AFRL
Certification of Composite Aircraft Structures

Stephen Clay, Ph.D.

Aerospace Systems Directorate – 20 July 2022

Outline

- Introduction

- Certification Guidance

- Recent and On-going Certification Research

- Upcoming Challenges

- Summary

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Primary Focus of Presentation

Certification of U.S. Military (*Air Force*)

Fixed Wing Aircraft

Composite Primary Structure
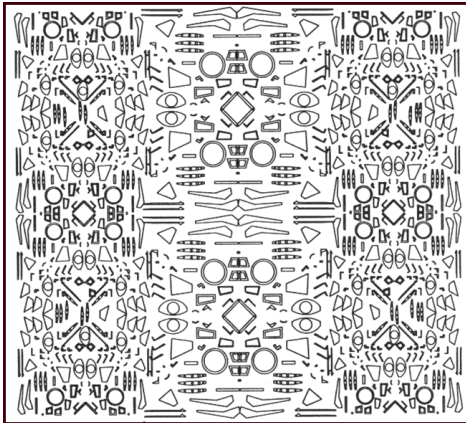
- Basis of discussion is MIL-HDBK-516C

- Many parallels to commercial aircraft

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INNOVATE, ACCELERATE, THRIVE – THE AIR FORCE AT 75   DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited. PA# AFRL-2022-3129   3

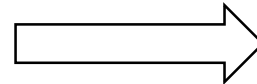# Damage Tolerant Unitized Composite Structures

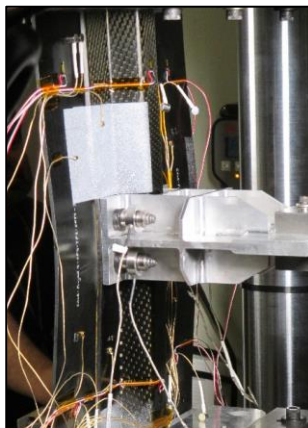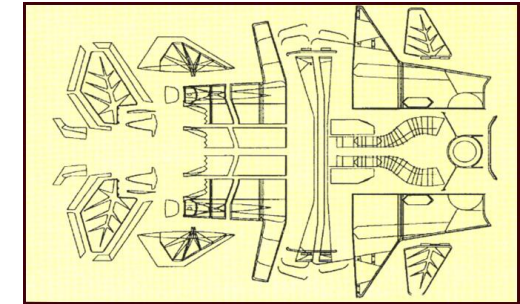| Current State-of-the-Art | → | Vision |

~ 11,000 metal components
~ 600 composite components
~ 135,000 fasteners

→

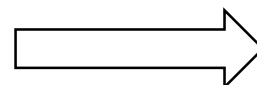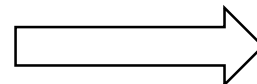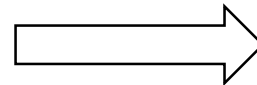~ 450 metal components
~ 89% composite
~ 6000 fasteners

Composite skins **bolted** to **metal** substructure

→

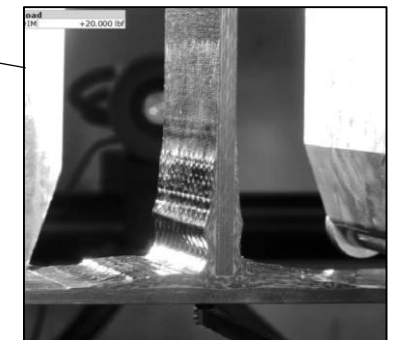Composite skins **bonded** to **composite** substructure

No damage growth certification

→

Slow damage growth certification

Certified by:
Test supported by analysis

→

Certified by:
Analysis supported by test

Why Unitized Composites?

Composites Affordability Initiative
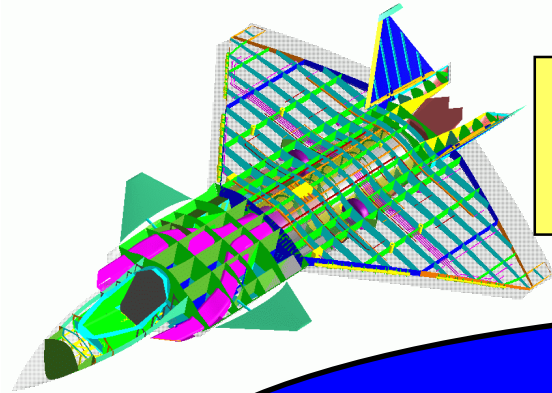
47% Cost Savings

44% Cost Savings
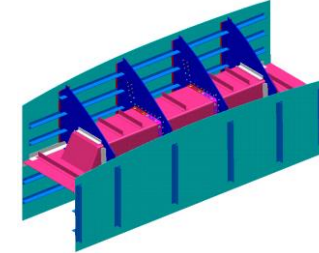
CAI Ph II cost studies and demonstrations showed that significant cost savings over conventional SOA airframe construction are achievable

39% Cost Savings

17% Cost Savings

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CAI Certification Plans (2003-2004)

Bonded Wing

- Validation of the models is the key issue in certification.

- Laser Bond Inspection (LBI) technique is an enabling technology for integrated bonded design and should be a proactive design tool to optimize designs, rather than an inspection tool after the fact.
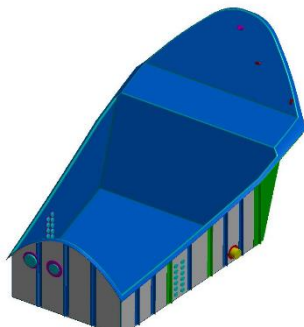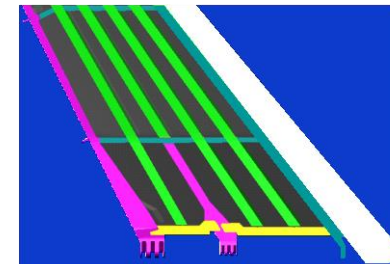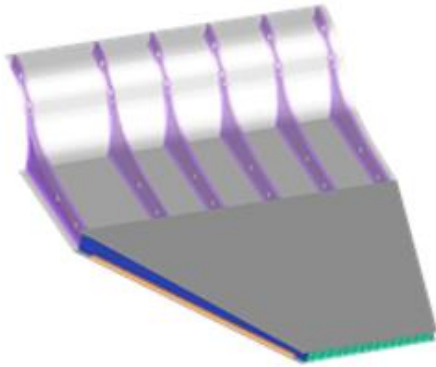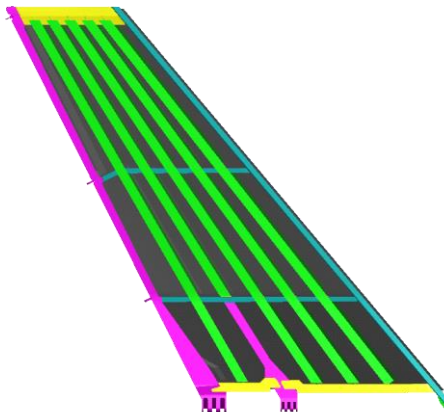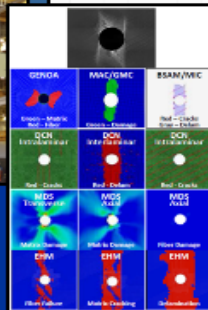
- Until now industry has lacked a method to interrogate a bondline and we lacked a universal approach to process control that everyone uses. They felt that if this program develops these two things, then that is a major accomplishment that will be useful in the future.

3D Preform/Z-Fiber Reinforced Vertical Tail

- **Joe Gallagher (AF/ASC/EN)**
  - The issues are always in terms of damage and how it propagates
  - Combination of QA, process controls & analytical tools is reasonable.
  - Concerned about slow-growth vs. no-growth.
- **Don Polakovics (Navy/NAVAIR)**
  - If the intent of this program is to gain acceptance of bonded/integrated structure then the analysis is the critical aspect. Once we have reasonable confidence in the tools we will go forward.
- **Larry Ilcewicz (FAA)**
  - On validation of analysis tools, the real key is you absolutely must have people involved who are intimately involved in structural production problems. You have to account for all the applicable defects.

e.g. manufacturing flaws (porosity, disbonds), impact (low/high energy), overstress, overtemp, …

Building on Success

Damage Arrestment
Slow Damage Growth Certification
Validated Damage Prediction
Demonstrated PC, NDI, LBI

2020's

FASTBUCS
NASA
Other DoD
Industry IRAD
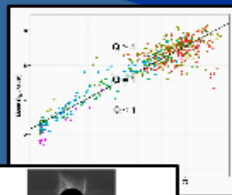
Damage Analysis
Process Modeling
Process Control
Bonding

2010's

- CALE
- DARPA TRUST
- NAVAIR ABCD
- NASA ACP
- ICM2
- Industry IRAD

PRSEUS
Out-of-Autoclave
Static Analysis Tools
Laser Bond Inspection

2000's

- CAI
- Multi-Role Transport
- F-16 UHT
- ACCA
- Industry IRAD

3-D Woven Pi Preforms
Z-Pinning
Stitching
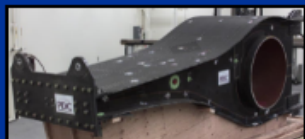
1990's

- RoCSS
- ALAFS
- CAI
- NASA ACT
- Industry IRAD

Certification Guidance

DoD Certification Guidance Documents

516C

NOT MEASUREMENT SENSITIVE

MIL-HDBK-516C
12 December 2014
SUPERSEDING
MIL-HDBK-516B
w/CHANGE 1
29 February 2008

DEPARTMENT OF DEFENSE
HANDBOOK

AIRWORTHINESS CERTIFICATION CRITERIA

THIS HANDBOOK IS FOR GUIDANCE ONLY.

DO NOT CITE THIS DOCUMENT AS A REQUIREMENT.

AMSC N/A   AREA SESS
DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

JSSG-2006

NOT MEASUREMENT SENSITIVE

JSSG-2006
30 October 1998

DEPARTMENT OF DEFENSE
JOINT SERVICE SPECIFICATION GUIDE

AIRCRAFT STRUCTURES

This specification guide is for guidance only.
Do not cite this document as a requirement.

AMSC N/A   FSG 15GP
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

1530D

NOT MEASUREMENT SENSITIVE

MIL-STD-1530D
31 August 2016
SUPERSEDING
MIL-STD-1530C (USAF)
1 November 2005

DEPARTMENT OF DEFENSE
STANDARD PRACTICE

AIRCRAFT STRUCTURAL INTEGRITY PROGRAM (ASIP)

AMSC N/A   FSC 15GP
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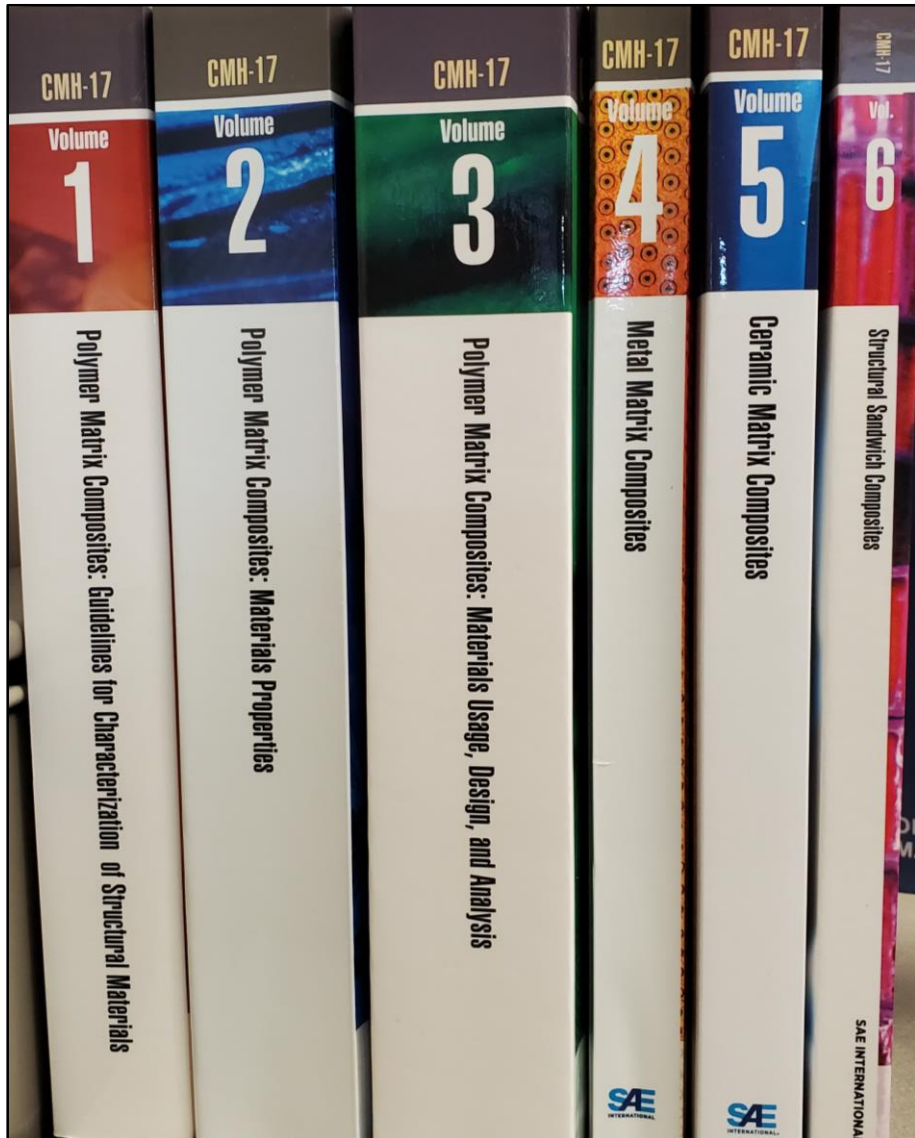
Composite Materials Handbook - 17

Current Chairmen: Larry Ilcewicz and Curt Davies - (FAA)
Current Secretariat: NIAR
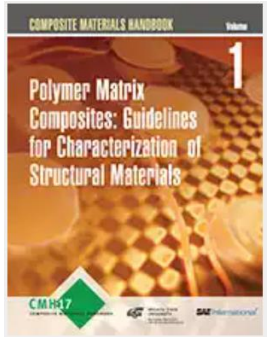
The Composite Materials Handbook-17 (CMH-17) provides <u>information and guidance necessary to design and fabricate end items from composite materials</u>. Its primary purpose is the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials. In support of this objective, the handbook includes composite materials properties that meet specific data requirements.

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DEPARTMENT OF DEFENSE HANDBOOK

AIRWORTHINESS CERTIFICATION CRITERIA

1. SCOPE

1.1 Purpose.

This document establishes the airworthiness certification criteria to be used in the determination of airworthiness of all manned and unmanned, fixed and rotary wing air vehicle systems. … This handbook is for guidance only. This handbook cannot be cited as a requirement. If it is, the contractor does not have to comply.

5.1.3 Foreign object damage (FOD). IDAT
- Birds, hail, runway, taxiway, and ramp debris

5.1.4 Repeated loads. CALE P8, FASTBUCS Fatigue
- Maneuvers, gusts, active oscillation control, gust alleviation, flutter suppression, terrain following, vibration and aeroacoustics, landings, buffet, ground operation loads, pressurization, loads from control surfaces, store carriage and employment loads, heat flux

5.3 Strength.

5.3.1 Static strength verification. CAI, NASA ACP

Criterion (Army and Air Force): Verify that sufficient static strength is provided to react to all design loading conditions without yielding and detrimental deformations (including delamination) at limit load, unless higher loads are specified, and without structural failure at ultimate loads.

5.3.2 Materials and processes. CAI, TRUST

Criterion: Verify that the allowables for materials are estimated minima derived using statistical compensations appropriate to part criticality and the nature of the material; are established considering component and assembly variability, the expected environmental extremes, fabrication processes, repair techniques, and quality assurance procedures; and are validated. Verify that conditions and properties associated with material repairs satisfy design requirements.

Method of compliance: verification methods include analysis, test, and inspection of documentation.

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5.4 Damage tolerance and durability (fatigue).

Damage tolerance is a means for preventing catastrophic structural failure or loss of control of the aircraft after a predefined limit of structural damage has occurred as a result of, but not limited to, low energy impact, in-service damage, loads environment, inherent materials defects, sub-critical cracks, manufacturing defects, repeated loads application, and ballistic damage.

5.4.1 Damage tolerance.

Criterion (Army and Air Force): Verify that all safety-of-flight (SOF) structure, including dynamic components, have adequate safe life or damage tolerance capability (depending on certification authority) for the required service life.

a. **Slow damage growth design concepts:** The initial flaws presumed to exist in the structure (defined below) do not grow to a critical size and cause failure of the structure due to the application of the maximum internal member load in two lifetimes of the service life and usage. … (typical for metallic structure)

   (6) For composite structures: **IDAT**

      (a) Surface scratch 4" in long and 0.02" deep.

      (b) Interply delamination equivalent to a 2" diameter circle with dimensions most critical to its location.

      (c) Damage from a 1" diam hemispherical impactor with 100 ft-lbs of kinetic energy or with that kinetic energy required to cause a dent 0.1" deep, whichever is less.

      (d) No significant growth resulting from manufacturing defects or high energy impact damages in two service lifetimes of usage. **FASTBUCS Fatigue**

b. **Fail-safe design concepts:** … **For composites, bonded structure is capable of sustaining the residual strength loads without a safety of flight failure with a complete bond line failure or disbond. FASTBUCS**

5.4.2 Durability. **CALE**

Criterion (Army and Air Force): Verify that the air vehicle structure has sufficient durability to preclude adverse effects on safety, economic, operational, maintenance, repair, and modification costs throughout its intended service life. Durability includes crack initiation, crack growth, fatigue and safe life.

Method of compliance: verification methods include analysis, test, and inspection of documentation.

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DRAFT Certification Flowchart

Structural Design & Analysis

Could Failure Cause Loss of Aircraft or Aircrew or Inadvertent Store Release?

No → Special Application?

No → Damage Tolerance Not Applicable

Yes (DT Evaluation)

Yes (SOF)

Validated DG & RS Analysis or Empirical Methods?

Yes → Single Load Path?

No (FSMLP & SDG can't be used)
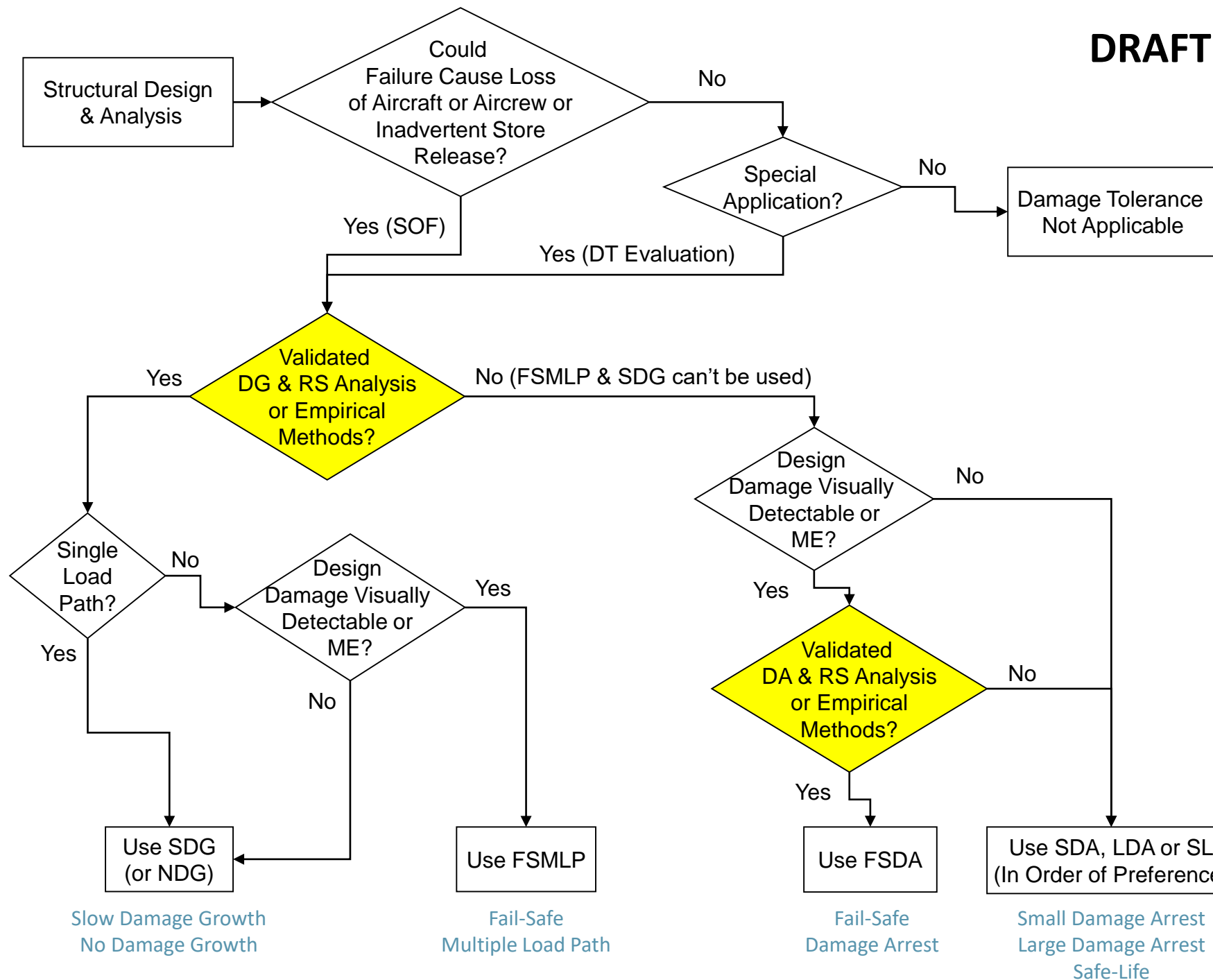
Design Concepts:
SDG: Slow Damage Growth
NDG: No Damage Growth (subset of SDG)
FSMLP: Fail-Safe Multiple Load Path
FSDA: Fail-Safe Damage Arrest
SDA: Small Damage Arrest
LDA: Large Damage Arrest
SL: Safe-Life

Other terms:
SOF: Safety-of-Flight
DT: Damage Tolerance
DG: Damage Growth
DA: Damage Arrest
ME: Malfunction Evident
RS: Residual Strength

Single Load Path?

No → Design Damage Visually Detectable or ME?

Yes → Use FSMLP

No → Use SDG (or NDG)

Yes → Use SDG (or NDG)

Design Damage Visually Detectable or ME?

No → Use SDA, LDA or SL (In Order of Preference)

Yes → Validated DA & RS Analysis or Empirical Methods?

No → Use SDA, LDA or SL (In Order of Preference)

Yes → Use FSDA

Use SDG (or NDG)
Slow Damage Growth
No Damage Growth

Use FSMLP
Fail-Safe
Multiple Load Path

Use FSDA
Fail-Safe
Damage Arrest

Use SDA, LDA or SL (In Order of Preference)
Small Damage Arrest
Large Damage Arrest
Safe-Life

Recent and On-going AFRL Certification Research

- CALE
- FASTBUCS
- IDAT

Sampling of PDA Methods evaluated by AFRL (not all-inclusive)

COTS – Abaqus, ANSYS, NASTRAN, etc.
- Built-in cohesive, VCCT interlaminar damage growth
- Built-in in-plane damage growth

CDMat – UT-Arlington
- Abaqus Explicit User Defined Material (VUMAT)
- continuum lamina using modified LaRC-04 (in-plane)
- non-linear elastic cohesive elements (interlaminar)

Enhanced Schapery Theory (EST) and Nth Cylinder (NCYL) – UM
- integrates with ABAQUS
- EST damage mechanics used for lamina level stiffness
- NCYL used for stiffness degradation

Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) - NASA Glenn Research Center
- rapid, standalone analysis based on semi-analytical (non-FE) micromechanics
- FEAMAC couples micromechanics with ABAQUS for nonlinear multi-scale analysis

Multiscale Designer - Altair
- multi-scale composite analysis
- reduces complex unit cells to manageable number of deformation modes and state variables

Rx-FEM – AFRL/RX, UT-Arlington
- Regularized finite element method
- imbed mesh independent through thickness cracks or in-plane delaminations

Eigendeformation-Based Homogenization Method (EHM) – Vanderbilt University
- integrates with Abaqus
- failure modeled at microstructure, evaluated w/RVE coupled to structure simulation

X-FEM with Discrete Crack Network - Global Engineering and Materials (GEM)
- integrates with Abaqus
- based on X-FEM discrete damage modeling of matrix cracking

GENOA - AlphaSTAR
- augmentation to commercial FEA
- multi-scale progressive failure analysis

Which one is best? It depends on your needs.
- **COTS with technical support**
- **Subroutine integrated with COTS**
- **Research code**
- **Higher fidelity/higher computational expense**
- **Lower fidelity/lower computational expense**

Composite Airframe Life Extension (CALE) Program

Develop and transition capability to assess continued airworthiness of advanced composite airframe structure
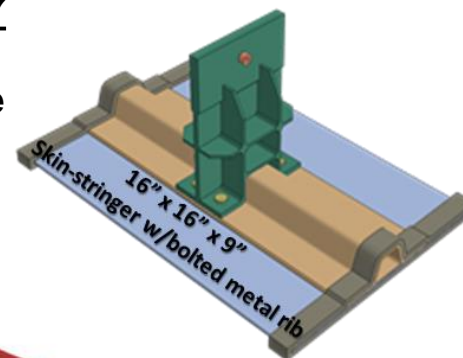
CALE P5 Jan 20-Apr 21
Predicting Airframe Stress due to Differential Thermal Strain

CALE P8 May 18-Feb21
Validation of Extended Durability Life
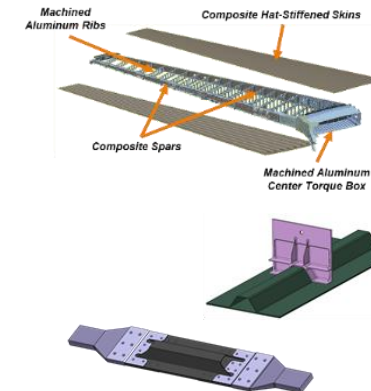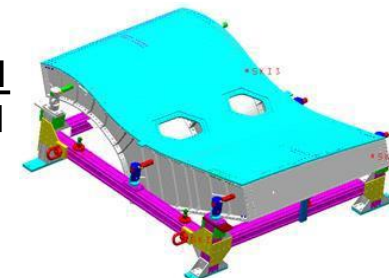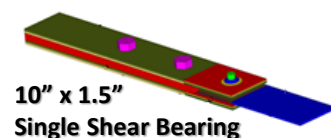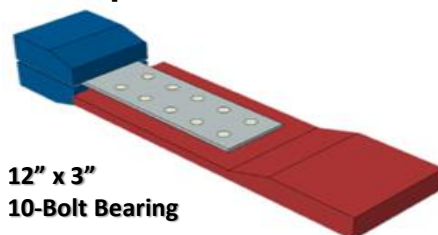
CALE P3 Sep 17- Nov 19
Quantification of Aging from Long-Term Exposure (QALE)
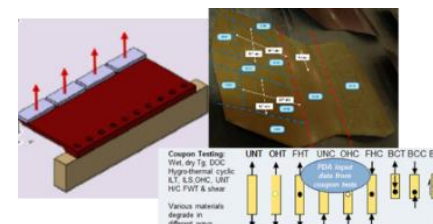
CALE P4 Feb 17-Feb 19
Durability and Damage Tolerance of Advanced Composite Structural Features

CALE P2 Jul 16-Sep 17
Tools for Assessing Durability and Damage Tolerance of Fastened Composite Joints

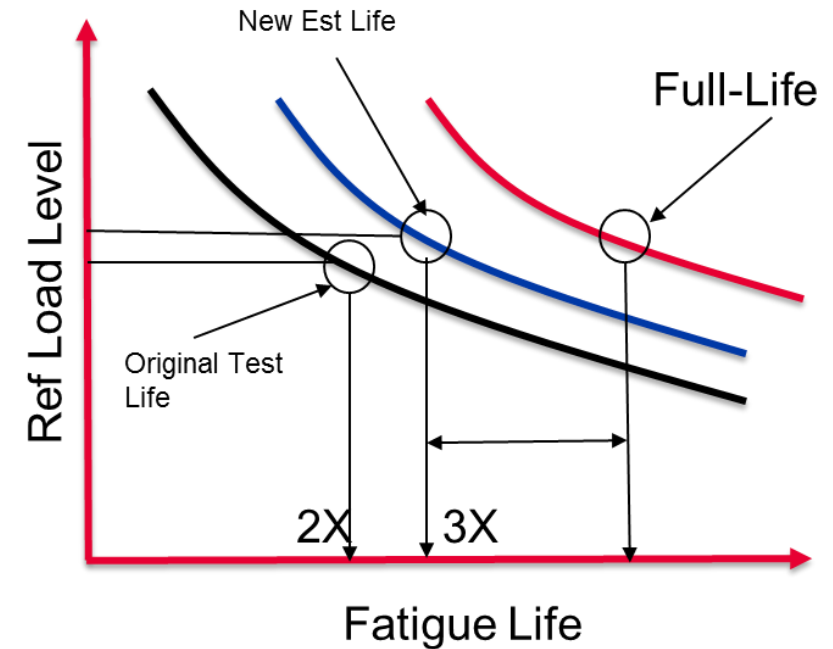**CALE P1 Dec 15-Jun 17**
Data Requirements for Progressive Damage Analysis of Composite Structures

16" x 16" x 9"
Skin-stringer w/bolted metal rib

12" x 3"
10-Bolt Bearing

10" x 1.5"
Single Shear Bearing

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Selected Service Life Extension Analysis Methods

1. **Fatigue Damage Severity Factor (FDSF)** based on Caprino fatigue model – Stress-Life Approach

2. **Progressive Damage and Failure Analysis** CDMat – continuum lamina + cohesive elements

3. **Residual Strength Tracking (RST)** based on the Sendeckyj equivalent static strength model (FACS[*] developed by NIAR)

Ref Load Level / Fatigue Life chart showing New Est Life, Full-Life, Original Test Life, 2X, 3X

> Requirement - choose a method that can assess the life of composite bolted joint under realistic service life loads

[*]Fatigue Analysis of Composite Spectra

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Fail-Safe Technologies for Bonded Unitized Composite Structures (FASTBUCS)

Vision

Significantly reduce the weight of next generation military aircraft by affordably certifying bonded unitized composite primary structure

Objectives

- Efficient fail-safe damage arrest design

- Slow-damage growth certification protocol

- Accurate predictions of fail-safe composite structural behavior

- Process control, NDI, and bondline interrogation w/damage arrestment

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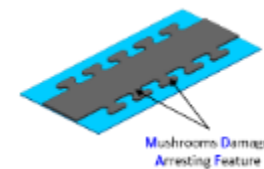
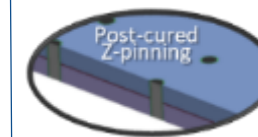# FASTBUCS Summary

Continuum Damage Model (CDMAT)

Discrete Damage Model (BSAM)

Cohesive Zone Model (Abaqus)

Breakable Glue
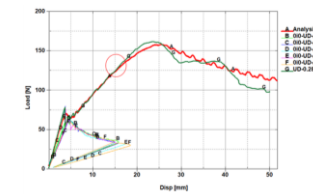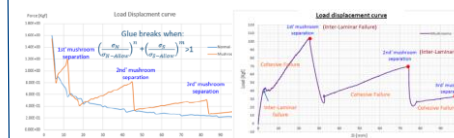
Tri-linear Cohesive (LS Dyna)

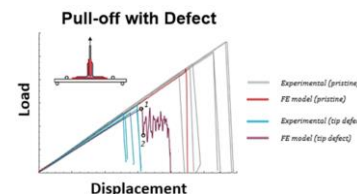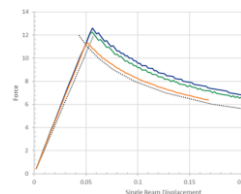Validation Testing | Validation Testing | Validation Testing | Validation Testing | Validation Testing

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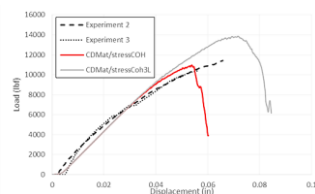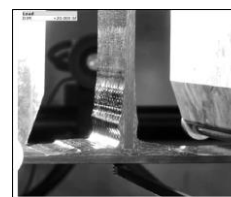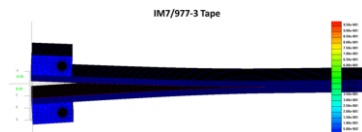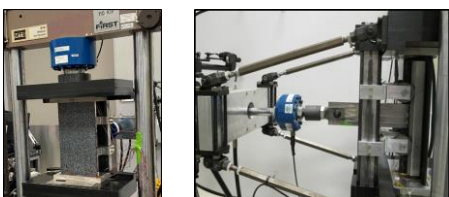
Impact Damage Analysis Tool (IDAT)

Objective: Advance analysis methods to reduce cost of certification and enable implementation of advanced unitized composite structures in future airframes

CALE and NASA ACP Tools

FASTBUCS
FASTBUCS currently addressing only static and fatigue skin-to-stringer debonding at element level
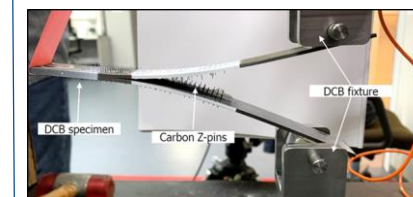
IDAT Phase II
Develop analysis capability to assess the DaDT of unitized composite structures: impact, CAI, tool validation at structural-scale.

IDAT Phase I
Determine the most feasible analysis methods to predict the damage state due to impact and improve their accuracy
– Developed/released LS-DYNA MAT299
– Developed Peridynamics capability
– Generated high-rate coupon input data

IDAT – LS Dyna MAT 299 (Improvements to MAT 261)

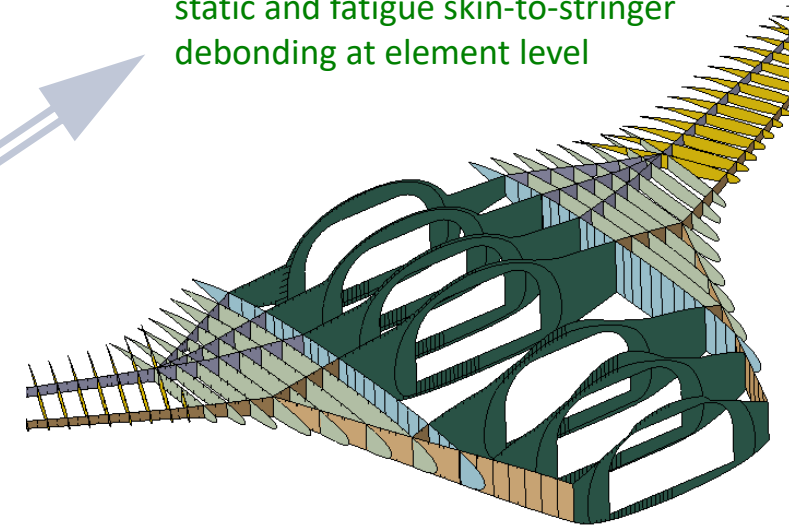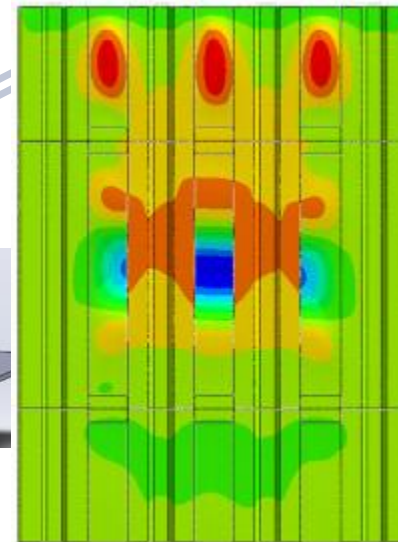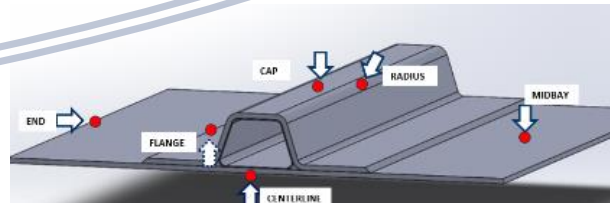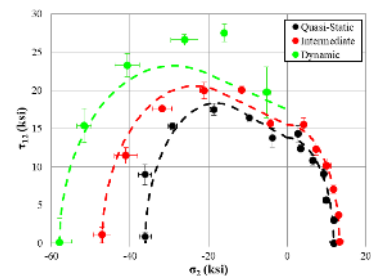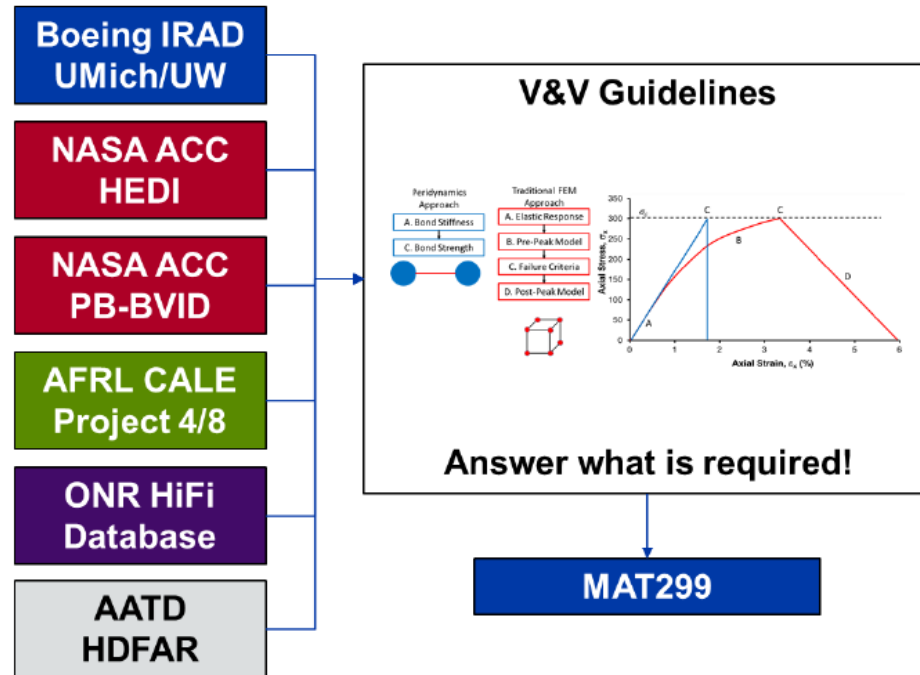| Priority	Technical Gap	Developmental Item
1	Material model relies on element erosion to ensure stability after crack develops yielding non-physical results	Update the 3D damaged stiffness matrix with appropriate damage variables to ensure physically relevant model
2	After traction separation law is exhausted, elements become unstable	Include an option for the user to specify the residual stiffness after an element fails
3	Localization effects are not captured with simple tension/compression failure modes	Implement a fiber tension-shear coupling to allow the fiber to fail due to local shear
4	Model does not have the ability to grow long cracks based on LEFM	Implement the deformation gradient decomposition (or similar) algorithm
5	Mesh regularization algorithm is tied to the global time step calculation and can yield incorrect fracture toughness values	Correct the characteristic element length based on the failure mode
6	Model does not include all strain rate sensitivities	Include strain rate sensitivities for strengths, non-linearity, and fracture toughness values
7*	No ability to predict dent depth	Update the shear non-linearity module to an appropriate elastic/plastic approach

* Not performed on this program

- Boeing's extensive evaluation of impact and PDFA material models with V&V protocols identified technical gaps early
- Modifications to MAT261 significant enough to warrant development of new material model

Upcoming Challenges

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Attritable Structures – Future Considerations

Tailored Certification Requirements

State of the Art	Vision
Structures technology following a traditional approach	**Manufacturing and certification optimized to an attritable paradigm**
• At-hoc certification for each platform	• Tailored MIL-HDBK-516C providing guidance and a common starting point
• Traditional low-risk manufacturing approaches	• Manufacturing optimized for specific benefits such as low cost, high throughput, or ease of assembly
• Expensive ground static and durability tests required to lower airworthiness certification risks	• Life limits in the absence of tests providing reliability through historical data
• Traditional well understood material choices	• Approaches to certify new additively manufactured structures

Attritable Structures – Future Considerations

Need to quantify risk and benefit

Baseline A/C Configurations

ACP

Materials/Structural Concepts

RAARD Effects - Analysis

RAARD Effects - Testing

Composites   Metals

% Cost Reduction
ISR - Composite

% Weight Reduction
ISR - Composite

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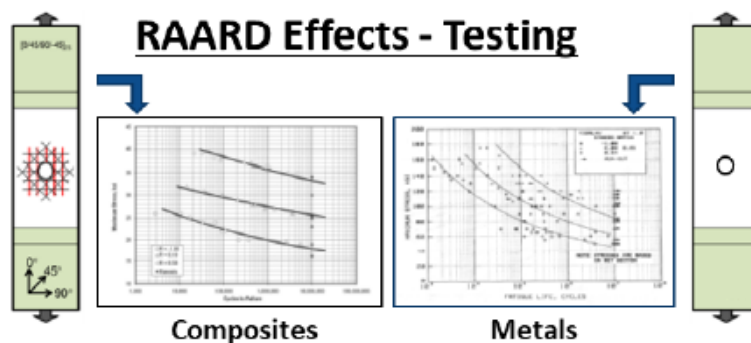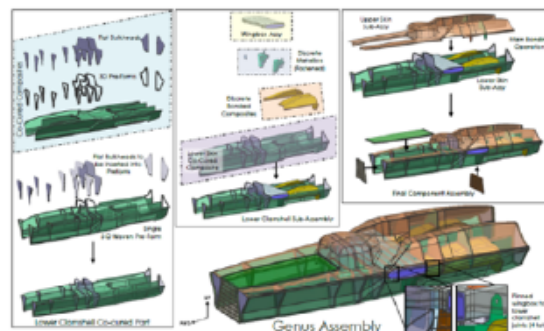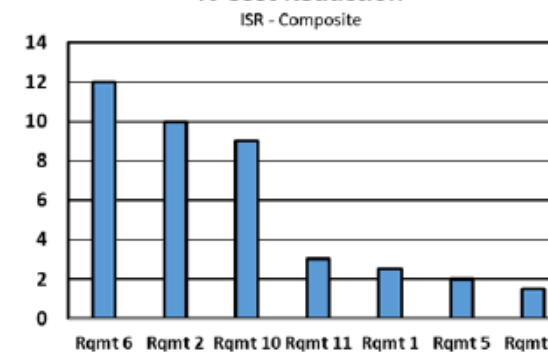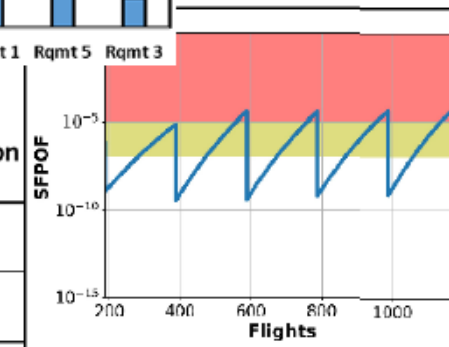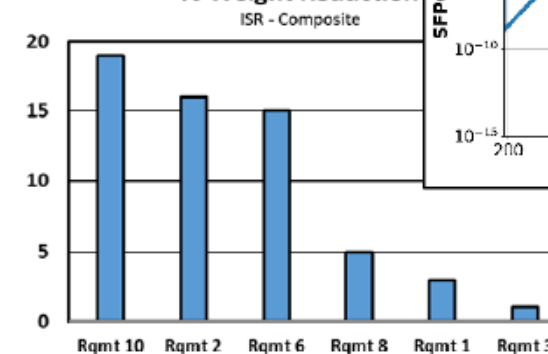
Topology Optimization – Additive Manufacturing

Additional Certification Challenges?

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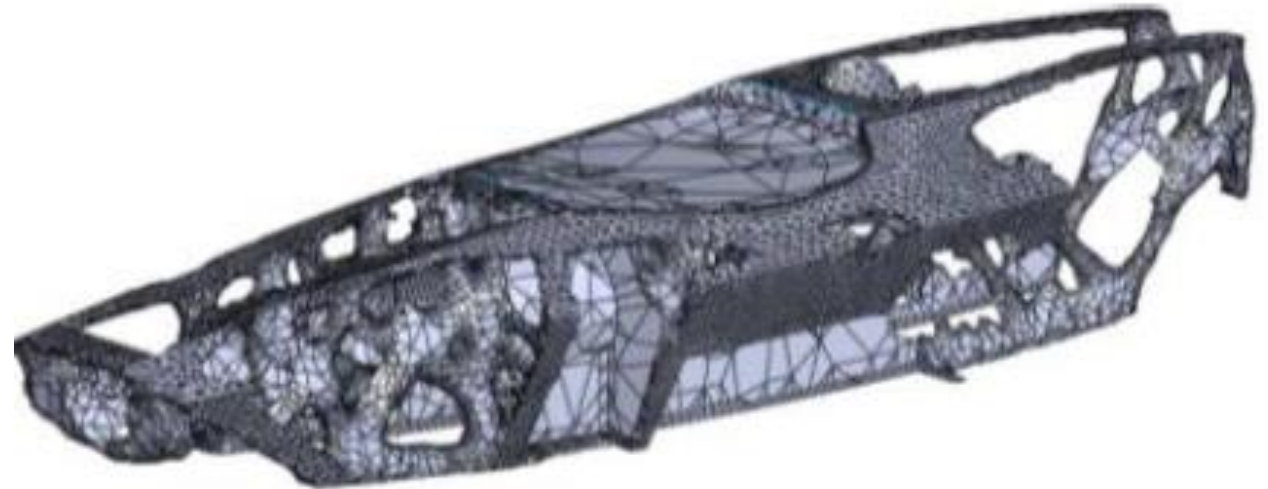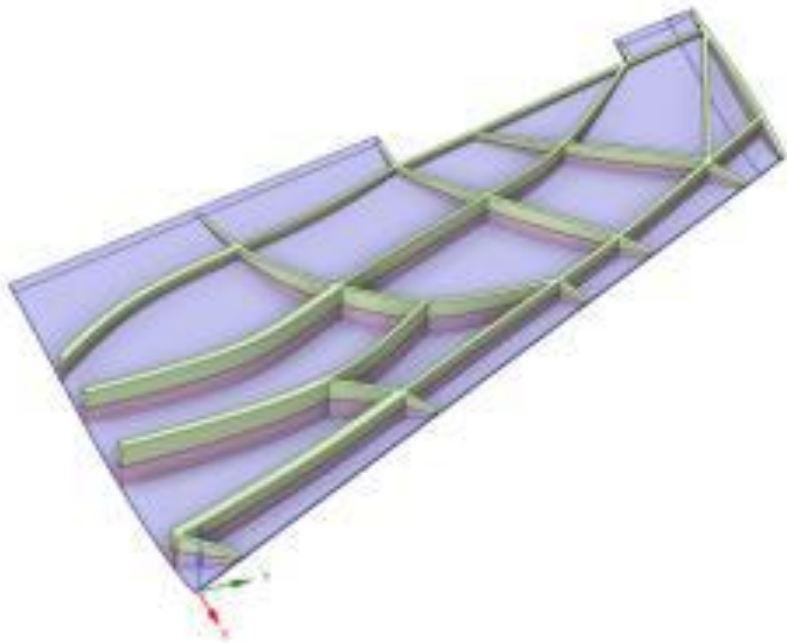
Summary

Quality Assurance + Process Control + Computational Tools

Method of compliance: verification methods include analysis, test, and inspection of documentation.

Progressive Damage Analysis (Static)

- Abaqus
- ANSYS
- NASTRAN
- CDMat
- EST
- MAC/GMC
- Multiscale Designer
- Rx-FEM
- EHM
- X-FEM with DCN
- GENOA

PDA (Dynamic – Impact)

- LS Dyna – MAT 299
- Abaqus – EST
- Peridynamics

Lifing

- FDSF
- FACS

QUESTIONS?

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Structural Integrity lifecycle diagram:

II. Producibility: Manufacturing Scale-Up

- Facility assessment
- Accept/reject criteria
- Process scale-up
- Manufacturing methods development
- Evaluation of producibility

I. Stabilized Materials and Processes

- Process development
- Material screening
- Material development

Structural Integrity (center)

III. Characterized Mechanical Properties (start of EMD)

- Allowables
- Element
- Subcomponent

IV. Predictability of Structural Performance

- Analysis
- Structural testing

V. Supportability

- Repairability
- Maintainability
- Reliability

Alternate Certification Approaches for Unitized Composite Structures

Damage Tolerance Design Concepts & Criteria when SDG (includes NDG) and FSMLP Design Concepts are NOT Viable (v6, 1 June 2017) (IOW, when Validated Damage Growth and Residual Strength Analysis or Empirical Methods DON'T Exist or Can't Be Developed)				
Q1: Design Damage (DD) visually detectable or malfunction evident?	Yes	No	No	No
Q2: NDI viable to detect sub-critical damage during production AND sustainment?	Yes or No	Yes for all critical damage types and locations	No	No
Q3: Validated DD arrestment and residual strength analysis?	Yes	Yes	Yes	No
Damage Tolerance Design Concept Based on Answers to Questions Above	FSDA (Fail-Safe Damage Arrest)	SDA (Small Damage Arrest)	LDA (Large Damage Arrest)	Safe-Life (Only if Approved)
Design Damage (DD) Criterion	Damage scenarios that achieve FSDA intent that are visually detectable or malfunction evident	Damage types, locations, and sizes based on verified NDI capability (90% PoD with 95% confidence)	Full damage extent between damage arrest features in the most critical location(s)	EOD and other damage types, sizes, locations are included in the testing used to establish the material and joint allowables.
Residual Strength (RS) Criterion	100% DLL (or higher if DLL probabilily exceeds E-07)	115% DLL without MLP structure 100% DLL with MLP structure (or higher if DLL probabilily exceeds E-07)	115% DLL without MLP structure 100% DLL with MLP structure (or higher if DLL probabilily exceeds E-07)	150% DLL (or higher if DLL probabilily exceeds E-07)
Factor for Service Life (SL) Analyses & Testing Criterion	2	2	2	4
DD Arrestment (DA) & RS Demonstration Criterion	Analysis validated via testing at environmental conditions with DD demonstrates DA & RS up to SL * Factor	Building block tests at environmental conditions with DD demonstrates DA & RS up to SL * Factor; and demonstrates NDI capability	Building block tests at environmental conditions with DD demonstrates DA & RS up to SL * Factor	Building block tests at environmental conditions with DD demonstrates DA & RS up to SL * Factor
Full-Scale Durability Test (FSDT) Criterion	90% severe spectrum and appropriate LEF	90% severe spectrum and appropriate LEF; include DD	90% severe spectrum and appropriate LEF; include DD	90% severe spectrum and appropriate LEF; include DD
Risk Assessment (RA) Criterion	Determine when multi-site damage (MSD) would be of sufficient size and density to defeat any DA feature and/or reduce RS below required level	SFPOF<E-07, conditional SFPOF<E-03 for discrete source damage, SFPOF<E-05 for detrimental deformation	SFPOF<E-07, conditional SFPOF<E-03 for discrete source damage, SFPOF<E-05 for detrimental deformation	SFPOF<E-07, conditional SFPOF<E-03 for discrete source damage, SFPOF<E-05 for detrimental deformation

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Alternate Certification Approaches for Unitized Composite Structures

Damage Tolerance Design Concept Based on Answers to Questions Above	FSDA (Fail-Safe Damage Arrest)	SDA (Small Damage Arrest)	LDA (Large Damage Arrest)	Safe-Life (Only if Approved)
Certified Service Life (CSL) Criterion	Lesser of: (1) DA analysis / Factor (2) FSDT / Factor (3) (FSDT - X) / Factor; where X is test reduction necessary to achieve RS (4) RA	Lesser of: (1) FSDT / Factor (2) (FSDT - X) / Factor; where X is test reduction necessary to achieve RS (3) RA	Lesser of: (1) FSDT / Factor (2) (FSDT - X) / Factor; where X is test reduction necessary to achieve RS (3) RA	Lesser of: (1) FSDT / Factor (2) (FSDT - X) / Factor; where X is test reduction necessary to achieve RS (3) RA
Recurring Inspections Criterion	Visual inspections	Building block tests establish NDI methods, capabilities and intervals	Not viable	N/A
Individual Aircraft Tracking Program requirements	Existing requirements	Existing requirements	100% valid data collection for all critical locations and conditions	100% valid data collection for all critical locations and conditions
Force management requirements for more severe actual usage/environment, longer FSLL, accidental damage, etc.	NDI, analysis, and testing as required for extrapolation	NDI, analysis, and testing as required for extrapolation	Testing must be repeated for new conditions	Testing must be repeated for new conditions
Potential applications	Metallic structure with tear straps	Bonded repairs (fail-safe member) over critical DADT details (the damage being arrested) where the critical failure mode of the fail-safe member is a disbond growing around the critical location that can be detected via NDI	Bonded joints with damage arrest features whose strength is verified during production via "traveler coupons" with no viable NDI or NDT option	Bonded joints without damage arrest features whose strength is verified during production via "traveler coupons" with no viable NDI or NDT option
Potential tailoring for unmanned applications	Use average spectrum for full-scale durability test	Use average spectrum for full-scale durability test; reduce RS to 100% DLL; no risk assessment	Use average spectrum for full-scale durability test; no risk assessment	Use average spectrum for full-scale durability test; no risk assessment

Notes:
EOD = effects of defects
M&P controls must be adequate & approved by the procuring agency
DD must account for all credible damage types (e.g. cracks, disbonds) in all structural locations
"Traveler coupons" must be an integral part of the production processes for each production aircraft, tested to failure, compared to structural allowables, and drive corrective actions as required
Building block tests should include coupons, elements, subcomponents and components as approved by the procuring agency

Composite Airframe Life Extension (CALE) Program

	FDSF	RST	PDFA
Tool Form	Spread Sheet	Windows App	FEA Plug-In
Run Time	Seconds	Seconds	Days
Fatigue Approach	CAS/RAS	Block - CAS	CAS
Full-Life Estimate	Yes	Yes	Yes
Residual Strength	No*	Yes	Yes

Method Primary Objectives:

- **FDSF:**
  - Spectrum severity comparison, and equivalent flight hours of life
  - *Residual Strength estimates are possible

- **RST :**
  - Tracks RS vs Cycles

- **PDFA:**
  - Prediction of life to damage onset or allowable limits, including with damage, or flaws
  - Post-Fatigue residual strength

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Designed to perform comprehensive fatigue analysis on empirical SN data