Past Experiences and Future Trends for Composite Aircraft Structure

11/10/09 Montana State University Seminar

- Main points
- Historical perspectives on composite usage
- Critical design, manufacturing and repair issues (including service damage considerations)
- Service experiences
  - AA587 transport accident investigation
- Barriers to expanded use
  - Scaling critical to product development
- FAA composite initiatives
  - Background & technical highlights
- Career challenges in composites

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Larry Ilcewicz
CS&TA, Composites

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Main Points

- Composite airframe applications are increasing
- Design and manufacturing integration is essential during composite product development and certification
- Structural details and service damage drive design
- Some service durability problems for minimum gage structures
- Composites used in empennage main torque box structures have had a good maintenance and safety history
- Advanced composite manufacturing, maintenance and structures technologies continue to evolve
- Resource dilution and a desire to be more efficient is driving industry to standardize and work together
- Ongoing FAA initiatives support industry advances
- Challenging career opportunities will be available

New Airframe Structures Technologies

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"Until the 1930's, wood was the primary material used in aircraft construction. It was plentiful and cheap, had large bulk and strength for its weight, and could easily be worked into any desired shape……"


Museum of Flight, Seattle, WA

"…. Skilled carpenters, cabinet makers, and seamstresses used their talents to help transform experimental aircraft shops into major manufacturing centers. The first planes they built were of a mixed construction that combined wood, fabric, steel and small amounts of aluminum for reinforcement. Manufactures used ash and spruce for the wings which were usually built around two I-shaped spars, and braced either by internal cables or by forming the leading-edge surface surface with ply. Seamstresses applied the final touches, covering wings with linen, cotton, or sometimes silk. After World War I, builders made the transition for the biplane configuration to monoplanes and other aerodynamic refinements. Among the many structural improvements of this time were the monocoque fuselage and better metals…."

"…transition to all-metal construction was gradual, in large part because of the high costs of new tooling and related retraining of personnel."

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Composite Benefits Driving the Initial Applications

- Weight reduction
- Improvements in fatigue resistance
- Corrosion prevention
- Other benefits noted in some programs
  - Potential fabrication cost advantages for parts with complex shapes
  - Performance advantages (e.g., damage tolerance)

Major Composite Components on Boeing Airplanes

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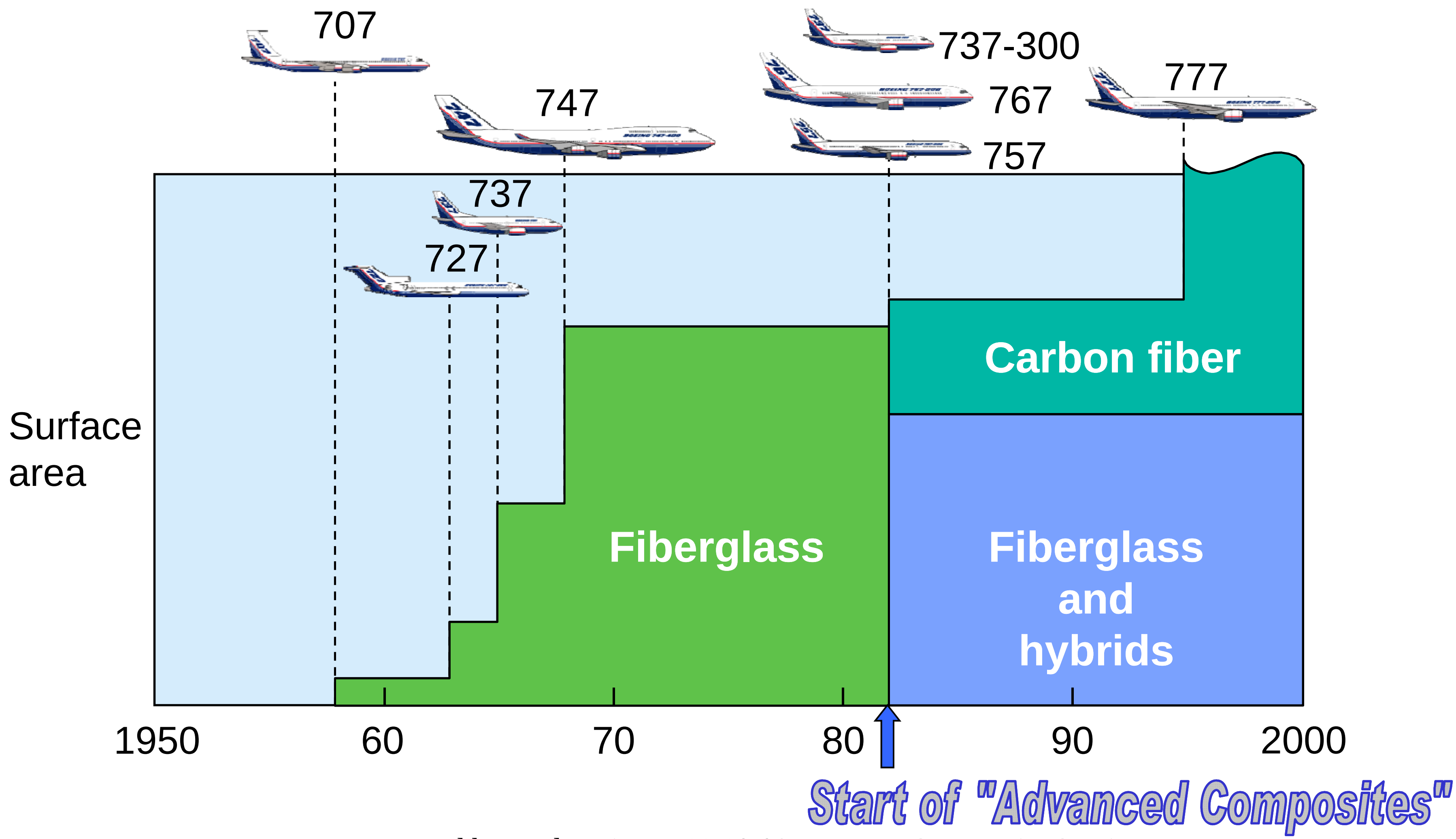

Composite Structural Weight in Commercial Transport and Military Applications

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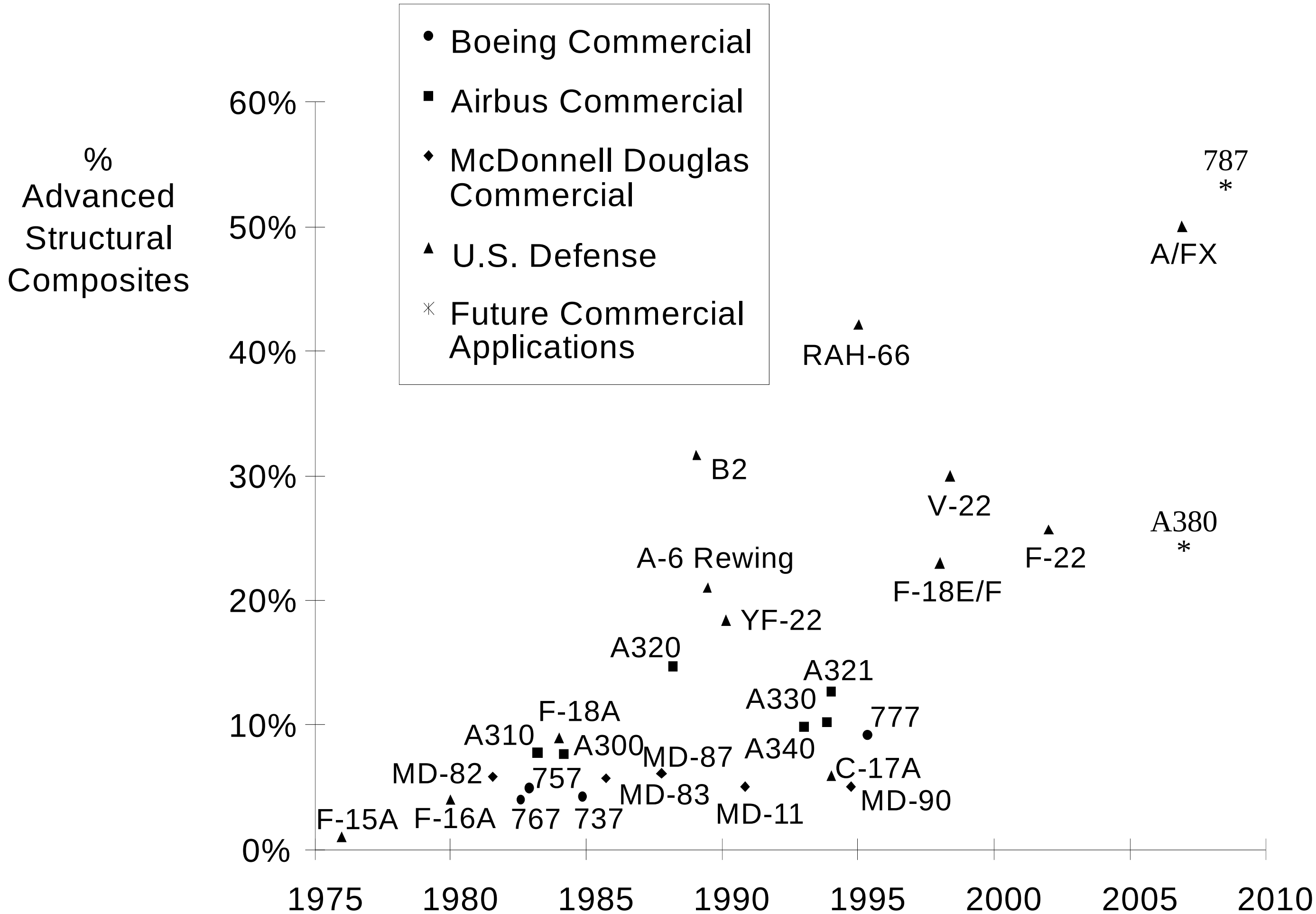

U.S. Development & Certification Basis

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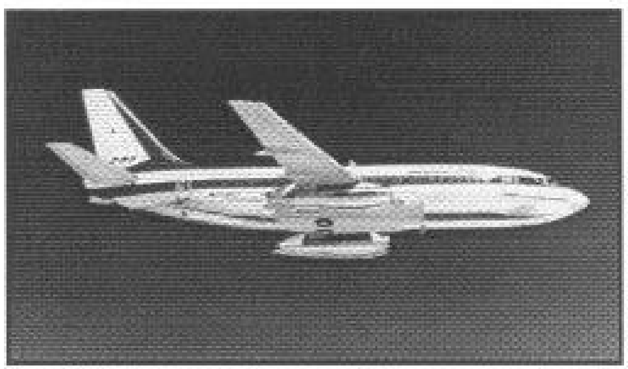
Advanced composite transport airframe structures were derived from NASA Prototype & military applications from the 1970/1980s

Boeing 777 Empennage
Certified in 1995



NASA—ACEE/Boeing
737 Horizontal Stabilizer
Certified in 1982 *

* Prototype aircraft application
(5 shipsets)

B-2 Bomber
60 foot wing box

V-22 Osprey
Wing & fuselage development

Implementation of Composites in Small Airplane and Rotorcraft Applications

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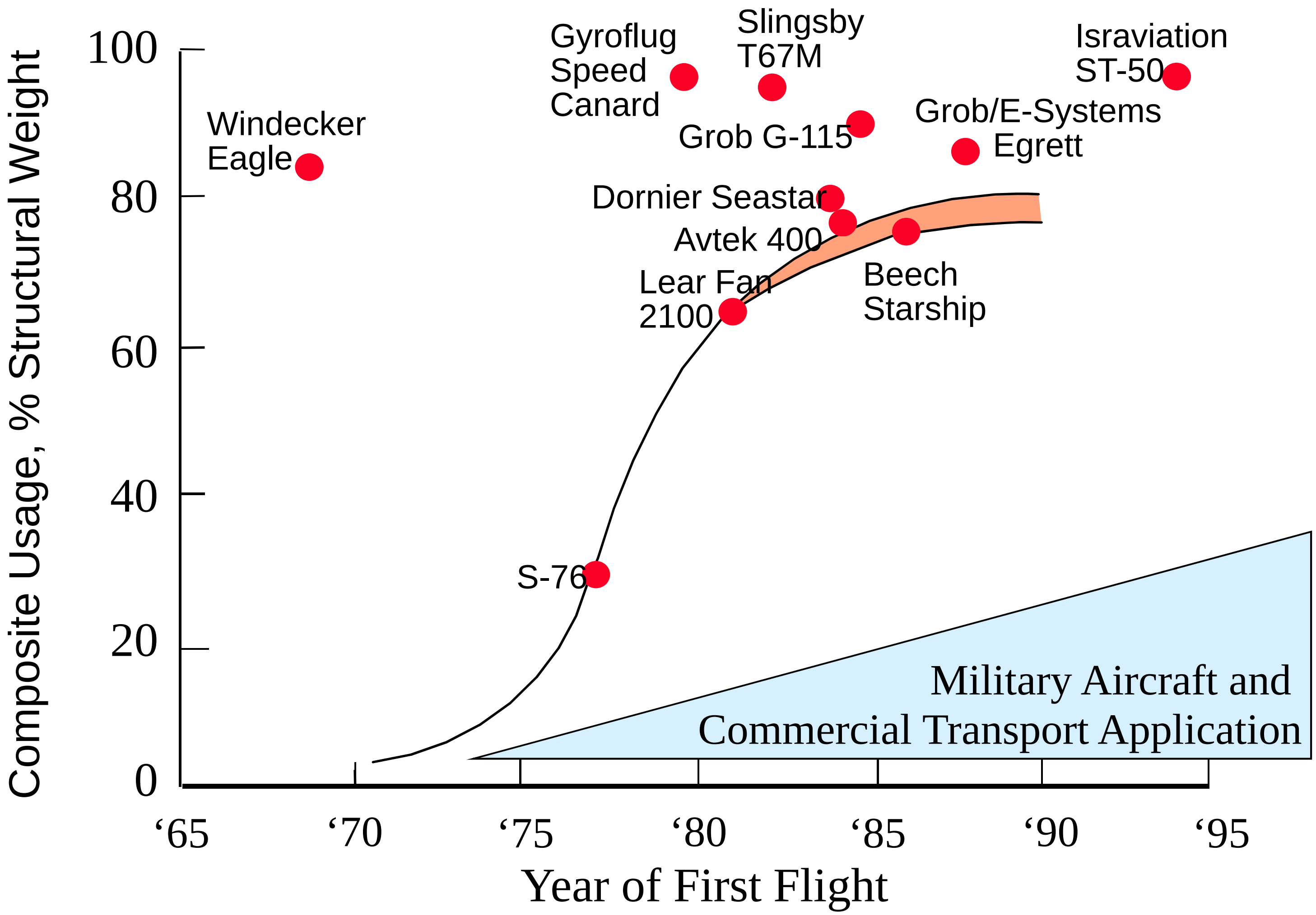

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Lancair and Cirrus Aircraft (Certified in 1998)

Most primary structure uses composite materials

Cirrus Design Corp. SR20

PAC USA Lancair LC40-550FG

Extensive use of adhesive bonding

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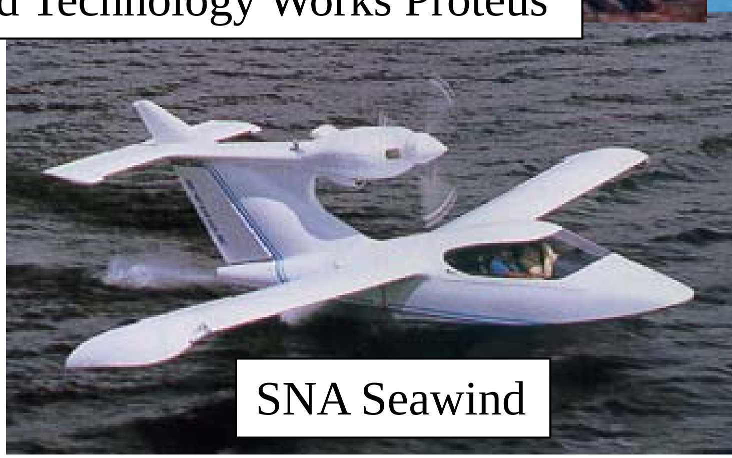
Other Small "All-Composite" Aircraft


Scaled Technology Works Proteus


Morrow Boomerang


SNA Seawind


Adams Aircraft

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Pressurized Business Jets Using Composites in Fuselage and other Primary Structure

Raytheon Premier I

Raytheon Horizon

Visionaire Corp. VA10 (Vantage)

AASI Jetcruzer 500

Composites in Advanced Rotorcraft, Including Dynamic Components of Rotor Structure

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Existing State-of-the-Art in Composite Aircraft Structures

Transport Aircraft

- Secondary structure
- Control Surfaces
- Empennage
- Wing & fuselage applications for new aircraft
- Some engine (e.g., fan blades)

Small Airplanes and Rotorcraft

- Most structures
  - Pressurized fuselage
  - Wing
- Dynamic components
  - Propellers & rotor blades
- Extensive bonding

Critical Issues for Composite Designs

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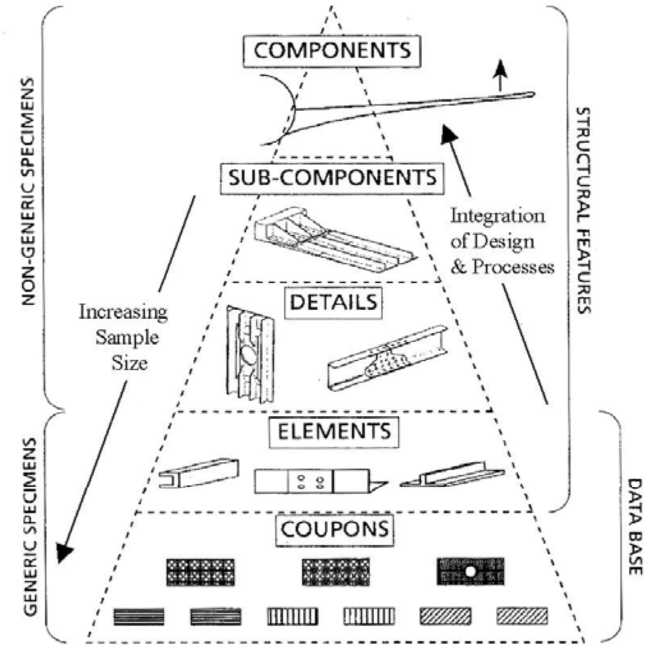
- Integration of structural design detail with repeatable manufacturing processes
  - Material and process control
- Design details, manufacturing flaws and service damage, which cause local stress concentration
  - Strength, fatigue & damage tolerance
  - Dependency on tests
  - Scaling issues
- Environmental effects
  - Temperature
  - Moisture content
- Maintenance inspection and repair



Manufacturing Factors Critical to Structural Properties*

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Continuous control of key process steps

- Most raw materials are perishable and require environmental controls (storage and use)
- Must eliminate contamination threats in lay-up and bonding process steps
- Reproducibility of lay-up and bagging process steps
- Systematic control of part cure/consolidation
- Many potential sources of defects in machining, handling and assembly of cured composites
- Training of manufacturing technicians

* Taken from the MIDO Course on "Composites for the Aviation Safety Inspector"

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Some Structural Design Details Causing Local Stress Concentration and Redistribution

- Bolted joints
- Doors and windows
- System provisions (penetrations and attachments)
- Access and drain holes
- Attachment tabs
- Stringer terminations (run-outs)
- Bonded attachments
- Ply drop-offs

Example design details given above can lead to static strength or durability problems if not accounted for with sufficient tests and analysis in structural development

Structural Design Detail Leading to Failure

Case study: JVX, V-22 Osprey full scale wing test box

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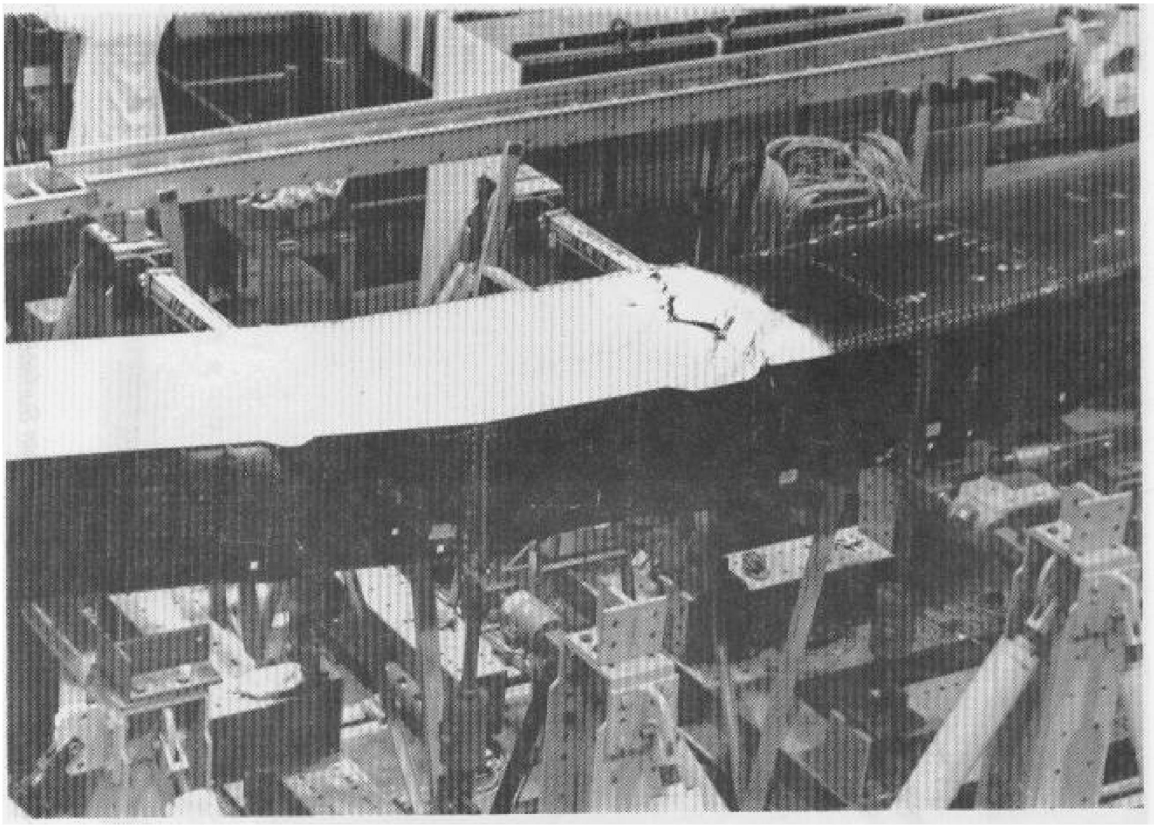

Premature failure of the forty five foot-long wing box structure, with upper surface compression cracking occurring in the central bay region during development tests.

Ref: "Composite Failure Analysis Handbook, Volume II - Technical Handbook, Part 3 - Case Histories," DOT/FAA/CT-91/23, Feb. 1992

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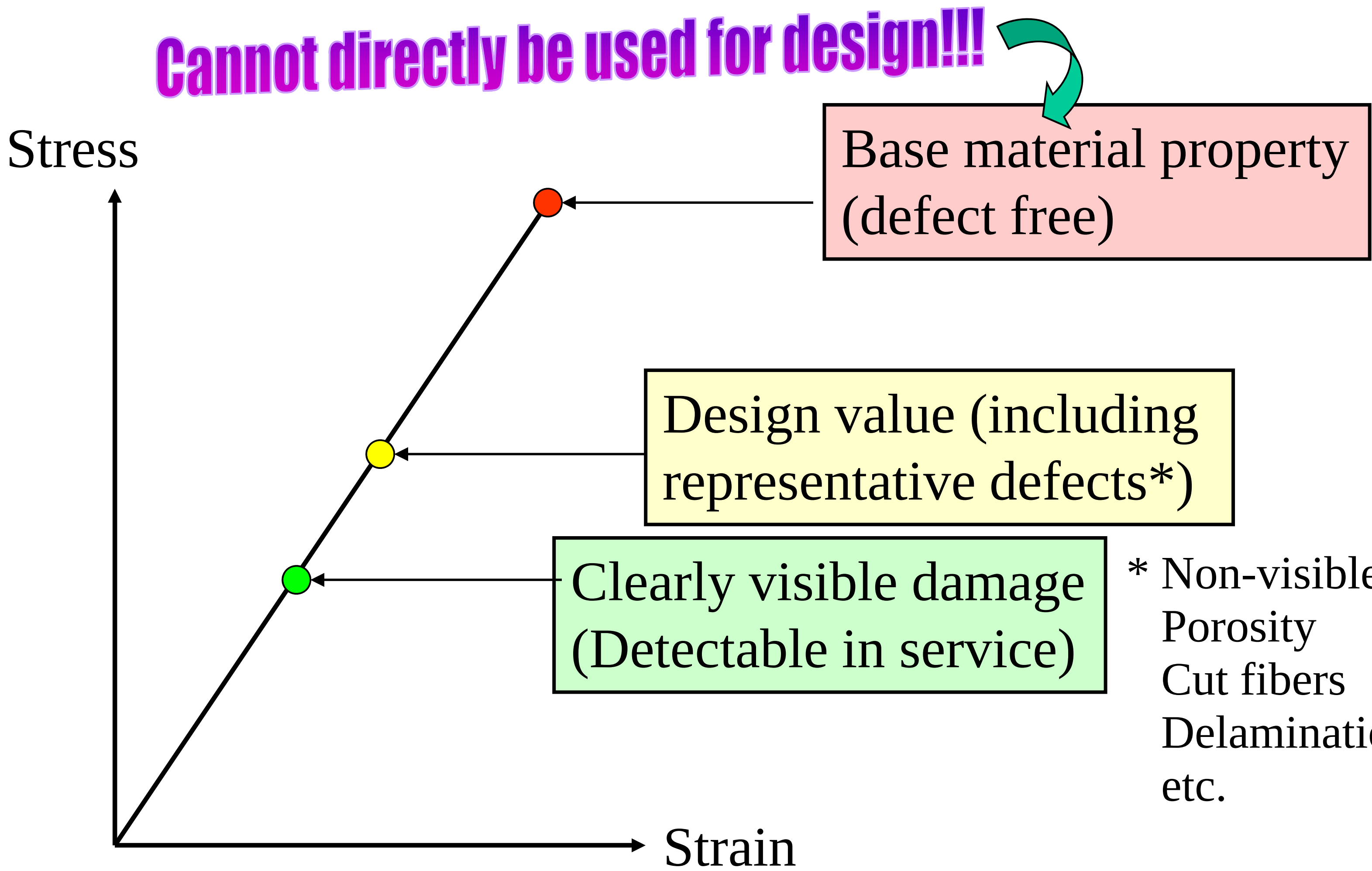
Allowed Strength for a Composite Design must Account for Defects and Damage



* Non-visible impacts
Porosity
Cut fibers
Delaminations
etc.

General Structural Design Load and Damage Considerations

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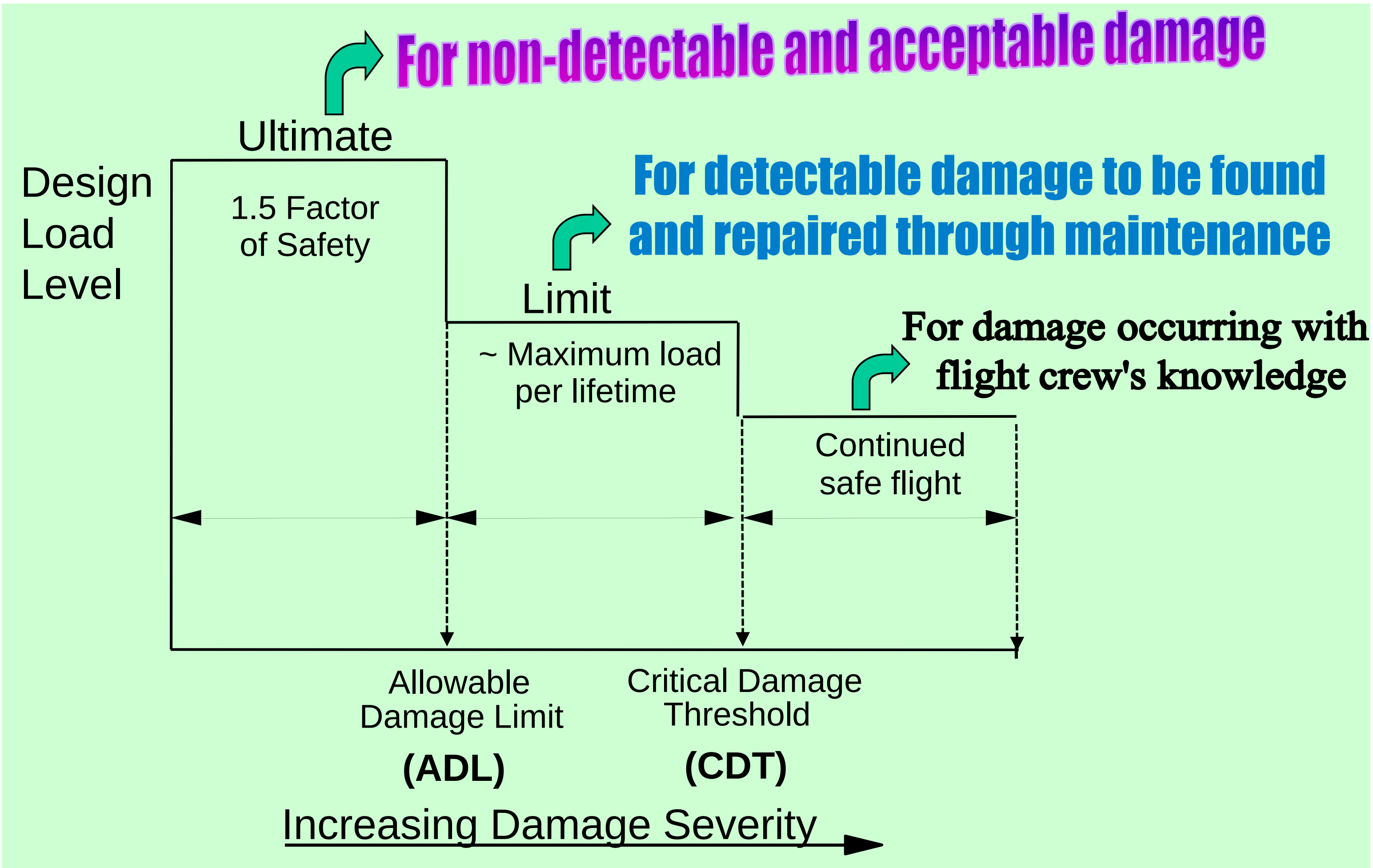

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Key Composite Behavior

- Relatively flat S-N curves & large scatter for repeated load cases
  - Relatively high repeated loads needed for growth
  - Load enhancement factors used to show reliability
- Environmental effects require careful consideration
- Relatively large manufacturing defects and impact damage are considered in design criteria
- Compression & shear residual strength are affected by damage *(critical for many structures)*
- Similar tensile residual strength behavior to metals *(e.g., strength versus toughness trades)*
- Limited service experiences yield unknowns

Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

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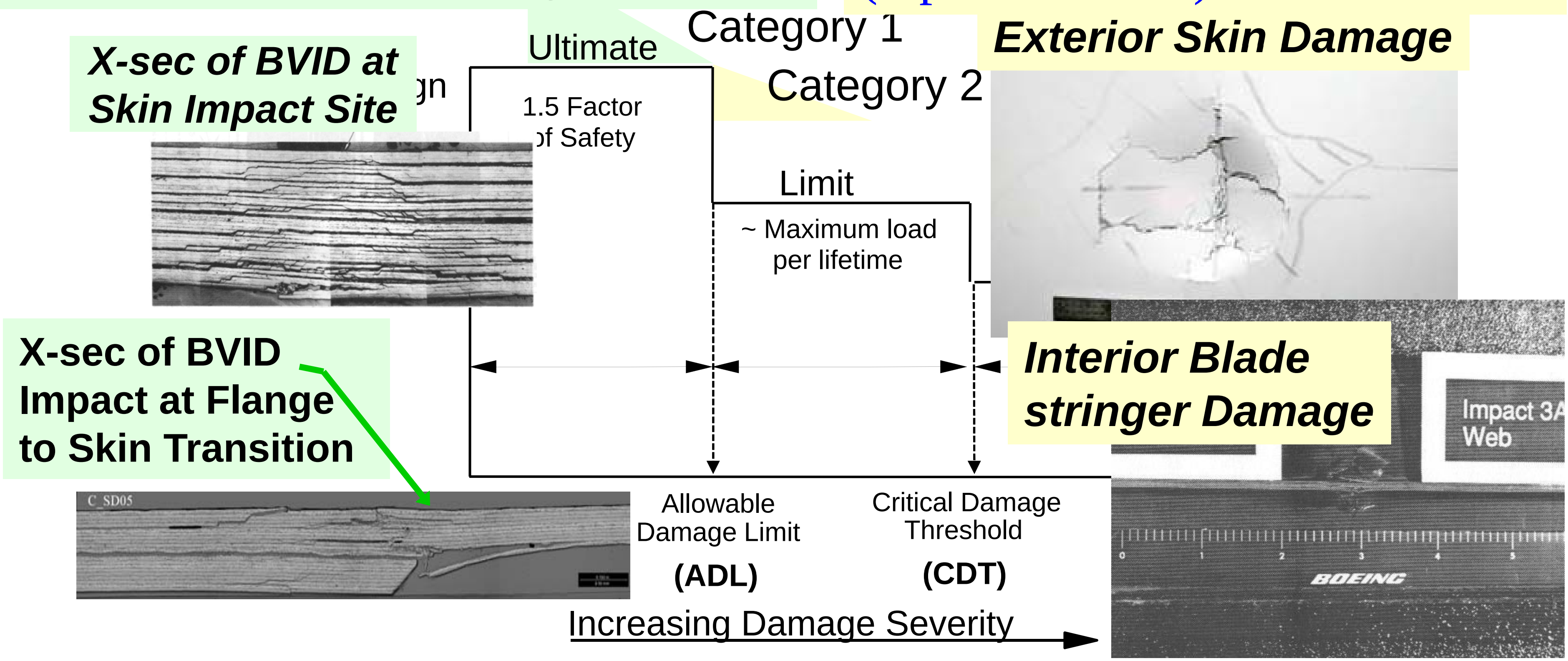
Category	Examples (not inclusive of all damage types)
Category 1: Allowable damage that may go undetected by scheduled or directed field inspection (or allowable manufacturing defects)	BVID, minor environmental degradation, scratches, gouges and allowable mfg. defects that must retain ultimate load for the specified life
Category 2: Damage detected by scheduled or directed field inspection @ specified intervals (repair scenario)	VID (ranging small to large), deep gouges, mfg. defects/mistakes, major *local* heat or environmental degradation that must retain limit load until found
Category 3: Obvious damage detected within a few flights by operations focal (repair scenario)	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
Category 4: Discrete source damage known by pilot to limit flight maneuvers (repair scenario)	Damage in flight from events that are obvious to pilot (rotor burst, bird-strike, lightning, exploding gear tires, severe in-flight hail)
Category 5: Severe damage created by anomalous ground or flight events (repair scenario)	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

Categories of Damage

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

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



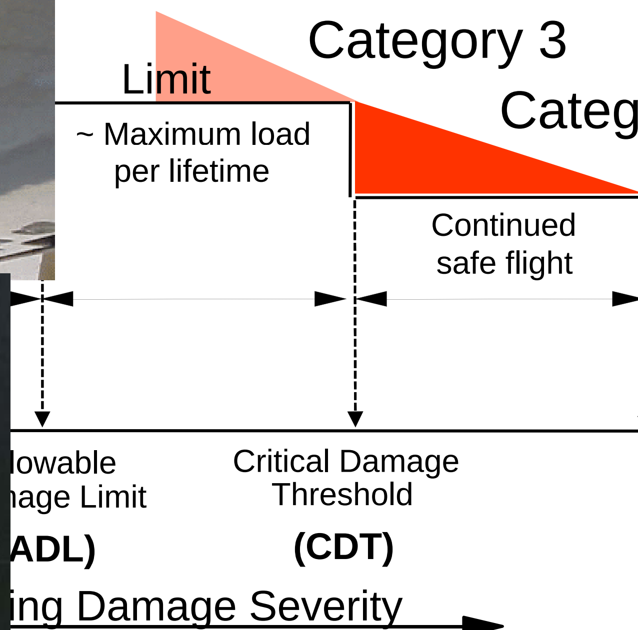
Categories of Damage

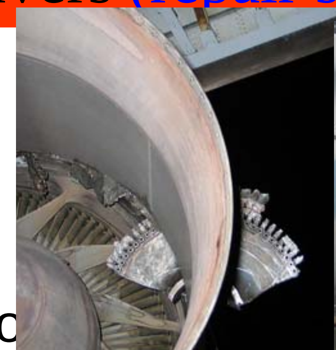
Category 3: Obvious damage detected within a few flights by operations focal (repair scenario)

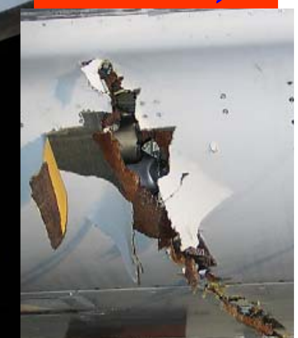
Category 4: Discrete source damage known by pilot to limit flight maneuvers (repair scenario)

Accidental Damage to Lower Fuselage

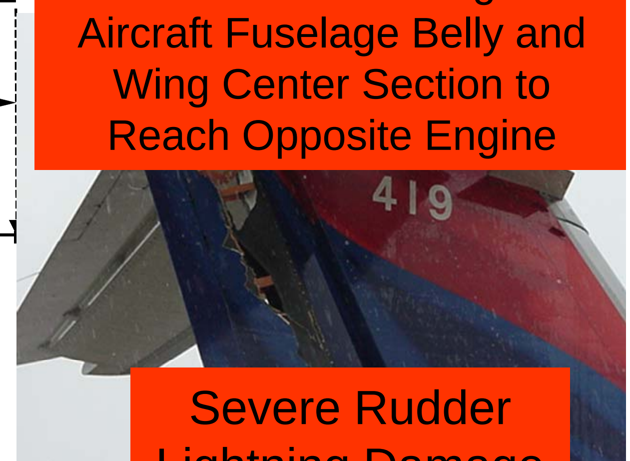
Lost Bonded Repair Patch







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



Severe Rudder Lightning Damage

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Categories of Damage

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

Boeing 737 Composite Horizontal Development and Certification

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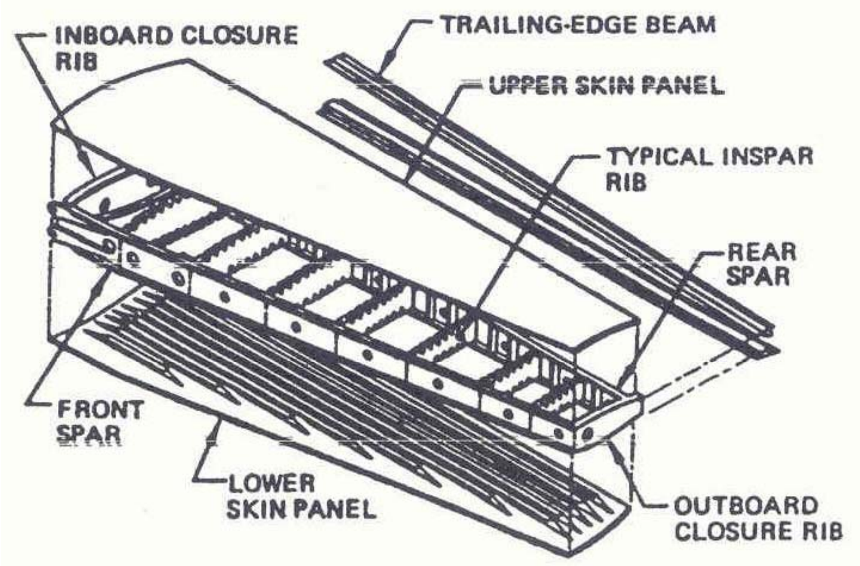
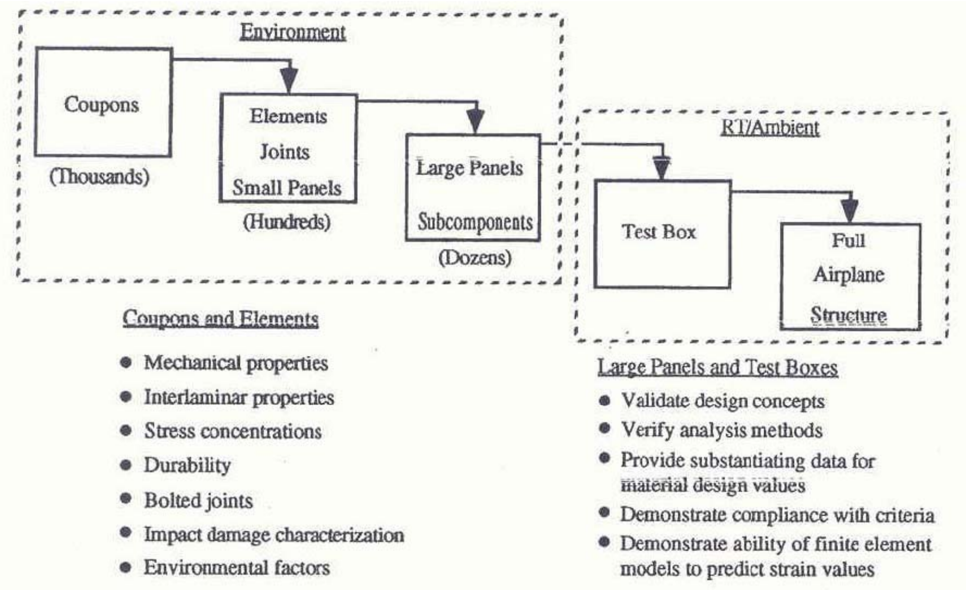
Developed and certified under NASA Aircraft Energy Efficiency, ACEE, program (1977-1982)

NASA ACEE 737 Horizontal Stabilizer Structural Arrangement



Building Block Approach



Taken from: "Structural Teardown Inspection of an Advanced Composite Stabilizer for Boeing 737 Aircraft," D. Hoffman, J. Kollgaard and Matthew Miller, 8th Joint FAA/DoD/NASA Aging Aircraft Conference, January, 2005.

Service Experiences for Boeing 737 Composite Horizontal Stabilizer

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- Five shipsets entered service in 1984
- Structural inspection program that included detailed visual inspection, with some pulse-echo ultrasound in specific areas to collect fleet data
- Four significant service-induced damage events to main torque box structure as of 2001 technical paper:
  - (1+2) De-icer impact damage to upper surface skins
  - (3) Fan blade penetration of lower surface skin
  - (4) Severe impact damage to front spar web and upper & lower chord radii

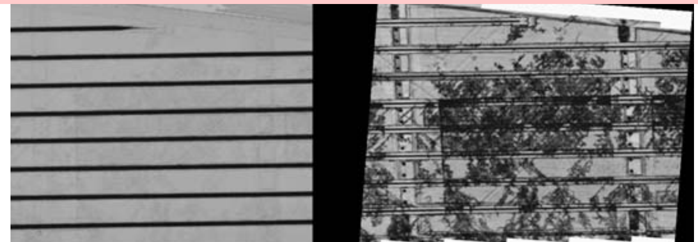
Taken from: "Composite Empennage Primary Structure Service Experience," G. Mabson, A. Fawcett and G. Oakes, CANCOM Conference, Montreal, Canada, August 2001.

B737 Horizontal Stabilizer Teardown Inspection

FAA

- Inspections found little deterioration due to wear, fatigue, or environmental factors
- Production NDI results indicated that today's factory "standard" is advanced beyond that of early 1980s
  - High levels of porosity are evident in much of the composite structure
- Mechanical tests of coupons and elements cut from B737 stabilizers had residual strength equivalent to those obtained more than 20 years ago

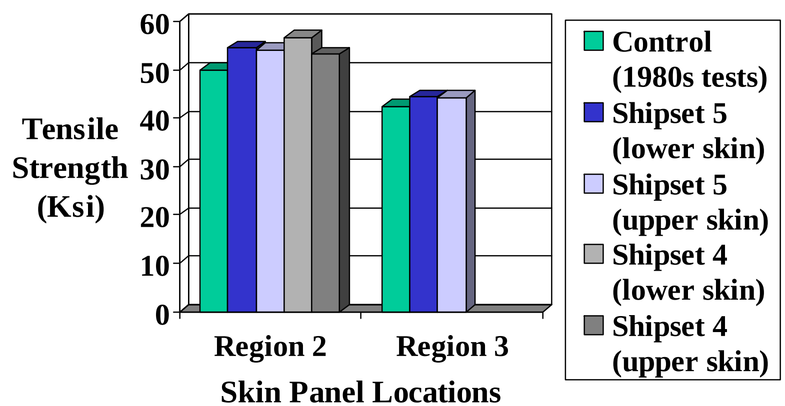
Factory Ultrasonic Scans of Skin Panels



1980's Vintage 1 MHz ATTU

Today's 3.5 MHz Thin Film Pulse Echo

Residual Strength After Service



History of Composite Service Problems

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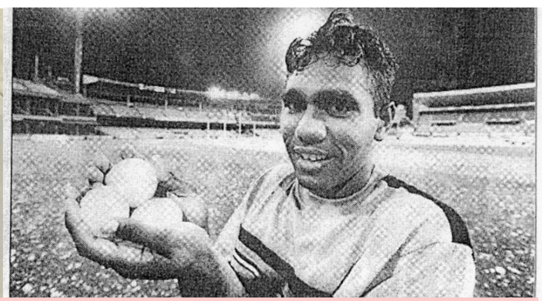
- Composites used in fragile, thin-gaged control surfaces and secondary structures pose some problems for airlines
  - Prone to damage from impact and environmental exposures (has not proved to be a safety issue, instead it has been an economic burden)
  - In many cases, the problems can be traced to bad design details
- Lack of industry standardization and training for maintenance

Dents and Punctures on Boeing 757 Inboard Aft Flap (thin skin of composite sandwich)



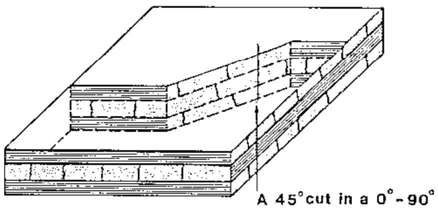
Example of Hail Damage from 1999 Sydney Storm

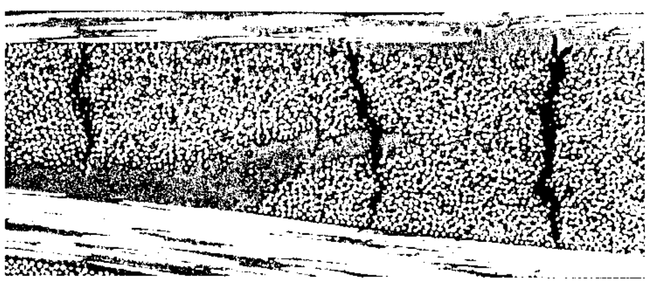
Dents on Boeing 777 Aft Flap (thin skin metal bonded sandwich)

Environmental Durability Problems from Early Use of Aramid/Epoxy Materials

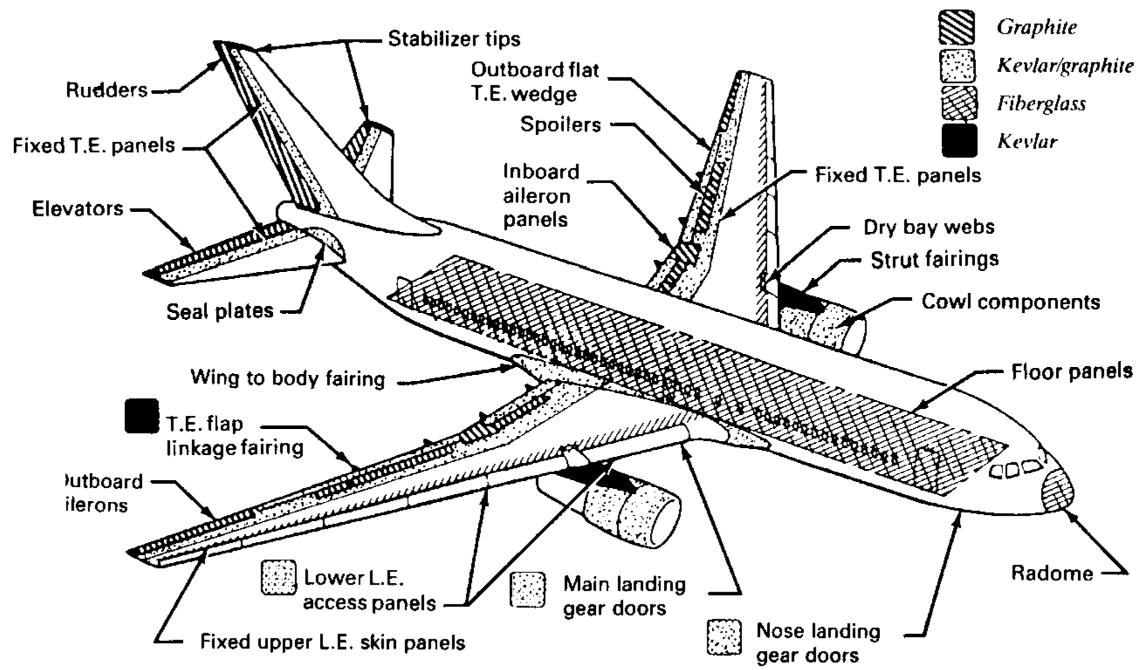
FAA

Transverse Matrix Cracking (TVM) of aramid/epoxy sandwich facesheets yielded a path for water ingression into honeycomb core





Electron Micrograph of TVM in Fabric



Boeing 767 Aircraft Developed in 1980s

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Recovery of AA587 Vertical Fin from Jamaica Bay, New York

Fuselage Attachment Structure at the AA587 Accident Site in Belle Harbor, New York

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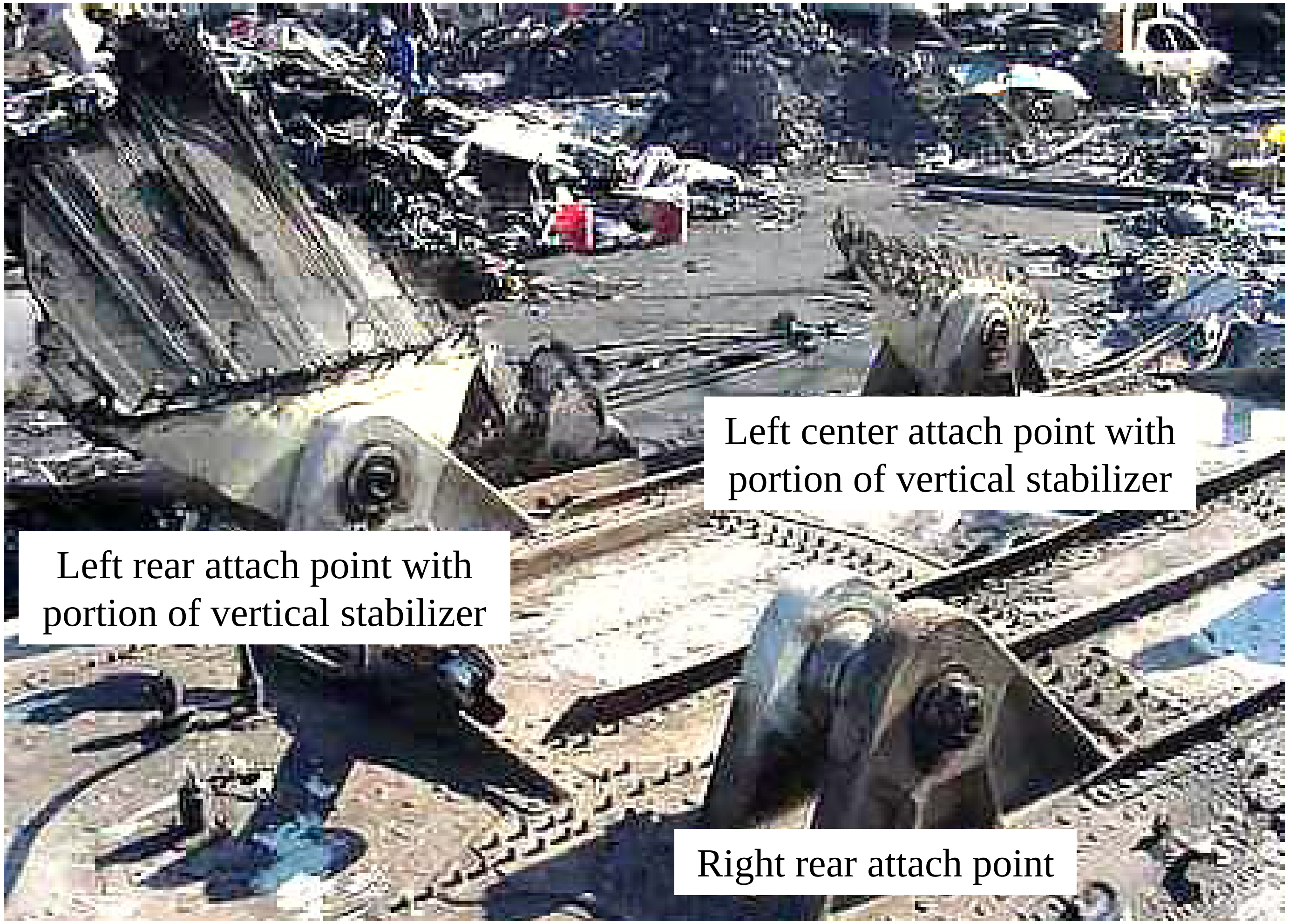

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Two Main Branches of the Fault Tree Being Studied for the AA587 Accident

Vertical Fin Failure

Vertical Fin Capability Less Than Expected

- Structural design
- Manufacturing quality
- Material degradation
- Service event and maintenance

Vertical Fin Loads Greater Than Expected

- Upset condition (e.g., wake vortex/turbulence)
- Rudder problems
- Loss of flight stability and control
- Pilot input

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Barriers to Expanded Application

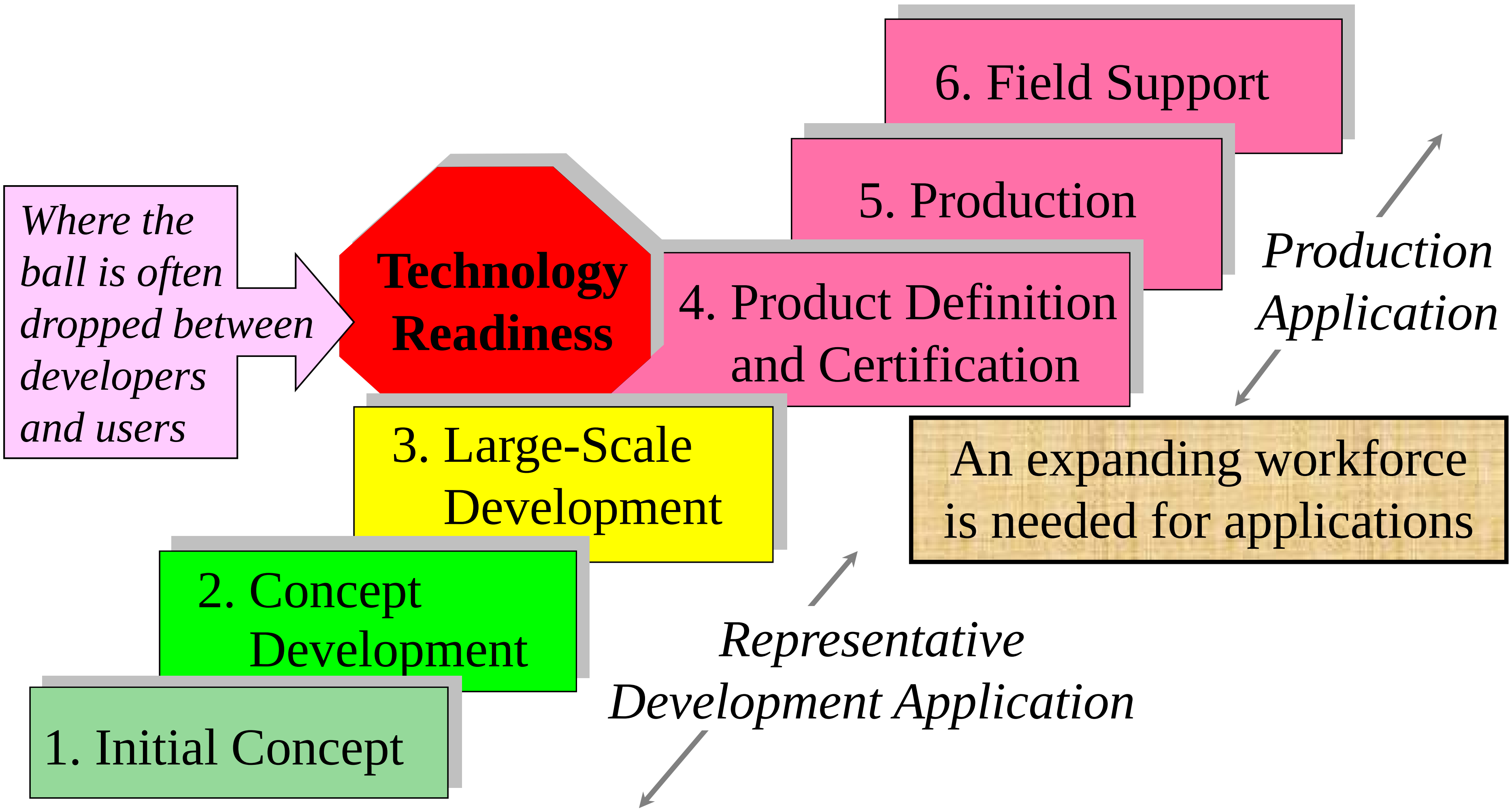
Transport Aircraft

- Manufacturing cost
- Non-recurring development costs
- Maintenance technology
- Limited resources with sufficient training (engineers & technicians)
- Lack of standardization

Small Airplanes and Rotorcraft

- Manufacturing cost
- Need to reach high production rates
- Maintenance technology
- Limited resources with sufficient training (engineers & technicians)
- Lack of stable material supplier base
- Lack of standardization

Consider Six Stages of Material Development and Application



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Definitions of Scaling Types

Size Scaling

Efforts to apply information at one scale of study to predict the behavior at a larger, more complete level

Product Scaling

Efforts to verify a technology basis, which links design components, factory process cells, maintenance procedures, and cost evaluations

References for charts 43 through 47

a) "Composite Technology Development for Commercial Airframe Structures," L.B. Ilcewicz, Chapter 6.08 from *Comprehensive Composites* Volume 6,, published by Elsevier Science LTD, 2000

b) "Composite Applications in Commercial Airframe Structures," L.B. Ilcewicz, D.J. Hoffman, and A.J. Fawcett, Chapter 6.07 from *Comprehensive Composites* Volume 6,, published by Elsevier Science LTD, 2000

Examples of Size Scaling

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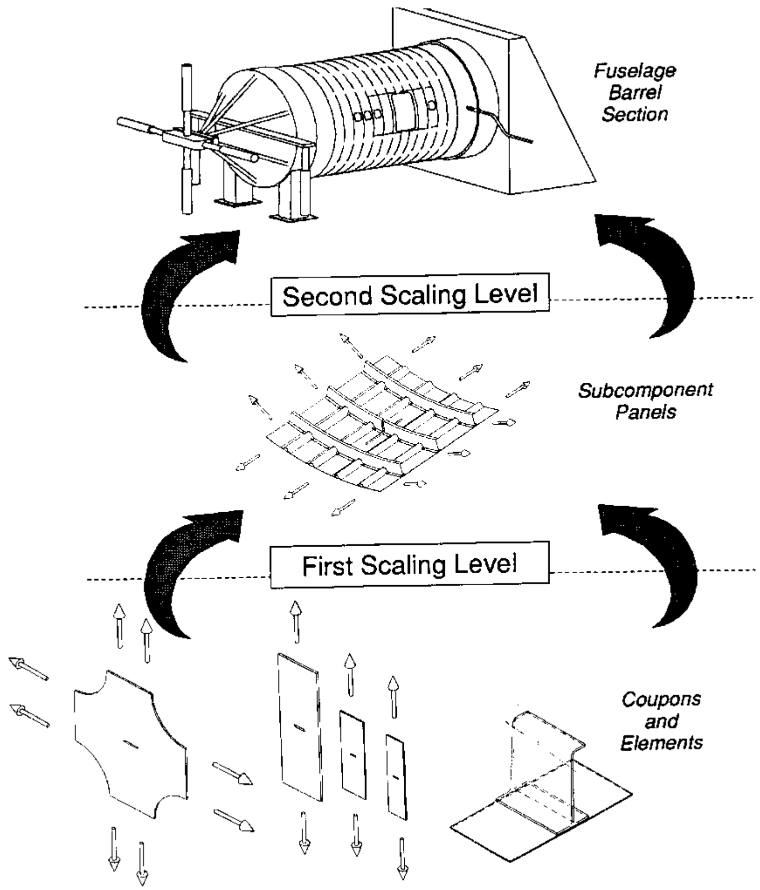
- Manufacturing
  - Process development
  - Tooling trials
  - Material & process control
- Structures
  - Design criteria, requirements and objectives
  - Building block tests & analysis for internal loads, including the effects of environment
- Maintenance
  - Inspection procedure development
  - Repair process development
  - Repair building block tests & analysis
- Manufacturing, structures and maintenance methods & procedures

Example: Fuselage Damage Tolerance



Examples of Product Scaling

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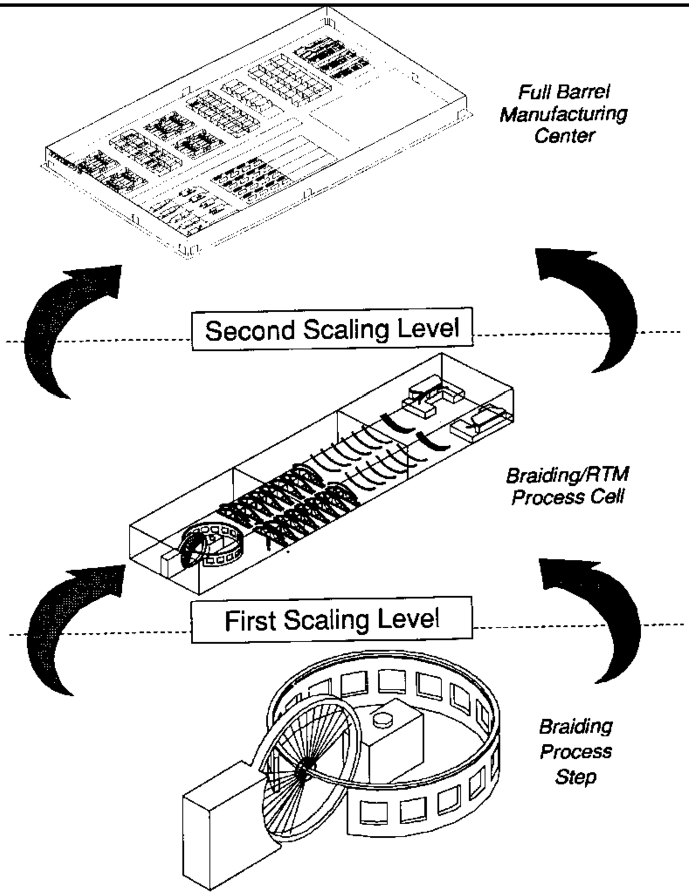
- Product Viability
  - Direct operating costs (acquisition, fuel, maintenance)
  - Performance (range, payload, speed)
  - Market (# aircraft, timing, external factors)
- Factory Definition
  - Floor space and process flow
  - Quantity of equipment and tools
  - Quality and process controls
  - Staffing needs
- Certification
  - Design, manufacturing, and maintenance definition/documentation
  - Design, manufacturing, and maintenance verification (material qualification, mfg. conformity and structural substantiation)

Example: Braided/RTM Fuselage Frames



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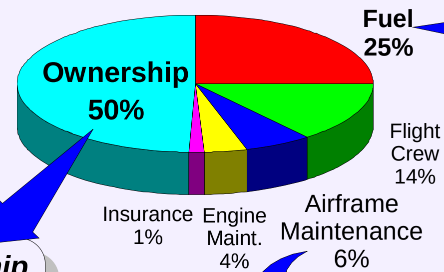
Product Value Assessment of New Technology

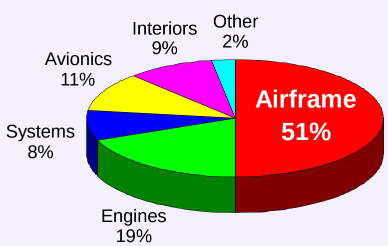
Composite technology is of interest in new aircraft products of all types because it can help decrease total direct operating costs (DOC) in 3 key areas (see example below from transport aircraft)

Typical Components of Total DOC



(1) Potential for lower manufacturing costs

Components of Ownership



Life-cycle cost related to structural weight savings

(3) Proven weight savings reduce fuel costs

Life-cycle cost related to structural reliability, inspectability, and repairability

(2) Potential for lower maintenance costs

Total DOC savings on the order of 5 to 8% appear possible with composites applied to both transport wing and fuselage

Reduced Cycle Time to Market is Equally Important to Increased Product Value

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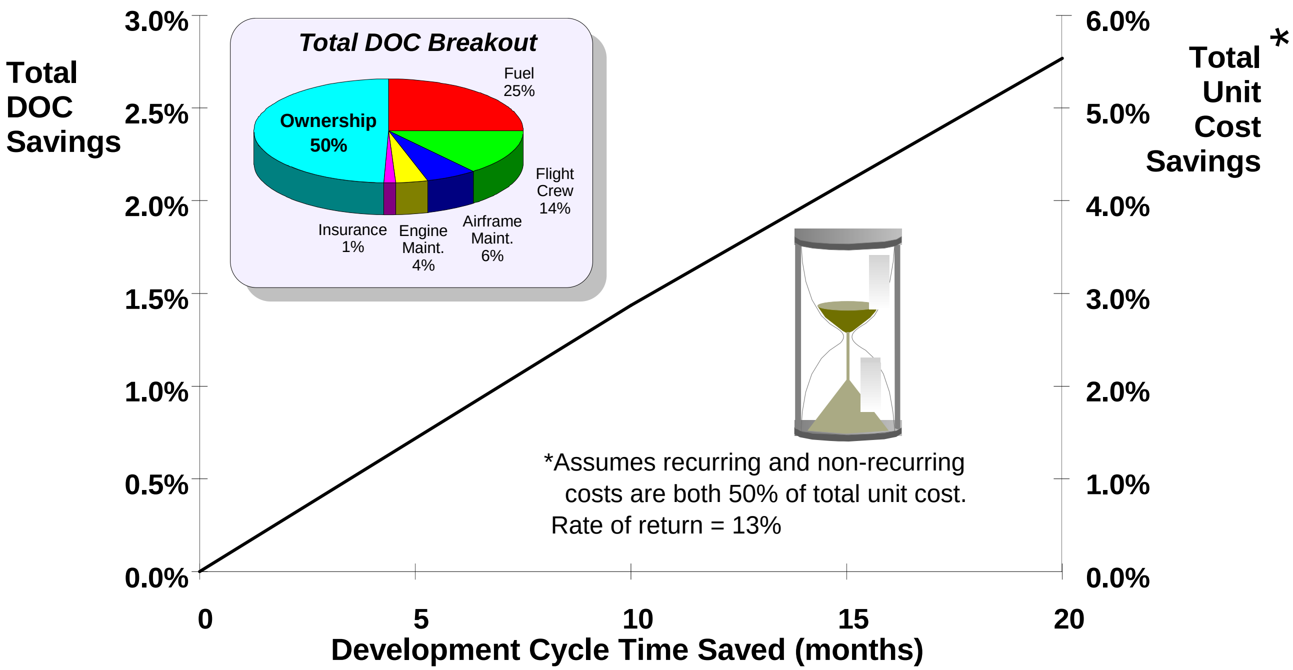
Unless new composites technology becomes as assessable to the engineering community as metals, Total DOC benefits are lost



Lack of composite standardization and engineering resource dilution pose serious safety & certification issues and limit aircraft product applications

Ongoing FAA Composite Safety and Certification Initiatives

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- Actively working with industry since 1999

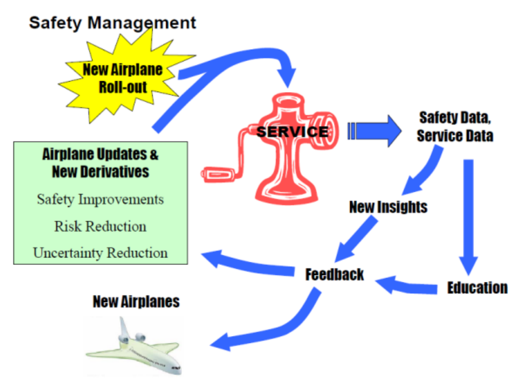
Objectives

1) Work with industry, other government agencies, and academia to ensure safe and efficient deployment of composite technologies used in existing and future aircraft

2) Update policies, advisory circulars, training, and detailed background used to support standardized composite practices

- Safety management (airworthiness) Task Groups initiated within composite industry standards organizations (CMH-17, CACRC)

Approach Following Principles of Safety Management



Composite Technical Thrust Areas

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Advancements depend on close integration between areas

Material Control, Standardization and Shared Databases

Damage Tolerance and Maintenance Practices

- Critical defects (impact & mfg.)
- Bonded structure & repair issues
- Fatigue & damage considerations
- Life assessment (tests & analyses)
- Accelerated testing
- Structural tear-down aging studies
- NDI damage metrics
- Equivalent levels of safety
- Training standards

Progress to Date

- AC 20-107B (9/09)
- 2 other Advisory Circulars
- 6 Policy Memos
- 11 Workshops
- 3 Training Initiatives
- 2 Technical Documents
- CMH-17 Updates
- SAE CACRC Standard
- ~50 FAA R&D Reports

Structural Substantiation

- Advances in analysis & test building blocks
- Statistical significance
- Environmental effects
- Manufacturing integration

Flammability & Crashworthiness

Support to cabin safety research groups

Bonded Joint Technical Issues

Advanced Material Forms and Processes

Significant progress, which has relevance to all aircraft products, has been gained to date

FAA Approach to Composite Safety and Certification Initiatives

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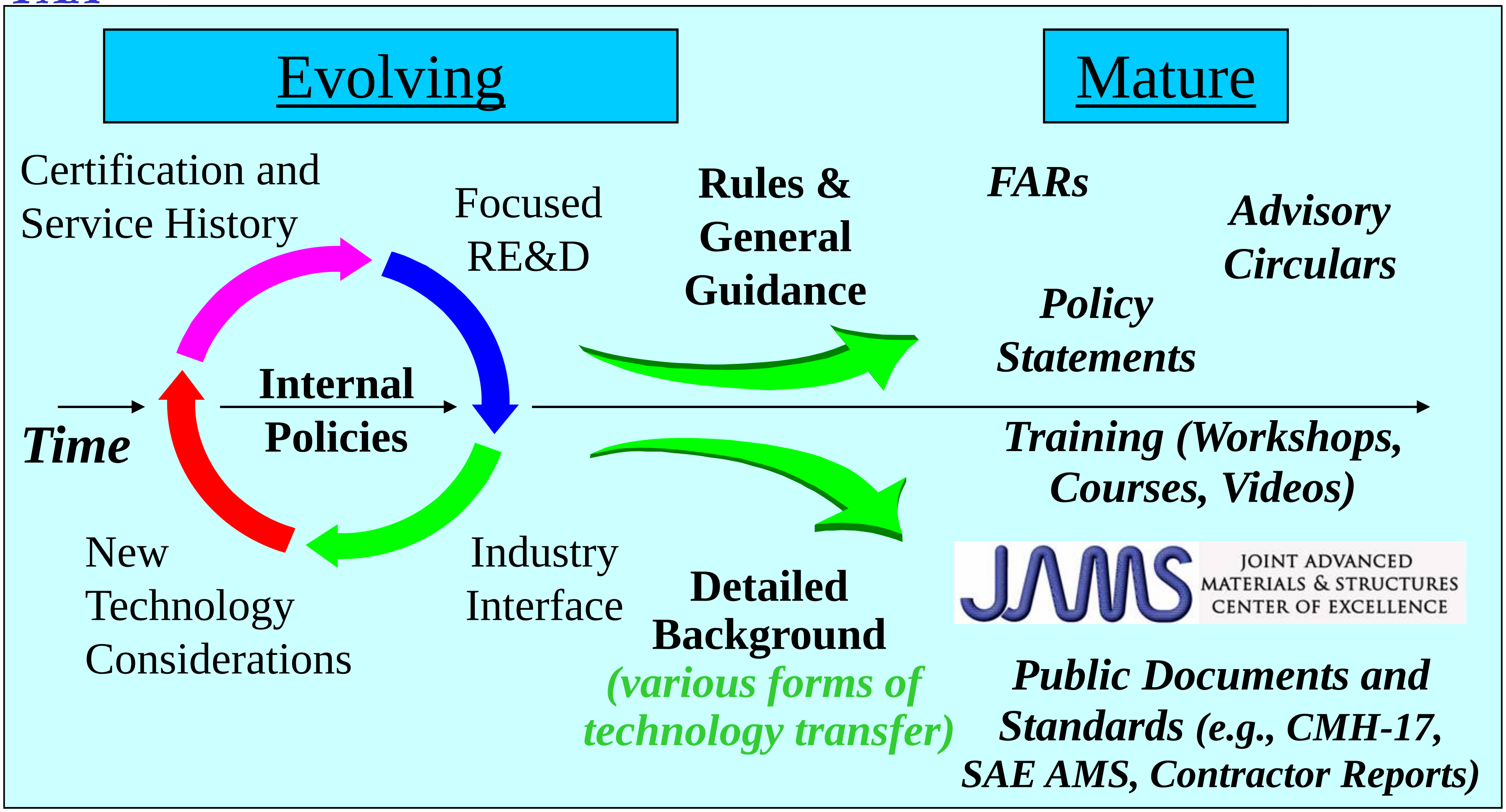

Important Teammates

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- **Partnerships with industry have been essential,** e.g., CMH-17, SAE P-17, CACRC, ASTM, SAMPE, AGATE, SATS, RITA, SAS/IAB/AACE

Training
Databases
Standardization
Engineering guidelines

- **NASA research and other support**
  - Significant research support since 1970/1980s
  - AA587, A300-600 accident investigation
- **DOD and DARPA research**
  - NCAMP support to material standardization
- **EASA and other foreign research/standardization**

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FAA Joint Advanced Materials and Structures (JAMS) Centers of Excellence

New FAA JAMS Centers of Excellence to provide research and training in support of expanding composite applications

CECAM
center of excellence for composites and advanced materials

FAA Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Wichita State University

- Northwestern University
- Purdue University
- Tuskegee University
- University of California at Los Angeles
- University of California at San Diego
- University of Delaware

University of Washington

- Edmonds Community College
- Oregon State University
- Washington State University
- University of Utah
- Florida International University

Past Milestones for Composite Safety & Certification Policy, Guidance & Training

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- ▼ (blue) Material & Process Control and Shared Databases
- ▼ (green) Bonded Joints & Structures
- ▼ (purple) Other CS&CI Initiatives

Policy on material selection guideline (ΔT rule)

Initiated sandwich damage tolerance studies

Initial material qualification and equivalency policy

AGATE Shared Database Workshop

Composite Structural Development Workshop

CS&CI 7-Year Plan

TTCP Bonded Structures Certification Document

UCSB Peel Ply Research

FAA/NASA/Industry Structures Workshop

Static Strength Substantiation Policy and Workshop

Italian Industry Shared Database Workshop

NTSB/Airbus/NASA/FAA AA Flt587 Accident Investigation (A300 Composite Vertical Fin)

New Rule & AC for Rotorcraft Fatigue & DT

FAA/Industry Prepreg M&P Spec. Workshop

NTSB/FAA/WSU SH Nimbus Accident Investigation

CMH-17 Revision F

Start Bonded Structures Initiatives

FAA/Industry LRM M&P Spec. Workshop

Update material qualification and equivalency policy

Composite Cert. Roadmap Tech. Doc.

Prepreg M&P Spec. Advisory Circular

ASTM Workshop for Composite Fracture

Secondary Structures Policy

FAA/Industry Bonded Structures Workshop I

FAA/Industry Bonded Structures Workshop II

FAA/Industry Composite Maintenance Training Workshop I

TSB/NTSB/FAA/Airbus Rudder Investigation

FAA Bonded Structures Policy

Draft Composite Maintenance Training Modules, FAA Technical Document & Workshop II

FAA/EASA/Boeing/Airbus DT & Maintenance WG

1999	2000	2001	2002	2003	2004	2005

Recent Milestones for Composite Damage Tolerance and Maintenance Initiatives

FAA

FAA/NRC Workshop (5/04) Composite Maintenance Overview

FAA Seattle Workshop (11/04) Initiate Composite Maintenance Training (CMT)

JAMS CMT Develop. (11/04-7/05) Draft Course Objectives/Modules

FAA/Industry CMT Workshop (9/05) Detailed CMT Review

Airbus/Boeing FAA/EASA Composite Damage Tolerance & Maintenance WG

Toulouse (9/05) Seattle (3/06)

Presentations, recaps and breakout session summaries at:
http://www.niar.wichita.edu/niarworkshops/

JAMS CMT Develop. (7/06-6/07)
SAE CACRC Course Standard

FAA/EASA/Industry Damage Tolerance & Maintenance Workshops

Chicago (7/06) Amsterdam (5/07)

FAA/EASA/TCCA WG Draft CMH-17 Certification and Compliance Chapter, V3C3 (9/07)

Ongoing CMH-17 Revision G Developments (2005-2007)

2004	2005	2006	2007

Future milestones for Composite Safety & Certification Guidance and Training

FAA

Release CMH-17 Revision G

- *Advances in statistics, test methods and data reduction protocol*
- *Major Volume 3 re-organization*
- *New Volume 6 (Sandwich)*
- *New certification & compliance chapter*
- *New crashworthiness chapter*
- *New safety management chapter*
- *Updates to damage tolerance & maintenance*

Implement Composite Maintenance Awareness Course

High Energy Blunt Impact Awareness

Release AC 20-107B (Composite Aircraft Structure)

NCAMP shared databases and specifications (CMH-17, SAE AMS)

New CACRC Airworthiness TG Initiatives (major repair)

FAA/Industry education initiatives

Composite damage tolerance guidance

Crashworthiness rule & guidance

2009	2010	2011	2012	2013

Career Challenges in Composites

- Numerous challenges in design/manufacturing integration require multiple engineering skills and teamwork
- Skills to advance manufacturing methods (i.e., tooling, process modeling, automation, quality controls, equipment design)
- Business/eng. skills to overcome economic issues, which limit applications (design cost and business case analyses)
- Skills to combine analysis methods, databases and engineering tools to evaluate the effects of damage and defects
- Skills to advance maintenance procedures (i.e., repair and NDI)
- Research and teaching skills with close links to applications (applied R&D, distance learning and continuous education)
- Willingness to lead or support a team, depending on the project