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Through Innovative Minds

Advanced Development Programs

CURRENT STATE-OF-THE-ART IN COMPOSITE FIXED-WING AIRFRAME DESIGN, ANALYSIS, AND CERTIFICATION

SME AEROSPACE COMPOSITE FORUM

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Presentation Outline

- Background and Objectives
- Airframe Design, Analysis, and Certification Process
  - Top-Level View of Technical and Programmatic Issues
  - Building-Block Certification Logic
  - Composite and Metallic Damage Tolerance
- Ramifications for Air System Risk vs Efficiency
  - Overall Air System Priorities vs Airframe Cost/Performance
  - Composites vs Metals for Various Airframe Components
- Ideas for Innovation and Research
  - Basic Research
  - Bridging the Final TRL Gap

Background

… written in 2013…

- **Over the past 10-20 years, there has been a growing disconnect between the basic/applied research communities and production airframe development programs regarding composite structures development and application:**
  - *While military programs were early adopters of advanced composites in the 1970's and 1980's, usage and materials have plateaued, despite continued composites R&D spending.*
  - *Fixed-wing civil aircraft use of composites started more slowly but has recently increased dramatically.*

Objectives

The objectives of this presentation are:

- *Provide a cursory overview of how aerospace OEM's currently design, analyze, and certify composite parts, and why they do so;*
- *What this current-SOTA approach means in terms of overall programmatic risk and cost/performance efficiency; and*
- *What basic and/or applied research could be done to improve this situation.*

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Airframe Design, Analysis, and Certification Process

Top-Level Technical and Programmatic Issues:

- *Overall scope (non-recurring cost/span, strategic teaming/sub-contracting, recurring-cost, anticipated production quantity/span, mods/sustainment/lifecycle cost-span, etc) is defined by similar legacy programs and current customer requirements.*
  - *New programs must generally stay within the historical norms;*
  - *Airframe structure is a relatively minor part of the overall program scope, and generally targeted to be low-risk and not the biggest cost- or schedule-driver (though it sometimes becomes so).*
- *Different decision-making in various phases of air vehicle lifecycle:*
  - *Pre-design*
  - *Lay-out*
  - *Drawing-release*
  - *Full-Scale-Testing*
  - *Final Strength Summary & Operating Restrictions*
  - *Factory MRB support*
  - *Field support*
  - *Modification, repair, sustainment, life-extension*

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Airframe Design, Analysis, and Certification Process

Top-Level Technical and Programmatic Issues, Roles and Responsibilities:

- *Designers determine form/fit/function and influence manufacturing, assembly, and make/buy sourcing decisions.*
- *Stress Analysts assure static and fatigue structural integrity, organize/lead structural certification process, and influence weight efficiency.*
- *Materials and Process, and Manufacturing Engineers insure that raw materials and manufacturing/assembly processes are reliable/repeatable and in control.*
- *Integrated Product Teams work together to make optimum collective decisions regarding airframe weight/cost/span;*
  - *Many non-structural constraints drive airframe design decisions, including machining and assembly limitations, fuel/environmental sealing, systems installation, maintenance access, etc.*
  - *Generally, IPT's choose whichever material or manufacturing process works best for each individual part, or as a system.*

Form/fit/function and applied loads generally determine material choice (no bias for or against particular materials or processes)

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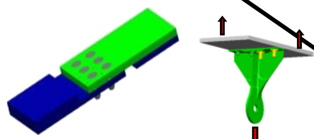
Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic:

From McSwiggen/Burt ASIP paper (2009)

Structure Design Criteria (SDC)

Define Strength Requirements

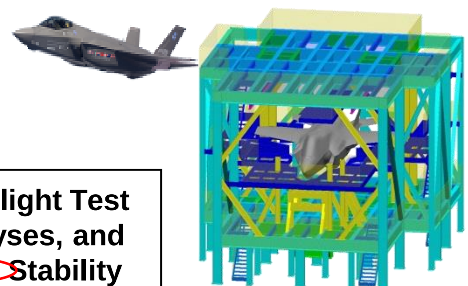


Coupon and Element Tests Generate Allowables for Critical Environments, Failure Modes, Effects of Defects, etc

B-basis allowable statistics

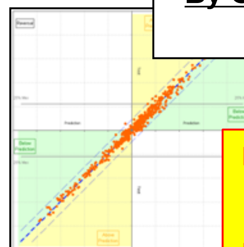
20% metal
40% composite
40% hybrid/other

Flexible span



Full Scale Ground and Flight Test Verifies Structural Analyses, and demonstrates Strength, Stability and Loads for critical points on the envelope.

True for civil, less-so for military



Structural Loads, Models, Methods and Analysis <u>Validated By Comparison to Test Measured Data</u>

FSST = AVFEM internal loads validation

FSDT = DaDT control point validation

Structure Certified for Full Envelope Flight

Airframe Strength is Certified Based on Final Strength Analyses That Incorporates Final Allowable Flight Loads, <u>Validated Internal Loads Models</u> & Stress Analysis Methods

See next chart

Certification by Analysis *(25k load cases)*, ***Supported by Test*** *(a few-100 sub-element configurations to validate strength methods)*

Sub-element data often from legacy programs

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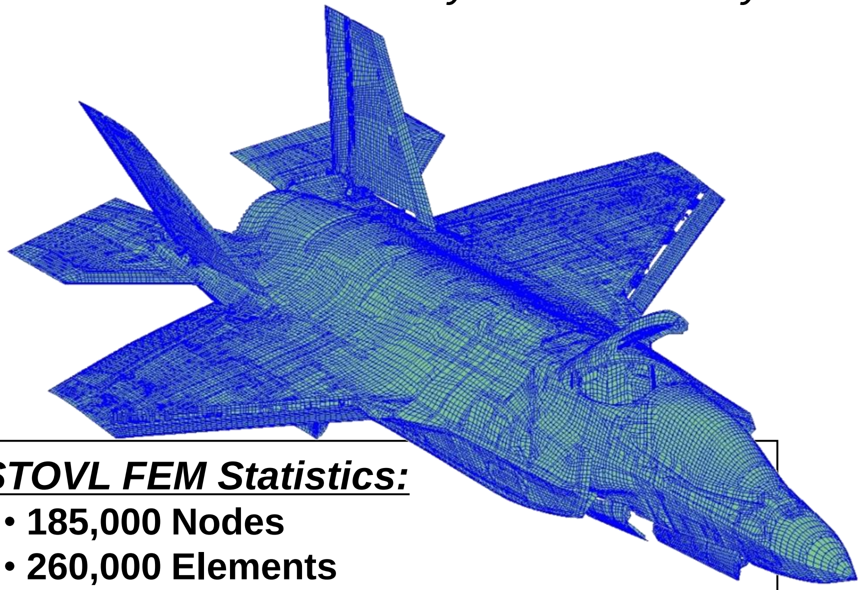
Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Internal Loads-Development:

- *Performed by FEM specialists at Air-Vehicle-level and IPT stress analysts at assembly- and component-levels.*



•STOVL aircraft structure is modeled and solved in numerous configurations based on parameters specified for any given load condition:

- **Positions of Control Surfaces**
- **Positions of Doors**
- **Positions of Landing Gear**
- **Engine Types**
- **Weapon Adapter Types**
- **Access Panel Stiffness Assumptions**

Cost/span = approximately 18 man-years over 9 months (industry average)

STOVL FEM Statistics:

- **185,000 Nodes**
- **260,000 Elements**
- **1,100,000 Degrees of Freedom**
- **26,194 Load Conditions**
- **2300 Configurations of Control Surface, Door and Gear Positions.**

Element Topology:

- **Skins, floors and webs modeled with SHELL elements.**
- **Stiffeners modeled with shell elements if the cross section is wide compared to its length and the resulting shell aspect ratios are acceptable, otherwise BEAM elements are used.**
- **3D (SOLID) elements are used for core applications and other areas where volume is significant as compared to surface area.**

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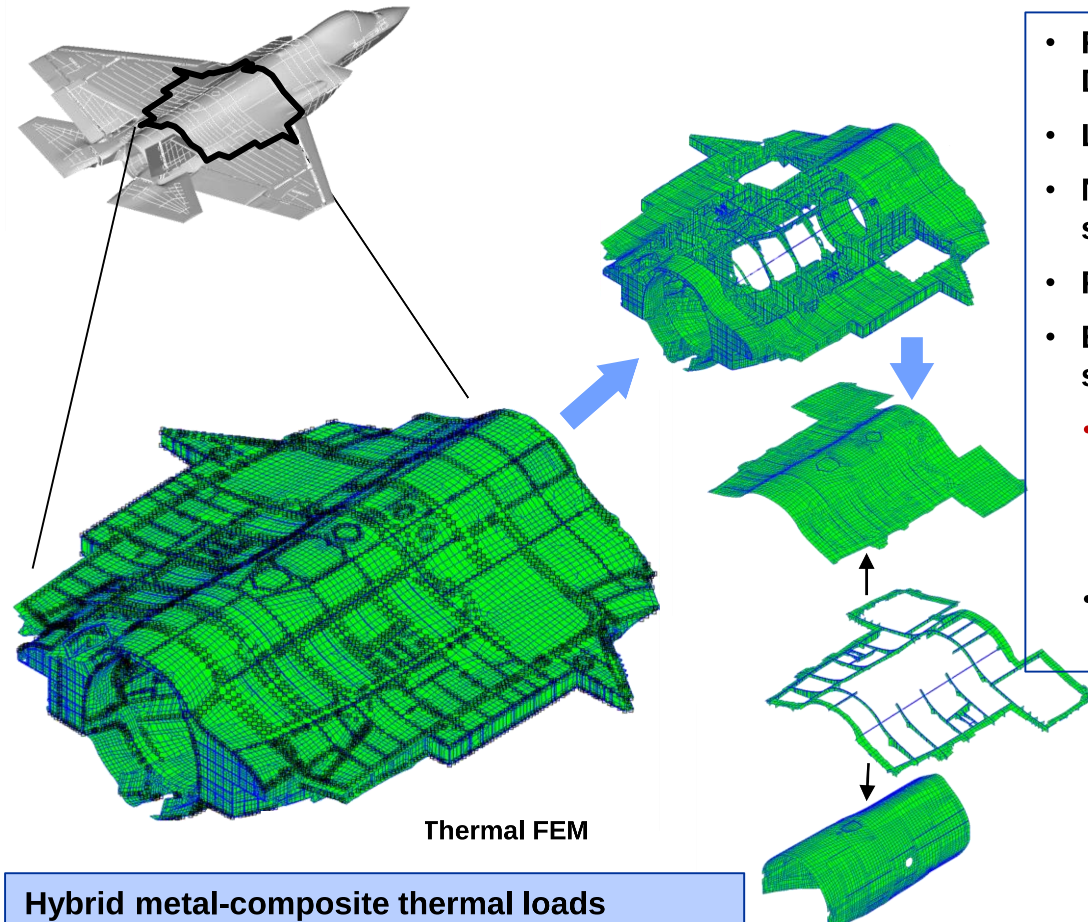
Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Internal Loads-Development:

- *IPT stress analysts build/run multiple fine-grid FEMs (fgFEMs) at assembly- and component-levels.*



Thermal FEM

- **Refined meshes yield FEMs with as many/more DOF than AVFEM**
- **Linear buckling always checked**
- **Non-linear response often also done (fuel pressure, snap-thru, etc)**
- **Fastener locations modeled with beam elements**
- **Element groups used to define mid-bays, lands, stiffeners, etc**
  - **Composite point stress analyses batch-post-processed for mid-bays, notch features, and each bolt location (not done w/in FEM) – very efficient**
  - **Metallic point stress analyses done in semi-automated manner using spreadsheets**

Hybrid metal-composite thermal loads captured by springing skins off sub-structure

<u>Generally (not for specific structure shown)</u>

Cost/span (stress ONLY) = approximately 1-3 man-months/part over 12 months

Span = 70% FEM-building, 30% batch-generation of MS's & report-writing

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Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Composite Stress Methods:

- Buckling Ratios-To-Requirements (not failure):
  - Linear Eigenvalues
  - Snap-Thru (nonlinear)
- Typical composite mid-bay MS's:
  - FHT/FHC for durability/repairability
  - Damage Tolerance MS only if fracture-critical (civil different, see later chart)
- Typical land MS's:
  - Bearing/by-pass
  - Bolt strength
  - Pull-thru
  - Interlaminar shear (ILS) - beam-shear, pressure, and/or heel-toe induced stress
- Edge-of-Part Notch MS's:
  - UNT/UNC at characteristic distance
- Hat (or similar features, like free flange) MS's:
  - Crippling
  - ILT/ILS in corners

Main objective of point stress analysis is to predict the *absence of failure*; not failure.

Thus, accuracy can be traded against simplicity/cost/span.

Examples of conservative deterministic rules which allow reduced cost/span:

- *Top-of-scatter loads, lower-bound strengths;*
- *1.50*DLL static factor of safety;*
- *Assume presence of damage;*
- *Design for 2+ lifetimes;*
- *No detrimental deformation at 1.15*DLL;*
- *No load redistribution;*
- *No damage growth (in composites);*
- *Fibers in (0/45/90) & stacking limited to 3 plies of same orientation*
- *Etc.*

Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Composite Allowables:

Why Notched-Strength Design Allowables Are Prevalent:

- *Enables much-reduced development cost/span relative to more-complex alternatives*
- *Accounts for typical manufacturing and design realities*
  - *Bag surfaces*
  - *Ply drops*
  - *Slight in-plane and out-of-plane fiber waviness*
  - *Fiber orientation deviation from design*
  - *Small inclusions / resin rich areas*
- *Allows for bolted repair*
- *Covers nuisance durability level damage criteria ("6 ft-lbs")*
- *Covers fatigue endurance (for fixed-wing airframe structures with modest ILS/ILT stresses)*
- *Usually covers DoD clearly-visible damage criteria*
  - *HW FHC or OHC < (1.5/1.15) x CSAI*
- *Caution – moving away from a notched-strain-controlled design would bring many of these items back into play*

Main objective of point stress analysis is to predict the *absence of failure*; not failure.

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Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Composite Stress Methods:

Element/Subcomponent/component tests may be static, durability, and/or residual strength

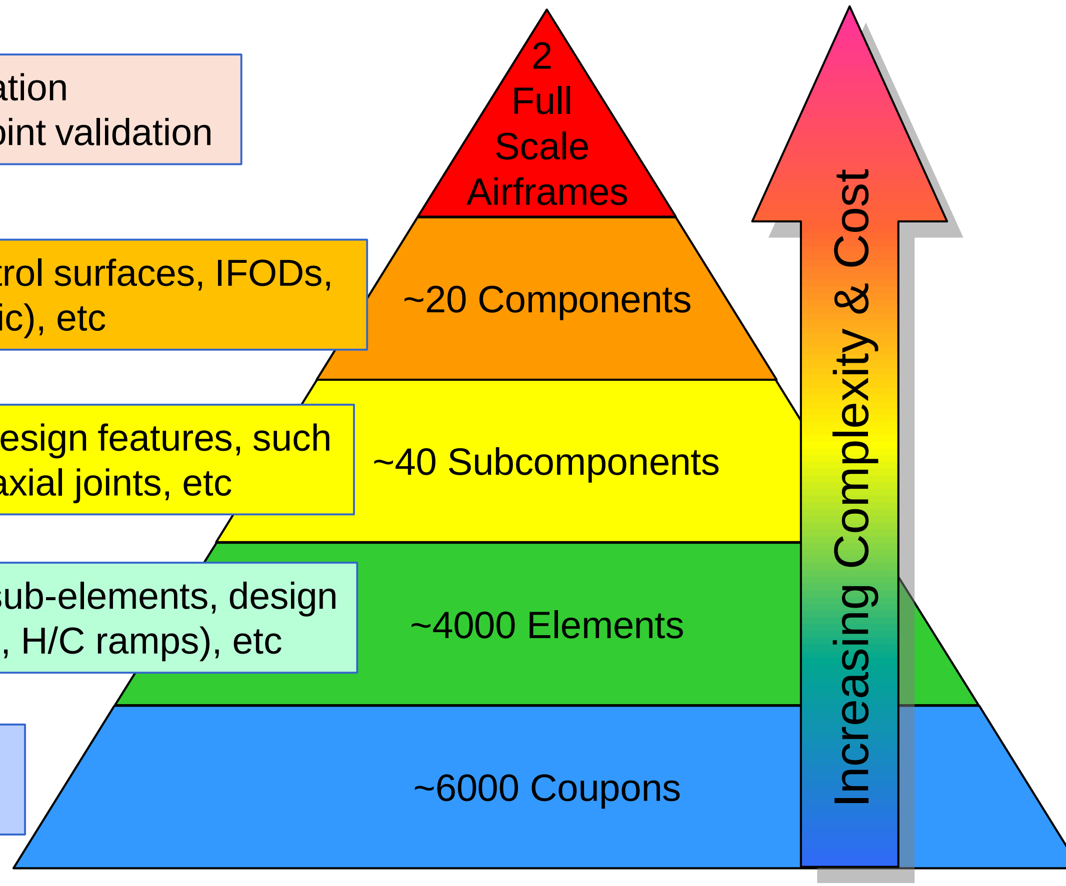
Applies regardless of material (metallic & hybrid-structure tests often fatigue; composites usually static)

Full-Scale Static Test (FSST) – AVFEM validation
Full-Scale Durability Test (FSDT) – control-point validation

Strength methods validation:

- Full-scale component tests, such as control surfaces, IFODs, combined loading (bird-strike, fire, ballistic), etc
- Typically more complex full-scale point-design features, such as 3- or 5-stringer panels, beams, multi-axial joints, etc
- Typically bolted or bonded joint sub-elements, design features (hats, chevrons, joggles, H/C ramps), etc

Laminate-level – B-basis allowable statistics
Ply-level – elastic properties, mat'l spec mins

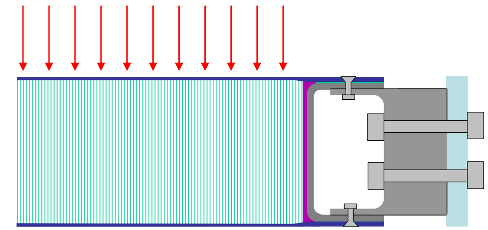


Airframe Design, Analysis, and Certification Process

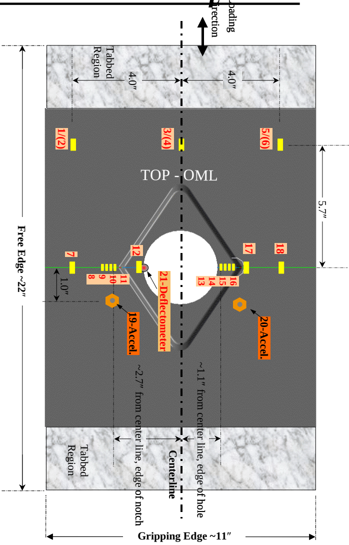
Building-Block Certification Logic, Composite Stress Methods:

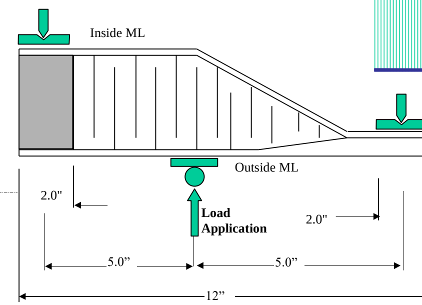
Element / Sub-Component / Component-Level Testing

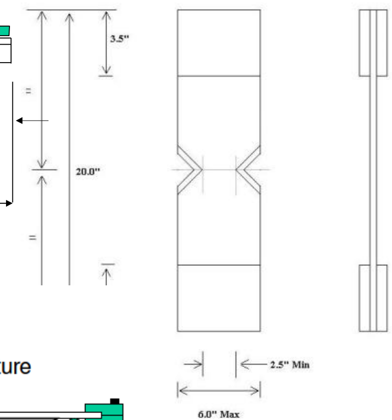
Required for Strength-Prediction Methods Verification/Validation

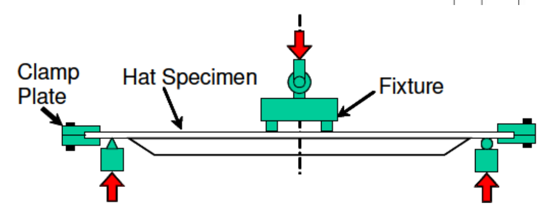


- *Composite Sub-Component-Level Examples:*
  - *CS&E Skin/Spar Joints*
  - *H/C Ramp Termination*
  - *Skin Joggles*
  - *Hat Run-out*
  - *Pi-Preform Joints*
  - *Chevron Notches*
  - *Flange Bending*
  - *Bullnoses/Blade-seals*
  - *Seal-grooves*
  - *Repairs*









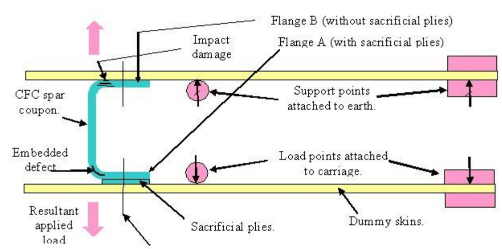
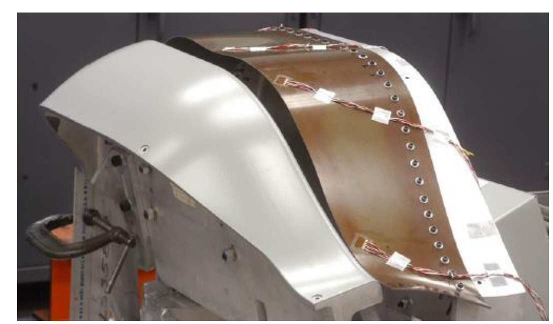
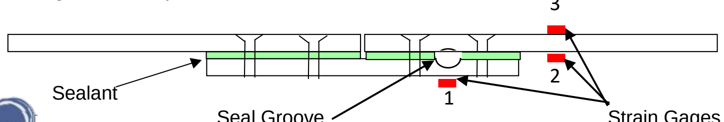


Fig. 3. Test Specimen Arrangement.



Single Shear Specimen with Seal Groove



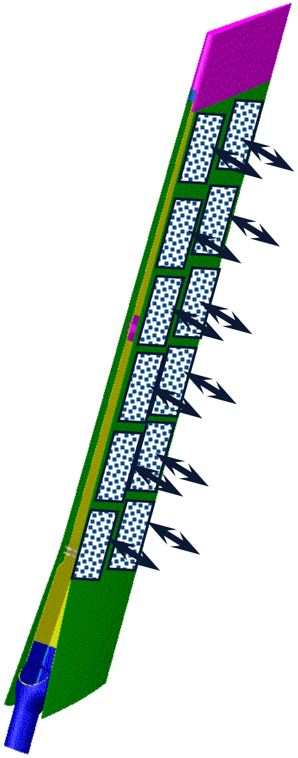
Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, Composite Stress Methods:

Element / Sub-Component / Component-Level Testing

Required for Strength-Prediction Methods Verification/Validation

- *Component-Level Example: Rudder Static and Fatigue Tests*
- *Overall:*
  - *Empirical verification/validation required for all failure criteria, so high-fidelity (e.g., expensive to develop/install/train/use in both cost and span) failure models don't start saving test-costs until at least their second use … but many features are design-specific.*
  - *Best cost/span solution is thus to use simple failure criteria with empirical correction factors.*
  - *These BBT levels also used to demonstrate certification requirements such as "no delamination growth", residual strength-after-damage, fail-safety, etc.*



Airframe Design, Analysis, and Certification Process

Composite and Metallic Damage Tolerance:

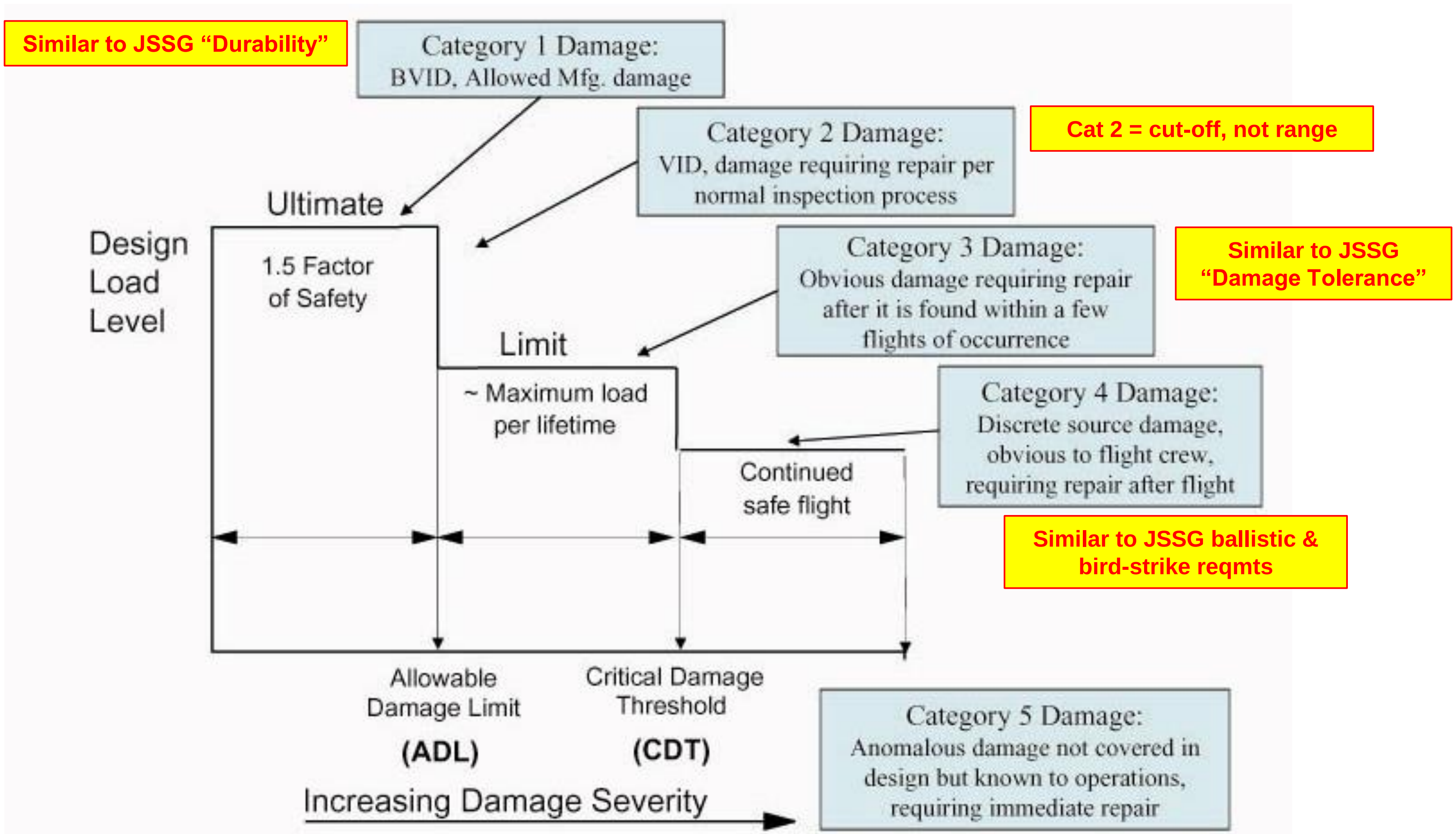
Very Cursory Overview (much has been done/written on this)

- FAA Part 25.571 and JSSG-2006 section 3.12 differ in certain details.
  - Terminology – fatigue vs durability
  - Load levels – 1.50*DLL vs Pxx*DLL (Pxx usually 1.05-1.15)
- General requirement to maintain adequate residual strength in the presence of defects and damage until detected is similar for civil and military, and independent of material.
- Means of *compliance* with this requirement differs significantly between metals and composites.
  - Physics of damage initiation and growth is very different in metals vs composites.
  - Metals exhibit self-similar fatigue crack initiation/growth from intrinsic flaws, but static strength is still adequate (*thus DT compliance demonstrated via FCGR fatigue life prediction and critical crack-length determination*).
  - Composites exhibit diffuse matrix cracking/delamination, and significant/sudden loss of static strength due to in-service delamination damage, but little/no loss of fatigue life (*thus DT compliance demonstrated via residual-static-strength-after-damage strain limit*).

Damage Tolerance requirements are material-independent.
Means of compliance with requirements are not.

Airframe Design, Analysis, and Certification Process

Composite and Metallic Damage Tolerance: *Differences in FAA and DoD*



Schematic diagram showing design load levels versus categories of damage severity

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Ramifications for Air System Risk vs. Efficiency

Overall Air System Priorities vs Airframe Cost/Performance:

Air System vs. Airframe

- *Air System includes Air Vehicle (Airframe, Vehicle Systems, Mission Systems, Software), Production Operations, Logistics/Support, Supply Chain Mgmt (at least).*
- *Airframe is often the least-costly (and thus least-important) of the broad management areas noted above, so Program managers are often dis-inclined to accrue risk on the airframe.*
- *Of all the above-noted areas, airframe is also often the most mature technology.*
- *Airframe Cost vs Weight*
    - *Weight-savings can generally only be realized during development when big bones are designed/sized (research only helps new programs).*
    - *Non-recurring cost savings in certification and tooling also only accrue in the development phase.*
    - *Recurring cost-savings, however, can be implemented throughout the lifecycle of existing Programs, and positively influence Prod Ops, Logistics, and SCM.*

Airframe is not biggest driver in Air System cost/performance

Significant R&D has been directed at Airframe recurring cost savings in recent time, but little toward weight-saving performance improvements

Airframe technology must be better, faster, AND cheaper (not just 2 of 3)

Ramifications for Air System Risk vs. Efficiency

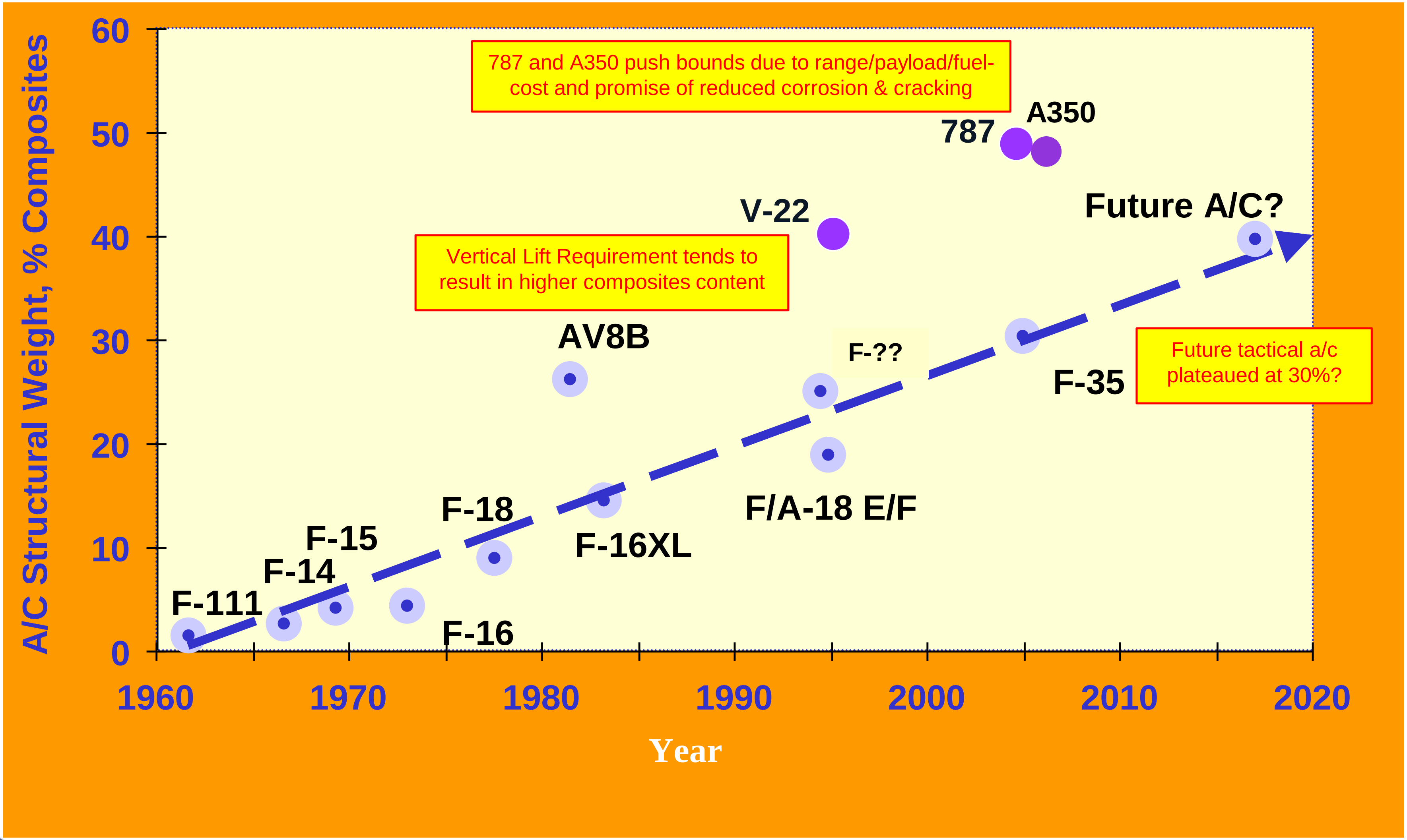
Overall Air System Priorities vs Airframe Cost/Performance:

Global Lessons Learned

- **Large programs must aggressively manage risk**
  - *Overall risk divided into small increments (IPTs)*
  - *Long term benefits of advanced technology may conflict with near term program requirements*
  - *Difficult to capture costs of advanced technology developments in estimation process for new programs*
  - *As cost estimates are refined, design decisions often favor mature technology*
  - *System level cost considerations may over rule local performance benefits*
- **Recognize that risk management – not technology insertion – is the paramount issue on large programs**
- **Risk adjusted return on investment has to be >> 1**
- **Technology Transition must address:**
  - *Production-friendly methodology gap*
  - *TRL gap*

Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:



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Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

Metals

- *Despite forgings being the longest-lead item of all, and DaDT-based design allowables strain-limiting the composite skins, Ti-6V-4Al and 7050 are still preferred for most complex parts.*
- *Metal parts are easier to "tweak" after initial design release (add stiffeners, change radii, etc).*
- *Steeper ramps, far better flange-bending capability, and thinner min-gauge make metal sub-structure parts lighter than the same part designed/built with composites (plus they are cheaper/faster to design/build).*

Composites

- *In-plane fatigue endurance limit above 0.67^*F_{UNC}, so generally considered to have infinite fatigue life (not true for ILS/ILT).*
- *More sub-element strength validation required for composites, than for metals (despite uncertainty in decades-old metallic empirical factors and MIL-HDBK-5 allowables).*

Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

Wings

- *Most clean-sheet designs now sport composite wing skins (big, contoured, tailored stiffness).*
- *Spars are also often composite – due to thermal-mismatch for long wings – except for tactical fixed wing aircraft with a ballistic survivability requirement (need metal flanges that yield under hydraulic-ram loading).*
- *Ribs, shear clips, etc often still metal due to small size, min-gauge, and complex shapes.*

Fuselages

- *Design constraints vary widely by application and size … "loads tell you what mat'l part wants to be made from".*
- *Skins most likely to be composite (min-gauge and post-buckling inhibit composite usage).*
- *Frames rarely composite, due to min-gauge and complex shapes (braided RFI 787 frames a notable exception).*
- *Keel beams and fighter carry-thru bkhds almost always metal (most complicated shapes, min-gauge, highly post-buckled)*

Empennages

- *Almost all-composite for weight/CG/dynamic reasons.*
- *H/C control surfaces have given composites bad reputation for poor reliability.*

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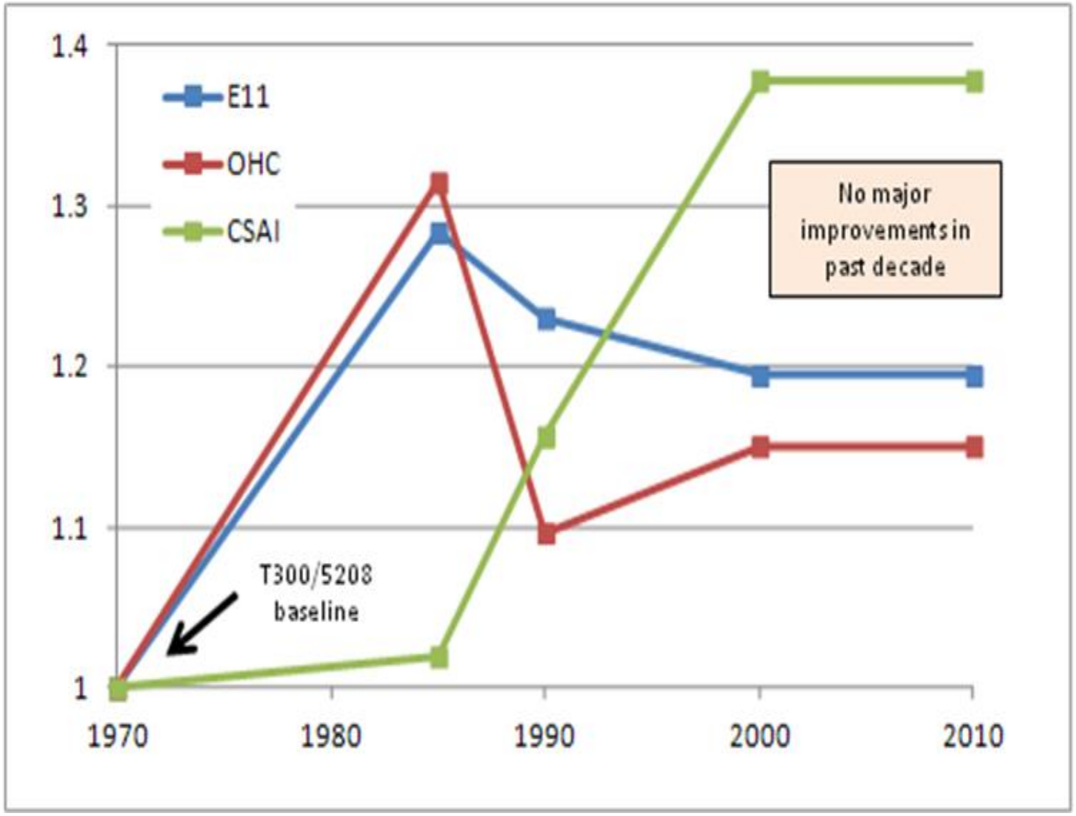
Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

Improved Materials?



Normalized Carbon/Epoxy Stiffness and Strength vs. Time

- **Aerospace grade carbon/epoxy has seen one 20 – 30% improvement in stiffness (the change from standard- to intermediate-modulus fiber) almost 30 years ago**
- **Steady, dramatic improvement in Compression Strength After Impact (CSAI) (at a given impact energy level) since the mid-1980's**
  - *CSAI (damage tolerance) improvement came at the expense of Open Hole Compression (OHC) strength and axial modulus (E11)*
  - *OHC strength decrease is due to tougher resins not allowing as much beneficial matrix cracking to blunt the stress concentration due to the hole*
  - *E11 decreased as resin content was increased in order to improve processability and impact damage resistance*

Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

Improved Materials?

- **CSAI increase may or may not increase damage tolerance (BVID or CVID) allowable strength, depending on the certification criteria being imposed**
  - **Dents are more visible in certain brittle resin systems, and thus can lead to lower impact energies and higher effective CSAI strengths than for "tough" resins**
  - **Differences in civil and military damage tolerance requirements (1.5*DLL vs Pxx*DLL) have led to**
    - *Use of very tough resin systems in recent civil aircraft designs (at the expense of hot/wet OHC strength)*
    - *Military applications continue to use older less-tough resin systems since CSAI does not size as much structure as does bolted joint strength, which is related most closely to OHC strength*

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Ideas for Innovation and Research

Basic Research:

- **Beat Ti-6V-4Al performance and 3D-Printing price/span.**
  - *Goal of enabling production of complex sub-structure components.*
- **Significantly increase stiffness and strength of composite materials.**
  - *50% (or more) increase in E11.*
  - *20% (or more) increase in OHC.*
  - *No reduction in other physical or mechanical properties.*
  - *No increase in material or processing cost or span.*
- **Better, lower-profile, fastening systems.**

Ideas for Innovation and Research

Bridging the Final TRL Gap:

- **Develop realistic FEM auto-meshing and run-optimization for composite structures.**
  - *COTS software vendors unresponsive and/or lack understanding.*
  - *(military?) OEMs unwilling to spend significant internal funds.*
- **Reconsider the 1.50*DLL static factor of safety (at least for UAVs).**
- **Combine FSST and FSDT articles (validate AVFEM with FSDT article at 1.15*DLL).**
- **Realize FAA vision of commodity composite materials (AMS specs audited by PRI, laminate-level allowables in CMH-17 Vol 2) by getting major OEMs to embrace/use.**
- **Implement physics-based pre-design optimization (to size big bones).**
- **Further reduce/optimize laminate-level allowables test matrices.**
- **Better, lower-profile, fastening systems.**
- **Make convincing cost/span/performance argument for bonded/unitized structure.**

Back-Up Charts

Airframe Design, Analysis, and Certification Process

Building-Block Certification Logic, AVFEM and fgFEM Fidelity:

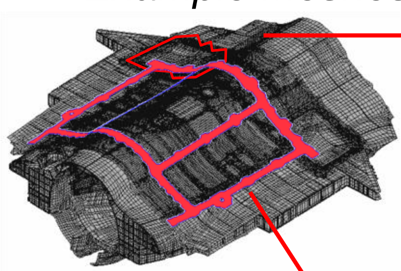
- *FEM fidelity is a trade-off between cost/span and Air System performance.*
- *Different types of structure are modeled differently (also depends on form of proprietary stress methods):*

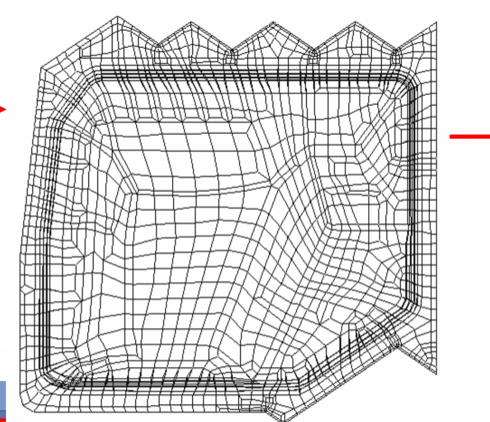
Feature	AVFEM	fgFEM	Uber-fgFEM
Bolted Joint	Not modeled (except for thermal model)	Discrete shell for each layer, bolt = beam elements	Same as fgFEM
Bonded Joint	Not modeled	Equivalenced nodes	Solid elements
Hat/Tee Stiffener	Bar or beam element	Discrete shells	Solid elements if metal (for DaDT)
H/C Panel	All-shell or shell/solid	Shell/solid	N/A
H/C Closeout	All-shell or shell/solid	Shell/solid	2D-slice all-solids
Bkhd Flange	Bar/beam or shell	Discrete shell	Solid elements if metal (for DaDT)
EOP Kt Feature	Not modeled	Shells w/accurate geometry	Refined shell mesh; 2D-slice all-solids

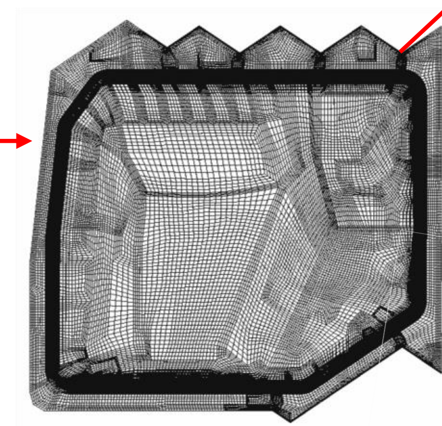
Airframe Design, Analysis, and Certification Process

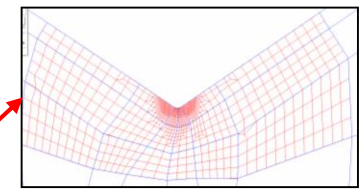
Building-Block Certification Logic, AVFEM and fgFEM Fidelity:

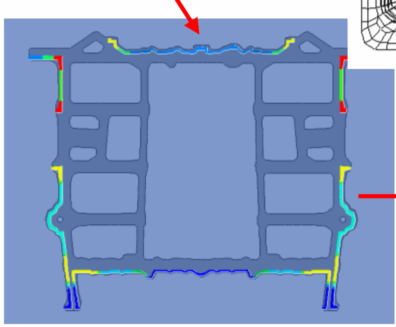
- *Modeling strategies/issues for composite laminates include:*
  - *Automation for shell properties (local coord sys, normal vector, mat files, stack files)*
  - *Limitations in physical correctness of shell and solid element formulations*
  - *Inability to use many advertised features, due to lack of reliability of COTS FE products*
  - *Pre- and post-processing limitations, and related manpower cost/span*
  - *Inability to train and maintain proficiency with specialized tools*
- *Example Meshes:*

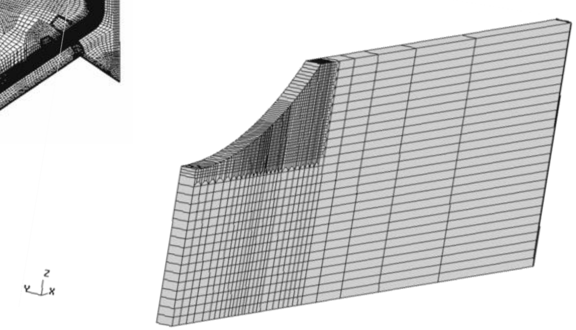












Solid Model FEM Representing Seal Groove

Airframe Design, Analysis, and Certification Process

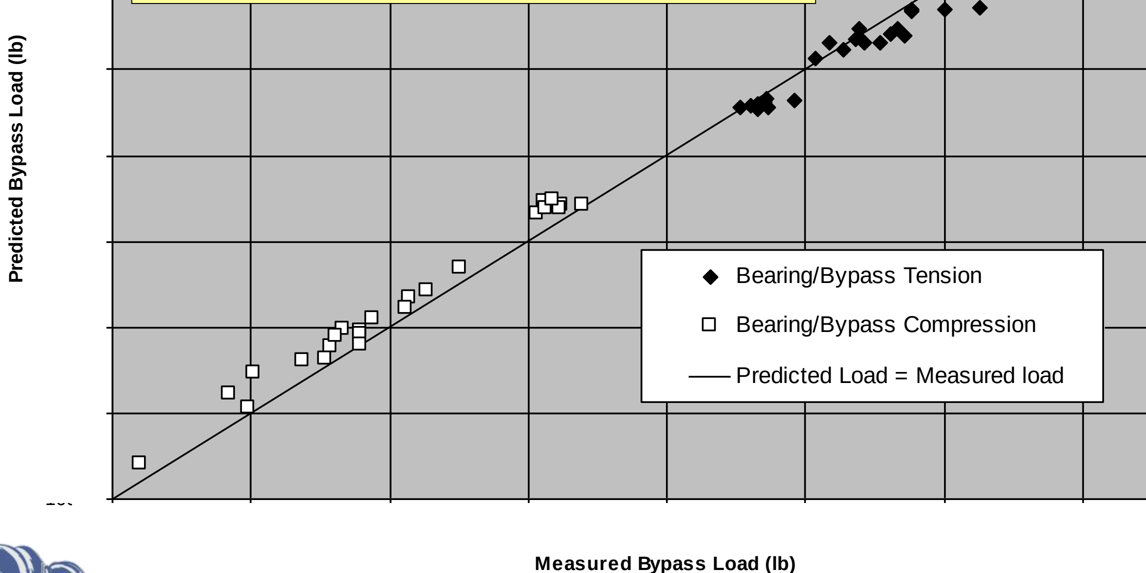
Building-Block Certification Logic, Composite Stress Methods:

Element / Sub-Component / Component-Level Testing

Required for Strength-Prediction Methods Verification/Validation

- *Element-Level Example: Bolted Joint Bearing/By-Pass Interaction*

- **joint configuration - double shear, 0.250-inch diameter protruding head bolts**
- **3 by-pass ratios**
- **7 tape-, and 3 fabric carbon/BMI lay-ups**
- **CTD, RTD, ETW environmental conditions**
- **Each point - average of three-to-five individual tests (239 tests, total)**



LM Proprietary IBOLT Methodology

- *All applied shell forces & bolt loads*
- *8 by-pass MS's around hole (1 at each fiber tangency point), tens/compr*
- *Bearing MS accounts for geometry, diameter, CSK, ply-%'s, stress-peaking & shim*
- *Element-level testing done once per customer for methodology*

LM Proprietary Bolt Methodology

- *6 static MS checks & fatigue endurance limit (4-life LL)*
- *Similar element-level correlation*

Advanced Development Programs

Airframe Design, Analysis, and Certification Process

Composite and Metallic Damage Tolerance:

- **Approach to certifying composite structures to be durable and damage tolerant leads to low strain levels** *(and non-weight benefits noted on prior charts)*
  - *Viewed by many as the source of significant weight inefficiency in today's production composite airframe structure*
- **Top-level civil and military aircraft durability and damage tolerance requirements are essentially the same for metallic and composite structure**
- **Very different means of compliance have evolved due to failure mode differences:**
  - *Metallics - fatigue crack growth life methods for metals*
  - *Composites - low-velocity-impact-related static strain limits*
- **Field survey data have shown that solid laminate composite airframe components have exhibited exemplary performance in terms of maintainability**
- **Findings of in-service damage incidences that compare to design criteria have been limited**

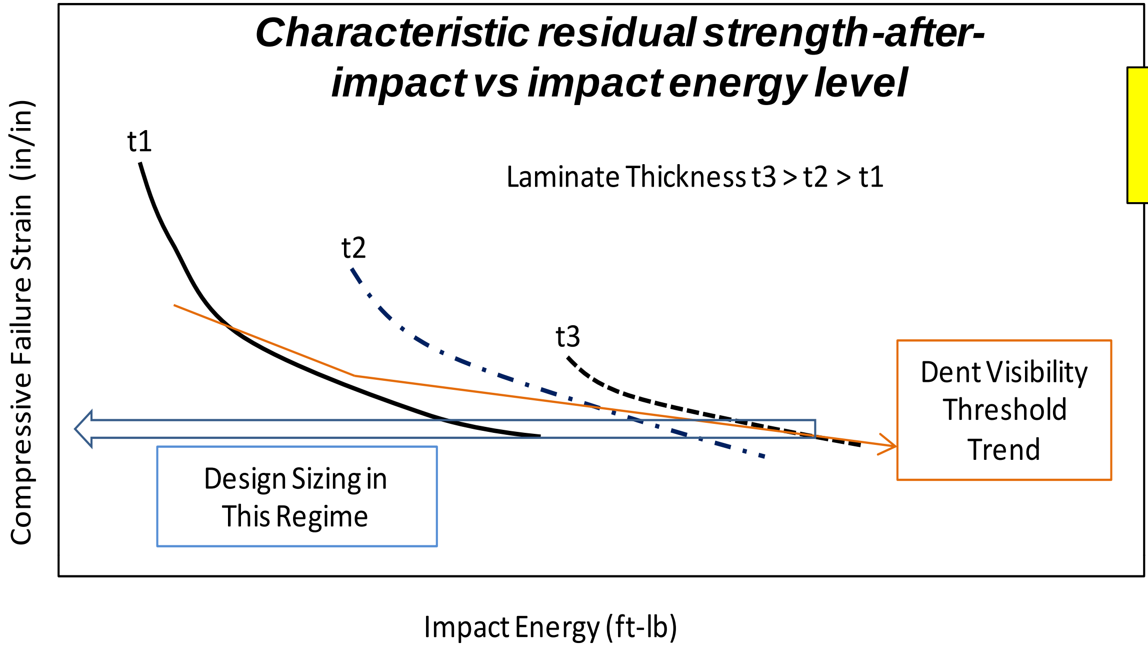
Airframe Design, Analysis, and Certification Process

Composite and Metallic Damage Tolerance:

- **Means of compliance with requirements for composite damage tolerance might be refined to yield higher operating strain limits and thus more weight-efficient composite structure**
  - *Focusing on threat assessment/reduction rather than inspection limitations*
  - *Consideration of strain-ranges and/or design configurations where residual strength is relatively insensitive to changes in (uncertain) impact energy*
- **Path to weight efficiency then becomes one of finding the material with the highest strength plateau region, and design details that are lightweight but not highly strained (hard caps and post-buckled webs/skins are two examples of this)**
- *(However, note that fixed-wing tactical military aircraft tend to not have much composite structure sized by the Pxx*DLL damage tolerance requirement)*

Airframe Design, Analysis, and Certification Process

Composite and Metallic Damage Tolerance:



(… but note that extensive testing is required to develop these curves)

- **Design sizing in the asymptotic response region makes the exact nature of the threat (energy level, dent depth, impactor geometry, velocity vs. mass, etc) somewhat unimportant as long as resulting operating far-field stresses are established coincident with probability of occurrence, and less so on detection**
  – *Experience has shown that rather large delamination damage, most often invisible from surface observation occurs due to events such as tire failure or ice removal*
  – *Thus, attempts at directly linking design requirements for 'visible' indentation depth and damage imposed by impacts from a steel impactor are questionable*

Advanced Development Programs

Ramifications for Air System Risk vs. Efficiency

Overall Air System Priorities vs Airframe Cost/Performance:

Global Lessons Learned Resulting from Legacy Composite R&D Efforts

- **Industry Conservatism Manifests Itself in:**
  - *Flight certification process/requirements*
  - *Problem resolution at the technology level*

- **Developmental Gap Between Technology and Program Communities**
  - *Program-critical factors not always realistically captured or accounted for during tech transition (design details, certification cost, design flexibility, subsystem integration)*
  - *Technology community often does not have the funding and/or expertise to develop Production-friendly stress analysis methods (e.g., simple, robust, highly-automated)*
    - *SDD BTP stress analysis must be done at a very fast pace and be performed concurrently by a large number of stress analysts, all of whom cannot be composites experts or 20-year veterans*
  - *Development lead times are long and SDD programs are schedule driven*

  …so program specific developmental work needs to start prior to the SDD funding availability (for both lead time and "buy-in" time)

Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

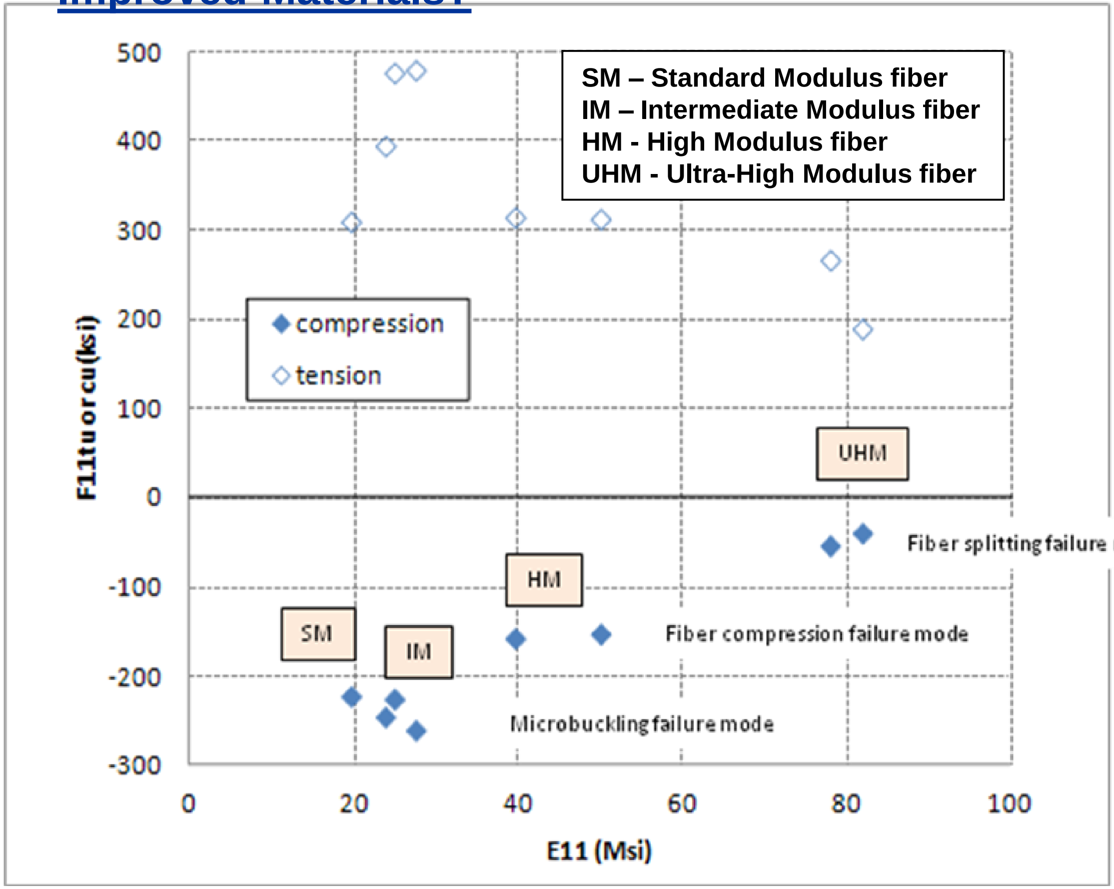
Improved Materials?

- **Perhaps the toughest challenge for industry and academia is how to simultaneously improve both fiber-direction stiffness and compressive strength**
  - **Reduction in compression strength with increased fiber modulus is due to a change in failure mode from**
    - *Microbuckling in PAN-based intermediate-modulus (IM) fibers to*
    - *Fiber compression failure in PAN-based high modulus (HM) fiber and*
    - *Transverse splitting in pitch-based ultra-high modulus (UHM) fiber*
- **Thus, it is obvious that research into increasing HM fiber compressive strength is necessary if significant gains in practical weight efficiency of composite structure are to be realized**

Ramifications for Air System Risk vs. Efficiency

Composites vs. Metals for Various Airframe Components:

Improved Materials?



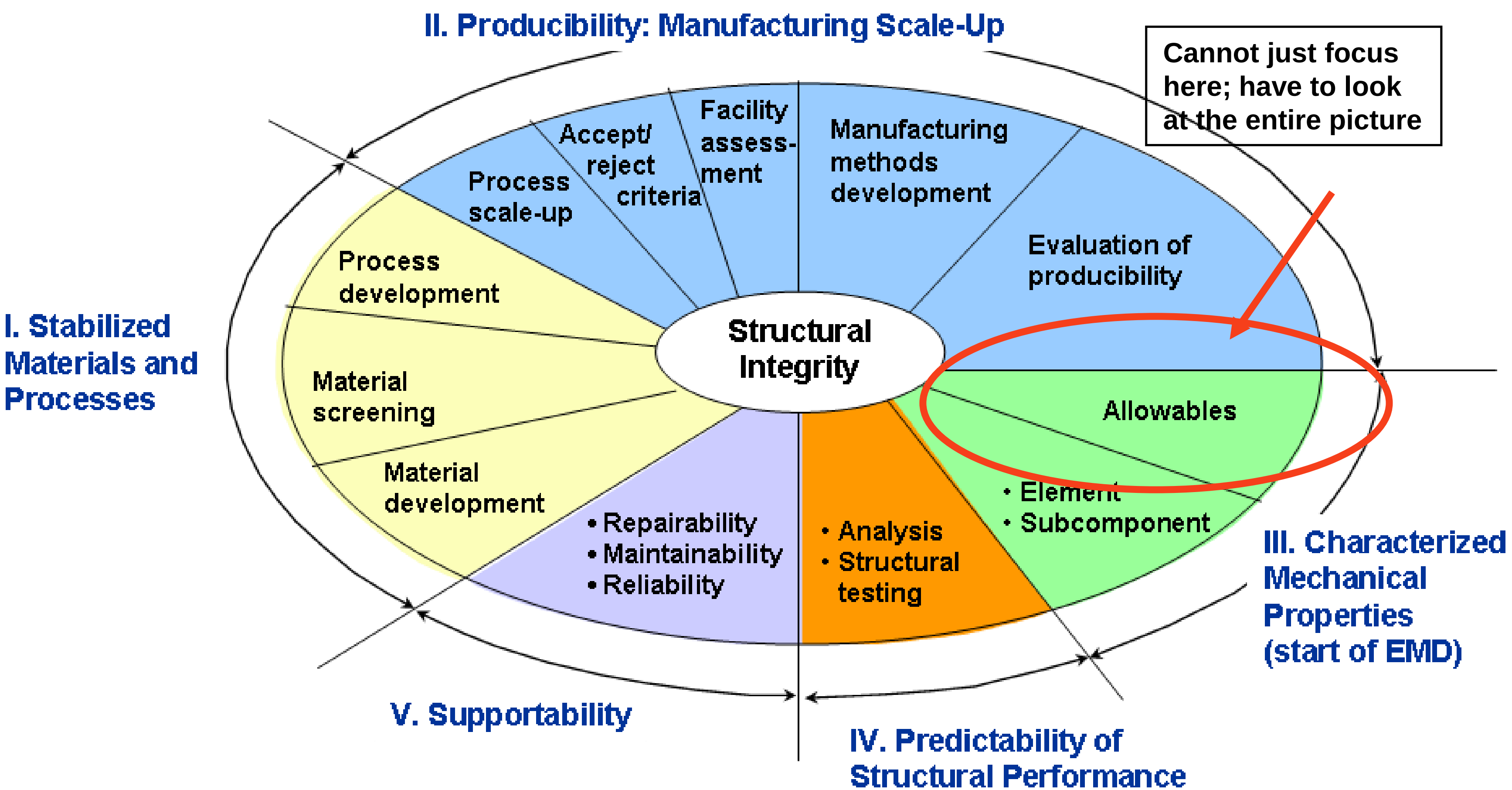
Fiber-Direction Carbon/Graphite Tape Compression/Tension Strength vs. Modulus

- *Carbon/graphite fiber technology development has yielded no practical improvement in intermediate-modulus fiber for the past 20+ years*
- *For today's HM fibers, tensile strength is reduced and, most importantly to airframe designs, compression strength goes down drastically*
- *OEM's have generally failed to devise ways to take advantage of high-stiffness/low-strength carbon fibers in local applications (e.g., spar caps, panel breakers, etc)*
- *"low cost" low performing carbon fibers offer very little benefit for aircraft primary structure*

Advanced Development Programs

Aircraft Structural Integrity Program

Five Factors for Technology Transition



Composite Aircraft Design Drivers

- **Aircraft Skins typically sized by stiffness, strength, buckling, damage tolerance, and repair allowables**
  - *Compression after impact, Open Hole Compression/Tension, Filled Hole Compression/Tension*
- **Joints sized by bearing/bypass, adhesive strength, subelement tests, damage tolerance**
- **Shear webs sized by shear strength, damage tolerance, repair allowables, and buckling**
- **Manufacturing, tooling, processing, QA, and manufacturing-scale-up issues greatly drive composite designs**

Materials and Material Processes

"Certification" approaches assume composite materials for structural components have been qualified

- **"B" Basis material characterization as a function of temperature, moisture, damage, defects, and fatigue**
  - *Material properties*
  - *Strength properties*
  - *Durability properties*
  - *Acceptance criteria*

Certification/Qualification of New Materials

- **For successful transition of structural materials**
  - *Must have a good set of generic notched laminate allowables ready when program requests the material*
  - *Recently projects are satisfying this need, and thus new material transition story is getting better*
  - *We don't need new cert/qual guidance*
- **LM Aero opinion - all multi-functional materials in use today only have non-structural applications**
  - *Since non-structural, then cert/qual not truly an issue*
  - *Thus, no need for special cert/qual plans for these materials*
- **Would we like to speed up the qualification process for new materials?**
  - *Yes, however it should be understood that in the big picture, the material qualification funding is small relative to the large scale certification tests performed on an SDD aircraft*