FAA Workshop on
Best Practice in Adhesive Bonding

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Overview

- Outline of service experience with bonded structures and repairs
- Identify safety critical issues
- Major cause of bond failure
- Substantiation of bond durability
- Problems with hot bonded repairs
- Testing of adhesives for fatigue
Background

- Adhesive bonding used for years
  - Sandwich panels, construction and repair
  - Fabrication of structural joints
- Field experience: Service may be variable
- Military experience: bonded repairs can give excellent bond durability
- Need to identify best practice
  - What distinguishes a good and bad bonds?
  - Are certification requirements adequate?
  - What are the critical safety issues in bonding?
Military Repair Metal Bond Experience

- 1992 Survey: 42% of bonded repairs were to fix a defective repair
- Changed:
  - Adhesive
  - Surface Preparation
  - Training
- Results: Only 2 bond failures in 14 years
- Similar results elsewhere

- Non-Bond Related 47%
- New Adhesive Defect 32%
- Defective Repair 21%
  (42% of Bond Related Defects)
Why are Issues Safety Critical?

- Material formed during process
  - Properties not measurable prior to fabrication
- No redundancy
- No NDT/QC assures bond integrity
- Environmental durability not dependent on structural loads: Not a design issue
  - Depends on integrity of interface
- No method for prediction of bond life
Understanding Bond Failures

• Bonding is a chemical process
  ◆ Ionic, covalent, metallic and attractive bonds

• Two possible failure modes:
  ◆ Cohesion by fracture of the adhesive (design)
    • Inadequate overlap length
    • Thermal stresses
    • Gross void defects (production)
  ◆ Adhesion by failure of the interface (processing)
    • Inadequate surface preparation
    • Ineffective surface preparation process
Service Experience with Adhesive Bonds

• You never hear reports about good bonds
  ❖ Data is anecdotal, poor statistical support

• Some OEMs claim good bonds, blame failures on operators: Not always true
  ❖ Inappropriate maintenance
  ❖ Exceeding design loads or fatigue envelope

• A properly designed bond applied using valid processes should NEVER fail
Causes of Service Bond Failures

- Inappropriate design methodology
- Inappropriate substantiation testing
- Inadequate design data
- Inappropriate quality assurance tests
- *Even with all of the above correct, many failures occur because of inappropriate process validation*
Consequence of Bond Failure

- Aloha 243 Incident: Separation of pressure cabin
- Identified Cause:
  - Multi-Site Damage due to cracking
- Cracking occurred after bond failure
The Real Cause

- Cold Bond Film Adhesive
- Condensation caused disbond, corrosion
- Fasteners overloaded, cracked (MSD) and skin failed
- Initiated by bond failure
Examples of Bond Failures

- Aileron trim tab hinge from commuter aircraft
- Certified to JARs
- Cause: Interfacial failure due to ineffective surface preparation
  - Note serial number
Composite Kit Aircraft Failure

- Not related to crash
- Surface of main spar at skin bond
- No adhesive present
- Adhesive scraped off during fabrication
- Pencil mark still evident on bond surface. Preparation?
Sandwich Panel Failure

- Complete interfacial disbond
- Deficient surface prep at manufacture
- Note injection repairs
- Lessons learned:
  - Must validate prep.
  - Injection is useless
A Good Bond:

**F-111 Lower Wing Crack Repair**

- Fatigue crack at fuel flow point under spar
- Critical crack
- Bonded boron/epoxy
- Validated FEM, sub-component fatigue
  - 30,000 hrs
    - Growth 48mm - 64mm
    - Failed at 99% DUL

Wing withdrawn after 670 hrs, fatigued for 12000, unrelated failure
Composite Patch Failure

- Interfacial failure of repair to F/A-18
- Silicone coated peel ply used
- No instruction to remove peel ply in SRM
Boron Patch Failure

- Eight patches out of 180 failed in service
  - Seven applied in Malaysia in 1980
- Adhesive exhibited micro-voiding due to humidity during repair
- Remaining adhesive failed in fatigue

Lesson Learned: Environment must be controlled
Sandwich Panel Repair Failure

- F-111 external skin
- Patch departed in flight
- Causes:
  - Ineffective surface prep.
  - Undercure of adhesive
- Lessons Learned:
  - Use only valid processes
  - Can’t use just one heater blanket on complex structure
Deficient Surface Preparation

- Surface preparation is most significant factor in long term bond durability
  - Cause of most bond failures in service
- Most failures caused by ineffective processes not just contamination
- Requires clean, chemically active surface that is resistant to hydration
  - A clean surface alone is not sufficient
Substantiation of Bond Durability

- Lap shear tests per ASTM D1002 inappropriate
- Test is adequate for Quality Assurance
- Lap shear will NOT validate long term bond durability

![Graph showing bond strength over time for good and bad processes]

- Test early, all processes will pass
- Inferior processes will fail in service
**Substantiation of Processes**

- The key to metal bond durability is to validate using the wedge test ASTM D3762

- Acceptance criteria must be more stringent
  - Broad consensus:
    - $\Delta a < 0.20 \text{ in/24 hrs and } 0.25 \text{ in/48 hrs}$
    - $<5\%$ adhesion failure

- Durable bonds meet these criteria
Pro and Con

• For:
  - Service history shows:
    • Lap shear testing is not discriminating between good and bad processes
    • For metals, durable bonds meet wedge test criteria

• Against:
  - Test is not representative of service loads
  - Database is anecdotal
Validation for Composite Bonds?

• Data on wedge tests for composite bonds is very limited but shows some promise

• Problems expected:
  ◆ Lay-up to be used
  ◆ Top ply failure may occur

• Is there a better test??????
Peel Plies

- Poor performance of some peel plies demonstrates the need for a validation test
- Silicone, Teflon coated plies DO transfer
- Corona treated plies leave an inactive glazed surface
- RAAF experience: Always lightly grit blast
Quality Management

• Close attention usually paid to quality control testing to assure integrity
• QC, NDT only identify extremely bad bonds
  - Does not provide assurance of a good bond
• QC, NDT only of value if environmental durability is validated before using the process
• Best practice is to manage quality through process, not just to measure it after bonding
Repair Bonding

- Requirements are the same as construction
- The processes are different
  - Surface Preparation
    - Non tank, on-aircraft
  - Heating
    - Non-autoclave, usually heater blankets
  - Pressurisation
    - Non-autoclave, usually vacuum bag
- Materials must be suited to these processes
Heat Cured Repairs

- Risk of undercure of adhesive or overheating damage to structure
- Strongly influenced by heating methodology and temperature sensor usage
Dangers with Single Heat Sources

- Overheat
- Undercure
- Patch Heater Blanket
- Frame
- Longeron
- Thin skin
- Undercure
- Heater Blanket
- Overheat
- Thin skin

Patch

Longeron
Heater Configuration

Zone 1
Thin skin

Zone 2
Patch

Zone 3
Longeron

Zone 4
Temperature Sensor Installation

• Temperature sensors used for two purposes:
  ◆ To ensure structure is not overheated
  ◆ To provide assurance of full cure

• For control (overheating) *On surface being heated within each heated zone* where the *HIGHEST* temperature is anticipated

• For assurance of cure, *on surface being heated within 12 mm of repair to measure LOWEST temperature around the bond line*
• Sensors for assurance of cure

• Sensors for control
• Many OEMs design using an “allowable” average shear stress
  - Based on lap-shear data ASTM D1002
  - Usually with “building block” approach
    • Coupon, sub-component and component tests
• Designs can be unconservative
• Ignores the real shear stress distribution that occurs in bonded joints
Adhesive Load Capacity

• RAAF uses Hart-Smith’s bond load capacity to manage designs

\[
P_1 = \sqrt{2\eta\tau\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_t\left(1 + \frac{E_{t_i}}{E_{o_o}}\right)} \\
P_2 = \sqrt{2\eta\tau\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_{o_o}\left(1 + \frac{E_{o_o}}{E_{t_i}}\right)}
\]

• Methodology:
  - Calculate load capacity, compare with load case
  - Assess requirement for a more rigorous design
  - Provide enough overlap to achieve load capacity
Load Capacity Approach

- Possible to design bond stronger than parent material
- Adhesive will NEVER fail by shear
- Possible to reduce testing requirements
  - All specimens will fail outside bond
**RAAF use of Joint Condition**

- **Condition 1:**
  - Adhesive Load Capacity $> 1.2$ DUL
    - Joint should never fail in service
    - Testing should always fail structure away from joint

- **Condition 2:**
  - Adhesive Load Capacity $> DUL$ but $< 1.2 DUL$
    - Joint should be adequate
    - Requires more rigorous design and testing

- **Other conditions applicable only to fatigue enhancement or emergency repairs**
Application of approach

- Joint condition used in conjunction with assessment of significance to determine level of design rigour
  - Primary or significant structure or Condition 2 requires validation by FE and/or testing
  - Secondary or non-significant structure, then Condition 1 joint does not require validation or testing, simple design methods acceptable
Certification of Repairs

• Current USAF approach for repairs:
  ◆ 1.2DUL *without* the repair

• RAAF experience: valid designs, processes then bond *NEVER* fails

• Design should give credit for the repair
  ◆ RAAF proposes a Risk Based Analysis method
Design Data

- Database of adhesive properties is small and inaccurate
- Lap-shear, peel data are not suited to design
- Need a shared repository for design data (MIL HDBK 17?)
Fatigue Testing of Adhesives

- Lap shear ASTM D3165 is not a valid test
  - Short overlap causes entire joint to be plastic
  - No creep recovery due to lack of elastic zone
  - Adherend plastic behaviour near fatigue limit causes premature failure of adhesive
- Thick adherend ASTM D5656 not valid either
  - Entire joint becomes plastic, no creep recovery
Fatigue of Adhesives

- Real Joint: Adhesive can be fatigued past elastic limit without failure
- **Conclusion**: Fatigue tests should use realistic joints, not lap-shear specimens
Conclusions

• Substantiation of environmental durability is absolutely essential
  ◆ Must be a rigorous test method
  ◆ Must be part of certification basis

• Quality should be managed not measured

• Repair processes and materials may be different to construction
Conclusions

- Design on average shear is inappropriate
- Need a certification basis to give credit for repairs
- Fatigue tests should use realistic joints
Managing Adhesive Bond Integrity

- FARs rely on a process specification, quality control and NDT
  - Process Specifications are useless unless properly validated
  - QC tests usually short term strength tests
    - Does not test environmental durability
  - NDT only tells of bondline gaps
Recommendation

- Amend FAR Sec. 25.605
  - Fabrication methods.
  - [(a)] The methods of fabrication used must produce a consistently sound and durable structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification that has been demonstrated to produce a structure that is strong and durable.
  - [(b) Each new aircraft fabrication method must be substantiated by a test program that demonstrates that the process used is capable of producing a structure that is strong and durable.]

- Will require limited additional testing