European Union Aviation Safety Agency

Damage Tolerance and Fatigue Evaluation of Composite Rotorcraft Structures

Presentation by:

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Rotorcraft Structures Workshop

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Your safety is our mission.

European Union Aviation Safety Agency

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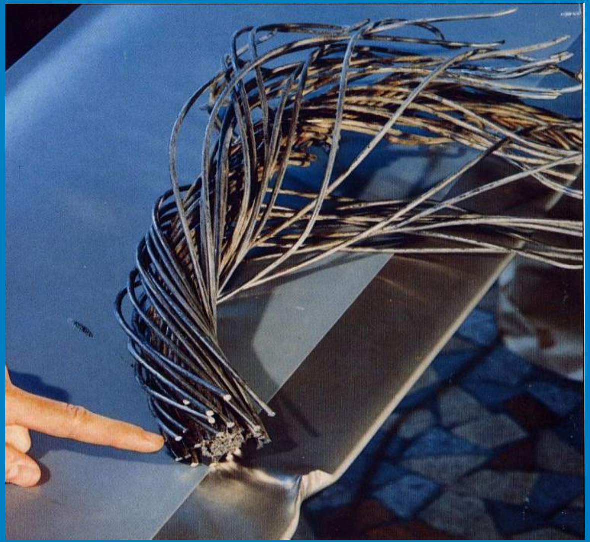
Damage Tolerance and Fatigue Evaluation of Composite Rotorcraft Structures

- Categories of Damages: AMC 20-29 & AC27/29.573
- Structural Bonding Certification
  - Definitions
  - General Requirements
  - Specific Requirements – Critical Bonded Joints
- Inspection Methods for Composite Structures
- CMH17 updates and composite initiatives involving EASA
  - EASA Webinar information

Categories of Damages

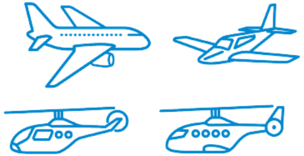
AMC 20-29 and AC27/29.573

Note for following slides:
RRS: Required Residual Strength
RS: Residual Strength
UL: Ultimate Loads
LL: Limit Loads



Courtesy of Airbus Helicopters

AMC 20-29 Categories of Damages and Residual Strength



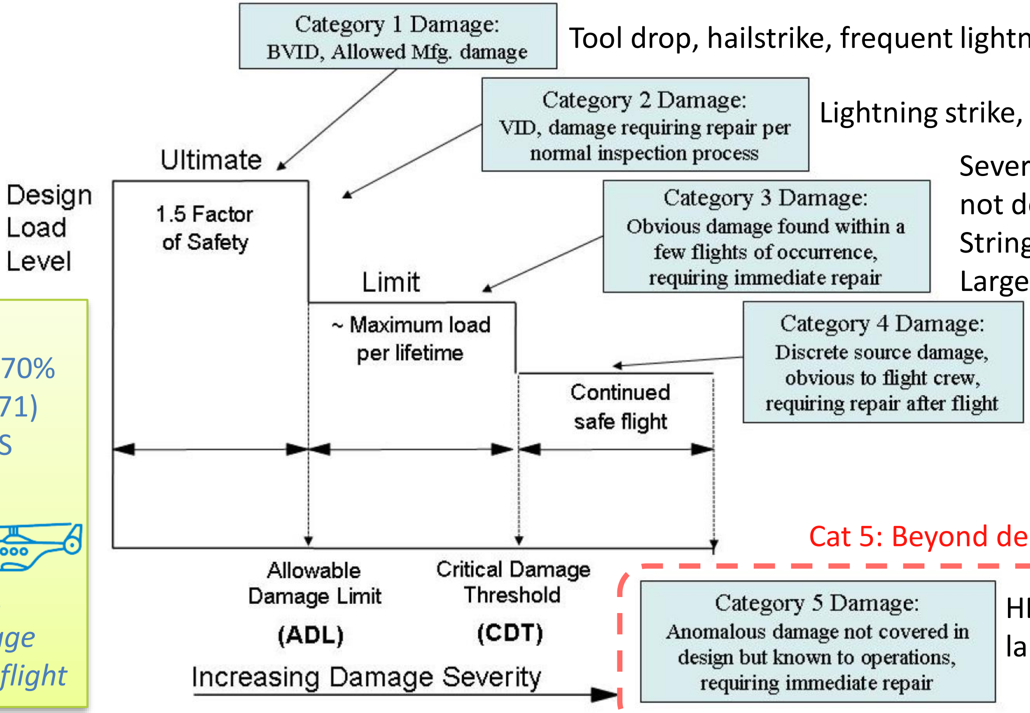


Figure 3 - Schematic diagram showing design load levels versus categories of damage severity.

Tool drop, hailstrike, frequent lightning strike, blunt impact

Lightning strike, maintenance impact, blunt impact

Severe Hail / lightning strike, birdstrike if not detectable during the flight – Stringer/patch disbond

Large notch, large disbond, blunt impact

Birdstrike, UERF, Tyre debris, blunt impact

Cat 5: Beyond design considerations (*)

HEWABI, flocks of birds, very large bird, wire strike

Discrete Source Damage:
- **Cat 4** : Get Home Loads (70% LL) as RRS (AMC/AC 25.571)
- **Category 2 to 4**: LL as RRS (AC27/AC29)

AC27/29.573:
- **Obvious discrete source,** *maybe not obvious damage*
- **LL as RRS:** *completion of flight*

(*) Severe damages created by anomalous ground or flight events should be identified. They may result in Cat 5 damages.

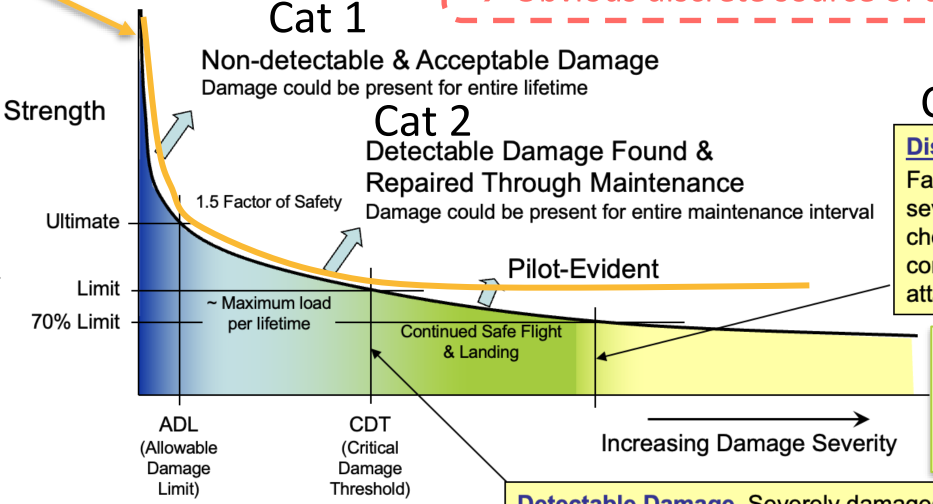
Residual Strength and Damage Severity

Rotorcraft: RS curve is **"flat"** with increasing damage severity

→ Low RS difference between cat 2 & cat 3

Discrete Source Damage: Cat 2 to 4 for Rotorcraft (AC27/29.573)
→ Obvious discrete source of damage with LL as RRS

Source: CMH17 rev H Vol3. Chapter 12.3



Cat 4

Discrete Source Damage
Failed or completely severed frame, stiffener, or chord with failed or completely severed attached skin or web

Large Aircraft: RS curve is **"flattening"** with increasing damage severity, up to GHL

Minimum capability as RRS → UL LL

Detectable Damage Severely damaged, frame or stiffener with associated damage to attached skin or web (or) Severely damaged, skin panel or web with associated damage to attached stringers, stiffeners, frame or rib.

Cat 3

Minimum Required Residual Strength is LL capability for Rotorcraft vs GHL for Large Aircraft (70%LL)

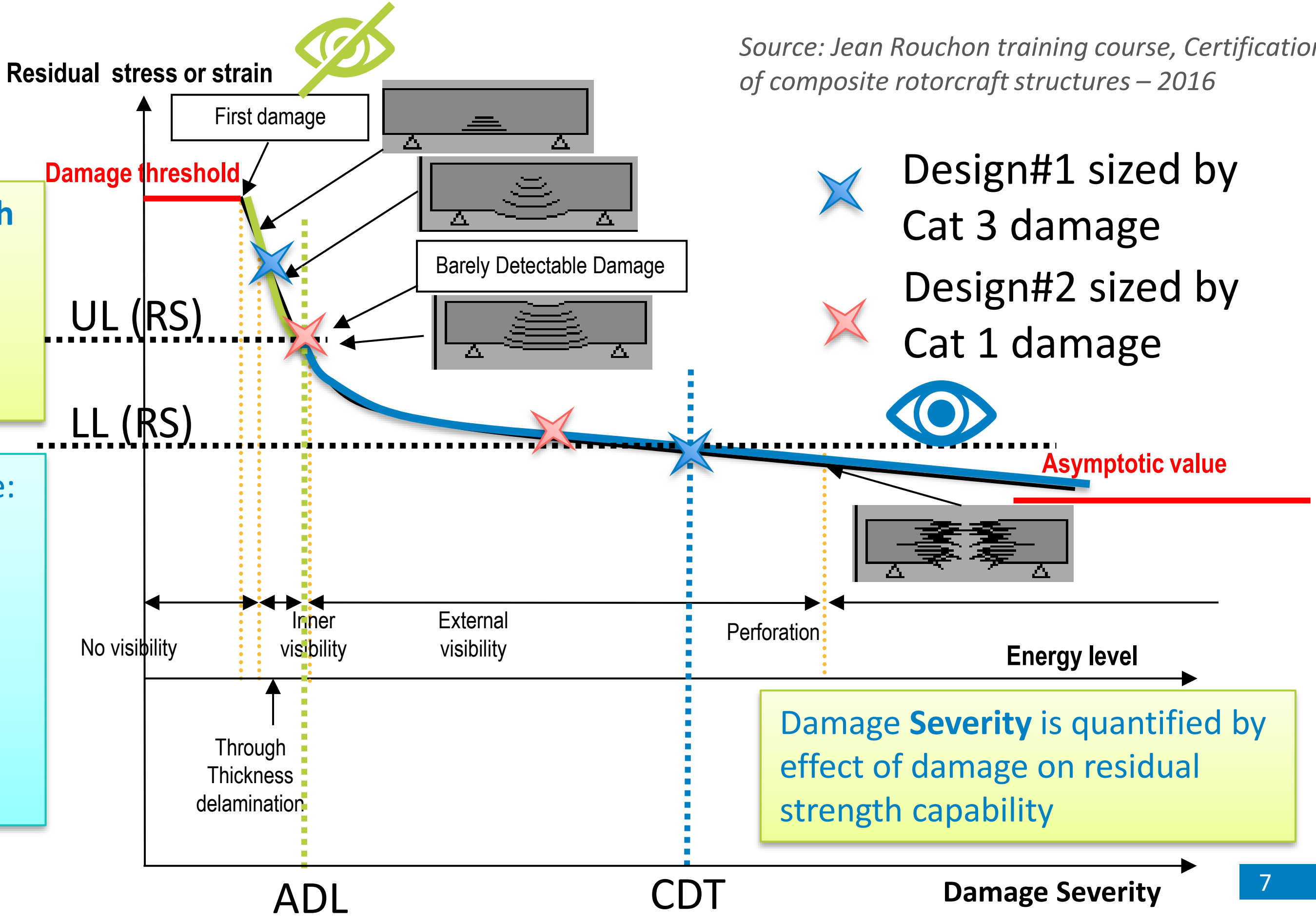
Damage Detectability and Residual Strength

Main drivers on **residual strength** curve are:

- ✓ Laminate material, thickness
- ✓ Layup
- ✓ Environmental conditions

Main drivers on **detectability** are:

- ✓ **Impact energy, Impactor shape**
- ✓ Laminate material, thickness
- ✓ Transverse or edge impact
- ✓ Relaxation, ageing
- ✓ Layup (damage extent)
- ✓ Paint color



Source: Jean Rouchon training course, Certification of composite rotorcraft structures – 2016

Design#1 sized by Cat 3 damage

Design#2 sized by Cat 1 damage

Damage **Severity** is quantified by effect of damage on residual strength capability

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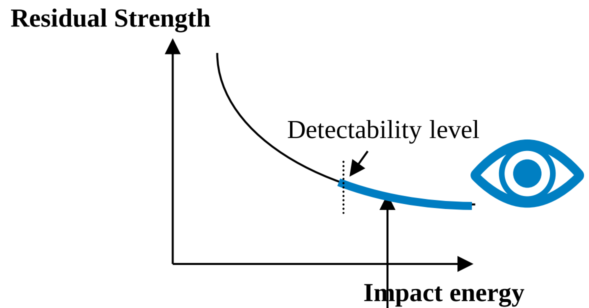
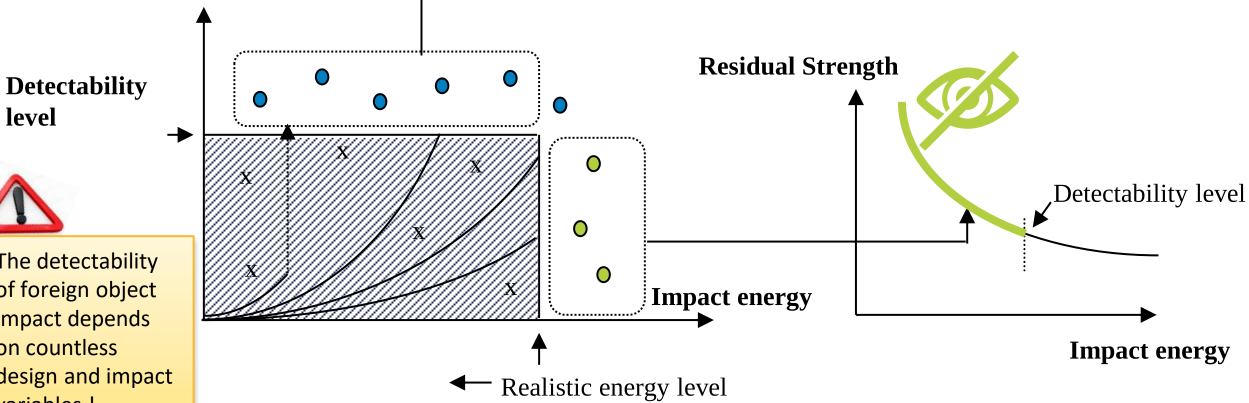
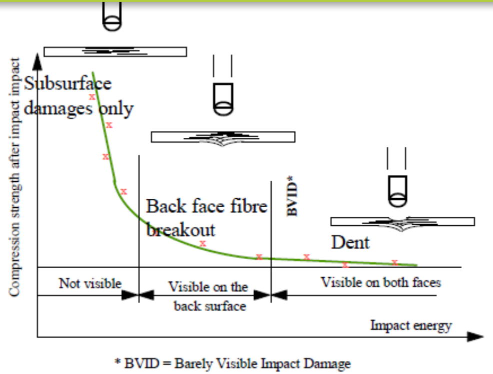
Effect of Impact Energy and Impactor Shape on Detectability:

"3-Zone Diagram"



- **x** In-service and in-manufacturing damages, below the detectability threshold with realistic energy level → Zone 1 / Cat 1, UL as RRS
- Damages **beyond detectability** level → Zone 2 / Cat 2 & 3, RS capability between LL and UL
- Damages **beyond realistic energy** level → Zone 3 / Cat 1, RS capability between LL and UL





The detectability of foreign object impact depends on countless design and impact variables !

Cat 1, Cat 2 and Cat 3 damages need to be addressed for DT considering **large range** of impact energies and impactor shapes

Source: Jean Rouchon, Certification of composite Structures

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AC27/29.573 vs AMC 20-29

- → The "3-zone" diagram is implemented in AC27/29.573
- → Zone 3 of this diagram is not addressed in AMC 20-29

Zone 2: LL ≤ RRS < UL, after inspection interval including LEF
- ✓ Detectable damage
- ✓ k x LL related to damage severity and damage (no)-growth behavior
- ✓ Cat 2 (> LL) and Cat 3 (LL)

Obvious Damage

Barely Detectable Damage

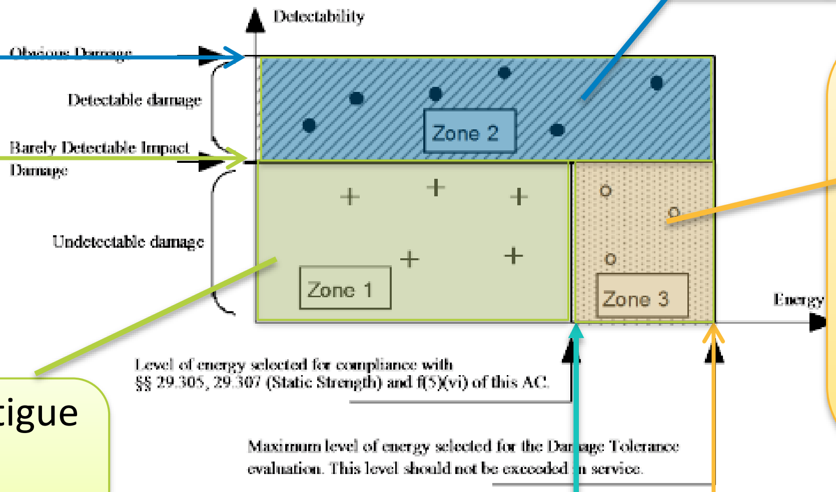


Figure A

Zone 3: LL ≤ RRS < UL
- ✓ Non detectable damage
- ✓ Use of **probabilistic** approach to determine k x LL
- ✓ **Or UL** considered for RS
- ✓ **Or energy** level **increased** to reach detectability and evidence LL as RS
- ✓ Not in AMC 20-29, ≈ **Cat 1**

Zone 1: RRS ≥ UL after fatigue including LEF
- ✓ Non Detectable Damage
- ✓ Cat 1 of AMC 20-29

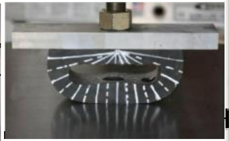
Realistic Energy Level (10-5/FH)

Extremely Improbable Energy Level (10-9/FH)

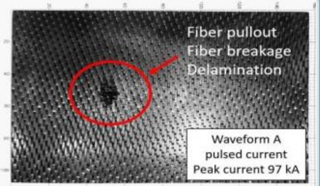
3-Zone Diagram Typical Examples

Photos Source: Impact Damage Formation on Composite Aircraft Structures, Hyonny Kim, UCSD, FAA/JAMS meeting – NIAR, 2009

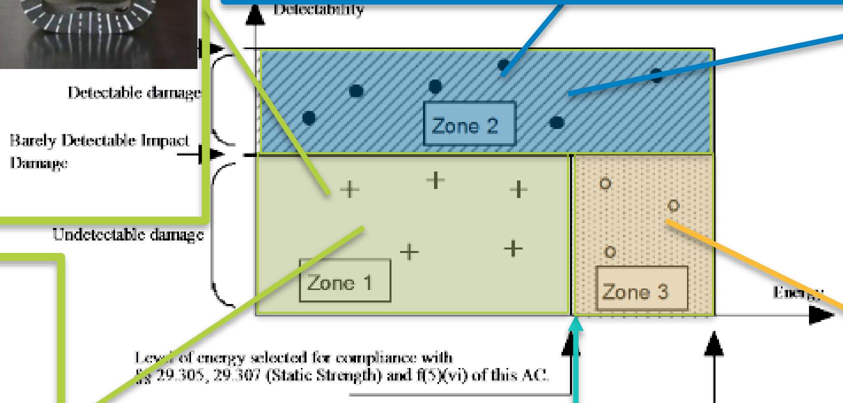
Zone 1: Damage following blunt impact from maintenance platforms



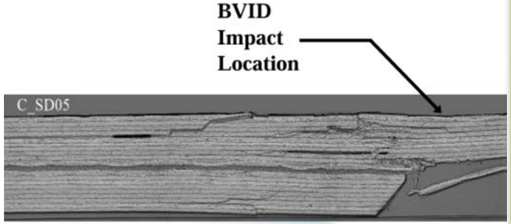
Zone 2 : Lightning strike damage on monolithic part



Zone 1 & 2 : Hail strike damages on sandwich



Zone 1: Tool drop impact damage below BVID



Zone 3: Damage following blunt impact from service vehicle collisions

https://www.dvidshub.net/image/7278983/mi-17-helicopter-transport

Energy cut-off typical examples (10-5/FH)
35J large aircraft typical fuselage, inner parts
25J-30J Rotorcraft thick parts

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A probabilistic approach can be valuable for Cat 1 Damages (Zones 1 & 3)

Summary

Composite DT and Fatigue Evaluation should include:

- A **threat assessment**, with identification of all **possible threats** to the composite structure and joints (in-manufacturing and in-service)
  - Energy levels in threat assessment should **not depend** on laminate design
  - Energy cut-offs should be derived from **in-service data** or good practices or robust rationale
- An evaluation of **detectability** of each damage on the composite design (thickness, layup,) accounting for damage relaxation and selected inspection method
- An evaluation of **damage severity**: effect of damage on residual strength, accounting for fatigue effect on damage growth behavior where needed
- Inspection Interval in ALS to detect the damage before it becomes critical and to restore UL capability.

The structure should be **designed** to comply with **Required Residual Strength (RRS)** depending on damage detectability as per AMC 20-29 and AC27/29.573.

Structural Bonding Certification

Structural Bonding Requirements and Compliance Demonstration

https://commons.wikimedia.org/wiki/File:SC_National_Guard_recovers_helicopter_141207-Z-ID851-005.jpg

Definitions

Structural Bonding: A structural joint created by the process of adhesive bonding, comprising of one or more previously-cured composite or metal parts (referred to as adherends) – AMC 20-29

3 different categories of joining processes:

→ **Cocuring**, **cobonding**, **secondary bonding**

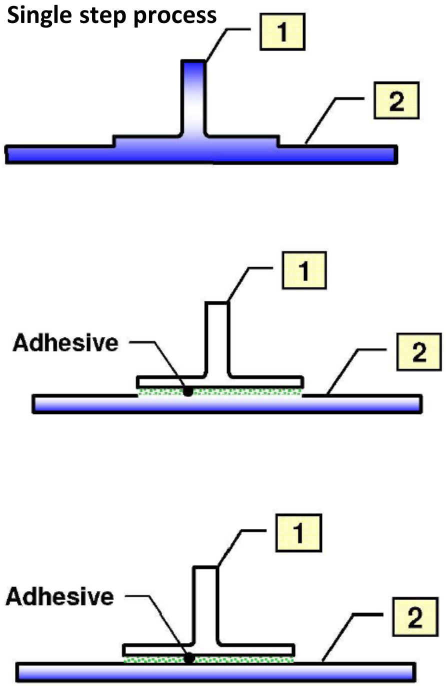
→ Cobonding and secondary bonding are **bonding processes**

→ **Cobonding** and **Secondary Bonding** both require at least one surface to be bonded with activation through surface preparation, to generate a new chemical bond with the adhesive

→ Any joining process for structural bonding should be compliant with **AC 21-26** "Quality System for the Manufacture of Composite Structures"

→ A joint is a **structural design detail**

Cocuring definition has been revised with FAA and differs here from the one in AC27/29.573



Co-Curing:

Components cured together

- Component 1 uncured
- Component 2 uncured

(may include additional adhesive and/or continuous structural plies common to both Components 1 and 2)

Co-Bonding
(Structural Bonding):

Components bonded together during cure of one of the components

- Component 1 cured*
- Component 2 uncured

or

- Component 1 uncured
- Component 2 cured*

* or metal
(may not necessarily include additional adhesive)

Secondary Bonding
(Structural Bonding):

Components bonded together with separate bonding operation

- Component 1 cured*
- Component 2 cured*

* or metal

Bonded Structure – Definitions From CM-S-005
Airbus – Composites Workshop Tokyo 2009

Bonding Requirements and Practices

Step 1 – Qualify the Bonding System

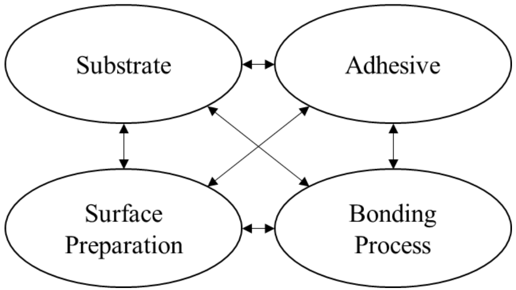
- → Characterize and control the substrate, adhesive, surface preparation and ancillary materials
- → Define the bonding process/ Evaluate the effectiveness of the bonding system, ensure compatibility of all materials
- → Comply with AC21-26A (process controls, inspections methods, …)

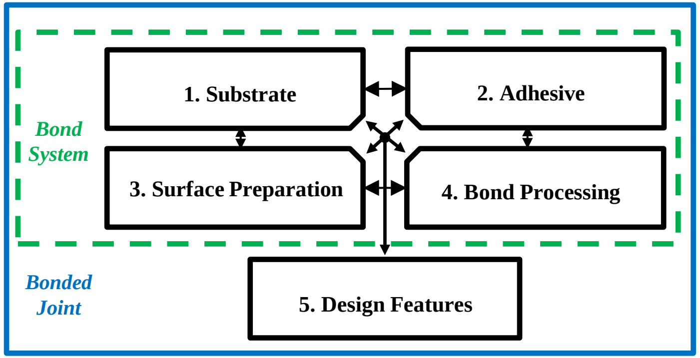
Step 2 – Certify the Joint

- → Ensure the joint design can be scaled and reproduces the bonding system with structural details
- → Typically done at the **component assembly level**
- → Tests should be performed at the element and detail scale to isolate bonded joint performance and/or develop design values

The performance of the bonding system may be affected by process variations within each of the constituents

Bonding System:





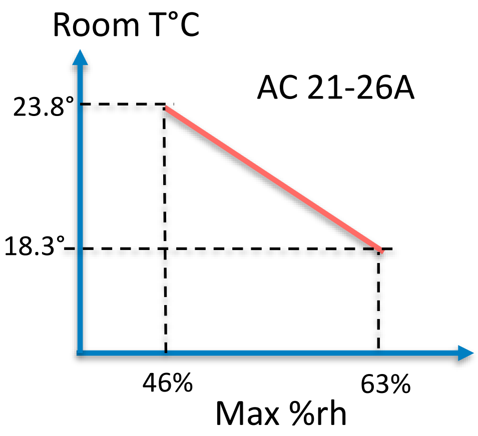
Reference: Ashforth et al., "Aerospace structural bonding: Qualification, quality control, substantiation, and risk mitigation," Advances in Structural Adhesive Bonding, 2nd Edition, Editor: David A. Dillard, Imprint: Elsevier, Published Date: June 10, 2023

Source: IRCWG Meeting, Charleston, US, June 2024

Structural Bonding Process Specification

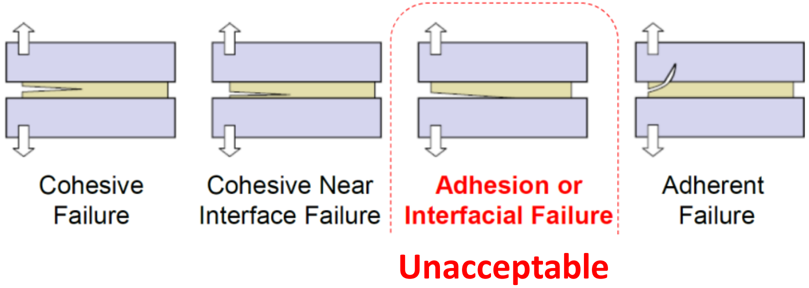
Structural Bonding **performance** is driven by **manufacturing process** and **materials**

- → The materials and manufacturing processes need to be specified (AC21-26A)
- → Defined **Range of process window**: most influencing parameters need to be **specified** for bonding process in **installation specification**:
  - → **Curing Time**: Min and Max time: Not less than 24H for curing at RT
  - → **Curing T°C**: Min and Max
  - → **Humidity rate** to process bonding: Min and Max
- → As a reminder:
  - → **Higher** Curing Temperature**, Faster** cure
  - → **Higher** Moisture**, Faster** cure



Failure modes & location in Test:

- ➔ **Critical** failures modes **out of bonding joint** are generally preferred (lower sensitivity to manufacturing process)
- ➔ **Adhesion** failure modes are **unacceptable** (AMC 20-29)



General Requirements for Structural Bonding

- **27/29.301**: Critical loading conditions in the bonded joint should be defined
- **27/29.303**: 1.5 Safety factor on limit loads
- **27/29.305**: Static Strength: **No failure** at ultimate loads, **full reversibility** of strains up to limit loads
- **27/29.307**: Proof of structure

  If demonstration is done by test only on a single test article, **the test article** should be representative of lower bound for:
  - **Design**, tolerances (e.g. bondline thickness)
  - **Manufacturing process**: at the boundary of process window specified in installation specification
  - **Materials properties**: materials variability may be covered by an overload factor applied on UL
  - **Environmental conditions**: Extreme environmental conditions should be considered in demonstration

- **27/29.601:** Design: The suitability of each questionable design detail and part must be established by tests
- **27/29.603**: Materials
  - **Materials** used should be listed and qualified
  - Effect of **Environmental conditions** must be considered
- **27/29.605**: Fabrication Methods
  - **Installation procedure** needs to specify bonding process
  - **Process window** for bonding needs to be defined
- **27/29.613**: **Variability** to be considered in design values, and/or in test
  - From Materials (batch)
  - From Manufacturing process
  - From Design

- **27/29.1529**: Installation specification should be part of ICA, including inspection intervals

For any design change involving structural bonding, **general requirements** are **applicable**

Specific Requirements for Structural Bonding

- → **Critical bonded joint**: A load bearing bonded joint whose integrity is essential in maintaining the overall flight safety of the aircraft – AMC 20-29
- → AMC 20-29 addresses **Large Damage Capability** for any **critical bonded joint**
  - → Reminds intent of CS23.573(a)(5) for damage tolerance substantiation of structure with bonded joints
  - → Mitigates the **lack of reliability** of inspection methods to detect a **weak bond**
  - → Applicable to **bonded repair** → CM-S-005 "Bonded Repair Size Limits"
  - → **Direct and indirect failure effects** should be considered for criticality assessment of bonded joint

Critical bonded joint of PSE

Large Damage Capability in bonded structure (and repairs) means demonstrating that when a **disbond** exists **between arresting features**, the remaining structure can still hold **limit loads**.

- → Cat 3 damage in threat assessment
- → Fatigue evaluation with large disbond may be needed for mission completion

Critical bonded joint of Non-PSE

Large Damage Capability in bonded structure (and repairs) means demonstrating that when a **large disbond** exists, the remaining structure can still hold **limit loads**.

- → Disbond size should be reliably detected during inspection from maintenance manual
- → Support selection of B-values for bonded joint design values (27/29.613)

Specific Requirements for Structural Bonding

CS27/29.573,
AC27/29.573, AMC 20-29
F&DT evaluation

Threat Assessment, including cat 1, 2, 3 and 4 damages (AMC 20-29)

Cat 1 damages
Fatigue + UL as RRS

AND

Cat 2 damages
Fatigue + > LL as RRS

AND

Cat 3 damage
Large Damage between arresting features + LL as RRS + Fatigue for mission completion

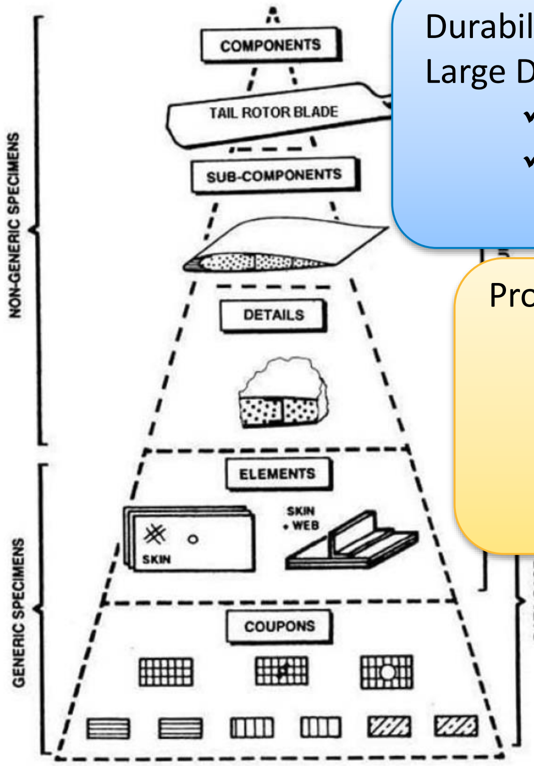
Retirement Time in ALS

AND

Inspection Intervals in ALS

- → **Large Damage Capability** is expected for any critical bonded joint
- → **Applicable to bonded repair**
- → **Design redundancies** are needed to evidence large damage capability
- → **NO STRUCTURAL BONDING JOINT as SLP PSE,** unless other design solutions are shown to be impractical

Summary: Structural Bonding Certification



Durability of bonded joint of PSE – Compliance with 27/29.573

Large Damage Capability (AMC 20-29) for critical bonded joints and bonded repairs

- ✓ LL capability with large disbond
- ✓ Design redundancies are needed to evidence LDC : No structural bonding as SLP PSE, unless other design solutions are shown to be impractical

Proof of structure 27/29.307

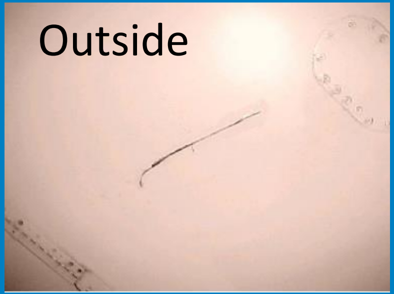
- ✓ Demonstration at component assembly level
- ✓ Representative loading conditions on test article
- ✓ Test article manufactured at the boundary of process window (27/29.605)
- ✓ Consideration of effects of environmental conditions (27/29.603)
- ✓ Consideration of variability of design, materials and processes (27/29.613)

Qualification of Bonding System (27/29.603/605, AC21-26A)

- ✓ Definition and qualification of the full bonding system
- ✓ Specification of bonding process including tolerances
- ✓ Repeatable and acceptable failure modes / repeatable failure locations

Inspection Methods for Composite Structures

« One Damage, One Method, One Threshold »



Background

- The following slides intend to provide **recommendations** for selecting the appropriate inspection methods for compliance demonstration of composite structures (AMC 20-29, AC 21-26A)
  - During manufacturing of parts to be tested (pre TC)
  - During certification tests (no growth of cat 1 & cat 2 damages, cat 1 manufacturing flaws)
  - During manufacturing of parts and critical joints (post TC)

- EASA does **not** approve **inspection methods**, but **quality system**
- A general reminder: **only what is known can be evaluated**: if no inspection, no pb (yet) !

"So far so good…"

Damage Detectability

Source: C. Fualdes, FAA Workshop for Composite Damage Tolerance and Maintenance, Chicago, July 19-21, 2006

→ Damage detectability **in service** should typically rely on **visual inspection** (DET, GVI) for any exposed external surface

AC43-204(*)

U.S. Department of Transportation

Federal Aviation Administration

Advisory Circular

Subject: VISUAL INSPECTION FOR AIRCRAFT | Date 8/14/97 | Initiated by: AFS-350 | AC No: 43-204 | Change:

1. PURPOSE. This advisory circular (AC) provides technical information to persons conducting a visual inspection of aircraft. The procedures presented in this AC are an acceptable means, but not the only acceptable means, for conducting visual inspections and inspection programs. Where the aircraft, engine, propeller, or appliance manufacturer has published a recommended inspection schedule or program for a particular aircraft, that program should take precedence over the recommendations of this AC.

2. RELATED READING MATERIAL.

a. AC 20-37D, Aircraft Metal Propeller Maintenance.

b. AC 43-3, Nondestructive Testing in Aircraft.

c. AC 43-4A, Corrosion Control for Aircraft.

d. AC 43-7, Ultrasonic Testing for Aircraft.

e. AC 43-12A, Preventive Maintenance.

f. AC 43.13-1A, Acceptable Methods, Techniques and Practices--Aircraft Inspection and Repair.

Richard O. Gordon
Acting Deputy Director, Flight Standards Service

1.1- Damage detectability

Supporting tests and analysis and in-service survey

DET Inspection

- Detection of damages on different composite panels (size: from 100*100mm to 0.8m², painted or not, glossy or mat, white, grey, blue or green paint, primer)
- Duration of inspection : not limited
- Distance of inspection : 50 cm
- Lighting condition : available lighting+grazing light (if required)
- Several impactor diameter : 6mm and 16mm
- A total of 902 inspections

FOR BVID
TRANSVERSE IMPACT

GVI Inspection

- Inspection on large panel (8m*1.2 m)
- Two configurations : horizontal or vertical panels
- Distance of inspection : 1m
- Duration of inspection : 30sec/panel
- Artificial lighting representative of Natural daylight
- Several impacts on painted panel: from 0.3mm deep to perforation
- Several impactor diameter : from 6 to 120mm
- A total of 240 inspections

→ In some cases, **other methods** may be used for inspections in service

→ The next slides are focused on **manufacturing inspections and DT tests monitoring**

→ **Maintenance inspections and link with SRM (ADL, CDT, ..)** are not addressed here

Why inspecting composite parts?

- → **“Zero defect”** does not exist in composite or metal, the acceptance quality level/ quality control plan should ensure the expected performance (AC 21-26A) and conformity with type design
- → Definition of acceptable criteria for cat 1 damage (AMC 20-29) is key:
  - → To allow some **tolerance in manufacturing**
  - → To design **damage tolerant parts** for in-service events with **adequate ADL** and UL capability
- → Relevant inspection method should be selected for:
  - → Definition of **cat 1 damages** in manufacturing and in certification tests
  - → Definition of **cat 2 damages** in maintenance and in certification tests
  - → Quantification of damage *before & after impact* during **certification tests** and *before & after* residual strength test, **for any damage category**
- → **Tap test** and **US inspection** cannot detect the same information
  - → **Tap test** is adequate for **thin part** to check **qualitatively** the absence of surface delamination. It is not seen adequate to **quantify** a delamination when found.
  - → **US inspection** is highly recommended for:
    - → Thick parts (blades, hubs) & joints as PSE
    - → Quantification of delaminated area or disbond
    - → Monitoring (no) growth of damage during certification tests

EASA

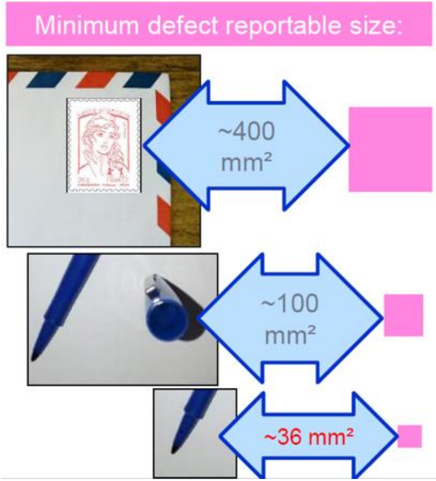
Inspection Method Selection

"Tell me what you want to detect and I will tell you which inspection method to be used"

→ Inspection method selection should be done depending on type of damage/threat, part design (thickness, shape)

→ Inspection thresholds are different between inspection methods (typically **600mm² for tap test, 36mm² for US**)

→ Beyond 2-3 mm thickness, tap test is not reliable to detect a delamination



→ The **inspection method** (and threshold) in manufacturing should be selected depending on flaws considered in design values (cat 1)

→ **NDI pass/fail criteria** is unique to each application / part → requires **unique calibration**

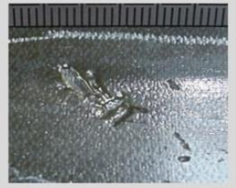
→ Inspection method selected for **no growth / growth** of damage should be **US inspection**: not enough precision of tap test to assess (no) growth of damage

Inspection Method Selection

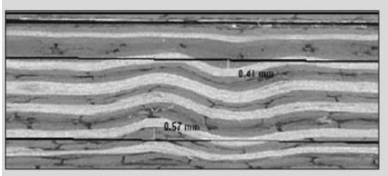
Method	Structure	Damage Detected
Visual	All Monolithic Sandwich	Surface Damage only Drying, resin pockets, thickness, dimensions Honeycomb offset, taper subsidence, telegraphing
Tap Test	Thin Laminate Sandwich	Surface delamination, disbond Skin to core delamination/disbond (thin skin)
Ultrasonic A-scan	Monolithic	Delaminations/Disbond, porosities and voids
Ultrasonic C-scan	Monolithic Sandwich	Delamination, disbond, voids and porosities, waviness Core: Crushed/Damaged/Water Impregnated Skin to core delamination and disbond
Thermography	All Sandwich	Disbonds/ Delaminations Water Impregnated Core
Radiography	All Sandwich	Disbonds/ Delamination, ply edge Crushed Core /Water Impregnated Core, insert filling, inserts

Typical composite flaws


Voids & Porosities


Scratches and Print


Hole delamination



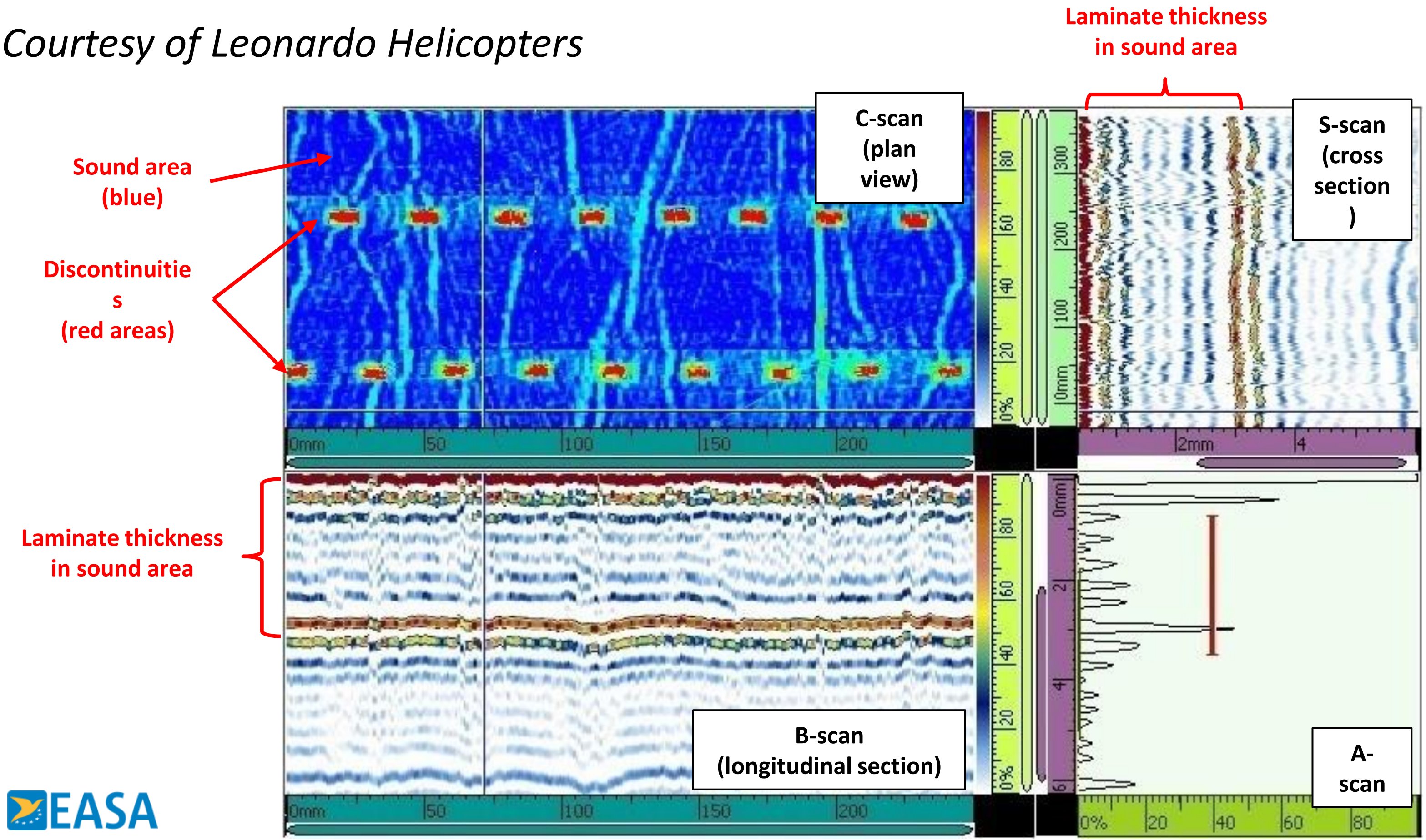
Waviness

Source: E. Dupuy, Airbus, JEC Conference –18th of May 2017, Ecole Normale Supérieure Paris-Saclay

➔ Adequate inspection **method** should be selected for each **detrimental** flaw in quality control plan
➔ Inspection **threshold** depends on method/application/damage or flaw

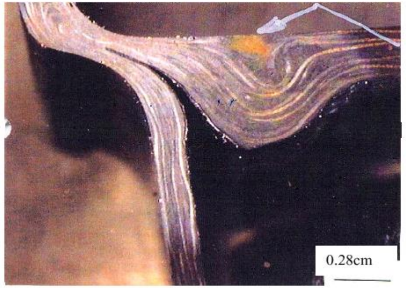
Example: Automated Ultrasonic Testing: A-B-C-S-scan images (Technique: Phased Array; Mode: Pulse-Echo), Carbon Fiber Solid Laminate

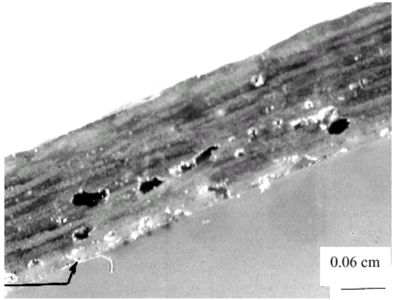
Courtesy of Leonardo Helicopters



Take away

- **Inspections are key** for composite applications as the quality obtained is highly driven by processing parameters and tolerances
- **Design values** should take into account **cat 1 damages** (impact and manufacturing flaws) to cover **quality acceptance level** achieved
- **Inspection methods** should be selected depending on flaw type, size and part type, thickness and shape
  - In manufacturing, to assess conformity of part vs type design and detect flaws beyond criteria
  - For certification tests monitoring (all scales)
- **Inspection plan** should be defined **during development**, not during certification !
- Critical joints / parts should be **100% US inspected** on all products !
- The objective should be to select the inspection method able to detect what could be **detrimental** regarding structural **performance** – not the one with the lowest detectability threshold !
- Inspecting composite parts represents **a cost**: no cost savings in long term !





CMH17 updates Composite Initiatives involving EASA

EASA Webinar information

EASA Webinar

- 26th of March, 3pm-5pm CET
- Registration open, **free of charge**
- Invitation only (link will be sent out)
- Awareness session
  - Composite Working Groups and Initiatives supported by EASA
  - CMH-17 Updates (Vol 3. and Vol 6.)

- https://www.easa.europa.eu/en/newsroom-and-events/events/composite-initiatives-involving-easa-and-introduction-cmh17-updates

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Thank you for your attention!