

ADHESIVE BONDING SURFACE PREP QUALIFICATION CONSIDERATIONS



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OVERVIEW



- **Background**
- **Surface Preparation Selection Issues**
- **Surface Preparation Qualification Approach**
- **PABST Program**
- **Wedge Test**
 - **Background and thoughts**
 - **Conditioning**
 - **AFRL/MLSA criteria**
- **Ongoing Related Efforts**
 - **Composite preparation (procedures & test method)**
 - **C-141 bonded repair evaluation**
- **Conclusion**



BACKGROUND

ADHESIVE BONDING IS ESSENTIALLY BASED ON TRUST

- Develop validated designs and processes
- Assure integrity of materials prior to processing
- Assure the validated processes are followed: trained personnel and quality control
- Nondestructively check prebond surfaces
- Nondestructively check for disbonds
- Proof tests (for certain applications) ?
- Process control (witness) coupons ? (for repair ???)
- Accept bond as good even though it cannot be “proved”

This Approach Does Work When Properly Applied

➡ Requires validated surface preparation process

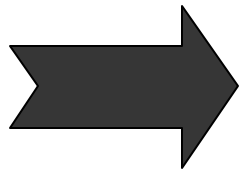


BACKGROUND



LACK OF CONFIDENCE LIMITS USE OF BONDING

- **Engineering Authorities & Regulators Mistrust Bonding (and do not really understand the technology)**
 - **Strength of bond cannot be nondestructively determined**
 - **Life of bond cannot be positively predicted**
 - **Previous failures abound (many due to improper practices involving surface preparation)**



**USAF Engineering Authority (ASC/EN)
Fail-Safe Criterion for Safety-of-Flight-
Critical Components – Must Carry Design
Limit Load (DLL) Without the Bond**



PREBOND SURFACE PREPARATION



- **“Good” Surface Preparations (to include pretreatments) must typically do the following:**
 - Remove contamination, native oxide layers, and any surface layers incompatible with adhesion
 - Form adherent surface layers that are mechanically and/or chemically compatible with the adhesive and stable in service
 - » Roughen the surface (macro or micro)
- **Surface Preparation is Critical for Achieving Long-Term Service**
 - The single most important factor (and most common root cause of failures)
 - Cannot be ignored, even for lightly-loaded structure
 - Moisture attack at interface is the primary problem (for metal)
- **Metal Adherends Are Big Concern, but Serious Issues Exist for Composite Materials (Failures Exist to Prove It)**



SURFACE PREPARATION SELECTION ISSUES



- **Compatibility with System (Substrates, Adhesive, etc)**
 - **Bond strength (static and dynamic)**
- **Environmental Durability**
 - **Temperature extremes, moisture (and interaction)**
 - **Aircraft and maintenance fluids, SO₂, salt fog, others**
- **Desired Component Service Life**
- **Acceptable Level of Risk (Critical vs Noncritical)**
- **Available Facilities, Equipment, Skilled Personnel**

HOW GOOD IS GOOD ENOUGH?



METAL VS COMPOSITE



- **Metal Adherends (Mostly Aluminum Alloys; Also Ti, Steels, Others)**
 - Long-term exposure to service environment can degrade metal-polymer interface (moisture is major culprit)
 - Proof tests and/or nondestructive inspection techniques not likely to provide assurances that bond will be good in long run
- **Composite Adherends (Wide Variety of Matrices/Reinforcements)**
 - Design should consider degradation of bulk polymer properties (adhesive and composite) upon environmental exposure, but does the interface degrade with time?
 - Proof tests may be beneficial if initial bond status is the key
 - » Can it be performed at ambient with unconditioned bonds?
 - » What percentage of bond area must be interrogated?



MANUFACTURE VS REPAIR



- **Available Facilities and Equipment**
 - OEM vs depot vs field-level
- **Skill Level of Personnel**
 - Training; workload required to remain proficient
- **On-component or On-aircraft vs Detail Part**
 - Access
 - Vulnerability of surrounding structure/systems
- **Time Crunch (Usually Worse for Repair)**
- **Hazardous Materials Issues (Usually Worse for Repair)**



SURFACE PREPARATION QUALIFICATION APPROACH



- **Assess Surface Prep Compatibility with Entire System**
 - **Coupon-level tests using application-specific adherends, adhesive and processes**
 - **Include prep in any element, detail, subcomponent & component testing (static & dynamic) required to certify overall design**
 - » **What if there is a change? What about repair?**
- **Include Proposed Prebond NDI**



SURFACE PREPARATION QUALIFICATION APPROACH



- **Assess Environmental Durability**
 - **Shear tests (static/dynamic) as currently practiced not sufficient, even if conducted hot/wet with moisture-saturated bonds**
 - » **Modification to obtain test that can generate a design “allowable” would be ideal**
 - **For now, wedge test is key for metal preps (must standardize)**
 - **Need analogous test for composite adherends?**
 - **Other tests may be necessary (remember PABST)**
 - **Coupon-level for effects of aircraft/maintenance fluids? What are exposure conditions/time?**



USAF PABST PROGRAM



- **Primary Adhesively Bonded Structure Technology**
 - USAF Flight Dynamics and Materials Labs; Douglas Aircraft
 - Mid to late 1970s; approximately \$20M (then-year dollars)
- **Objective: Dem/Val Significant Improvements in Cost, Weight Reduction, Integrity and Durability of Primary Fuselage Structure by Application of Adhesively Bonded Joints**
- **Multidisciplined Approach to Validation of Bonding “Primary” Structure**
 - Design philosophy
 - Aluminum surface prep; adhesive/primer system
 - Tests for validating design and processes
- **Technically Successful, but Did Not Raise Confidence to the Level Needed to Bond Safety-of-Flight-Critical Structure**
- **In Many Ways, Still Defines Bonding State-of-the-Art**



PABST AND SURFACE PREP



- **Three Surface Preps Evaluated**
 - PAA per Boeing; CAA per Bell; FPL control per Boeing
- **Wedge Test Primarily Used to Assess Surface Prep Durability**
 - Conditioning at 140°F (60°C) and 95-100% RH for 1 hr
 - Crack growth and failure mode evaluated
 - PAA more robust than others (wider operating windows)
- **Long-Term Outdoor Wedge Tests (El Segundo Beach)**
- **Conditioned Lap Shear & T-Peel (Moist, Temp, Salt Spray, Fluids)**
 - Little information on which to base durability decisions
- **Sustained and Cyclic Stress Durability (140°F and 100% RH)**
 - Raab and similar specimens (string of shear specimens)
 - Slow cycling showed greatest effect (on 60 min, off 15 min); more of a polymer effect than an interface issue



PABST CONCLUSIONS



- **Key Words and Catch Phrases from PABST that Defined 1979 State of the Art for Adhesive Bonding Technology (metal bonding):**
 - **Clad is bad**
 - **Prep is paramount**
 - **Control it**
 - **Chromates are critical**
 - **Demand durability**
 - **If you are going to do it, DO IT RIGHT**
- **Another Key PABST Observation (paraphrased):**

The inherent weakness of NDT inspection is its present inability to determine strength between adhesive and adherend. This problem must be resolved for future programs. The present industry position is to impose stringent in-process quality assurance.



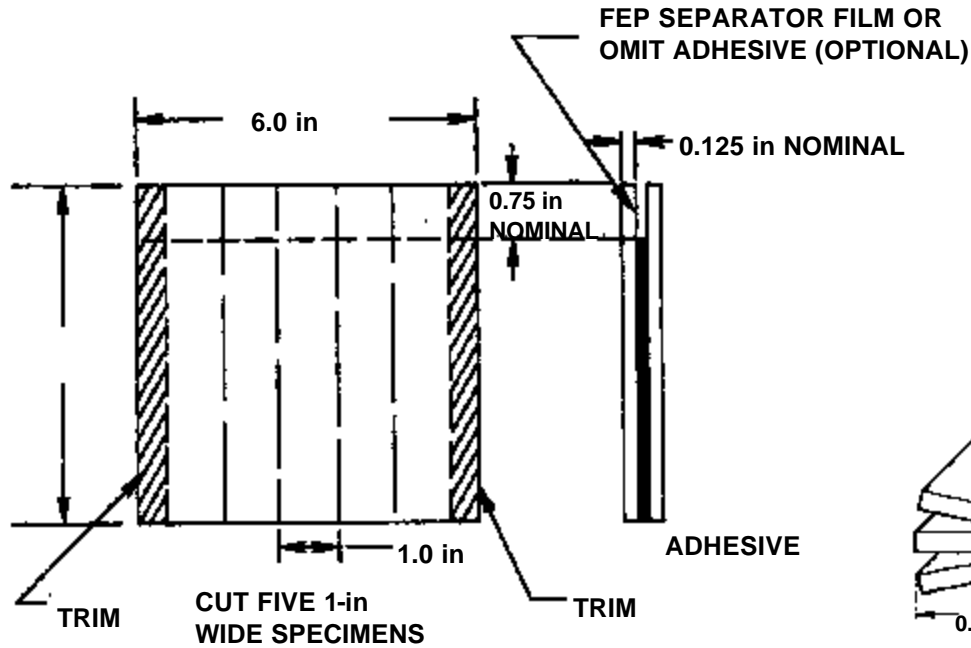
WEDGE TEST



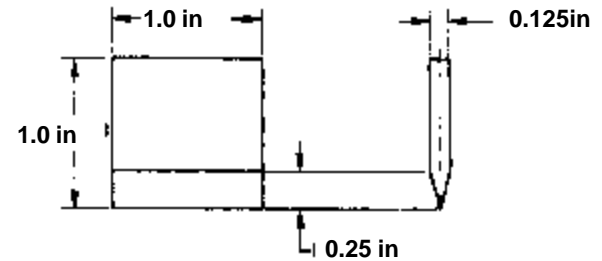
- **Boeing Learned Via Double Cantilever Beam (DCB) Testing that Environmental Exposure of Mode I Loaded Specimens Duplicates In-service Performance Better than Do Lap Shear and Peel Tests (aluminum bonding)**
- **Wedge Test Is a Simplified DCB Approach**
- **Implemented by Boeing for QC of FPL then PAA Preps**
 - **Adherends, adhesive, etc held constant to assess prep**
- **Used Extensively by Douglas A/C During PABST**
- **Early correlations to Service Life Led to Pass/Fail Criteria**
 - **Criteria now considered extremely lenient (unacceptable)**
- **Not Standardized for Environmental Exposure & Pass/Fail**



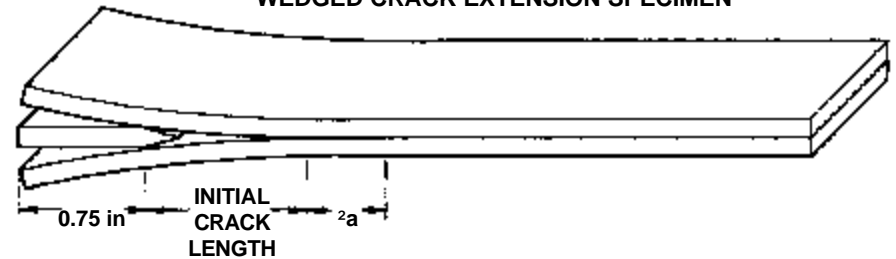
ASTM D 3762 WEDGE TEST



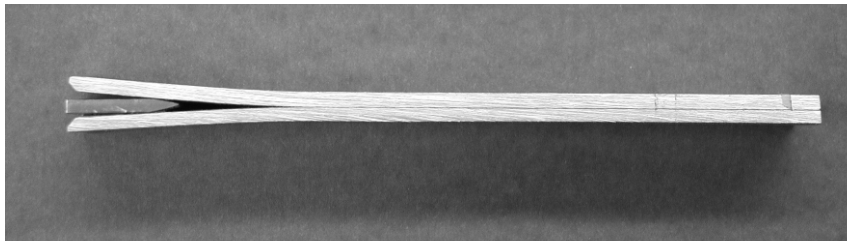
ALUMINUM OR STAINLESS STEEL WEDGE



WEDGED CRACK EXTENSION SPECIMEN



$2a$ = CRACK GROWTH AFTER EXPOSURE





WEDGE TEST THOUGHTS



- **Wedge Test Can Be Readily Misused**
 - Correlations to service life are very limited (case-by-case); could change given larger/broader statistical sample
 - OK as comparator between surface preps with all other potential variables held fixed (screening)
 - Best used with a control prep having known service history
 - Do not use to derive fracture toughness values (do not use fracture toughness – polymer property – to assess prep)
- **Wedge Test is Semiquantitative**
 - Mainly evaluate failure mode
 - Look to initial crack length as indicator of test severity
 - Crack growth can indicate failure mode but currently cannot be used to quantify service life



WEDGE TEST THOUGHTS



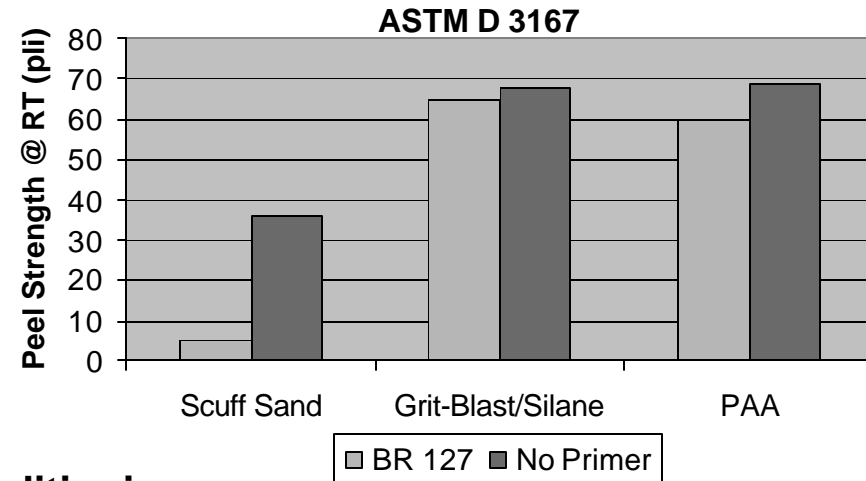
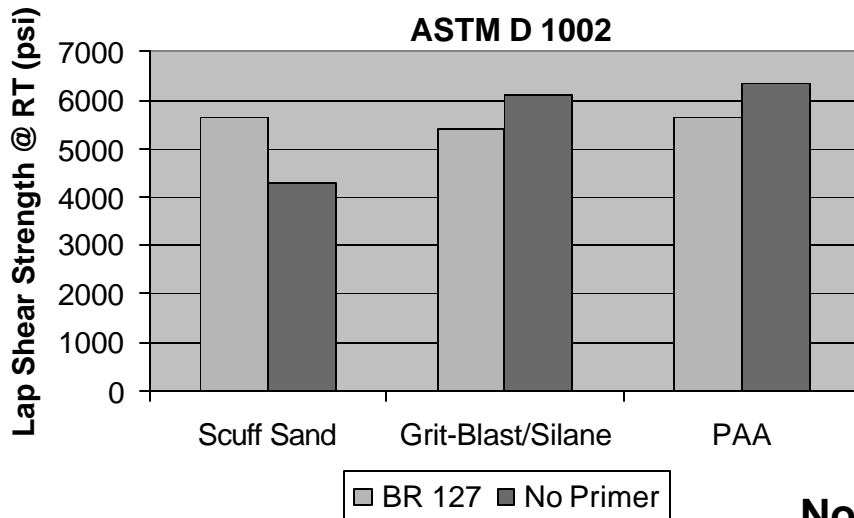
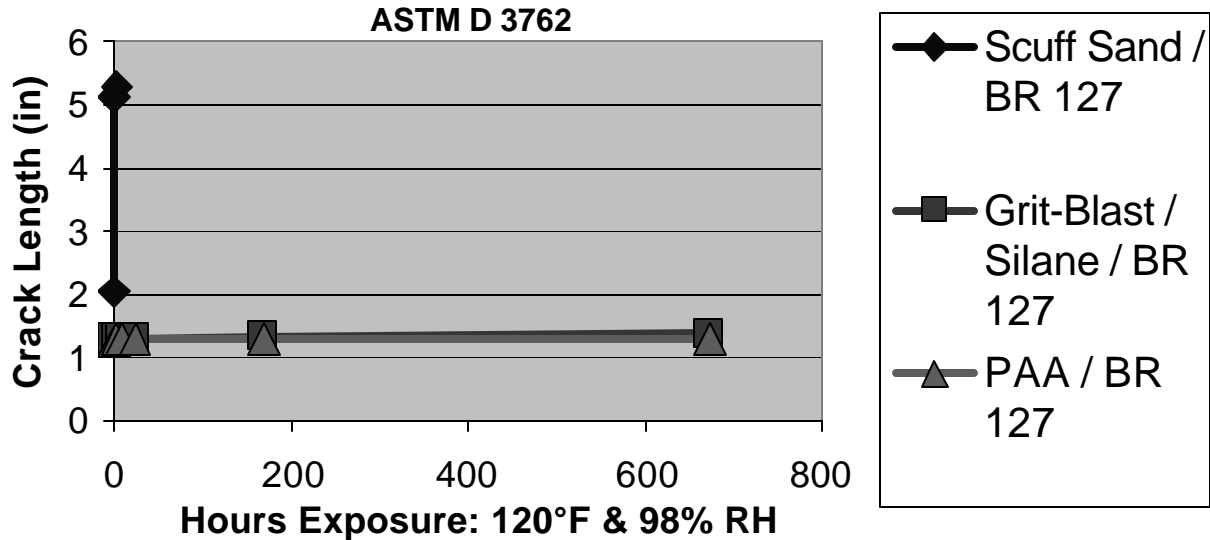
- **Wedge Test Is a “Contrived” Test**
 - **Is meant to accelerate effect of moisture environment in a simple laboratory test**
 - **Is not intended to mimic actual loads or environmental conditions, including temperatures, seen in actual bonding applications**
 - **Cannot be used to derive an “allowable” for design**
 - **Depending on test parameters, can be too severe (but can still be “passed” using viable surface preps)**
 - **Higher temperatures can weaken adhesive and make a less stringent test for surface prep (interface)**
- **Wedge Test Cannot Currently Answer Question: “How Good Is Good Enough?”**



WEDGE TEST VERSUS LAP SHEAR AND PEEL



AF 163-2 Adhesive



No Conditioning

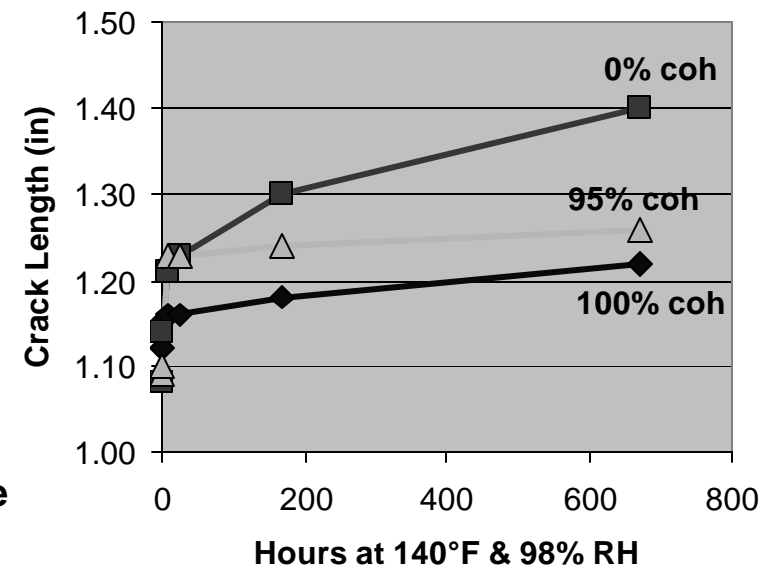
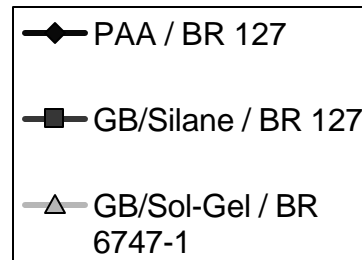
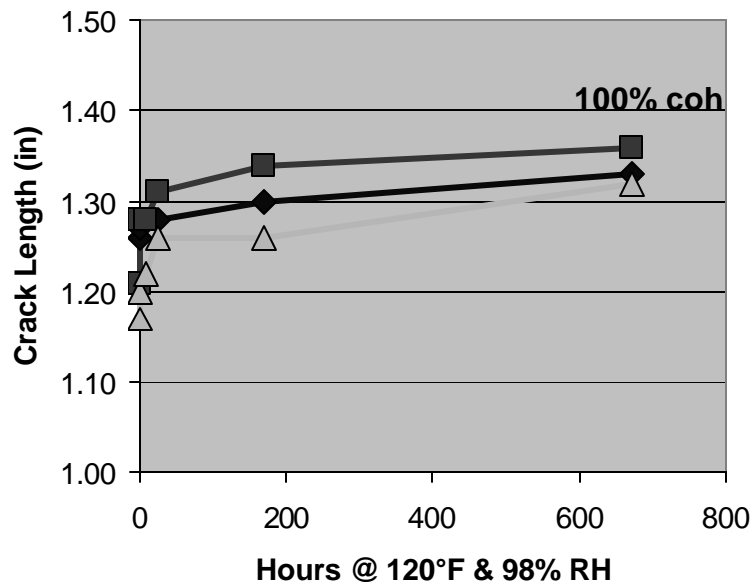
What about a shear test given the “right” conditioning & enough time?



WEDGE TEST CONDITIONS 120°F vs 140°F



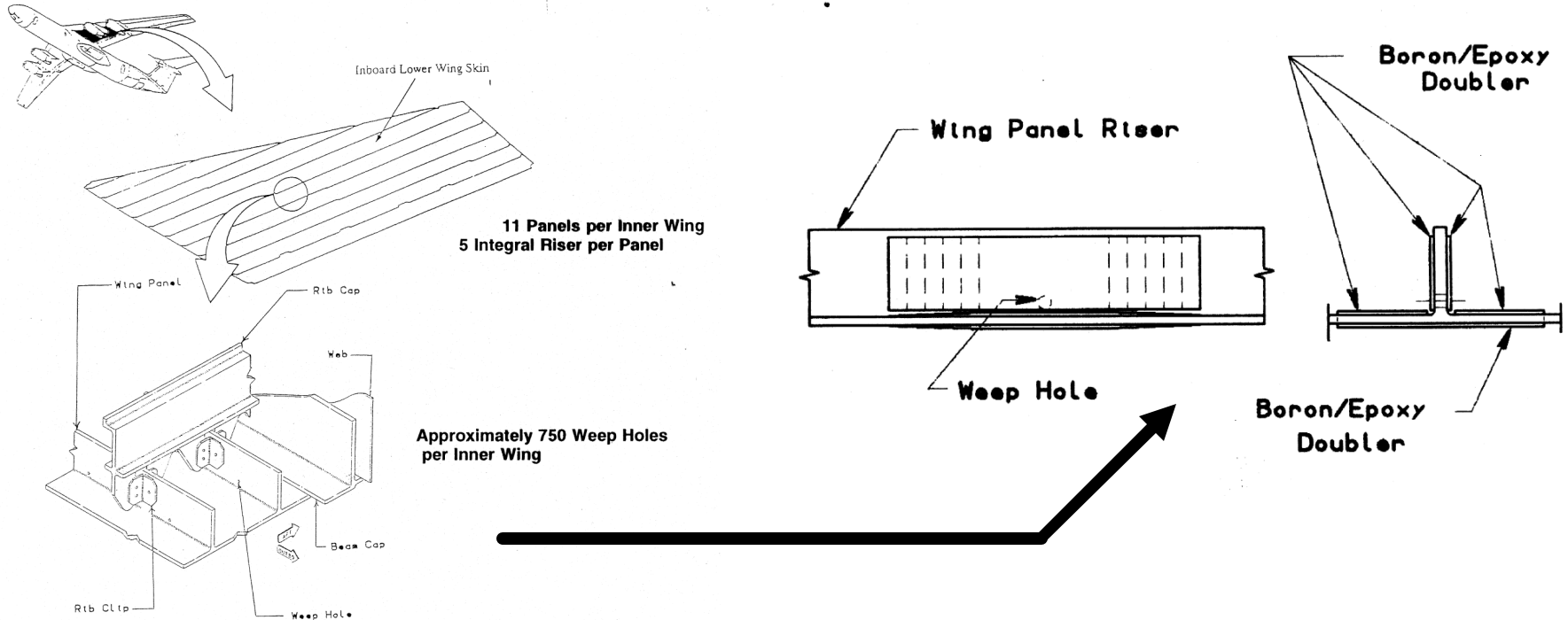
Wedge test conditioning at 140°F (60°C) and 95-100%RH can distinguish between PAA/primer and certain repair surface preparation techniques where 120°F (49°C) wedge test cannot



GB/Silane “Fails” 140°F Wedge Test but Has Performed Well in Service for C-141 Weep Hole Repairs for 10+ Years



C-141 WEEP HOLE REPAIRS



- More than 750 Repairs to About 170 Aircraft (7075-T6 Aluminum)
- Grit-Blast/Silane (GBS) with Primer Employed for Most Repairs
- B/Ep Doubler Prep for > 50% Repairs: Resin-rich Nylon Peel Ply
- Over 2,000 Patches with 8-10 Years Successful Service using GBS
 - Two known failures (both at metal); one traced to operator error ²⁰



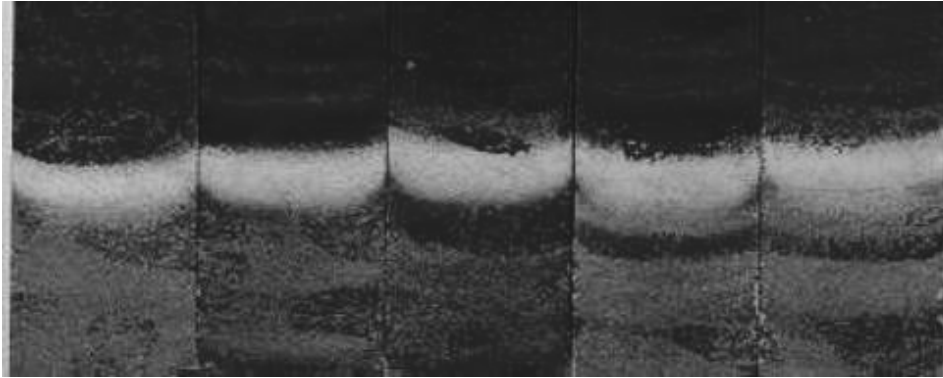
WEDGE TEST PER AFRL/MLSA



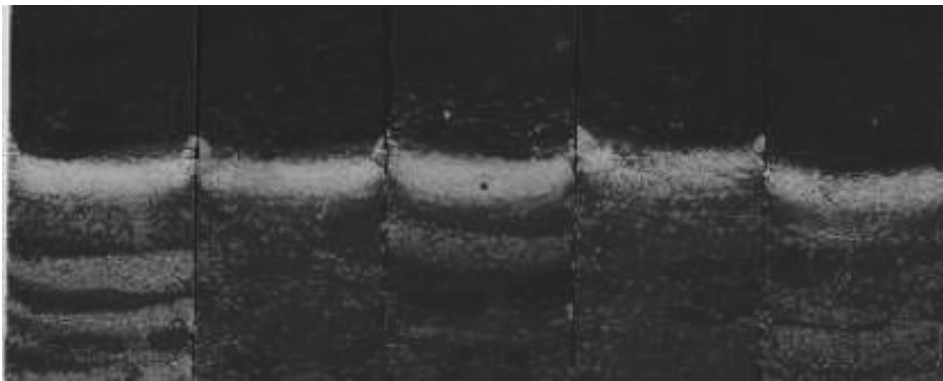
- Preferred Conditions: 140°F (60°C) & 95-100% RH
- Acceptable Conditions (Good Enough?): 120°F (49°C) & 95-100% RH
- Check Initial Crack Length to Ensure Test is Valid
- Measure Crack Growth at 1, 4, 24, & 168 hr and 28 days
- Test Duration: 28 Days
 - Significant data available (not quantifiably correlated to service)
 - Others have used 1 hour to over 10,000 hours
 - Marginal preps can “pass” 1hr and even 24hrs & fail 28 days
- Pass Criteria: ³95% Cohesive Failure (Within Adhesive) with Interfacial Failure Only At Edges
- Adhesive Must Generate Adequate Stress at Crack Tip and Sufficient Resistance to Conditioning Environment
 - May not be acceptable using adhesive for specific application
- Compare to Control w/ Known Service History (Similar Applications)



WEDGE TEST FAILURE MODES



100% Cohesive Failure: Ideal



90-95% Cohesive Failure: Marginal



COMPOSITE BOND FAILURE (CASE STUDY)



- **Precured Gr/Ep (w/ FG surface ply) Bonded to Al Honeycomb**
- **Surface Prep Via Polyester Peel Ply Removal (No Abrasion Step)**
- **New Adhesive Qualified for Application (Nonasbestos)**
 - Qualification testing did not use production peel ply?
- **Small Edge Delaminations Noted on Parts After Adhesive Change**
 - Glass prepreg evaluated to replace peel ply (hard to remove)
 - Abrasion after polyester peel ply removal (improves situation)
- **Composite Skin Departs Aircraft in Flight**
 - Adhesive remains on a/c; intact on aluminum honeycomb core
 - Early example of bond with new adhesive (prior to abrasion)



COMP BOND FAILURE (CONT)



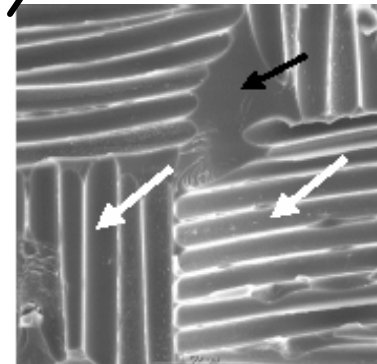
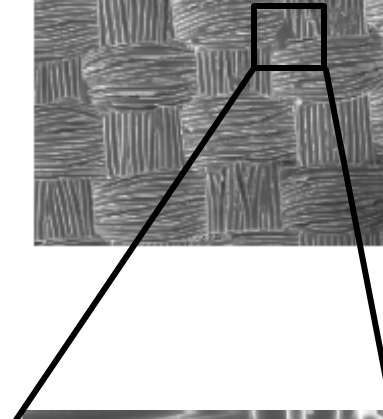
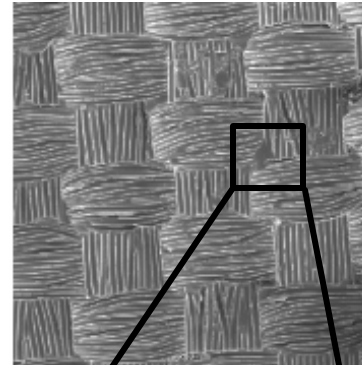
- **Peel Ply Imprint Found in Adhesive (Intimate Contact)**
- **No Fracture Surface Over Most of Bond Area (Peel Ply Fibers)**
 - No contamination found on surface
 - Small amounts of fracture at interstices of peel ply
- **Second Nonasbestos Adhesive Shows Greater % Fracture**
 - Tested on components using peel ply surface prep
- **Simple removal of polyester peel ply left overall “rough” surface due to peel ply imprint, but majority of resin on surface was smooth (unfractured) where it contacted peel ply fibers**
- **Surface Prep Adequacy Was Adhesive Dependent**
- **Although intimate contact was made and no contamination was present, one adhesive did not yield adequate strength**
- **Actual Full-up System Was Not Tested Prior to Implementation**



SAME ONLY DIFFERENT



Different Aircraft, Same Results



**Peel Ply Imprint
Found on »57% of
Doubler Surface**

**white arrows – fiber imprints (unbonded – no fracture)
black arrow – adhesive failure**

**Approx. 15% Void; >70% Unbonded Area
Polyester Peel Ply Removal w/o Abrasion**



COMPOSITE PREP QUESTIONS



- **Peel Ply or Tear Ply or Not?**
 - Keep laminate surface free from contamination
- **Which Peel Ply?**
 - Could be system dependent (one size may not fit all)
 - Be careful of transfer (of peel ply constituents)
 - Nylon is cursed, but resin-rich (prepreg) nylon appears to work
- **Treat After Peel Ply Removal?**
 - Abrasion via “sanding” or grit blasting
 - Plasma or other
- **How Remove Abrasion Debris?**
 - Water wipe or solvent wipe or dry removal
- **If Solvents are Used (at Any Point), Which Are Acceptable?**
- **Check for Water Break?**
- **Dry the Component?**

WHAT TEST(S)?



ONGOING RELATED USAF EFFORTS



- **Composite Surface Preparation Study**
- **C-141 Bonded Repair Evaluation**
- **Sol-gel Surface Preparation Implementation**
- **Long-term Outdoor Exposures**
- **Prebond Surface Preparation NDI (SwRI and WR-ALC)**
- **Finalizing Guidelines for Composite Repair of Metal**
- **In-situ Monitoring of Bonded Joints (Efforts Related to “Smart Patch” in AFRL/ML and AFRL/VA)**
- **Composites Affordability Initiative (CAI)**



AFRL/MLS COMPOSITE SURFACE PREP STUDY



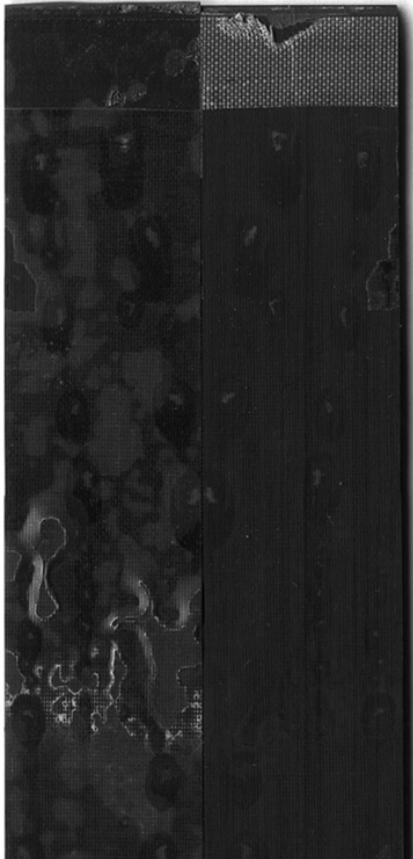
- **Relatively Small Internal Program to Answer Questions**
 - External collaboration on portions of effort
- **Investigate Test Methods**
 - **Composite DCB**
 - » A “contrived” test that is not meant to simulate the actual structure; must have 0° ply against adhesive
 - **Peel**
 - **Modified Flatwise Tension**
 - **Fatigue**
- **Generate Data to Support Surface Prep Approach**



COMPOSITE “WEDGE TEST”



AS4/3501-6; [0]₁₆; Porous Teflon (Coated Fiberglass Release Ply)



**Remove Release Ply
Apply Release Agent**



**Remove Release Ply
Solvent Wipe**



**Remove Release Ply
Grit Blast**

Distinguished Good from Horrible but Not Good from Bad



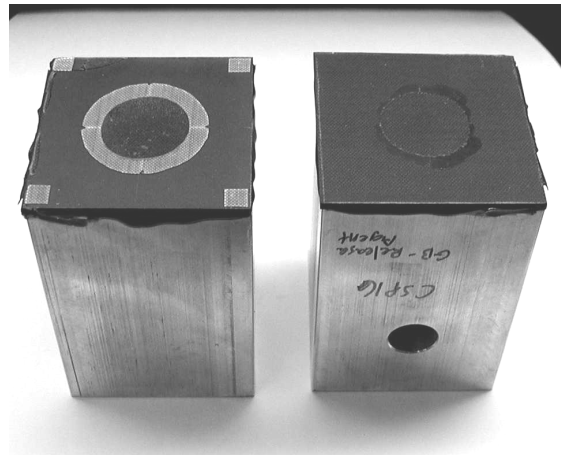
MODIFIED FLATWISE TENSION



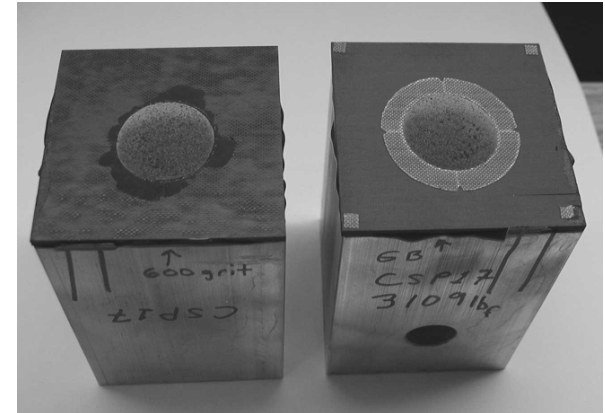
AF 163-2 Adhesive



Grit-Blast (good)



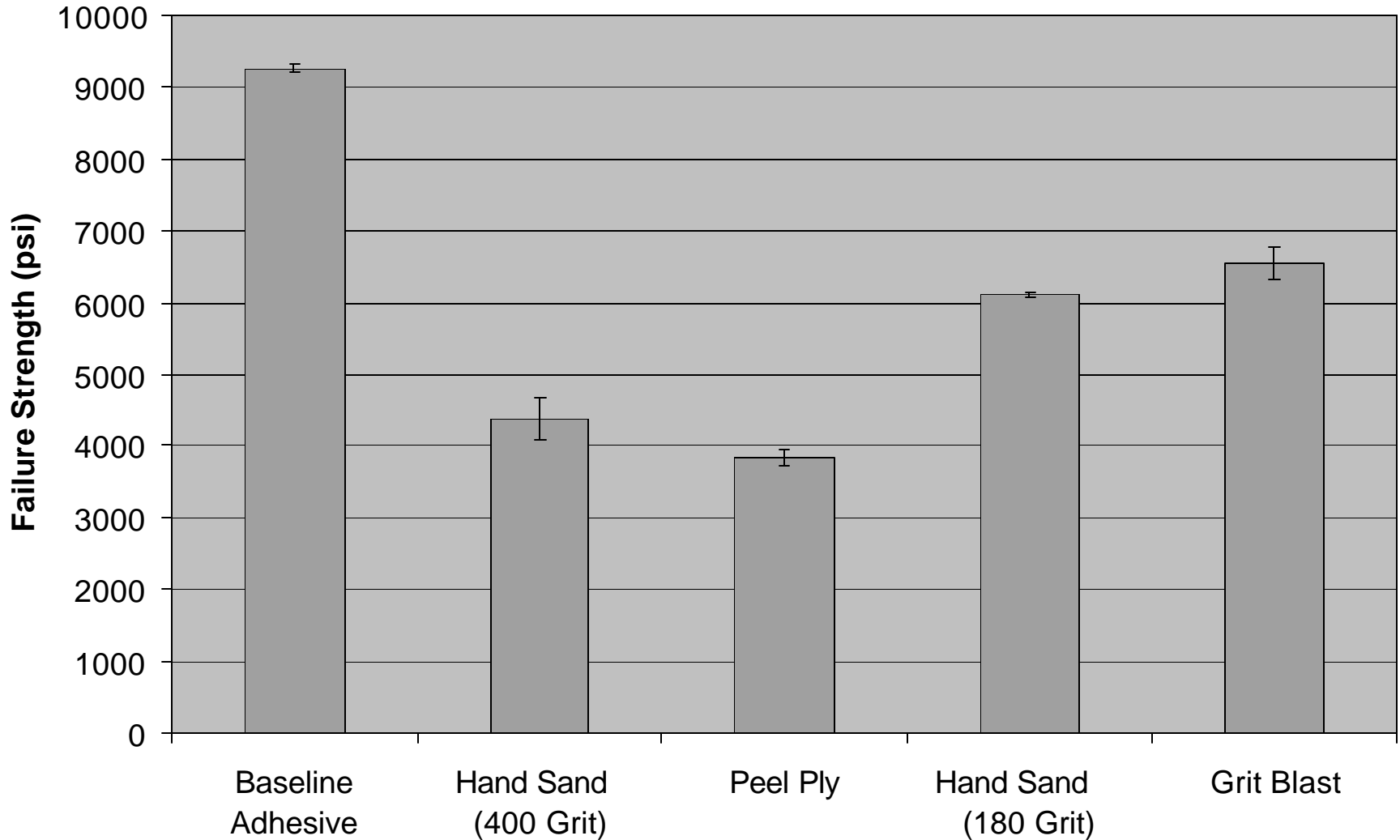
Release Agent (bad)



Light Sand (mediocre)



MODIFIED FLATWISE TENSION



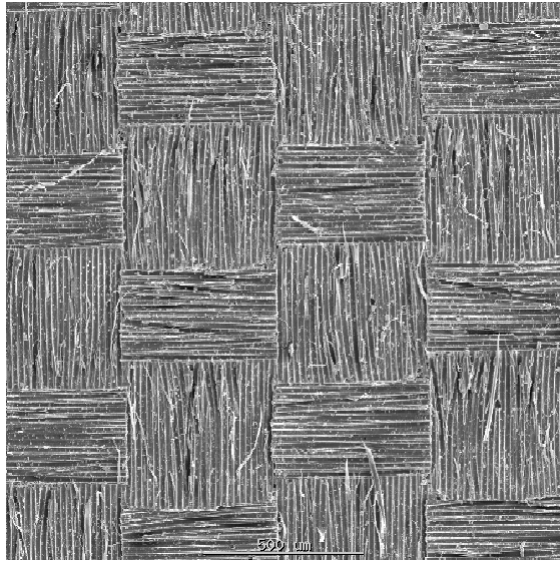
EA 9696 Adhesive



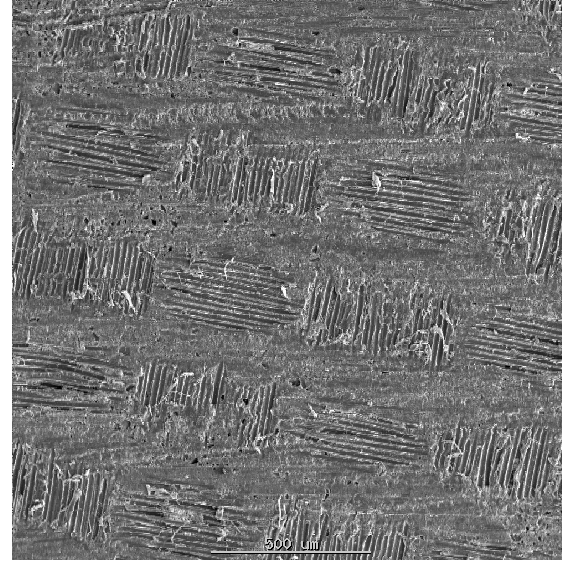
ABRASION AFTER PEEL PLY REMOVAL



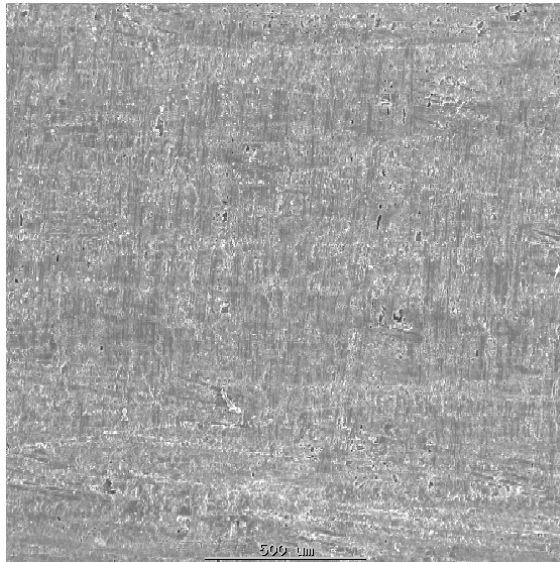
Peel Ply Imprint



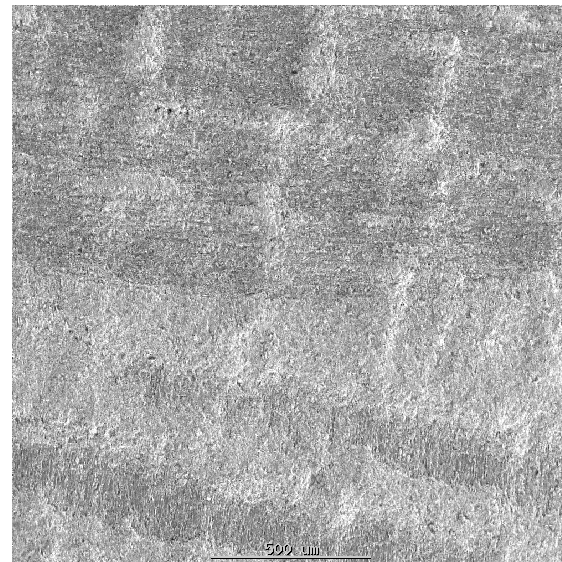
Light Abrade



“Proper” Abrade



Grit Blast





C-141 BONDED REPAIR EVALUATION



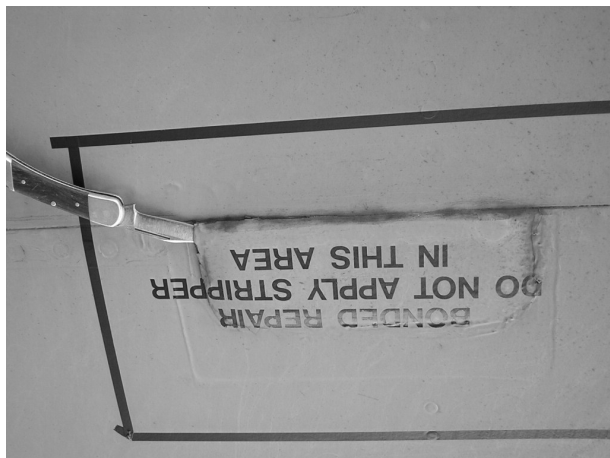
- **Effort Involving WR-ALC, ASC and AFRL/ML**
- **Assess Largest USAF Bonded Repair Effort**
- **Generate Data to Convince USAF Engineering Authority (ASC/EN) that Bonded Repairs Can Be Trusted**
 - Increase usage of technology (via ASC/EN push)
 - Some relaxation of fail-safe criteria?
- **Test Plan Not Yet Finalized**
 - Fatigue and residual strength after service
 - Evaluate several factors, including: surface prep variations, organization installing repair, unbond growth, patch location, NDI technique
- **Correlate with Wedge Test?**
- **Coordinate with DSTO Efforts**



C-141 BONDED REPAIR EVALUATION



- **Number of Available Repairs Changes with Time as Planes are Scrapped**
- **Resources Limit Scope of Effort; Priority Repairs are Identified and Saved**
- **To date, 11 External Repairs Inspected via Thermography and Over 200 Evaluated visually and via tapping**
 - **All GBS prep repairs appear to be sound**
 - **About 10/20 acid etch repairs show some delamination**
- **65 repairs from 43 Aircraft Salvaged to Date; Now at WR-ALC**





CONCLUSION



CAN REQUIRED LEVEL OF TRUST BE ESTABLISHED?

- **Perhaps, If the Following Occur:**
 - **Train design engineers in bonding technology**
 - **Greatly reduce failure rates by specifying adequate procedures and practicing proper process control ***
 - **Develop better tools to assess bond integrity**
 - **Develop better means to predict bond life (via improved accelerated testing and/or quantitative correlations with service life)**
 - **Health Monitoring for Certain Applications ?**

*** Dilemma: Efforts to provide simple field-level surface preps that greatly improve performance over current practices may still allow some failures and be counterproductive to some extent**