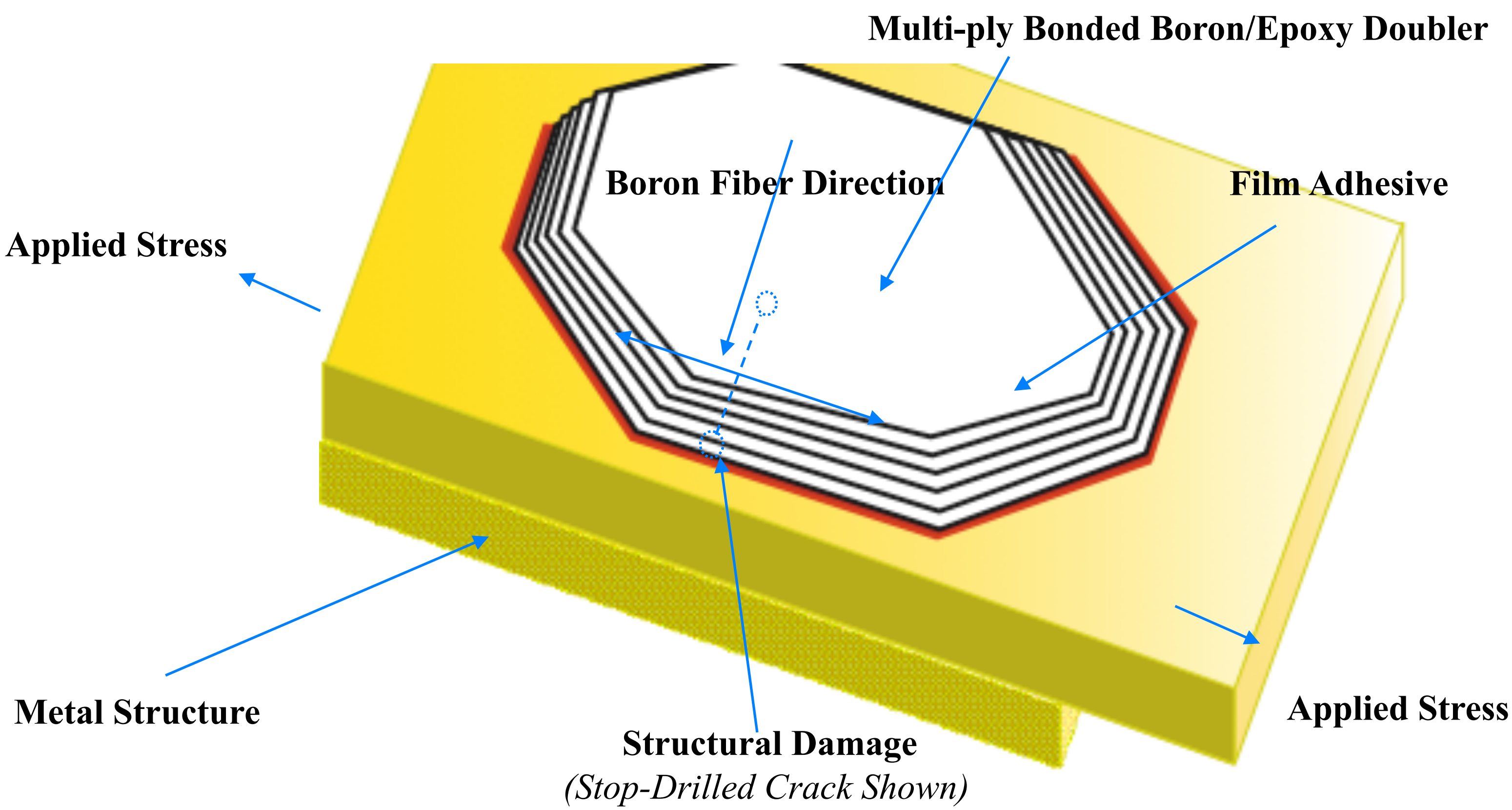
Bonded Boron/Epoxy Doublers for Reinforcement of Metallic Aircraft Structures

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



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
  - Doublers Can Be Pre-cured for Specific Configurations

INSTALLATION PROCESS

- Aluminum Surface Preparation

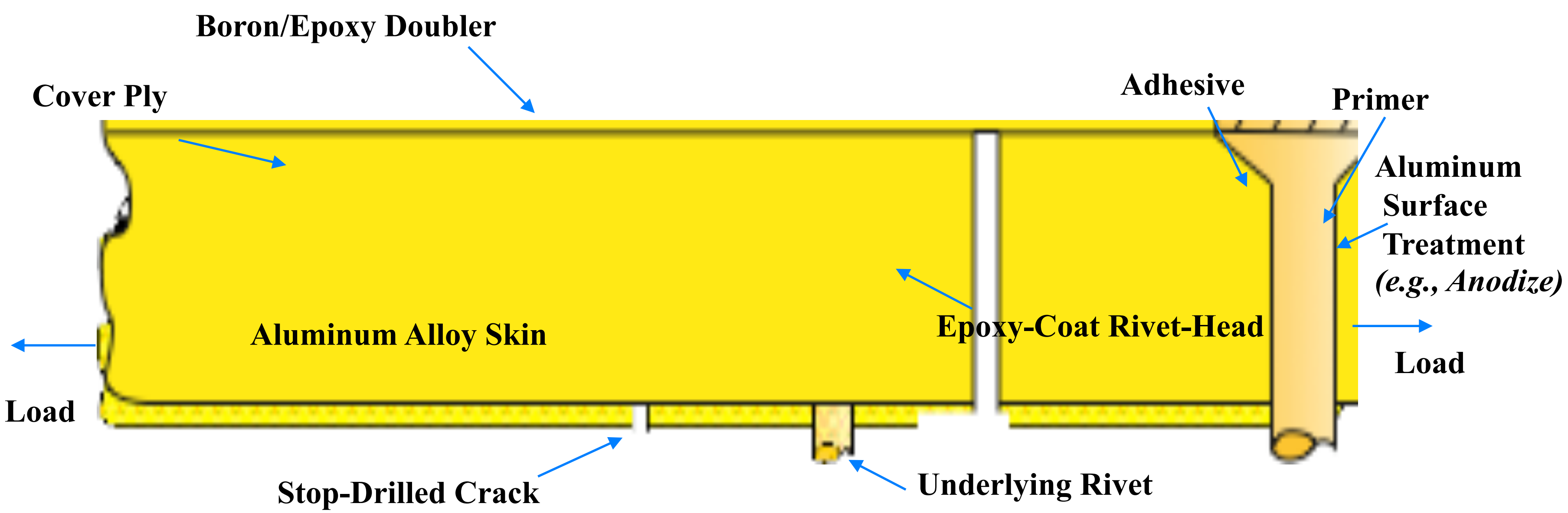
➲ **Most Critical Step**

  – 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

INSTALLER	AIRCRAFT	DESCRIPTION	# AIRCRAFT	COMMENT
ROCKWELL	B-1	DORSAL LONGERON	100	OEM INSTALLATION
USAF	F-111	LOWER WING PIVOT	411	
AUSTRALIAN AIR FORCE	F-111 C-130 MACCHI MIRAGE	WING PIVOT WING STIFFENER WHEEL WING SKIN		APPROX 3500 DOUBLERS ON VARIOUS AIRCRAFT
LOCKHEED	C-141 C-130	WING PLANK LEADING EDGES ETC.	20	VARIOUS "BLANKET" APPLICATIONS
USAF	B-1	25 DEGREE LONGERON	96	FATIGUE CONSIDERATIONS
CANADIAN A.F.	F-5	UPPER WING SKIN	~40	
USAF	C-141	WING RISER WEP HOLES	~150	OVER 2000 DOUBLERS
BOEING WICHITA	B-52	WING SKIN	1	DEVELOPMENT

MILITARY APPLICATIONS UNDER DEVELOPMENT

Aircraft	Doubler Location
F-15, F-14	Lower Wing Skin
B-1	Horizontal Stabilizer Spar
C-130	Outer Wing Stringers
B-52	Upper Wing Skin
F-16	Lower wing Fuel Vent
T-38	Lower Wing door Frame
C-5	Nose Landing Gear Door
KC-135	Upper Wing Skin

COMMERCIAL APPLICATIONS

INSTALLER	AIRCRAFT	DESCRIPTION	# AIRCRAFT	COMMENT
DASSAULT (FRANCE)	MERCURE	DOOR FRAMES	11	
ARL AUSTRALIA	767	KEEL BEAM	1	CORROSION REPAIR
	727	FUSELAGE LAP JOINT	1	DEMO
	747	VARIOUS	1	DEMOS
BOEING	747	STATIC FATIGUE	1	
FEDERAL EXPRESS	747	25 LOCATIONS	2	DEMO
FEDERAL EXPRESS	MD-11	FUSELAGE	1	WRINKLED SKIN
LYCOMING AND SUBS	BAE-146	ENGINE COWL	~100	ALF-502 ENGINE
CESSNA	CITATION V	FUSELAGE	1	DEMO
DELTA	LL1011	DOOR FRAME	1	FAA APPROVAL

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^{o}F, -54^{o}C)
    - Geometry Sensitivities
    - Impact

FATIGUE TARGETS

Aircraft	Design Stress	Design Cycles	Test Stress	Test Cycles
737	0 to 15 ksi (0 to 103 MPa)	75,000	3 to 20 ksi (21 to 138 MPa)	300,000
747	0 to 18 ksi (0 to 124 MPa)	20,000	3 to 20 ksi (21 to 138 MPa)	300,000

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^{o}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