IS FAILURE FORENSICS MORE IMPORTANT THAN DAMAGE TOLERANCE IN ASSESSING DEFECTS IN DISBONDING STRUCTURES?

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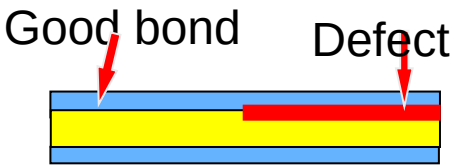
Introduction

- Damage Tolerance Analysis (DTA) is effective for managing cracks in metallic aircraft structures
  - Demonstrate strength, fatigue resistance with defects of a known size
  - Mandated by FAR 2x.573
- DTA often used for bonded structures and joints
  - Testing, analysis assume localised bond separation in good bond

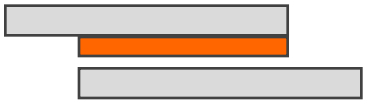


- Some types of defects change bond strength and negate the applicability of DTA
- This presentation demonstrates that adhesive bond failure forensics is essential to management of bond structural integrity

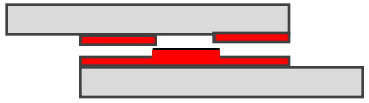
Adhesive bond failure types

- Three types of bond failure:
  - Cohesion failure
    - Adhesive layer is fractured
    - High strength
  - Adhesion failure
    - Separates from the surface of the adherend(s)
    - Low (no?) strength
  - Mixed-mode failure
    - Variable combination of adhesion and cohesion failure
    - Intermediate strength
- The features of these failure types and the implications to DTA will be discussed

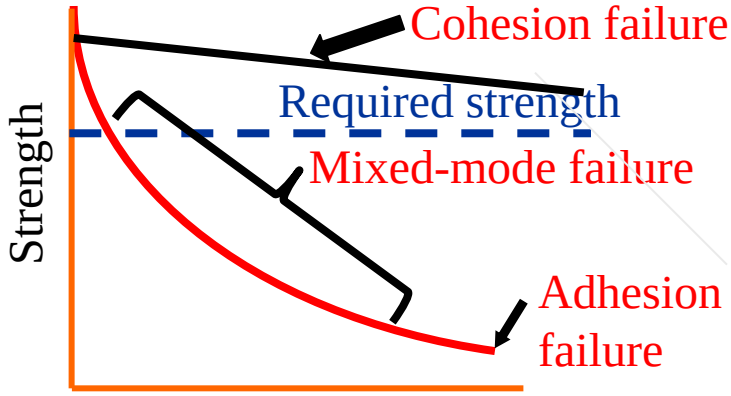
COHESION FAILURE



ADHESION FAILURE



MIXED-MODE FAILURE

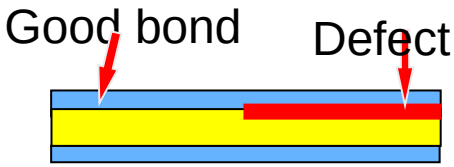


Adhesive bonding mechanisms

- Adhesive bonds rely on chemical bonds at the interface
  - Easy to generate short-term strength with simple treatments
- Long-term strength depends on the durability of those interfacial chemical bonds
- Interfacial degradation over time may cause adhesion, mixed-mode failure ➔ lower strength
  - Due to hydration of surface oxides over time (**metals**) e.g. $Al_2O_3 \rightarrow Al_2O_3.2H_2O$
  - Chemical metal-to-adhesive bonds dissociate, causing disbonding
- Failure may happen without ***any*** flight loads

Application of DTA to adhesives

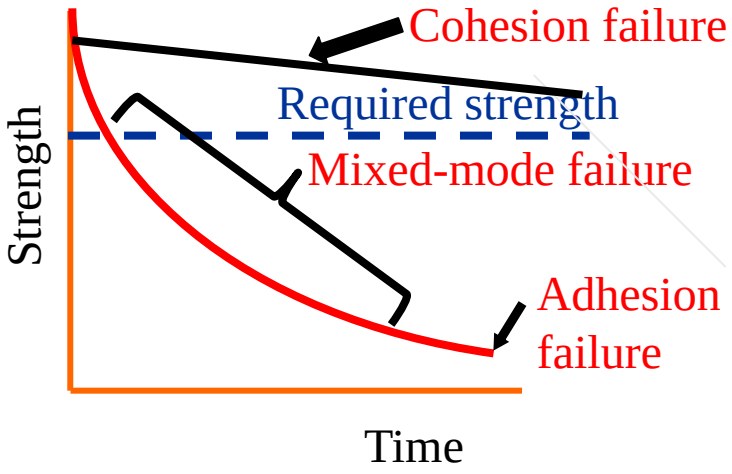
- DTA of adhesive bonds is usually based on:
  - Strength tests with embedded artificial disbonds, or
  - FEA with artificial defects in model
- Both methods:
  - Infer surrounding adhesive maintains original strength
  - Assume a defect combined with loads cause failure



- DTA is only applicable for localised defects occurring in otherwise pristine bonds

Defining the issue

- Why is bond failure forensics important?
- Because FARs and DTA assume cohesion failure
- Real failures often involve adhesion or mixed-mode failure at lower strength
- Assumptions for DTA about residual bond strength are ***invalid*** for most defect types
- Type of defect must be correctly identified to verify applicability of DTA



Limitations of NDI for adhesive bonds

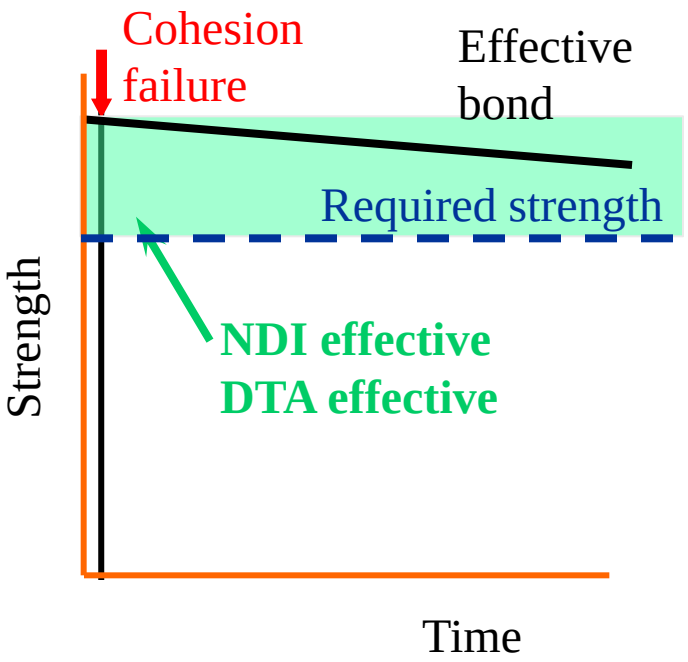
- DTA of adhesive bonds requires effective NDI
- NDI depends directly on detecting air gaps
- NDI can not assess the integrity of the adhesive-to-adherend interface
  - No air gaps
- NDI can not assess bond strength
  - Double-sided adhesive tape will pass the “tap” test
- Can only find an in-service defect <u>after disbonding has commenced</u>

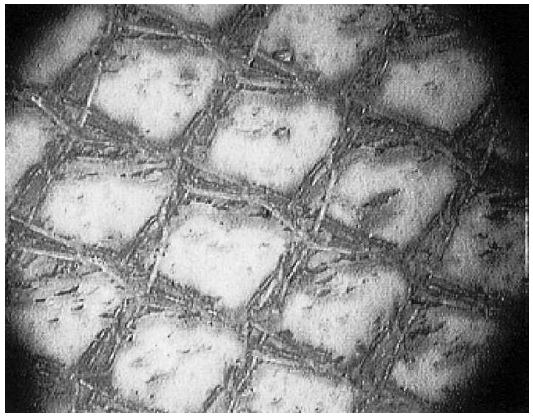
Limitations of DTA

- Adhesive problems which are not compatible with DTA:
  - Interfacial degradation in service
    - Mixed-mode or adhesion failure
  - Micro-voiding during production leading to fatigue failure, and
  - Ineffective (injection) repair of production and service disbonds
- These problems:
  - May not be detectable using post-production NDI
  - May result in significant reduction of bond strength
  - May not be localised to just the detectable defects

Cohesion failure

- Occurs through carrier cloth
- Strength is high
- NDI can find large defects
- DTA is appropriate

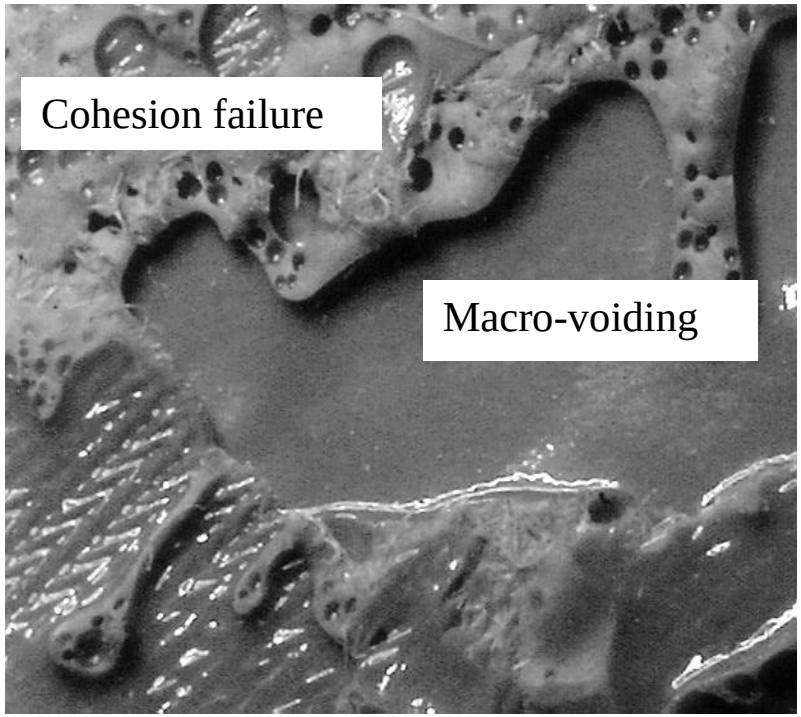




- Design causes:
  - Thermal stresses
  - Stiffness mismatch
  - Inadequate bond overlap
  - Inadequate temp. capability
  - Addressed by certification
- Production causes:
  - Macro and micro voids
- Service causes:
  - Overload

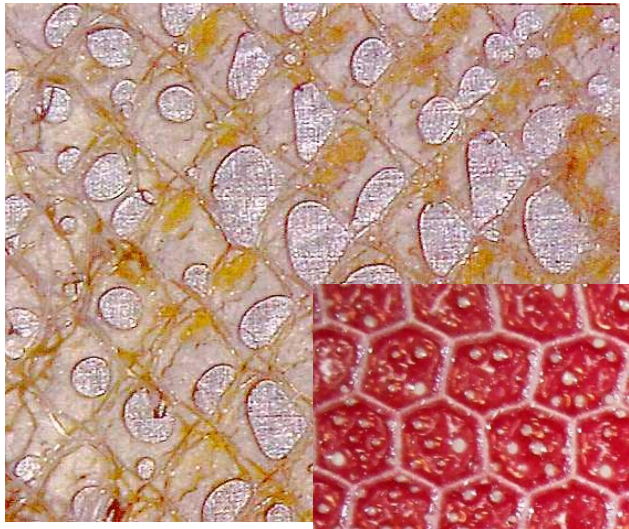
Cohesion failure due to macro-voids

- Large voids in bondline
- Found by post-production NDI
- Residual bond overlap may be inadequate
- Surrounding adhesive is strong
- DTA *is* appropriate
- Often “repaired” by injection
  - Discussed later
- **NOT** caused by service loads or environment
- This is what is modelled by DTA



Cohesion failure due to micro-voids

- Widespread multiple small voids
- Evolution of absorbed moisture during production cure cycle
- Sufficient contact to pass NDI
- Total defect size may exceed DTA
  - Bond is weak
- Micro-voids do not initiate in service
  - May cause disbonds from fatigue, impact, high loads in service



Bonded Joint

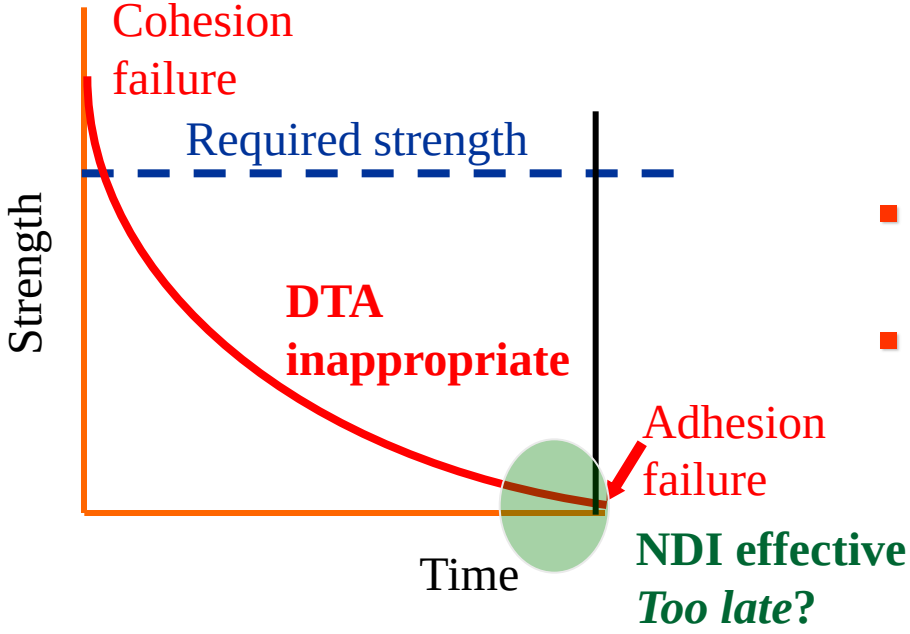
Sandwich Panel

Significance of micro-voiding

- **FM300 adhesive exposed to 30°C and 70% RH for 4 hrs**
  - 53% loss of T-peel strength (ASTM 1876)
  - 28% loss of honeycomb peel strength (ASTM D1781)
- Suppose bonds are certified in dry environment but production is outsourced to Gybrobia (30°C, 70% RH), exposure > 4hrs
- Honeycomb peel: $\text{Strength} = 1.5 \times \text{DLL} \times 0.72 = 1.08 \times \text{DLL}$
- T-peel: $\text{Strength} = 1.5 \times \text{DLL} \times 0.47 = 0.705 \times \text{DLL}$
- Strength is marginal at DLL for honeycomb peel, unconservative for T-peel
- Micro-voids also reduce shear strength
- DTA inappropriate unless based on reduced strength

Adhesion failure

- Fully hydrated bond
  - Very weak
  - Fails at interface
- Causes
  - Poor processing (contamination)
  - Interfacial degradation in service

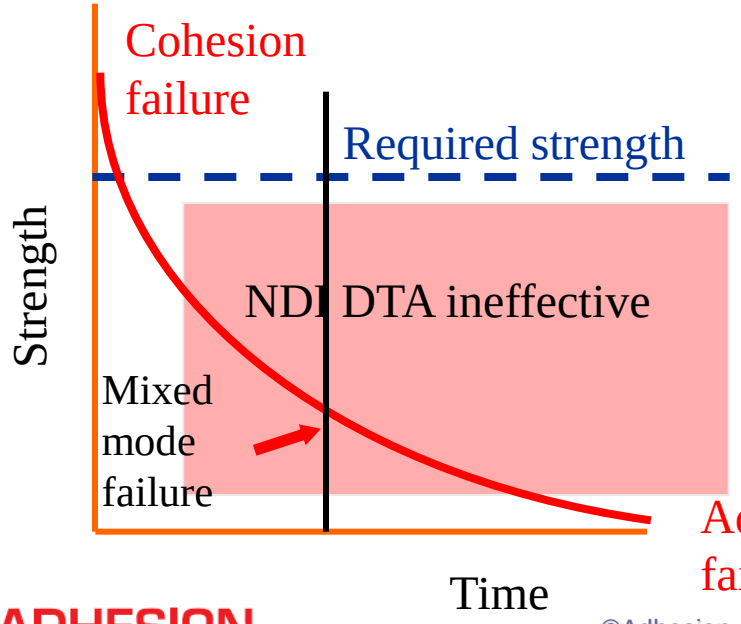


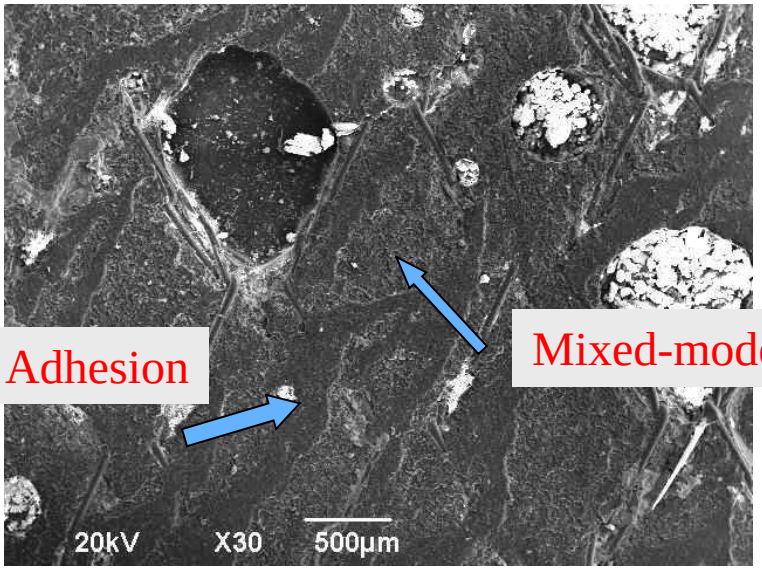
- NDI can only find disbonds *after they occur*
- DTA inappropriate
  - Strength is much lower than certification tests

ADHESION ASSOCIATES

Mixed-mode failure

- Partially hydrated bond
  - Some adhesion/cohesion failure
  - Fails away from carrier cloth
- Failure occurred before interface fully degraded
  - Reduced strength

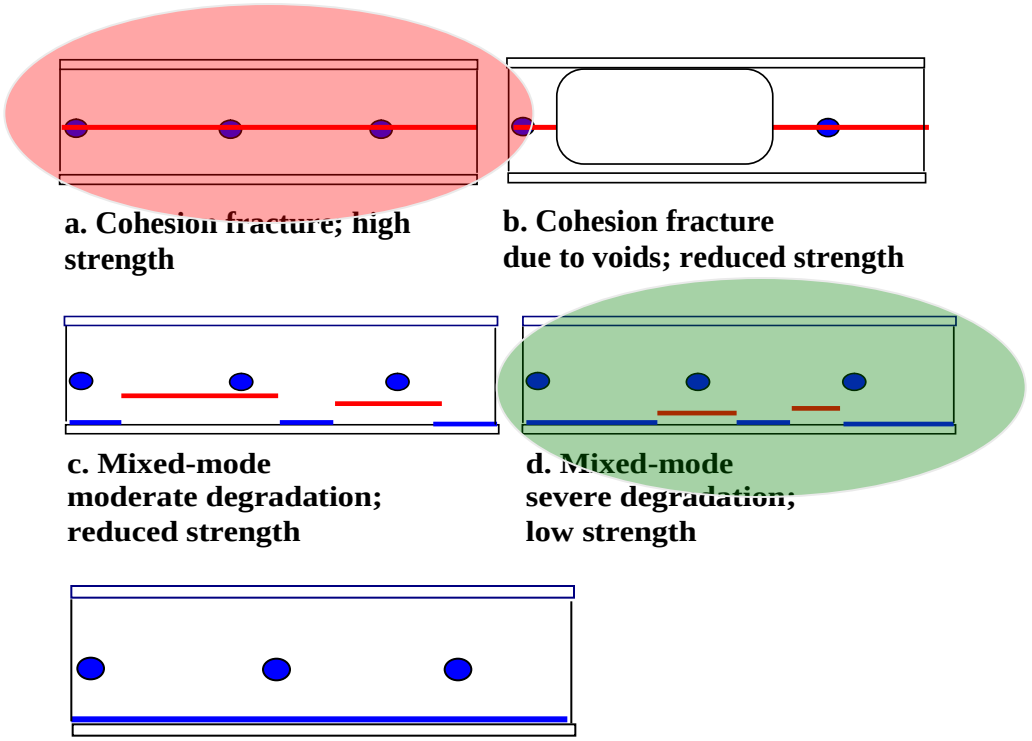




- Failure may occur without pre-existing disbond
  - Not detected by NDI
  - DTA inappropriate
- Structure ***IS*** certainly weaker

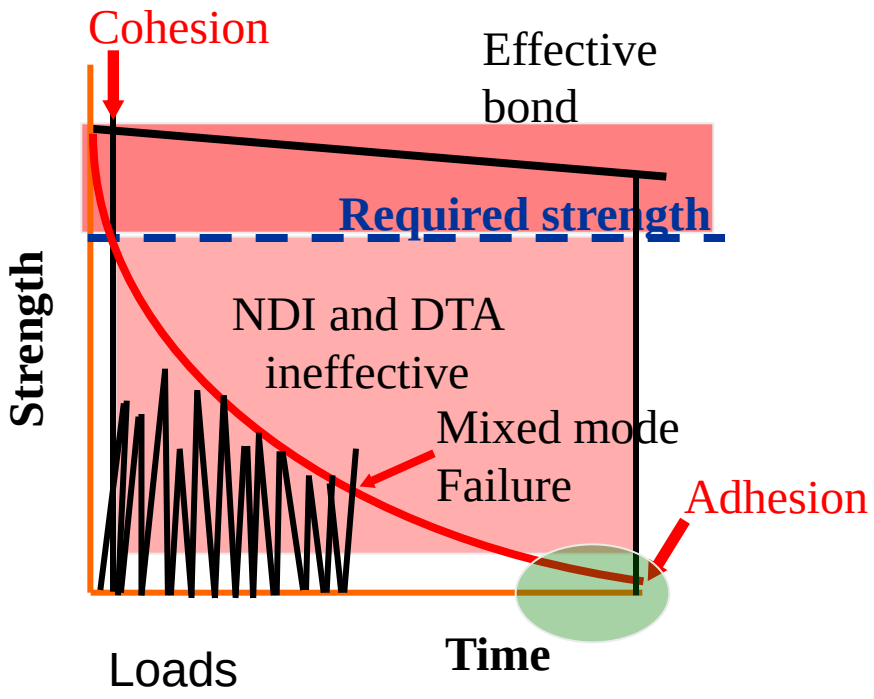
Explaining mixed-mode failures

- Cohesion failure occurs through carrier cloth
- As interface degrades:
  - Mixed-mode failure occurs towards interface
  - Strength reduces
- Eventually adhesion failure occurs at interface
  - Very weak
- Safety investigators note:
  - Thin residue of adhesive on surfaces do **NOT** mean strong cohesion failure



Let's be clear

- NDI only finds disbonds after complete separation
- Regulations, damage tolerance assume cohesion failure
- NDI can't find mixed-mode degradation until adhesion defect actually occurs
- *Bond may fail mixed-mode at low loads before any disbond can be detected*
- DTA ineffective for mixed-mode, adhesion failures, micro-voids



- There is a real risk to continuing airworthiness by applying DTA to these defects

In-service defects

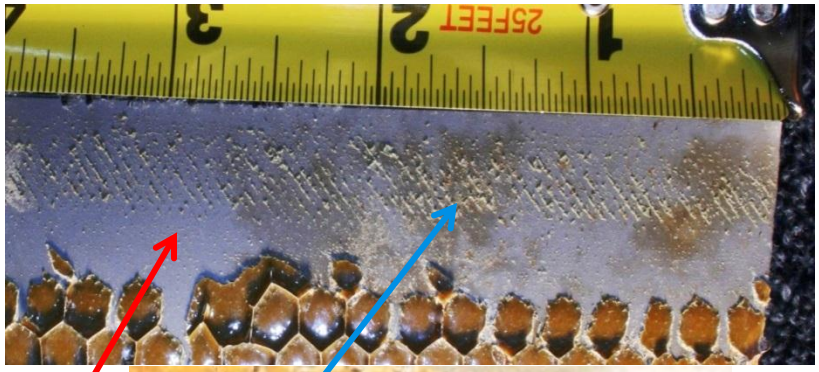
- Defects discovered in service must be:
  - Mixed-mode failure
  - Adhesion failure or
  - Fatigue failure due to micro-voiding
- Fatigue can only occur in conjunction with pre-existing defects or bad designs
- Only detected by NDI *after* disbonding has initiated
- For short overlap lengths, failure may occur without detectable defects
- NOT represented by DTA based on high bond strength
  - Strength of surrounding adhesive is *always* reduced

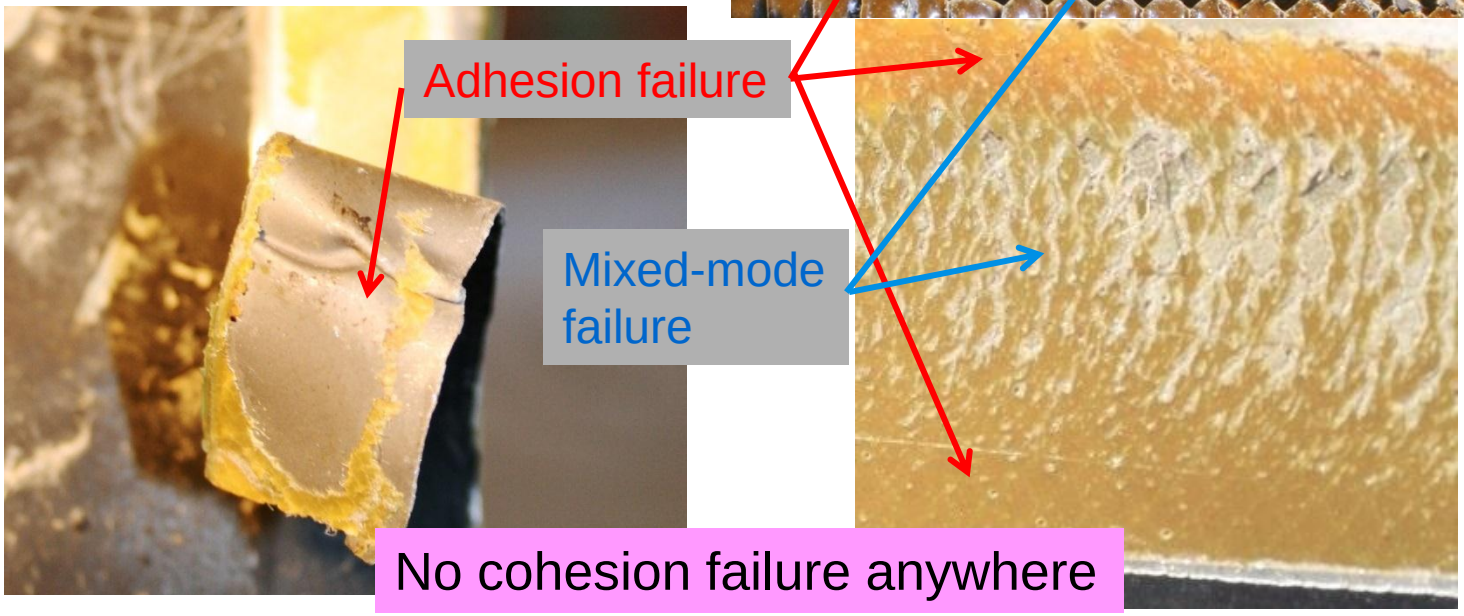
Case study: helicopter crash

- Aircraft tracking to pick up tourists in tropical location
- Experienced pilot only occupant
  - >5000 hrs, >3000 on type
- Clear sunny day, light winds, approx 500 ft ASL
- One blade departs plane of rotation, multiple strikes on fin and boom, aircraft crashed into sea, pilot deceased
- Blade had been inspected 80hrs before crash
  - Defect found within SRM limits - (tap test)
    - Not located at subsequent bond failure sites
- Investigator eliminated other causes except for failure of main rotor blade

Case study: helicopter crash

- Adhesion, mixed-mode failure over large proportion of blade
- Would be substantially weaker than original manufacture
- Very short overlap length





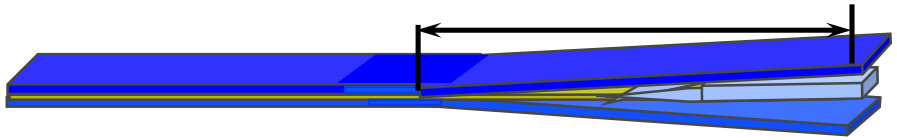
Case study: helicopter crash

- Can not definitively state bond failure caused the crash
  - Causal and consequential mixed-mode failures are similar
- Equally not possible to exclude weak bond strength as a significant factor
- Parts of blade first items in debris path
- Investigator concluded that in the absence of other causes, blade failure due to bond degradation was the most probable cause of the crash
- Official report is yet to be released

Preventing hydration

- Adhesion and mixed-mode failures are avoided by hydration resistant interfacial chemical bonds
  - Depends totally on the method used to prepare the surface for bonding
- Most effective means to demonstrate: wedge test ASTM D3762

50 ^{O}C,
95% RH



- Acceptance criteria in DOT/FAA/AR – TN06/57 *Best Practice in Adhesive Bonded Structures and Repairs*
- Bonds meeting these requirements have a demonstrated history
  - RAAF twenty years < 0.07% bond failures (technician malfunctions)
  - USAF fourteen years no failures reported
- Some OEM processes will not meet these requirements
- **Many** SRM repair methods are also deficient

Regulations, policy and advice

- FAR 2x.573 analysis or testing with artificial disbonds, NDI and/or proof testing
  - Won't prevent adhesion or mixed-mode failure in later service
- FAR 2x.603 processes must produce a "sound" structure
- AC20-107-B recently recognised adhesion failures
  - No certification if adhesion failure occurs
  - In-service adhesion failures, part should be quarantined
- PS-ACE100-2005-10038 recommends the wedge test
- Path to durable bonds is there but obscure
- FAR 2x.603 should mandate bond **durability** testing

Injection repairs

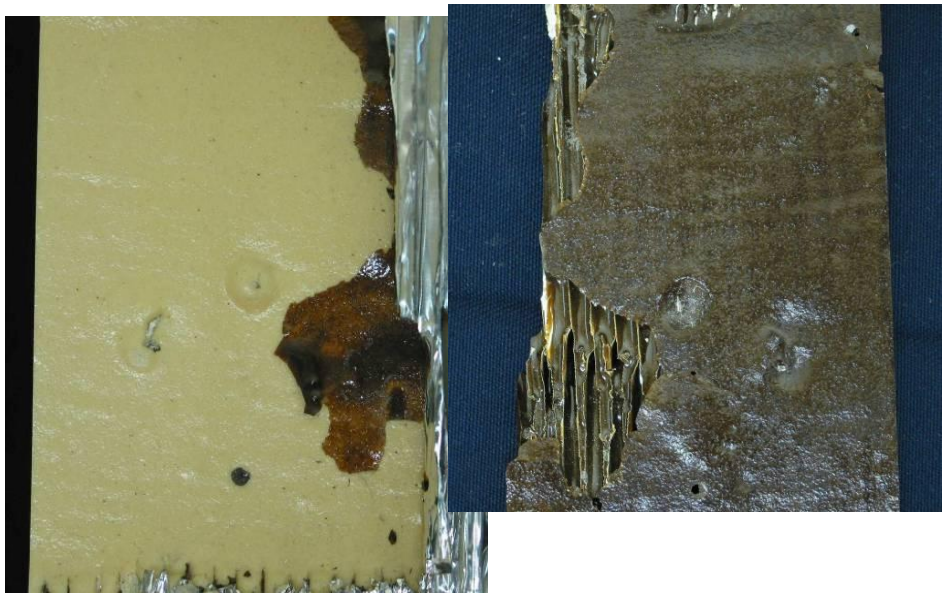
- "Repairs" macro-voids detected by post-production NDI
  - Injected paste adhesive fills the void
  - NDI can no longer detect void
- Strength not restored in any way
  - Adhesive bonds rely on chemical reactions
    - Surface of void is fully reacted out during cure cycle
    - Not sufficiently energetic to enable a bond to occur
- *Same applies for repair of production voids in laminated composites*
- SHOW ME THE MONEY!!!
  - Is there ANY evidence to demonstrate ANY strength restoration?
  - Yet these are considered approved "terminating" repairs
- Should be limited to production macro-voids smaller than DTA limits

Case study: rudder production defect

- Rudder failed at high loads
- Fatigue cracking in skin adjacent to mast
- Large area of injection “repair” between core and mast

Case study: rudder production defect

- Injection easily separated from original adhesive
  - Was never bonded
  - Repair was totally ineffective
- Shear loads from core had to be transferred by the skins
  - Led to fatigue cracking of skin
- Crack was critical at high loads, failure occurred
- Injection repair was *never* effective and exceeded DTA limits
- Injection must be banned*



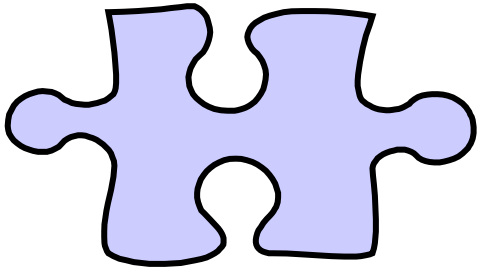
Nirvana

- If *and only if*:
  - Adhesion/mixed mode failure is prevented by using hydration resistant processes
  - Design methodology is based on excluding bond failure
  - Micro-voiding is avoided by environmental controls, and
  - Injection repairs limited to non-significant production defects
- THEN bonds should NEVER fail
- NDI and DTA only for accidental damage, not repetitive inspection for disbonding
- How much would the cost of maintenance be reduced?
- How much would flight safety improve?

Conclusions

- DTA and NDI are effective for production macro-voids
- DTA and NDI are **NOT** effective for production micro-voids or service disbonds
- Failure forensics must be the first step in assessing bond failures, or attempts to use DTA for anything other than macro-void cohesion failures may be a risk to flight safety
- Injection repairs must be banned except for production macro-voids within DTA limits

Question time



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