National Aeronautics and Space Administration

# NASA Langley Structures and Materials Research Overview

**Presented to the AIAA Structures Technical Committee**

**SciTech 2015 TC Meeting**

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**Dr. Stephen Scotti (stephen.j.scotti@nasa.gov)**

**Advanced Materials and Structural Systems Lead**

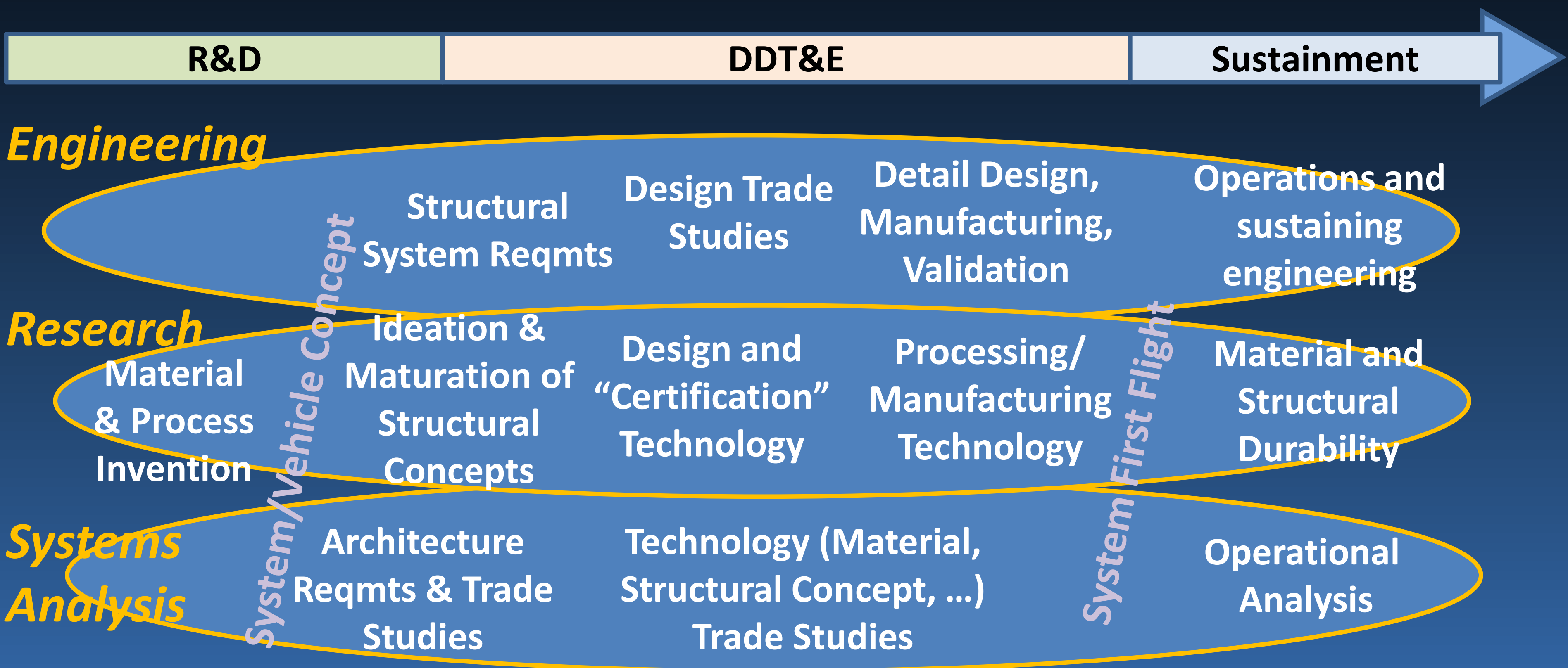
**NASA Langley Research Center**

# Advanced Materials & Structural Systems – Description 1/2

- 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 supports 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

# Advanced Materials & Structural Systems – Description 2/2

- “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.**

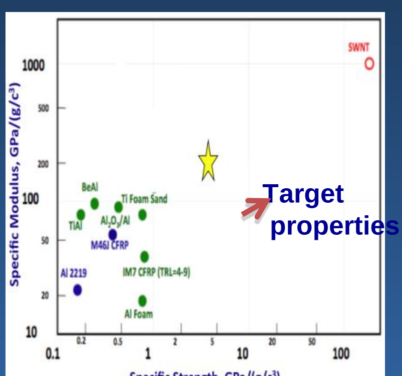
# Advanced Materials & Structural Systems – PL Vision (at 30,000 ft)

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

| R&D (Invention) | DDT&E | Sustainment |
|---|---|---|

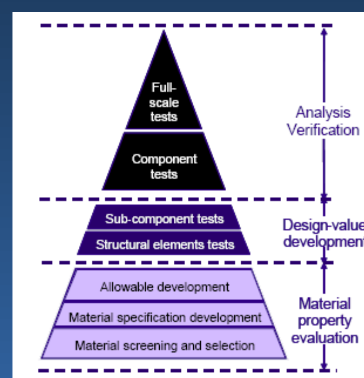
**Dramatic mass savings from emerging materials**

- Computationally driven
- Manipulate at atomic/ molecular level
- Multifunctional materials and structures



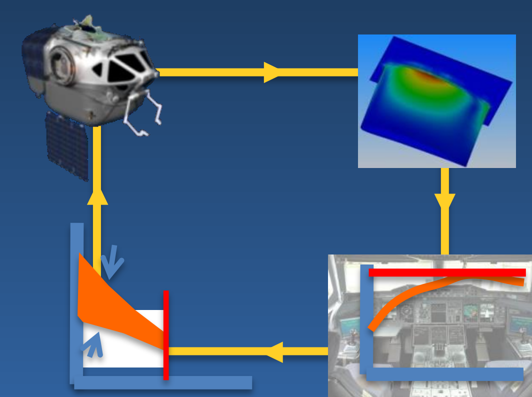

**Rational design technology for quantified reliability; reduced time/expense**

- Fusion of sequential design, fabrication, and validation steps
- Advanced testing/characterization integrated with Mod/Sim




**Ultra-high reliability and autonomous sustainment**

- Materials/Structures durability tailored for specific needs
- Material state awareness and vehicle/system level prognosis



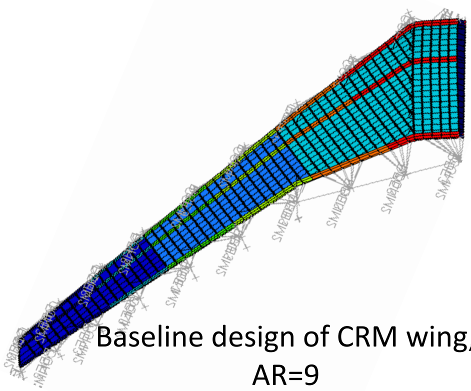
- **Organization Vision**
  - **Eliminate stovepipes among branches and directorates**
  - **Incorporate latest technologies into flight projects/NASA missions**

# Overview of Langley Structures Efforts

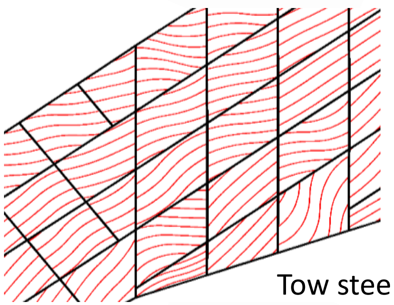
- **Aeronautics**
  - Tailored Structures
  - Crashworthiness
  - Stitched Composites - PRSEUS Development
  - Design/Certification Technology - Advanced Composite Project
- **Space**
  - Developing Next-Gen Structural Materials - Carbon Nanotube Composites
  - Metallic Shell Structures – Innovative 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

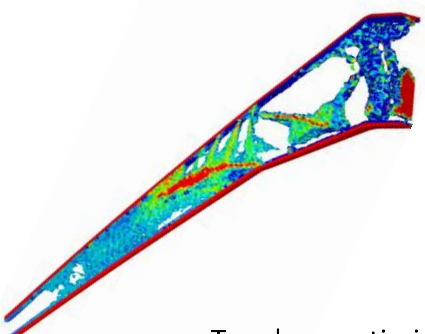
# Tailored Structures - Passive Aeroelastic Design



Baseline design of CRM wing, AR=9



Tow steered skins



Topology optimization

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

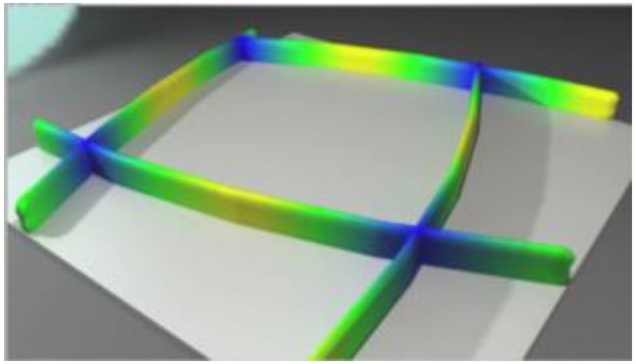
- Gen1 passive aeroelastic tailored wing structure being developed at LaRC based on Common Research Model (AR=9); Gen2 uses same strategy for weight reduction while increasing AR to 14
- Aeroelastic tailoring of materials and structures are being considered for broad design space
  - Bend/twist coupling 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

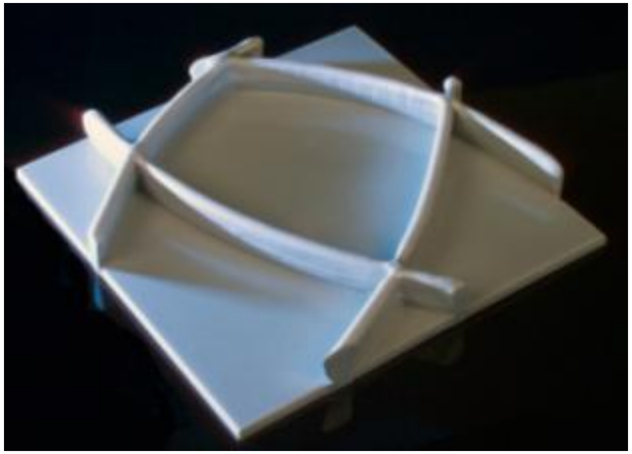
# Tailored Structures - Functionally Graded Metals

**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**:

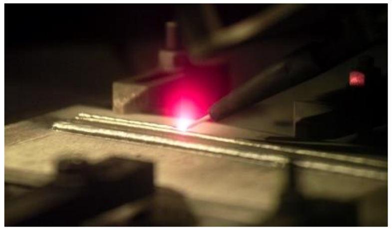
- Additive manufacturing via Electron Beam Freeform Fabrication (EBF$^3$)
  - Electron beam and multiple wire feeders enables changing chemistry and properties (strength, stiffness, toughness) at various locations in a single-piece structure
  - Enables materials gradients with abrupt or gradual changes 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 curviliearity (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***

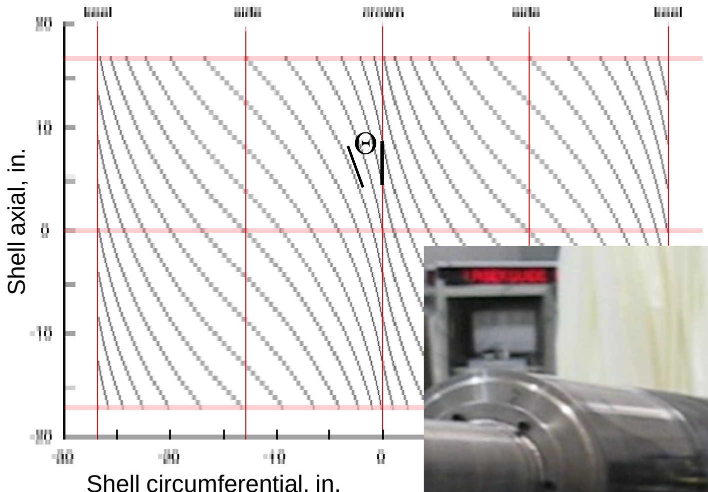
- Electron beam melts pool on substrate, metal wire added to build up parts in vacuum environment
- Large build volume (72” x 48” x 24”) and high deposition rates (3 to 30 lbs/hr) possible with lower resolution for parts that will be finish machined
- Dual wire-feed and free-standing, 6-axis part manipulation 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

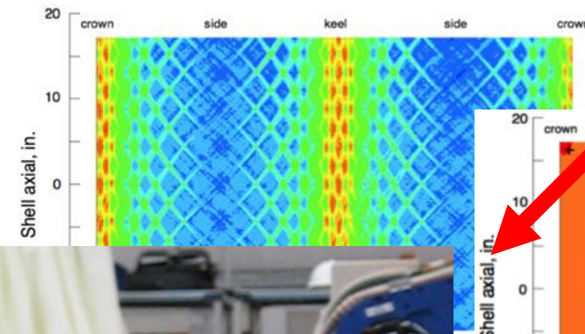
## ***Portable Systems for In-Space Simulation Experiments***

- 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

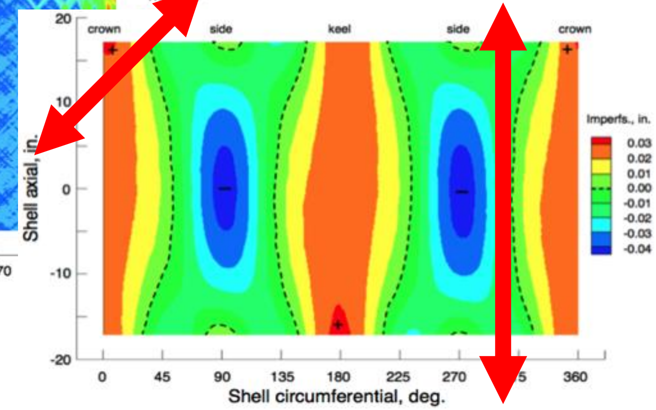
*POC: Karen.M.Taminger@nasa.gov*

# Tailored Structures - Composite Tow-Steered Shells

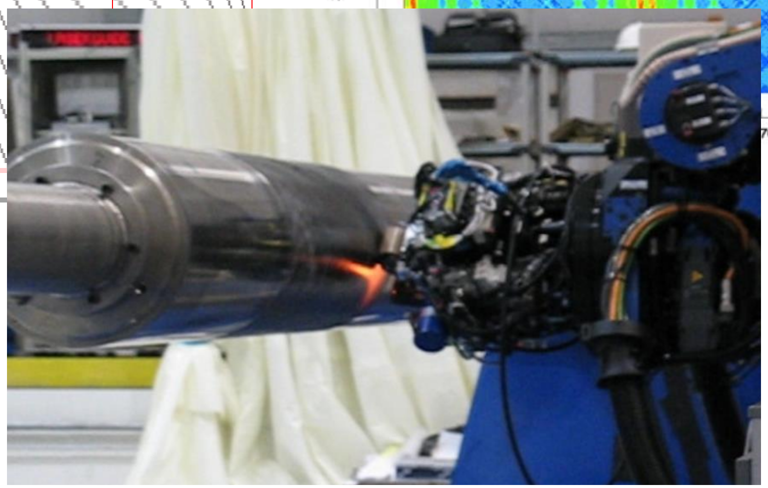



**Characterization of As-Built Shells**

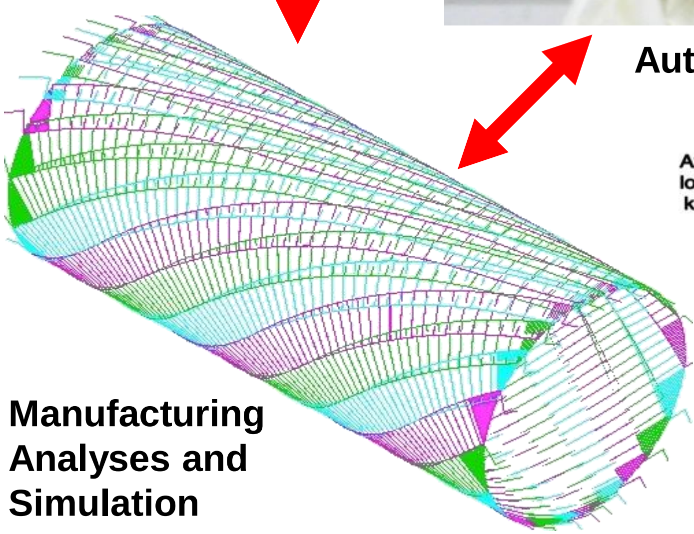



**Structural Concepts, Design and Analyses**

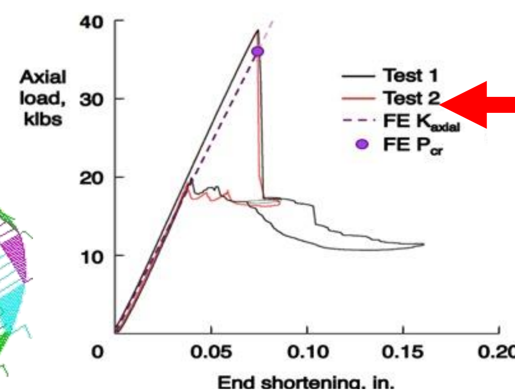


**Automated Fiber Placement**

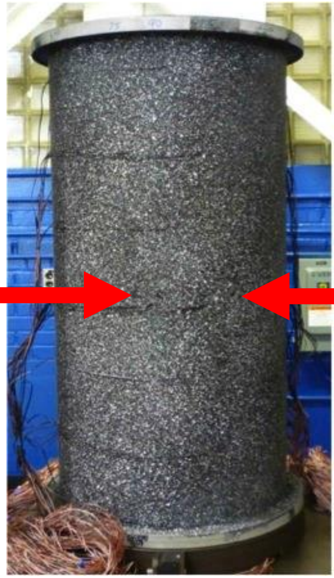
**Structural Analyses with Nonlinearities**



**Manufacturing Analyses and Simulation**

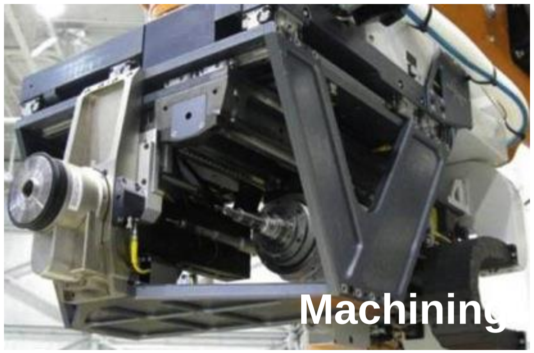



**Test-Analysis Correlation**

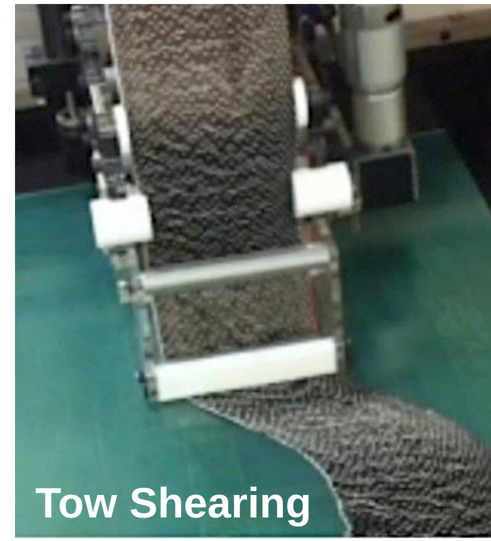


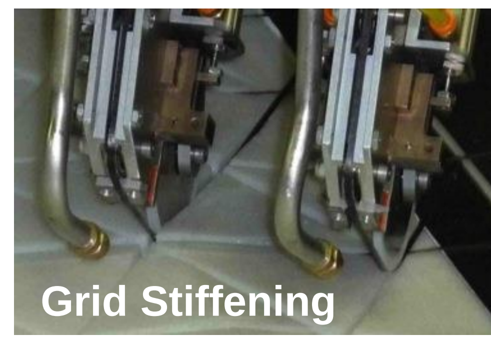
**Testing**

# Tailored Structures – For Composites is Enabled by Integrated Structural Assembly of Advanced Composites (ISAAC)






**A robot-based system that utilizes multiple end effectors to develop and evaluate next generation composite materials, processes, structural concepts, manufacturing, and inspection techniques**

*POC: K Chauncey Wu <k.c.wu@nasa.gov>*

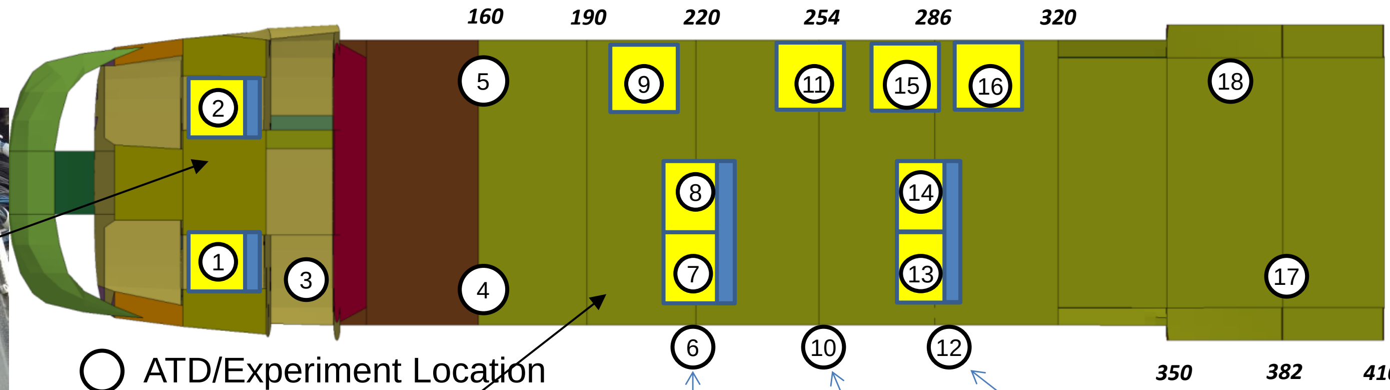
# Crashworthiness - TRACT 1 and TRACT 2 Tests

- **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.


NASA LaRC Landing and Impact Research Facility

# Crashworthiness - TRACT 2 Configuration

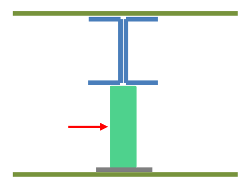
**Cockpit ATDs**

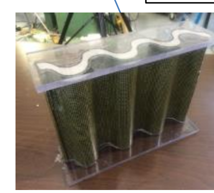



**Side and forward facing cabin ATDs**

DLR/ACS Subfloor

NASA Composite Subfloors





**Composite Subfloor Retrofit**

- 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

*POC: martin.s.annett@nasa.gov*

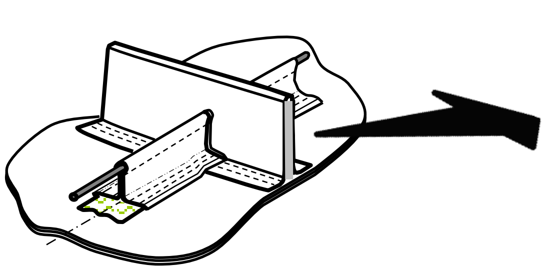
# Stitched Composites - Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS)

- 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)

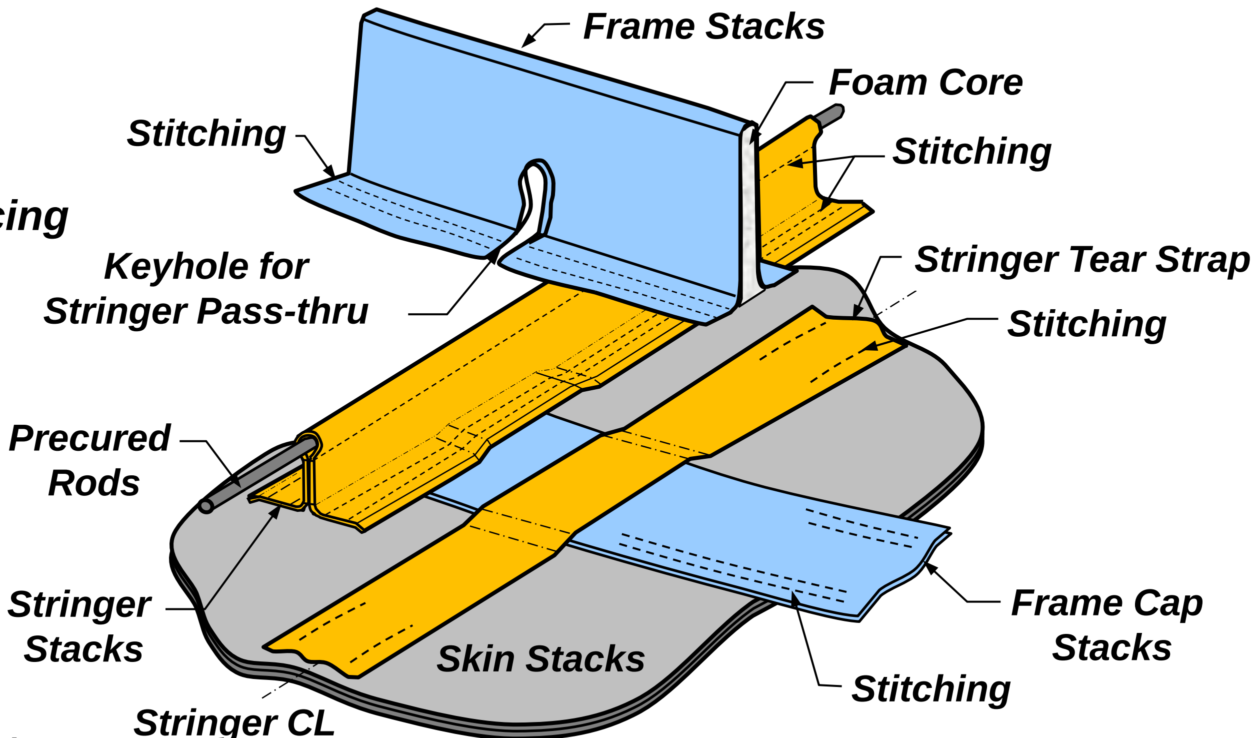
***Study Panels*:**

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

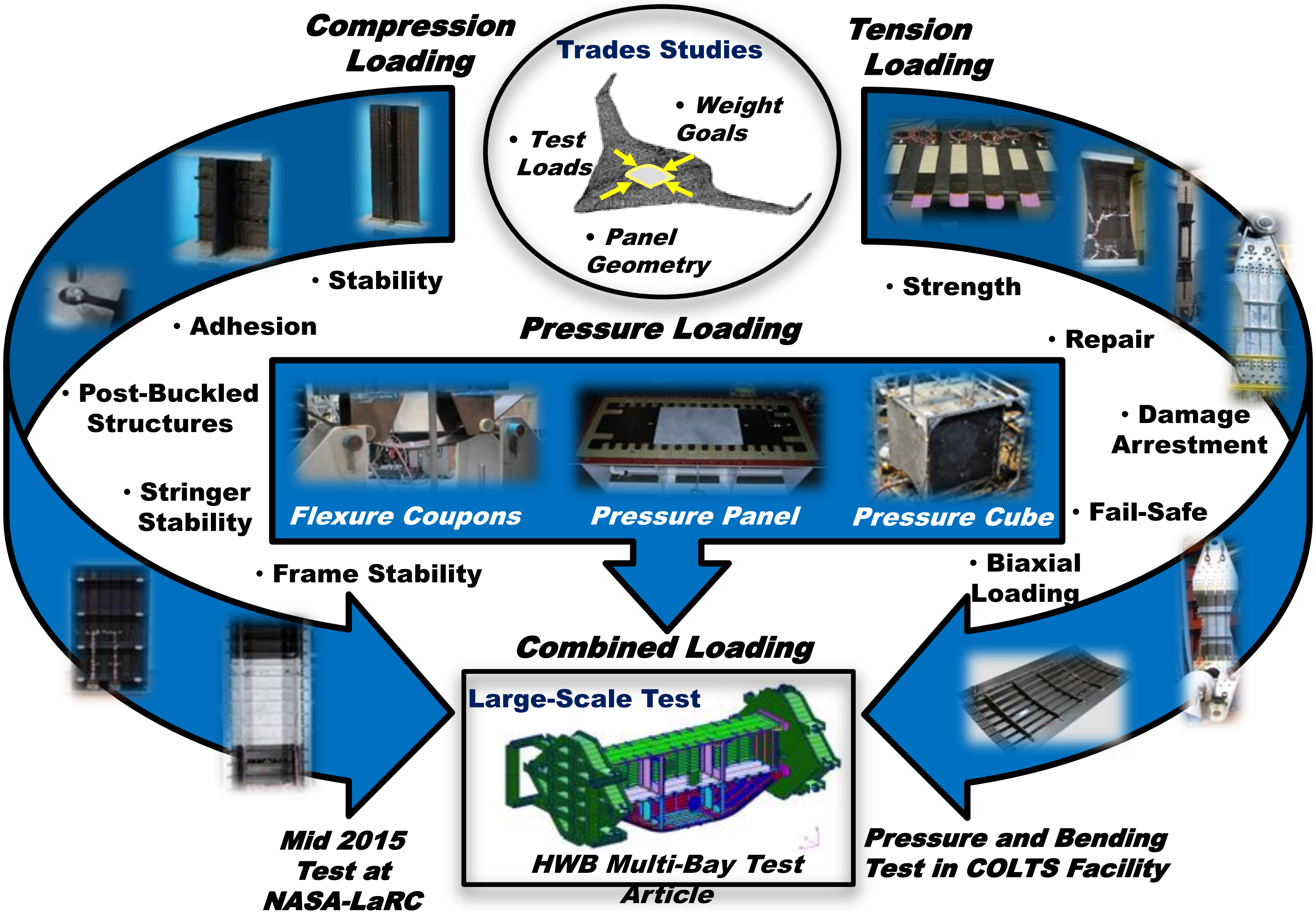
***Frames:***
***6.00 in. tall, 24 in. spacing***



***1 Stack → 0.052 in.***
***7 Plies (+45, -45, 0, 90, 0, -45, +45)***
***(0º → 44.9%, ±45º → 42.9%, 90º → 12.2%)***

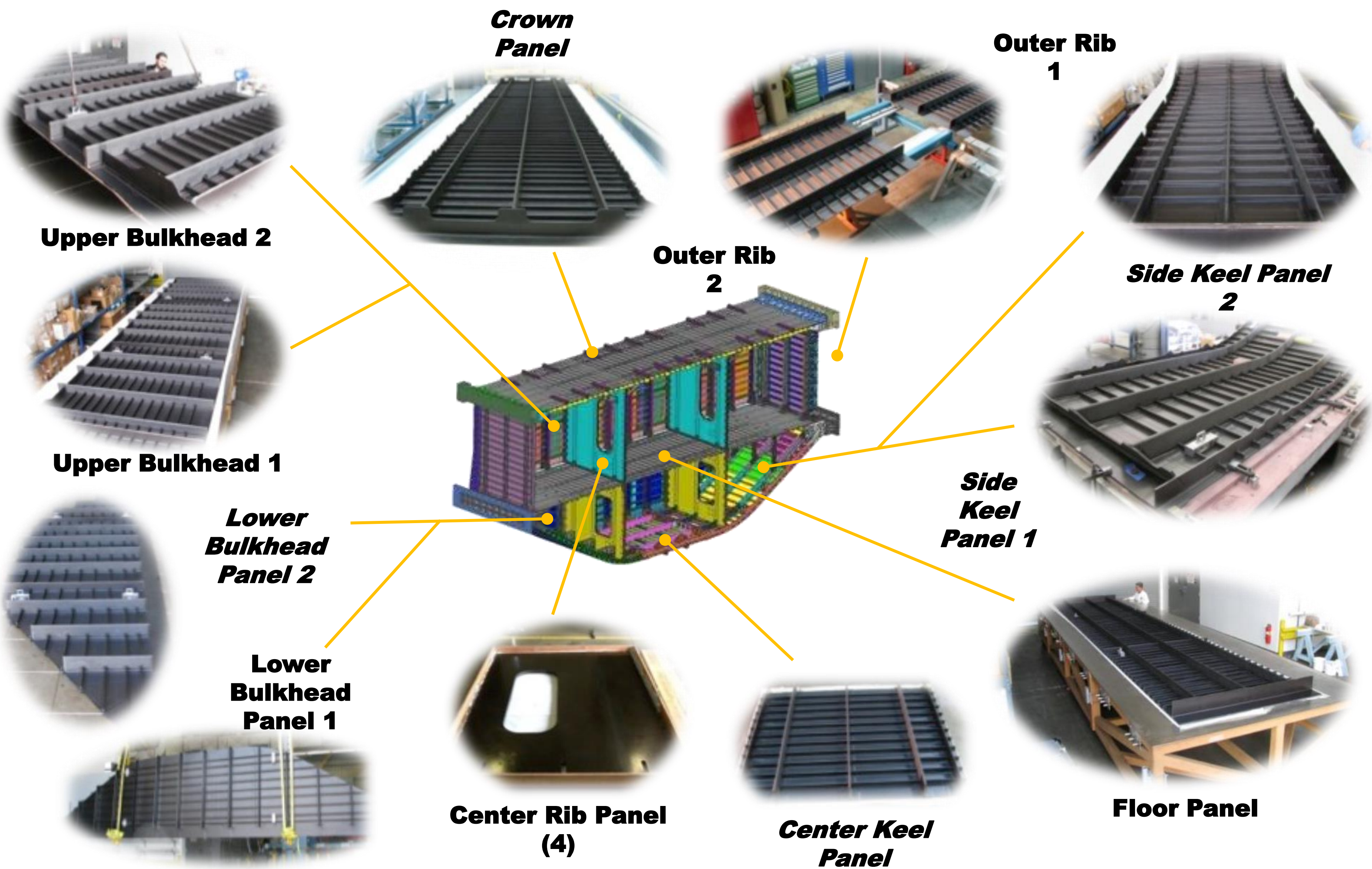


# Stitched Composites - Building Block Testing



# Stitched Composites – Manufacturing Scaled to Large PRSEUS Panels

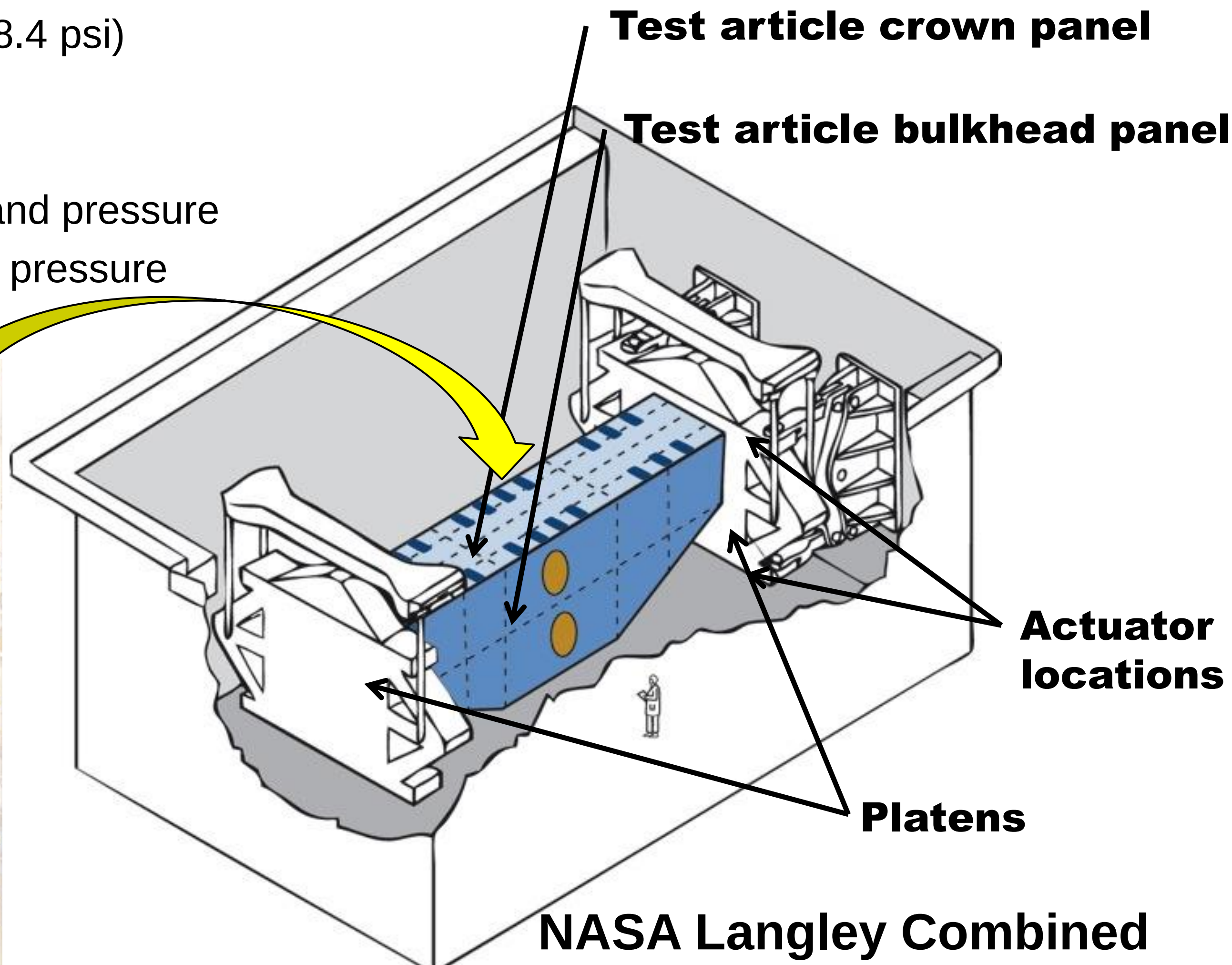
# Stitched Composites – Many Specialized Panels Needed for the Multi-Bay Pressure Box



# 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

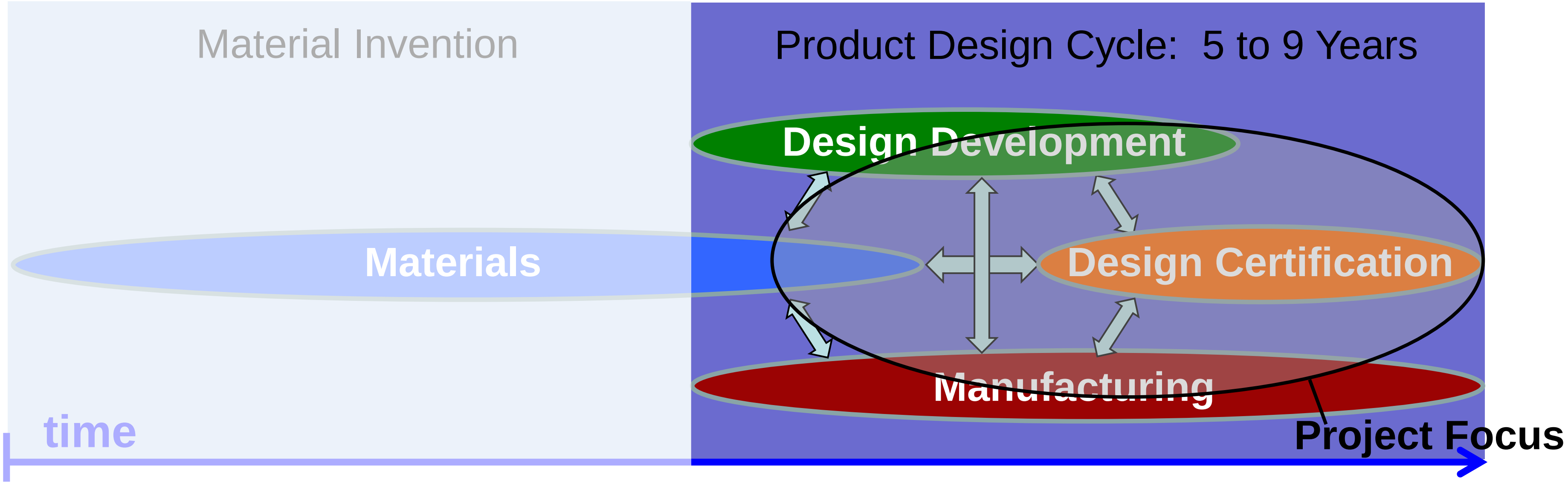



NASA Langley Combined Loads Test System (COLTS)

POC: dawn.c.jegley@nasa.gov

# 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

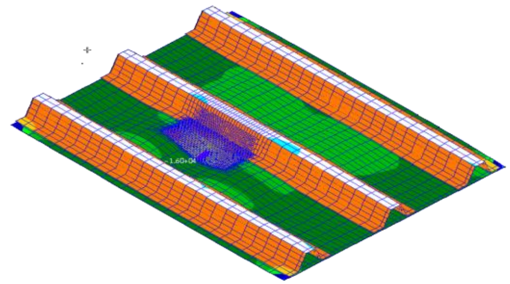


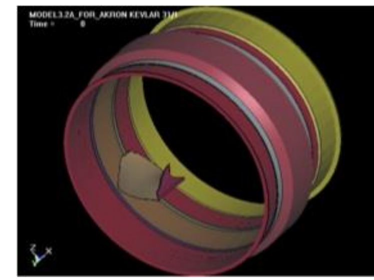

**Goal:** Reduce product development and certification timeline by 30%

# Design/Certification Technology - ACP Technical Challenges

## Predictive Capabilities

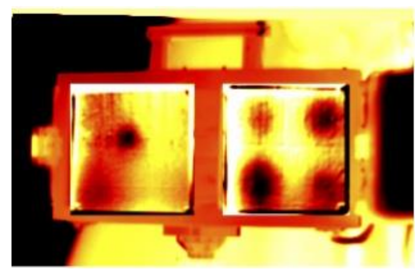
- Robust analysis reducing physical testing
- Better prelim design, fewer redesigns





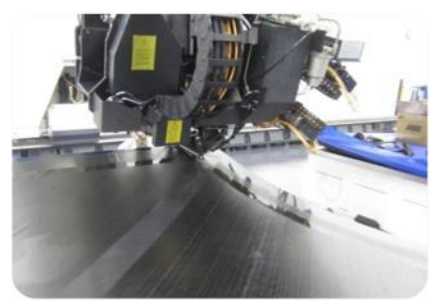
## Rapid Inspection

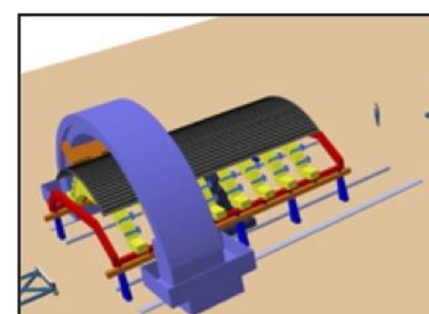
- Increase inspection throughput
- Quantitative characterization of defects
- Automated inspection



## Manufacturing Process & Simulation

- Reduce manufacture development time
- Improve quality control
- Fiber placement and cure process models



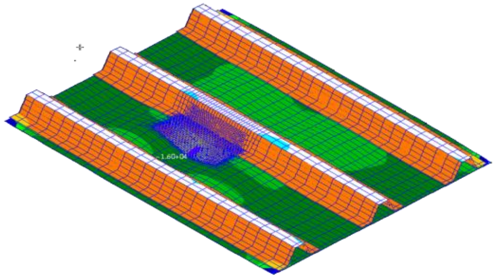


*POC: rick.young@nasa.gov*

# Design/Certification Technology - ACP TC1- Predictive Capabilities

## GOAL:

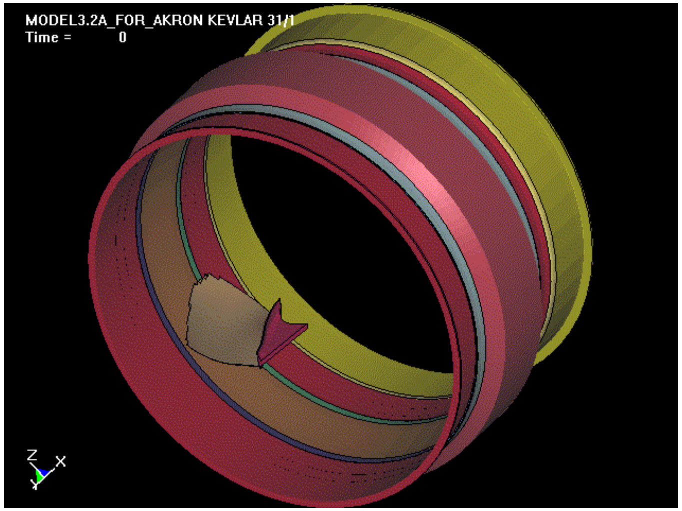
Develop new and improved analytical methods and rapid-design tools to reduce composite structural design cycle time and testing effort during the development and certification process

**Experiments document damage progression** → **Validate new improved predictive models**

## 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



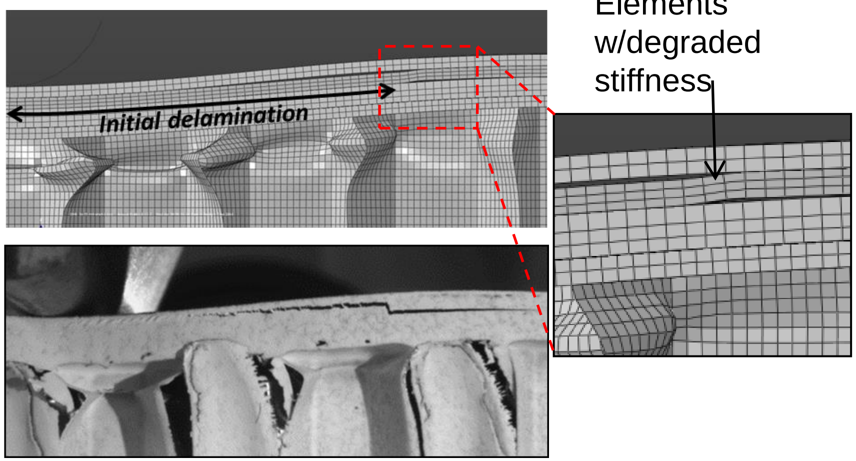

*POC: thomas.k.obrien@nasa.gov*

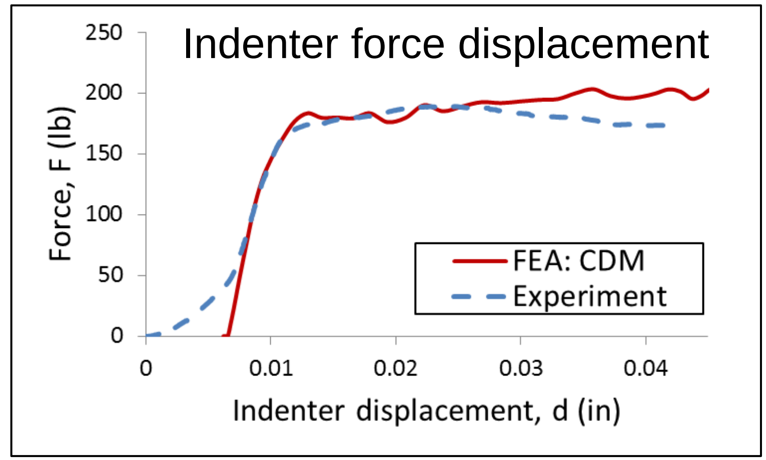
# Design/Certification Technology - ACP TC1 Example

Apply different damage modeling techniques to predict damage progression

## Continuum Damage Model results

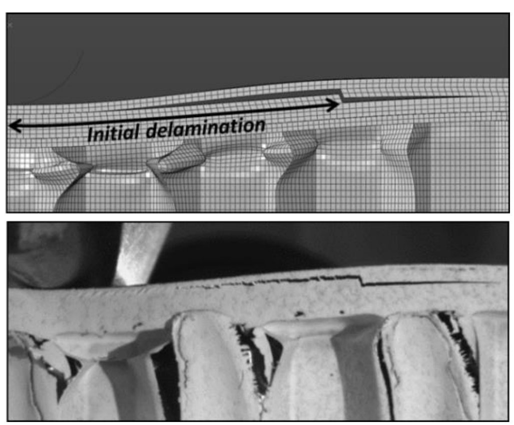
Visual correlation

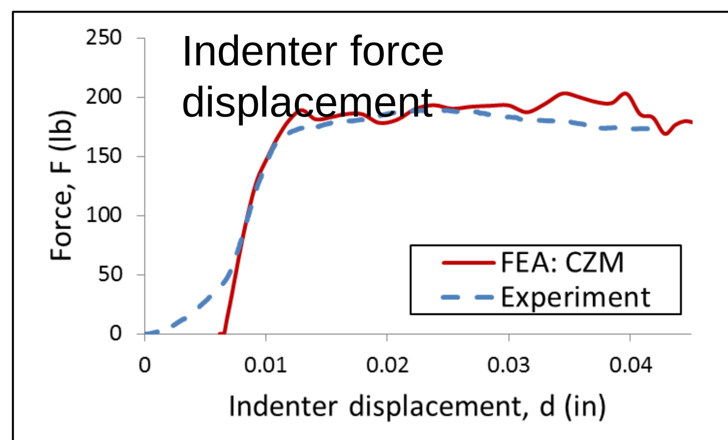



## Cohesive Zone Model results

Visual correlation



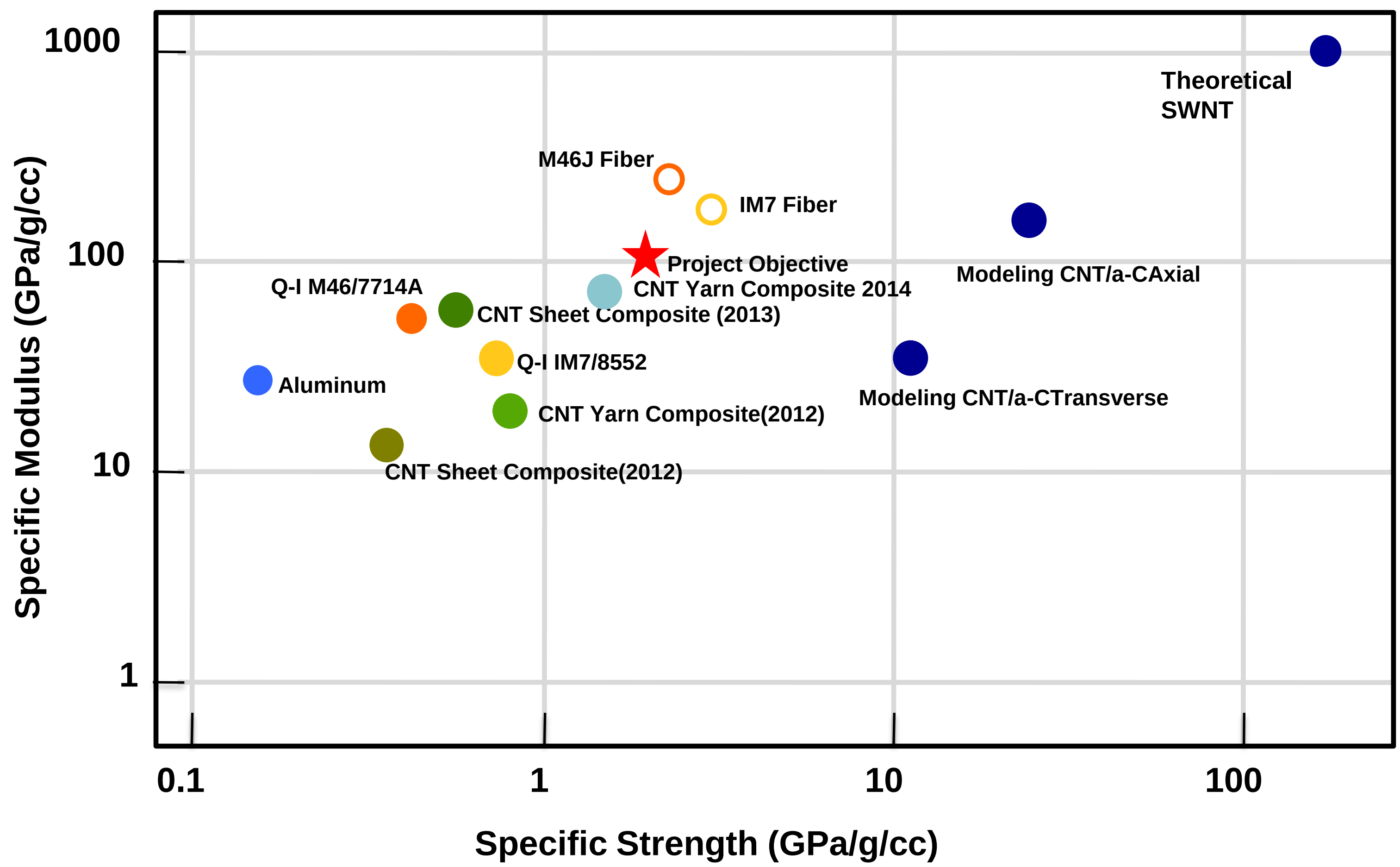




*POC: james.g.ratcliffe@nasa.gov*

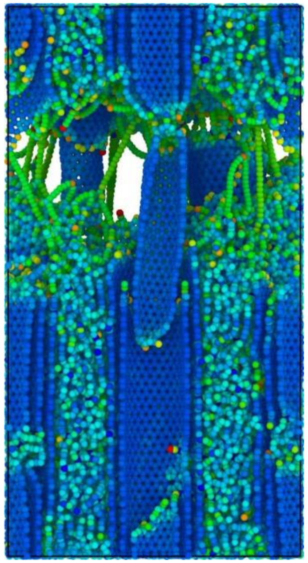
National Aeronautics and Space Administration

# Selected Space Efforts

# Developing Next-Gen Structural Materials - Carbon Nanotube (CNT) Composites

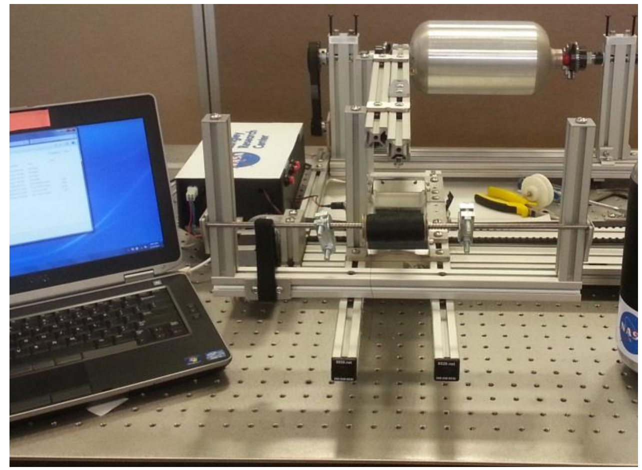


# Developing Next-Gen Structural Materials - 2014 Technology Firsts

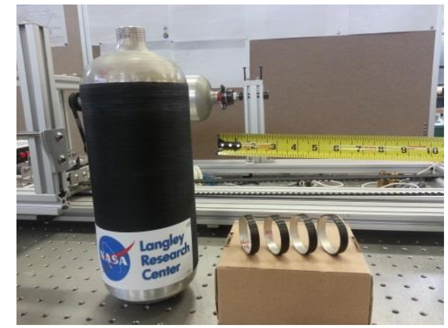


**Computational model of CNT composite**

**CNT composite wound 1.5” ring**



**In-house developed CNT filament winder**




**Demonstrate winding a 4” diameter pressure vessel**

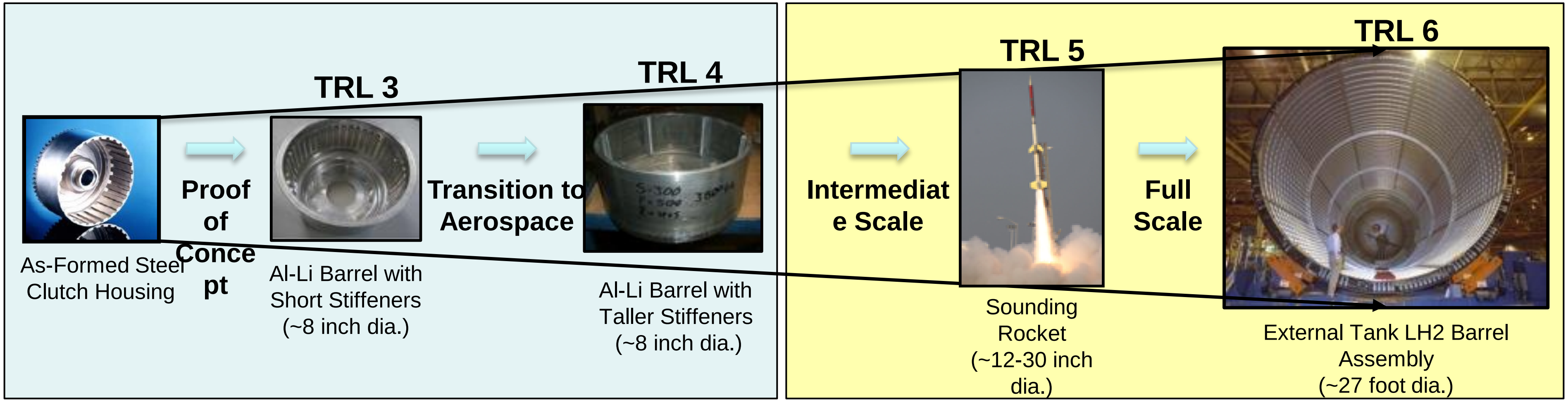
- Computational modeling of CNT composites to determine axial and transverse tensile properties confirming validity of project goal.
- CNT composite wound ring with tensile properties exceeding equivalent carbon fiber composite wrapped ring.
- Scale-up of CNT filament winder to allow winding of CNT yarn 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

*POC: emilie.j.siochi@nasa.gov*

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

## Accomplishments and Technology Firsts:

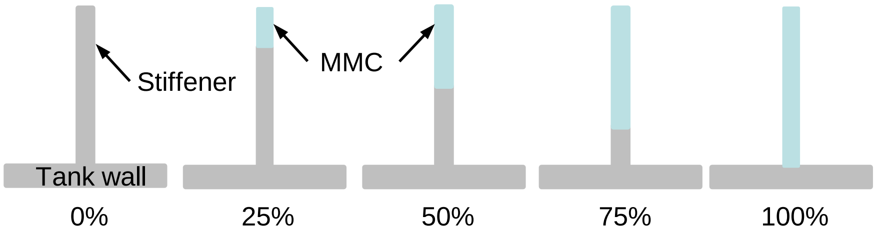
- Established the ISC process to successfully form single-piece Al-Li alloy 2195 cylinders with cryogenic tank scale stiffeners (> 0.75 inches tall).
- Demonstrated feasibility of in-situ reinforcement of stiffeners using metal matrix composite (MMC).
    - Achieved ~30% increase in bending stiffness 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.

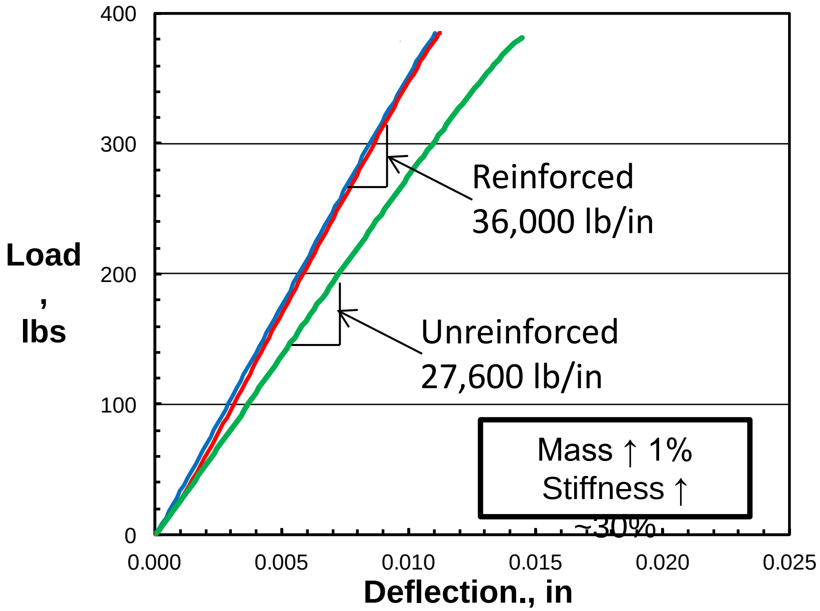


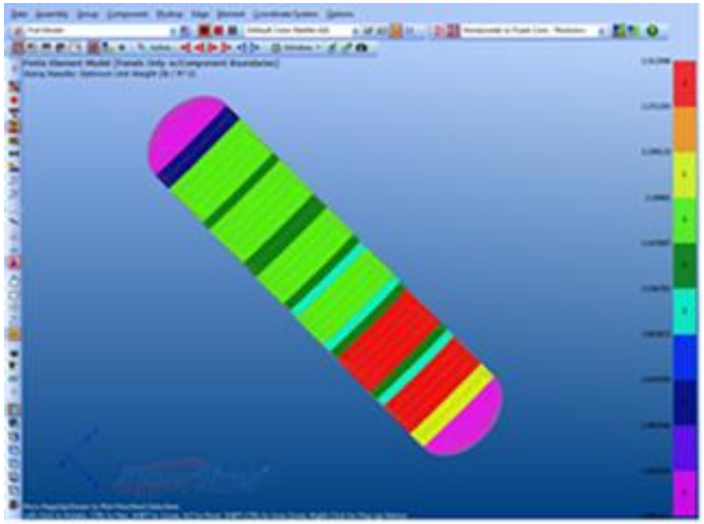

Accomplished to Date

Future Plans

# Metallic Shell Structures - In-situ Forming with MMC Reinforcement

Ares-5 scale cryogenic tank FEA results indicate weight savings of 3 to 20% depending on configuration[2]

## 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 $LH_2$ tank suggests **weight savings of 20% are possible with MMC reinforced stiffeners.**

*POC: john.a.wagner@nasa.gov*

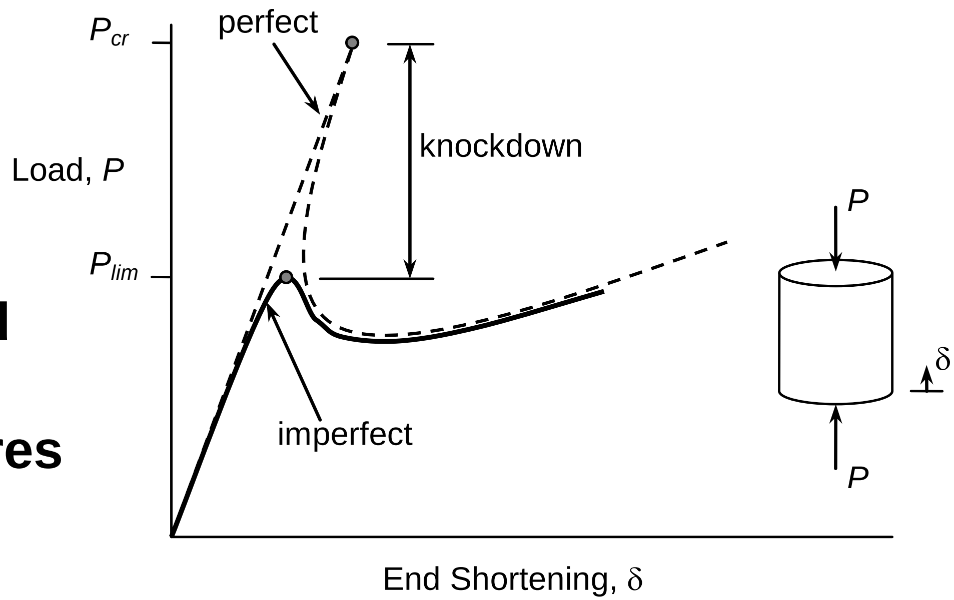
# Design Technology – Updated Shell Buckling Knockdown Factors

## 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



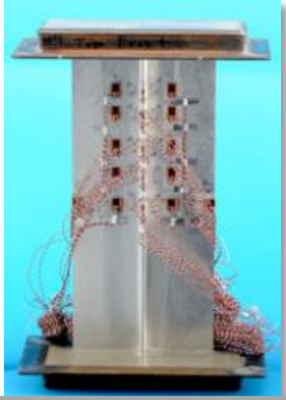

## Expected outcome

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

*POC: mark.w.hilburger@nasa.gov*

# 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**

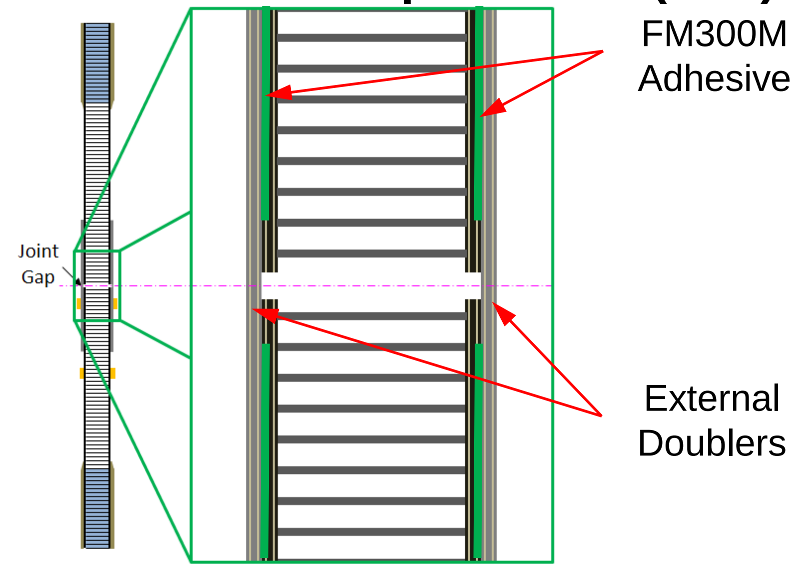
**Subscale launch-vehicle cylinders**

**Full-scale launch-vehicle cylinders**

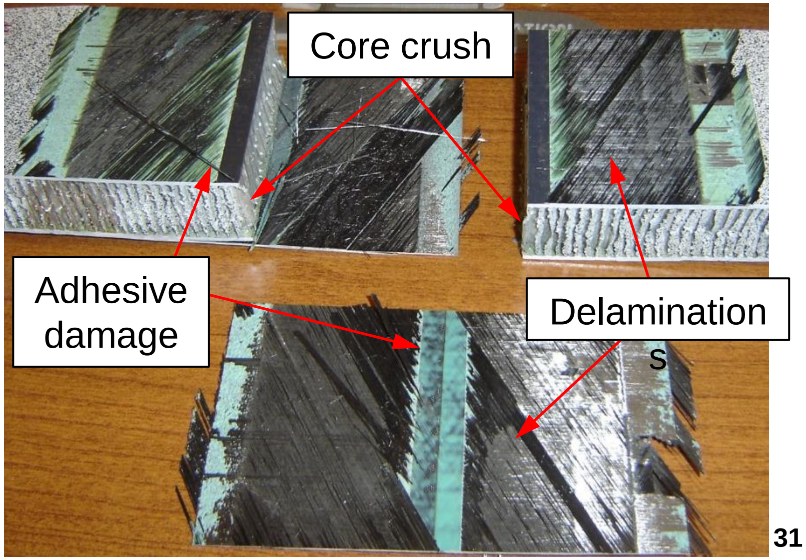
# Design Technology – Bonded Sandwich Joint Design and Failure Prediction/Validation

- 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

**Conventional Splice Joint (CSJ)**



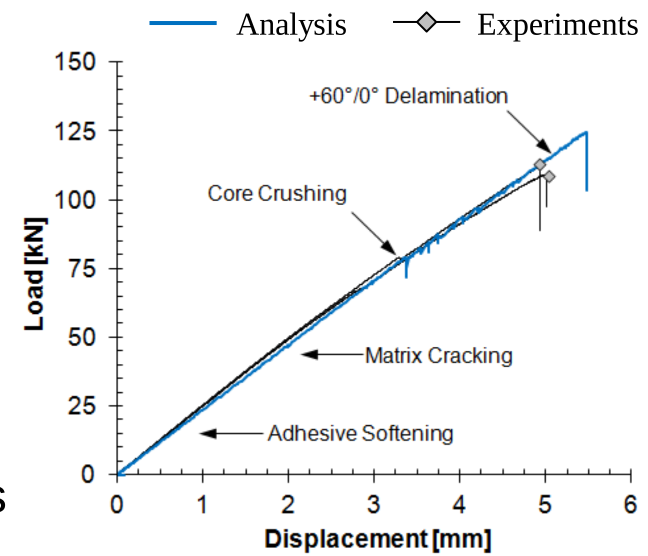

**CSJ Tension Specimen, post-failure**



# 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

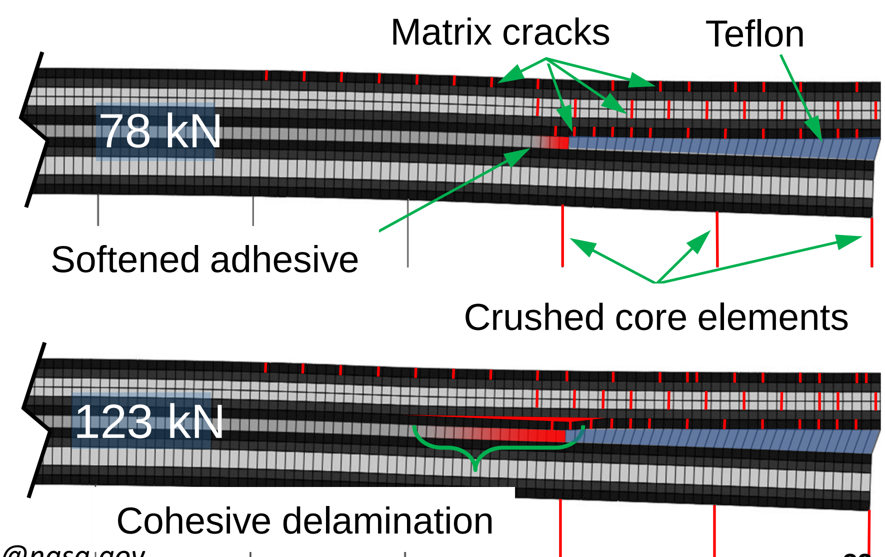
## CSJ Tension Results




<u>LaRC-developed damage modeling tools:</u>

- 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 Damage Mode Predictions




*POC: carlos.g.davila@nasa.gov*

# 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

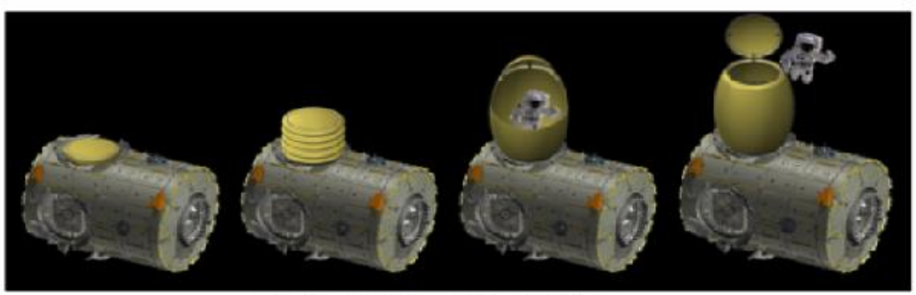
# Prototype Systems: Flexible structures for Habitats – Airlock/Soft Hatch

<u>The Problem</u>

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

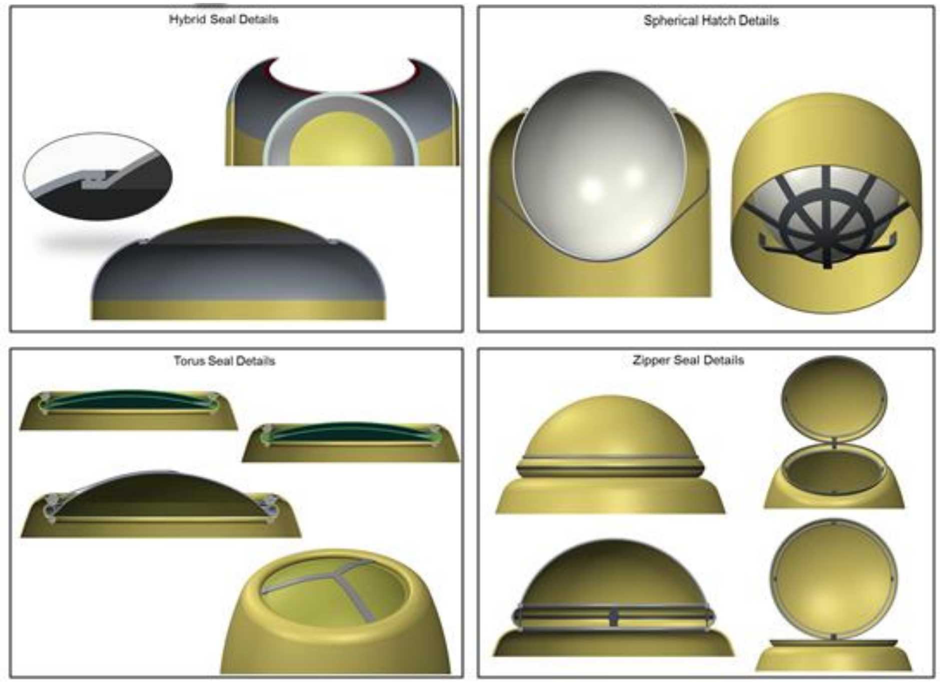
<u>The Solution</u>

- 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.



*Deployment of a notional airlock*

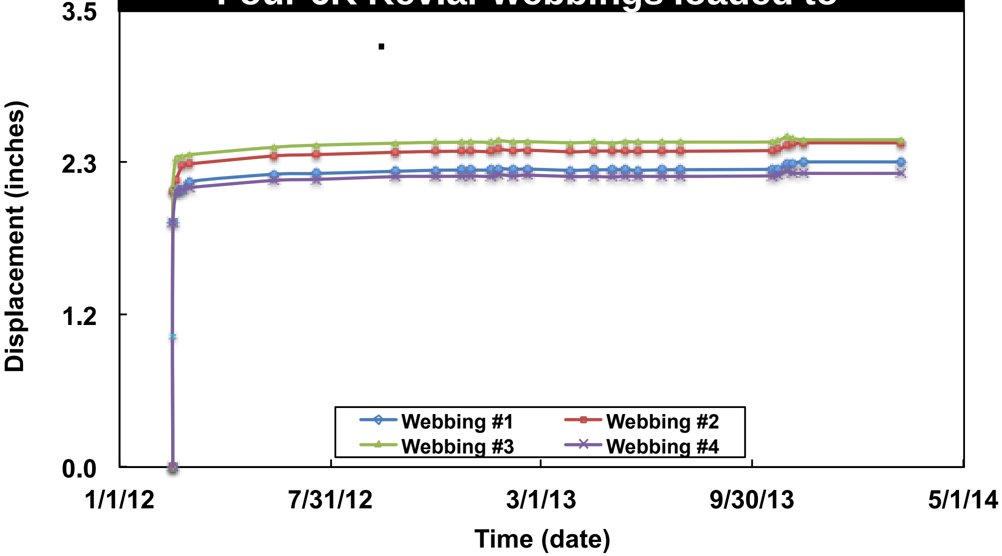
## Status



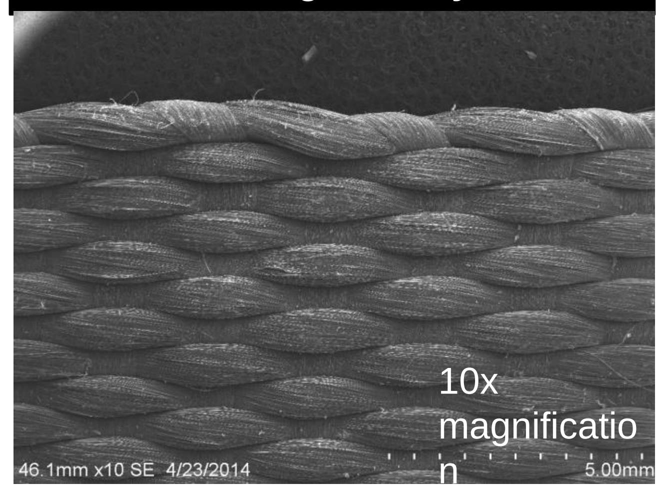

- Trade Study Completed and Baseline Concept Selected in FY14
- Component Concept Design Development in FY15
- Component Technology Demonstration in FY16

# Prototype Systems: Flexible structures for Habitats – Softgoods Creep Issue

Four 6K Kevlar webbings loaded to




Webbing after 2 years




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

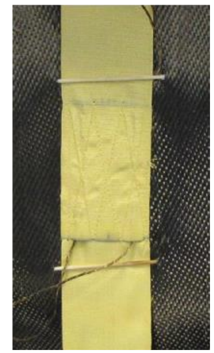
## IS Material Property Testing

- Webbing: Kevlar, Technora, Carbon, Zylon
- Cord: Kevlar, Technora, Carbon, Zylon
- Gas Barriers: Silicone, PTFE

## Component Testing

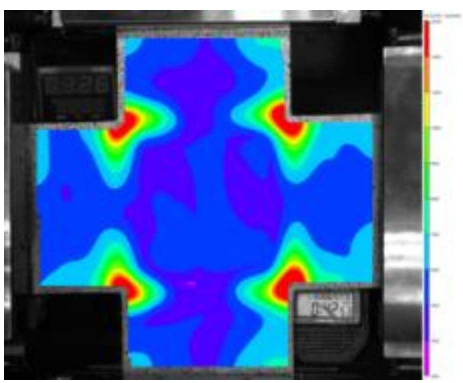
- Burst Testing
- Strap Indentation Tests
- Joint and Adhesion tests
- Packing Tests

Gas Barrier Test Fixture



Stitched Joint

Beam Burst Test



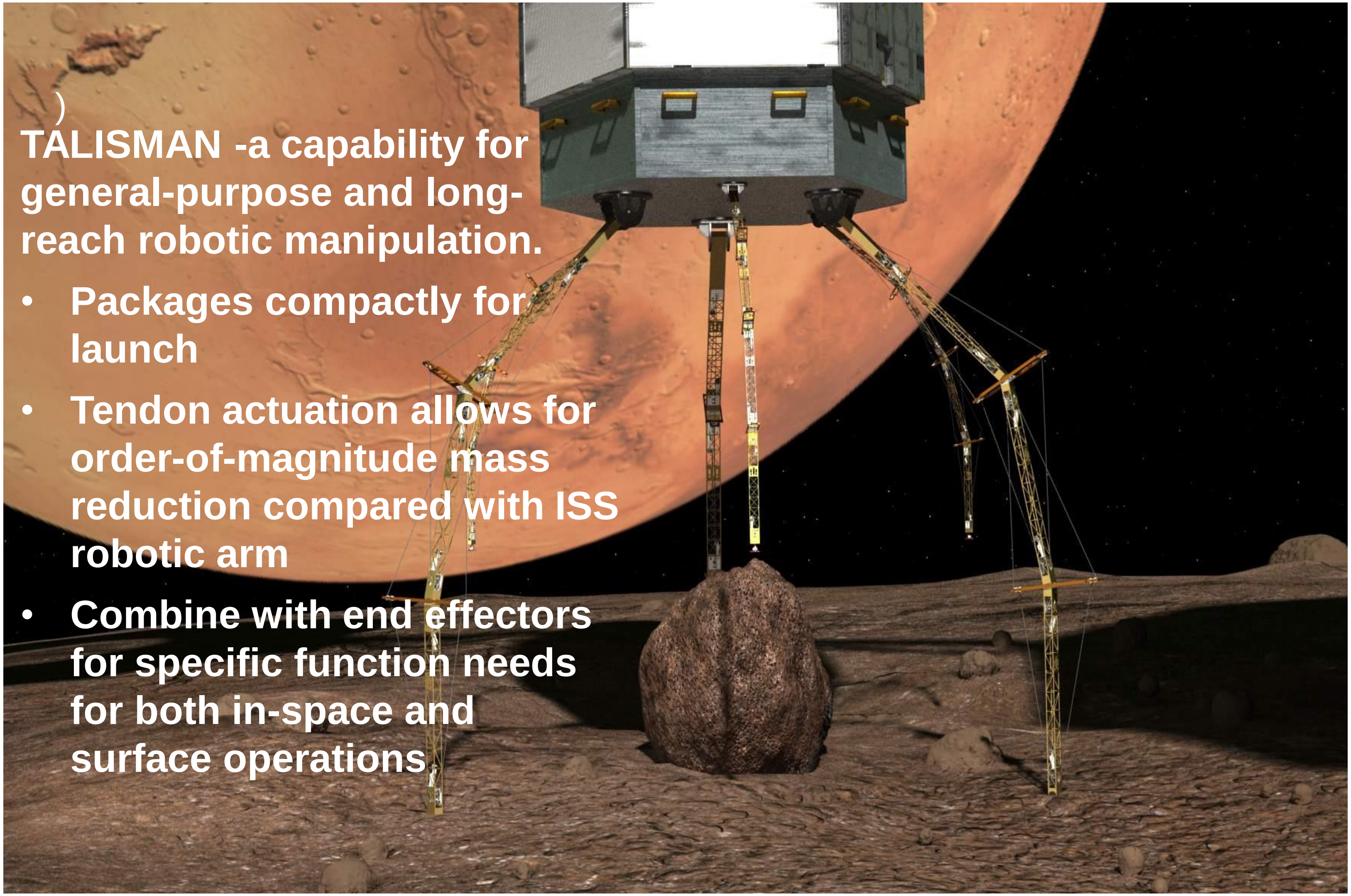
Heating capacity to 500 deg C in 1 minute

Strap Indentation Tests

Folded toroid

# Prototype Systems: Manipulator System for Exploration - TALISMAN

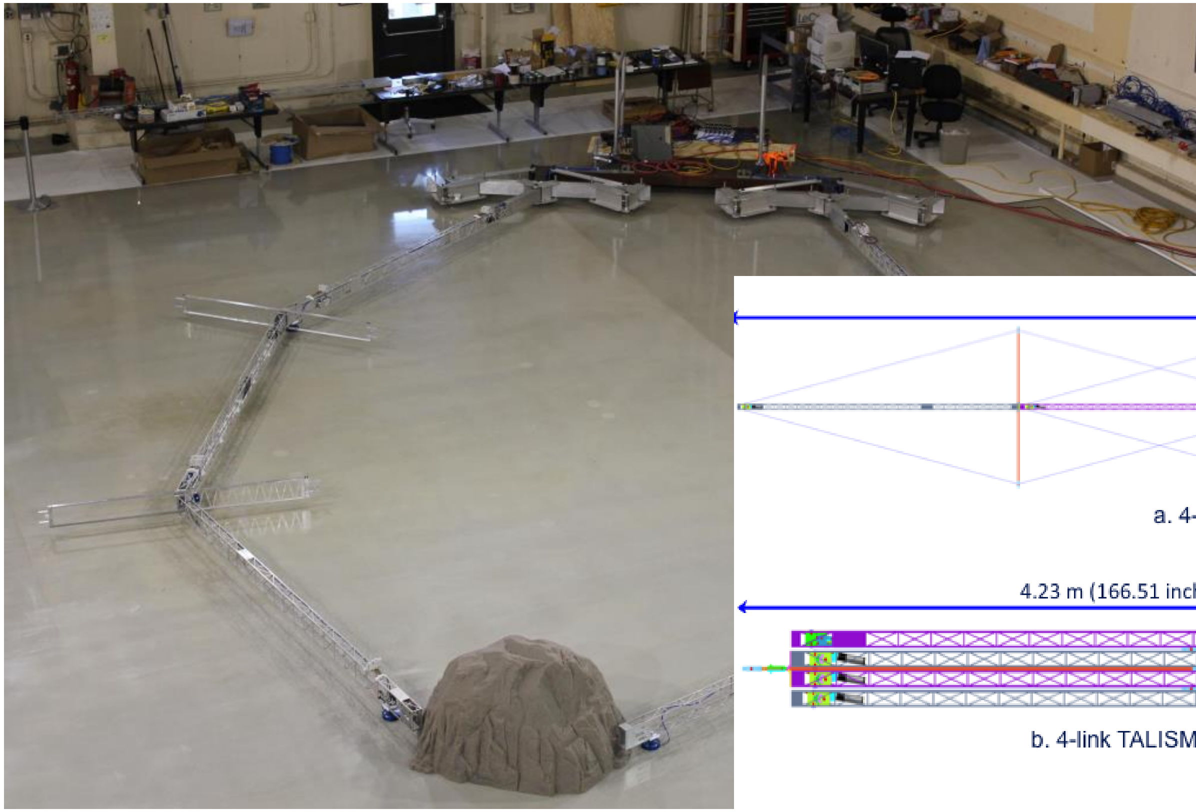
## ARM Concept B TALISMAN-Based Capture System: Retrieve Single Boulder From Large Asteroid



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

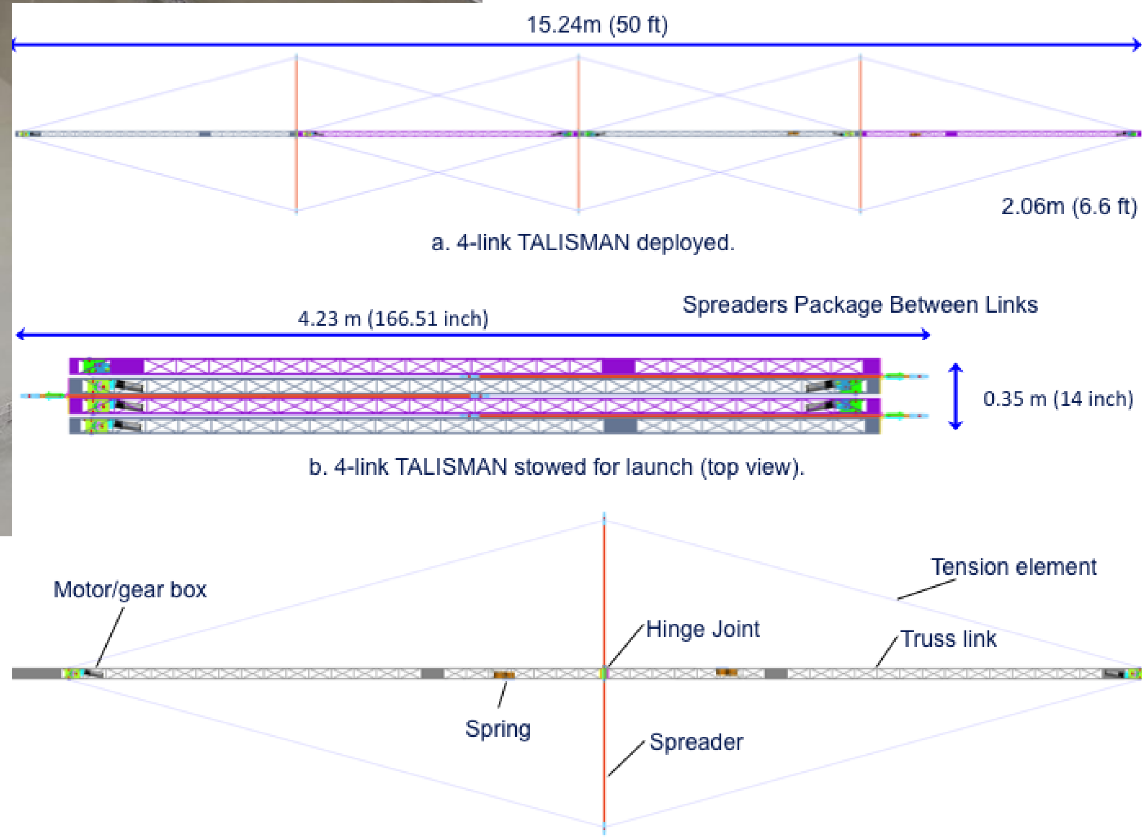
- Packages compactly for launch
- Tendon actuation allows for order-of-magnitude mass reduction compared with ISS robotic arm
- Combine with end effectors for specific function needs for both in-space and surface operations

# 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.

National Aeronautics and Space Administration

# Thank You!