Composite Aircraft Structures – A Design Perspective

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Presentation Outline

- Introduction to Composites Certification
  - Building Block Approach
- Testing of Composite Materials & Structures
  - Material & Process Qualification and Testing
  - Structural Testing

Introduction

- Composites are unlike metals in many aspects
  - Anisotropic (at best, orthotropic)
  - Heterogeneous
- Composite failure is still not as well-understood so as to make predictions with high levels of confidence or certainty
- Composite materials and structures are realized concurrently

Demonstration of airworthiness is a little more complicated!

Composites Certification (Civil)

- Different agencies: FAA, EASA, TC, DGCA
- Parts 23, 25, 27 & 29 – Airworthiness Standards
- Key Paragraphs for each aspect
  - Materials & Fabrication Development: 603, 605, 609, 613, 619
  - Proof of Structure (Static): 305, 307
  - Proof of Structure (F&DT): 571
  - Etc.. (Crash Worthiness, Flutter, Flammability, Lightning protection, etc)
- Advisory Circulars (FAA) or Acceptable Means of Compliance (EASA)
  - AC 20-107B / AMC 20-29 are specific to composite structures

Means of Compliance

AC 20-107B (FAA)

"This advisory circular (AC) sets forth an acceptable means, but not the only means of showing compliance with the provisions of Title 14 Code of Federal Regulations (14 CFR) parts 23, 25, 27, and 29 regarding airworthiness type certification requirements for composite aircraft structures, involving fiber reinforced materials, e.g., carbon and glass fiber reinforced plastics. Guidance information is also presented on the closely related design, manufacturing and maintenance aspects. The information contained herein is for guidance purposes and is not mandatory or regulatory in nature."

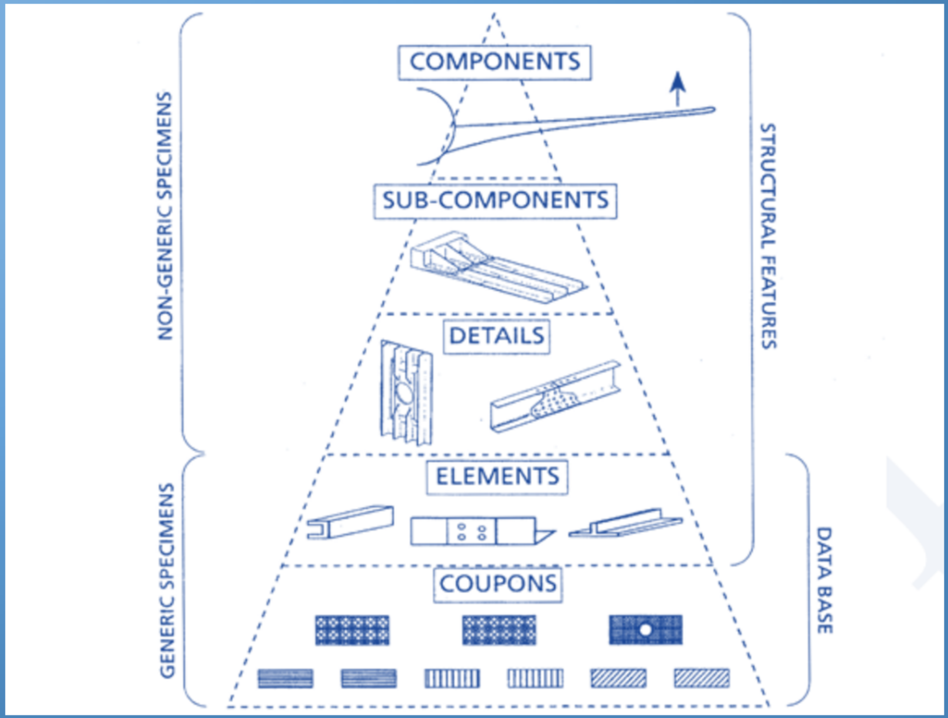
Design Criteria

- What are we designing the structure for?
  - Loads
    - Flight, Ground, Pressurization
  - Static Strength
  - Stiffness/Flutter
  - Durability & Damage Tolerance
  - Environment
    - Service Temperature
    - Humidity
  - Discrete events
    - Bird strike, Fan blade-out, etc.
    - Lightning strike
    - Crashworthiness

What Else?

- The design should also ensure
  - Scalability
  - Repeatability/Reproducibility
  - Reliability
  - Maintainability

The "Building Block" Approach



Source: Chapter 4, The Composite Materials Handbook—MIL 17, Vol. 3, Rev. F.

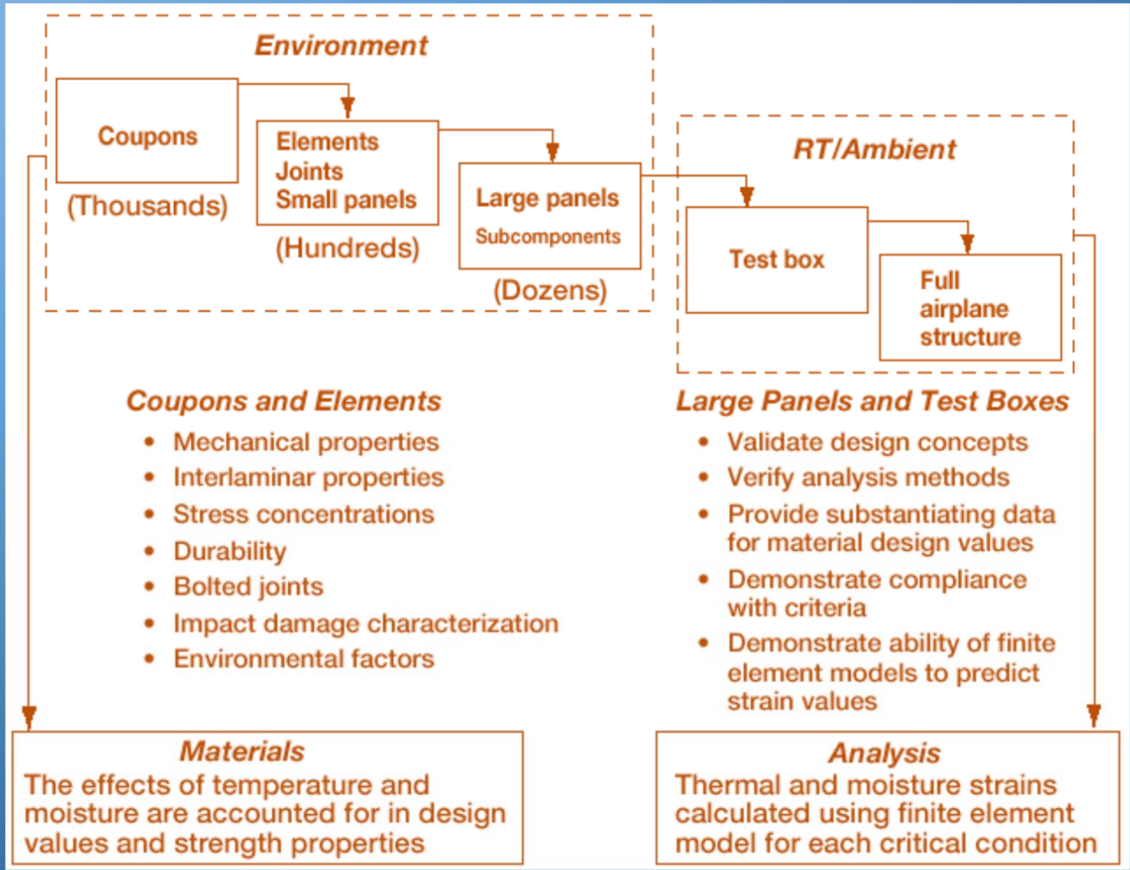
The "Building Block" approach forms a key strategy towards designing, developing, manufacturing and maintaining airworthy composite aircraft structures

Some Definitions*

- Coupon – A small test specimen (e.g., usually a flat laminate) for evaluation of basic lamina or laminate properties or properties of generic structural features (e.g., bonded or mechanically fastened joints)
- Element – A generic part of a more complex structural member (e.g., skin, stringers, sandwich panels, joints or splices)
- Detail – A non-generic structural element of a more complex structural member (e.g., specific design configured joints, splices, stringers, stringer runouts, or major access holes)
- Sub-component – A major three-dimensional structure which can provide completed structural representation of a section of the full structure (e.g., stub-box, section of a spar, wing panel, body panel with frames)
- Component – A major section of the airframe structure (e.g., wing, body, fin, horizontal stabiliser) which can be tested as a complete unit to qualify the structure

* Taken from Appendix 2 of AMC 20-29

Objectives of Approach



Source: Chapter 4, The Composite Materials Handbook—MIL 17, Vol. 3, Rev. F.

Coupon & Material Testing

Objectives of Coupon/Material Testing

- Quality control and assurance
  - Supplier Qualification
  - Purchaser Qualification
  - Process Qualification

- The mechanical properties depend on the several variables of the composition:
  - Properties of the fiber
  - Properties of the matrix phase
  - Volume fraction of the fiber and the matrix phase
  - Spatial distribution and orientation of the fiber
  - Nature of the interface between fiber and the matrix phase

Typical Equipment

Viscometer
Measures the resin viscosity

Differential Scanning Calorimeter
Measures the Glass Transition temperature (Tg)

Gel Timer
Measures the gel time of the resin

Thermal Mechanical Analyzer
Measures Young's Modulus of polymers

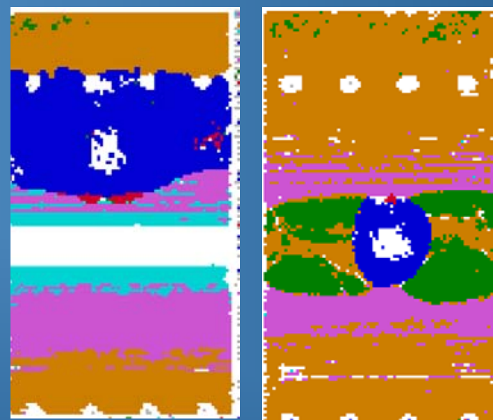
Non-Destructive Evaluation

Manufacturing Defects

Delaminations
Debonds/Disbonds
Voids
Porosity
Foreign material
Resin richness/dryness

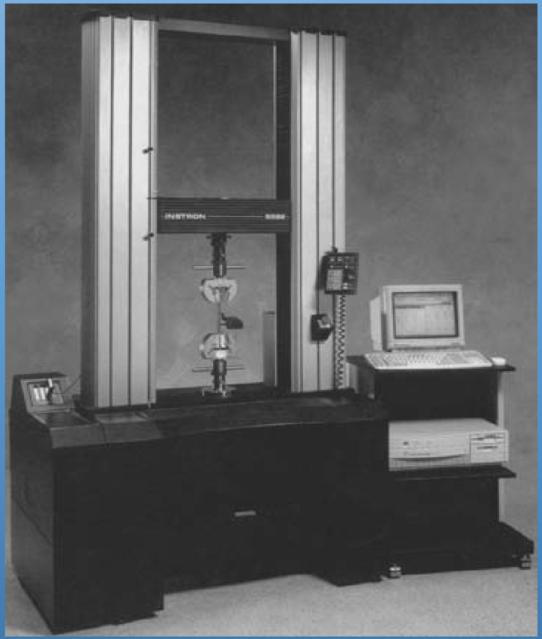
Common NDE Techniques

Ultrasonic Methods
Infrared Thermography
X-ray



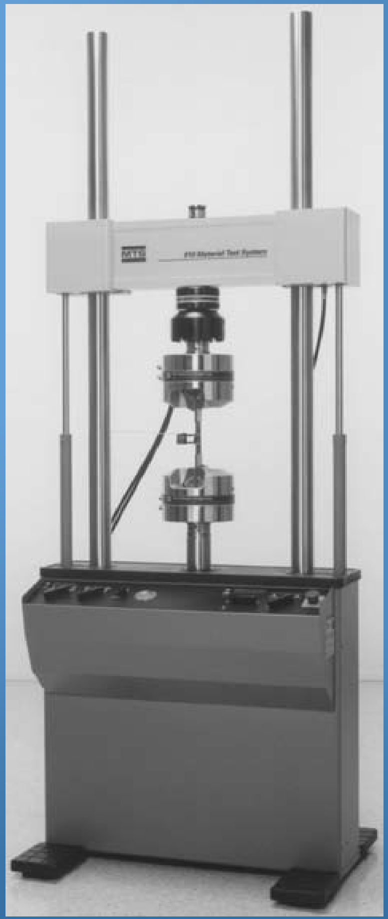
- Non-Destructive Inspection (NDI) checks and validates the manufacturing process

Typical Equipment (contd.)



Typical Electromechanical UTM

(Courtesy of Instron Corporation)



Typical Servohydraulic UTM

(Courtesy of MTS corporation)

Test Measurands

- Prepreg Physical properties
- Prepreg Chemical properties
- Laminate (cured prepreg) Physical Properties
- Laminate (cured prepreg) Mechanical Properties

Prepreg Physical Properties

- Resin content
- Fibre areal weight
- Measured by dissolving the resin of laminate samples in a solvent.

Laminate (cured prepreg) Physical Properties

- Ply thickness
- Laminate density
- Fiber volume percent
- Glass Transition Temperature

Ply Thickness Test

- Test panels are prepared
- Using a micrometer, the panel thickness is measured
- The reported ply thickness is the average of at least ten measurements uniformly distributed over the laminate and divided by the number of plies in the laminate.

LAMINATE DENSITY/FIBER VOLUME TEST

- Specimens are taken from any laminate prepared for mechanical testing
- Measure the density of a laminate specimen

Fiber Volume (%) = $\frac{\rho_L - \rho_R}{\rho_F - \rho_R} \times 100$

where,

ρ_L = Laminate density

ρ_R = Resin density (as per supplier spec)

ρ_F = Fibre density (as per supplier spec)

Tg Measurement using DSC

- Tg is the Glass Transition Temperature, the temperature region at where the polymer transitions from a hard, glassy material to a soft, rubbery material
- Tg is measured using the Differential Scanning Calorimeter (DSC)
- Tg is important in determining the service temperature
- Tg is determined by the cure cycle

Mechanical tests

Laminate (cured prepreg) Mechanical Properties

- Tension Strength
- Tension Modulus
- Open Hole/Filled Hole Tension Strength
- Open Hole/Filled Hole Compression Strength
- Compression Strength
- Compression-After-Impact (CAI) Strength
- Inter Laminar Shear Strength
- Interlaminar Fracture Toughness
  - GIc, GIIc

ASTM standards for Mechanical tests

Test	ASTM Standard
In-plane tensile	ASTM D 3039, D 638, D 5083, D 5450
In-plane compression	ASTM D 6641, D695, D3410, D5467, D5449
In-plane shear	ASTM D 3518, D 5379, D4255, D5448
Interlaminar shear strength	ASTM D 2344
Flexure	ASTM D 790, D 6272, D 6416
Fracture Toughness	ASTM D 5528, D6671
Notched Tension	ASTM D 5766
Notched Compression	ASTM D 6484
Bolted Joints (Static Bearing)	ASTM D 5961

- The standards specify the specimen dimensions, ply layup and testing parameters

Laminate Mechanical Tests: General Guidelines

- Typically, five specimens are tested for each laminate property.
- Machine test specimens to ± 1 degree of the fiber test direction.
- Except as otherwise noted in the test method, mechanical property calculations shall be based on nominal thickness

Environmental Conditioning

- Humidity
  - Specimens conditioned in accelerated manner to simulate the service conditions.
  - Specimens placed under conditions of 85% relative humidity and 70°C until moisture saturation
- Temperature
  - Specimens are to be tested at -55°C, RT, 70°C, 120°C to quantify the effect of temperature on mechanical properties

A typical test matrix*

Properties	Number of batches to be tested normally six specimens per batch						
	Test Conditions						
	Dry				Wet (70°C/85% r.h.)		
Glass transition temperature	5				5		
	-55°C	RT	70°C	120°C	RT	70°C	90°C
Tensile Strength (0°)	1	5	1			1	1
Tensile Modulus (0°)	1	5	1			1	1
Poisson's Ratio (0/90°)		1				1	1
Tensile Strength (90°)	1	1				1	1
Tensile Modulus (90°)	1	1				1	1
Compression Strength (0°)	1	5	1			5	5
Compression Modulus (0°)	1	5	1			5	5
Compression Strength (90°)		1				1	1
Compression Modulus (90°)		1				1	1
In-Plane Shear Strength (45°)	1	5	1	1	1	5	1
In-Plane Shear Modulus (45°)	1	5	1	1	1	5	1
Interlaminar Shear Strength (0°)	1	5	1	5	1	5	5
Compression After Impact		5				5	5
G_{1C}		3			1		1
G_{2C}		3			1		1

*Hallett, S.J., "Derivation of Design Allowables at Airbus Filton Site", 2nd International Conference on Composites Testing and Model Identification, 21-23rd September, 2004

Design Allowables & Knockdown Factors

- Allowables: "Material values that are determined from test data at the laminate or lamina level on a probability basis (e.g., A or B basis, with 99% probability and 95% confidence, or 90% probability and 95% confidence, respectively)." [Appendix 2, AMC 20-29]
- Knockdown Factors
  - Holes
  - Impact
  - Temperature
  - Moisture

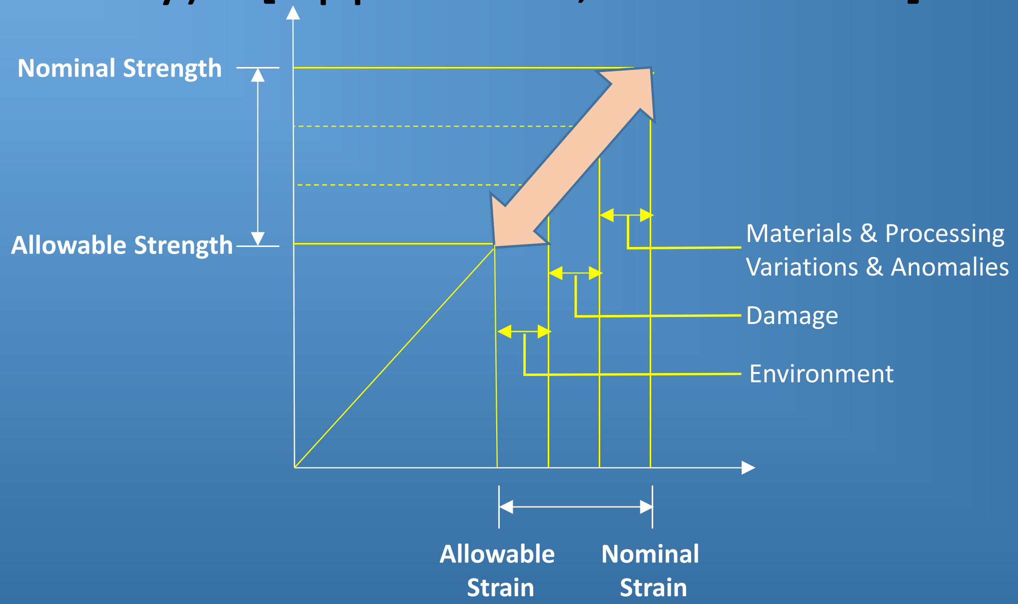
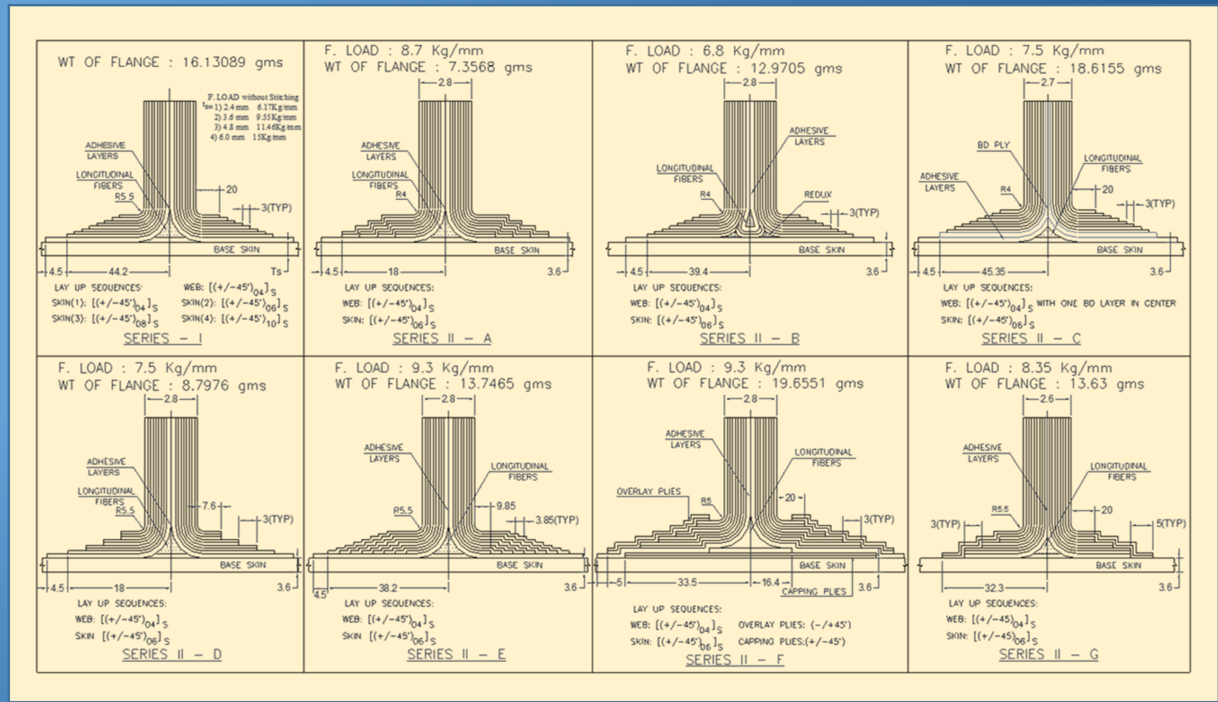
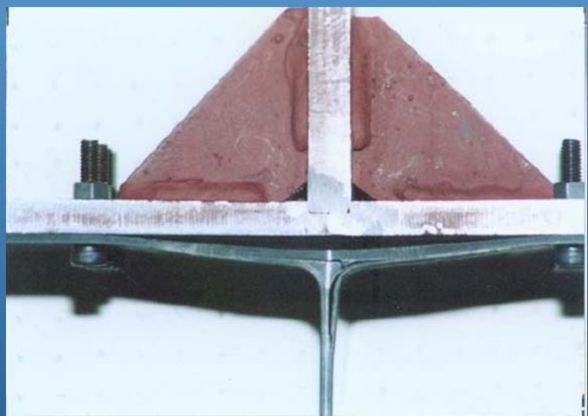


Fig. 9, Composite Materials Strength Determination within the Current Certification Methodology for Aircraft Structures, Feraboli, P., J. Aircraft, Vol. 46, No. 4, 2009.

Elements - T-joint as an Example

- Different configurations tested
- Pull strength, shear strength, combined strength
- Effect of environment, impact
- Obtained useful design inputs
- Valuable experimental data for validating models



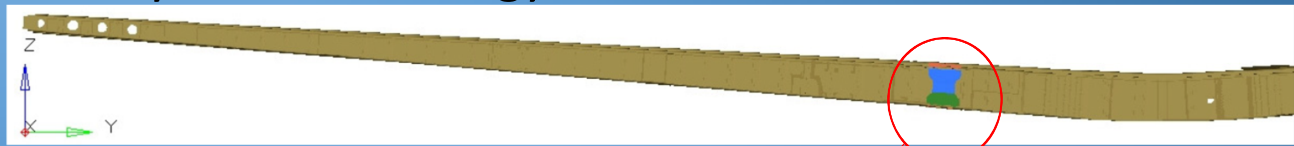


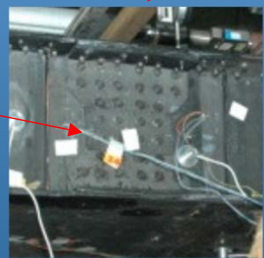
Verma, K.K., Kamath, G.M., Ramchandra, H.V., and Rao, M.S., Experimental Studies on Co-cured Composite T- joints, PD AC 1106, 2011, National Aerospace Laboratories
Courtesy: Advanced Composites Division, NAL

Details Testing & Analysis

- Skin-Stringer Panels
  - Buckling, Crippling, Validation of analysis methodology
- Splice joints
  - Validation of Analysis Methodology

Source: GKN Aerospace

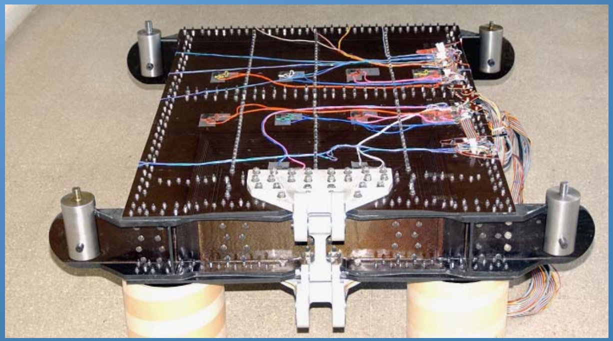


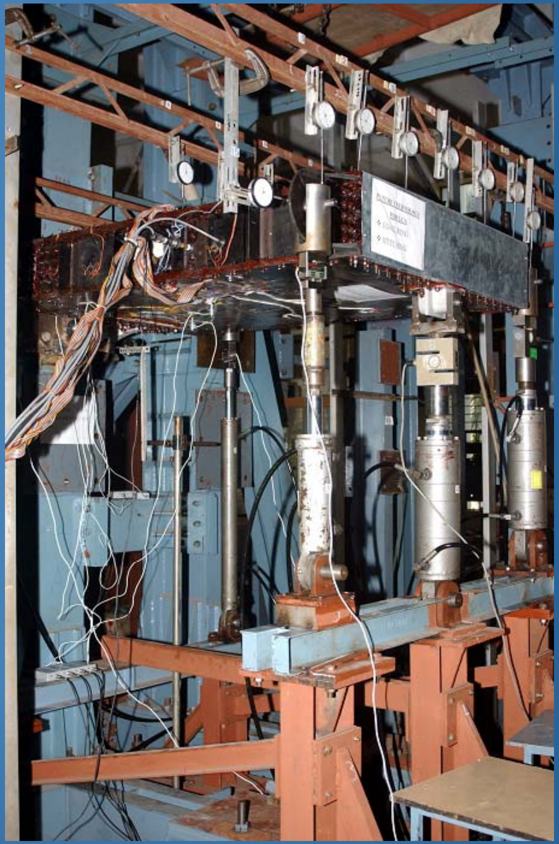


James, P., Kotresh, G., Varughese. B., and M. Subba Rao, "Realisation of Shear Flow at Crucial Spar Splice Joints of Composite Wing in Idealised Wing Test Box," 1st International Conference on Structural Integrity, ICONS-2014

Sub-Component Testing & Analysis

- Design, fabrication and testing composite testbox
- Wingbox similar to that of the LCA
- Proof-of-concept and validation of design
  - Static test
  - Hot-wet test
  - Damage tolerance test





Ramanaiah, B., Varughese, B., Kamath, G.M., and Subba Rao, M., Static Test Report on Typical Aircraft Wing Test Boxes, PD AC 0921, September 2009, National Aerospace Laboratories. Courtesy: Advanced Composites Division, NAL

Component Testing

- General objectives
  - Validation of design (ultimate loads)
  - Validation of assembly process
  - Validation of analysis methodology
  - Tests for durability & damage tolerance
  - Validation of repair

The *CSeries* aircraft composite demonstrator wing

Photo: bombardier.com

Fatigue Testing of F18 wing

Full Scale Tests

Boeing 787 Full-scale Static Test

Photo: Boeing

F-16 Durability Test

Photo: Lockheed Martin

- Static Tests
- Durability & Damage Tolerance Tests
- Many other tests too (e.g., Systems integration, Ground Vibration tests)

Boeing 777 Empennage Certification

Test Type	Number of Tests
Ply properties	235
Long-term environmental exposure	200
Laminate strength	2,334
Interlaminar strength	574
Radius details	184
Crippling	271
Stress concentrations	118
Effects of defects	494
Bolted joints	3,025
Durability	385
Bonded repair	239
Total	8,059

Coupon & Element Level Tests*

Test Type	Number of Tests
Bolted Joints (Major Splices)	110
Rib Details	90
Spar Chord Crippling	50
Skin/Stringer Compression Panels	26
Skin/Stringer Tension Panels	4
Skin/Stringer Shear/Compression	6
Skin/Stringer Repair Panels	6
Skin Splice Panels	2
Stringer Runouts	4
Spar Shear Beams	6
Total	**305**

Sub-component Level Tests**

* Fawcett, A., Trostle, J., Ward, S., "777 Empennage Certification Approach," 11th International Conference for Composite Materials, 1997.
**Chapter 4, The Composite Materials Handbook—MIL 17, Vol. 3, Rev. F.

Challenges of this approach

- High Cost of Material, Manpower, Testing
- Longer product development cycle
- Difficulty in introducing a new material

Shared Material Database

- NCAMP – An initiative to reduce costs and reduce product development time
- Material characterized and data approved by FAA
- User only has to perform the "equivalency" test

National Center for Advanced Materials Performance

Both the Federal Aviation Administration (FAA) the European Aviation Safety Agency (EASA) accept composite specification and design values developed using the NCAMP process.

FAA Memorandum AIR100-2010-120-003

EASA Certification Memorandum CM-S-004

What is NCAMP?
NCAMP, the National Center for Advanced Materials Performance, works with the FAA and industry partners to qualify material systems and populate a shared materials database that can be viewed publicly. NCAMP started as a FAA-funded program within the National Institute for Aviation Research at Wichita State University and stemmed from NASA's 1995 Advanced General Aviation Transport Experiment (AGATE).

What is the benefit to aircraft manufacturers?
Instead of qualifying an entire material system, manufacturers can pull a system from the NCAMP database, prove equivalency and gain FAA certification in a quicker and cheaper manner than a typical qualification approach.

What is the benefit to materials suppliers?
Material suppliers can work with NCAMP to qualify material systems without having to be linked to an ongoing aircraft certification program. This allows the material supplier to get their material out into the market via a public forum with generated allowables and FAA certification.

Which material systems are currently NCAMP-qualified?

- Hexcel 8552
- Newport NCT4708
- Cytec MTM45-1 - *For equivalency material availability, please contact Chris Ridgard, Chris.Ridgard@cytec.com*
- Tencate TC250
- Cytec 5320-1 (available Fall 2015) - *For equivalency material availability, please contact Chris Ridgard, Chris.Ridgard@cytec.com*
- Cytec EP2202 (pending Data Review process) - *For equivalency material availability, please contact Chris Ridgard, Chris.Ridgard@cytec.com*

NCAMP Website: http://www.niar.wichita.edu/coe/ncamp.asp

Summary

- The complexity of composite material behavior results in higher reliance on empirical measures (compared to metals)
- The Building Block approach is the standard approach in the aircraft industry
  - Ensures aircraft airworthiness through integration of structures and processes
- Industry is working towards decreasing dependency on tests and improving prediction and analysis capabilities
  - To reduce cost
  - To shrink product development cycles

Resources & References

- Federal Aviation Administration (FAA): www.faa.gov
- European Aviation Safety Agency (EASA): www.easa.europa.eu
- Composite Materials Handbook CMH-17 (formerly MIL-HDBK-17), Vols 1-3.