FAA Workshop on

Best Practice in Adhesive Bonding

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Overview

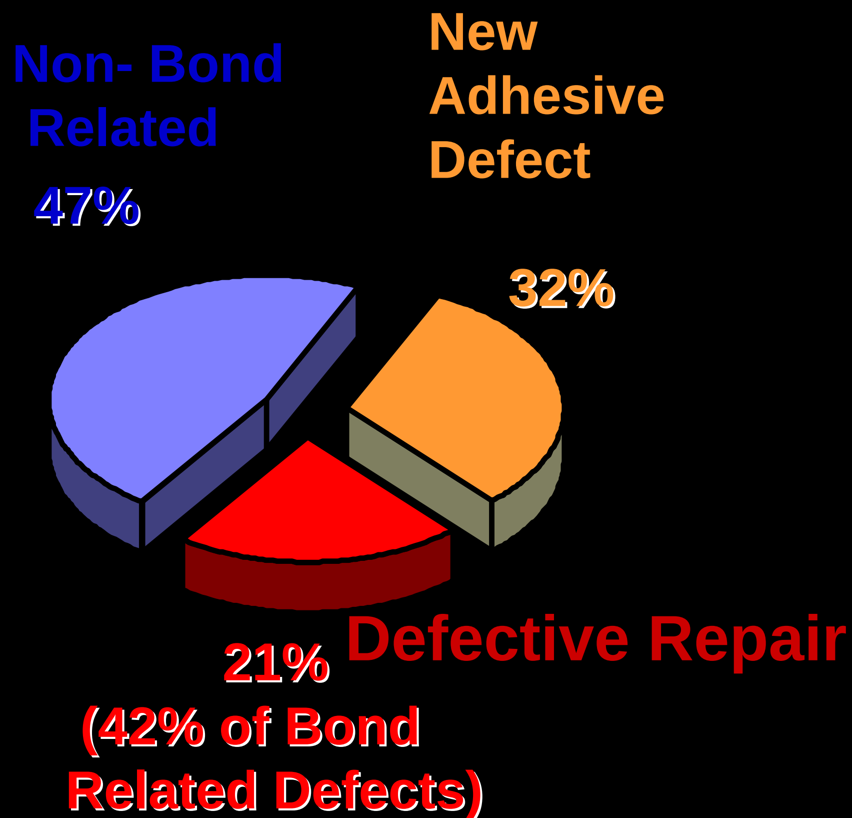
- Outline of service experience with bonded structures and repairs
- Identify safety critical issues
- Major cause of bond failure
- Substantiation of bond durability
- Problems with hot bonded repairs
- Testing of adhesives for fatigue

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



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

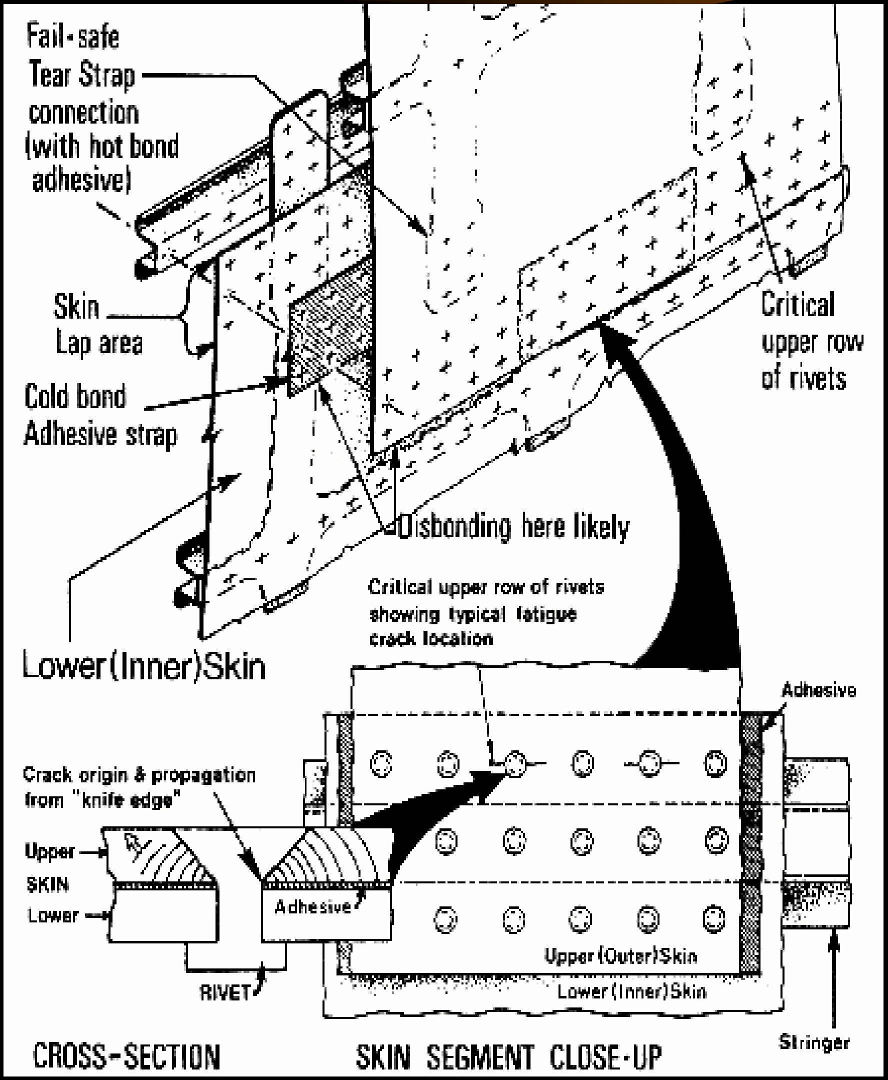
- Inappropriate design methodology
- Inappropriate substantiation testing
- Inadequate design data
- Inappropriate quality assurance tests
- *Even with all of the above correct, many failures occur because of <u>inappropriate process validation</u>*

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 RealCause

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

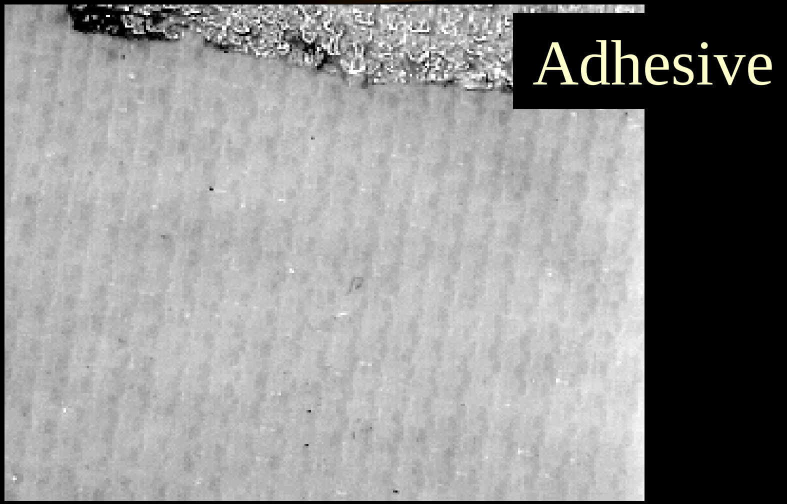


Examples of Bond Failures

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

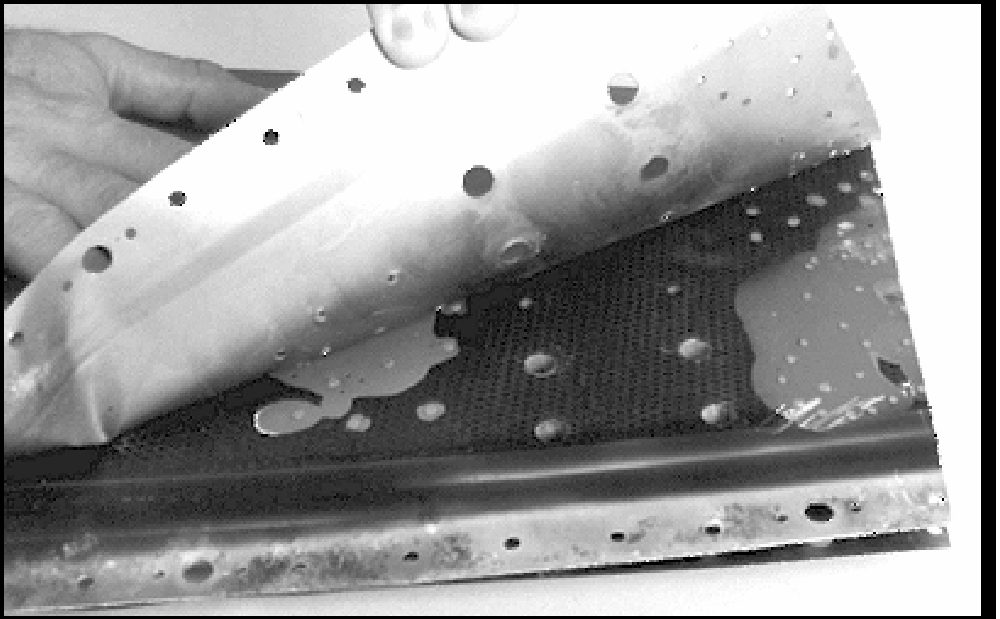
Composite Kit Aircraft Failure

- *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?



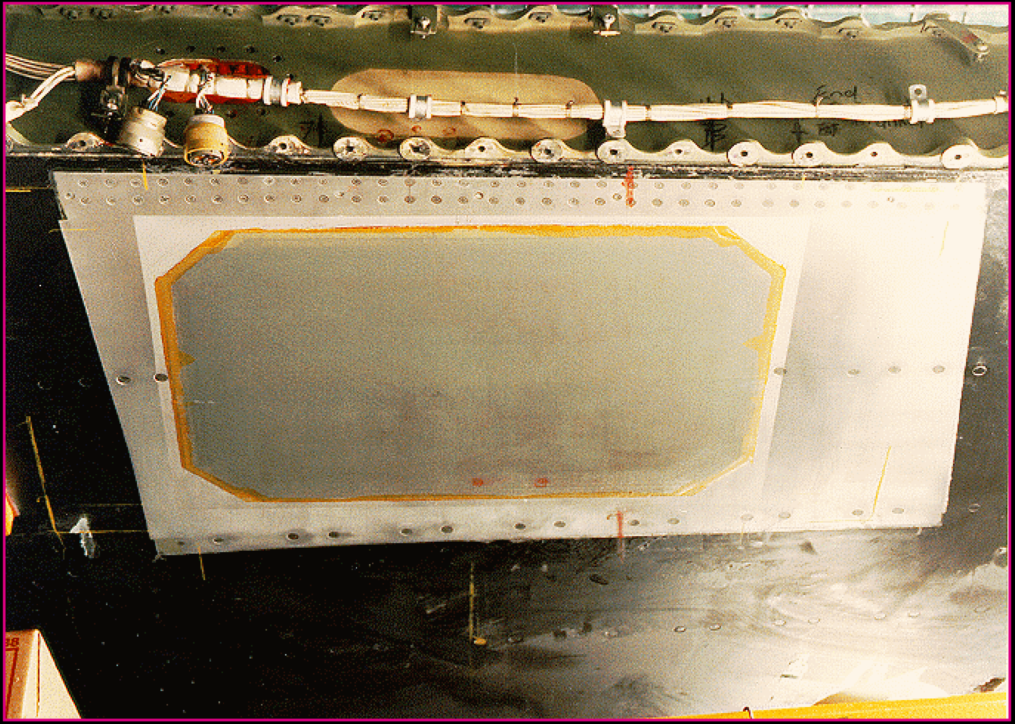
Sandwich Panel Failure

- 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



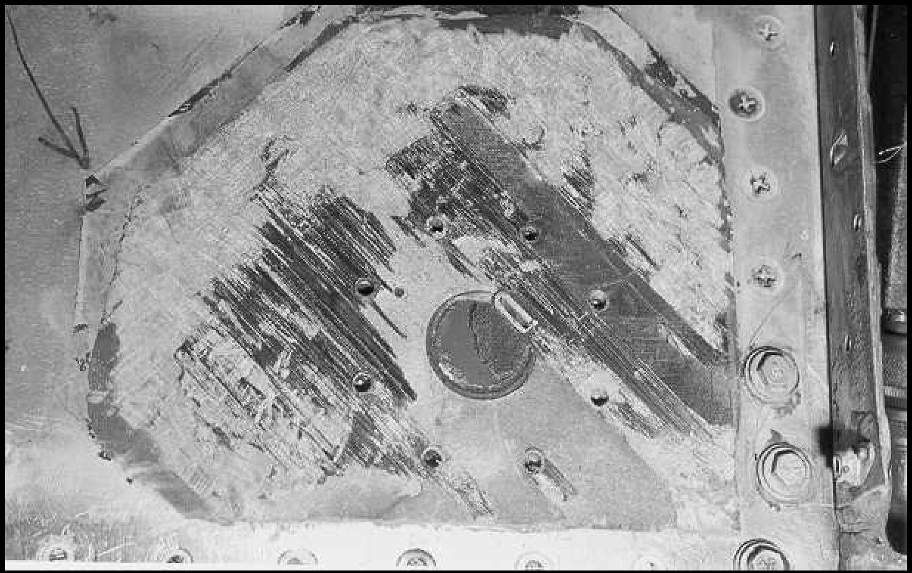
Wing withdrawn after 670 hrs, fatigued for 12000, unrelated failure

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

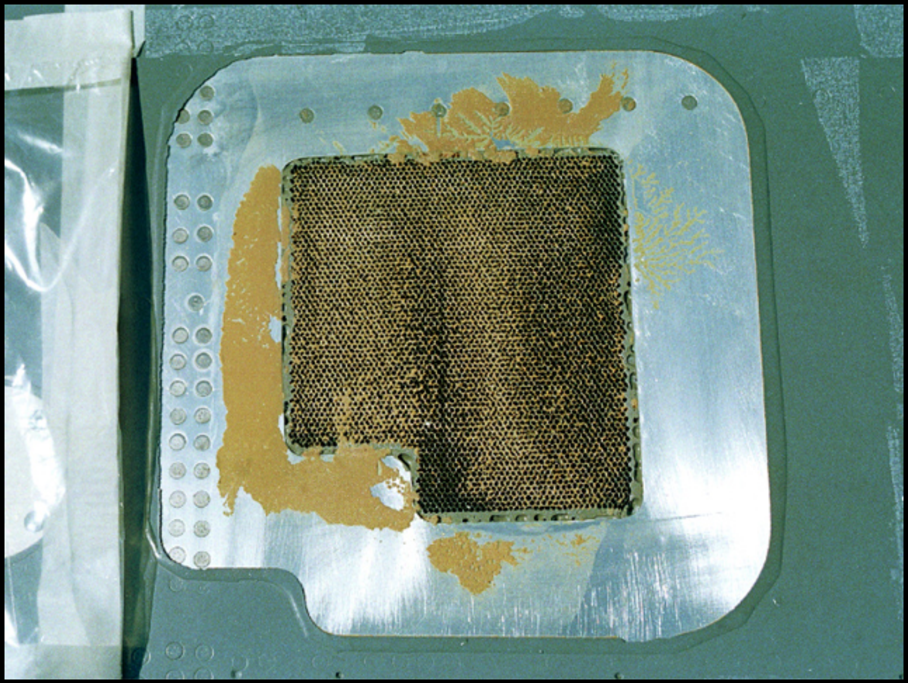


Lesson Learned:

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

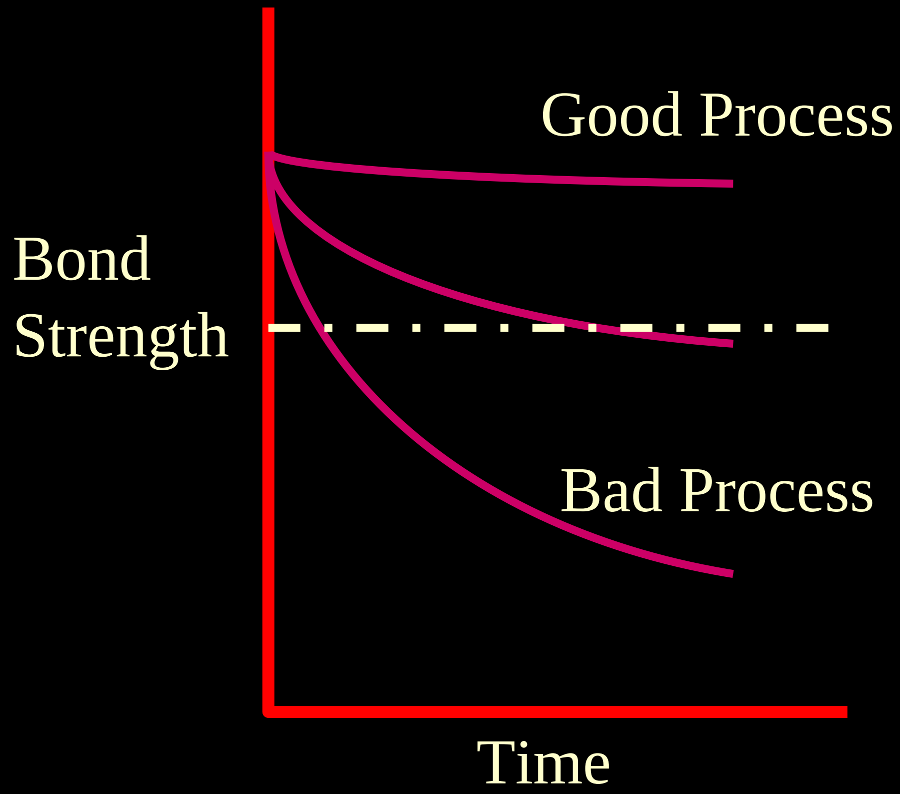


Deficient Surface Preparation

- 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

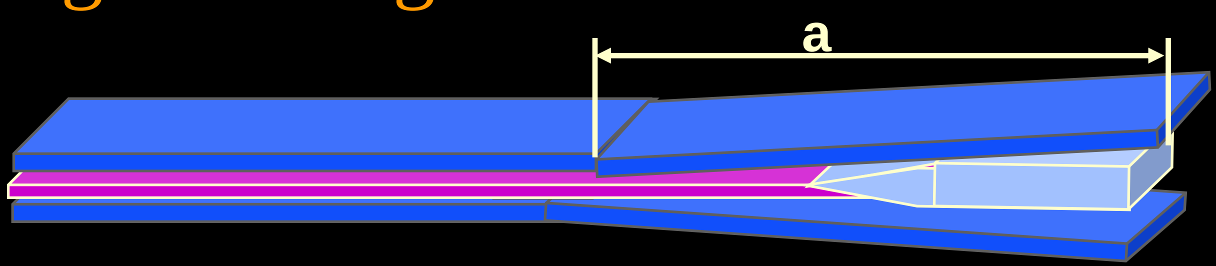
- Lap shear tests per ASTM D1002 inappropriate
- Test is adequate for Quality Assurance
- Lap shear will NOT validate long term bond durability



- 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:
    - $\Delta a < 0.20$ in/24 hrs and 0.25 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 <u>before</u> using the process
- Best practice is to manage quality through process, not just to measure it after bonding

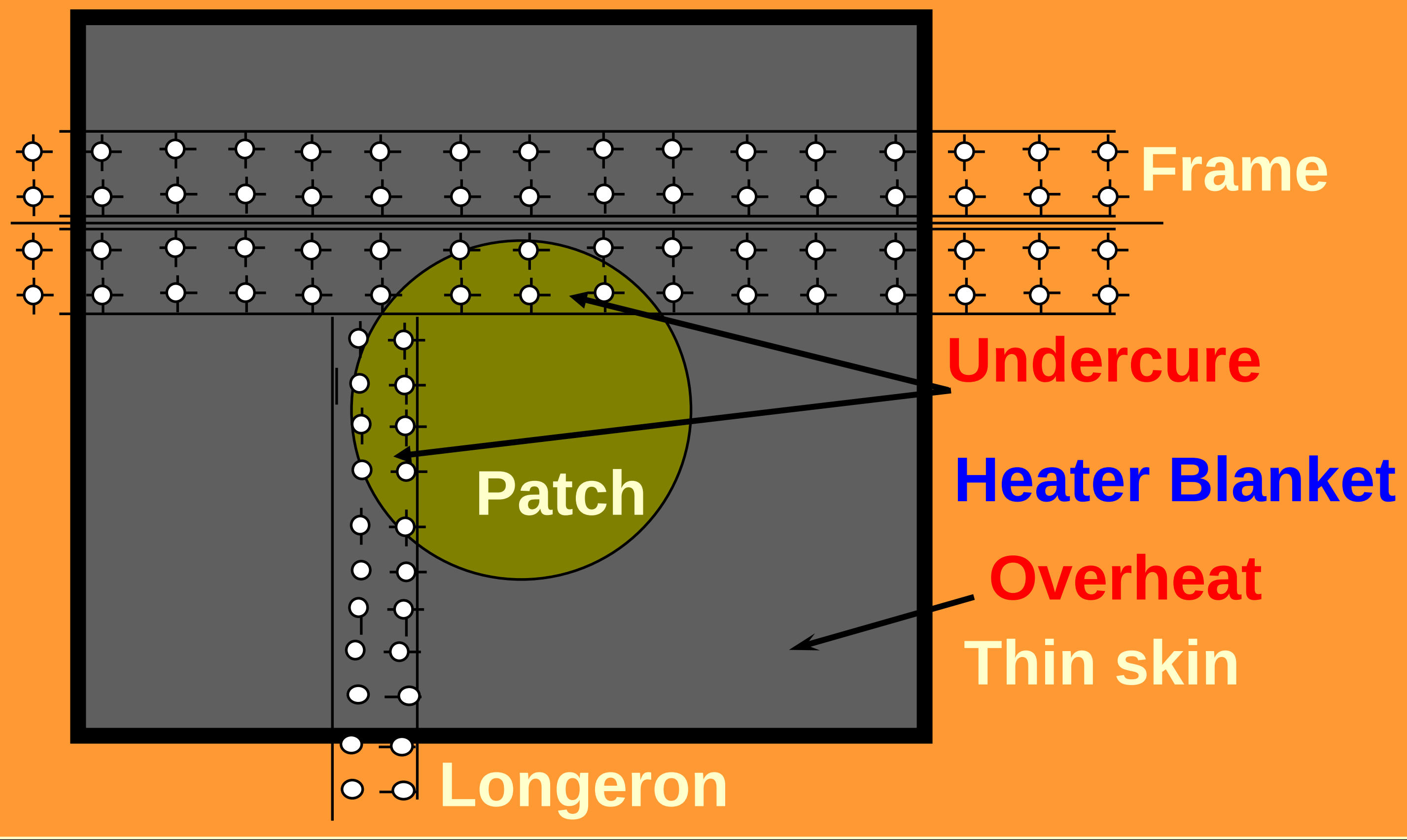
Repair Bonding

- 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

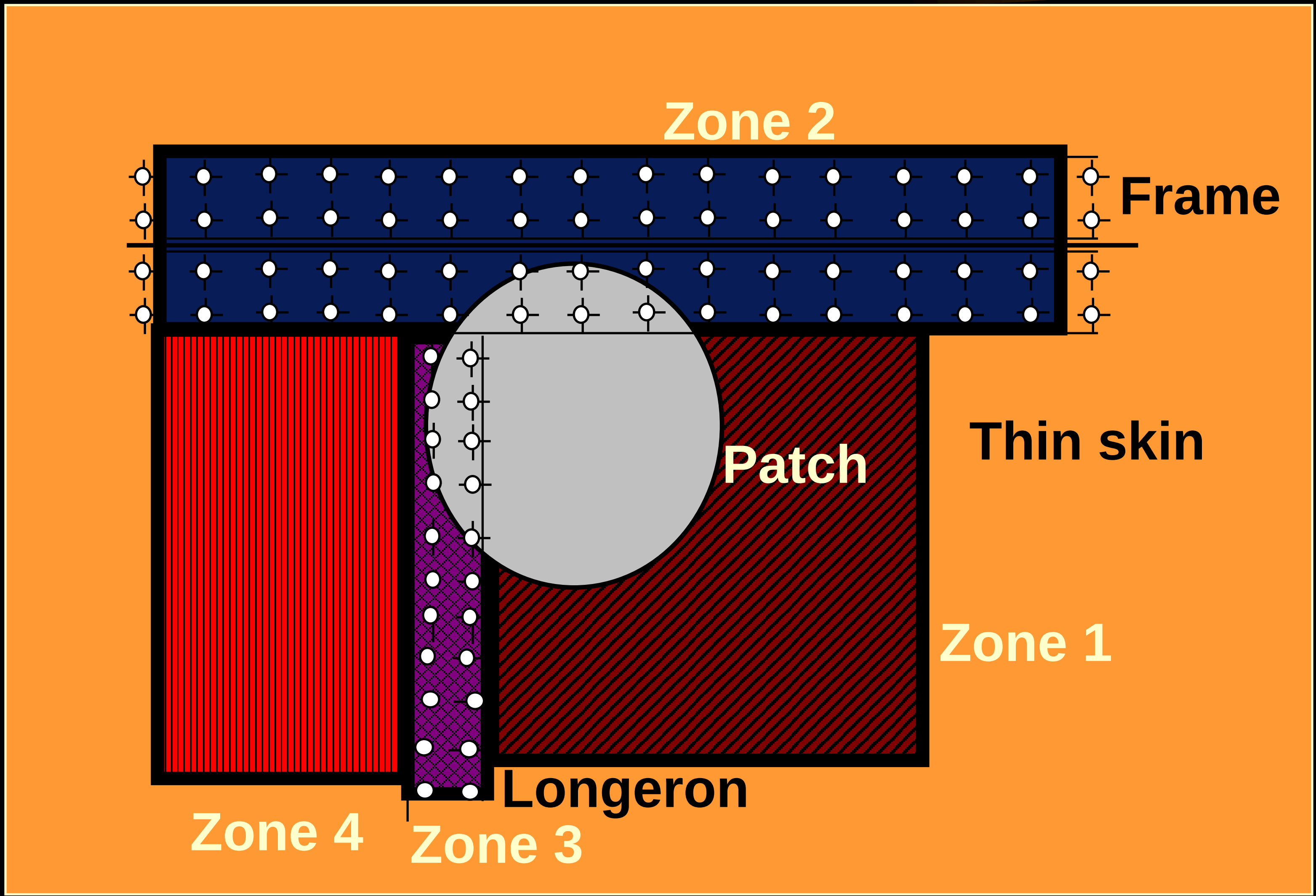
Heat Cured Repairs

- Risk of undercure of adhesive or overheat damage to structure
- Strongly influenced by heating methodology and temperature sensor usage

Dangers with Single Heat Sources



Heater Configuration

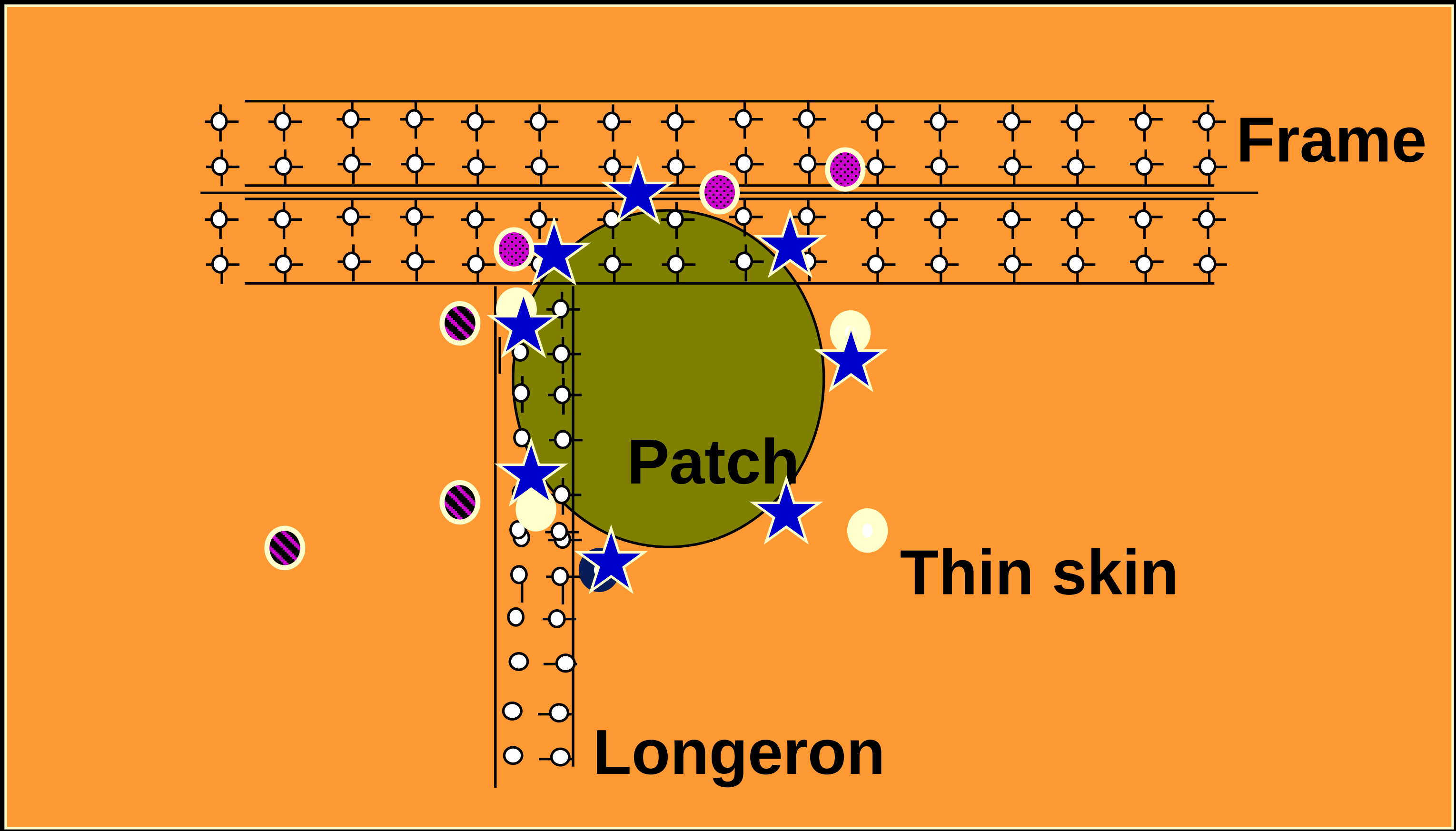


Temperature Sensor Installation

- 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 Location

- Sensors for assurance of cure
- Sensors for control



Design Issues

- 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

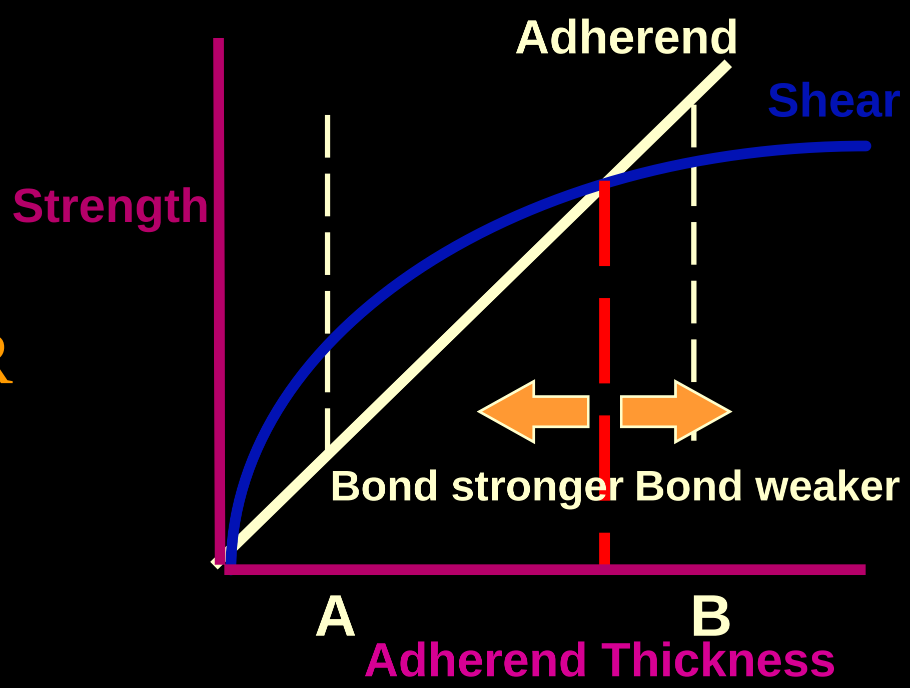
- RAAF uses Hart-Smith's bond load capacity to manage designs

$$P_1 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_i t_i\left(1 + \frac{E_i t_i}{E_o t_o}\right)} \qquad P_2 = \sqrt{2\eta\tau_p\left(\frac{1}{2}\gamma_e + \gamma_p\right)E_o t_o\left(1 + \frac{E_o t_o}{E_i t_i}\right)}$$

- 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 <1.2DUL
    - 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

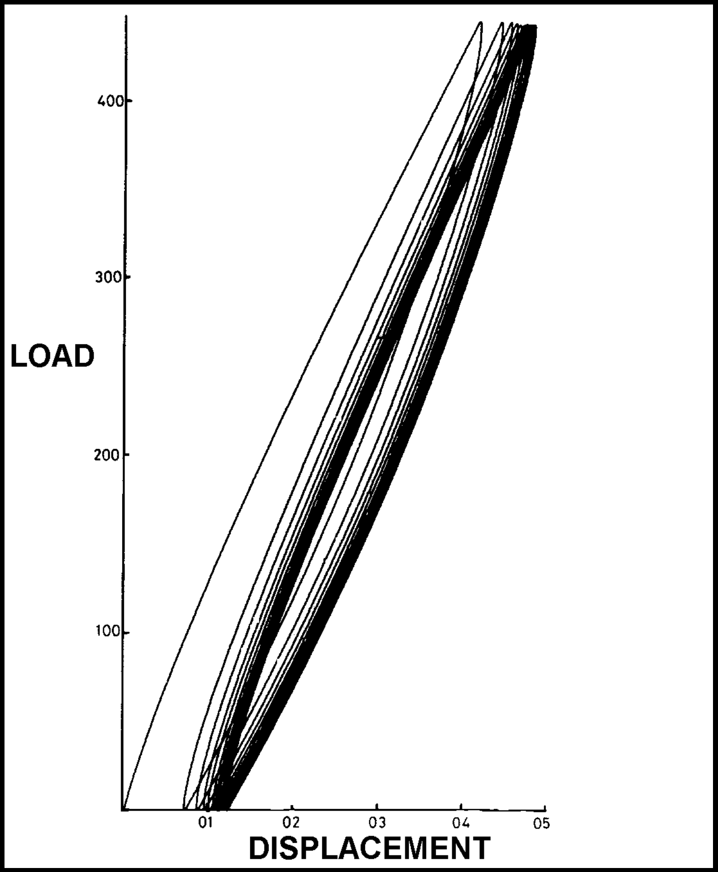
- Database of adhesive properties is small and inaccurate
- Lap-shear, peel data are not suited to design
- Need a shared repository for design data (MIL HDBK 17?)

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