CERTIFICATION OF BONDED REPAIR OF COMPOSITE AIRCRAFT STRUCTURES – A CURRENT STATUS AND ROADMAP

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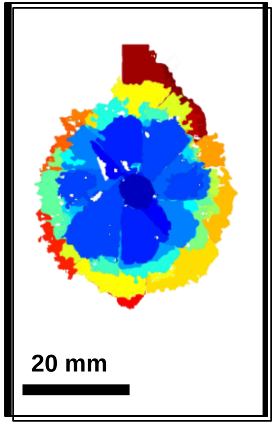
Outline

- Introduction to Adhesively Bonded Repair of Aircraft Structures
- Challenges of Certification of Repair of Aircraft Composites Structures
- Proposed Roadmap of Bonded Repair of Primary Aircraft Structures
- Technology Gaps and Research Directions

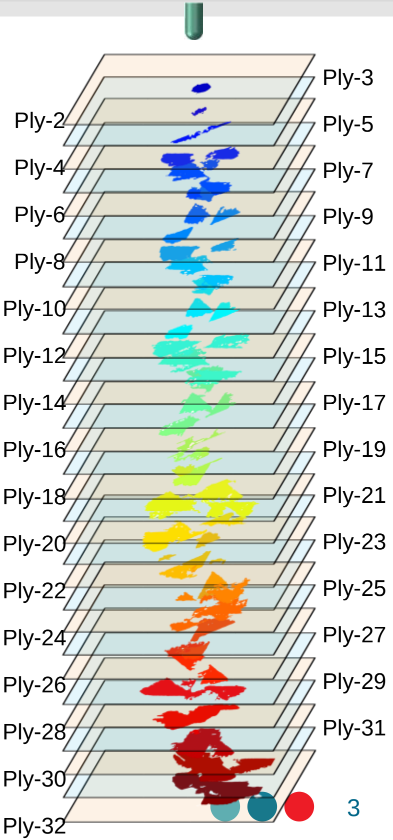
Intro
Challenges
Roadmap and Gaps

Damage and Degradation of Composites

- Impact damage – dropped tools, runway gravel, hail damage, bird strike;
- Environmental conditions - fluid, heat and fire damage;
- Manufacturing and assembly processes – porosity, fibre waviness, edge delamination, mis-located or elongated holes;
- Others



X-ray CT impact damage (75J of impact energy)



Structural Repair of Composite Aircraft Structures

Remains to be one of the key challenges for aerospace industry

- Large, often bonded, composite components – wing, fuselage, radome;
- Expensive to replace;
- Inherent complex damage behaviour;
- Specialized repair is often required;
- Major challenges in certification of bonded repairs of primary structures

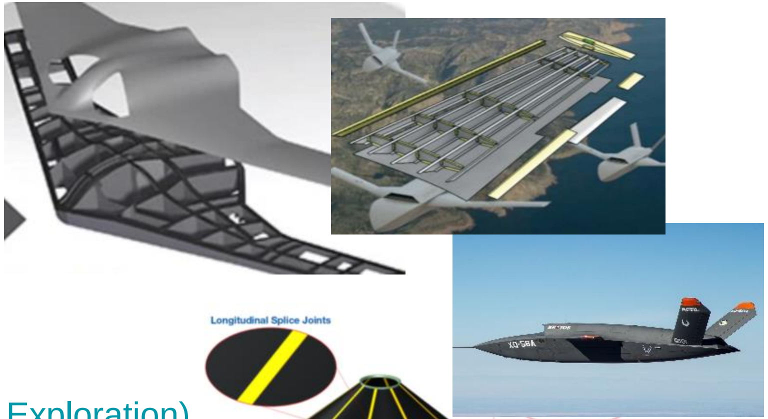
Airbus A380 bonded components

Terminology: Primary structures, load critical, and safety of flight

Global Large-scope Effort of Certification of Adhesively Bonded Joints on Load Critical Structures

TRUST:by DARPA
Unitized, adhesively bonded composite primary structures

BOPACS by EU-FP7
Boltless assembling Of Primary Aerospace Composite Structures



NASA CTE (Comp Tech for Exploration)
Lightweight composite joints on launch vehicle structures

US Department of Defence

- Composites Affordability Initiative (CAI)
- Fail-Safe Technologies for Bonded Unitized Composite Structures (FASTBUCS)
- Low Cost Attritable Aircraft Technology (LCAAT)

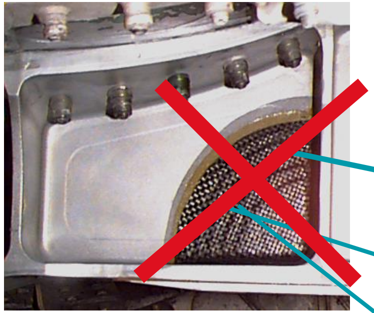
The full cost and weight savings of composites cannot be realized until bonded joints can be certified without fasteners

Bonded Repair Challenges

- Challenges with materials supply, storage and handling and repair environment
  - Availability, lead time, low-temp storage, material handling and humidity control
- Challenges with on-aircraft repair
  - Bond areas often contaminated and drying often required (sandwich structures)
  - Often restricted access
  - Limitation of cure temperatures, non-uniform bondline temperatures, heat sink, overheat damage
  - Porosity issues related to vacuum bagging
- Challenges with training and logistics
  - Inadequate training
  - Insufficient workload to maintain proficiency
  - Environmental and safety/health concerns for some M&P
- Challenges with certification
  - Significant hurdles related to bonded repairs of load critical primary structures

Regulatory Guidance for Bonding (including Bonded Repair) of Primary Structure

FAA AC20-107B Methods for Bonded Structure Compliance



CF-188 Y470.5
Bulkhead X-19
bonded repair

For any bonded joint, the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods-

(i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or

(ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or

(iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.

Defence JSSG-2006 (Paragraph 3.10.5 Static strength)

- Sufficient static strength shall be provided in the airframe structure for reacting all loading conditions loads without degrading the structural performance capability of the airframe. Sufficient strength shall be provided for operations, maintenance functions, and any tests that simulate load conditions, such that:
  - No detrimental deformations at 115% of design limit load (DLL)
  - No rupture or collapsing failures at design ultimate load (DUL)
  - Use nominal dimensional values
  - Bonded structure shall be capable of sustaining the residual strength loads of 3.12.2 *(i.e. DLL)* without a safety of flight failure with a complete bond line failure or disbond.

- The Defence Certification Authority sees continuing airworthiness as the most difficult issue facing certification of bonded joints on primary structures
  - Risk of in-service failures due to human error and other factors during bonding
  - Lack of validated analysis techniques and ability to ascertain bond strength
  - Bonded joint likely see more severe usage than anticipated

Roadmap for Certification of Bonded Repair of Primary Structures

- **Bonded repairs that could meet existing certification requirements**

- **Bonded repairs beyond existing certification**
  - **Risk-based certification approach for primary structure bonded repairs**
  - **"Slow Growth" Based Bonded Repair on Primary Structures**

Consideration of Different Categories of Structures and Damage Types

Fail-Safe, Multiple Load Path Structures

- Due to their high property scatter, most composite structures where B-basis design allowables are used (e.g. wing skins, wing planks) are fail safe, multi-load path structures:
    - Relatively low reliability requirement
    - Bonded repairs more likely to meet the existing certification requirements
- Repairs often essential - to maintain multi-load path and prevent damage growth;
- More opportunities for bonded repair applications:
    - Advanced modelling capability of residual strength analysis - more accurate allowable damage size for repairs to be determined, potentially expanding repair opportunities.
    - Repair design critical – to assess load redistribution behavior and the required minimum redundancy level of a fail-safe structure in the absence of the bonded repairs;

Consideration of Different Categories of Structures and Damage Types

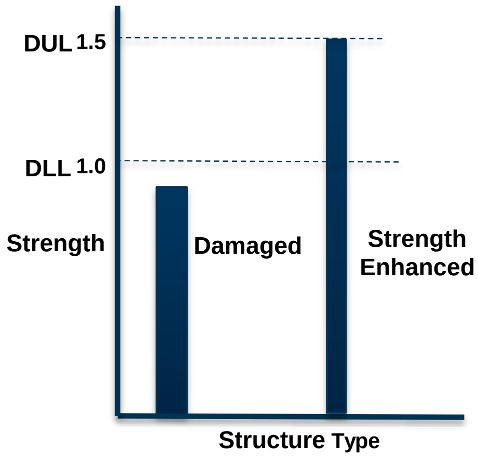
Military Aircraft – Battle Damage Tolerance Requirement

- For military aircraft, this safety requirement must be maintained;
- Battle damage tolerance – often means an "additional" static strength safety margin with the pristine structure, in terms of normal flight loading and the damage limit considered for civilian aircraft;
- Multi-load path structures help increase the survivability and are often preferred;
- The reliability requirement of battle damage is relatively low. Thus bonded repairs would mostly likely meet the requirement for restoring the additional safety margin;
- Since often there is limited communication between people working in the aircraft structural integrity area and people working in the vulnerability area, this important point may have not been duly considered.

Consideration of Different Categories of Structures and Damage Types

Hybrid Repair Approaches - Residual Strength Could Be Enhanced

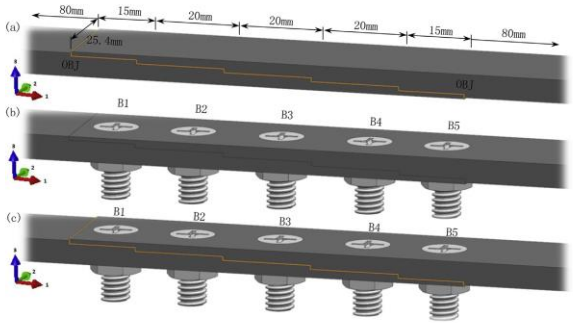
- Hybrid repairs - residual strength can be enhanced by means of mechanical fasteners/Z-pinning and/or optimum damage cut-out
- Such residual strength enhancement
  - allows the bonded repairs to meet certification requirement
  - prevents catastrophic failure, and allows sufficient time for disbond detection, should kissing/weak bond be present
  - would maintain during service when bond quality is satisfactory
- Hybrid repair design is a non-trivial task, requiring optimum design from multiple perspectives: (i) damage cut-out, (ii) riveted/bolted patch repairs, and (iii) bonded patch repairs
- Significant further research scope/opportunities in this area.



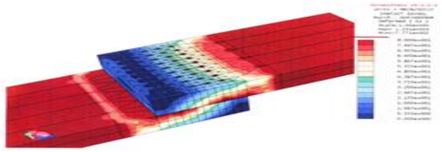
Consideration of Different Categories of Structures and Damage Types

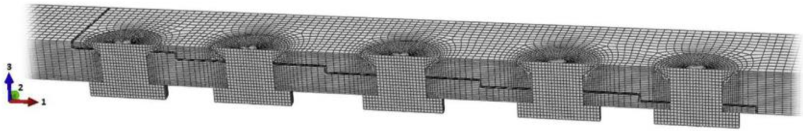
Hybrid Repair – Bonded Repair Combined with Mechanical Fasteners/Z-pinning/ other crack arrest mechanisms

- Unlike for production of aircraft structures, the fasteners used for repairs do not significantly increase the weight
- Computation/experiment indicated (with adequate designs) the fasteners increased the bonded joint static strength slightly and fatigue life significantly
- Disbond readily detected using existing NDI methods within a fraction of the fatigue life provided by the fasteners only
- Z-pinning performed similarly in a hybrid joint



Bonded, bolted and hybrid composite joint specimens

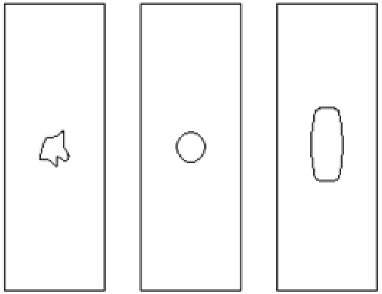

FEM analysis of a Z-pinned joint


FEM model of a hybrid step lap joint

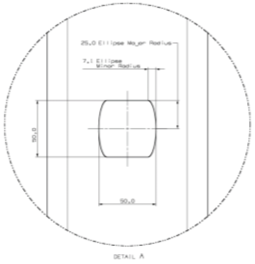
Consideration of Different Categories of Structures and Damage Types

Hybrid Repair – Bonded Repair Combined with Damage Optimum Cut-out

- Damage optimum cut-out increases the residual strength by reducing stress concentration
- A test of a composite specimen with impact damage showed that
  - The ultimate strength is higher by over 20% with the optimum shape cut than that with round cut
  - The ultimate strength is further increased significantly with the bonded patch repair
- Damage optimum cut-out can be used together with mechanical fasteners
- Many different application types (significant scopes)



Impact Damage Round Cut Optimum Cut



Optimum cut-out shape

A test

Consideration of Different Categories of Structures and Damage Types

Significant Applications – Past Examples

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Table A1 Australian Applications of Bonded Patch Repairs and Reinforcements to Military Aircraft

Aircraft *Application* [58]	Problem	ST Patch* Adhesive	Remarks
C130 *Repair*	Stress corrosion cracked stiffeners in wing, aluminium alloy 7075, 3 mm thick	GB initially GBS later Boron/epoxy $[0_4]$ ×2 FM73	Over 20 years of additional service with no crack growth or durability problems, over 3000 repairs made [59]
Mirage III *Repair*	Fatigue cracking in lower wing skin, aluminium alloy AU4SG, 3.5 mm thick	PANTA Boron/epoxy $[0_7]$ FM73	180 wings repaired or reinforced. Eight bond durability problems over approximately 8 years, associated with adhesive voiding caused by extreme humidity in the tropical repair station [58]
F-111C *Reinforcement*	Secondary bending in wing pivot fittings leading to a fatigue problem. Steel D6ac 7 mm thick fastened to aluminium alloy wing skin 2025-T851 ~ 7 mm thick	GBS Boron/epoxy $[0_{120}]$ FM73	The reinforced wing passed the cold proof test residual strength but several problems with fatigue of doublers were experienced subsequently [60]
F-111C *Repair*	Stress corrosion cracking in weapon bay longeron flange, aluminium alloy 7075 T6	GBS Carbon/epoxy EA 934	Over 10 aircraft repaired. No bond problems over approximately 8 years' service
F-111C *Repair*	Stress corrosion cracking in longeron adjacent to refuel receptacle 7049-T6	GBS Boron/epoxy EA 9321	Over 10 aircraft repaired. No bond durability problems in 8 years
Orion P-3C *Reinforcement*	Corrosion pitting in horizontal tail, aluminium 7075-T6	GBS Aluminium alloy FM73	No bond durability problems over a 10 year period

Adhesively Bonded Repair/Reinforcement of Metallic Airframe Components 55

Table A1 Australian Applications of Bonded Patch Repairs and Reinforcements to Military Aircraft—cont'd

Aircraft *Application* [58]	Problem	ST Patch* Adhesive	Remarks
Sea King Helicopter *Repair*	Fatigue crack in frame	GBS + P Boron/epoxy FM73	Operated in an offshore ship-borne environment for 4 years with no reported problems
F-111C *Repair*	Fatigue crack in lower wing skin at fuel flow hole under forward auxiliary spar. 2025-T851 4 mm thick	GBS Boron/epoxy $[0_2/\pm45/0_3]s$ FM73	No crack growth in service for 670 flying hours and a further 9000 simulated flying hours [61] Residual strength shown to exceed 1.2 DLL after teardown [62]
F/A-18A *Reinforcement*	Limited fatigue life centre fuselage bulkhead 7050-T7451	GBS Boron/epoxy FM73	Doubler provided a strain reduction of 23% and withstood over 4.5 lifetimes of severe spectrum loading [63] and residual strength exceeded DUL
PC 9 *Repair*	Fatigue cracks in full-scale fatigue test mainly in lower wing skin	GBS Boron/epoxy FM73 Some with Acrylic Click Bond CB200	Repairs [64] highly successful in enabling the test to complete 50,000 simulated flying hours with minimum down time

Consideration of Different Categories of Structures and Damage Types

Significant Applications – Past Examples

t0025 **Table A2** Other Counties Applications of Bonded Patch Repairs and Reinforcements to Military Aircraft

Aircraft Country *Application*	Problem	Surface treatment patch* Adhesive	Remarks
C141 USAF *Repair*	Fatigue cracking in wing riser weep holes 7075–T651 5 mm thick	GBS + P Boron/epoxy $[0]_5$ 3 patches FM73	Around 770 individual repairs made to 120 aircraft and all returned to unrestricted flight with no evidence of crack growth [65]. Extra life required was 15,000 flying hours. Subsequent residual strength testing of repairs after retirement of the aircraft all except one had residual strength above design ultimate [66]
C130 USAF *Reinforcement*	Regions thinned by corrosion grind out. 7075–T7351 3 mm thick	GBS + P Boron/epoxy FM73	Over 130 reinforcements applied [65,67]
C5A *Repair*	Multiple fatigue cracking in crown section of fuselage skin 7079–T6 1.25 mm	GBS + P GLARE 2 mm AF 163–2 M	Several years operation with no crack growth at the time of reference [68]
Hawk RAF *Repair*	Fatigue cracks in fastener holes in upper wing skin caused by buffeting	GBS Carbon/epoxy Redux 312/5	No further crack growth in service until retirement of the wings after approximately 400 and 1000 flying hours [69]
Harrier RAF *Repair*	Fatigue cracks in fuselage side skins	GBS Carbon/epoxy Redux 312/	No further crack growth for over 200 flying hours [69]

Table A2 Other Counties Applications of Bonded Patch Repairs and Reinforcements to Military Aircraft—cont'd

Aircraft Country *Application*	Problem	Surface treatment patch* Adhesive	Remarks
F/A-18C Finland *Reinforcement*	Require strain reduction in centre bulkhead 750–T7451	GBS + P Boron/epoxy $[0_8]$ FM73	Estimated strain reduction 18%. The reinforcement survived over 6000 spectrum hours [70]; although a disbond occurred near one end it did not reduce reinforcing efficiency. In service
F16 USAF *Repair*	Fatigue cracking lower wing- skin vent hole 7475–T7351, 5 mm	SG + P Boron/epoxy $[\pm 45/0_7]s$ FM300-2	Twenty aircraft from three countries have been repaired [71,72] with no crack growth experienced at the time of the references
F16 Israel *Repair or Reinforcement*	Fatigue cracking upper fuselage skin splice	PANTA + P Boron/epoxy $[0_8]$ Film adhesive	Successfully demonstrated as a preventative reinforcement in flight operation [73]
F16 Netherlands	Fatigue cracking in fuselage longeron flanges 2024–T62, 2 mm thick	GB + P TiAl 6V 0.5 mm 2 patch Acrylic Agomet 310 F	No further crack growth for the required 400 flight hours [74]
CF-116 Canada *Reinforcement*	Fatigue cracks in upper wing skin fastener holes 7075–T651, 8.5 mm	GBS + P Boron/epoxy $[0_{23}]$ FM73	40% strain reduction achieved on compression surface [75]. Thirty-two in-flight reinforcements gave good results but some disbonds occurred in full-scale test programme

Continued

Consideration of Different Categories of Structures and Damage Types

Significant Applications – Past Examples

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Table A2 Other Counties Applications of Bonded Patch Repairs and Reinforcements to Military Aircraft—cont'd

Aircraft Country *Application*	**Problem**	**Surface treatment patch* Adhesive**	**Remarks**
L159 Czech Republic	Fatigue cracking in fuselage auxiliary stringers during full-scale fatigue test	GBS Boron/epoxy [$\pm45/0_3$] FM73	Early structural detail testing very successful but no details on full-scale fatigue test [76]
F15 USAF *Repair Reinforcement Damping*	Sonic fatigue to damage fuselage door	GBS Boron/epoxy Damping layer included epoxy paste adhesive	In service on Boeing/USAF flight test aircraft for over 2 years [77]. Also full-scale test with SHM

Balanced short-, medium- and long-term research in the roadmap

For those damage scenarios where current repair certification requirement for residual strength can be met (e.g. primary structures with RS.>K.DLL prior to repairs, or non-primary structures)

- Applications listed in previous three slides or similar can continue to be applied (promote bonded repairs and obtain benefit)
- Challenging repairs, such as F/A-18 IWSLJ bonded repairs conducted by CREDP – with high economic benefit (R > 1.5 DLL prior to repair, different challenges – including to prove “R > 1.5 DLL” prior to repair)
- Opportunities to try/verify new techniques:
  - Enhanced advanced modelling tools for residual strength analysis
    - e.g. F/A-18 IWSLJ bonded repairs
  - Optimized cut out and patch design;
  - Automation, digitalization, 3D printed mould for patches, and printed patches;
  - New and novel materials and new repair concepts etc.

Balanced short-, medium- and long-term research

For those damage situations where the current repair certification requirement for residual strength prior to repairs cannot be met (that is, for primary structure when RS < K.DLL)

- No clear pathway forward, hugely challenging, but offer significant benefits
- Needs for extending bonded repair certification/application ranges
- Provide opportunities to demonstrate repair reliability/verify new approaches – support research for more challenging repair applications

- Short/Medium term goals:
  - Novel joint design for crack arrest as per AC20.107B
  - Technology readiness of proof testing method such as Laser Bond Inspection

Balanced short-, medium- and long-term research

Critical structures that currently cannot be certified, i.g. bonded repair of load-critical, single-load path structures (RS < K.DLL)

- Long-term development, forward looking and disruptive technologies
  - (i) enhance repair process to guarantee sufficient repair reliability – *risk-based certification approach*
- Quality assurance - If the statistics (verified by tear-down) proves the current quality insurance can guarantee B-basis reliability, is it sufficient to meet the certification requirement for a structure that requires B-basis reliability with a damage case where R < DLL prior to repair?
  - (i) Develop reliable methods (NDI or others) to measure bond strength *– Proof testing, NDI and SHM*
  - *(ii) "Slow-growth" certification approach, if driving force is ~ constant and environmental durability assured*

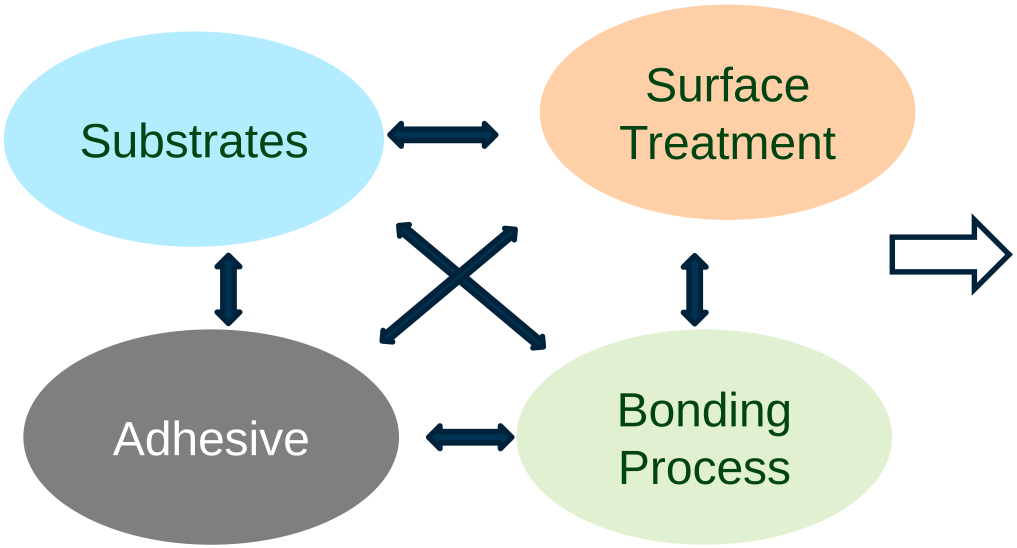
Risk-based: Linking Process Control to Reliability

Bonded Repair

- Material quality control
- Bonding process
- Advanced NDI
- In-service inspection and SHM
- Training
- Optimized damage cut-out
- Advanced patch design and Analysis
- Linking requirements to overall processes

Quantifying a system through quantifying sub-systems

Surface Treatment is the Key to Process Reliability



Four elements of a bond system

Adhesion

- Cohesion / substrate failure
- Adhesion failure

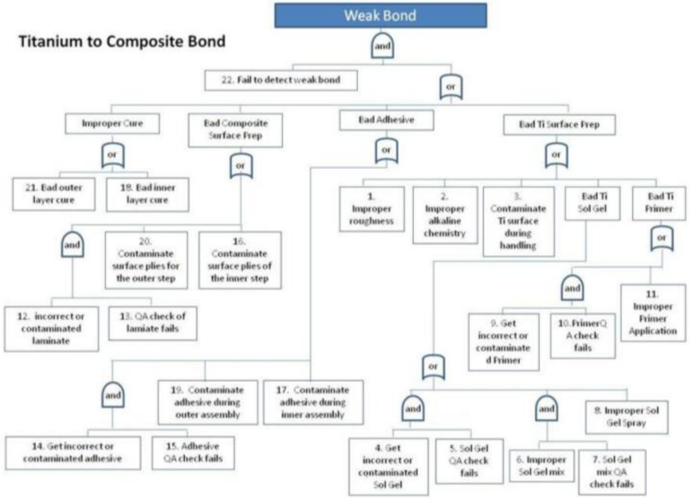
Strength

- Lap shear, thick adherend shear
- Flatwise tension
- Fracture toughness

Durability

- Time, temperature, humidity loading

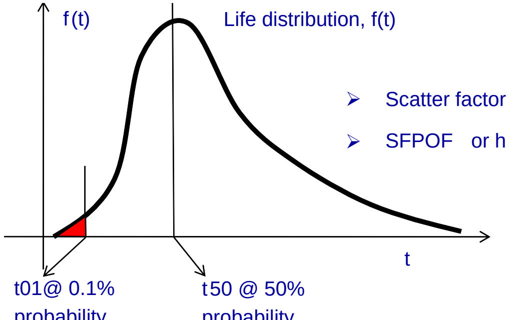
Risk-based Certification of Bonded Repair of Primary Structures



Quantifying reliability of bonded repair through quantifying subsystems:

- Fault tree analysis and probabilistic analysis (i.g. Bayesian network – Boeing
- Six-sigma to achieve robust bond process – Airbus
- Closely control and track process parameters and quantify the impact of variations
- Quantify against (& to achieve) B or A-basis reliability

Boeing Fault tree analysis



Many R&D opportunities exist

Achieving Reliability

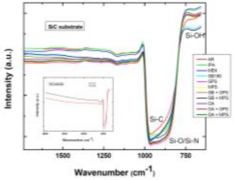
- Automation and high quality treatment
  - Open-air plasma, laser and other surface treatment methods
  - Digitalized process with quantifiable outcome

- Pre-bond surface inspection:
  - Contact angle, surface energy
  - Fourier Transfer infrared spectroscopy (FTIR)
  - Optically stimulated electron emission (OSEE)
  - Laser induced breakdown spectroscopy (LIBS)
  - Peel strength measurement

Opportunities: manufacturing 4.0

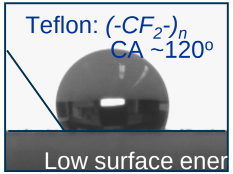
NRC Open-air plasma

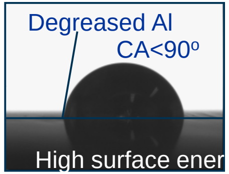
Handheld FTIR

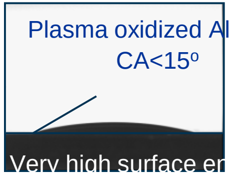


FTIR of plasma treated surface

NRC Laser treatment



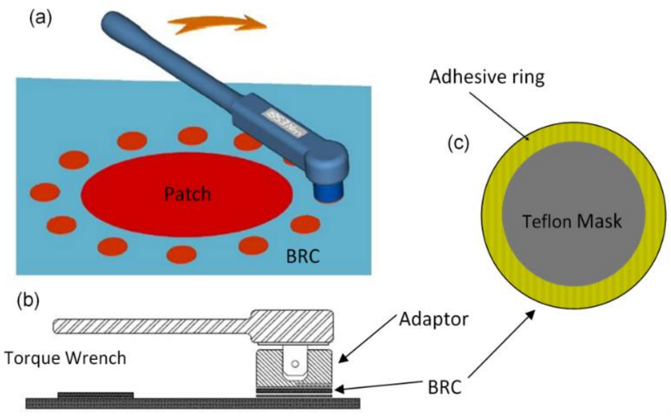




Surface energies

Proof testing, NDI, SHM for Bond Integrity

- **Proof testing:** Direct mechanical loading on bonded joints – used on helicopter blade bond certification, but not practical for most applications
- **Laser shock inspection**
  - Strictly speaking not proof testing - Indirect proof testing
  - Remains to be qualified for on-aircraft application
- **NDI for bond strength** – non-linearity ultrasonic under development
- **Proof testing of bond integrity and durability** – BRCs
- **Tear-down assessment** – retired/replaced components
- **SHM** – strain transfer measurement, lamb wave, fibre optics



Repair patch and satellite bonded repair coupons (BRCs)

Challenges and opportunities: complexity and reliability; on-aircraft application; probability of detection (POD)

“Slow Growth” Based Bonded Repair on Primary Structures

- Future aircraft designs are expected to rely on primary bonded composite structure due to expected cost, production, and sustainment benefits
- Proposed Roadmap to extend repair application range and inspection intervals for “slow damage growth” under damage tolerance design approach
  - Demonstration of slow, stable and predictable growth of bonded repair
  - Validated damage growth models that account for the repair
  - Likely limited applications using slow growth certification approach for bonding only applications – possibly rapid increase in crack driving force with increasing disbond size;
  - Relies on ability to nondestructively inspect structure through installed repair
  - Dependent on a repair system that is sufficiently mature (stable M&P, producibility, characterized mechanical properties, predictability of structural performance, and supportability)

Summary

- The Roadmap addresses different scenarios of bonded repairs based multiple/single path, residual strength, etc.
  - The short/intermediate term goal is to expand the applications and advance technologies of bonded repair in situation where the current certification requirement, RS > K. DLL prior to repairs, can be met
  - The long-term goal is to develop certification approach to certify bonded repairs on single load path, primary structures where RS < K. DLL
- Significant R&D opportunities exist:
  - New joint design
  - Modelling and simulation tools;
  - Enhancing Material/process reliability
  - Testing and validation, proof testing, NDI and SHM technologies

THANK YOU

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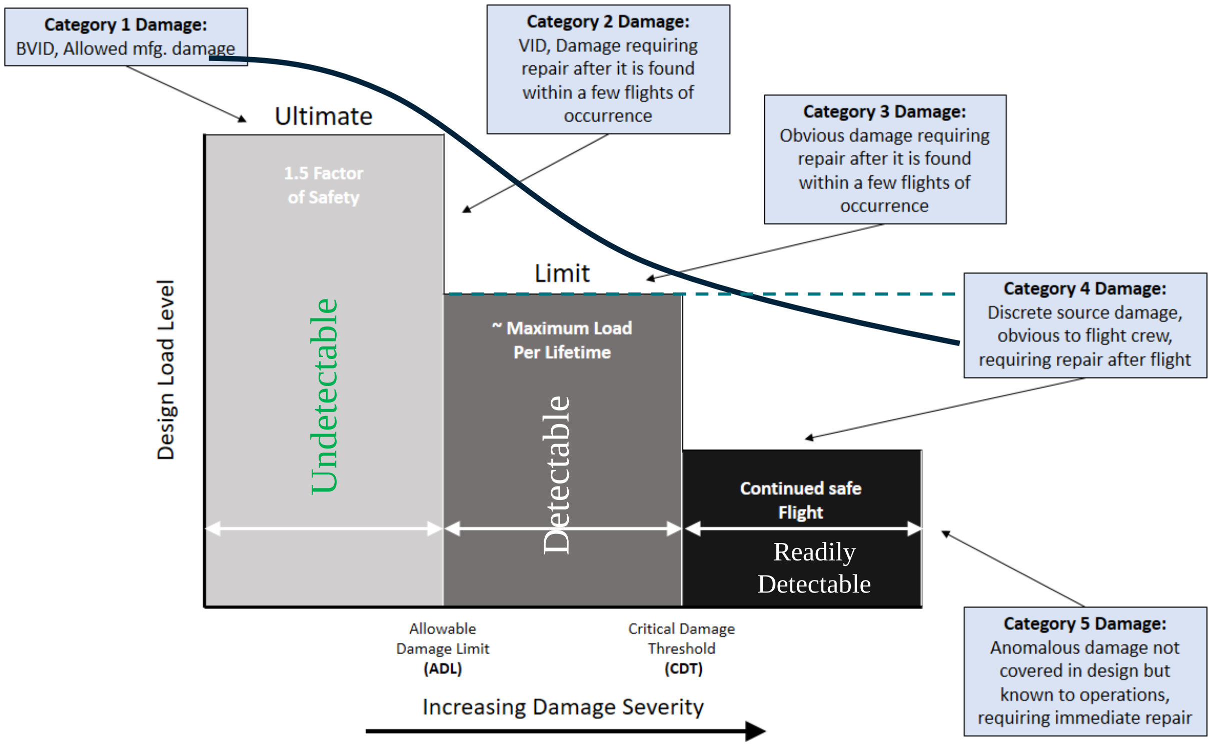
Composite Damage Tolerance (FAA AC20-107B)



Damage severity and design loads