Composite Certification Tutorial

Hosted by: Wichita State University, National Institute for Aviation Research

Instructor: Cindy Ashforth, FAA Senior Technical Specialist for Composites

August 21, 2017
# Agenda

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Eclipse
Introduction

• This tutorial covers the requirements for certifying products and articles made with composite materials
• Assumes a knowledge of composite basics
• Begin with certification basics and composite technical challenges
• Then discuss specific requirements and means of compliance for composite structures
  ➢ Describe the content, background, and intent of AC 20-107B, “Composite Aircraft Structure”
Tutorial Methodology

Certification Basics

Composite Basics & Technical Challenges

Composite Certification (AC 20-107B Content)
Part 1: Certification Basics

• **Types of Certification**
  - Design Approval
    - TC, STC, PMA, TSOA
  - Production Approval
    - PC, PMA, TSOA
  - Airworthiness Approval

• **Continued Airworthiness**

• **Regulatory Requirements and the role of Policy, Guidance and Industry Publications**

• **Role of Designees**

• **Likely Composite Certification Scenario**
Civil Aircraft Certification

• The FAA, EASA, and other civil aviation authorities provide three types of certification related to aircraft
  ➢ Design Approval
  ➢ Production Approval
  ➢ Airworthiness Approval

• Persons who have applied for a design or production approval are “Applicants”
  ➢ Once granted, they become a design approval holder (DAH) or production approval holder (PAH)

Note: The term “Aircraft” will be used throughout the tutorial and refers to both airplanes and rotorcraft
Types of Approvals

• Design Approvals are granted for *products* and *articles*
  - A *product* is an aircraft, aircraft engine, or propeller
  - An *article* is a material*, part, component, or appliance

• Production approvals allow a person to produce a product or article in accordance with an approved design

• Airworthiness approval is granted for a product or article after it is demonstrated it meets its approved design and is in a condition for safe operation

* Although the regulations allow for certifying a material, there are currently no standards for composites
Design Approval

• Design approvals are granted after an applicant has shown the design meets applicable airworthiness requirements

• Four main types of Design Approvals:
  - **Type Certificate (TC)** – New airplane, engine, propeller
  - **Supplemental Type Certificate (STC)** – Modified airplane, engine, propeller
    – Most likely way to get composite parts on an aviation product
Design Approval

• Types of Design Approvals (continued):
  - **Parts Manufacturer Approval (PMA)** - replacement and modification articles for specific type-certificated products
    - Not for base materials that comprise an article
  - **Technical Standard Order (TSO)** – a means to self-certify to a minimum performance standard for an article (such as a radio), which then requires installation approval under a TC or STC
    - Makes the TC/STC process easier
Type Certificate

- Type certificates are only granted for aircraft, engines, or propellers
  - Materials are not approved independently, but credit can be taken for material data developed under different projects
- Applicant must show compliance to the applicable airworthiness regulations
- The FAA publishes many documents that provide guidance on design approvals, one comprehensive “how to guide” is *The FAA and Industry Guide to Product Certification*
Type Design

• Regulations require the design approval holder (DAH) to fully define the Type Design of their product, including:
  ➢ Drawings and specifications to define configuration
  ➢ “… materials and processes necessary to define the structural strength of the product.”

• Type Design typically includes drawings, specifications, and digital data files for complex geometries that cannot easily be represented by a drawing.

• Type design may include tooling or more detailed process instructions beyond standard material and process specifications.
Type Design

- Drawings, or other means of part and assembly definition, should include:
  - Geometric features
  - Ply sequence
  - Ply orientation (sign convention)
  - Dimensions and tolerances
  - Material and process specifications
  - Tooling

- Part 21 Certification Procedures for Products and Parts
- Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
- Part 25 Airworthiness Standards: Transport Category Airplanes
- Part 27 Airworthiness Standards: Normal Category Rotorcraft
- Part 29 Airworthiness Standards: Transport Category Rotorcraft
- Part 33 Airworthiness Standards: Aircraft Engines
- Part 35 Airworthiness Standards: Propellers
FAA Regulations

• Part 21 identifies general requirements to get a design approval (TC, STC, PMA or TSO)

• Parts 23-35 define the airworthiness requirements for the specific products
  ➢ For aircraft, there are sections on: General, Flight, Structure, General Design and Construction, Powerplant, Operational Limitations and Instructions
  ➢ For engines, there are sections for: General, Design and Construction, Block Tests, Special Requirements

• Part 21 also defines requirements for production and airworthiness approvals
Certification Basis

• The certification basis is the list of “applicable regulations.” It includes:
  - Airworthiness regulations from Parts 23-35 that were in effect on the date of application
  - Environmental and Noise regulations from Parts 34 and 36
  - Special Conditions
  - Exemptions

• Applications are good for 3 or 5 years
  - May be extended, but the applicant has to update the certification basis to 3 or 5 years before the final date
    - (e.g., application with a cert basis of January 2010 that is not complete by January 2015, may extend the application to January 2017, but the cert basis becomes January 2012)
Composite Regulations

- The relevant airworthiness regulations for composites are for structural strength, fatigue and damage tolerance, and general design and construction.
- Part 25 has no regulations that are specific to composite materials; Parts 23*, 27, and 29 have one for Damage Tolerance (§2x.573).

*Part 23 rewrite effective August 2017 changes to performance-based standards that no longer reference composite materials.
Composite Regulations

• In addition to Fatigue and Damage Tolerance, relevant regulations for composite structure are:
  - 2x.307 Proof of Structure - Static
  - 2x.603 Materials and workmanship
  - 2x.605 Fabrication methods
  - 2x.613 Material strength properties and design values

• Crashworthiness, Flammability, and Lightning Protection are other relevant subjects where composite structures may have unique means of compliance
Product Modification

• After TC, the DAH must get regulatory agency approval for all changes to type design.

• Changes are classified as either “Major” or “Minor”
  - Minor change – one that has no effect on weight, balance structure strength and reliability, operational characteristics, or airworthiness
  - Major change – All others

  - Note: EASA “major” terminology is slightly different (see 21.A.435 and 21.A.91)
Supplemental Type Certificate

- STCs are granted to a party to allow them to modify a product
- The STC applicant must show compliance to the applicable airworthiness regulations for the area affected by the modification
  - One significant regulation that must be addressed during a STC is the “changed product rule” of §21.101 (guidance in Advisory Circular 21.101-1)
    - Applicants must meet the latest regulations in effect at the time of the application, unless the applicant can determine the change is not significant, and then meet the regulations that were in effect at the time the original product was certified
    - Applicants follow policy and guidance at the time of the application, regardless of the certification basis
Parts Manufacturer Approval

• A PMA is a *design and/or production* approval
• PMA *design approval* is for an article that is intended to replace one that is already installed on a certified product
• Applicant shows the design meets the applicable airworthiness standards by either:
  1. Show that the PMA article’s design is identical to the currently certified design
  2. Use test and computation to show the PMA article meets the airworthiness requirements
Technical Standard Order Authorization

- A **Technical Standard Order (TSO)** is a minimum performance standard (MPS), defined by the FAA, used to evaluate an article
  - Article – material, part, component, process, or appliance
  - Each TSO covers a certain type of article, such as a radio, oxygen mask, galley cart, etc.

- A **Technical Standard Order Authorization (TSOA)** is both a design *and* production approval issued to the manufacturer of an article that has been found to meet a specific TSO.
Technical Standard Order Authorization

- To get a TSOA, the Applicant submits:
  - Statement of Conformance
  - Description of their quality control system
  - Data specified in the applicable TSO

- Unlike a TC, STC, or PMA, the FAA is typically not involved in the development of data used to demonstrate compliance to the TSO

- A TSOA is not an approval to install and use the article in an aircraft
  - Installation approvals are done separately under TC or STC
Production Approval

• Three main types of production approvals
  - Production Certificate (PC)
  - Parts Manufacturer Approval (PMA)
  - Technical Standard Order Authorization (TSOA)

• Other Countries have similar approvals
  - EASA IR Part 21, Subpart G
  - TCCA Standard 561

• In the U.S., production approvals cannot be issued before a design approval, but they can be granted concurrently
Production Approval

- **Production Certificate**
  - Granted to TC or STC holders

- **Parts Manufacturer Approval**
  - PMA is design and/or production approval
  - For production approval, the applicant shows they have an approved design
    - May be from tests and computation, a showing of identicality, or licensing agreement from another DAH

- **Technical Standard Order Authorization**
  - A design and production approval that must be granted simultaneously
  - Design must be shown to meet the applicable TSO MPS
Production Approval

All production approvals require an approved design and an acceptable quality system that ensures each product and article conforms to its approved design and is in a condition for safe operation.
Production Approval

• Key elements to ensure control of a type certified product include:
  ➢ Production implementation that reproduces the type design
  ➢ Manufacturing quality control of all critical processes to ensure reproducibility
  ➢ Defect detection and disposition per substantiated engineering methods/data and thorough manufacturing records
  ➢ Sufficient substantiation of all modifications to the production process
  ➢ MRB (Material Review Board) actions on defective parts
Quality System

The production approval holder (PAH) is required to have a **quality system** that includes:

- Design data control
- Document control
- Supplier control
- Manufacturing process control
- Inspection and testing
- Inspection, measuring, and test equipment control
- Inspection and test status
- Nonconforming product and article control
- Corrective and preventive actions
- Handling and storage
- Control of quality records
- Internal audits
- In-service feedback
- Quality escapes
Airworthiness Approval

• Final approval necessary for an aircraft to be legal for flight
• Several types of airworthiness approvals
• Most common is a “standard airworthiness certificate” granted to aircraft with:
  - Design approval
  - Produced under a production approval
  - Have all modifications from the original configuration approved by the FAA
Airworthiness Approval

• Special Airworthiness Certificates are all other types of flight permits:
  ➢ Primary
  ➢ Restricted Limited
  ➢ Light-Sport
  ➢ Provisional
  ➢ Special Flight Permits
  ➢ Experimental

• Design and production approvals are granted to *individuals* – airworthiness approvals are associated with a *product*
Continued Airworthiness

• After an aircraft is shown to be airworthy and granted an airworthiness approval, additional regulations govern continued airworthiness of the aircraft
  ➢ Part 43 governs aircraft maintenance
  ➢ Parts 91-135 govern operation

• The airworthiness certificate is valid as long as the FAA finds that the aircraft conforms to the type design and is in a condition for safe operation
Continued Airworthiness

- TC/STC holders define instructions for continued airworthiness (ICA) as part of initial type certification
  - Although not required, most also publish a Structural Repair Manual (SRM) with approved repair information
- Operators are required to follow portions of the ICA related to fatigue and damage tolerance and certain systems regulations
Continued Airworthiness

• DAH and PAH must report certain safety-related service incidents to the FAA

• Using statistical risk-based methodologies, the FAA will determine if:
  – An “unsafe condition” exists
  – It is likely to exist or develop in other products of the same type design

• If an unsafe condition exists, the FAA will publish mitigating actions in an Airworthiness Directive (AD)
  ➢ ADs may be issued against a product or appliance

• Operators must follow instructions in ADs
Continued Airworthiness

- When repairs and alterations are performed, they are classified as “Major” or “Minor”
- Major Repair - May affect weight, balance, structural strength, performance, power plant operations, flight characteristics, other qualities affecting airworthiness
  - Cannot be done by elementary methods or is not done according to accepted practice and regulatory agency approval required
- Minor Repair - All other, and based on accepted data
Regulations and Guidance

- FAA regulations are contained in Title 14 Code of Federal Regulations (14 CFR)
  - Deviations only allowed through exemptions, which must be in the public interest
  - When the regulations do not contain adequate or appropriate safety standards because of a novel or unusual design feature, the FAA issues a special condition
  - Exemptions and special conditions are published in the federal register with opportunity for public comment

- FAA may issue an Equivalent Level of Safety (ELOS) finding if the applicant meets the intent of the rule, but not the exact requirement as written
Regulations and Guidance

• The FAA issues Orders, which set responsibilities and procedures FAA employees and designees follow

• FAA publishes Advisory Circulars, Policy Statements, and Policy Memorandums
  - Guidance provides “means of compliance” (MOC)
  - *Always* considered one means, but not the only means, of meeting the regulation
  - Applicants encouraged to follow published guidance to streamline the certification process
  - Applicants are free to propose other methods, but will likely take longer to certify
Regulations and Guidance

• If the applicant chooses a different MOC, the FAA may document technical discussions and decisions in an “issue paper”
  ➢ An issue paper is a permanent record
  ➢ Not made available to the public

• FAA guidance may reference industry standards

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(2) Existing references (e.g., The Composite Materials Handbook (CMH-17) Volumes 1 and 3, FAA Technical Report DOT/FAA/AR-03/19), addressing composite qualification and equivalence and the building block approach, provide more detailed guidance regarding batch and test numbers and the appropriate statistical analysis up to laminate level. Changes at higher

• If no FAA guidance exists, look for industry standards, like CMH-17
FAA “Desigee”

• **What is a FAA Desigee?**
  - A private person or organization designated to act as a representative of the Administrator.

• **Why do we need designees?**
  - The FAA doesn't have the resources to do all the certification activities necessary to keep up with an expanding aviation industry. Using designees for routine certification tasks allows the FAA to focus its limited resources on safety critical certification issues as well as new and novel technologies.
FAA “Designee”

• What types of designees are there?
  ➢ There are two types of designees: individuals and organizations.
    − Individual designees can either be a company employee or an individual consultant.
    − Delegated organizations are made up of two or more individuals who are designated to perform the authorized functions of the FAA.
  ➢ Whether an individual or an organization, both are considered to be designees and the FAA is responsible for their oversight and management.
FAA “Desigee”

• What do we delegate?

➢ Certification of Aircraft
  - Engineering design – *Designated Engineering Representative (DER)*
  - Manufacturing – *Designated Manufacturing Inspection Representative (DMIR), Designated Airworthiness Representative (DAR)*
  - Operations
  - Maintenance

➢ Certification of People
  - Medical Examinations
  - Pilots
  - Mechanics
  - Parachute Riggers
  - Dispatchers
  - Knowledge Testing
Now let’s look at a

Likely Composite Certification Scenario
You make Composite materials...

Can I certify my material to be on an airplane?

No!
You make Composite parts…..

I make widgets out of composite materials. Can I certify them on a plane?

Yes, you can!
Supplemental Type Certificate

Typical steps for the most likely way to install a composite part on an aviation product...

• Apply for an STC through your geographic ACO Branch
  ➢ FAA Form 8110.12
  ➢ Certification Plan and Compliance Checklist*

*The Compliance Checklist identifies the pertinent airworthiness regulations and describes how they will be met (test, analysis, etc.)
Supplemental Type Certificate

• Certification follows five phases:
  1. Conceptual Design
  2. Requirements Definition
  3. Compliance Planning
  4. Implementation
  5. Post Certification Activities
Certification Process
Implementation Phase
Implementation Phase

• Implementation is the “meat” of certification
• Applicant and FAA work closely to ensure certification requirements are met
• Tasks
  - Demonstration of compliance
  - Compliance and conformance requirements verification
  - Final Certification Board Meeting
• Required Information
  - Design and production analysis
  - Witnessing
  - Inspection results
  - Safety analysis
Demonstrating Compliance

• The applicant *shows* compliance to each applicable regulation
  ➢ Substantiating data necessary to show compliance must be provided to the FAA along with a statement of compliance prior to FAA issuance of the certificate, PMA or major change approval.

• The FAA (or their designee) *finds* compliance to each applicable regulation

• After all regulations are complied with, the FAA issues the STC

Simple, right?
Demonstrating Compliance

- The devil is in the details of showing compliance
- While the regulations are the same, whether metallic or composite structure, the means of compliance (MOC) differ
- Tests must be performed
  - Requires FAA “conformity” of test articles
- Material and Process Controls must be developed, inspected, and approved
- Design values must be developed
- Analyses must be validated
- Etc.
Conformity

• During the type certification process, test articles will require “conformity,” or FAA inspection, to ensure the test article was manufactured in accordance with required design features (including intentional defects) and material and process instructions.
Demonstrating Compliance

• Where to begin when determining how to show compliance with the regulations for composite structures?

• We will review AC20-107B in Part 3 of this tutorial after reviewing some key composite technical challenges.
Questions?
Part 2: Composite Technical Challenges

- Non-Standard Technology
- Differences between Metallic and Composite Material Behavior
- Material and Process Controls
- Assembly Considerations
- Building Block Approach
- Testing and Analytical Modeling Challenges
- Repair Challenges
## Non-Standard Technology

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<th>Disadvantages of Composite Structures</th>
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<td>Typically do not exhibit fatigue properties or corrode</td>
<td>Lack of standardization</td>
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<td>Fewer parts and assemblies</td>
<td>High-value assemblies require sophisticated repairs</td>
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<td>Higher strength-to-weight ratio</td>
<td>Greater statistical variability and environmental effects</td>
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Non-Standard Technology

• Infinite number of composite materials (resin and reinforcement combination)
  ➢ A single material processed at different cure temperatures will have statistically different material properties

• International standards do not define chemical formulas or physical and mechanical properties, the way they do for metals
  ➢ Leads to few published material databases
Non-Standard Technology

• Limited published data exists, but cannot be used without a demonstration that the information is relevant to the materials, processes, and design features used by the applicant in their specific product or article

• Each manufacturer selects unique, often proprietary, material systems and processes, as well as customized structural design features
Non-Standard Technology

• Design methods are not standardized
• Rules of thumb are highly conservative
• Higher-level design values and analytical tools are in proprietary company standards
• Repair materials and processes are not standardized
  ➢ Greater safety risk
• Lessons learned are not shared across industry
Non-Standard Technology

• The end result from the lack of standardization is:
  - Increased cost
  - Resource dilution
  - Evolving technology
  - No sharing of safety-related lessons
Differences Between Metallic and Composite Material Behavior

• Fundamental differences in behavior of metals and composites at the structural level lead to a different approach to certification

• Main differences are:
  1. Environmental sensitivity and statistical variability
  2. Notch sensitivity
  3. Fatigue behavior

• A challenge to show that monocoque single load-path sandwich structure has equivalent safety to traditional metallic construction with reinforcements and multiple load paths
  ➢ Greater factors of safety, lower operating strains
Differences Between Metallic and Composite Material Behavior

• Composites commonly lose strength at high and low temperature extremes and at high humidity
• Many composites have higher statistical variability than traditional metallic materials
• Must account for these features during structural substantiation, typically with overload factors and/or reduced design allowables
Differences Between Metallic and Composite Material Behavior

- **Composites are “notch sensitive”**
  - Designers cannot take advantage of base strength properties
  - Ultimate allowable strengths are knocked down for non-detectable damage or common design details
  - Failure typically initiate at local stress concentrations caused by design details, damage or manufacturing flaws

- **Metallic failures also originate at stress concentrations, but…**
  - There are no consistent stress concentration factors that can be applied to composite holes, notches or damage sites – each one must be developed separately
Differences Between Metallic and Composite Material Behavior

- Composites typically have a relatively flat S-N curve and large scatter compared to metals
Differences Between Metallic and Composite Material Behavior

• Behavioral differences lead to one significant philosophy change between certification of metallic and composite structure:
  
  ➢ *Metals are certified by demonstrating that any cracks that develop during operation will be detected and repaired prior to reaching a critical size.*

  ➢ *Composites are certified to show that some level of damage is acceptable for the entire life of the structure.*

• The inclusion of **intentional damage** is an important theme
Material and Process Controls

• **Sharing of** Material and Process Controls are essentially non-existent compared to metallic materials; however, they are more standardized than any other issue related to composite certification

• Limited number of FAA-accepted material databases available through the National Center for Advanced Materials and Processes (NCAMP) affiliated with Wichita State University
Material and Process Controls

Before published databases can be used, the applicant must demonstrate the data is applicable to their design, as explained in FAA policy AIR100-2010-120-003
Material and Process Controls

- Applicant must demonstrate statistically equivalent strength and stiffness properties
- “As good or better” is not acceptable as statistically equivalent
  - A limited number of properties are characterized in the published material database, and only a small portion are checked for equivalence
  - As with metals, composites may have an inverse relationship between static ultimate strengths and damage tolerance or durability
Material and Process Controls

- Both metals and composites follow similar trades in large notch vs small notch (or yield) strength

  Therefore, if static strengths are “equal or better” there is likely a decrease in critical properties that are not measured in equivalence exercises
Assembly Considerations

- Using composites reduces assembly steps, but does not eliminate them
- Two types of assembly:
  1. Mechanical Fastening
  2. Bonding and Co-Curing
Assembly Considerations - Fastening

• Mechanical fastening typically requires a type design process specification because standard metallic techniques are not suitable for composites
• Most common fastening systems are pin-collar designs, such as bolts and nuts, lock bolts or Hi-Loks
• Rivets generally avoided; however rivnuts are common
Assembly Considerations - Fastening

• Metals often use close tolerance, transition fit or interference fit fasteners – Composites are generally sized for clearance fit
  ➢ Composites more sensitive to fit-up tolerances; excessive clamp forces cause delamination

• **Shimming (metal, composite, or liquid) often used**

![Diagram showing laminates, spar, as designed, as manufactured, and shims.]

As designed  
As manufactured  
(unsatisfactory)
Assembly Considerations - Fastening

- External curved surfaces often require countersinking for flush fit with fastener head
- Galvanic corrosion is a potential issue between some fasteners and the composite material
  - Aluminum and carbon are a common combination with potential for galvanic corrosion
  - Typically a layer of glass, a sealant, or other inert substance is used between the two layers
Assembly Considerations - Bonding

• In theory, there are three types of bonding processes – co-curing, co-bonding, and secondary bonding
Assembly Considerations - Bonding

• Co-curing occurs during initial part fabrication, where two laminates are fabricated as one component and all cured at once
  ➢ Not treated as a “bond” in FAA guidance

• Co-bonding and Secondary Bonding both require at least one surface to be cured (or metallic), such that the surface to be bonded requires activation to generate a new chemical bond with the adhesive
Assembly Considerations - Bonding

• Bonds are fully characterized by five factors:
  1. Adhesive,
  2. Substrate material(s),
  3. Surface preparation technique,
  4. Cure/Process instructions, and
  5. Design features

• Adhesive characterization is easiest to achieve, but not standardized in the industry
  ➢ FAA guidance forthcoming

• No non-destructive inspection (NDI) techniques to evaluate if the bond has full strength
  ➢ NDI can only find disbonds and voids
Building Block Approach

- Structural substantiation generally requires a complex mix of test and analysis.
- A “building block” approach provides systemic step-by-step sequence of tests and analyses progressing from lamina to full scale.
Building Block Approach

- Large quantity of tests for statistical basis comes from lowest levels (coupons and elements)
- Performance of structural details validated in a lesser number of subcomponent and component tests
- Detail and subcomponent tests used to validate analytical methods to predict local strains and failure modes
- Component tests provide the final validation to account for combined loads and complex load paths
Building Block Approach

- Regulations only require testing at the lowest level of the building block to develop design values and at the full-scale level as part of structural substantiation.

2x.305 “Strength and Deformation”
2x.307 “Proof of Structure”

2x.613 “Material Strength Properties and Design Values”
Building Block Approach

- All middle steps are voluntary, but considered best practice
- Exceptions are some general aviation manufacturers who implement an inverted building block doing only bottom and top-level testing and later filling in missing data only as required
  - Inverted building blocks are successful when manufacturing and testing full-scale articles are less expensive than developing validated analytical tools
  - Inverted building block typically also associated with a limited number of structural configurations (e.g., consistent laminate layups, joint details, etc.).
Building Block Approach

• Building blocks most commonly used for structural substantiation through testing and analysis

• Can also be used to substantiate manufacturing processes and quality control procedures
  - For example, procedures used to create flat laminates are expanded to include curved structure, complex geometries, and assembled structures
  - Inspection methods are evaluated throughout the process to ensure they are effective on more complex structure
Conformity During the Building Block Approach

• Test articles should include manufacturing defects, field damages and repairs that may occur in production and service
  ➢ Conformity must ensure features are in the intended locations (may or may not be detectable in fully assembled structure)

• Conformity may need to take place before material and process specifications are complete
  ➢ Testing is then performed at-risk, considering that the materials used in the test article may not meet future standards
Testing and Analytical Modeling Challenges

- Testing challenges begin at the coupon level and exist throughout the building block
  - Largest challenge is selecting a configuration to test and develop a property for
  - The infinite number of configurations create a challenge to develop a “base property” that can be used in multiple locations on a structure without a point design
## Testing and Analytical Modeling Challenges

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<th>Testing Challenge</th>
<th>Analysis Challenge</th>
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| Lamina               | • Strain gage size and position – in large weave fabrics (e.g., 12k flat tow), it can be difficult to meet recommended guidelines to have a strain gage that is 3x the weave size and yet fits on the test specimen.  
• Statistical equivalence must be shown at this level in order to use published material properties.  
• Many standard composite tests are susceptible to invalid failure modes that must be closely watched for.  
• Tests must be performed at multiple temperature/humidity conditions to fully characterize behavior under the extremes of the operating envelope and identify worst-case conditions. | • Base material properties are important to quantifying variability, environmental effects and moduli, but have limited use in predicting static strength. |
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| Laminate             | • Laminate configurations must be selected that encompass the design, including isotropic laminates with open hole (notched) properties, bearing strengths, and strength after impact.  
• Sandwich structure enters at this level and should be investigated with all combinations of core, adhesives, face sheets, and core splice materials.  
• Cyclic loading is often performed at this level. | • Design values are typically developed at coupon, element and detail levels.  
• May allow proper studies on various manufacturing defects and smaller damage types.  
• Environmental effects generated at this level have more meaning to the structural tests at higher levels of the building block tests.  
• Used to validate laminate layup effects on stiffness. |
## Testing and Analytical Modeling Challenges

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</thead>
</table>
| Element              | • Bonded and bolted joints enter in at this level; bonds should be investigated for a full range of thicknesses, substrates, and surface preparation techniques  
                       • Shaped/curved elements should be tested to determine actual failure modes under combined loading conditions                                                                                          | • Evaluate manufacturing tolerances on bonded and bolted joint details.  
                       • Allow for some of the secondary loading affects owed to eccentricities in load paths for assembled joints  
                       • Stability and fracture elements are used for stiffener crippling and radius bend details at this level.                                                                 |
## Testing and Analytical Modeling Challenges

<table>
<thead>
<tr>
<th>Building Block Level</th>
<th>Testing Challenge</th>
<th>Analysis Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Details</td>
<td>• Fastened and bonded assemblies may be added at this level</td>
<td>• Analytical tools are often developed or “calibrated” at this level such that they can be used with confidence in higher-level assemblies. For example, a single element might be created to model the behavior of a fastened joint, rather than have a model that distinguishes fastener from laminate</td>
</tr>
<tr>
<td></td>
<td>• Tests at this level are used to validate analytical techniques built on data from the coupon - element level tests</td>
<td></td>
</tr>
</tbody>
</table>
Testing and Analytical Modeling Challenges

<table>
<thead>
<tr>
<th>Building Block Level</th>
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</tr>
</thead>
</table>
| Sub-Components       | • Sub-component tests may be able to be used for certification credit, particularly to investigate details that are not easily tested at a higher level, such as thermal stresses that develop in hybrid structure during service conditions  
• Combined load testing for empennage, wing, and fuselage structures with damage in critical locations  
• Also typically appropriate for the largest scale of environmental testing (e.g., static strength and thermal loads in hybrid structures) | • Semi-empirical engineering approaches are typically used to address the many factors that localize damage and affect static strength (e.g., larger cutouts and stiffened panel tests with skin buckling and frame or rib details added) |
# Testing and Analytical Modeling Challenges

<table>
<thead>
<tr>
<th>Building Block Level</th>
<th>Testing Challenge</th>
<th>Analysis Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components / Full-Scale</td>
<td>The greatest challenge at the full scale level is applying accurate loads. Overload factors are often used to account for statistical variability and environmental effects (if the test is performed at room temperature instead of worst-case conditions). These overload factors can affect behavior of any metallic components in the test. In some situations, two test articles may have to be built and tested to ensure all structure is adequately substantiated.</td>
<td>Validate predictions of structural load paths, stress concentrations in reinforcements for major cutouts, and secondary loads for the approach using analysis supported by test evidence. Final proof-of structure demonstrations of static strength, fatigue and damage tolerance.</td>
</tr>
</tbody>
</table>
Repair Challenges

• Repair challenges include:
  ➢ Few standard practices for repair designers or repair technicians
  ➢ Materials and processes different between manufacturers
  ➢ Repair technician training is not standardized
  ➢ Repair design extremely difficult without a knowledge of base structure materials, processes, and design philosophy
    – Reverse engineering techniques are not mature
  ➢ Repairs are performed in less controlled environments
Questions?
Part 3: Composite Certification

• Material and Process Control
  ➢ Manufacturing Implementation

• Static Strength Substantiation

• Fatigue and Damage Tolerance
  ➢ Categories of Damage

• Other Requirements
  ➢ Aeroelastic Stability
  ➢ Repair/Maintenance
  ➢ Crashworthiness
  ➢ Flammability and Thermal Management
  ➢ Lightning Protection
Overview

- AC 20-107B is the FAA’s most comprehensive guidance for certification of composite structures
  - Harmonized with EASA AMC 20-29
  - Relatively high-level
  - Attempts to address regulatory requirements utilizing a safety management philosophy
AC Table of Contents

1. Purpose
2. To Whom This AC Applies
3. Cancellation
4. Related Regulations & Guidance
5. General
6. Material and Fabrication Development
7. Proof of Structure – Static
8. Proof of Structure – Fatigue & Damage Tolerance
9. Proof of Structure – Flutter & Other Aeroelastic Instabilities
10. Continued Airworthiness
11. Additional Considerations

Appendix 1. Applicable Regulations & Relevant Guidance
Appendix 2. Definitions
Appendix 3. Change of Composite Material and/or Process

AC 20-107A 11 pages
AC 20-107B 37 pages
(new sections highlighted by blue)
Paragraph 6: Material and Fabrication Development

6a: Requirement for qualified materials & processes

- Promotes a need to demonstrate repeatable processes at sufficient scale as related to material and process control of product structural details
- Notes that regulatory bodies don’t certify materials and processes independent of aircraft product certification
- Material requirements need to be based on qualification test results
  - Environmental durability tests recommended for structural bonding
- Requirement to link material specs & process info with shared databases
- Includes content on equivalency sampling tests for new users of shared databases
Paragraph 6: Material and Fabrication Development

6b: Manufacturing Implementation

- Reference use of specifications and documentation to control materials, fabrication and assembly steps in the factory
- Control the environment and cleanliness of manufacturing facilities to levels validated by qualification and proof of structure testing
- Production tolerances should be validated in building block tests
- Highlight value of manufacturing records for allowed defects, rework and repair
- Content on “new suppliers for previously certified aircraft products”
Manufacturing Control

• Manufacturing control is a balance act
  - Level of control in the type design vs the level of details in the manufacturing system
  - Up-front control of material and processes vs post-production checks and inspections
  - Application criticality is always a factor
Example Quality Control Balance Act – Cure Cycle

Example of balancing type design control versus manufacturing control

• Situation – Engineering type design defines this oven cure cycle:
  ➢ Ramp to 270 ± 5°F at 1-3°F/minute
  ➢ Dwell at 270 ± 5°F for 60-120 minutes
  ➢ Cool to a minimum of 120°F at < 10°F/minute
  ➢ Maintain a minimum vacuum pressure of 22” Hg

• What does the cure cycle used in manufacturing look like?
Cure Cycle Variations

![Graph showing Cure Cycle Variations]

- Nominal Ramp
- Fast Ramp
- Slow Ramp
- Dwell Ramp

Temperature (F) vs. Time (minutes)
Example Quality Control Balance Act – Cure Cycle

- All of the cure cycles meet type design
- In this situation, the decision on which cure cycle to use is given to manufacturing
  - That’s technically acceptable, but make sure that’s what you intend to happen
  - Must ensure entire envelope is accounted for in certification, for all configurations, unless type design is narrowed down (perhaps on a part drawing)
Example Quality Control Balance Act - Inspections

Example of trading up-front controls for post-process controls

• Situation - Part manufacturer ABC has these controls in place:
  ➢ Supplier testing on each batch of material
  ➢ Repeats testing upon receipt of each batch of material
  ➢ Strict process control with in-process traveler coupons
  ➢ Performs 100% c-scan on each part

• Is this acceptable? (of course!)
• But what about this?...
Example Quality Control Balance Act - Inspections

• Situation - Part manufacturer XYZ has these controls in place:
  ➢ Minimal material definition – purchasing only to a material supplier part number
  ➢ No receiving inspection
  ➢ No in-process traveler coupons
  ➢ No NDI except visual and dimensional inspection
  ➢ However…..Make only one part number, with multiple parts at one time and they destructively test one part per lot

• Is this acceptable?
Example Quality Control Balance Act – Inspections

- The first example is the gold standard of composite quality assurance
- Is the second example acceptable?
  - Yes, it is
  - It trades up-front controls for post-process testing
Example Quality Control Balance Act – Inspections

How to reach an acceptable level of quality assurance?

- Post-Process Testing
- Post-Process Inspection
- In-Process Testing
- In-Process Control
- Receiving Inspection
- Supplier Control
Example Quality Control Balance Act – Additional Factor

All the above is good in theory…

H owever

• The additional factor is part criticality
Example Quality Control Balance Act – Additional Factor

• The more critical the part, the tighter the type design control
  ➢ Processing may not be effective at all corners of the envelope for complex parts
  ➢ May have insufficient structural margins with some processing parameters

• The more critical the part, the greater the level of up-front controls
  ➢ Example ABC was for fatigue critical structure
  ➢ Example XYZ was for a non-structural part
  ➢ Back-end controls are often insufficient to find all deficiencies that are prevented with up-front controls
Paragraph 6: Material and Fabrication Development

6c: Structural Bonding

- Not just secondary bonding
- Outlines the need for qualified materials and bond surface preparation for metal bonding and composite secondary bonding
- Guidelines for physical, chemical and mechanical qualification tests, including tests for evaluating proper adhesion (e.g., some form of peel test)
- Description of in-process control of critical bond processing steps
- An explanation of the intent of 14 CFR 23.573(a)(5) for damage tolerance substantiation of structure with bonded joints (explanation of the 3 options in addition to a well-qualified bonding process and rigorous QC)
- Thoughts on actions to be taken for adhesion failures found in service
Structural Bonding

Rule governing bonding
(adapted to parts 27, 25, 29 via AC 20-107B/AMC 20-29)

23.573(a)(5): ‘For any bonded joint, the failure of which would result in catastrophic loss of the aeroplane, 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) (i.e. critical limit flight loads considered ultimate) 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;

Note: Not to be used to address poor processing; poor process is unacceptable, ref. 2x.605
Structural Bonding

Rule governing bonding (continued)
(adapted to CS 27, 25, 29 via AC 20-107B/AMC 20-29)

or

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

Note: Not practical for large aircraft, does not address degradation

or

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

Note: ‘Weak Bonds’ and ‘Tight Disbonds’

• cannot be reliably detected by Visual Inspection
• have not been shown to be reliably detected by NDI at a production scale
Paragraph 6: Material and Fabrication Development

6d: Environmental Considerations

- Identify critical environmental exposures
- Generate material data at the environmental conditions
- Determine effects of environmental exposures on material and structural performance, including thermal stresses

6e: Protection of Structure

- Protect against deterioration of composite structures due to weathering, abrasion, erosion, UV radiation and chemical environments
- Protect against corrosion, especially galvanic corrosion
Paragraph 6: Material and Fabrication Development

6f: Design Values

- Design values must be derived from stable materials and processes
- Must be generated at the scale that best represents the material as it appears in the part, or by tests of material substructure

6g: Structural Details

- Point design value may be used to account for features such as holes and joints
- Metrics are required to quantify the severity of composite structural damage states caused by impacts (i.e., equivalent of a metallic crack length)
- Testing often needed to characterize residual strength
Material and Process Control

- **Material selection** will be made on a number of factors – a key one is operating environment
- Material must be stable at the maximum operating temperature (MOT) and not near the temperature where the material properties will degrade.
- **Options for DAH:**
  - Select a laminate material that has a glass transition temperature, $T_g$, that is 50ºF greater than the MOT.
    - Adhesives should be 30ºF greater than MOT
  - Perform series of tests at a range of temperatures near the MOT to show no degradation in strength or other parameters.
Material and Process Control

Initial Material Qualification (IMQ)

- All materials (prepreg, core, adhesive, etc.) and their constituents (fibers, resins, etc.) must be certified for use on civil aircraft products
- IMQ refers to developing base material properties
  - Material data must be statistically defined to generate design allowables
Material and Process Control

- IMQ data is also used for quality assurance purposes, and should include chemical, physical, and mechanical properties
- Data obtained during qualification is used to:
  - Demonstrate that properties meet final property requirements
  - Validate the material’s long term stability (multi-batch)
  - Allow purchase of material for “conformed” certification tests
  - Validate the use of material with fabrication processes
Material and Process Control

Material and Process Control: Stable Processes

• Having a stable manufacturing process is required to make the more complex testing relevant to the final product.

• For the building block approach to be viable the materials which form the base must be stable.
Material and Process Control

- Example of Controlled Materials

Representative of acceptance testing run chart showing data over time from numerous batches.
Material and Process Control

• Is This a Stable Material Property?

An example of material that “meets” specification minimum standard but could not be considered as being “controlled.”
Material and Process Control

Initial Material Qualification (IMQ)

• Materials are evaluated at maximum and minimum operating temperatures with ambient and high humidity conditions.

• Material properties are tied not only to a base material, but also to the process that is used to form and cure the resin.

  For example, a material processed at 250ºF with an oven cure will have statistically different properties than when it is processed at 350ºF in an autoclave.
Material and Process Control

Initial Material Qualification

- IMQ should consider exposure to different types of fluids, such as de-ice and hydraulic fluids
  - Typically done during the lowest levels of the test pyramid
- Process controls should ensure core materials are not exposed to fluids, including water
  - It is not uncommon to find that the most detrimental fluid for epoxy matrix materials is water
Material and Process Control

Equivalency

- Equivalency is used to demonstrate statistically equivalent design values for:
  - Minor material changes
  - Manufacturing facility changes
  - Minor processing changes

IMQ (Reduced Data Set)
Material and Process Control

Equivalency

- Major changes must be managed by investigation further up the pyramid –
  - May lead to new qualification (new allowables, new margins, different failure modes, etc.)
Material and Process Control

- **Quality system** requirements are the same whether manufacturing metallic or composite parts and assemblies.
  - Composite manufacturing generally requires a higher level of in-process inspections as product quality often cannot be checked after the fact.
  - Material suppliers generally require a high level of oversight
    - Few industry standards that materials can be produced to.

- **Production Approval Holder (PAH) quality system** is responsible for assuring supplier quality control.
  - PAH should have strict contractual arrangements with the materials supplier to ensure no changes are made to the material systems without notification.
  - DAH is responsible to approve any changes to base materials.
Material and Process Control

- **Material Specifications** control procurement of raw materials
- Defines chemical, physical and mechanical properties
Material and Process Control

• Process specifications control manufacturing procedures, operator qualification, and inspection requirements

1.0 Scope
2.0 Applicable Documents
3.0 Requirements
3.1 Personnel
3.2 Required Materials
3.3 Required Equipment
3.4 Facilities
3.5 Tooling
3.6 Required Procedures
4.0 Quality Assurance
4.1 Responsibility for Inspection
4.2 Inspection
4.3 Documentation
4.4 Test Methods
5.0 Notes
Manufacturing Process

• All composite production follows similar steps, regardless of material or process

• Critical process steps:
  ➢ Raw Material Manufacture
  ➢ Transport, Incoming QC and Storage
  ➢ Tool Prep, Cutting, Layup, and Bagging
  ➢ Cure and Solidification
  ➢ Trim and Drill
  ➢ Inspection
  ➢ Bonding and Part Assembly
  ➢ Paint and Finish
  ➢ Handling and Storage
  ➢ Defect Disposition
Raw Material Manufacture:

- Drawings identify materials and processes in sufficient detail.
- Supplier/user relationships must be established and maintained
  - Qualification testing of key properties to develop statistical population
  - Continuous quality testing to sample materials over time

Manufacturing Process

Fiberglass  Aramid  Carbon

Hot Melt process for pre-impregnation of unidirectional tape

With Resin

Graphite tow collimation  Heat source  Squeeze rolls
Resin-coated paper
Tape prepreg
Normally 3-in (76mm) or 12-in (304mm) wide
Manufacturing Process

Transport, Incoming QC, Storage:

- Raw materials, particularly prepregs, some resins and some adhesives, require cold transport and storage
- Materials must be kept at low temperatures to prevent premature advancement of cure (hardening)
- Many of these materials also have defined shelf lives
- Using expired or improperly stored and handled material can adversely affect the quality and ease of manufacture of the final part
- Cores may require drying prior to use
Manufacturing Process

Tool Prep, Cutting, Layup, Bagging:

- Tool design must be defined in a way acceptable to the FAA, such as:
  - CAD drawings,
  - Data sets (such as 3D solid models)
  - Based on a master tool /mold

- Tool quality must be monitored and evaluated for damage and wear
Manufacturing Process

Tool Prep, Cutting, Layup, Bagging:

- Bagging materials, including consumable materials, should be defined and have minimum controls.
- Pinholes or other damage in bagging material compromise pressure application on the part and can lead to excess voids, gaps and porosity in the final part.
- Vacuum, once established, should be monitored for leaks.
Manufacturing Process

- Monitor equipment gages, thermocouples and other sensors to check parts during cure
  - Heating and cooling rates
  - Temperature plateaus
  - Exothermal reactions
  - Time and magnitude of pressure and vacuum
  - Time and temperature of cures
- Maintain manufacturing work orders and buy-off records of materials and processes details for each part
- Logbooks to record changes and repairs to cure tools
Manufacturing Process

Trim and Drill:

• High wear ratio on special cutting and drilling tools
  ➢ Manufacturing defects are more common as tools begin to dull

• Special procedures and training for each particular part
  ➢ Dependent on specific fiber/matrix combination (types and volume fractions), fiber orientations and part thickness
Manufacturing Process

Trim and Drill:

• Dust and coolants can cause machine maintenance, health, contamination and part liquid ingression problems

• Common source of local manufacturing defects
  ➢ Many factory dispositions for hand-drilled holes
  ➢ Engineering practices needed to cover delamination, fiber pullout, fiber reorientation, matrix chipping and matrix thermal degradation
Manufacturing Process

Inspection:

• Performed throughout the manufacturing process, but all parts must typically be inspected after trim and drill for:
  ➢ Dimensional fidelity, including warpage
  ➢ Inclusions, defects, delaminations, etc.

• Several composite part NDI techniques exist:
  ➢ Visual inspection
  ➢ Tap testing
  ➢ Ultrasound, etc.
When to Perform Inspections?

• In general, include an inspection prior to any process step that will make the earlier work uninspectable

• Examples:
  - Prior to cure
    - Check number and orientation of plies
  - Prior to close-out
    - Check internal features
    - Check bondline thickness
Manufacturing Process

Inspection:

- NDI pass/fail criteria is unique to each piece of equipment, equipment setting and part being inspected
  - Requires unique calibration standards
Manufacturing Processes

Inspections

- Not all NDI techniques can be used for all defects and damages

<table>
<thead>
<tr>
<th>Method</th>
<th>Structure</th>
<th>Damage Detected</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>All</td>
<td>Surface Damage</td>
<td>Good</td>
</tr>
<tr>
<td>Tap Test</td>
<td>Thin Laminate</td>
<td>Delaminations</td>
<td>Good</td>
</tr>
<tr>
<td>Ultrasonic / Pulse Echo</td>
<td>All</td>
<td>Delaminations/Disbonds</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Sandwich</td>
<td>Core: Crushed/Damaged/Water Impregnated</td>
<td>Poor</td>
</tr>
<tr>
<td>Shearography</td>
<td>All</td>
<td>Disbonds/ Delaminations</td>
<td>Good</td>
</tr>
<tr>
<td>Thermography</td>
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<td>Disbonds/ Delaminations</td>
<td>Good</td>
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<tr>
<td></td>
<td>Sandwich</td>
<td>Water Impregnated Core</td>
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<tr>
<td>Radiography</td>
<td>All</td>
<td>Disbonds/ Delaminations</td>
<td>Poor</td>
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<tr>
<td></td>
<td>Sandwich</td>
<td>Node Separation</td>
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</tr>
<tr>
<td></td>
<td>Sandwich</td>
<td>Crushed Core</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Sandwich</td>
<td>Water Impregnated Core</td>
<td>Good</td>
</tr>
</tbody>
</table>
Manufacturing Process

Inspections:

• **Traveler coupons**
  - Made with the same materials and in the same process as the part they represent
  - Various lab scale tests can then be performed to check the quality of the coupon
  - Care must be taken so that the traveler coupons do indeed represent the actual part
  - In some cases, samples may be cut from an extension of the part (prolong)

• **A part may be destructively tested to demonstrate quality for a group of parts that were produced at the same time**
Manufacturing Process

Bonding and Part Assembly:

- Bonded assembly steps *must carefully follow specs and drawings*
  - Environment and surface condition of pre-cured and uncured parts must be controlled prior to bonding to avoid pre-bond moisture and contamination
  - Tool proofing and pre-bond assembly checks (gap and shimming limits)
- Light grit blasting or thorough mechanical abrasion are proven bonded surface preparations for composite substrates
Manufacturing Process

Bonding and Part Assembly:

- Issues associated with removable surface plies require special attention
  - Use of release fabric (with or without surface abrasion) should be avoided
  - Some manufacturers have been able to successfully bond without surface prep after removal of some peel plies (problems in controlling peel ply also noted)
- **Must have strict bonding process controls in place**
  - No reliable NDI procedures to detect “weak bonds” in production
Manufacturing Process

Mechanical Fastening:

• Bolted assembly steps must follow specifications and drawings
  ➢ Special tools for drilling
  ➢ Machine hole tolerances to closely match fastener size
  ➢ Control fastener hole spacing

• Ordinary fasteners are not designed to protect laminated composites against delaminations, crushing or pull-through
  ➢ Carbon-reinforced materials require special fasteners (e.g., titanium lock bolts)
Manufacturing Process

Paint and Finish:

• Finishing techniques (including surfacing films applied during layup) must be tested and qualified.
• Monitor product shelf life to ensure expired materials are not used.
• Finishing processes are critical to prevent UV damage, and can be critical for lightning protection.
• Common surface imperfections are pinholes (caused by off gassing) and print through (from core materials and tool imperfections).
Handling and Storage:

- Procedures and preventative measures must be in place to avoid damage during handling and storage of cured composite parts.
- Internal damage from an impact during handling or storage may not be visible on the surface.
- Skins should not be moved or handled without appropriate protection, such as fixtures.
- Use and monitor appropriate environmental conditions for storage (moisture content, temperature, UV protection, etc.).
Manufacturing Process

• As part are inspected, flaws and damages will be recorded

• All composite parts have some level of flaws inherent in their manufacture (e.g., porosity)
  ➢ The more complex the part or structure, the greater the likelihood of additional manufacturing flaws, such as wrinkling or bridging
Manufacturing Process

• **Not all flaws and damages are defects.**
  - The term “defect” implies that the part or assembly is unacceptable.
  - Flaws and damages only truly become a defect once the part or assembly is in a condition where it cannot meet its performance requirements (typically a strength or stiffness requirement)

• **If the flaw or damage is outside the allowable limits, then the part is dispositioned (i.e., use-as-is, repair, rework, scrap)**
Questions
Paragraph 7: Proof of Structure - Static

*Introduces damage tolerance* – effects of non-detectable defects, allowed defects, and service damage

7a: Effects of repeated loading and environmental exposure that can reduce material properties should be addressed during static strength evaluations. Three options given:

1. Cycle test article, condition for environment, test statically
2. Use coupon, element and subcomponent test data to characterize effects of repeated loading and environmental exposure. Account for the degradation in static strength test (via overload) or in analysis (showing positive margin of safety with reduced design values)
3. Combine the first two options, such as by applying an overload to account for humidity while testing at elevated temperature
Paragraph 7: Proof of Structure - Static

7b: Building block approach is explained
   - At a minimum, the bottom and top levels are required for regulatory compliance

7c: Environment must be accounted for (see 7a)
7d: Test articles must be representative of production processes, with representative defects
7e: Material and process variability must be accounted for
   - May apply test overload factors to account for the requirement to substantiate a “worst-case” material (i.e. A- or B-basis, while assuming the test article is actually nominal)
   - May substantiate by validated analysis showing positive margins of safety
Paragraph 7: Proof of Structure - Static

7f: Likely manufacturing and service damage up to the level of detectability must be assumed and substantiated to ultimate load

- Include manufacturing defects and service impacts
- May substantiate through intentional damage in the test article
- May substantiate by validated analysis

7g: Changes to material and processes must be substantiated (reference Appendix 3)

- See also the discussion of equivalence earlier
Static Strength Substantiation

• Base material properties are important to quantifying variability, environmental effects and moduli, but have limited use in predicting static strength

• Analysis and test iterations between the various levels of study should be anticipated in developing a complete substantiation of static strength
  ➢ All details, which cause local stress concentration, should be understood to avoid premature failures in component tests
“Canned” Software

• Validating software tools for structural analysis is not as simple as plugging lamina material properties into a commercially available program
  ➢ Validation must be on more than a “book case” level

• One challenge is that stress concentration factors are not consistent for composites the way they are for metals
  ➢ Each hole, notch or other figure will have a different stress concentration factor based on material, process and design features (i.e., layup)

• Once validated, interpolation is allowed but extrapolation is not
Static Strength Substantiation

• Static structural strength must be shown for critical load cases
  ➢ Effects of the environment, repeated loading, manufacturing tolerances, and material and process variability

• Building block tests and analysis should be used at the coupon, element and sub-component levels to address variability, environment, structural discontinuities, damage, and manufacturing defects

• Substantiation must consider:
  ➢ Manufacturing defects
  ➢ Service damage in the most highly strained areas
  ➢ Repairs
  ➢ Time-related degradation mechanisms
Static Strength Substantiation

Two options for Static Strength Substantiation

1. Substantiation by *Analysis Supported by Test*

2. Substantiation by *Test*
Static Strength Substantiation

Analysis Supported by Test:

• If static strength is substantiated through analysis supported by test, Design Values must be selected:
  - At the worst-case environmental conditions,
  - At the appropriate statistical reliability, and
  - With expected damage

• All analyses must be validated
  - Match strains
  - Predict failure modes
Static Strength Substantiation

Substantiation by Test:

• When substantiating through test, static testing will likely:
  
  ➢ Include an overload factor to account for environmental effects of temperature and humidity (unless test is performed at those conditions)

  **AND**

  ➢ Include an overload factor to account for material and process variability

• Do not combine composite overload factors with metallic overload factors (e.g. fitting factors)
Static Strength Substantiation

• When substantiating by test, Overload Factors need to be determined for each material system and failure mode
  - Overload factors are not the same as the load enhancement factor used to demonstrate reliability in fatigue and damage tolerance testing
• Overload factors may conservatively be determined from lamina properties as follows:
  - Statistical Overload = Mean / A- or B-Basis Strength
  - Environmental Overload = Mean RTD / Mean Strength at worst-case environmental condition
  - Combined Overload = Mean RTD / A- or B-Basis Strength at worst-case environmental condition
Environmental and Aging Effects

• Commonly stated that “composites don’t age”
  - True that they do not corrode or show crack growth mechanisms as metals do, however…
  - Composites may have aging mechanisms we do not yet understand

• Current practice is to remain in a design space where environmental effects are shown to not occur
  - Fleet leader programs are highly recommended to monitor the effects of time in service
Questions?
Paragraph 8: Proof of Structure - Fatigue and Damage Tolerance

8a. Damage Tolerance Evaluation
1) Damage threat assessment
2) Structural tests for damage growth
3) Extent of initially detectable damage
4) Extent of damage/residual strength
5) Repeated load testing
6) Inspection program
7) Discrete source damage
8) Environmental effects

8b. Fatigue Evaluation

8c. Combined Damage Tolerance and Fatigue Evaluation
Paragraph 8: Proof of Structure - Fatigue and Damage Tolerance

- Fatigue and damage tolerance regulations differ, but...

  all require an evaluation to show catastrophic failure due to fatigue, environmental effects, manufacturing defects or accidental damage will be avoided throughout the operational life of the aircraft

  ➢ Part 25, in particular is metal-centric (ARAC in process to rewrite rule and/or guidance)
Paragraph 8: Proof of Structure - Fatigue and Damage Tolerance

8a: Damage Tolerance Evaluation begins with a **Damage Threat Assessment**

- Five categories of damage defined

![Diagram showing the Damage Threat Assessment process with categories 1 to 5 defined.](Image)
## Categories of Damage

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category 1</strong>: Allowable damage that may go undetected by scheduled or directed field inspection (or allowable mfg defects)</td>
<td>Barely visible impact damage (BVID), scratches, gouges, minor environmental damage, and allowable mfg. defects that retain ultimate load for life</td>
</tr>
<tr>
<td><strong>Category 2</strong>: Damage detected by scheduled or directed field inspection @ specified intervals</td>
<td>VID (ranging small to large), deep gouges, mfg. defects/mistakes, major local heat or environmental degradation that retain limit load until found</td>
</tr>
<tr>
<td><strong>Category 3</strong>: Obvious damage detected within a few flights by operations focal</td>
<td>Damage obvious to operations in a “walk-around” inspection or due to loss of form/fit/function that must retain limit load until found by operations</td>
</tr>
<tr>
<td><strong>Category 4</strong>: Discrete source damage known by pilot to limit flight maneuvers</td>
<td>Damage in flight from events that are obvious to pilot (rotor burst, bird-strike, lightning, exploding gear tires, severe in-flight hail)</td>
</tr>
<tr>
<td><strong>Category 5</strong>: Severe damage created by anomalous ground or flight events</td>
<td>Damage occurring due to rare service events or to an extent beyond that considered in design, which must be reported by operations for immediate action</td>
</tr>
</tbody>
</table>
Relationships Between Categories of Damage for Impacts

- **Category 1**: More common “small damage”, which could be covered by standards (e.g., impactor size/shape, energy cutoffs) if the same limits are *not* maintained in moving to Categories 2 and 5.

- **Category 2**: Less common, “more significant damage.” Impact standards generally don’t exist for this damage.

- **Category 3**: Uncommon, large damage that ensures the damage tolerance of the structure without getting into a significant experimental effort on the effects of impactor variables & accidental damage detection.

- **Category 4**: Defined by regulatory event and area of the damage threat

- **Category 5**: Everything else.
Categories of Damage

**Category 1:** Allowable damage that may go undetected by scheduled or directed field inspection (or allowable manufacturing defects)

**Category 2:** Damage detected by scheduled or directed field inspection at specified intervals (repair scenario)

**Exterior Skin Damage**

- **Ultimate Limit**
  - ~ Maximum load per lifetime

**Interior Blade stringer Damage**

- **1.5 Factor of Safety**
  - Code: FOS

**X-sec of BVID at Skin Impact Site**

**X-sec of BVID Impact at Flange to Skin Transition**

**Continued safe flight Limit**

### Categories of Damage

- **Category 1:** Allowable damage that may go undetected by scheduled or directed field inspection (or allowable manufacturing defects)

- **Category 2:** Damage detected by scheduled or directed field inspection at specified intervals (repair scenario)

- **Ultimate Limit**
  - ~ Maximum load per lifetime

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- **Continued safe flight Limit**

**Exterior Skin Damage**

- **X-sec of BVID at Skin Impact Site**

- **X-sec of BVID Impact at Flange to Skin Transition**

**Interior Blade stringer Damage**

- **Allowable Damage Limit** (ADL)
- **Critical Damage Threshold** (CDT)

**Increasing Damage Severity**

Composite Certification Tutorial
August 21, 2017
Categories of Damage

**Category 3:** Obvious damage detected within a few flights by operations focal (repair scenario)

**Category 4:** Discrete source damage known by pilot to limit flight maneuvers (repair scenario)

**Accidental Damage to Lower Fuselage**

**Lost Bonded Repair Patch**

**Rotor Disk Cut Through the Aircraft Fuselage Belly and Wing Center Section to Reach Opposite Engine**

**Severe Rudder Lightning Damage**
Categories of Damage

**Category 5**: Severe damage created by anomalous ground or flight events *(repair scenario)*

- **Birdstrike (flock)**
- **Birdstrike (big bird)**
- **Maintenance Jacking Incident**
- **Propeller Mishap**
Categories of Damage Support
F&DT Compliance

AC 20-107B 8a. Damage Tolerance Evaluation
(2) Structural tests for damage growth

- Figures from 8a. (2)
Complexities of Foreign Object Impact

Factors critical to type and extent of damage, as well as its detectability. Note there were many interactions, which were as important as the main effects.

Impact Design Experiment Results

Environmental & Accidental Damage

Damage Threat Assessment

• Not easily derived for new composite structure
  ➢ Metal has relied on service experience
  ➢ Selection of impact damage locations difficult when following a “certification by test approach”
    - Seek areas of bonded structure attachment and termination
    - Rely on results from “impact surveys” to determine most critical (least detectable, most severe)
  ➢ Conservative engineering judgment, fail-safety and large damage assumptions help overcome lack of service experience
Factors Affecting Placement of Damage Threats in Categories

• Design requirements, objectives and criteria

• Structural design capability
  ➢ Impact damage resistance
  ➢ Detectability of different damage threats
  ➢ Residual strength
  ➢ Damage growth characteristics

• Inspection methods
  ➢ Visual detection methods ➜ generally larger damage sizes
  ➢ NDI ➜ needed if Category 2 damage can’t be visually detected

• Other considerations: service experience, costs, customer satisfaction and workforce training
Factors Affecting Placement of Damage Threats in Categories

Foreign-Object Impact is Complex

1 in. dia. impactor

3 in. dia. impactor

Some NDI may be needed to place damage at the left into Category 2
Other Factors Affecting Placement of Damage Threats in Categories

Caution!: – Potential Damage Mode Change

It is tempting to show ‘no-damage growth’ with higher impact energy visible damage ‘A’, when lower impact energy invisible damage ‘B’ is potentially less conservative*!

- similar arguments regarding impactor:
  - radii (larger radius, blunter impact)
  - materials (softer iced cotton ball v metallic)

* similar concept applies to other damage threats
Other Factors Affecting Placement of Damage Threats in Categories

**Caution!**: – Competing Failure Modes – e.g. Hole versus Delamination

**Do not** test only at highest energy level which might make a hole. **Do** create a full range of impact energies and test the worst case for each failure mode.
Category 1 Damage

- Allowable damage
- Small and difficult to detect
- May go undetected
- Ultimate load capability is maintained
- Good for lifetime of airframe
- Examples include: BVID, small delaminations, porosity, small scratches, small gouges, allowable defects

X-sec of BVID at Skin Impact Site

X-sec of BVID Impact at Flange to Skin Transition
Category 1 Damage

- One example of acceptable Category 1 damage definition without POD studies
Category 2 Damage

- Small damage
- Detectable via scheduled or directed inspection
- Capability between Limit & Ultimate
- Needs to be repaired when found
- Examples include VID, deep gouges, deep scratches, small delamination.

Exterior Skin Damage

Interior Blade stringer Damage
Category 2 Damage

• Insufficient to simply apply 137 joules and because it is “over Category 1”
  ➢ Include realistic impacts (diameter, energy)
• Must consider range of impacts – a hole punched through a skin is not necessarily the worst case
• Cycle for 2x inspection interval and demonstrate limit load residual strength
• One example of acceptable Category 2 damage definition:

Impact damage with over 1mm dent or 1” dia. hole is defined as Category 2 Damage Criteria.
Category 3 Damage

- Visible damage
- Detected within a few flights
- Capability is near limit load
- Needs to be detected quickly and immediately repaired
- Examples include large VID and other obvious damage that will be caught during walk around

Accidental Damage to Lower Fuselage

Lost Bonded Repair Patch
Category 3 Damage

- Often the most difficult Category to define
- Stiffness-driven structure can be subjected to very large damages and still show limit load capability
- Does not need to be cycled; can be demonstrated during static testing
- Not always readily apparent where worst-case impact location is
- Look for flat part of residual strength curve
Category 3 Damage

- May not find any correlation between impact diameter and damage size (damage may extend to arrestment feature, regardless of impactor size)

Three damage configurations are assumed based on structure configuration and impact survey data conservatively for residual strength assessment. “D” and “W” are parameters in residual strength analysis.
Large Damage Capability/Residual Strength Curve Shape

- General response for uniaxial loading of a notch severing a central stiffener
  - Damage growth in the skin
  - Arrest at intact stiffener
  - Failure of stiffener and/or skin/stiffener attachment
  - Unstable damage growth in the skin

The uncertainties of impactor variables versus the visual detectability of relatively small impact threats like Category 1 (e.g., BVID) and small Category 2 damage can effectively be balanced by “large damage capability” such as Category 3 damage.

Tom Walker, CMH-17, Damage Tolerance TG Mtg., SLC, UT (March, 2015)
Category 4 Damage

- Discrete Source damage
- Bounded design criteria
- Capability near Limit (specified “get home” loads)
- Examples include rotor burst, design bird strikes, exploding MLG or NLG tires, sever in flight hail

Severe Rudder
Lightning Damage

Rotor Disk Cut Through the Aircraft Fuselage Belly and Wing Center Section to Reach Opposite Engine
Category 5 Damage

- Severe damage
- Unbounded “Rare Event”
- Capability may be below limit load
- Beyond design considerations

E.g. severe collisions with service vehicles, flight overload conditions, severe impacts with very large birds or flocks of birds.
Our Tenth Anniversary Year Studying a Key Area
HEWABI = High Energy Wide Area Blunt Impact

According to comments on Flightaware:

Occurred March 23 2014, UPS Boeing 757-200 (N462UP) on Spot 90 at the Miami International Airport Repaired by AAR Aircraft Services Miami, and returned to flight status on April 13.

The truck belongs to a catering company. It was being driven by a female who was not supposed to be driving, hence the reason they jumped out and switched really quick. The passenger told security he was the driver, but once they reviewed this footage they saw he clearly wasn't. They were both fired.
Category 5: HEWABI

UCSD
FAA/JAMS

Frame03 - Load 2
Dynamic Test

March 6, 2012
Stroke: 222 mm at 0.5 m/s
Category 5: HEWABI

*Major Damage Produced with No Obvious Exterior Visibility*
Damage Category / DT Means of Compliance

• **Step 1 – Threat Assessment**
  ➢ Define relevant energies, locations and impactor geometries from real service environment

• **Step 2 – Impact Survey**
  ➢ How much damage is caused by the defined impacts? How visible is it?

• **Step 3 – Conservative Determination**
  ➢ Put the damages into the appropriate categories
Paragraph 8: Proof of Structure - Fatigue and Damage Tolerance

8b: Fatigue evaluation required (in addition to damage tolerance)
- Account for environmental effects
- Include acceptable manufacturing and service damage
- Demonstrate that stiffness properties have not changed beyond acceptable levels, and set replacement lives accordingly

8c: Combined Fatigue & Damage Tolerance
- Need to establish both an inspection interval and service life for critical composite structure
- Implies that there will be a limit to service life (similar to metals)
Importance of Linking Damage Tolerance and Maintenance

• One of the main purposes for damage tolerance is to facilitate safe & practical maintenance procedures.

• Findings from the field help improve damage tolerance and maintenance practices in time.

  ➢ Structural safety, damage threat assessments, design criteria, inspection protocol, documented repairs and approved data all benefit from good communications between OEM, operations and maintenance personnel.

• Structural substantiation of damage tolerance, inspection and repair should be integrated.
Outcome of Fatigue and Damage Tolerance Compliance...

Reliable demonstration of inspection interval for detectable damage and replacement time for non-detectable damage
Spectrum Development Overview

- **Usage Definition (aircraft missions)**
  - Anticipated loads and environments
- **Global spectra**
- **Selection of critical locations**
  - Analysis of principal structural elements (PSE)
- **Damage definition(s) and source(s)**
- **Develop load spectra for each PSE**
  - Test load cases for analysis and test that adequately represent service loads
Exceedance Curves

- Flight/taxi test data are converted to exceedance curves for different events.
- Exceedance curves are then converted into load spectra.
- Spectrum (sequence) is developed.
- Analysis spectrum is then modified for cyclic test:
  - Truncation & clipping high loads to avoid retardation/plasticity.
  - Life factor to account for uncertainties in usage.
  - Load-enhancement factor to reduce test duration for composites.
Cycles for Fatigue Testing

“. . . Should be statistically significant, and may be determined by load and/or life considerations”

AC 20-107A, Composite Aircraft Structure, Sec. 7(a)(2)

- 90% probability / 95% confidence (B-basis) level generally acceptable (unless single load path)
- Adjust number of fatigue cycles using load enhancement factor to minimize duration of fatigue testing
- AC 20-107B expands these thoughts to ensure the relevance of load and/or life factors to specific structural detail (material/process & design features)
Life Factor Approach

Structure is tested for additional fatigue life to achieve the desired level of reliability

- Life Scatter Factor (LSF)

\[ N_F = \frac{\Gamma \left( \frac{\alpha_F + 1}{\alpha_L} \right)}{\alpha_L} \left\{ -\ln(R) \left\lfloor \frac{\chi^2(2n)}{2n} \right\rfloor \right\}^{\frac{1}{\alpha_L}} \]

<table>
<thead>
<tr>
<th></th>
<th>n = 1</th>
<th>n = 5</th>
<th>n = 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites Alpha = 1.25</td>
<td>13.558</td>
<td>9.143</td>
<td>7.625</td>
</tr>
<tr>
<td>Metals Alpha = 4.0</td>
<td>2.093</td>
<td>1.851</td>
<td>1.749</td>
</tr>
</tbody>
</table>

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Load-Life Enhancement Factor Approach

Increase applied loads in fatigue tests so that the same level of reliability can be achieved with a shorter test duration

- **Combined load-life approach**
  Whitehead, et. al (NAVY/FAA research for F-18 certification)

- **Load Enhancement Factor (LEF)**

\[
LEF(N) = \frac{1}{\alpha_L \gamma_{\alpha_X}} \left[ \Gamma\left( \frac{\alpha_L + 1}{\alpha_L} \right) \right]^{\frac{\alpha_L}{\alpha_X}} \frac{1}{\alpha_L} \left[ -\ln(R) \cdot N^{\alpha_L} \right]^{\frac{1}{2}} \sqrt{\chi^2(2n)} \right]
\]

\[
LEF(N) = \left( \frac{N_F}{N} \right)^{\frac{\alpha_L}{\alpha_X}}
\]

LEF is a function of the test duration
LEF Curves

Strength Shape Parameter: $\alpha_R = 20$
Life Shape Parameter: $\alpha_L = 1.25$

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>One Lifetime Test</th>
<th>1.5 Lifetime Test</th>
<th>Two Lifetime Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-Basis</td>
<td>B-Basis</td>
<td>A-Basis</td>
</tr>
<tr>
<td>1</td>
<td>1.324</td>
<td>1.177</td>
<td>1.291</td>
</tr>
<tr>
<td>2</td>
<td>1.308</td>
<td>1.163</td>
<td>1.276</td>
</tr>
<tr>
<td>5</td>
<td>1.291</td>
<td>1.148</td>
<td>1.259</td>
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<tr>
<td>10</td>
<td>1.282</td>
<td>1.140</td>
<td>1.250</td>
</tr>
<tr>
<td>15</td>
<td>1.277</td>
<td>1.135</td>
<td>1.245</td>
</tr>
<tr>
<td>30</td>
<td>1.270</td>
<td>1.130</td>
<td>1.239</td>
</tr>
</tbody>
</table>
Selection of shape parameters from a single SN curve is not a practical method of deriving LEFs and/or $N_F$ for a particular structure.

- LEF (NAVY-Whitehead) approach links strength and life scatter and provides a LEF as a function of test duration. Engineering judgment is subjective $\Rightarrow$ select modal value (Weibull distribution)

Use of modal strength and shape parameters from representative design details produce a single LEF curve for a given structure.
Effects of Damage on $\alpha$

- **Damage Tolerance Element Tests**
  - Data scatter associated with final failure is conservative or representative of scatter at onset of damage propagation
  - Fatigue data scatter reduced as the damage severity is increased.
Spectrum Truncation & Clipping

- Differences between composite and metallic spectrums
  - Metals: severe flight loads result in crack-growth retardation ➔ Clipping
  - Composites: severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life
  - Flaw growth threshold for metals may be lower load level than that for composites and critical stress ratios are different ➔ Different Truncation Levels
LEFs for Complex Structure

- Modern aircraft structures are generally composite-metal hybrid structures
- Significant differences in damage growth mechanics and load spectra for composite and metal structure make the certification of composite-metal hybrid structures challenging, costly and time consuming.
- Application of LEF to hybrid structure must not adversely affect the damage growth mechanics, i.e., retardation on metal
  - Composite damage growth mechanics are influenced by high loads, while low-loads can be truncated based on endurance limit.
  - Conversely, the metal damage accumulation is influenced by low loads, while high loads must be truncated to prevent crack growth retardation and plastic deformation
Hybrid (Load-Life) Approach for Hybrid (Composite-Metal) Structures

(1) Load Factor

(2) Combined Load-Life (LEF) Approach

Clipping Level for Metal

Typical LEF Application

(3) LEF Hybrid (LEF-H) Approach

Repeated for required N

FAA-Sponsored Research Ongoing in this Subject
Widespread Fatigue Damage

Widespread Fatigue Damage (WFD):

- Characterized by cracks originating at multiple locations of sufficient size and density that the structure no longer maintains its required residual strength
- Crack interaction
- Damage tolerance analysis from a single or dual crack origins is not sufficient to preclude WFD
- Separate WFD assessment and determination of specific maintenance actions is necessary
- Operation should not be allowed beyond a certain point in the life of the airframe, known as the Limit of Validity (LoV) of the structural maintenance program.
Widespread Fatigue Damage

WFD: Limit of Validity (LOV) of Maintenance Program and Evaluation of Widespread Fatigue

Evidence suggests:

- Some structures experience multiple simultaneous cracks
  - Multi Element Damage (MED)
  - Multi Site Damage (MSD)
- Crack interaction (invalidates predictions and large damage capability (LDC))
- May not be addressed by existing inspection programs
- Composites are not “WFD Susceptible Structure” due to due to lack of fatigue crack formation and growth mechanisms that simultaneously occur at multiple locations
Widespread Fatigue Damage

Multiple Element Damage (MED): A source of widespread fatigue damage characterised by the simultaneous presence of fatigue cracks in similar adjacent elements

Examples of MED
- Frames: at stress concentrations, such as stringer cut-out at successive longitudinal locations
- Tear straps: critical fastener row in skin at tear strap joint
Widespread Fatigue Damage

Multiple Site Damage (MSD): A source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural element

Examples of MSD:
- Lap joints (outer skin upper rivet row, inner skin lower rivet row)
- Butt joints (skin outer rivet row, doubler inner rivet row)
- Lap joints with inner radius (inner radius)
Means of Compliance

**F&DT Substantiation Options**

- **Flaw tolerance/safe life**
  
  Demonstrate ultimate load capability after fatigue life
  
  – For selected damage (Category 1) and/or structure not requiring inspection

**Outcome:** reliable demonstration of replacement time
Means of Compliance

F&DT Substantiation Options, cont.

• Damage tolerance options
  1. **No-growth**: inspection interval dependent on arrested damage size
  2. **Slow growth**: similar to metal fracture mechanics in application
  3. **Arrested growth**: inspection interval dependent on arrested damage size

**Outcome**: reliable demonstration of *inspection intervals*
No-Growth Approach

• **Damage shown to NOT grow** for a satisfactorily significant number of cycles

• For defects that are below the detectability threshold of field inspection techniques
  - Structure must withstand repeated loads without detrimental damage growth for the design lifetime
  - Load and life factors are typically used to address statistical requirements

• For detectable large damages
  - Reliable demonstration of damage containment for several inspection intervals assuming that an inspection would be missed
  - Probability of detection may be studied
Slow-Growth Approach

- Slow, stable, and predictable damage growth within inspection intervals
- For defects that are below the detectability threshold of field inspection techniques
  - Inspection intervals and method of inspections must be established to ensure that the damage is found as soon as it becomes detectable
  - Damage is detected with a high probability before the residual strength drops below critical threshold (generally, limit load)
- Once the damage is detected, the structure is repaired to restore ultimate strength or replaced
Arrested-Growth Approach

- Damage growth is mechanically arrested or terminated before the residual strength drops below the critical threshold (generally, limit load)
  - Damage growth must be slow, stable, and predictable so that the inspection interval can be defined
  - Require statistically significant test demonstration to ensure that the residual strength of the structure is above the critical threshold, including environmental effects
  - Damage growth must be readily detectable
  - For cases where residual strength reduction closer to the limit load, rigorous (shorter) inspection intervals are required
Synopsis of Time-Related Composite Degradation Mechanisms

- Moisture absorption, which occurs over time, combines with high temperature exposure to significantly reduce matrix-dominated strength (e.g., compression)
- Composite materials generally have very good resistance to repeated loading
- Environmental conditions and loads, which result in systematic matrix failure should be understood
  - Best dealt with through material selection and limits on design stress levels, rather than developing a database for the effects on strength, stiffness and function of the part
Time-Related Material Degradation

Property Changes

Residual strength

- Stiffness loss
- Dimensional stability
- Physical property changes
- Matrix damage accumulation

Nonlinear material behavior

- Moisture residual stress (swelling)
- Moisture absorption
- Moisture desorption

Time Dependent Stress Relaxation

- Ultraviolet exposure

Hygro, Thermal & mechanical fatigue

- Static and dynamic structural loads
- Temperature and moisture dependent pressure gradients in thin-gage laminate honeycomb sandwich panel designs

Thermal residual stress (shrinkage)

- Moisture residual stress (swelling)

Surface Phenomena

1) Diffusion rate
2) Finish integrity
3) Part location
4) Environmental history

Solvent resistance

Thermal Aging

- Static and dynamic structural loads
- Temperature and moisture dependent pressure gradients in thin-gage laminate honeycomb sandwich panel designs

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Inspection Intervals

- Regarding the duration of damage between Ultimate and Limit Loads, AC 20-107B paragraph 8(a)(6)(a) (EASA AMC similar) states:

  ‘For the case of the no-growth concept, inspection intervals should be established as part of the maintenance program. In selecting such intervals, the residual strength associated with the assumed damages should be considered’

- The larger the strength reduction, the sooner the damage should be detected (probabilities could be considered – if substantiated)

- No crack growth data available to define inspection (unlike metallic structure), therefore consider probabilities
Composite Fatigue & Damage Tolerance Evaluations

- *Lost Ultimate load capability should be rare* (with safety covered by damage tolerance & practical maintenance methods)

- Fatigue evaluations to ID damage scenarios and demo life

- Damage tolerance evaluations to show sufficient residual strength for damage threats (accidental, fatigue, environmental and discrete source)

- Both fatigue & damage tolerance evaluations support maintenance (e.g., inspection intervals and replacement times)
Questions?
Other Requirements

- Flutter and Other Aeroelastic Instabilities
- Defect Inspection and Repair Competency
- Crashworthiness
- Fire Protection, Flammability and Thermal Issues
- Lightning Protection
Paragraph 9: Proof of Structure – Flutter and Other Aeroelastic Instabilities

- Aeroelastic stability evaluations must consider the effects of service damage on critical properties such as stiffness, mass, and damping
  - One critical example: sandwich panel disbond and/or water ingestion
  - Control surfaces and large secondary structures (e.g., antennas) are especially susceptible to developing instabilities due to stiffness loss or mass increase
    - These structures are not strength critical, but stiffness driven
Potential Flutter Problems with Minimum Gage Control Surfaces or other “Critical Structures”

Highlights of Airbus presentations from 2009 FAA Workshop in Tokyo, Japan

1. Airbus shared essential safety data on a rare composite growth phenomena
2. Minimum-gage sandwich disbond growth under GAG cycles [Growth rates = f (disbond size)]
3. Multiple potential sources: bonded repair problem, square edge honeycomb core design

Initial Flaw Enlarged due to Poorly Bonded Repair Patch
Paragraph 9: Proof of Structure – Flutter and Other Aeroelastic Instabilities

• Procedures are the same for both metallic and composite structures, where effects of speed, damping, mass balance, etc. are evaluated for critical parts, excitation modes, and tolerances.

• Composite material evaluation needs to account for unique effects:
  - Repeated loading (if there is damage growth)
  - Environmental exposure (e.g., water ingestion)
  - Service damage scenarios (large damages)

• These conditions must be evaluated to determine their effect on stiffness, mass, and damping.
Paragraph 10: Continued Airworthiness

- Importance of skilled resources

10a: Important to *design for maintenance*

- All potential damages and representative field repairs should be included in original structural substantiation

- Structural Repair Manual (SRM) provides repairs limits and substantiated repairs
Paragraph 10: Continued Airworthiness

10b: Detailed maintenance, inspection and repair documentation is required because there are few standard practices for composites

- Section divided into Damage Detection, Inspection, Repair, and Documentation and Reporting

- Repairs for damage exceeding SRM limits require additional repair substantiation, usually involving the OEM

- Repair stations with proper regulatory authority may be involved with repairs outside the repair documentation
Paragraph 10: Continued Airworthiness

10c: Repair substantiation

- Document acceptable damage limits (ADL) and repairable damage limits (RDL)
- Recognizes the difficulty to substantiate repairs beyond those generated by the design approval holder
Repair Substantiation

• Repair designs must meet the same performance requirements as the base aircraft structure

• Supporting data for repairs includes:
  - Damage limits, Drawings, Qualified materials, Specifications, Processing instructions, Tooling, Equipment, Quality control procedures/Inspections

• Repair design and substantiation efforts depend on damage size, its location, affect on structural performance, environment

• Lightning strike protection and fire safety need to be addressed for certain repairs
Repair Design

• Operators and design organizations must:
  ➢ Fully understand the limits of repair instructions
  ➢ Avoid extending repairs beyond previous structural substantiation

• Reverse engineering techniques for composite materials have not yet matured to an acceptable level of confidence
  ➢ Reverse Engineering is not recommended. Possible to identify base materials, but difficult to identify processes used to cure them.
Repair Design

• Repairs – intended to restore load path and load distribution

• Repair Design Options
  - Bonded versus bolted repair
  - Single scarf vs Double scarf
  - Bolted adhesive

• Types of repair are related to damage assessment
Repair Design

**Bonded repairs**
- Provide effective load transfer: Capable of restoring the original strength of the damaged part
- More efficient for thin laminates (< 2 mm) – less weight
- Requires increased technician skills due to greater complexity

**Bolted repairs**
- More efficient for thick laminates: Less material removed from undamaged sections
- More easily inspected for structural integrity than bonded repairs
- Do not require the same strict bond surface preparation and controls necessary for bonded repair
**Repair Design**

**Scarf repairs**

- Maintain aerodynamic smoothness
- Difficult to apply to thick laminates
- Scarfed or stepped joints for thick materials require very long overlaps/scarfed areas
  - Typically recommended scarf length of 50 to 80 times the thickness of the material being repaired
Repair Design

• Type of Repair is often Related to Practical Requirements
  - Low observability = flush bonded
  - Airflow is critical = flush bonded
  - Heavily loaded laminate structure = bolted
  - Sandwich construction = bonded
  - Quick, temporary patch = bolted
Repair Design

Post-Process NDI:

- **Repair documentation should specify NDI procedures**
- **NDI can identify voids, delaminations and porosity from cure cycle due to:**
  - Poor tooling, insufficient ply consolidation
  - Low autoclave pressure, loss of vacuum during the cure cycle
- **Post-Repair NDI can also detect:**
  - Handling damage on laminate edges, Impact damage
  - Delaminations from poorly machined parts (i.e., drilled holes or edge trim), Improper assembly
Paragraph 10: Continued
Airworthiness

10d: Damage Detection, Inspection and Repair Competency

- Ref. SAE AIR 5719 on training for awareness of safety issues in composite maintenance and
- Need for technician, inspector and engineering training on the skills necessary for damage disposition and repair
- Describes the need to train pilots, line maintenance, and other operations personnel to be aware of anomalous damage events
Damage Detection, Inspection and Repair Competency

• Damage Detection
  – Damage tolerance substantiation and procedures for detecting degradation in structural integrity are linked to protection of structure (incl. degradation in lightning protection system as related to structural integrity, fuel tank safety and electrical systems)
  – Details on considerations for visual methods used in damage detection (lighting conditions, inspector eye sight standards, dent depth relaxation, and surface color, finish & cleanliness)

• Inspection
  – Describes the need for substantiation of in-process & post-process inspection procedures
Damage Detection, Inspection and Repair Competency

• Some composite repair details cannot be reliably verified by practical post-process inspections
  ➢ Poorly formed adhesion (i.e., weak bonds)
  ➢ Ply layup and stacking sequence
  ➢ Use of qualified materials and processes

• In-Process and post-process inspections provide the necessary and nearly “fail-safe” conditions for reliable composite repairs
  ➢ Due to limited confidence with being able to detect weak disbonds, bonded repairs have size limitations
**Bonded Repair Size Limit Policy**

**FAA Policy Statement (PS-AIR-20-130-01, 2014)**

**Bonded Repair Size Limits**

1. Repair processes that produce a consistently sound structure and critical fabrication processes must be performed under approved process specifications using approved and qualified repair materials.

2. Repair designs must have structural substantiation based on tests or analyses supported by tests.

3. Data supporting the bonded repair must include inspections that are capable of detecting complete or partial failure (within arresting design features) of the bond line.
Repair Processes

• Processing of composites is a SYSTEM governed by APPROVED PROCESSES
  ➢ Parts - Equipment and Materials - Skill of team-members
  ➢ Team must be capable of satisfying procedural, regulatory and other technical requirements

Important considerations

Understanding and interpreting source documentation
Complex maintenance environment issues:
  ➢ Compensating for cold sinks (including thermocouple placement, heating zones, etc.)
  ➢ Following approved curing conditions of repair (equipment reliability)
  ➢ Adjustments to thermal conditions (exothermic reactions)
Damage Characterization

- OEM damage tolerance substantiation forms the basis for detection and disposition of damaged parts.

Detection of damage

Mapping of damage

Complete damage characterization

Component records and source documentation consultation for ADL and RDL

ADL: Allowable Damage Limits
RDL: Repairable Damage Limits
Damage Characterization

• **Required for accurate damage disposition**
  - Visual detection usually requires additional NDI to fully characterize damage

• **Consult OEM source documentation (e.g., SRM)**
  - Within ADL – no repair required
  - Outside ADL – repair required
    - Within Repairable Damage Limits (RDL) – repair per SRM
    - Outside RDL – consult OEM

• **Additional considerations**
  - Previous repairs within proximity of damage
  - Replacing protective surface layers
  - Involvement of OEM as determined by source documentation
Damage Characterization

Nondestructive Testing Overview:
- OEMs typically use through-transmission automated 100% inspection
- Operators/MROs typically use tap test and pulse echo (P/E)
- Other techniques used depending on organization capabilities and size
Damage Characterization

Nondestructive Testing Techniques Issues:

• Inspector variability: Training and physical limitations such as eye sight

• NDI for non-visible damage
  ➢ Wide variety of NDI techniques
    – Variety mandates specialized experience and training
    – Each NDI will reveal different damage assessments
  ➢ Standards
    – Calibration
    – Pass/fail criteria available in procedure
Integration of Composite Maintenance and Damage Tolerance

- **Design for Repair**
  - Early development of maintenance procedures
  - Efficient, low-cost NDI procedures to locate damage (that always find CDT)
  - Cost-effective repair with minimal down time when damage is found
  - Reliable and simple NDE to quantify effects of damage

- **Well-defined ADL**
  - Design Load

- **Damage tolerant design, including significant CDT**
  - Ultimate
  - Limit
  - Maximum load per fleet lifetime
  - Continued safe flight
  - Allowable Damage Limit (ADL)
  - Critical Damage Threshold (CDT)

Increasing Damage Size

Paragraph 11 – Additional Considerations

11a: Crashworthiness

• Content has a basis in special conditions developed for composite transport fuselage crashworthiness
  ➢ Recognizing differences between unique rules for each aircraft product type (more considerations for transport airplanes & rotorcraft)
  ➢ Realistic and survivable crash impact conditions seeking equivalent levels of safety with comparable metal aircraft types
  ➢ Allowance for an approach using analysis supported by test evidence
Crashworthiness

• Four main criteria areas to contrast between composite and metal aircraft structure
  − Protection from release of items of mass
  − Emergency egress paths must remain
  − Accelerations and loads at seat locations must not exceed critical thresholds
  − Survivable volume must be retained

• Outlines a need for transport airplane fuel tank structural integrity for a survivable crash as related to fire safety

• Lists considerations for valid analyses and test evidence used in making a comparison of metal and composite crashworthiness
Crashworthiness

Current crash protection regulations:

- Are written to test occupant protection while seated under specific dynamic loading conditions
  - “Seat tests”- defined by seat load conditions and measuring resultant occupant loads
- Are based on historical knowledge of energies occupants are exposed to in survivable crashes of metallic aircraft
- Do not account for different dynamic behavior of composite aircraft, and how that may affect passenger loading under crash conditions
Crashworthiness

• Composites are heterogeneous and display different failure mechanisms, including:
  - Tensile fiber fracture
  - Compressive fiber kinking
  - Matrix cracking
  - Interlaminar separation / Delamination

• Different loading conditions and geometric features will promote or inhibit different failure mechanisms

• To consider composites brittle is only a partial truth: it depends on the failure mode and on the type of composite
Crashworthiness

The figure shows that metal alloy absorbs 12.3 times more energy in tensile failure than the composite, HOWEVER… Since composites are not homogeneous and display different failure mechanism under different loadings, they may actually perform comparably or better than their metal counterparts.
Crashworthiness

Aviation Rulemaking Advisory Committee - New Task assigned in 2015

Purpose: To provide recommendations regarding the incorporation of airframe-level crashworthiness and ditching standards into Title 14, Code of Federal Regulations (14 CFR) part 25 and development of associated advisory material.
Crashworthiness

• Until then, composite transport aircraft will be subjected to specific aircraft-level loading conditions, and perform equal or better than metallic aircraft according to four criteria:
  1. Occupants must be protected during impact from release of seats, overhead bins, and other items of mass
  2. Emergency egress paths must remain
  3. Acceleration and loads experienced by occupants must not exceed critical thresholds
  4. Survivable volume of occupant space must be retained

• Compliance may be shown by test or analysis supported by test
Paragraph 11 – Additional Considerations

11b: Fire Protection, Flammability and Thermal Issues

- Background on traditional flammability safety concerns (firewalls, engine mounts and other powerplant structures), with discussion of issues for expanded use of composites in transport wing and fuselage structures
  - In-flight cabin fire protection and the role of composite airframe structure
  - Exterior fire protection after crash landings: fuel-fed fire exposures for fuselage and wing structures (time for passenger egress & fuel tank fire safety issues)

- Likely need for special conditions to outline expectations
  - In-flight fire protection: use of composite structures should not add to in-flight fire hazards (release of toxic gas, fire progression) vs. existing metal structures
  - Post-crash fire protection: exterior fuel-fed fire exposure should allow the same level of safe passenger egress (toxic gas, burn-through) as existing metal structure
Paragraph 11 – Additional Considerations

11b: Fire Protection, Flammability and Thermal Issues

- Content on thermal issues for composite structure exposed to high temperatures
  - List of potential sources of high temperature (failed systems, engine and interior fires)
  - Description of irreversible heat damage as related to thresholds in composite material properties (glass transition temperatures)
  - Need for special inspections, tests and analyses to determine the airworthiness of structures exposed to high temperatures (inspection data defining damage metrics for disposition)
Fire Protection, Flammability and Thermal Issues

• Historically flammability has only been considered an issue for interior materials
  - Structural materials typically met the requirements for fire proof and fire resistant by definition (steel is a default fire proof material and aluminum is fire resistant)
  - There are few regulations that specifically state aircraft structure must be fire proof or fire resistant, outside of some fuel tank requirements
    - When necessary, special conditions are applied
• The use of composites in primary structural elements requires managing thermal exposures for composites subjected to high temperatures (e.g., near engines).
• The effects of associated heat damage on the required structural integrity must be understood
Fire Protection, Flammability and Thermal Issues

• Civil Aviation Fire Threats
  ➢ In-flight Fires: Accessible Areas; Inaccessible Areas
  ➢ Post-crash Fires
  ➢ Fuel Tank Flammability

• Composite Structure Concerns
  ➢ Flame propagation in hidden areas
  ➢ Post-crash burn through protection including toxicity
  ➢ Fuel tank heat transfer capabilities
Composite Burn & Toxic Gas Issues

• See special conditions & issue papers applied to transport aircraft with extensive composite fuselage and wing applications
  ➢ Cabin safety experts have relied heavily on demonstration of equivalent levels of safety (metal versus composites)
  ➢ Special Conditions for novel composite applications

• Fire safety experts at FAA Technical Center helped define realistic structural testing

• Industry has relied on system/design solutions instead of advanced, more fireproof resins
Paragraph 11 – Additional Considerations

11c: Lightning Protection

- Issues related to composite structures
- Lightning Protection for Structural Integrity
  - Typical Design Features (e.g., mesh)
  - Lightning Damage should be considered in Categories 2-4
- Lightning Protection for Fuel Systems
  - Eliminate structural penetration, arcing, sparks, or other ignition sources
  - Typical Design Features (mesh, joints, fasteners, and plumbing support)
- Lightning Protection for Electrical and Electronic Systems
  - Description of the Issue
  - Typical Design Features (mesh or foil shielding and electrical bonding)
Lightning Protection

Lightning Effects on Composites

• Carbon Fiber Composites
  - Resin vaporization and delamination at lightning attachment points
  - Sparking and hot gas ejection at fasteners
  - High induced current and voltage on wiring and tubes

• Non-Conducting Composites (fiberglass, aramid fiber)
  - Puncture through non-conducting composites
  - Subsequent explosive pressures inside enclosed radomes, fairings and caps
Lightning Protection

- Composite structures have much higher electrical resistance compared to aluminum structure
  - Lightning strikes to insulated structure, without conductive paths, present a threat to the structure and attached systems and may cause catastrophic structural failures

- Composite structure should include proper protection against lightning for each zone of the aircraft
  - Typically provided with mesh materials placed on the outside of the structure
  - Paint and primer thickness over the mesh must be carefully controlled to ensure the mesh is effective

- Lightning strike damage must be included in the fatigue and damage tolerance evaluation of the structure
Appendices 1-3

• **Appendix 1. Applicable Regulations and Relevant Guidance**
  - Starting with harmonized table of rules created for CMH-17 Vol. 3/Ch. 3
  - Includes a list of applicable composite guidance (AC and Policy Statements)

• **Appendix 2. Definitions**

• **Appendix 3. Change of Composite Material and/or Process**
  - Based on updates to EASA CS 25.603, AMC No. 1, Para. 9 and No. 2
Questions
For More Information

• Consider taking the Composite Structural Engineering Technology (CSET) class here at WSU
• Cindy Ashforth, STS for Composites, cindy.ashforth@faa.gov
• Larry Ilcewicz, CSTA for Composites, larry.ilcewicz@faa.gov
• Rusty Jones, STS for NDI and Composites, rusty.jones@faa.gov