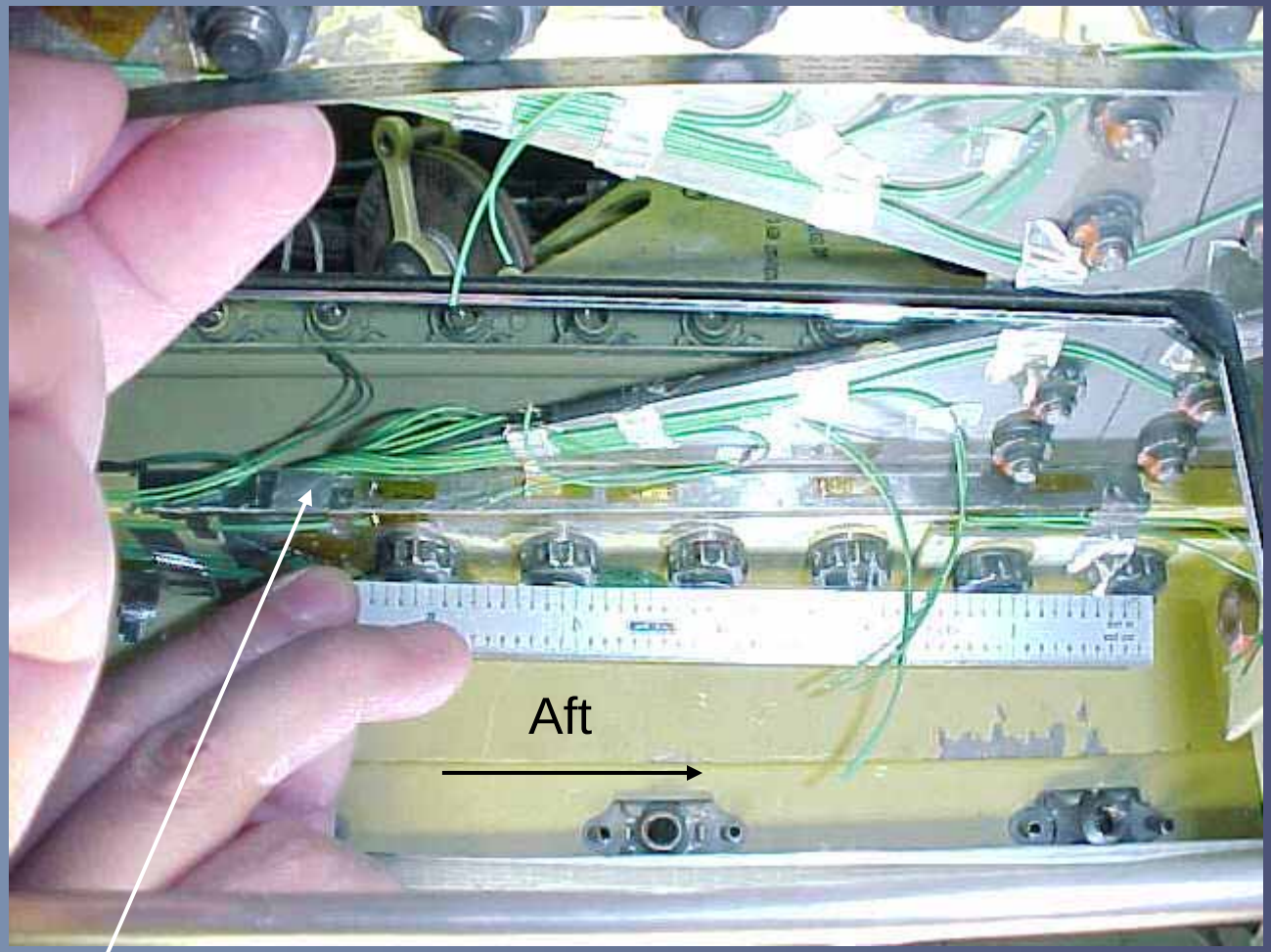
Ground Strain Survey Test

- **Test Sequence**
  1. **Take readings On Gear, leave strain gage system turned on**
  2. **Jacks Aircraft and Take readings**
  3. **Remove 4 bolts while on jacks, leave bolts out, de-jack**
  4. **Take readings On Gear, leave strain gage system turned on**
  5. **Jacks Aircraft and Take readings, turn strain gage system off**
  6. **Re-install 4 bolts while on jacks, de-jack**

Ground Strain Survey Test

- Instrumentation
  - Dorsal Longerons, 13 Left Side, 5 Right Side
  - Shoulder Longerons, 2 Left side, 2 Right Side
  - Total of 22 axial strain gages measuring longitudinal stresses, 1 gage reading vertical stress

Predicted vs Measured Stresses – Gage Locations



Lower Edge Surface of Longeron Standing Leg

Predicted vs Measured Stresses - Model Correlation

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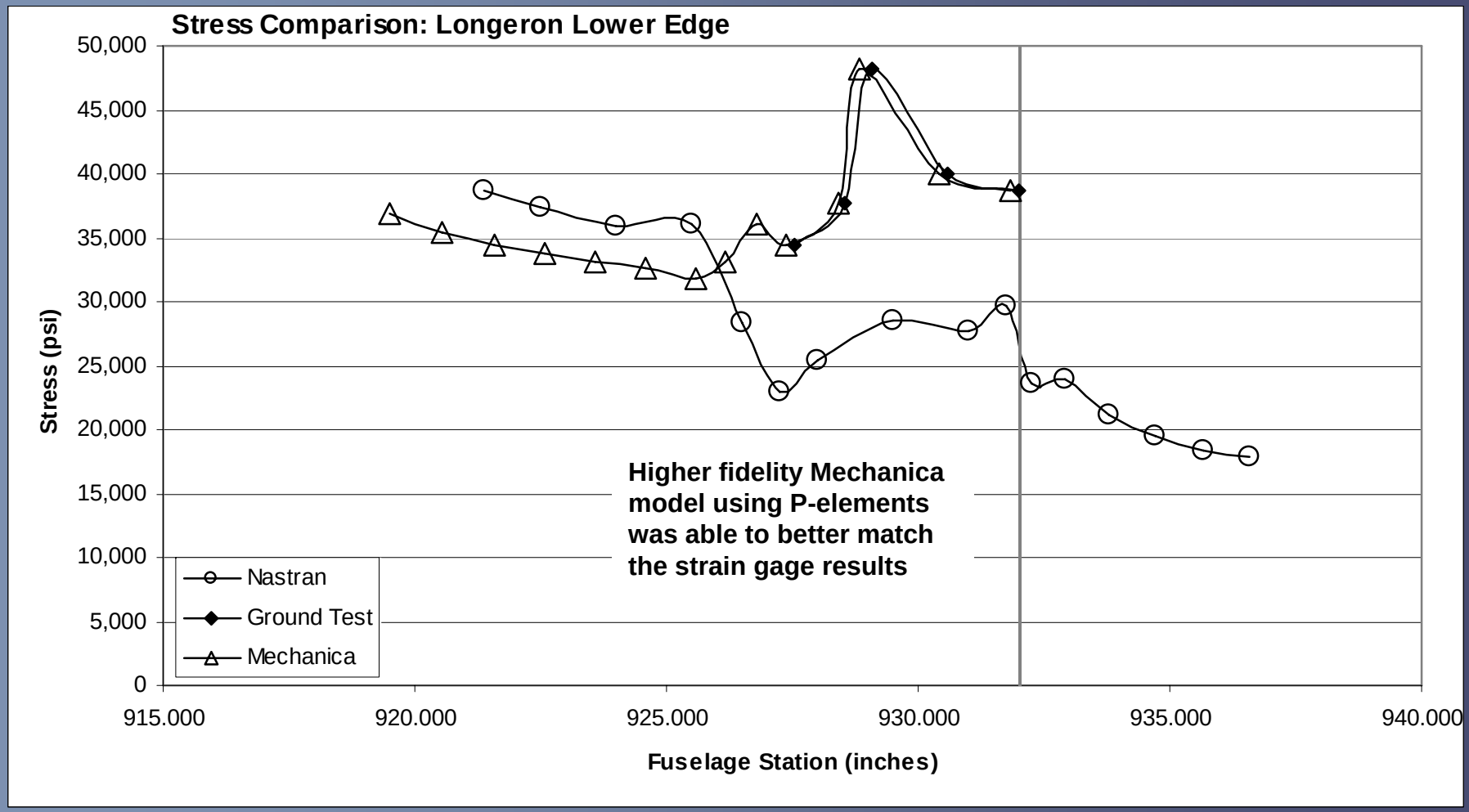

Predicted vs Measured Stresses

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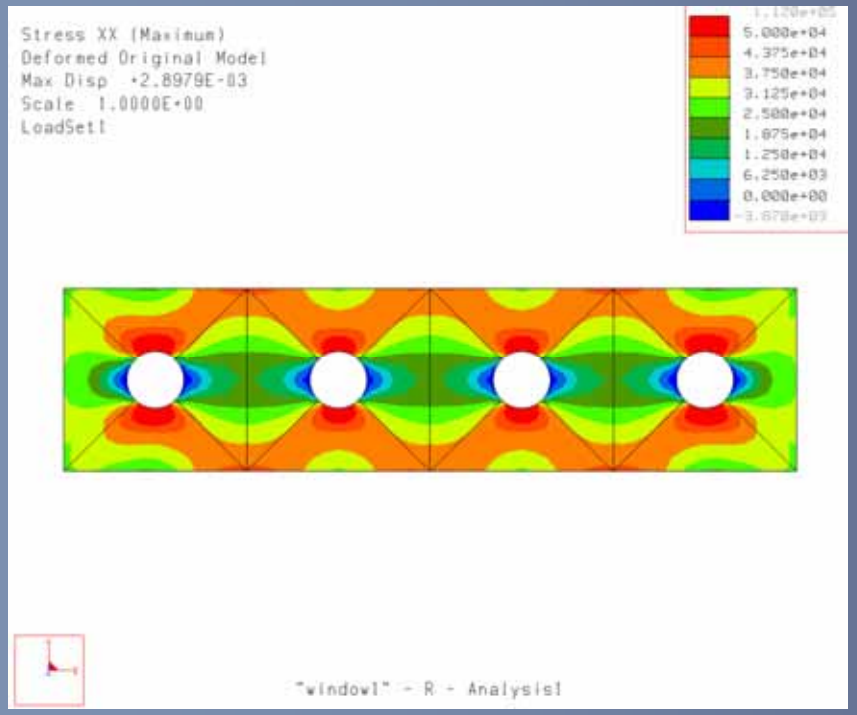

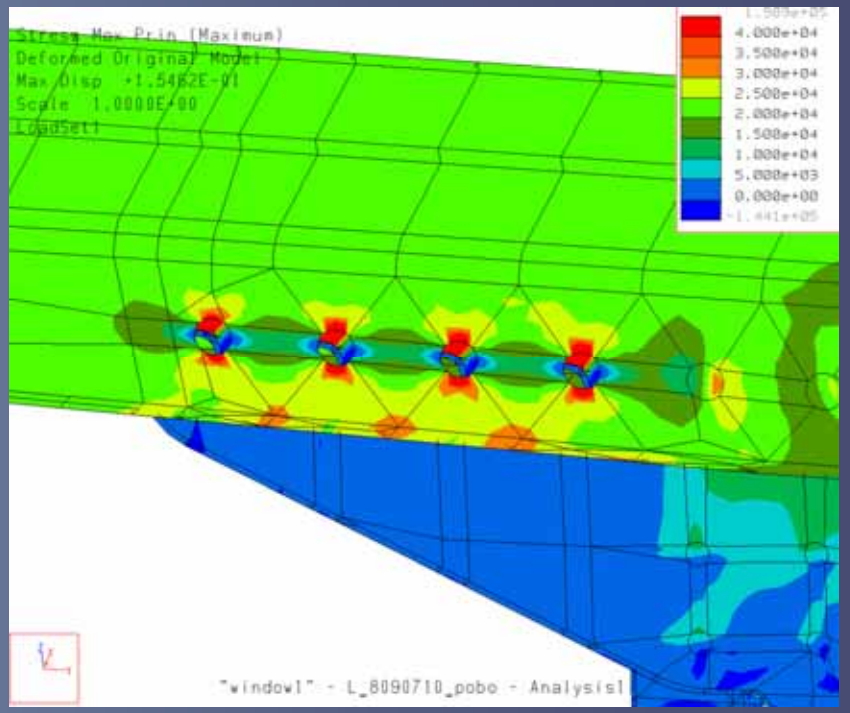

Predicted vs Measured Stresses – Model Correlation

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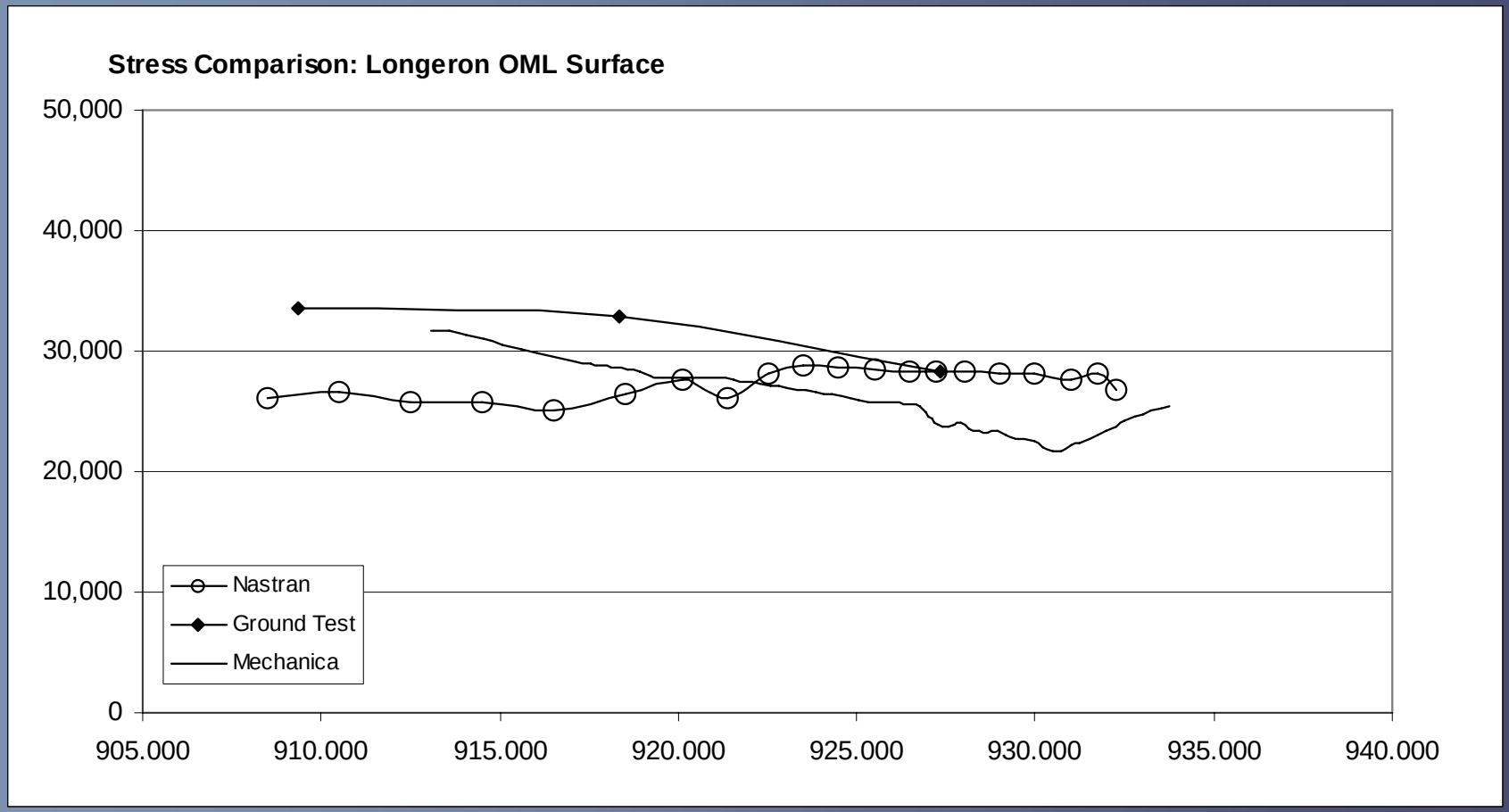

Repair Development Goals

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- Keep B-1 fleet flying safely
- Repair longerons currently with small or no cracks so that they can remain in service until the year 2040
- Economical for fleet wide implementation
- Robust – overkill where possible

Repair Design Criteria

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- Safety Factors
  - Limit loads = Maximum design loads
  - Ultimate = Limit x 1.5 Safety Factor
  - No yielding at Limit Load
  - No failure below Ultimate Load
- DADT Requirements
  - Slow Crack Growth
  - Spectrum based on actual usage
  - Durability criteria
    - Considers history and damage accrued since production
      - Except cold working restarts clock
    - .010 initial flaw size at non-cold worked holes
    - .010 initial flaw size at cold worked holes times a life factor of 2.0
  - Life predictions of 2040 or greater

Long Term Repair Development

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- Many concepts considered
  - ‘Brain-storming’ sessions
  - Internal and external reviews
- Repair concepts analyzed with Mechanica
- Additional analysis performed on viable alternatives
  - Strength
  - Crack growth
  - Bond line
- Potential challenges considered
- Structural and non-structural testing identified

Mechanica Model Development – Repair Concepts

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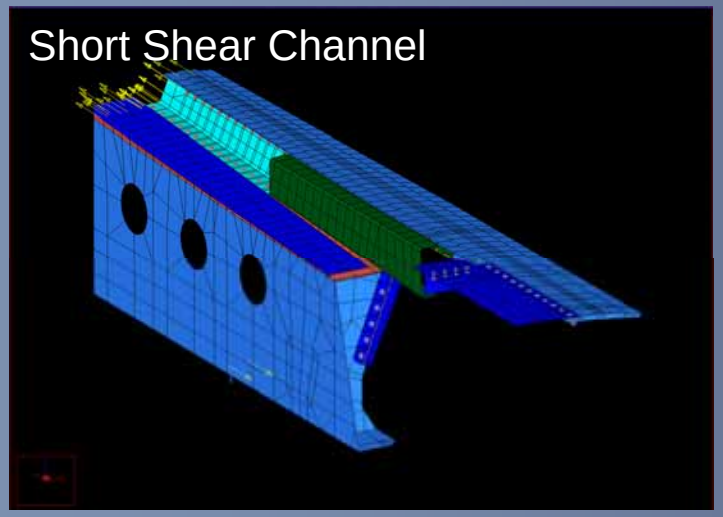
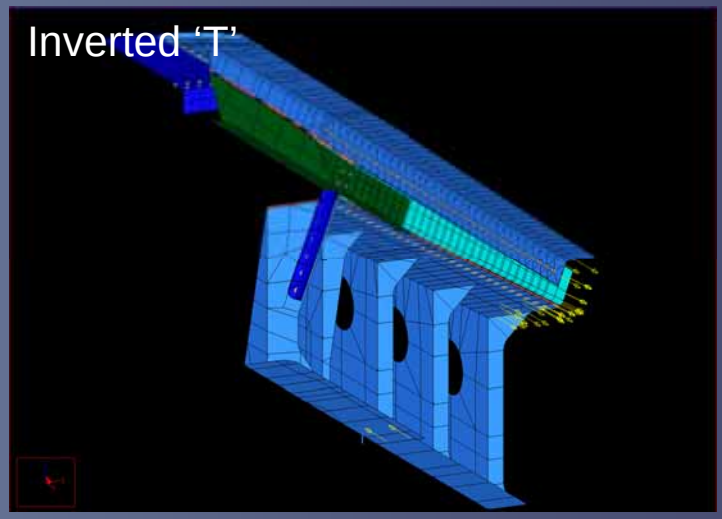
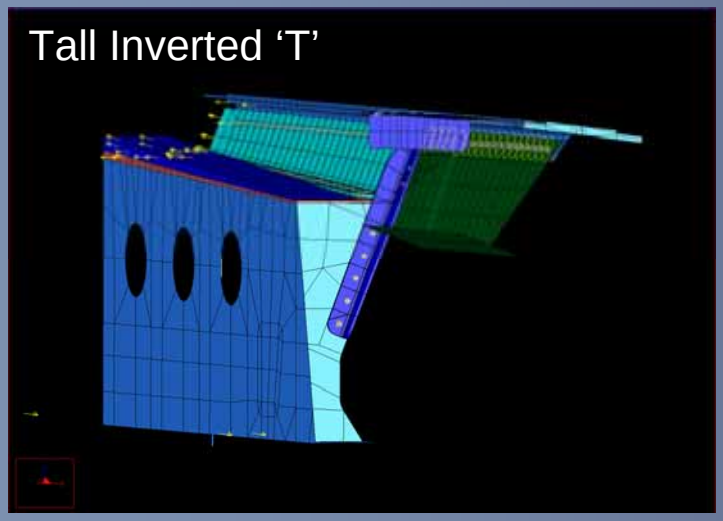
Short Shear Channel



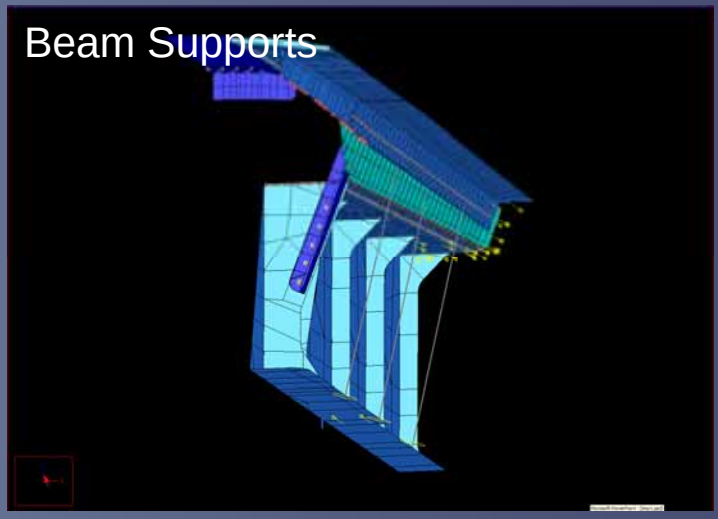
Inverted ‘T’



Tall Inverted ‘T’



Beam Supports



Mechanica Model Development – Repair Concepts

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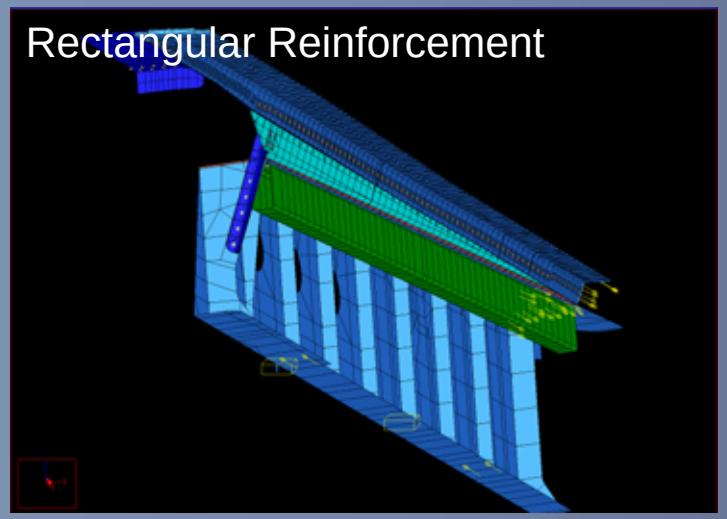

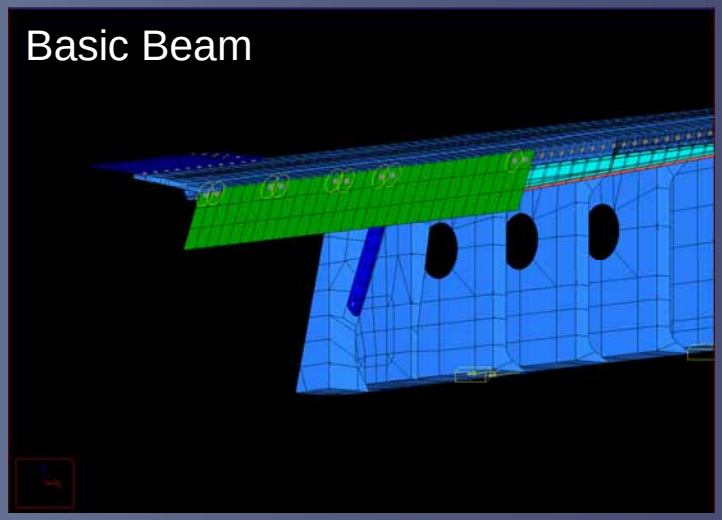

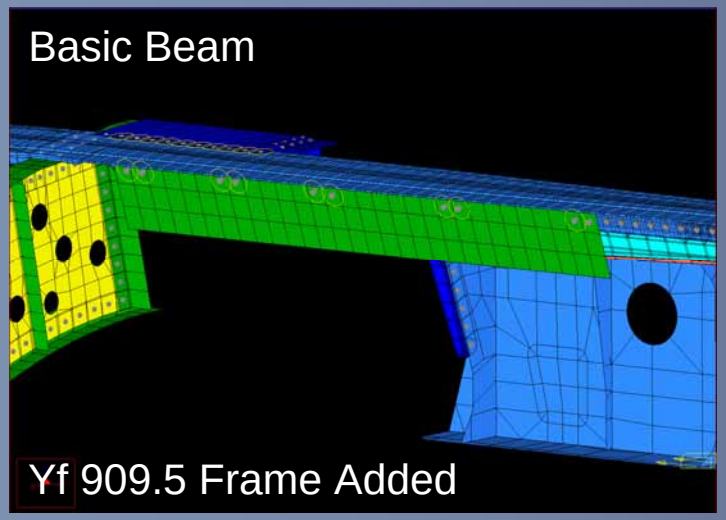

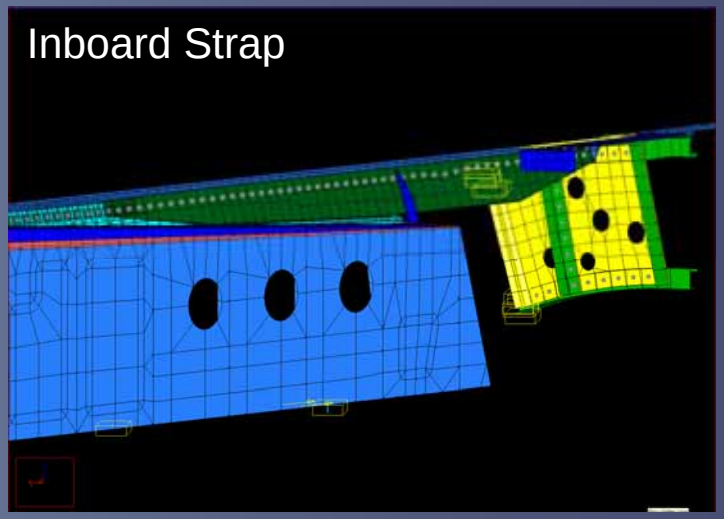

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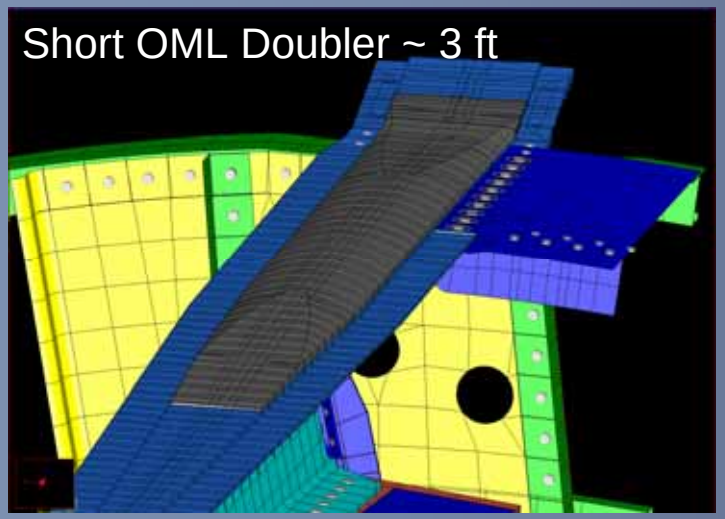

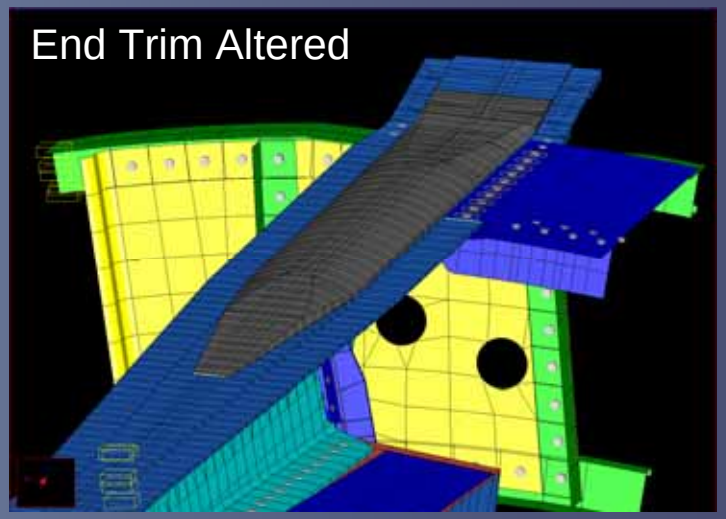

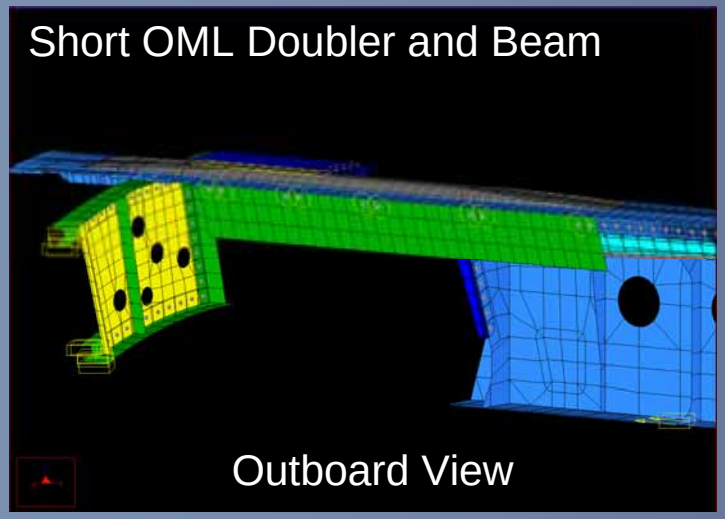

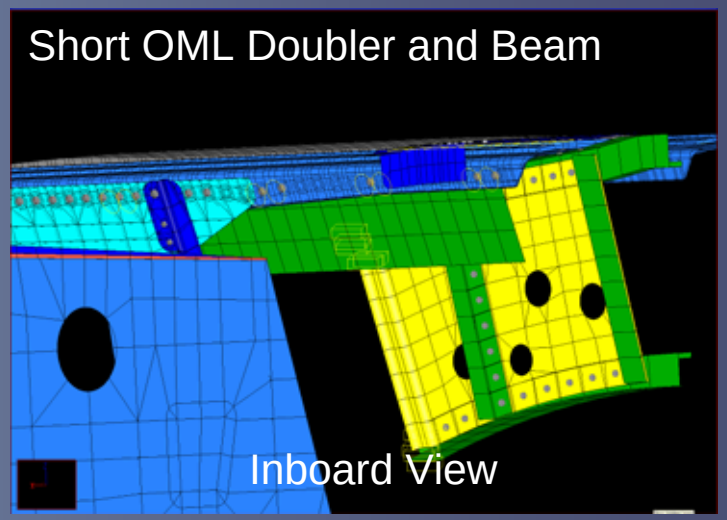

Mechanica Model Development – Repair Concepts

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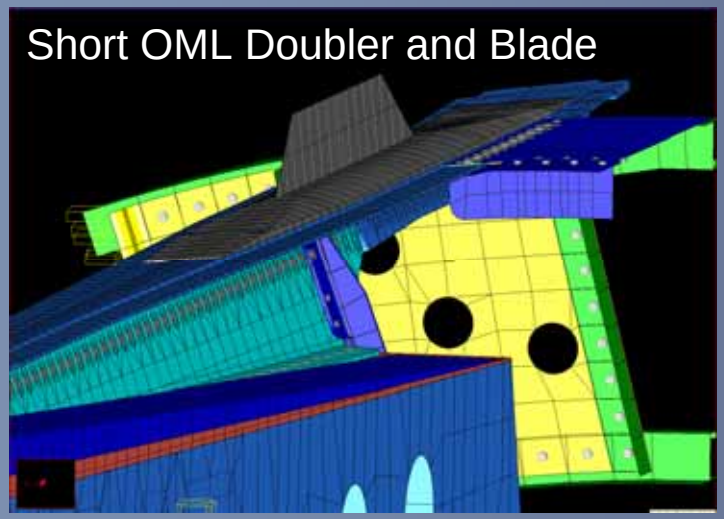

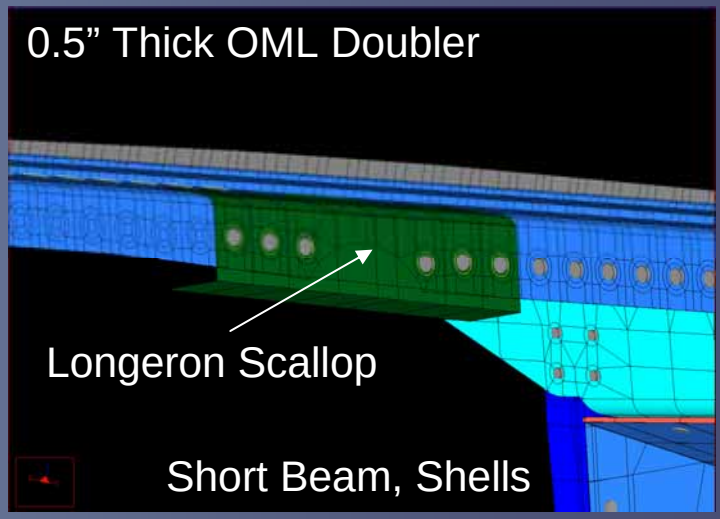

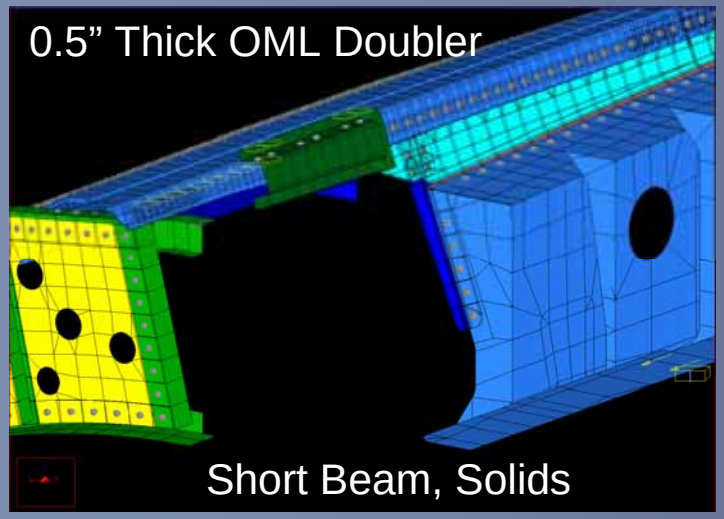

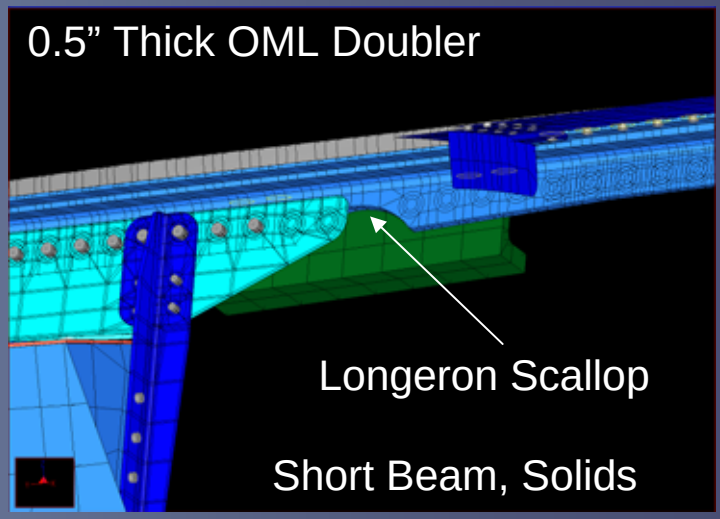

Mechanica Model Development – Repair Concepts

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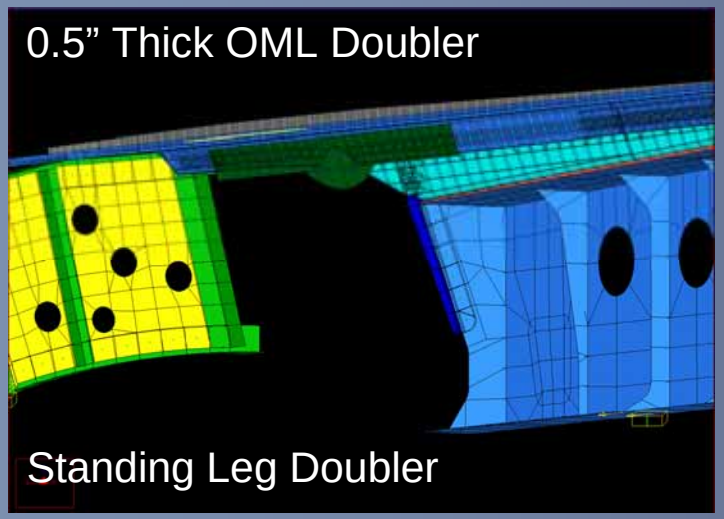

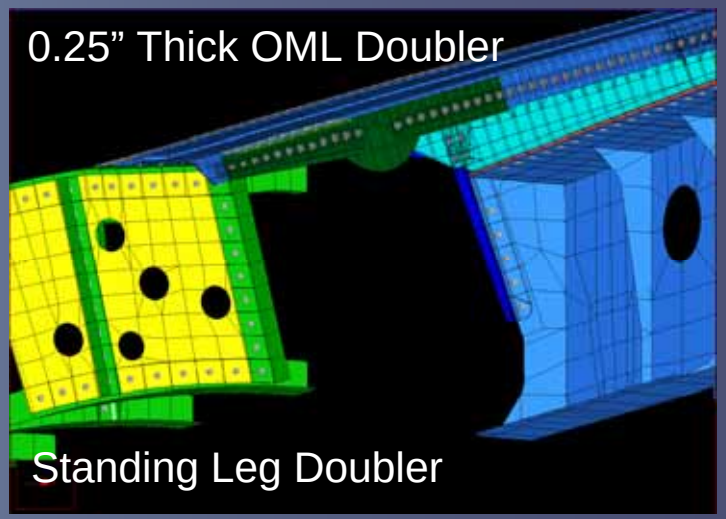

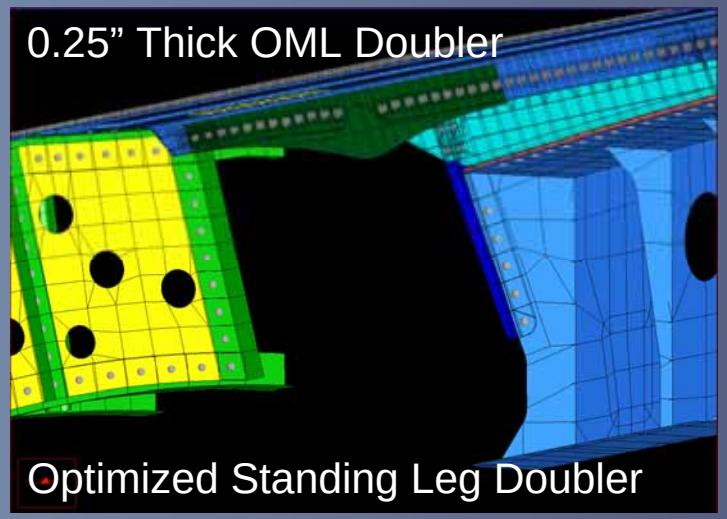

Repair Approaches and Application

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			Repair Applicability			
	Purpose	Implementation	Cracks down that can be reamed out	Cracks down- too big to be reamed out, Cracks up- can be reamed out	Cracks up- too big to be reamed out	Relative Cost
Remove 4 Bolts	Slow Cracking	Fleet	Slow Growth			Very Low
Interim Strap Repair	Restore Aircraft to Flight Status	86-0130, 85-0065			Temporary Repair	Med
Scallop Repair	Delay cracks from growing up	85-0065, 85-0073		Temporary Repair		Low
Bonded Doubler	Permanent Repair for Small Cracks	Under Development	Permanent Repair		Possible supplement to make Strap Repair a Permanent Repair	Low
Bonded Doubler, Scallop & Bolted Strap	Supplement to Bonded Doubler	Under Development		Permanent Repair		Low - Med
Replace Longeron	Permanent Repair for Large Cracks	Under Development			Permanent Repair	Very High

Permanent Repair Approaches for Majority of Fleet

B-1 Bomber

			Repair Applicability			
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Doubler Sizing Consideration

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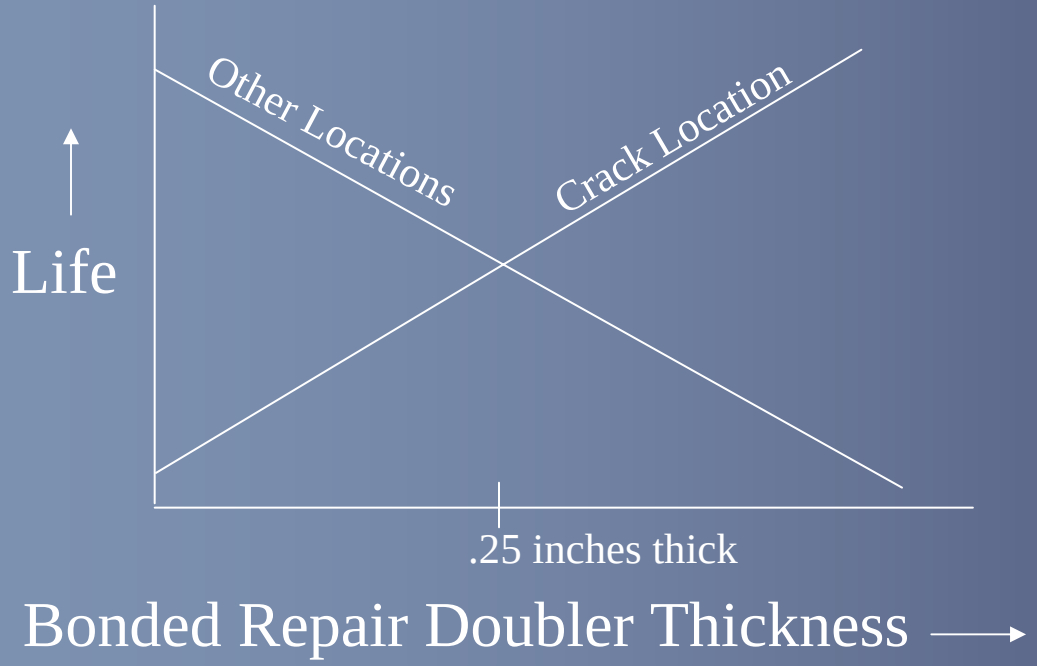
- **Delicate balancing act to <u>not</u> chase cracking elsewhere**
  - **Originally thought only isolated area needed to be fixed**
  - **Analysis determined that there are many more "hot spots" on longeron**
  - **Developing repair more complicated than anticipated**



Thicker repair doubler reduces stress and increases life locally but attracts more load to longeron decreasing life elsewhere

Doubler Material Selection

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- **Metallic versus Composite**
  - **Both considered**
  - **Thermal expansion compatibility mandated use of steel over composite**

Dorsal Longeron Repair OML Doubler

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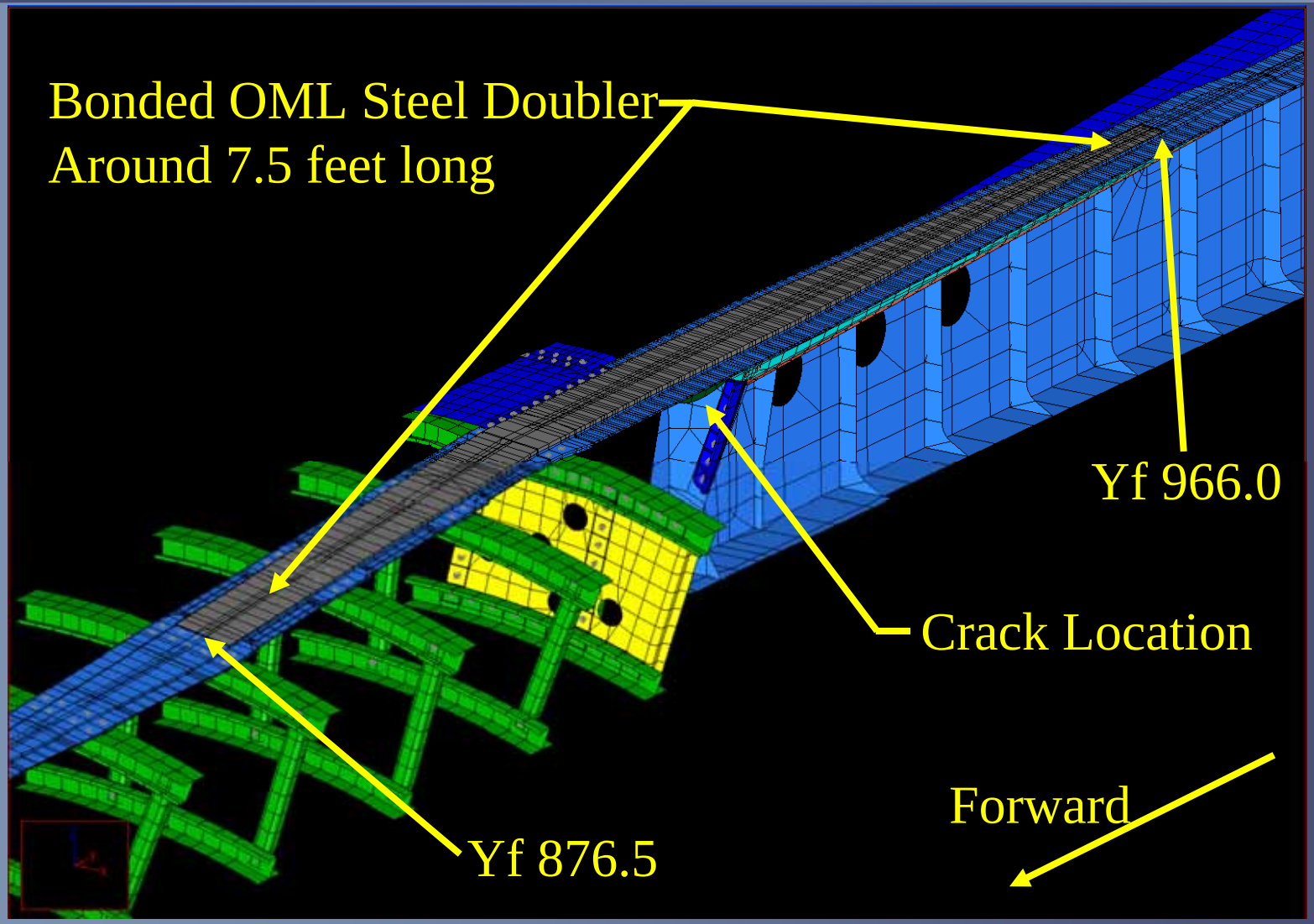
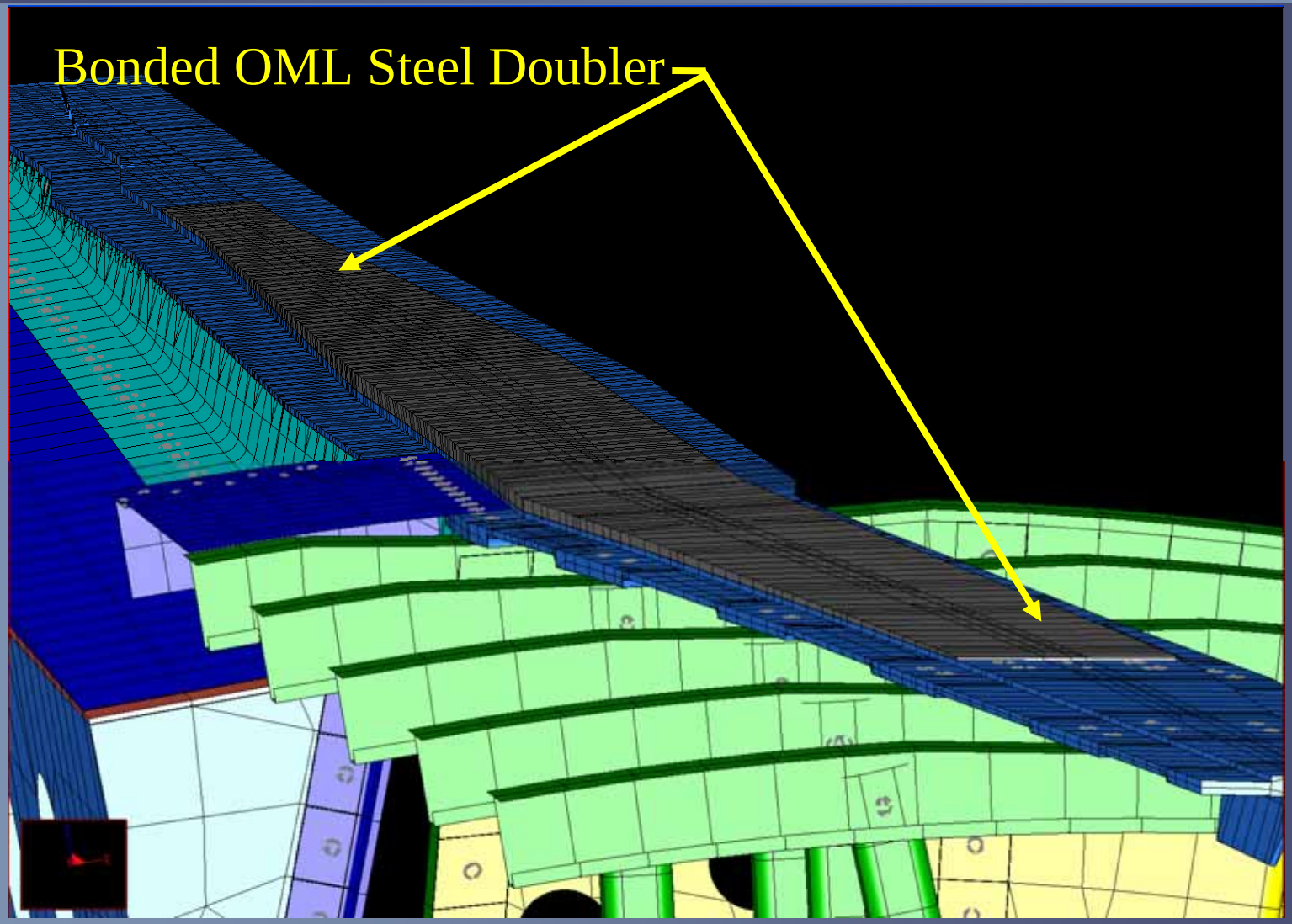


Dorsal Longeron Repair OML Doubler



Dorsal Longeron Repair IML Doubler

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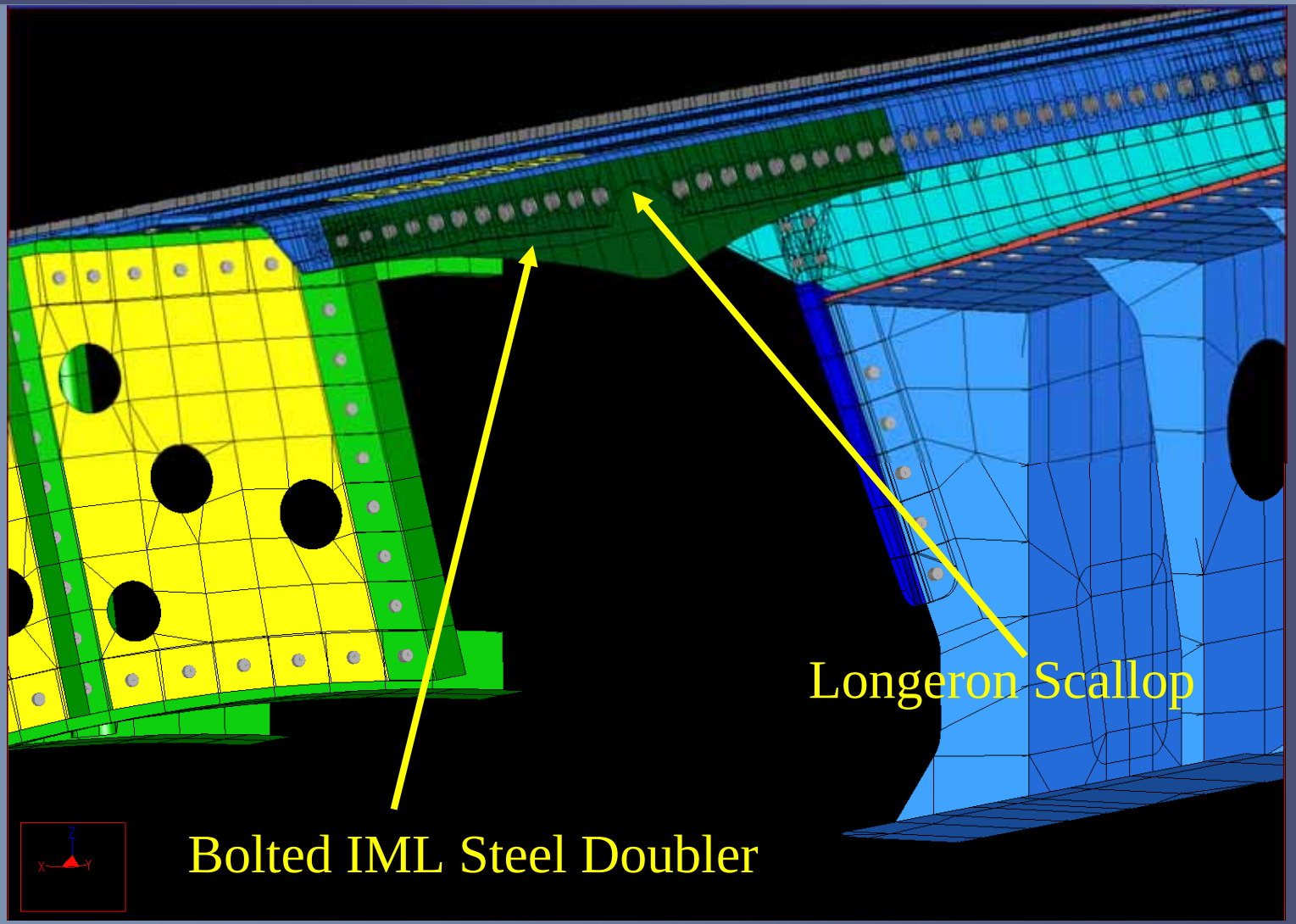

Structural Testing

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- Structural testing
  - Coupon test
  - Full scale fuselage top deck test
- Bondline testing
  - Thermal Dissipation on A/C during curing
  - Bondline mismatch of complex surface
  - Vacuum bagging of large area of A/C during bonding process
  - Surface preparation of steel
  - Vacuum cure properties of adhesive

Coupon to demonstrate cause of cracking

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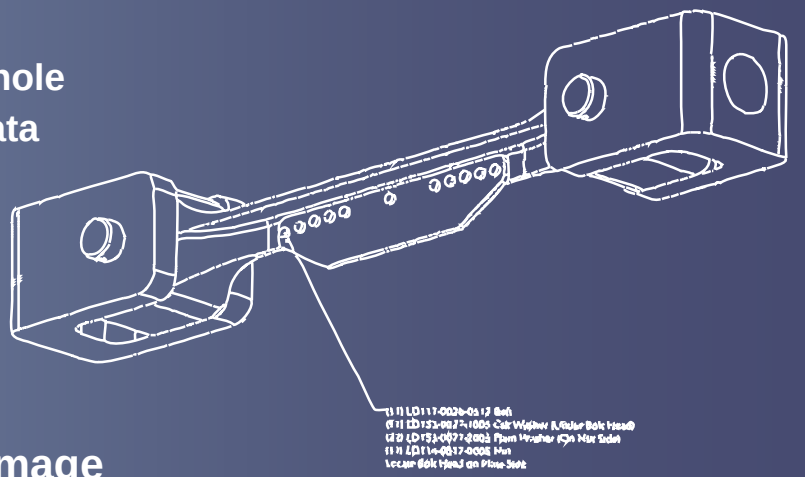
- Demonstrate that cause of cracking is understood
- Validate models and spectra
- Baseline Test specimen
  - Simulates cracked area, match stress around 1st hole
  - Symmetric about center to obtain 2 samples of data
- Test load spectrum
  - Based on latest actual A/C usage (2003 DADTA)
  - 100 flight block
  - Very few negative loads in spectrum removed
  - Cycles with low range removed
    - Account for insignificant amount of damage
    - Reduce number of cycles needed for test
  - Minor adjustments made to remaining cycles to analytically match predicted life
- Duration 2 A/C lives or catastrophic failure
- Periodic bolt hole NDI



Coupon to demonstrate cause of cracking

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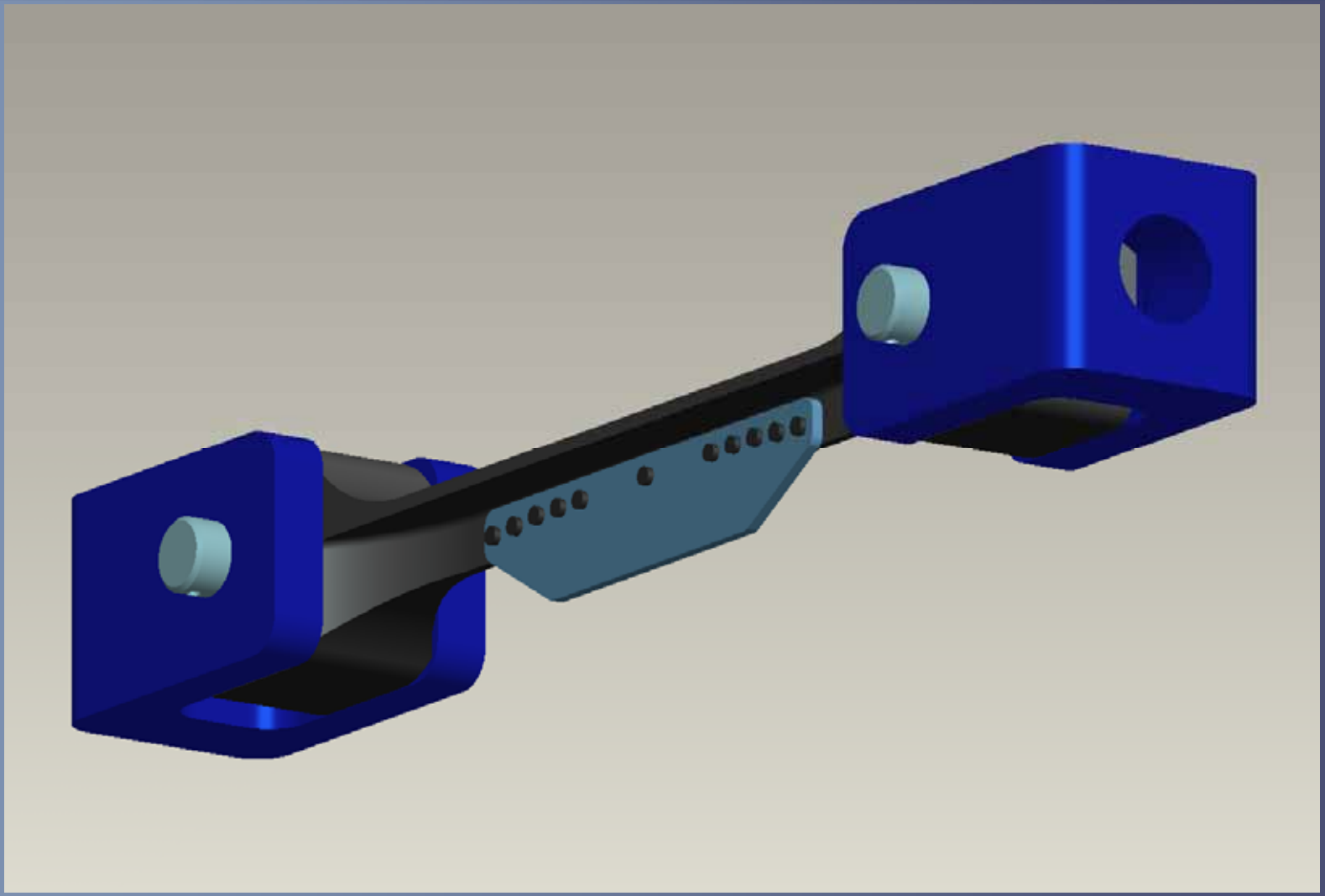

Coupon to demonstrate cause of cracking

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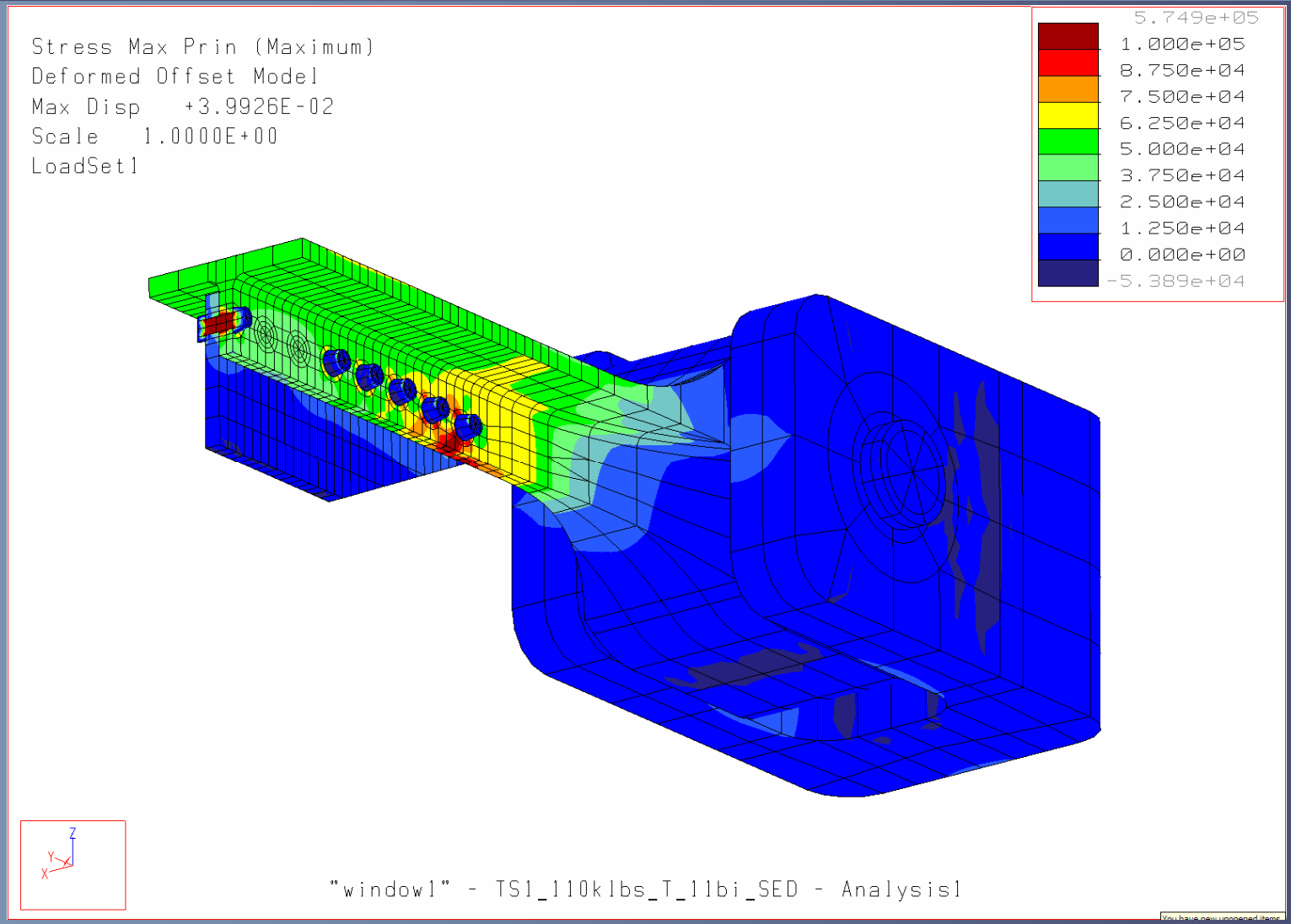


Full Scale Fatigue Test Article

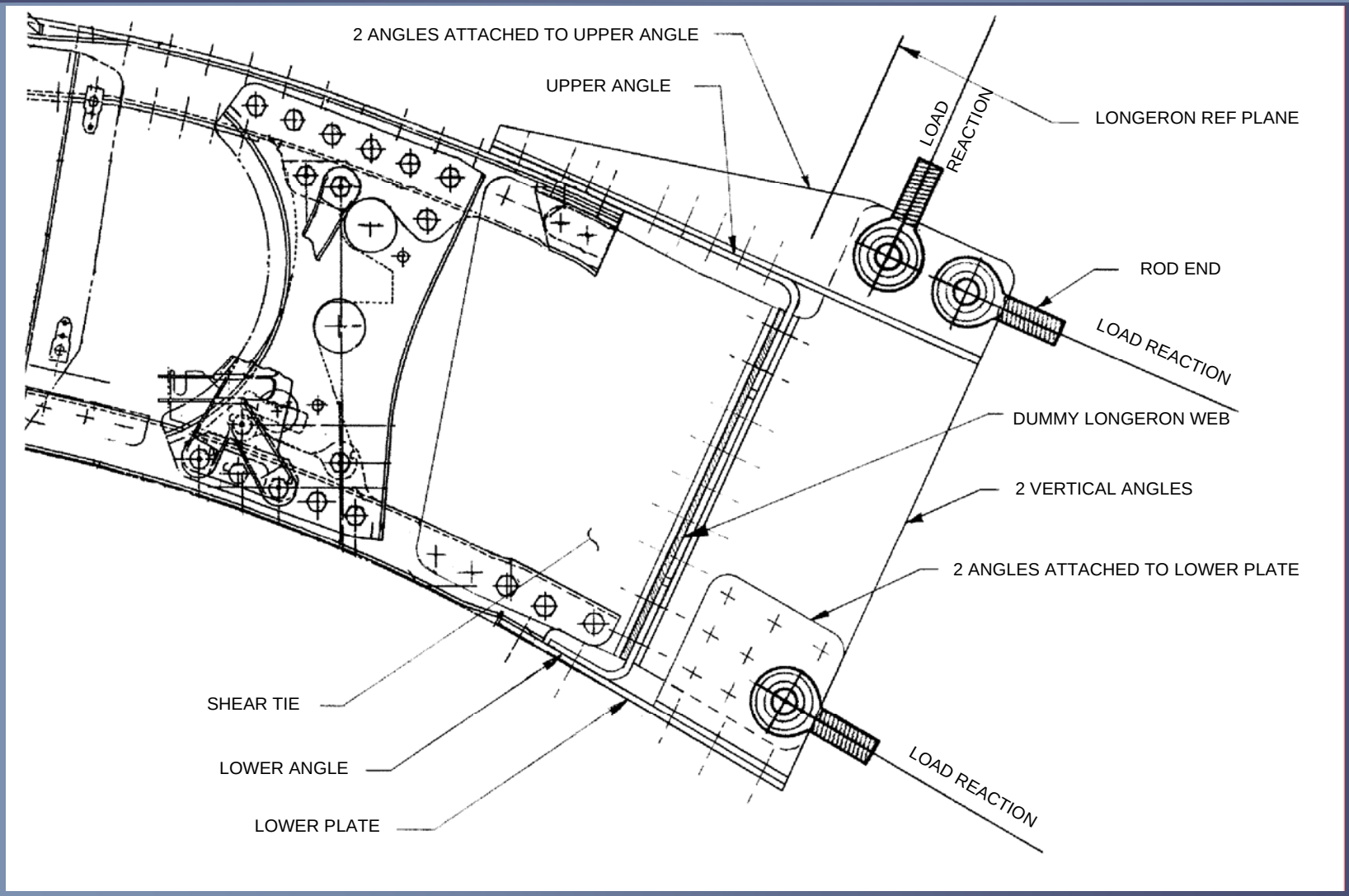
- **Reclaimed structure from retired B-1 at AMARC**

Full Scale Fatigue Test Article

B-1 Bomber

- **Test article - Yf 542-Yf 992, A/C 84-0056**
  - **No crack in either of dorsal longerons**
  - **Accumulated 4720 flt hrs (Fleet avg = 5556, Max = 7178, 06/2006)**

Support at Frame (Typical)



Full Scale Fatigue Specimen FEM

- Generated NASTRAN FEM of the 40-ft test article
- Model dummy LH & RH shoulder longerons of various thickness to control the load in the dorsal longeron
- Longitudinal loads applied @ aft end of dorsal longeron
- Bending loads (vertical) applied near crack location
- Loads will be reacted with fittings on the dummy shoulder longerons @ fwd end
- Supports allow for-aft or longitudinal movement
- Matching loads in dorsal longerons
  - YF 542.00 to YF 648.00 bad correlation (greater than 2.0%)
  - YF 648.00 to YF 962.00 good correlation (within 2.0%)
  - YF 962.00 to YF 992.00 bad correlation (greater than 2.0%)
  - Dorsal longeron splice @ YF 820.50, cracked area @ YF 927.00

Full Scale Fatigue Test Sequence

B-1 Bomber

- Pre-test inspection
  - Hot spots identified by FEM and DADTA
- Strain survey checkout
- Fatigue cycle to crack initiation
  - Expect crack initiation at hole 1
- Stop and perform doubler repair
  - External bonded doubler and internal bolted doubler
- Fatigue cycle 1 additional life
- Stop and induce crack(s) for damage tolerance testing
- Damage tolerance cycle 2 additional lives
- Residual strength test at design limit load
- Tear down inspection

Risk Reduction Activities for Bonding

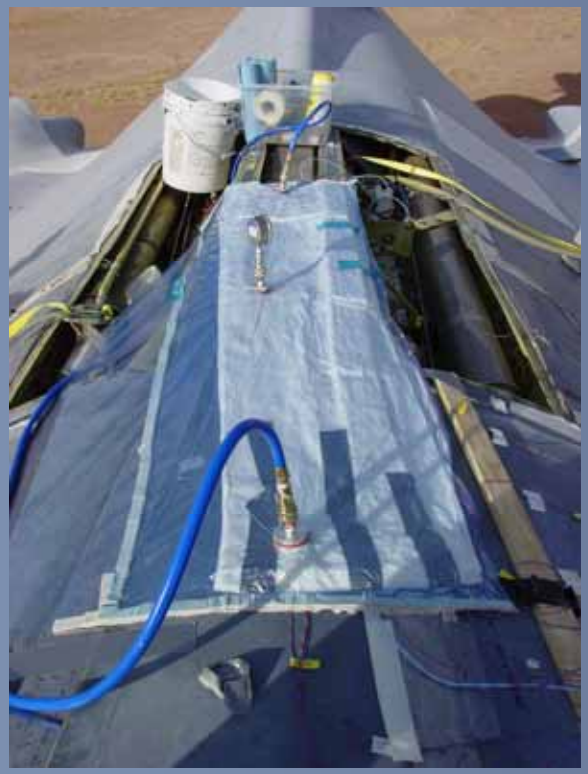
B-1 Bomber

- Thermal survey at AMARC
  - Check ability to achieve required bond line temperatures
  - Check ability to achieve good seal to aircraft for vacuum bagging
- Photogrammetry survey at AMARC
  - Check variation in mold line between various vintage of aircraft
  - Calculate resulting variation in bond line thickness
- Laboratory Adhesive Testing

Thermal Survey at AMARC

B-1 Bomber

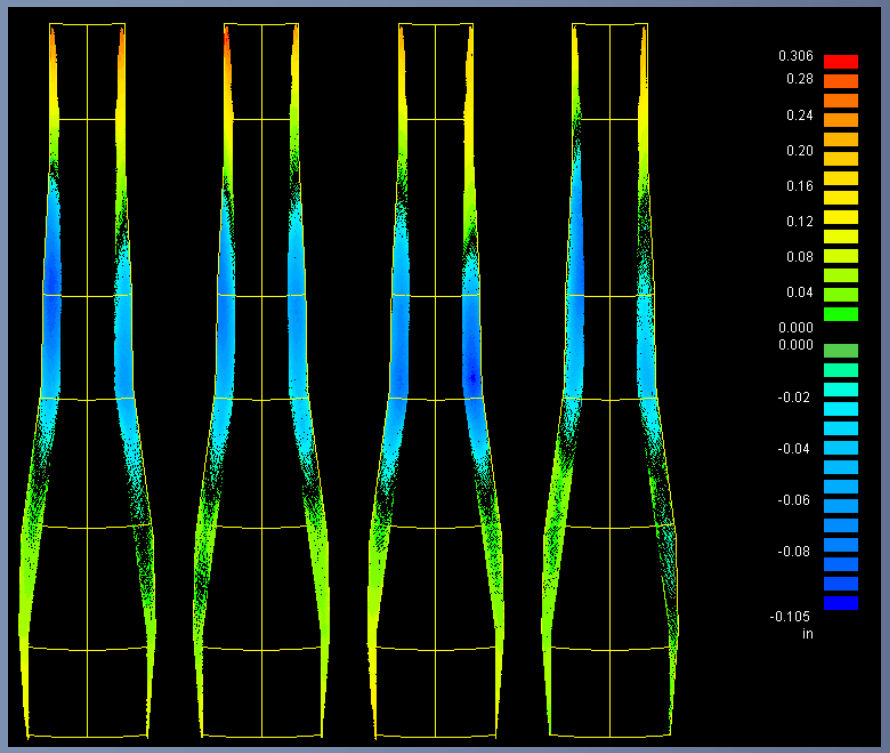
- Vacuum Bag, Heater Blankets, multi channel Controller
- Required temperature 250 F achieved in steel, no hot spots in aluminum
- Minimal leakage, structure well sealed at fastener holes



Mold Line Survey at AMARC

- Photogrammetry
  - 4 aircrafts
  - LH & RH dorsal longerons mold line scan

B-1 Bomber



RHS Longeron OML Delta (Actual – Loft)

B-1 Bomber

Simple Supports:

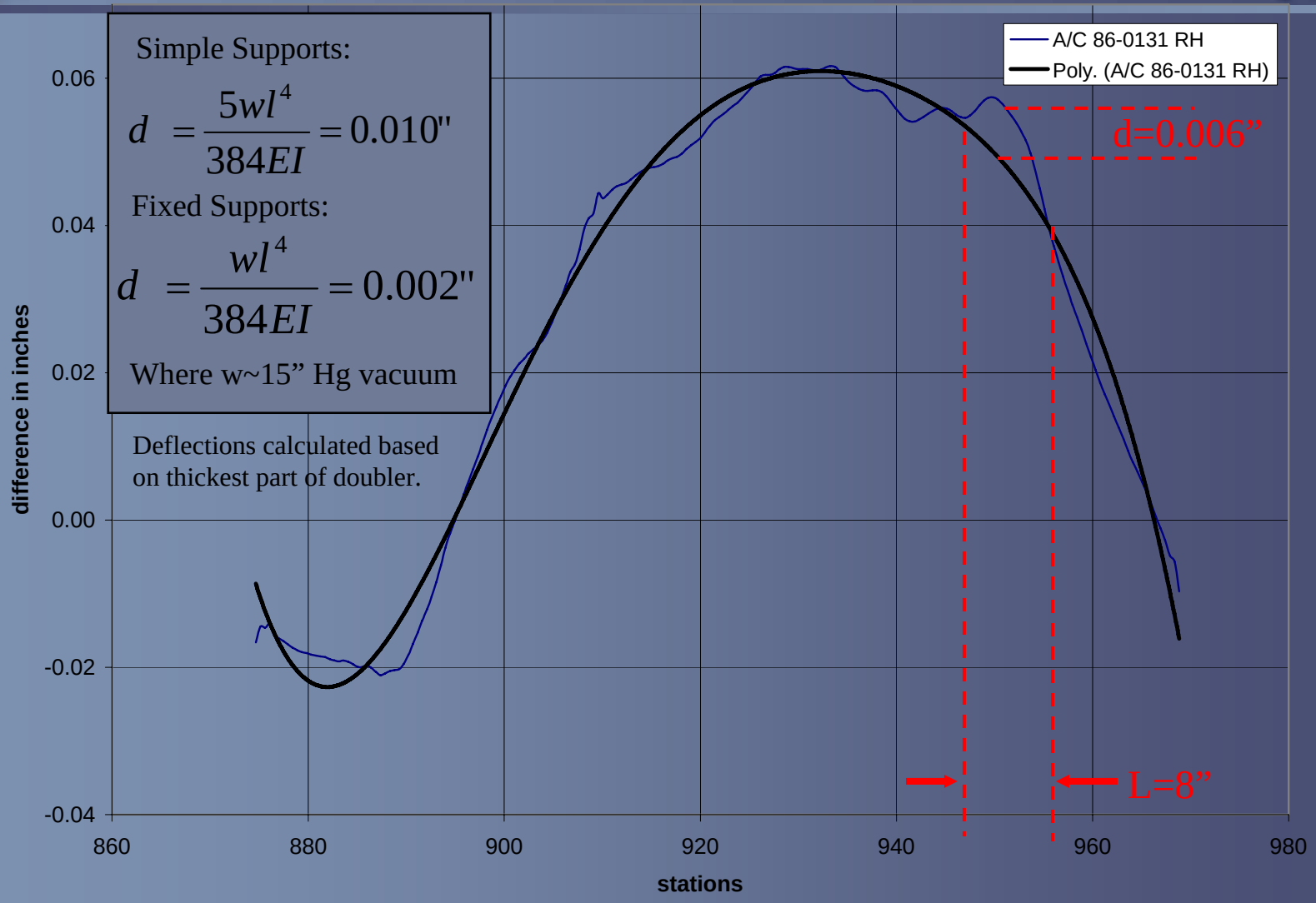
$$d = \frac{5wl^4}{384EI} = 0.010''$$

Fixed Supports:

$$d = \frac{wl^4}{384EI} = 0.002''$$

Where w~15” Hg vacuum

Deflections calculated based on thickest part of doubler.



Accomplishments

B-1 Bomber

- Developed unique temporary repairs
- Improved analysis tools
- Conducted ground strain survey test to correlate aircraft stress levels with FEM's
- Fabricated and currently testing baseline crack verification coupon
- Examined entire longeron, not just where it cracked
- Examined root causes and effectiveness of various repair concepts
- Conducted tests at AMARC to determine feasibility of bonded repair
- Developed and traded multiple repair concepts
- Developed adhesive test plan and have begun adhesive coupon testing
- Developed and released detail drawing for repair strap
- Excised full scale test specimen from AMARC
- Developed concept for test set-up for full scale test specimen

Look Ahead

B-1 Bomber

- Verification fatigue test
  - Lab test using top center section of reclamation aircraft
  - Prove cause of cracking
  - Test effectiveness of repair
- Conduct adhesives test
  - Surface prep variables
  - Standard lap shear (ASTM D-1002)
  - Thick adherend lap shear (ASTM D-5656)
  - Flatwise tension (ASTM D-2095)
  - Dog bone small scale bond line stress simulation test
- Working long lead items in preparation for prototype repair of fleet aircraft
  - Repair doubler material
  - Replacement longeron
  - Hardware

Questions

Additional Thanks to:
Rick Binder, The Boeing Company
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Rodney Harberson, USAF



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