Bonded Boron/Epoxy Doublers for Reinforcement of Metallic Aircraft Structures
PRESENTATION OUTLINE

• Boron Doubler Description
  – Reinforcement Concept
  – Advantages

• Installation Process
  – Surface Preparation
  – Materials and Bonding Process
  – Inspection

• Applications
  – Military
  – Commercial

• Test Programs
Boron Epoxy Doublers
Boron Doubler Reinforcement Concept

- Metal Structure
- Applied Stress
- Structural Damage
  (Stop-Drilled Crack Shown)
- Multi-ply Bonded Boron/Epoxy Doubler
- Film Adhesive
- Boron Fiber Direction
- Applied Stress
ADVANTAGES OF BORON/EPOXY DOUBLERS

• Bonded Installation
  – No Additional Holes in Aircraft
  – No Fastener-Associated Stress Risers
  – Only One Side Access Required
  – Can Reinforce Where Riveting is Not Possible

• High Specific Modulus
  – Efficient Load Transfer
  – Thinner, Lighter
ADVANTAGES OF BORON/EPOXY DOUBLERS

• Non-Metallic Material
  – Conformable
  – Does Not Corrode
  – Galvanically Inert

• Used for Damage Repair and Structural Enhancement
Doubler Installation Process
INSTALLATION PROCESS

• Lay-Up
  – Design for Specific Load Configuration
  – Standard Laminate Convention
  – Can Be Assembled Ahead of Time
  – Doubler Can Be Pre-cured for Specific Configurations
INSTALLATION PROCESS

• Aluminum Surface Preparation

 Most Critical Step
  – Paint Removal Per Conventional Process
  – Clean and Abrade Surface Seal Underlying Fasteners
  – Surface Treatment
    • Phosphoric Acid Anodize - PACS Process
    • Silane
    • Others
  – Apply and Cure Primer
INSTALLATION PROCESS

• Bond Onto Aircraft
  – Structural Film Adhesive
  – Portable Cure Equipment
  – Vacuum Bag Pressure
  – Doubler Can Be Co-cured

• Inspect
  – Ultrasonics for Bond/Composite flaws
  – Eddy Current for Underlying Crack Growth

• Seal/Paint
Boron Doubler Installation Schematic
Applications
# MILITARY APPLICATIONS

<table>
<thead>
<tr>
<th>INSTALLER</th>
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## MILITARY APPLICATIONS UNDER DEVELOPMENT

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<td>B-52</td>
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# COMMERCIAL APPLICATIONS

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Performance Test Programs
PERFORMANCE TEST PROGRAM

- Performed By Boeing Technology Services
- Objectives:
  - Installation Process Specification Development
  - Structural Analysis - Bonded Line Stresses
  - Performance Testing
    - Validation of Structural Enhancement - Static Tests
    - Validation of Crack Growth Suppression - Fatigue
PROCESS SPECIFICATION DEVELOPMENT

- Specification Number D658-10183-1
  - Detailed Documentation of Materials, Equipment and Processing Steps
  - Oriented Toward Boeing Process Specifications
  - Critical Steps Validated Through Empirical Testing
STRUCTURAL ANALYSIS

- INCAP - Laminate Analysis Program Used to Size Doublers for Testing
- COSMOS - 2D FEA Used to Analyze Internal Stresses Due to Cure Temperatures
- NIKE - 3D FEA Used to Evaluate Specimen Geometries
- ANSYS - FEA Used to Characterize Thermal and Residual Stresses
STRUCTURAL ANALYSIS

- Information Gained from Analysis
  - Shear and Peel Stresses Peak at Doubler Edge
  - Stresses in Front of Doubler are 25% Higher Than Applied Axial Stress
  - Residual Stresses from Bonding Operations (thermal) Oppose Axial Stresses During Service - Reducing Peak Stress in Doubler
PERFORMANCE TESTING - STATIC TESTS

- Objective: Determine if Doubler Restores Ultimate Aluminum Strength (78 ksi, 538 MPa) to Cracked Specimen
- Tests on Baseline Specimens Before and After Fatigue Testing
PERFORMANCE TESTING - STATIC TEST RESULTS

- **Pre-Fatigue - Quantity: 12**
  - All Specimens > 78 ksi (538 MPa) Requirement
  - Most Broke in Aluminum Outside Doubler

- **Post-Fatigue - Quantity: 91**
  - 87 Tests > 78 ksi (538 MPa)
  - 4 Tests 42 to 76 ksi (290 to 524 MPa)
    - Aluminum Failure with Doubler Intact
PERFORMANCE TESTING

• Tension - Tension Fatigue
  - Primary Objectives:
  - Determine if Doubler Restores Cyclic Capability of Aircraft Structure
  - Baseline Specimens at Room Temperature
  - Parametric Studies Relating to Doubler Design
    • Sub-Ambient (-65°F, -54°C)
    • Geometry Sensitivities
    • Impact
## FATIGUE TARGETS

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<tr>
<th>Aircraft</th>
<th>Design Stress</th>
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<td>(0 to 124 MPa)</td>
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</table>
FATIGUE RESULTS

- Unpatched Specimens Fail at 4000 Cycles
- Baseline: 15 Specimens
  - 12 Specimens - No Failure - No Crack Growth
  - 1 - Crack Growth at 161,385 cycles - No Failure
  - 1 - Crack Growth at 17,464 cycles - No Failure
  - 1 - Failure at 89,454
  - Failure and Crack Growth a Result of Imperfections in Stop Drill Hole
FATIGUE RESULTS

- Observations From Parametric Studies
  - Baseline Performance Minimally Affected By:
    - Variations in Doubler Geometries
    - Changes in Cure Pressure
    - Increased Crack Length (1”, 2.54 cm)
    - Moisture and Solvent Immersion
    - Impact @ 100 and 300 Lb-in
    - Edge Disbonds 0.5” in (1.27 cm) Diameter
FATIGUE TESTING

• Observations from Parametric Studies
  - Crack Re-initiation More Likely to Occur:
    • With In-Line Rivets Near Cracks
    • Disbonds Beneath Cracked Area
    • -65 Degree F (53.8° C) Environment
    • No Stop Drill Hole
    • Too Thin a Doubler
  - When Crack Re-initiation Occurs the Crack Growth is Linear (Not Catastrophic)
CONCLUSIONS

• Boron Epoxy Doublers Have Been Successfully Used on Aircraft For Many Years
• Process Has Been Defined and Documented
• When Properly Designed and Applied, Boron Epoxy Doublers Restore Structural Integrity