NASA Langley Structures and Materials
Research Overview

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AM&SS Product Line (PL) researches, develops and integrates new materials, advanced manufacturing and assembly technologies, structural concepts, design/analysis tools and certification methods for aircraft, aerospace vehicles, space structures, and space-based sensor systems and provides these products to NASA program & projects, other government agencies, and commercial customers.

Products in the portfolio - matured from concept/invention to flight/proof-of-concept – include:

1. Materials Products
2. Structures Products
3. Mechanisms/Manipulators
4. Advanced Manufacturing Technology
5. Flight-qualified Structures

Products incorporate physics-based simulation components that support the research, DDT&E, and sustainment phases of the life cycle for an aerospace system.

Products are developed using a systematic approach fusing experiments with modeling/simulation and advanced statistical methods to: quantify uncertainty and its propagation, perform sensitivity analyses and model calibration, and ultimately enables a risk-based certification of the technology for safety critical applications.
“Concept to flight” goal covers all three LaRC Directorates and all three phases of aerospace structural system lifecycle...

AM&SS Product Line is a Virtual Construct with 20 Participating Branches from Langley’s Research, Engineering, and Systems Analysis and Concepts Directorates.
Advanced Materials & Structural Systems – PL Vision (at 30,000 ft)

- **Technology Vision** – address all three phases of structural system lifecycle...

- **R&D (Invention)**
  - Dramatic mass savings from emerging materials
    - Computationally driven
    - Manipulate at atomic/molecular level
    - Multifunctional materials and structures

- **DDT&E**
  - Rational design technology for quantified reliability; reduced time/expense
    - Fusion of sequential design, fabrication, and validation steps
    - Advanced testing/characterization integrated with Mod/Sim

- **Sustainment**
  - Ultra-high reliability and autonomous sustainment
    - Materials/Structures durability tailored for specific needs
    - Material state awareness and vehicle/system level prognosis

- **Organization Vision**
  - Eliminate stovepipes among branches and directorates
  - Incorporate latest technologies into flight projects/NASA missions
Overview of Langley Structures Efforts

➢ Aeronautics
  ▪ Tailored Structures
  ▪ Crashworthiness
  ▪ Stitched Composites - PRSEUS Development
  ▪ Design/Certification Technology - Advanced Composite Project

➢ Space
  ▪ Developing Next-Gen Structural Materials - Carbon Nanotube Composites
  ▪ Metallic Shell Structures – Innovative Concepts using Advanced Forming
  ▪ Design Technology – Updated Shell Buckling Knockdown Factors
  ▪ Design Technology – Bonded Joint Design and Failure Prediction/Validation
  ▪ Development of Prototype Systems:
    ▪ Composite - Exploration Upper Stage
    ▪ Flexible structures for Habitats
    ▪ Flexible structures for Entry Vehicles
    ▪ Manipulator System for Exploration - TALISMAN
Selected Aeronautics Efforts
Goal: Explore design space to enable aeroelastically tailored wing structures to increase aspect ratio (from 9 to 14 or 20) and reduce weight by 20-25% without impacting aeroelastic performance

- Gen1 passive aeroelastic tailored wing structure being developed at LaRC based on Common Research Model (AR=9); Gen2 uses same strategy for weight reduction while increasing AR to 14

- Aeroelastic tailoring of materials and structures are being considered for broad design space
  - Bend/twist coupling can be achieved using internal structure reorientation
  - Curvilinear stiffeners, blending of spars and ribs enable modification of moments of inertia (I or J)
  - Functionally graded or tow steered composite engineered materials enables changing moduli (E or G)

- Design/analysis tools
  - Parametric studies (in-house)
  - Topology optimization (in-house/Univ. of Bath, Dr. Alicia Kim)
  - Curvilinear stiffener and SpaRibs (VA Tech, Dr. Rakesh Kapania)
  - Multidisciplinary optimization (Univ. of Michigan, Dr. Quim Martins)
  - Analytical evaluations being performed in NASTRAN

- Next: build structural test article for static loads and ground vibration testing to validate FEM analyses

- Future: build dynamically scaled model for wind tunnel or flight testing to evaluate flutter and GLA performance
**Tailored Structures - Functionally Graded Metals**

**Goal:** Optimize tailored structures with functional gradients and curved stiffeners for maximum structural efficiency and minimum weight (target = structural 20-25% weight reduction)

**Technologies included:**

– Additive manufacturing via Electron Beam Freeform Fabrication (EBF³)
  - Electron beam and multiple wire feeders enables changing chemistry and properties (strength, stiffness, toughness) at various locations in a single-piece structure
  - Enables materials gradients with abrupt or gradual changes in modulus for stiffness tailoring throughout a structure
  - Work being done in-house at NASA LaRC

– Curvilinear stiffener, functionally graded structural design for multi-objective optimization
  - EBF3PanelOpt is a local optimization code where panel stiffeners and skins can be tailored in thickness, height, location, and curvilinearity (demonstrated 20% reduction in weight for vertical tail structure, compared to conventional unitized structure, all aluminum)
  - EBF3WingOpt is a global optimization code that optimizes and blends wing Spars and Ribs into “SpaRibs” to minimize weight and aeroelastic flutter
  - Developed by VA Tech (Dr. Rakesh Kapania), funded by NASA Fixed Wing and Supersonics projects

Functionally graded curvilinear stiffened metallic structures
Tailored Structures – For Metals is Enabled by Electron Beam Freeform Fabrication (EBF3) Capability

**Ground-Based System for Large Structural Components**
- Electron beam melts pool on substrate, metal wire added to build up parts in vacuum environment
- Large build volume (72” x 48” x 24”) and high deposition rates (3 to 30 lbs/hr) possible with lower resolution for parts that will be finish machined
- Dual wire-feed and free-standing, 6-axis part manipulation enables functional gradients and addition of details onto simplified preforms
- Alloys deposited include aluminum (2219, 2139, 2195), stainless steel (316), nickel (In625, In718), titanium (Ti-6-4, CP Ti), copper

**Portable Systems for In-Space Simulation Experiments**
- First successful microgravity demos February 2006
- Microgravity tests support fabrication, assembly and repair of space structures and in-space manufacturing of spare parts
- Smaller build volume (12” x 12” x 12”) with finer wire for more precise deposits minimizing or eliminating finish machining
- Two systems designed and integrated in-house to assess different approaches for reducing power, volume and mass without impacting build volume

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Structural Concepts, Design and Analyses

Manufacturing Analyses and Simulation

Automated Fiber Placement

Test-Analysis Correlation

Testing

Characterization of As-Built Shells

Structural Analyses with Nonlinearities

Tailored Structures - Composite Tow-Steered Shells
A robot-based system that utilizes multiple end effectors to develop and evaluate next generation composite materials, processes, structural concepts, manufacturing, and inspection techniques.
Crashworthiness - TRACT 1 and TRACT 2 Tests

• **OBJECTIVE**
  - Evaluate transport category rotorcraft crash response under combined horizontal and vertical loading.
  - Evaluate structurally efficient energy absorbing composite airframe structure.

• **APPROACH**
  - Acquired (2) medium-lift US marine CH-46E fuselages
  - TRACT 1 conducted with novel crashworthy features and variety of ATDs
  - Introduced energy absorbing composite subfloor concepts for TRACT 2.

• **EXPECTED SIGNIFICANCE**
  - Improved crashworthiness of NextGen airframe structures.
  - Crash certification by analysis.

[Image - NASA LaRC Landing and Impact Research Facility]
Collaborations with US Navy, US Army, FAA, Rotorcraft industry, crashworthy systems manufacturers, and composite airframe researchers

(18) unique experiments onboard, including restraints, specialized ATDs, energy absorbing seats, patient litters, composite subfloor, and emergency locator transmitters
Crashworthiness - TRACT 2 Configuration

- Velocity conditions, 26 ft/sec vertical, 35 ft/sec horizontal, severe but survivable
- Soil impact surface, combination sand/clay mix
- 350+ channels of data recorded
- 40+ high speed and high definition camera, external and onboard
- Full field photogrammetry

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Stitched Composites - Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS)

- Highly-integrated and light-weight (fewer joints)
- Damage-tolerant (delamination- and crack-arresting capabilities)
- Cost-effective (made of stitched dry fabric preforms, resin infused, no metal inner mold line tools and no autoclave required)

**Study Panels:**

**Stringers:**
1.49-1.65 in. tall, 6 in. spacing

**Frames:**
6.00 in. tall, 24 in. spacing

1 Stack $\rightarrow$ 0.052 in.
7 Plies (+45, -45, 0, 90, 0, -45, +45)
($0^\circ \rightarrow 44.9\%, \pm 45^\circ \rightarrow 42.9\%, 90^\circ \rightarrow 12.2\%$)
Stitched Composites - Building Block Testing

Compression Loading
- Stability
- Adhesion

Trades Studies
- Test Loads
- Weight Goals
- Panel Geometry

Tension Loading
- Strength
- Repair

Pressure Loading
- Post-Buckled Structures
- Stringer Stability
- Frame Stability

Flexure Coupons
Pressure Panel
Pressure Cube

Combined Loading

Large-Scale Test
Mid 2015 Test at NASA-LaRC

HWB Multi-Bay Test Article

Pressure and Bending Test in COLTS Facility

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Stitched Composites – Manufacturing Scaled to Large PRSEUS Panels
Stitched Composites – Many Specialized Panels Needed for the Multi-Bay Pressure Box

- Upper Bulkhead 1
- Upper Bulkhead 2
- Lower Bulkhead Panel 1
- Lower Bulkhead Panel 2
- Crown Panel
- Outer Rib 1
- Outer Rib 2
- Outer Rib Panel
- Side Keel Panel 1
- Side Keel Panel 2
- Center Rib Panel (4)
- Center Keel Panel
- Floor Panel
Stitched Composites – Multi-Bay Pressure Box Test In COLTS Facility in 2015

Loading Conditions
- Pressure loading to 2P (18.4 psi)
- Upbending to 2.5G
- Downbending to -1G
- Combined downbending and pressure
- Combined upbending and pressure

Test article crown panel
Test article bulkhead panel
Actuator locations
Platens
NASA Langley Combined Loads Test System (COLTS)

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Design/Certification Technology - Advanced Composites Project (ACP)

- Focus on reducing the timeline for development and certification of innovative composite materials and structures, which will help American industry retain their global competitive advantage in aircraft manufacturing

**Goal:** Reduce product development and certification timeline by 30%
Design/Certification Technology - ACP Technical Challenges

**Predictive Capabilities**
- Robust analysis reducing physical testing
- Better prelim design, fewer redesigns

**Rapid Inspection**
- Increase inspection throughput
- Quantitative characterization of defects
- Automated inspection

**Manufacturing Process & Simulation**
- Reduce manufacture development time
- Improve quality control
- Fiber placement and cure process models

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Design/Certification Technology - ACP TC1- Predictive Capabilities

GOAL:
Develop new and improved analytical methods and rapid-design tools to reduce composite structural design cycle time and testing effort during the development and certification process.

APPROACH:
- High Fidelity Analysis Methods
  - Progressive failure analysis for residual static strength of airframe components
  - Transient dynamic failure analysis of engine and airframe components subjected to high-energy impact events
  - Progressive fatigue failure analysis of airframe and dynamic components
- Rapid Design Tools
  - Assess state of the art and gaps
  - Develop new / improved methods

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Design/Certification Technology - ACP TC1 Example

Apply different damage modeling techniques to predict damage progression

**Continuum Damage Model results**

- Visual correlation
- Elements w/degraded stiffness

**Cohesive Zone Model results**

- Visual correlation

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Selected Space Efforts
Developing Next-Gen Structural Materials - Carbon Nanotube (CNT) Composites

Specific Modulus (GPa/g/cc)

Specific Strength (GPa/g/cc)

- Aluminum
- Q-I M46/7714A
- CNT Sheet Composite (2012)
- CNT Sheet Composite (2013)
- Q-I IM7/8552
- CNT Yarn Composite (2012)
- M46 Fiber
- IM7 Fiber
- Project Objective
- CNT Yarn Composite 2014
- Modeling CNT/a-CTransverse
- Modeling CNT/a-CAxial
- Theoretical SWNT
Computational model of CNT composite

- Computational modeling of CNT composites to determine axial and transverse tensile properties confirming validity of project goal.
- CNT composite wound ring with tensile properties exceeding equivalent carbon fiber composite wrapped ring.
- Scale-up of CNT filament winder to allow winding of CNT yarn composite around size of pressure vessel to be used in flight test.

FY15 Goal: Demonstrate CNT Composite Overwrapped Pressure Vessel performance in ground tests and in sounding rocket flight tests

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Metallic Shell Structures - Integrally Stiffened Cylinder (ISC) Process Development

Accomplishments and Technology Firsts:

- Established the ISC process to successfully form single-piece Al-Li alloy 2195 cylinders with cryogenic tank scale stiffeners (> 0.75 inches tall).
- Demonstrated feasibility of in-situ reinforcement of stiffeners using metal matrix composite (MMC).
  - Achieved ~30% increase in bending stiffness with only 1% increase in mass.
  - Structural analysis suggests weight savings of 20% are possible for cryogenic tanks with MMC reinforced stiffeners.
- Developed strategy for scale-up and technology infusion.
  - Identified machine with larger scale (up to 30 inch diameter) ISC capability.
  - Identified Sounding Rocket (~12 – 30 inch diameter) for small scale flight application.

Accomplished to Date

- TRL 3: Proof of Concept
- TRL 4: Transition to Aerospace
- TRL 5: Intermediate Scale
- TRL 6: Full Scale

Future Plans

- Sounding Rocket (~12-30 inch dia.)
- External Tank LH2 Barrel Assembly (~27 foot dia.)
Significance:
- Capability for in-situ reinforcement of stiffeners enables greater structural efficiency and expands cryogenic tank barrel design space.

Significance:
- Preliminary analysis of a full component Ares-5 size LH₂ tank suggests weight savings of 20% are possible with MMC reinforced stiffeners.

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Design Technology – Updated Shell Buckling Knockdown Factors

NASA Engineering and Safety Center (NESC) assessment

• 2007 – Present

Objective

• To develop and validate new analysis-based shell buckling Knockdown Factors (KDF) and design guidelines for stability-critical launch-vehicle structures
  • Metallic cryotank and dry structures
  • Composite dry structures

Expected outcome

• Reduce structural mass and mass-growth potential
• Enable new structural configurations
• Increase KDF fidelity to improve design trades and reduce design cycle time/redesigns

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Design Technology – Developing New SBKF Design Factors

• Validated high-fidelity analysis are being used to generate the design data (virtual tests)
• Building Block testing serves to validate/anchor the analysis
• New factors will account for the following:
  – The quality of the shell (build tolerances) including shell-wall geometry (out-of-roundness) and fit-up tolerances (end imperfections that cause nonuniform loading)
  – Modern launch-vehicle structural configurations and material systems
  – Combined mechanical and pressure loads
  – Joints
• Careful data archiving

Stiffened panel subcomponents
Subscale launch-vehicle cylinders
Full-scale launch-vehicle cylinders
Design Technology – Bonded Sandwich Joint Design and Failure Prediction/Validation

- Application of composite materials to large space structures requires out-of-autoclave bonding and joining methods
- Two bonded joint concepts evaluated:
  - Conventional Splice
  - Durable Redundant (Smeltzer, US8697216 B2)
- Bonded joint specimens tested to failure in tension, compression, and bending
- Complex, combined failure process:
  - Honeycomb core crush
  - Adhesive failure
  - Intralaminar matrix cracking
  - Interlaminar delamination
- Experiments performed to provide data for failure analyses and to validate progressive damage tools for splice joints
Design Technology – Bonded Sandwich Joint Design and Failure Prediction/Validation

• Developed new test methodology for characterizing adhesive materials
• Predicting all failure mechanisms requires multiple damage modelling tools
• Good agreement between damage models and tests in terms of peak load and failure process
• Parametric studies conducted to study how changing design parameters change structural failure processes

LaRC-developed damage modeling tools:
- Honeycomb core crush (Ratcliffe et al., 2012)
- Thick cohesive element for mixed-mode adhesive failure (Sarrado and Leone, 2014)
- Mixed-mode interlaminar delamination (Camanho and Dávila, 2002)
- Mixed-mode intraply matrix cracking (Leone, 2011)

CSJ Tension Results

CSJ Damage Mode Predictions

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Prototype Systems: Composite - Exploration Upper Stage (MSFC, LaRC, GRC team)

• Objectives
  – Address Impediments to Composites (Overconservatism)
  – Damage Tolerance (Effective methodology for LV)
  – Risk Reduction (Validate @ relevant scale)
  – Methodologies (Transferable to other applications)

• LaRC Responsibilities:
  – Materials verification testing – panel fabrication and testing (verification against allowables databases)
  – Skirt joints development (longitudinal and circumferential), fabrication, and testing
  – Design/analysis – to support the production work at MSFC
  – Fabrication at LaRC using the ISAAC system as pathfinder for production work to be performed at MSFC
Prototype Systems: Flexible structures for Habitats – Airlock/Soft Hatch

The Problem

• Mass and volume parameters of proposed space vehicles need to be reduced to enable future exploration missions.

The Solution

• Minimalistic soft goods hatch development will contribute to a reduction in launch mass and volume.
• Minimalistic soft goods hatch development will facilitate efficient EVA from inflatable airlocks.

Status

• Trade Study Completed and Baseline Concept Selected in FY14
• Component Concept Design Development in FY15
• Component Technology Demonstration in FY16
Prototype Systems: Flexible structures for Habitats – Softgoods Creep Issue

Long term operations of habitats raised issue of softgoods creep… Long-term experimental creep tests show creep strength is less than 50% UTS after 2 years.
Prototype Systems: Flexible Structures for Entry Vehicles

Hypersonic Inflatable Aerodynamic Decelerators (HIADs) Show Promise for Mars Entry Systems

- Large Drag Area Necessary for Thin Martian Atmosphere
- Launch Vehicle Payload Shroud Dimensional Constraints make Rigid Decelerator Infeasible

Building Block Test Approach being used to Develop HIADs
Prototype Systems: Flexible Structures for Entry Vehicles – Building Block Tests

**IS Material Property Testing**
- Webbing: Kevlar, Technora, Carbon, Zylon
- Cord: Kevlar, Technora, Carbon, Zylon
- Gas Barriers: Silicone, PTFE

**Component Testing**
- Burst Testing
- Strap Indentation Tests
- Joint and Adhesion tests
- Packing Tests

Gas Barrier Test Fixture

Stitched Joint

Beam Burst Test

Heating capacity to 500 deg C in 1 minute

Strap Indentation Tests

Folded toroid
TALISMAN - a capability for general-purpose and long-reach robotic manipulation.

- Packages compactly for launch
- Tendon actuation allows for order-of-magnitude mass reduction compared with ISS robotic arm
- Combine with end effectors for specific function needs for both in-space and surface operations
Prototype Systems: Manipulator System for Exploration - TALISMAN Features and Components

TALISMAN prototype in Spacecraft Structures Lab

TALISMAN Concept – Stowed and Deployed

a. 4-link TALISMAN deployed.

b. 4-link TALISMAN stowed for launch (top view).

c. Major TALISMAN components.
Thank You!