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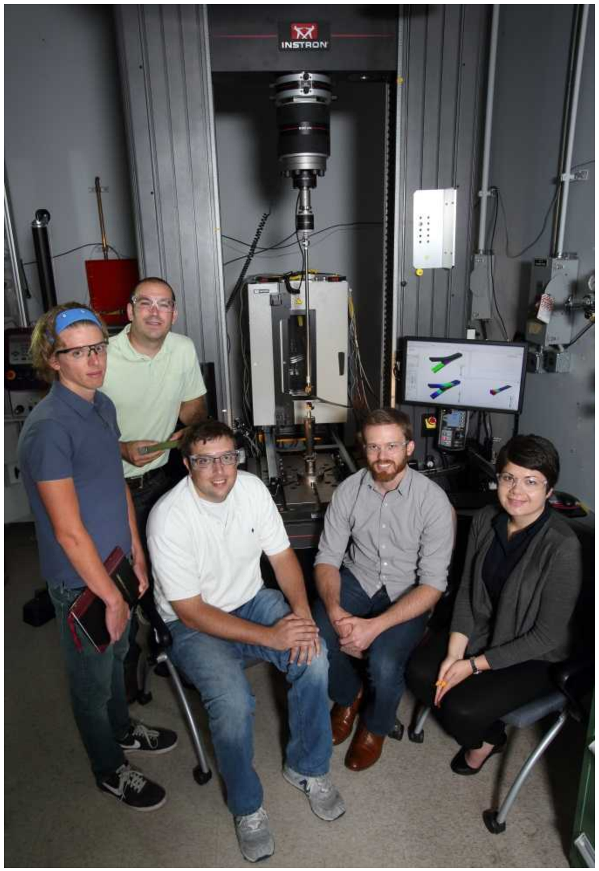
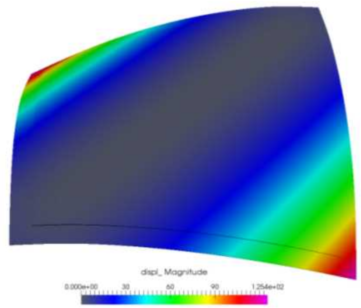
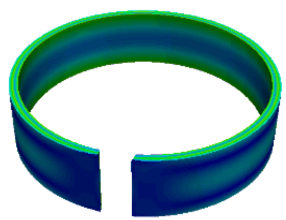






Sandia – AFRL

Technical Interchange

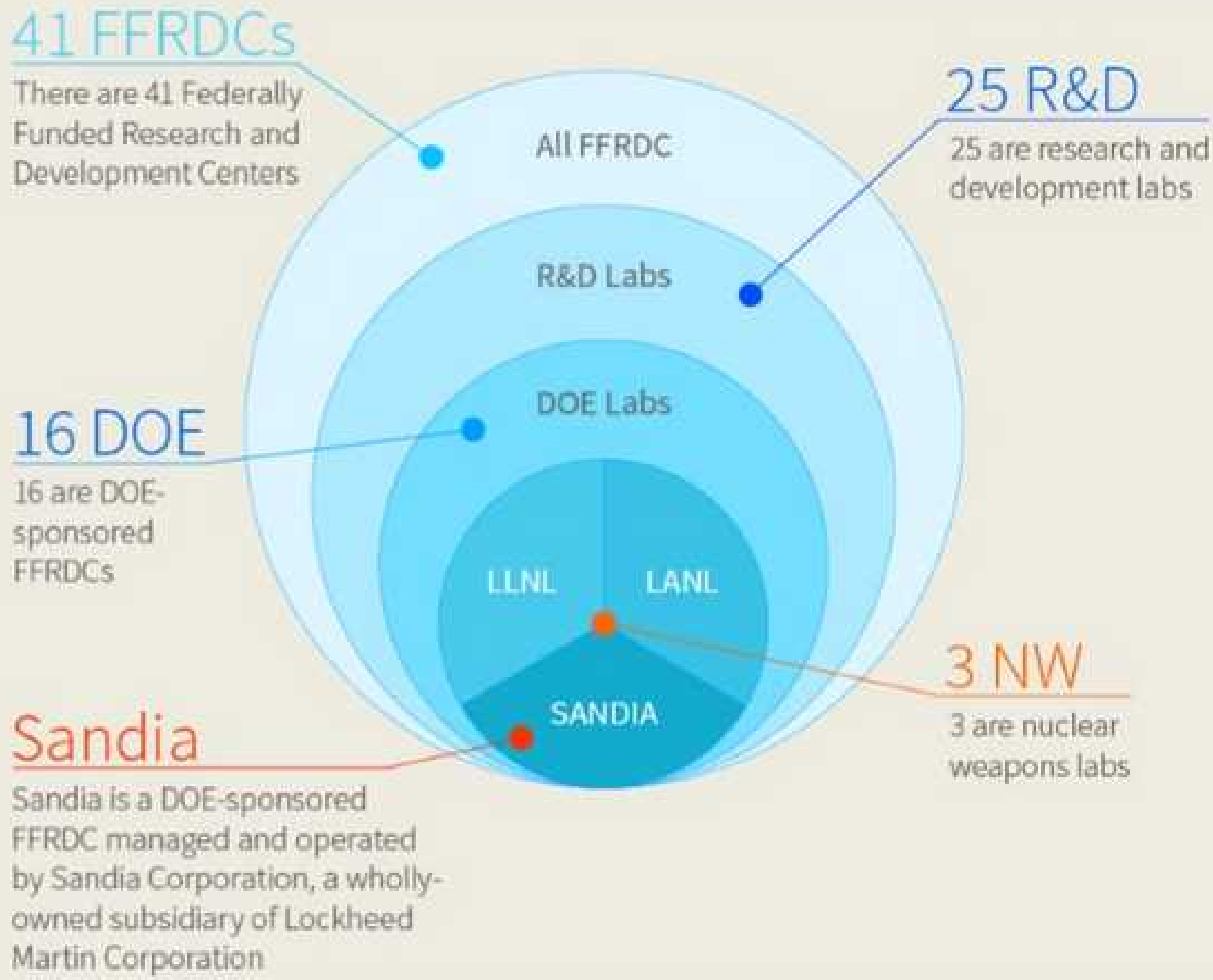
Feb 8th, 2017

Dr. Timothy Briggs
Alex Hanson
Dr. Brian Werner
Dr. Stacy Nelson

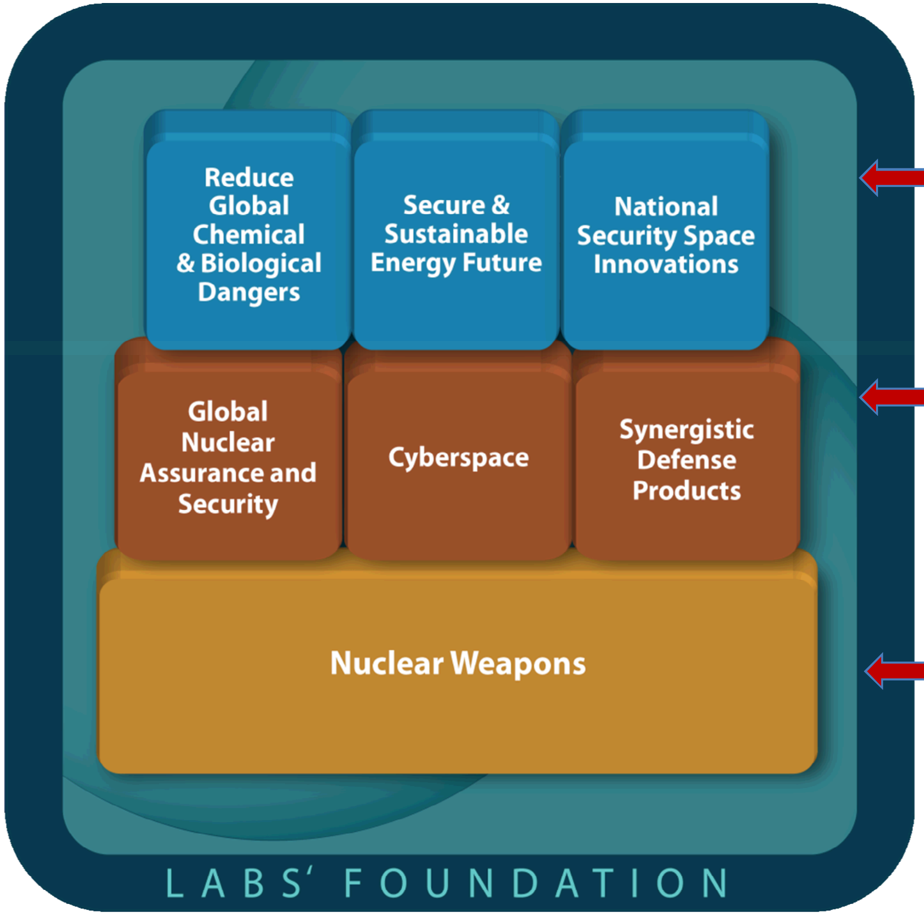
Agenda

- Intro to Sandia National Laboratories and the Mission
- Research Framework and Platform
- Programmatic Investigations
- Composite Material Consolidation Capabilities
- Mechanical Testing Capabilities
- Modeling Capabilities
- Case Studies of Interest

Sandia National Laboratories is an FFRDC



National Security Mission Areas

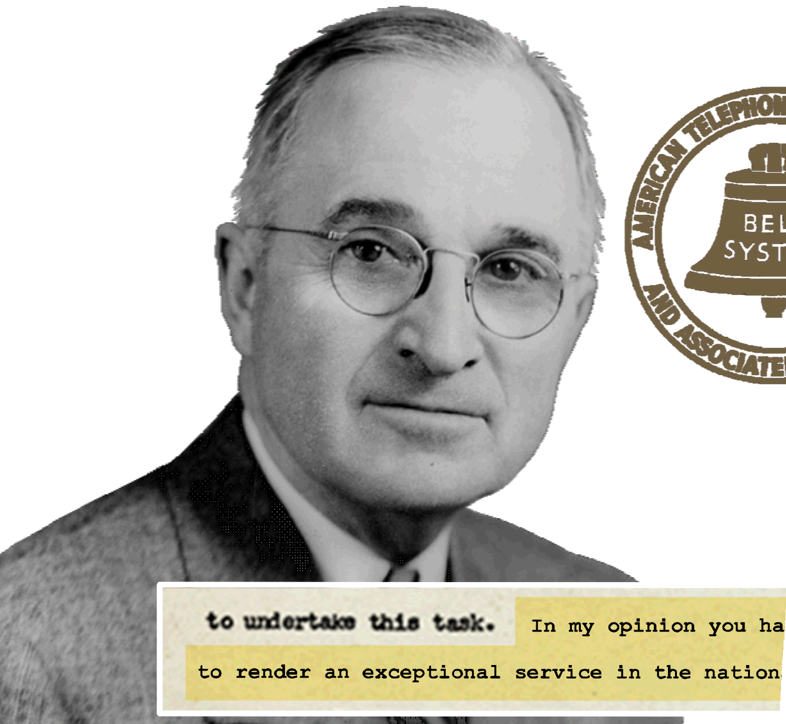


- Top row: Critical to our national security, these three mission areas leverage, enhance, and advance our capabilities.
- Middle row: Strongly interdependent with NW, these three mission areas are essential to sustaining Sandia's ability to fulfill its NW core mission.
- Bottom row: Our core mission, nuclear weapons (NW), is enabled by a strong scientific and engineering foundation.

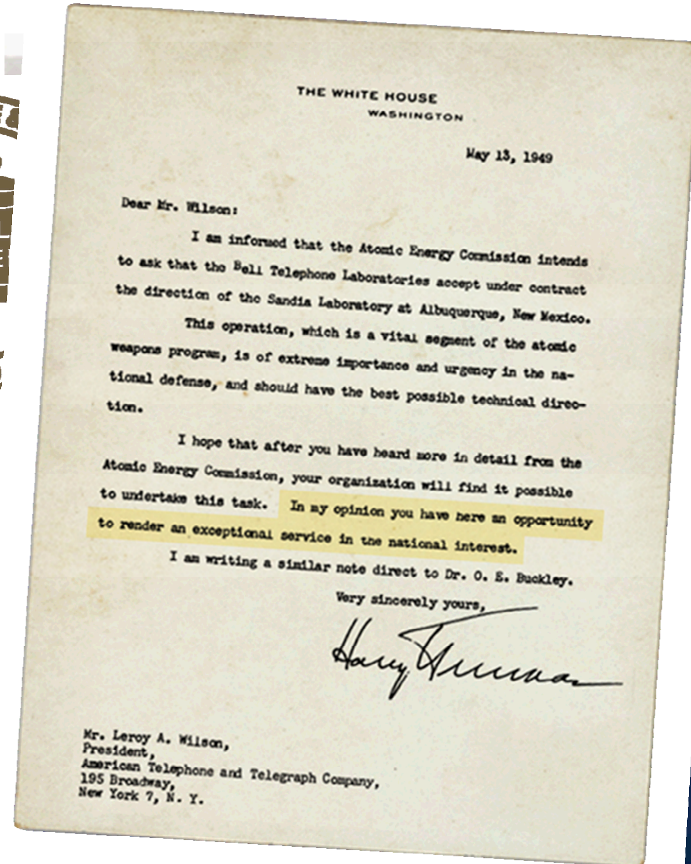
Sandia is a DOE National Laboratory

Origins of Sandia National Laboratory

Exceptional service in the national interest



to undertake this task. In my opinion you ha
to render an exceptional service in the nation



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

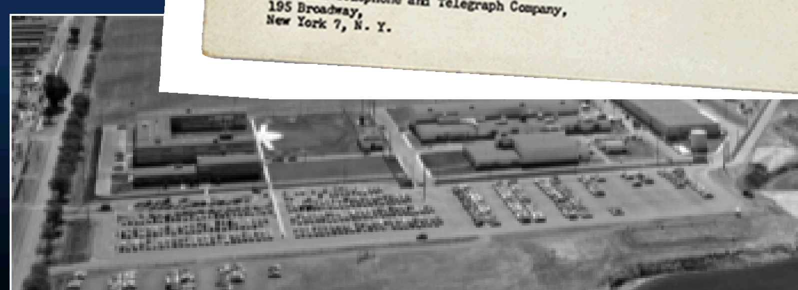
Harry Truman

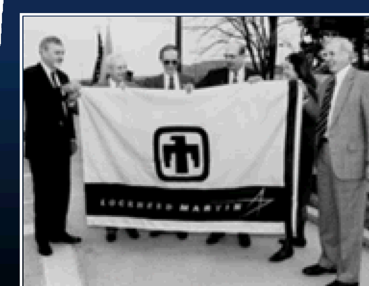
Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

July 1945: Los Alamos creates Z Division

November 1, 1949: Sandia Laboratory established

- **1952:** University of California Radiation Laboratory at Livermore (now LLNL) established
- **March 8, 1956:** andia officially establishes second laboratory at the ivermore site





Sandia Addresses National Security Challenges

1950s
Nuclear weapons
Production and manufacturing engineering

1960s
Development engineering
Vietnam conflict

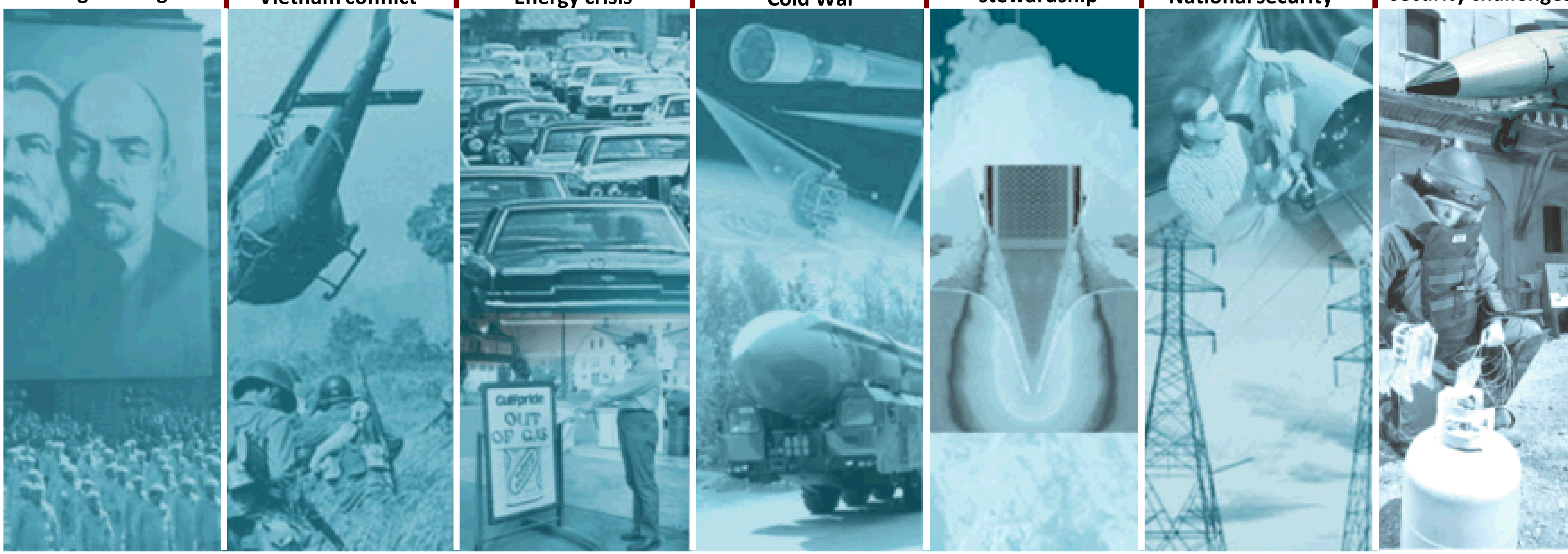
1970s
Multiprogram laboratory
Energy crisis

1980s
Missile defense work
Cold War

1990s
Post–Cold War transition
Stockpile stewardship

2000s
START
Post 9/11
National security

2010s
LEPs
Cyber, biosecurity proliferation
Evolving national security challenges



Sandia Sites

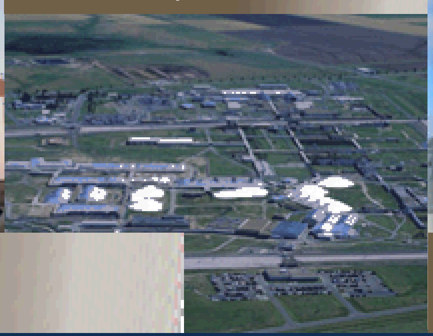
Albuquerque, New Mexico

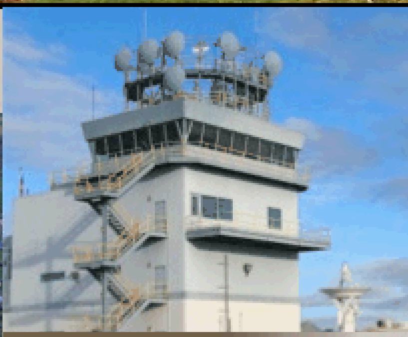
Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas





Tonopah, Nevada

Sandia California Demographics

On-site workforce: ~1,300

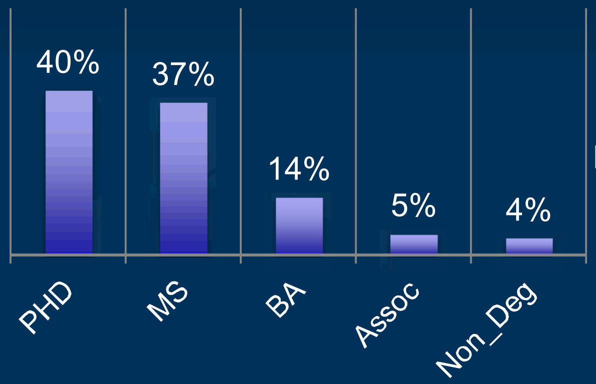
R&D staff: ~500

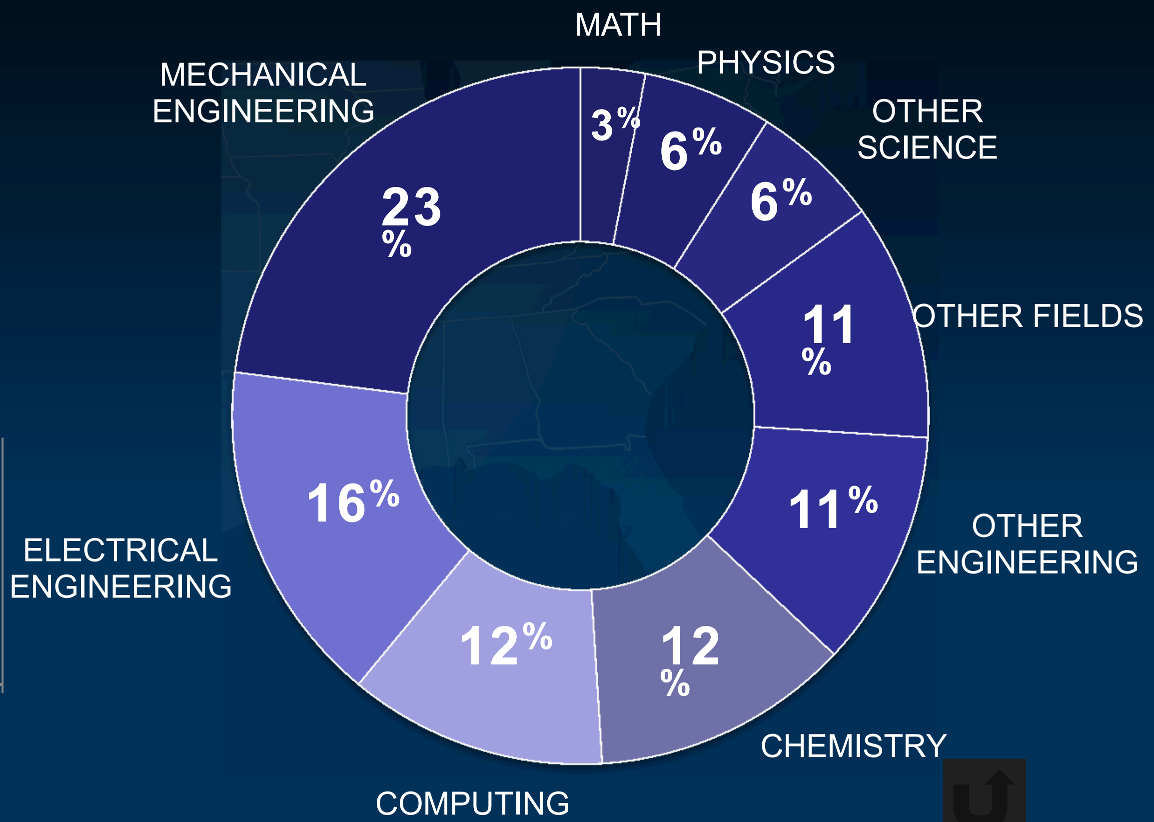
(excluding R&D Tech)

Distinguishing research capabilities:

- Applied Biosciences
- Combustion Research
- Information Systems
- Micro & Nano Technologies and *more*

Degree Level



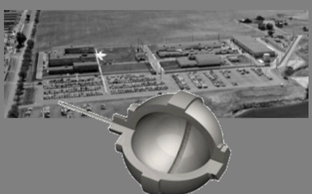


California Laboratory History

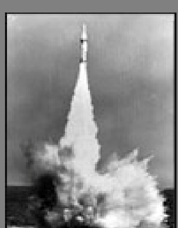
1956

California Laboratory opens, singular NW mission

1960s



Gas Transfer



Polaris - W47

Poseidon - W68

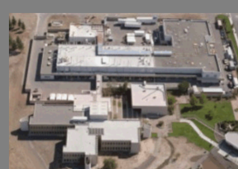
Strong NW mission, Energy crisis

1970s

W62

Minuteman III

Lance - W70



Combustion Research

Solar Tower

Strong NW mission, “Star wars”

1980s

STRATEGIC DEFENSE INITIATIVE

DEPARTMENT OF DEFENSE

AFAP – W79

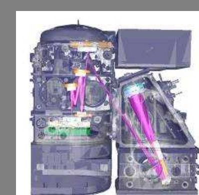
B83

Peacekeeper - W87

“Tech Transfer”, Stockpile stewardship

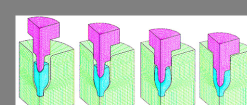
1990s

SEMATECH



Extreme Ultraviolet Lithography

Demil



Stockpile Stewardship

Broader national security

2000s

Homeland Security

m - Chemlab

ALCM - W80 LEP

SANDIA NATIONAL LABORATORIES

50 Years

CALIFORNIA

Stockpile modernization, Open campus

2010s

JBEI

JOINT BIOENERGY INSTITUTE

LVOC

B61 LEP

LRSO/W80-4

The California Laboratory is Strategically Located

- **National Laboratory Partnerships**
  - **Lawrence Livermore**
  - **Lawrence Berkeley**
- **University Collaborations and Partnerships**
  - **access to world-class minds and unique facilities**
- **International Partnerships**
- **Industry Collaborations**
- **State of California – leadership in energy policy**

LVOC enables partnerships that benefit the entire breadth of Sandia's mission space

Sandia's Current Nuclear Weapons Activities

esign Agency for

s

G
Trans
systems

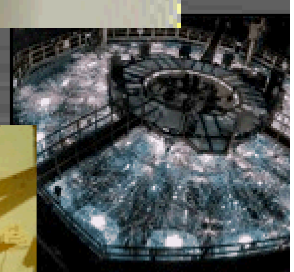
Arming, fuzing, and firing systems

Safety systems

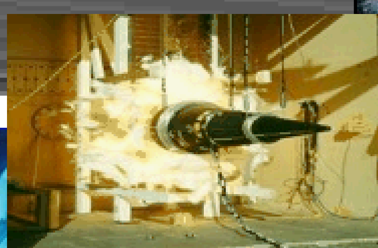
An extensive suite of multi-disciplinary capabilities are required for Design, Qualification, Production, Surveillance, Experimentation / Computation

MESA Microelectronics

Major Environmental Test Facilities and Diagnostics



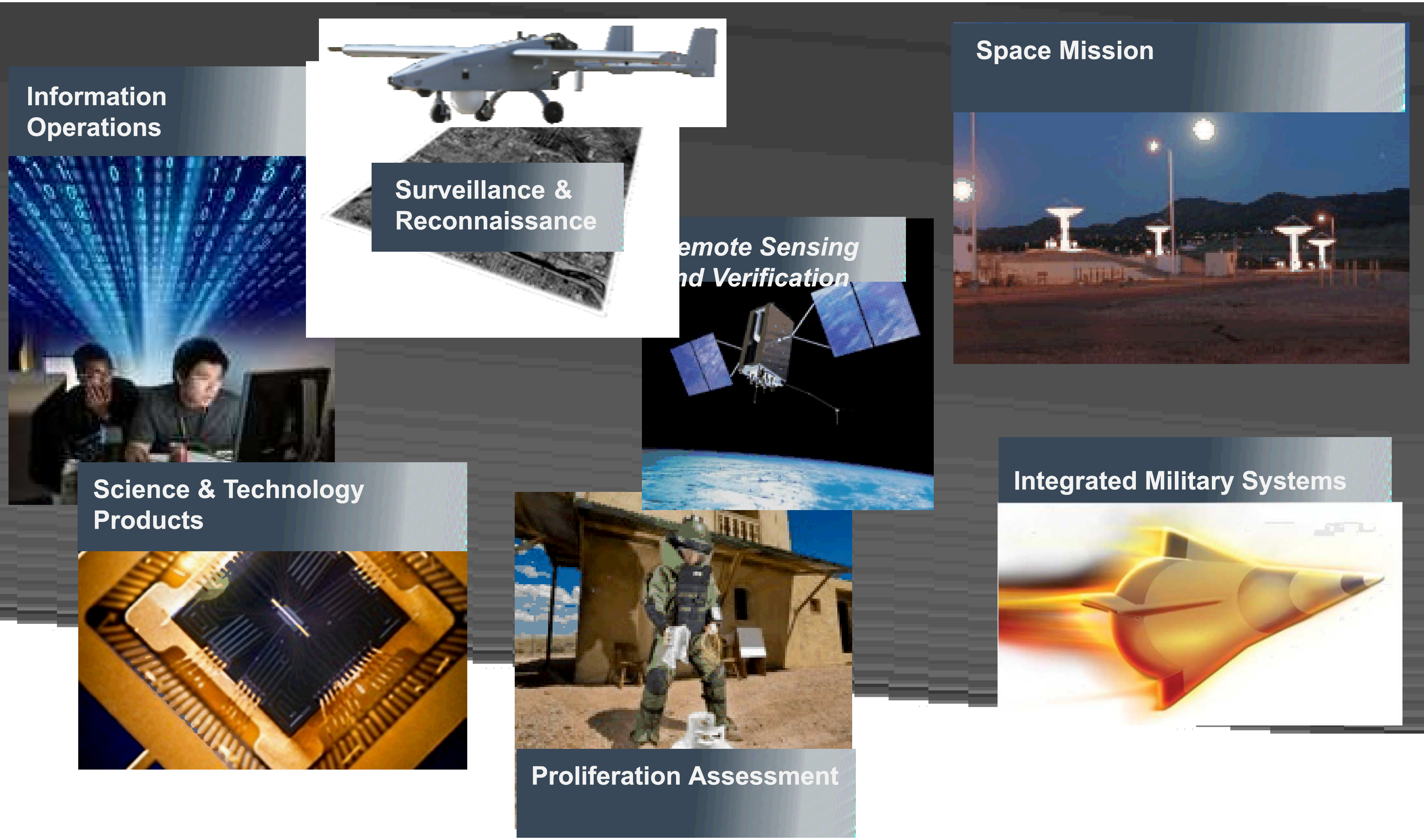
Z Machine



Light Initiated High Explosive

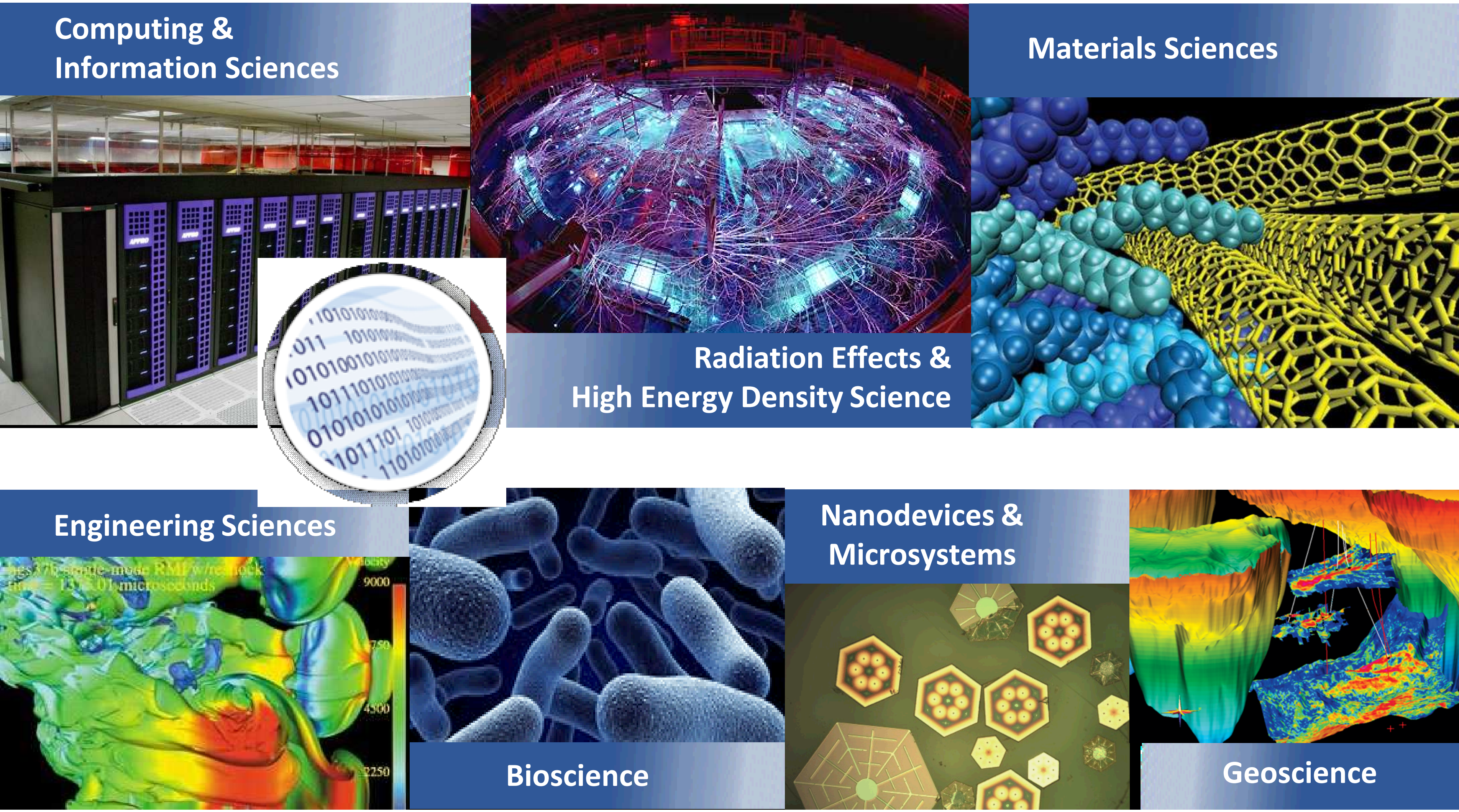
Annular core research reactor

Defense Systems & Assessments Programs



Our Research Framework

Strong research foundations play a differentiating role in our mission delivery



Strategic Partnerships

Sandia

Division 1000: 1200/1500/1800
Division 2000: 2800
Division 5000: 5900
Division 6000: 6600
Division 8000: 8100, 8200, 8300

Production Agencies

NSC

Industry

Vendors of interest

Academia

University of Washington
Northwestern University
UC Davis
UCLA
CAL Poly

Government

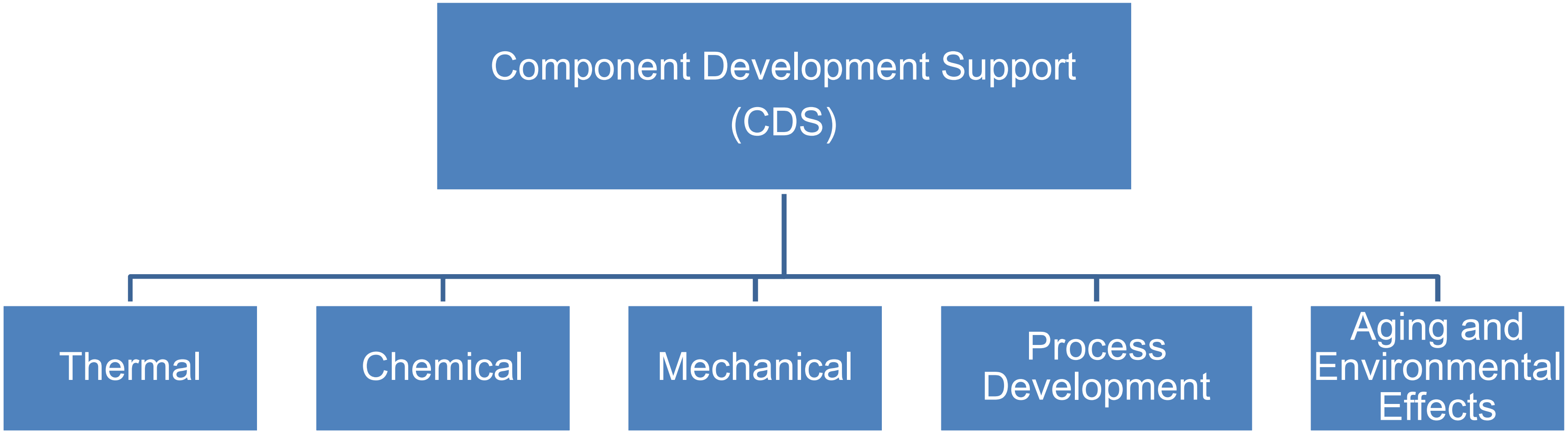
NNSA

NASA Langley

Air Force Research Lab

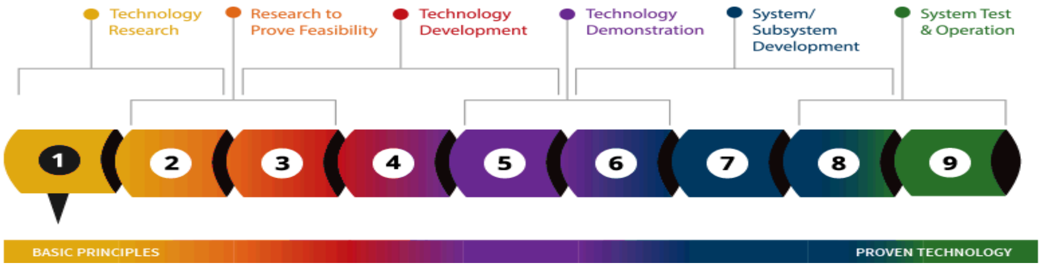
We are continually seeking opportunities to engage and challenge the S&T community with our materials and engineering applications. We encourage a diversified portfolio to leverage the spirit of the various NNSA programs to synergistically partner and meet dependent objectives.

Research and Development Platform



- Unique model managed by R&D staff embedded within our organization
- Provides a platform to physically decompose and break problems down
- Cross-disciplinary investigations promote collaboration
- Research efforts are planned directly with the PRT
- System pull and technology push drive our priorities and timelines
- The R&D portfolio is aimed at providing the technical basis needed to justify our design decisions
- Down-select solution options stem from these efforts that are both practical and scientifically rooted

TRL Levels

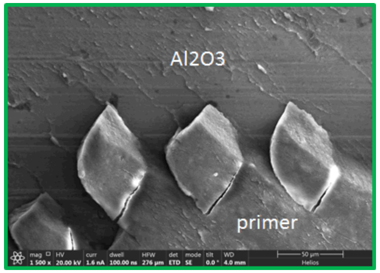


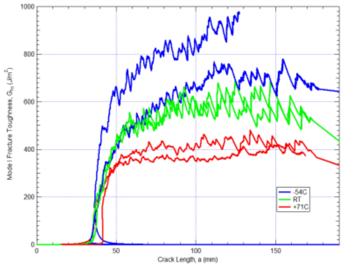
Much of our efforts are in the lower TRL levels, but do span beyond to development and qualification

We are an engineering lab but our decisions and designs are deeply rooted in science.

TRL	Sandia Definition	NASA Definition	DoD Definition
1	Basic principles observed and reported	Basic principles observed and reported.	Basic principles observed and reported
2	Concept and/or application formulated	Technology concept and/or application formulated.	Technology concept and/or application formulated
3	Concept demonstrated analytically or experimentally	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical and experimental critical function and/or characteristic proof of concept
4	Key elements demonstrated in laboratory environment	Component and/or breadboard validation in laboratory environment.	Component and/or breadboard validation in laboratory environment
5	Key elements demonstrated in relevant environment(s)	Component and/or breadboard validation in relevant environment.	Component and/or breadboard validation in relevant environment

Mechanical Characterization – Fracture

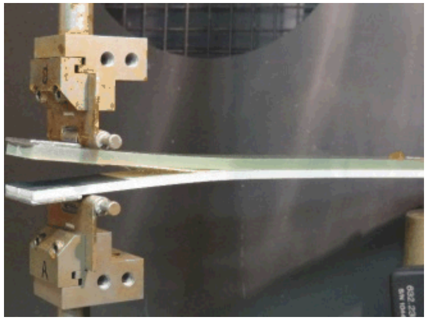




Project Goal: Characterize relevant bi-material Mode I fracture properties across a range of temperatures from -54°C up through +71°C.

Purpose: Down-select design options. Provide strain energy release rates to ASC collaborators for temperature dependent orthotropic modeling.

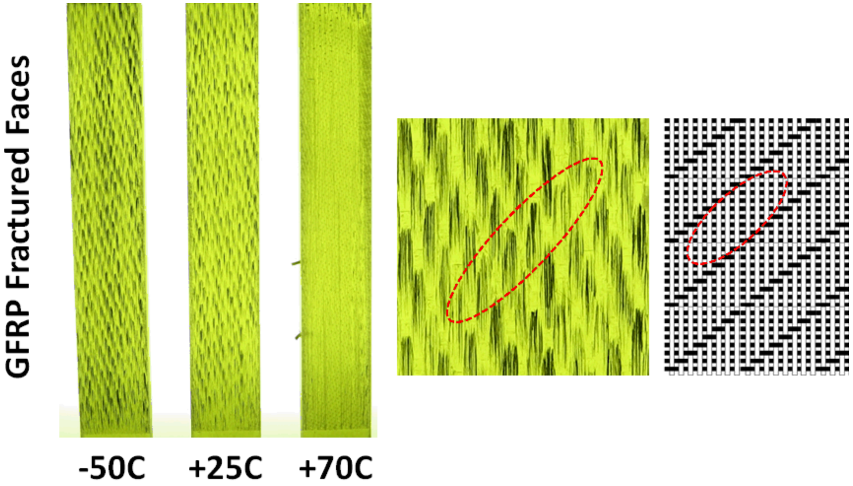
Configurations	Joining Method
GFRP/GFRP	Co-cure
CFRP/CFRP	Co-cure
GFRP/CFRP	Co-cure
Aluminum/GFRP	Co-bond
Aluminum/GFRP	Co-bond w/film adhesive
Aluminum/GFRP	Secondary Bond



Impact: Finite element code is updated with G_{Ic} values for each respective interface. Much higher fidelity failure criterion using cohesive zone elements for component-level models. Necessary insight to make justifiable and informed design choices.

Next Steps: Mode II fracture and mode mixity

$$G_C = \frac{P^2}{2B}\frac{\partial C}{\partial a}$$



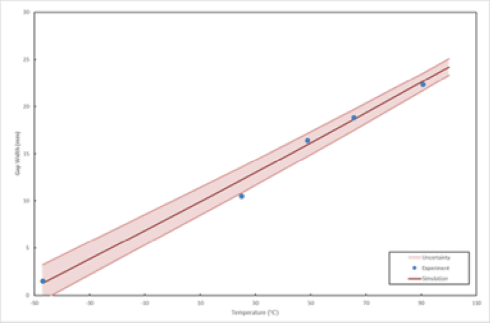
Mechanical Characterization – Residual Stress

Project Goal: Understand and quantify the effects of residual stresses formed at relevant bi-material interfaces through a building block approach.

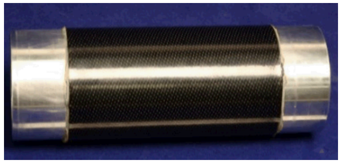
Purpose: Residual stresses are formed within adherends and often concentrated at interfaces. These interfaces are often the weakest region and under the highest stresses. We must understand, anticipate, and mitigate these effects.

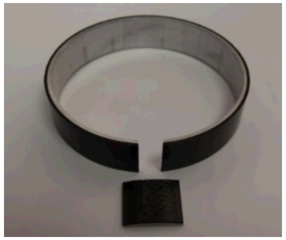
Impact: Providing confidence to designers and customers that our structures are reliable and will pass the test of time regarding in-service loading. Providing the necessary V&V data for modeling efforts.

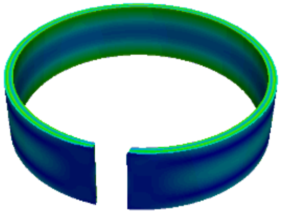
Next Steps: Manufacturing sub- and full-scale components with CMM inspections during the production phase. The residual stresses will distort the components to a level that should be predictable and measurable. This data will further validate computational models both in terms of strains and stresses.



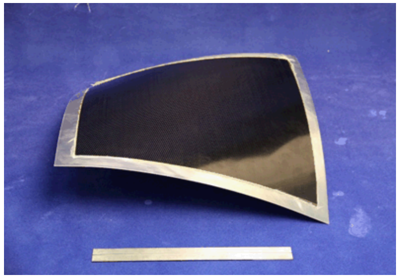
Uncertainty band determined by partnering with ASC V&V project (Nelson)

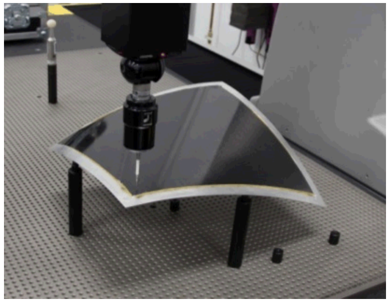


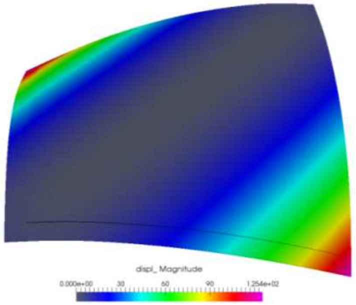




Predictions of the gap closure agree well in the relevant temperature range







Predictions of the “stingray’s” deformations are within 1% of measured

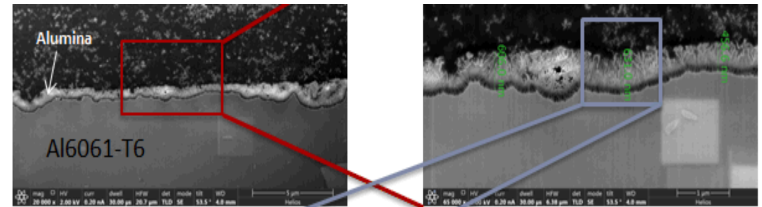
Chemical Characterization – Surface Preparation

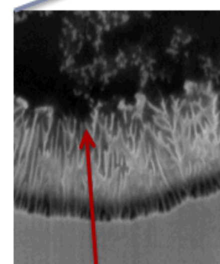
Project Goal: Define the specific processing steps needed to facilitate adequate bond interaction between composite materials and structural supports.

Purpose: The bi-material interfaces of interest involve bonding (either co-bond or secondary bond) of composite material to an aluminum alloy. This bond must be reliable and durable over the lifecycle of the component.

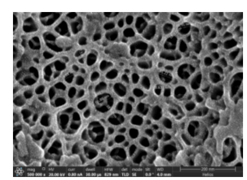
Impact: Providing high level of confidence to designers and customers that our component can survive and perform for all relevant environmental scenarios.

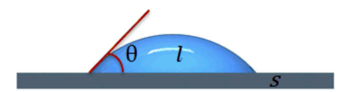
Next Steps: Developing new process and material specifications to formally define the method of approach for production implementation. Evaluate the effectiveness of the bond from a durability and aging perspective.

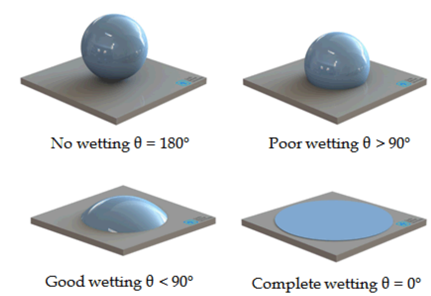


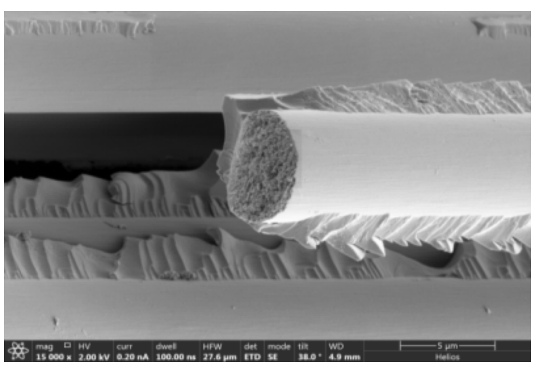


High Res. transmission electron microscopy (TEM) analysis of the cross section of the primer and the anodized surface is pending









Chemical interactions relate surface functionalization and bond groups to the chemical species present. Considerations such as surface energy and tension as related to wettability are good indicators of potential bond quality.

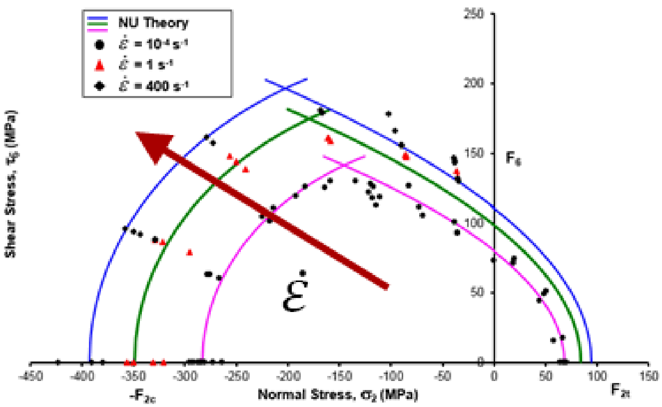
Mechanical interactions relate the surface topology and orientation to increases in surface area and directional dependence of bond performance.

Strain Rate Dependence of Composite Materials

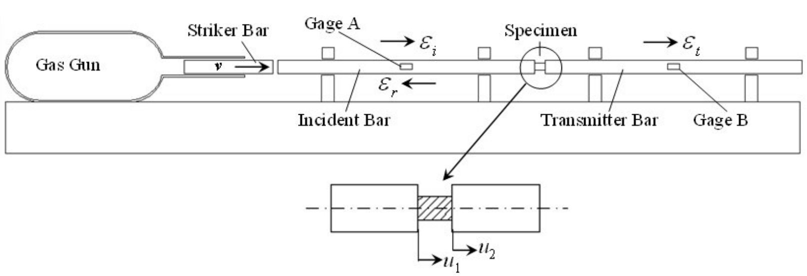
Technology Gap: Strain rate dependent material response of orthotropic materials. Evaluation of the current modeling fidelity, approach, and providing validation data. Coupling temperature dependent material models with credible combinations of strain rate.

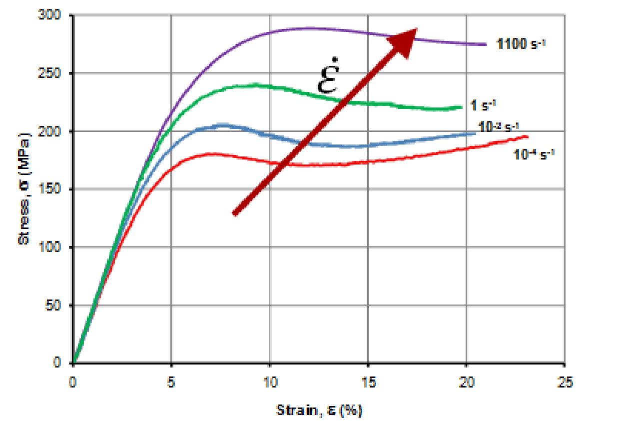
Applications: Dynamic and impulsive loading scenarios throughout various environments.

Potential Impact: More cost effective computational design iterations, and to validate experiments. A deeper understanding of the constituent-level role to rate dependence and implications material choice selection and modification.



Rate effect on resin dominated failure





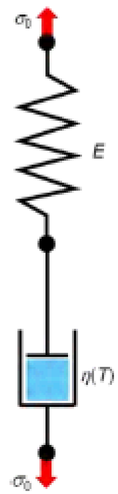
Rate effect on epoxy in compression

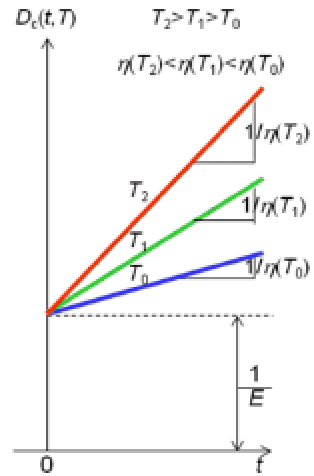
Viscoelastic Effects of Composite Material Aging

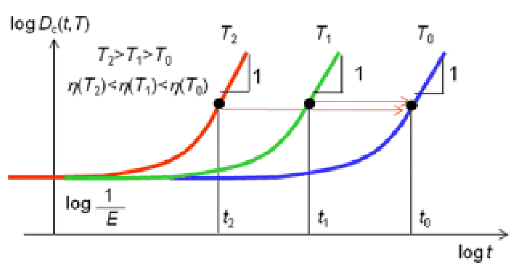
Technology Gap: Creep and relaxation response of our orthotropic materials of interest. Understanding limitations of these time-temperature compensation techniques to our specific polymers and adhesives.

Applications: Applications utilizing composite materials and structural adhesives for various applications.

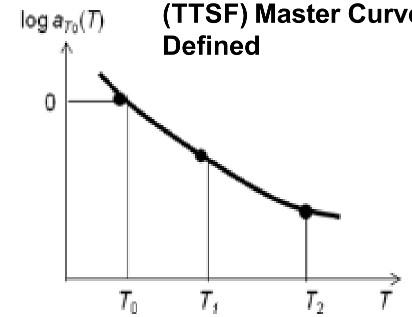
Potential Impact: A new ability to determine maximum preload levels needed for assembly in order to maintain adequate rigidity over the lifecycle of the system. Quantifying the effect of relaxation on an overall decrease of residual stresses (and resulting fracture toughness in the presence of residual stresses) with time.





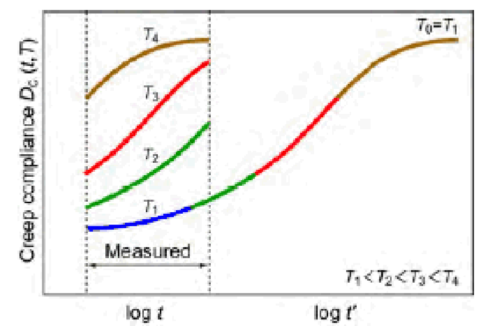


Time-Temp Shift Factor (TTSF) Master Curve Defined



$$a_{T0}(T_i) = \frac{t_i}{t_0} = \frac{t_{si}}{t_{s0}} = \frac{t_{ci}}{t_{c0}} = \frac{t_{fi}}{t_{f0}}, i = 1,2,3\ldots,$$

Can the long-term effects of deformation and strength be predicted from the measured short-term responses at elevated temperature testing?



Miyano, Y., et al, Society of Experimental Mechanics, 2016.

R&D Portfolio

Component Development Support

Process Development – Composites Machining

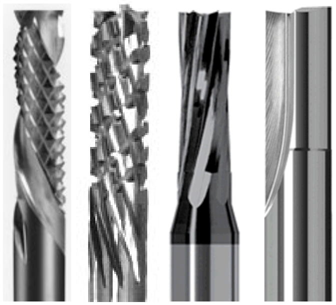
Sandia National Laboratories

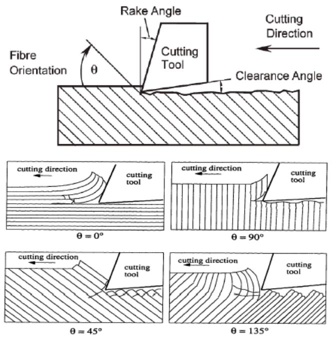
Project Goal: Develop and understanding of the relevant process parameters to properly machine our composite materials.

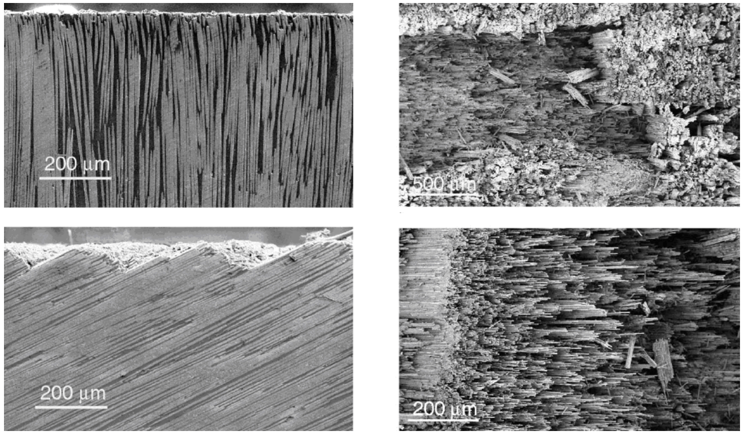
Purpose: Provide guidance and direction, as appropriate, for production level manufacturing of composite components. Maintain consistency in the approach and minimize manufacturing-induced defects from post-processing operations.

Impact: Research has shown that there are detrimental effects to machining-induced defects when cutting, facing or trimming composite materials. The fiber direction dependence to the material removal process can induce cracking, thermal damage and fiber pullout. These small-scale defects have been shown to be precipitation points for both subsequent stress concentrations and failure initiation sites.

FY17 Scope: Benchmark the industry and identify relevant tooling for lathe turning axi-symmetric parts. Identify and procure viable tooling choices to evaluate on our specific materials and geometries of interest. Make decisions based on findings for optimal process definition.

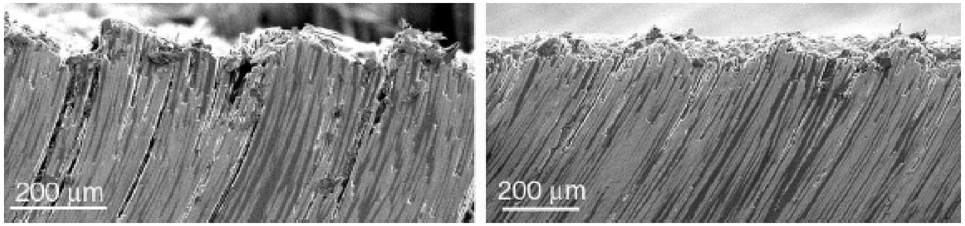






R&D Portfolio

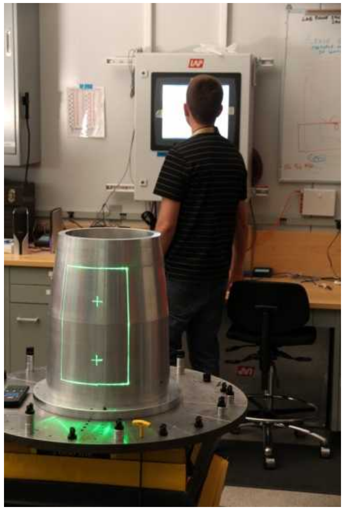
Component Development Support



Ramulu, et al.

Mission-Focused Infrastructure

Sandia National Laboratories



Laser Projection System
Accurate and repeatable composite ply location

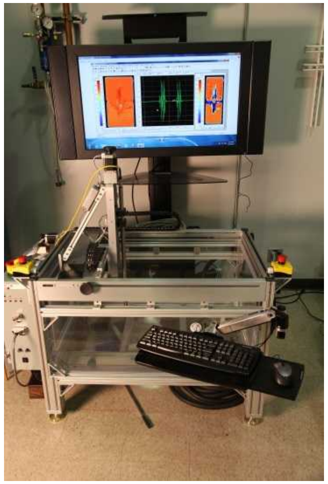
All of our critical operations are concurrent with our Production Agency at The National Security Campus.

Filament Winding System
6-Axis system identical to PA capability

Autoclave System
Pressure, temp and vacuum for curing composites

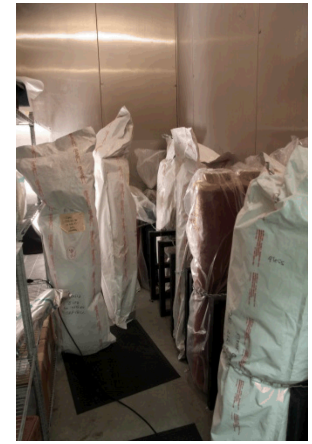
Picasso: Automated Paint Robot

LWSL Infrastructure

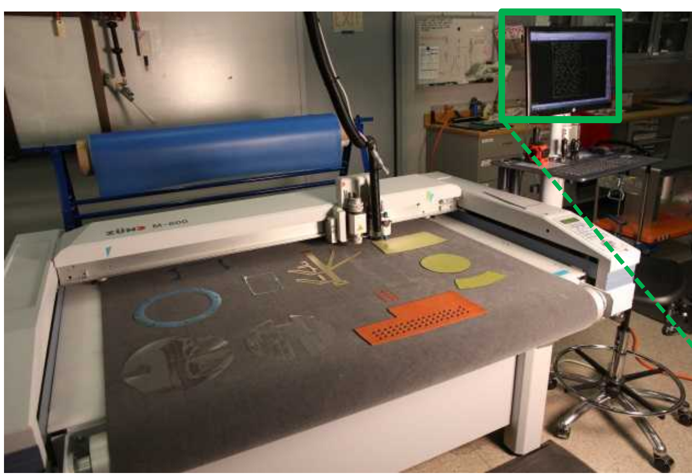



Non-Destructive Evaluation

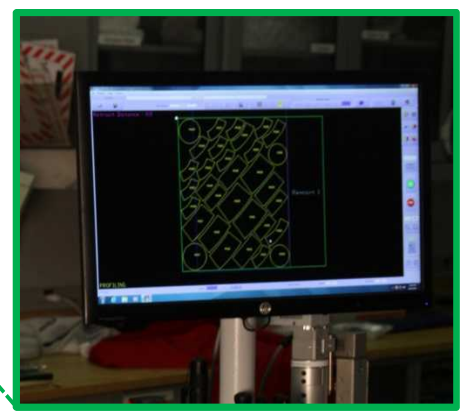
Hand Lay-up



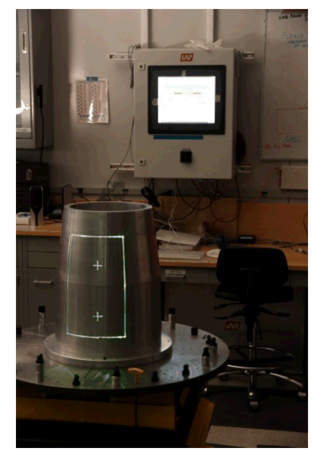
Maintain Material Stock



4-Axis CNC Ply Cutting



Design / Optimization

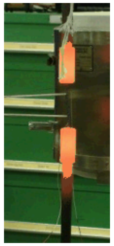


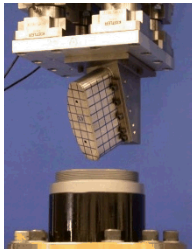
Laser-Assisted Layup

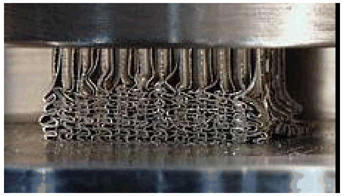
Mechanics Testing Capabilities

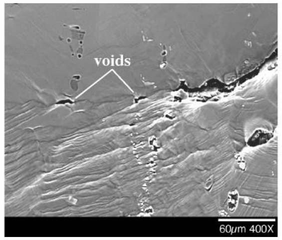
Experimental Mechanics

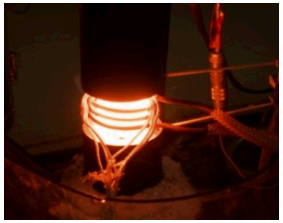
- Research and development of new experimental methods and diagnostic measurements
  - Micromechanics
  - Damage evolution
  - Failure
  - Rate effects
  - Multiphysics phenomena
- Large deformation mechanical characterization experiments over wide temperature and strain rate ranges to provide strong coupling between experiments and modeling
- Design and execute experiments to provide computational model validation for mechanical and coupled thermomechanical behavior of engineered systems
- Experience with a wide range of materials including foams, metals, polymers, ceramics, and composites

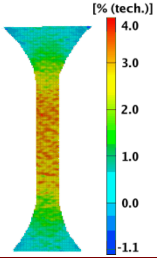






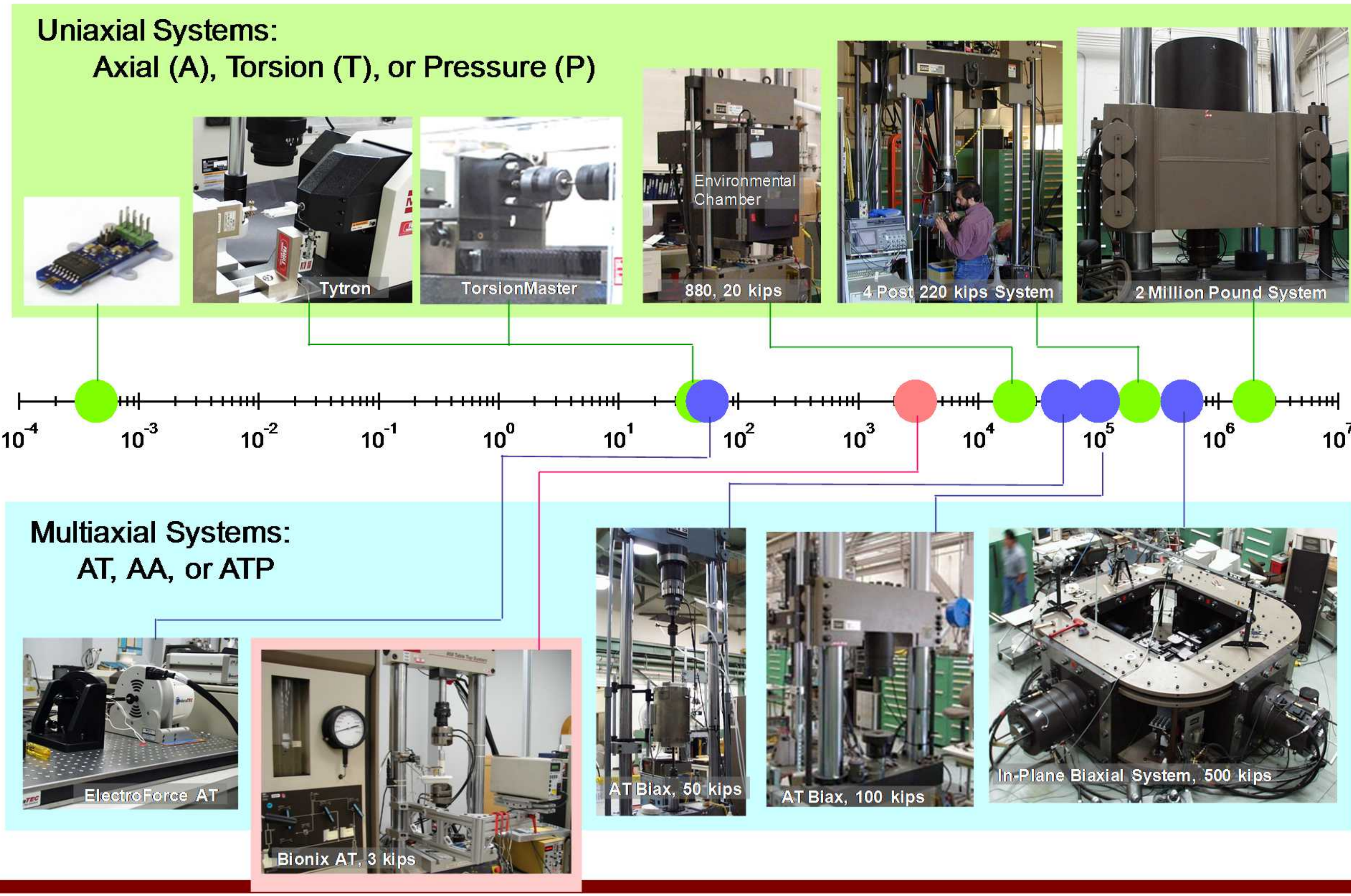




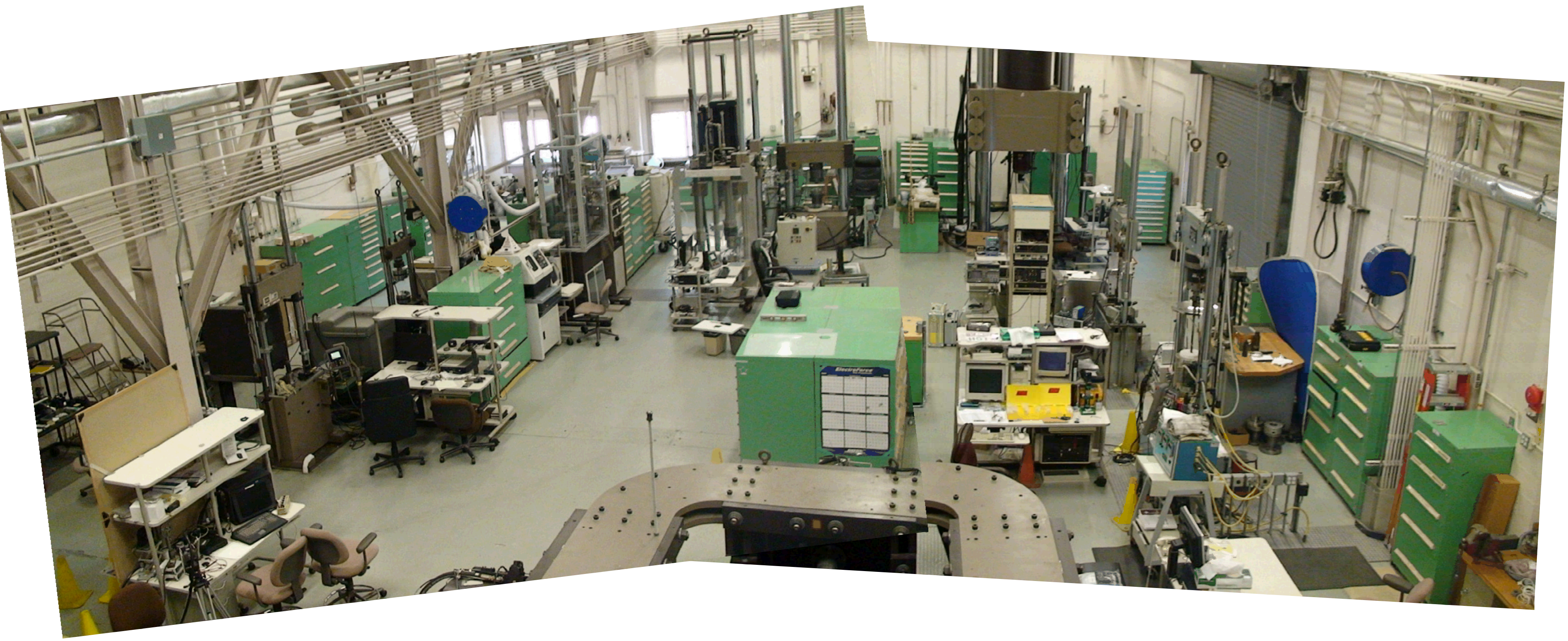


Loading Capabilities

- Capacities ranging from 2 million pounds to less than1 μN/1 μm load/displacement resolution



972 High Bay Servohydraulic (MTS) Frames

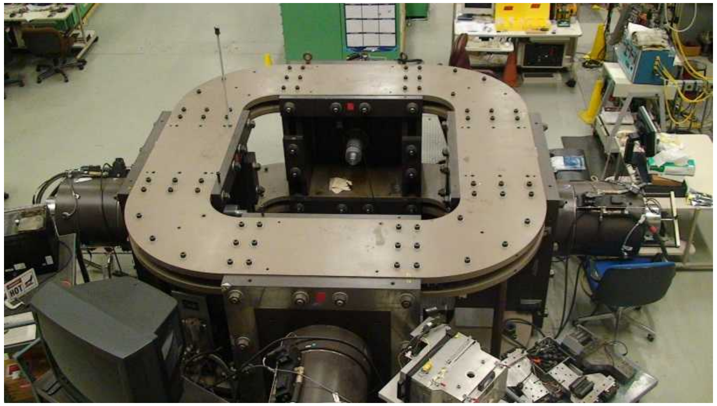


972 High Bay

Servohydraulic (MTS) Frames

20Kip 880 Test Frame

500Kip BiAx Test Frame



Hi-Rate Test Frame

100Kip Axial/Torsional Test Frame

972 High Bay

Servohydraulic (MTS) Frames

220Kip Test Frame

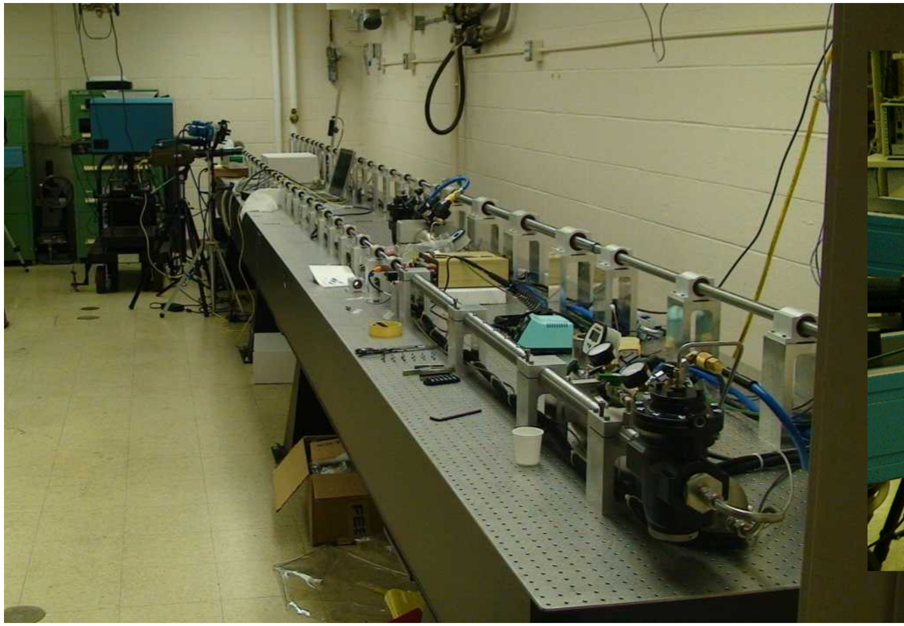
2M lb Test Frame

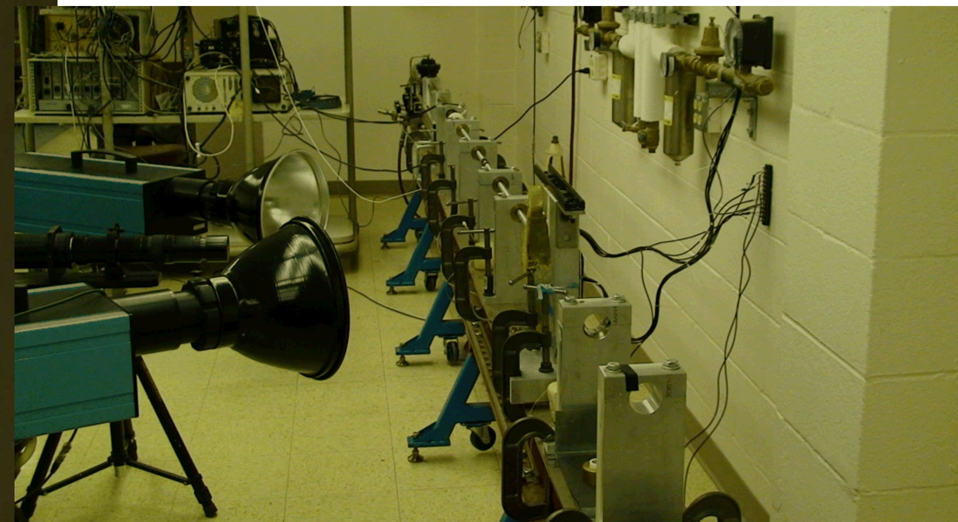
220Kip Test Frame

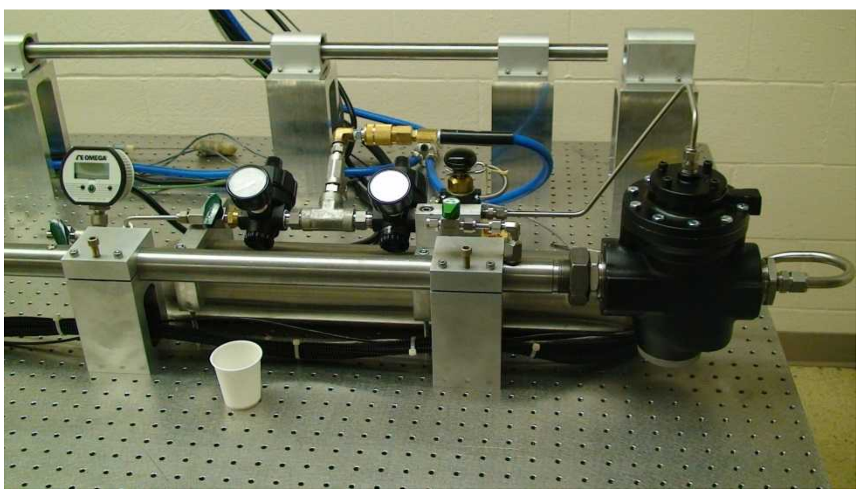
50Kip Axial/Torsional Test Frame

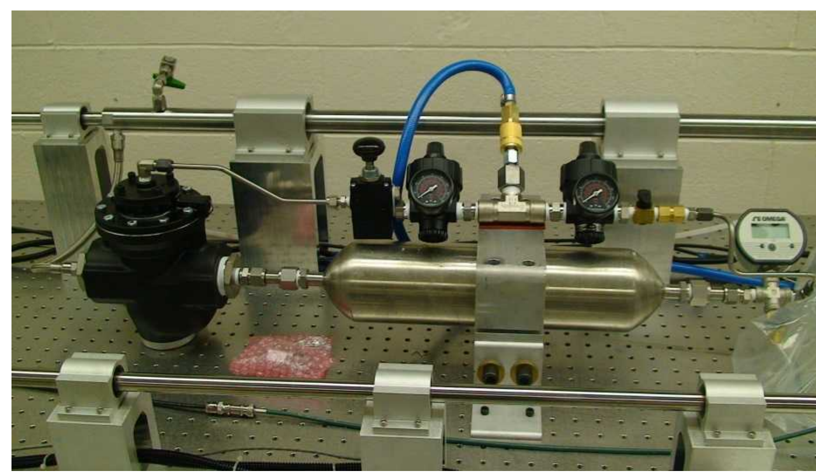
972 Hopkinson Bar Facility

Sandia National Laboratories







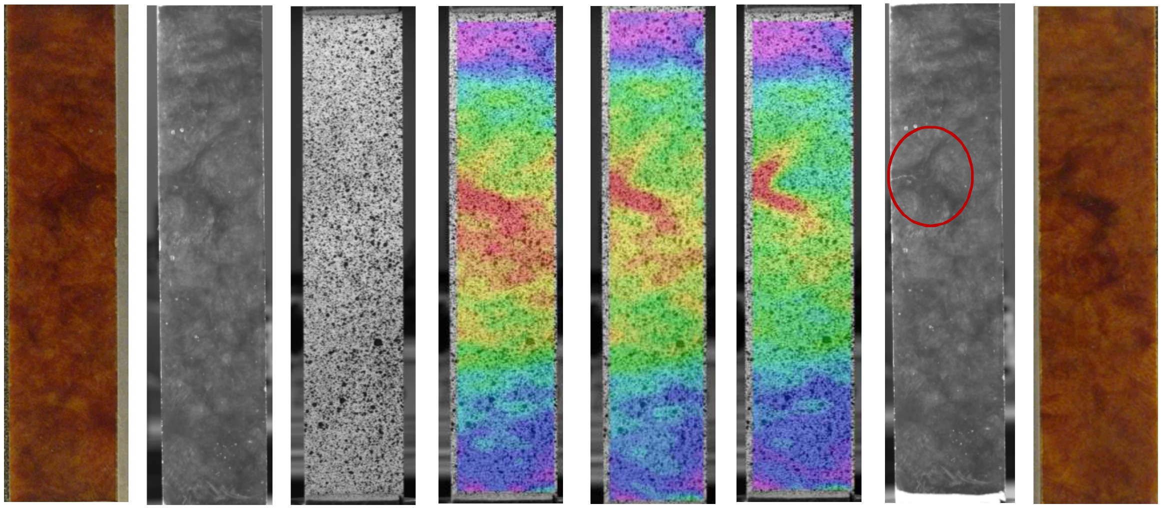


Micromechanics Lab (942/1334)

Lightweight Structures Testing Lab (941/1123)

Digital Image Correlation (DIC)

- DIC provides full field tracking of the strain field throughout the test
- 3D DIC utilizes two cameras to determine out of plane deformation
- Provides information on strain localization
- VIC-3D from Correlated Solutions and GOM from Aramis



Color image of the original specimen front surface

In-situ specimen surface and DIC pattern

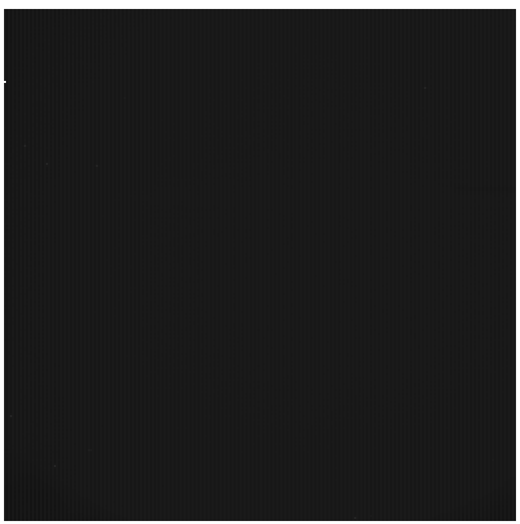
Strain concentration obtained from DIC

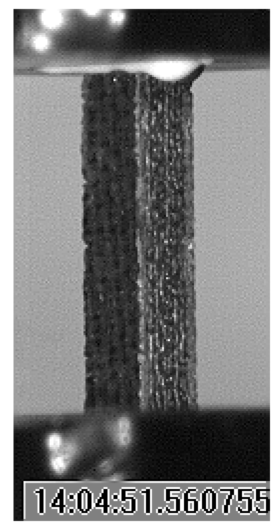
Specimen surface

Color image of the original specimen back surface

High Speed Photography

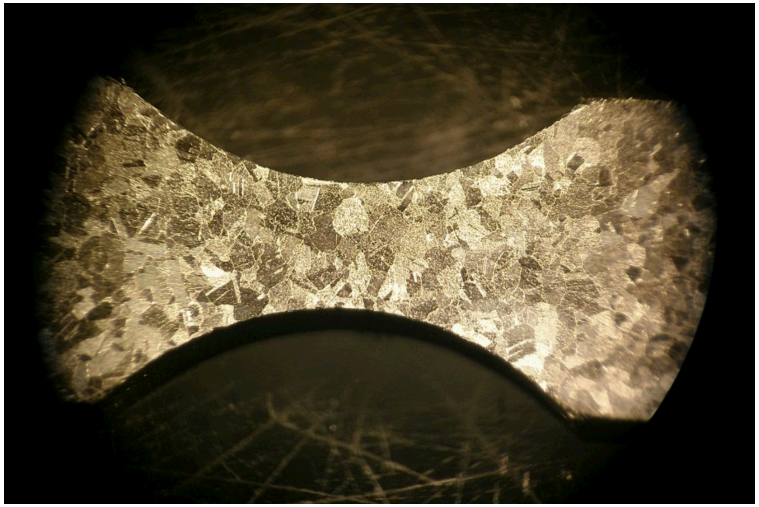
- Two Phantom V12.1 high speed cameras
  - 1280x800 resolution
  - Over 100,000 fps
  - Can be used with DIC
- Cordin ultra-high speed camera (up to 2 million fps)

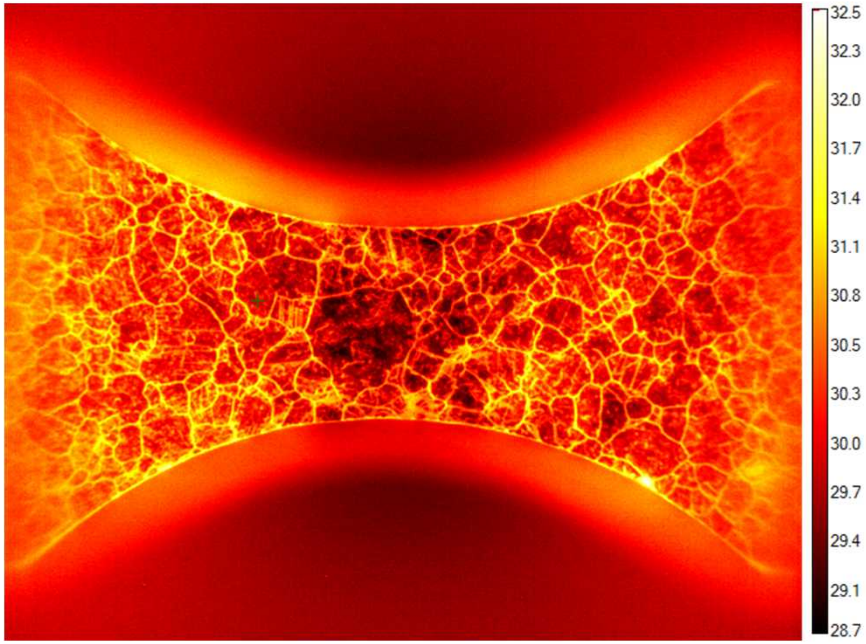




Thermography

- FLIR 6100SCR
  - 640x512 resolution, 565 fps at full resolution, up to 35,000 fps (64x4)
  - Can be calibrated up to 2000° C
- Optical pyrometer
  - Provides noncontact temperature spot readings



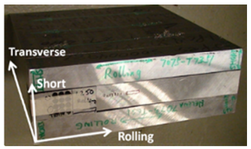


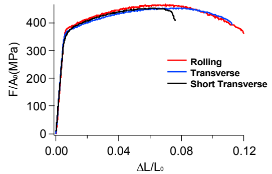
Damage Evolution in Aluminum 7075-T7351

Sandia National Laboratories

Motivation:

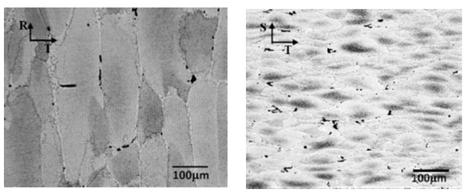
- Anisotropic ductility is demonstrated by the stress-strain curves of three principal material orientations.



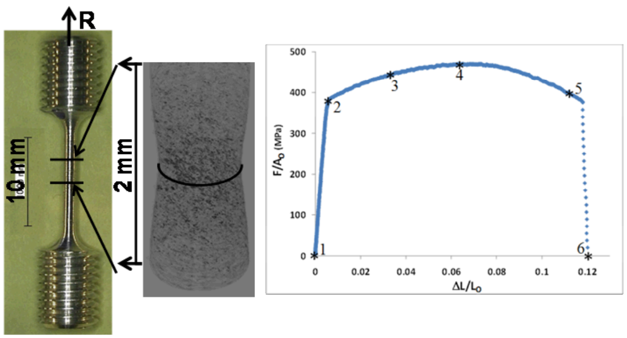


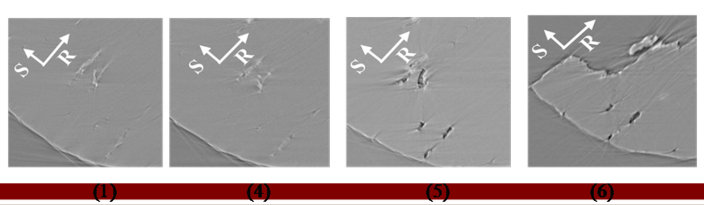
Experiment:

- Optical micrographs of the material show grains are elongated.



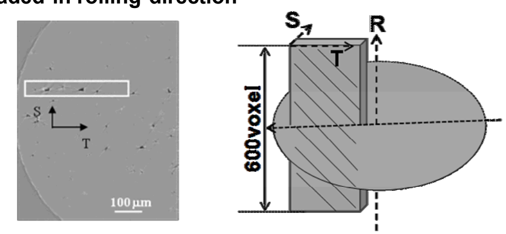
- In-situ X-Ray CT enables us to observe damage evolution during tensile testing.

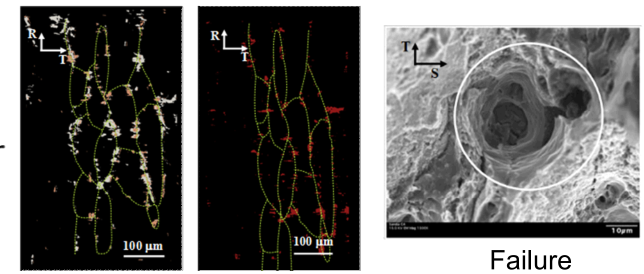




Analysis of Tomography Data:

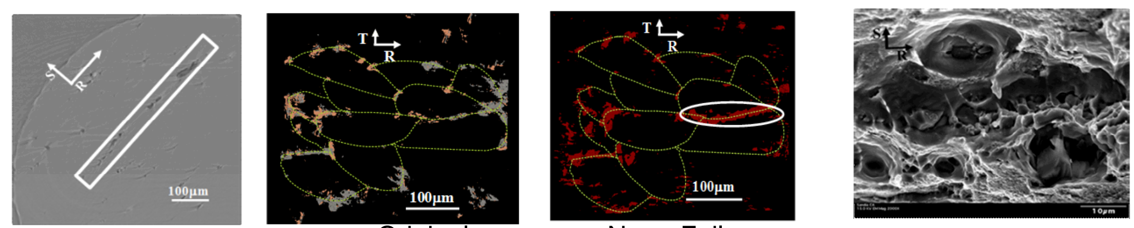
- Loaded in rolling direction





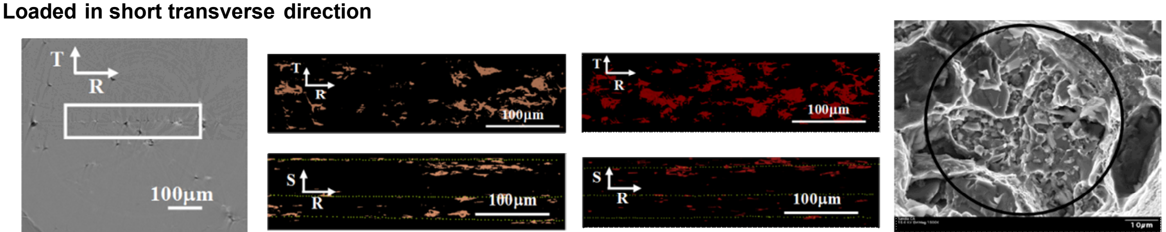
Original   Near Failure   Failure

- Loaded in transverse direction



Original   Near Failure   Failure

- Loaded in short transverse direction

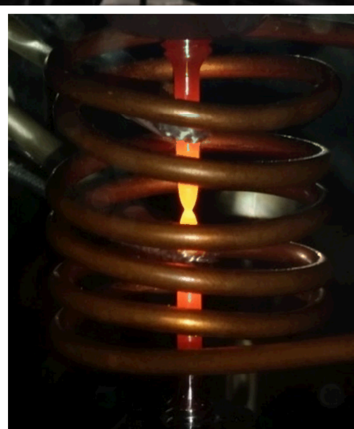


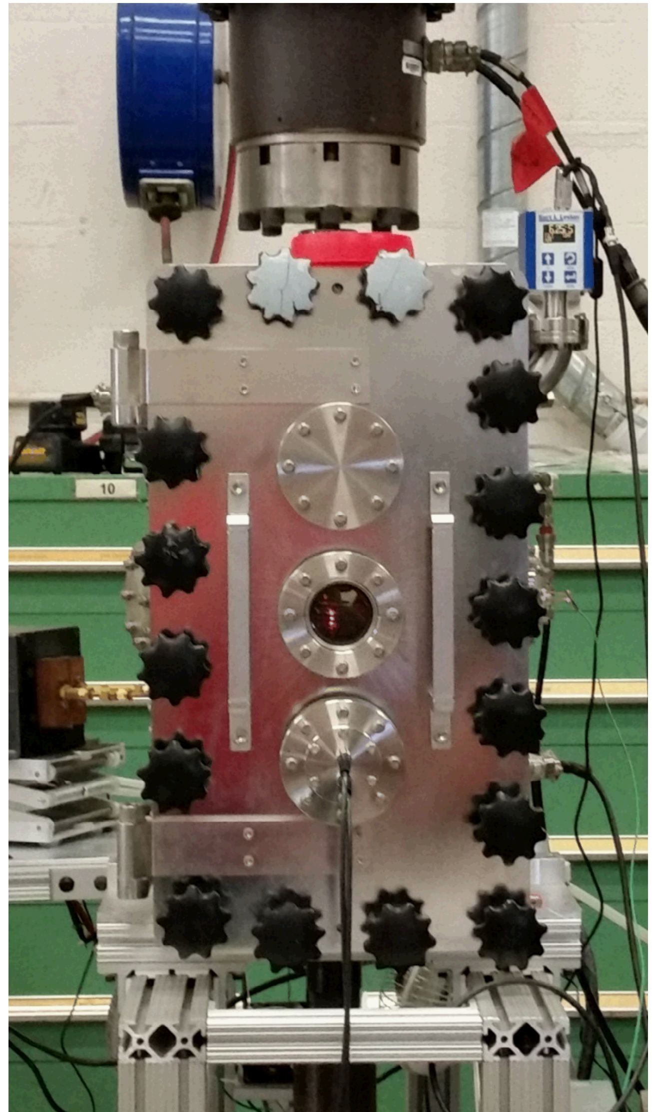
Original   Near Failure   Failure

Conclusions:

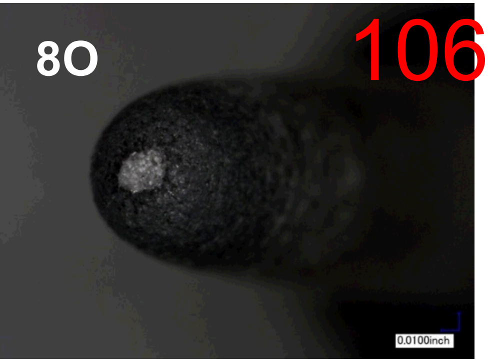
- Voids were closely associated with particles and they were mostly distributed along the grain boundaries.
- The mechanism for the void growth and coalescence were different in three loading orientations.
  - For specimens loaded in the rolling direction, the void growth was nearly isotropic and there was no dramatic void coalescence in any direction.
  - For specimens loaded in the transverse direction, the void growth and coalescence had one-dimensional preference along “stringers” in the rolling direction.
  - For specimens loaded in the short transverse direction, the void growth and coalescence favored a pancake layout in the R-T plane.

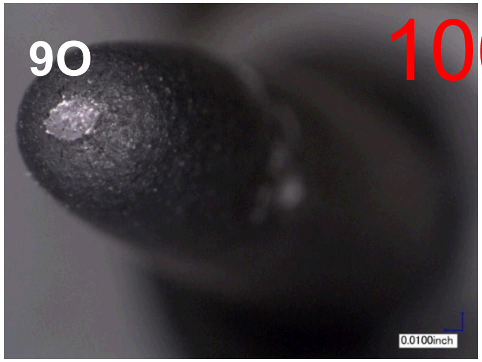
High Vacuum, Elevated Temperature Capability

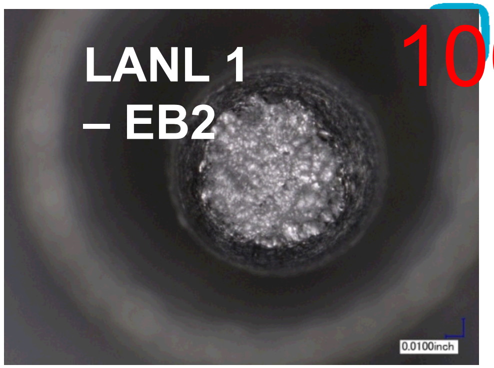


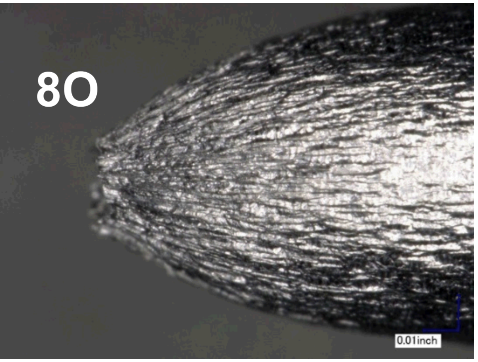


- Load cell internal to chamber, modified for vacuum use, water-cooled
- Contacting extensometer with range to > 50% strain
- Induction heating, custom coil and grip cooling
- Type S T/Cs used on trials to achieve uniform heating along gage length
- Test temperatures in the range of 750C - 1160C
- Optical pyrometer is used and recorded during tests
- Chamber pump down time to <1E-06 torr in 12-18 hours


8O
1060C
0.0100inch


9O
1060C
0.0100inch


LANL 1
– EB2
1060
0.0100inch


8O
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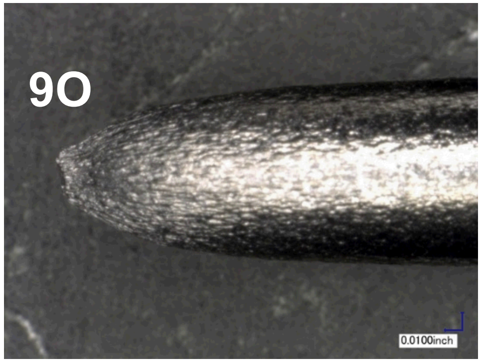
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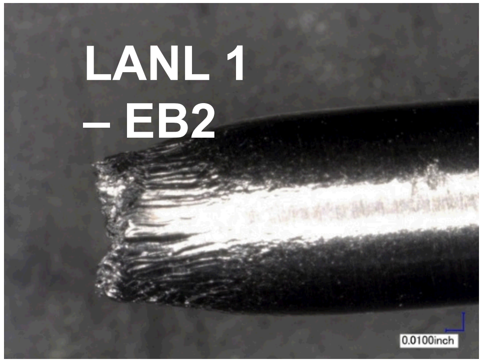
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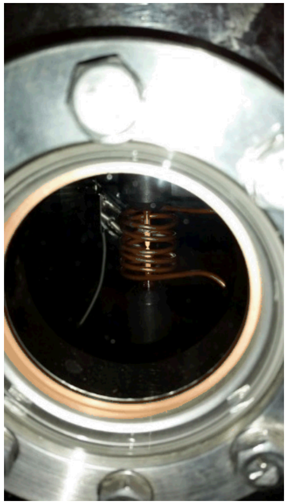
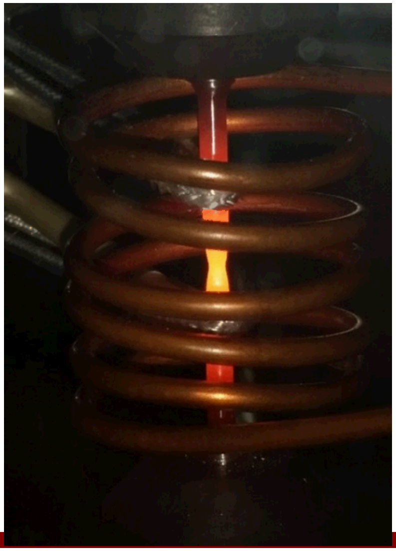
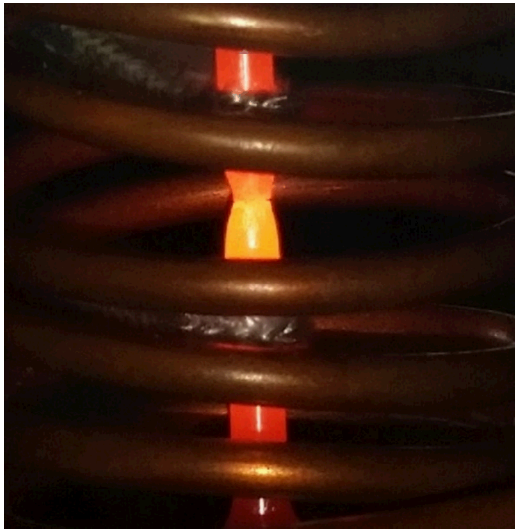


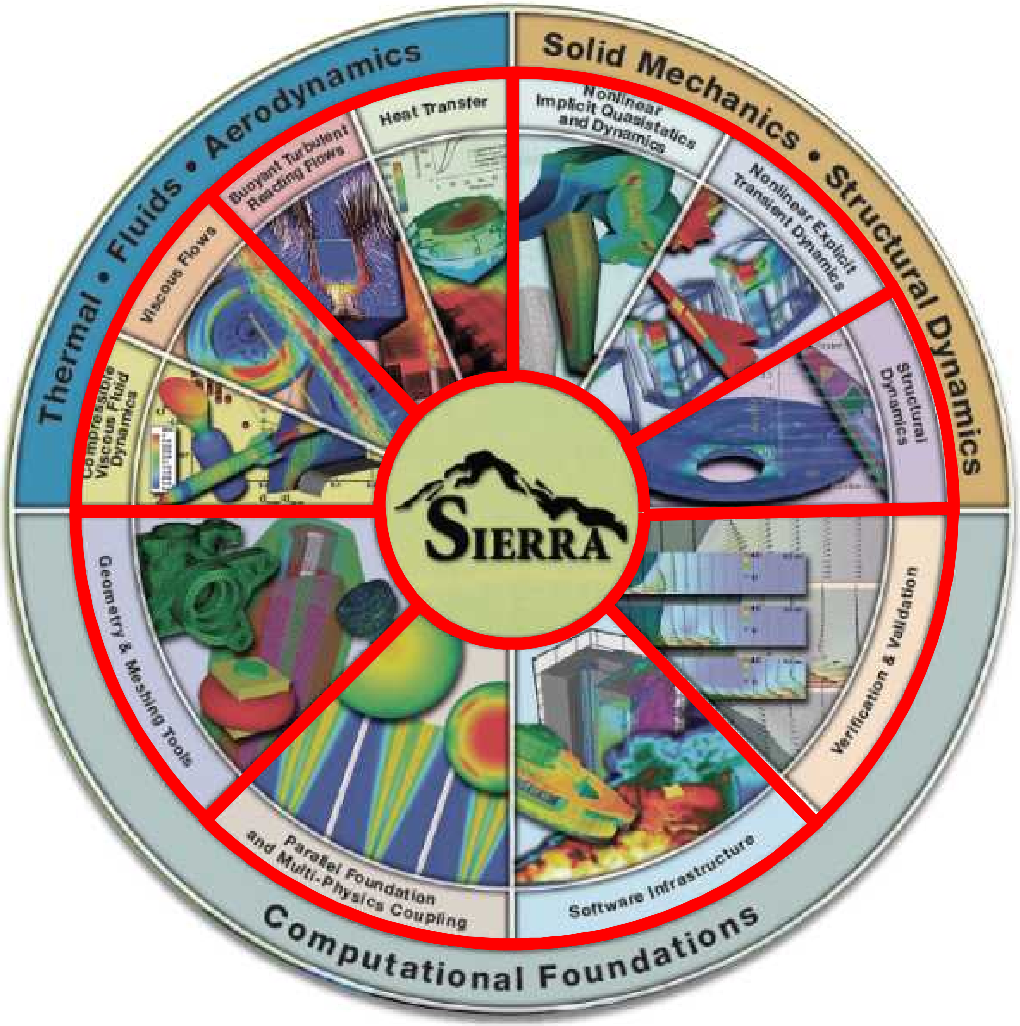




MODELING CAPABILITIES

SIERRA

Sandia National Laboratories



Solid Mechanics

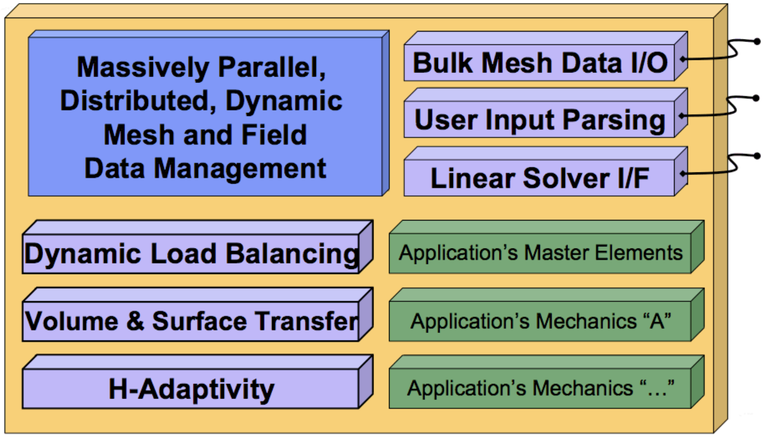
- Implicit quasi-statics
- Explicit, transient dynamics
- Multiple element types and formulations, including solid and shell ... and cohesive ... element methods
- Multiscale modeling methods are currently in development

Geometry and Meshing

Structural Dynamics

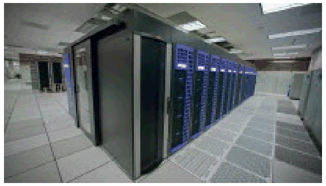
Sandia's HPC Resources

- All SIERRA codes and code-to-code coupling are parallel processing capable with dynamic mesh/field data management
- Sandia analysts process simulations on five available supercomputers



System Name: ***Redsky***
\# of Nodes: ***2846***
Cores/Node: ***8*** *(2.93 GHz)*
GB RAM/Node: ***12***

System Name: ***Sky Bridge***
\# of Nodes: ***1848***
Cores/Node: ***16*** *(2.6 GHz)*
GB RAM/Node: ***64***

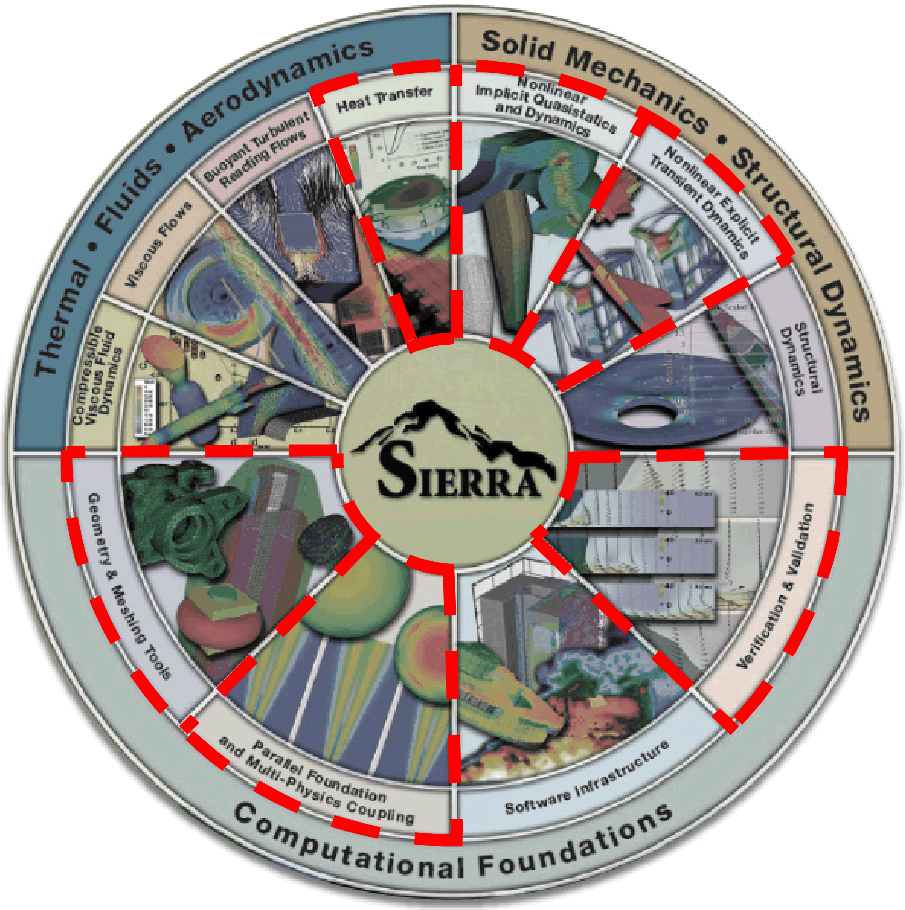


System Name: ***Chama***
\# of Nodes: ***1232***
Cores/Node: ***16*** *(2.6 GHz)*
GB RAM/Node: ***64***

System Name: ***Uno***
\# of Nodes: ***201***
Cores/Node: ***16*** *(2.7 GHz)*
GB RAM/Node: ***128***

System Name: ***Serrano***
\# of Nodes: ***1,122***
Cores/Node: ***36*** *(2.1 GHz)*
GB RAM/Node: ***128***

SIERRA for Composites Modeling



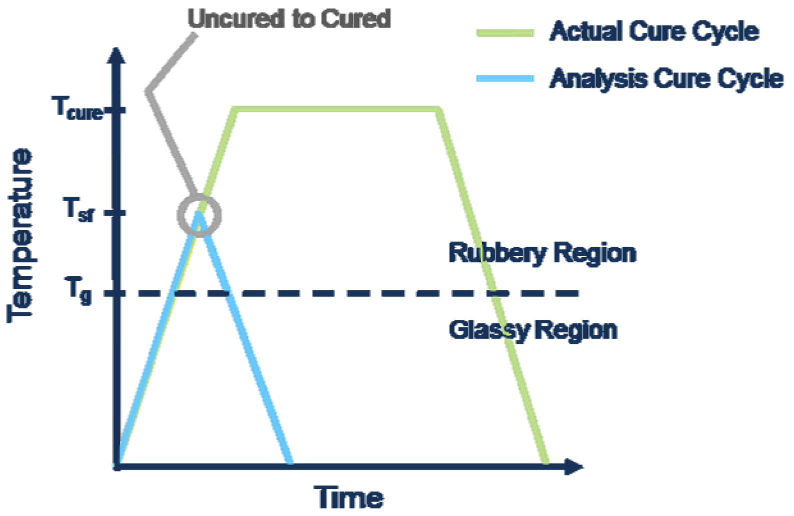
- *SIERRA/Solid Mechanics* predicts manufacturing induced residual stresses and structural response to implicit and explicit load cases
  - Orthotropic material models with and without failure
  - Cohesive zone methods for delamination prediction
  - Open code infrastructure and framework supports development of new material models as necessary
- *SIERRA/V&V* tools allow for material model calibration and statistics based predictions in the absence of exact material property data
- *SIERRA/Thermal Mechanics-to-SIERRA/Solid Mechanics coupling* allows for accurate predictions of a composites structural response in varying thermal environments
  - Will support the future development of a NLVE orthotropic material model

Case Study 1

Predictions of Residual Stresses

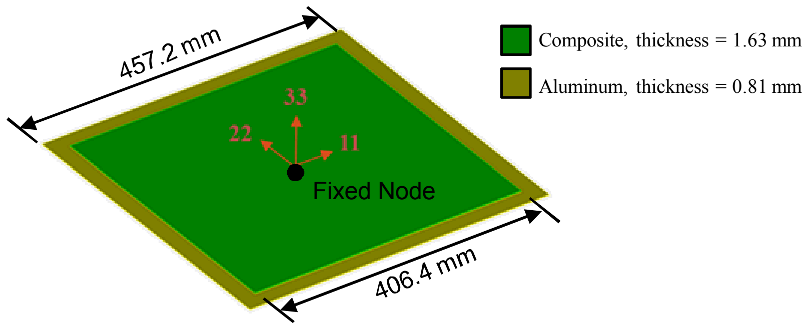
Residual Stress Modeling with SIERRA/SM

- Residual stress development
  - ***CTE mismatch***
    - CTEs for glassy and rubbery regions are differentiated
  - ***Polymer Shrinkage***
    - “Cure” temperature is the experimentally determined stress free temperature
- ***Constant mechanical properties*** do not vary with temperature
- ***Isothermal specification*** of the thermal cycle
  - No heat transfer analysis done (temperature soak is irrelevant)
- ***Instantaneous change from a uncured to cured*** state at stress free temperature
  - Compliant elements representing uncured composite are deactivated
  - Elements defined with composite’s material properties are activated with zero stress

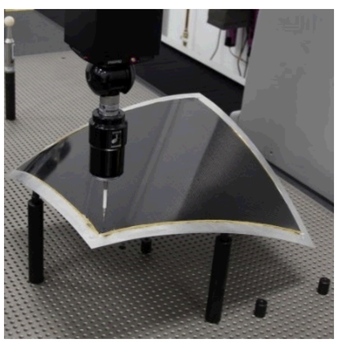


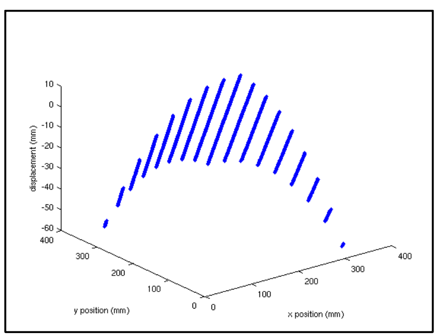
Residual Stresses in a Bi-Material Plate

- Carbon composite perfectly bonded to aluminum
- ***Hexahedral, fully-integrated, high quality solid elements***
- SIERRA's ***implicit dynamics*** approach applied to improve convergence

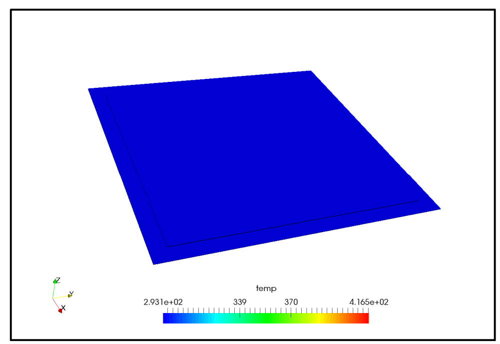


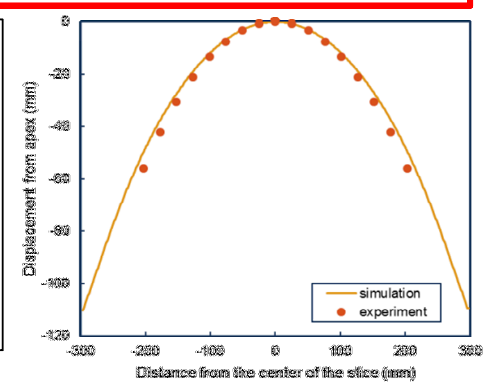
Experiment





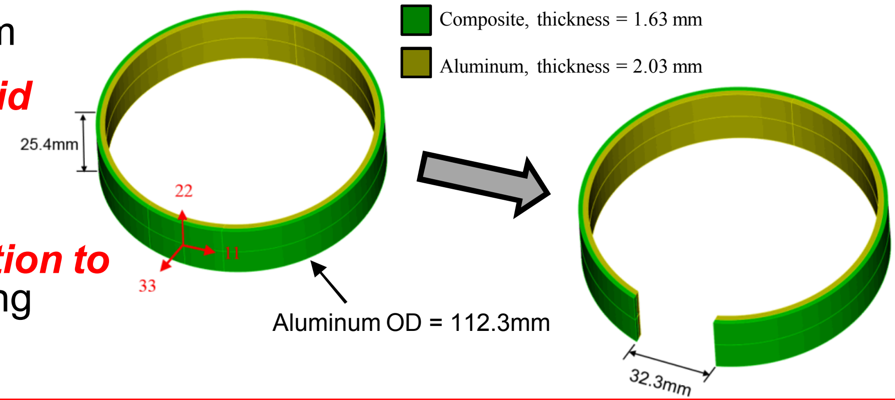
Simulation

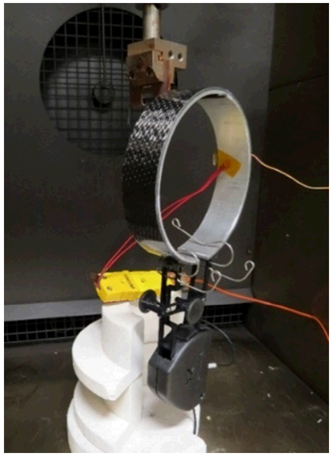




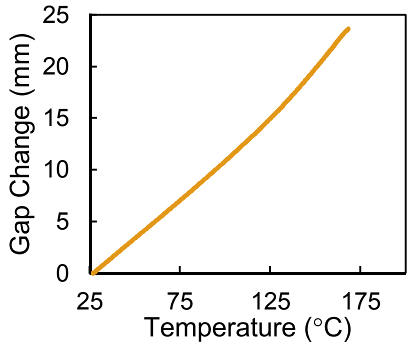
Residual Stress in a Bi-Material Split Ring

- Carbon composite perfectly bonded to aluminum
- ***Hexahedral, fully-integrated, high quality solid elements***
- ***¼ symmetry*** applied for efficiency
- “Removed sector” modeled as a separate ***partition to be omitted*** during the simulation to mimic splitting

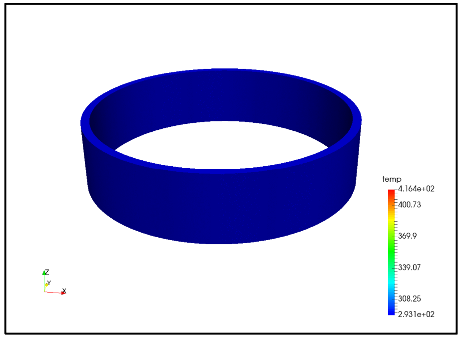


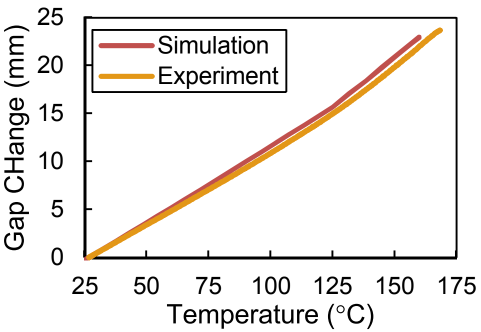


Experiment



Simulation

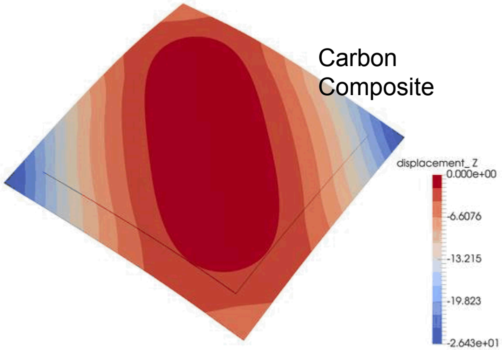




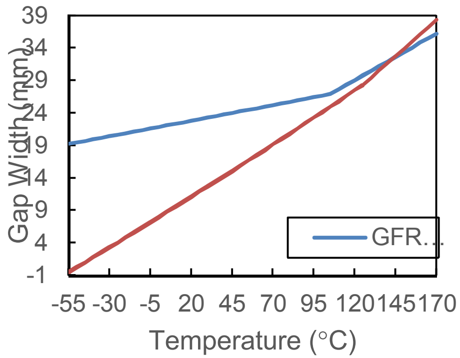
Planned Residual Stress Simulations and V&V

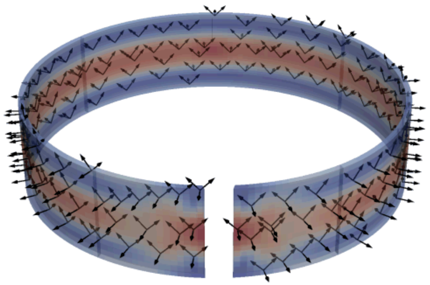
- Continue with bi-material plate and split ring geometries
  - Reduced size for the plate (254.0 mm vs. 457.2 mm)
- Examine both carbon and glass composites
- Examine $[0/90]_s$ and $[+45/-45]_s$ composite layups
- Compare multiple Sensitivity Study and UQ methodologies

Plate



Split Ring





Composite in a [+45/-45] configuration

Case Study 2

V&V of Residual Stress Predictions

Verification and Validation Methodology

- V&V methods should be applied to simulations to build confidence in predictions
  - Begin with an extrapolation based mesh convergence study
  - Apply a sensitivity study to the convergent mesh to determine critical model parameters
    - "Which model parameters effect the simulated outcome the most?"
  - Rigorously characterize the critical parameters as distributions of uncertainty
  - Propagate parameter uncertainty through simulation to determine corresponding response distribution

This process was applied to the bi-material plate and ring simulations

MESH CONVERGENCE STUDY

↓

PARAMETER SENSITIVITY STUDY

↓

CRITICAL PARAMETER CHARACTERIZATION

↓

UQ PREDICTED RESPONSE DISTRIBUTION

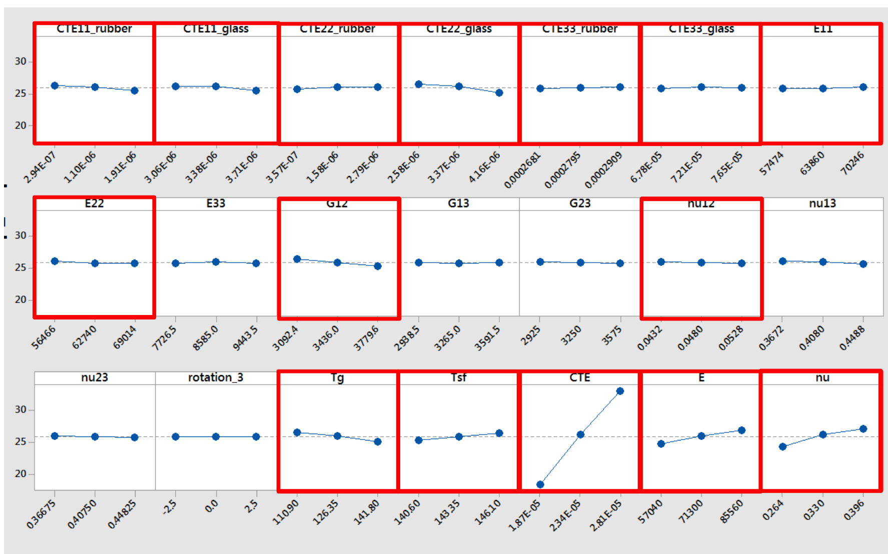
Sensitivity Study Methods with SIERRA/V&V

- ***Computer experiments*** can sample a high dimensional parameter space and determine a range of simulation outputs and the most influential parameters
- ***Box-Behnken approach*** chosen to sample the parameter space
  - Does not create extreme parameter combinations or sample outside of the process space
  - Requires slightly fewer samples/simulations than similar approaches for a small number of parameters
    - $N = 2k(k-1)+1$
      - N= number of experiments, k = number of parameters
- Parameter sensitivities can be determined with ***ANOVAs and main effect plots***

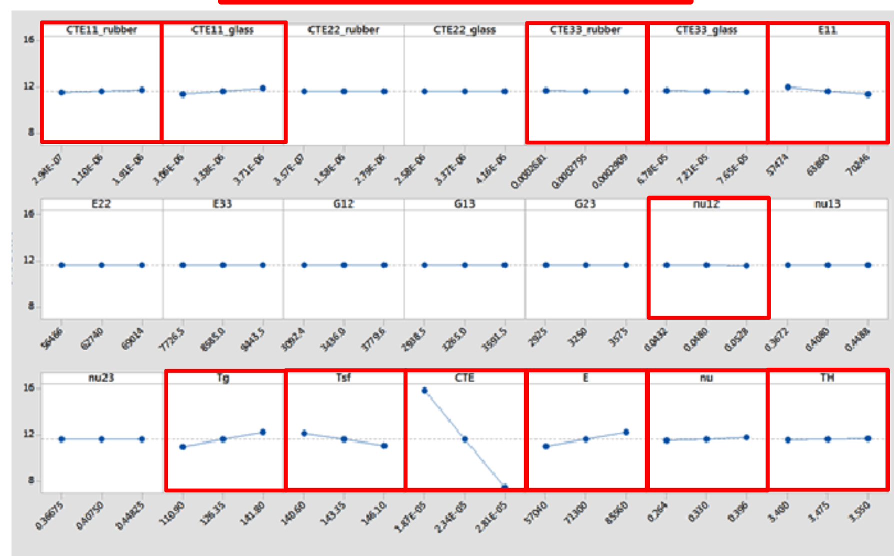
Sensitivity Study Results

- Parameter spaces defined by material properties and manufacturing variables (i.e., laminate thickness and fiber skew) were defined for plate and ring models
- Box-Behnken method was applied and main effects plots were calculated

Bi-Material Plate

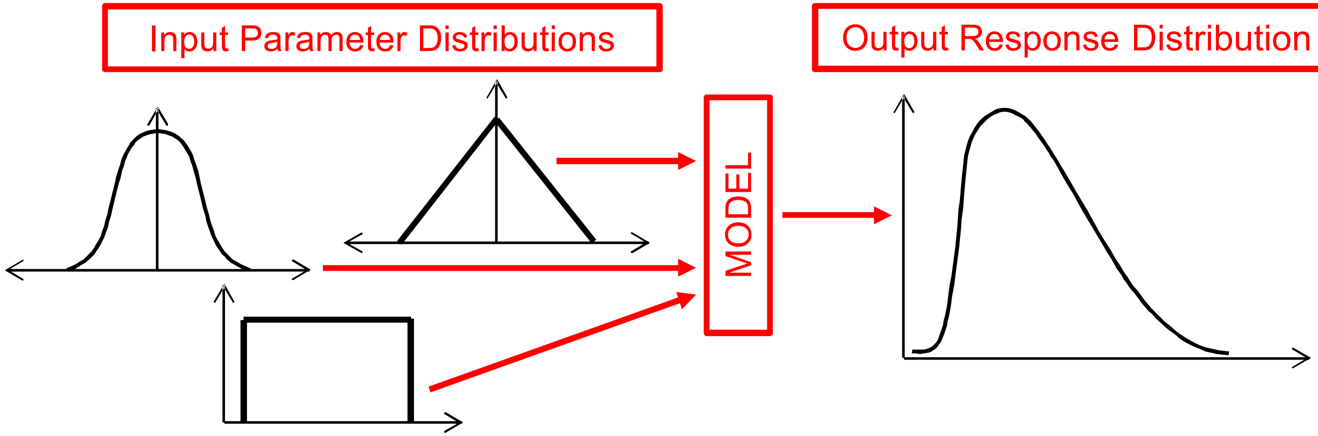


Bi-Material Ring



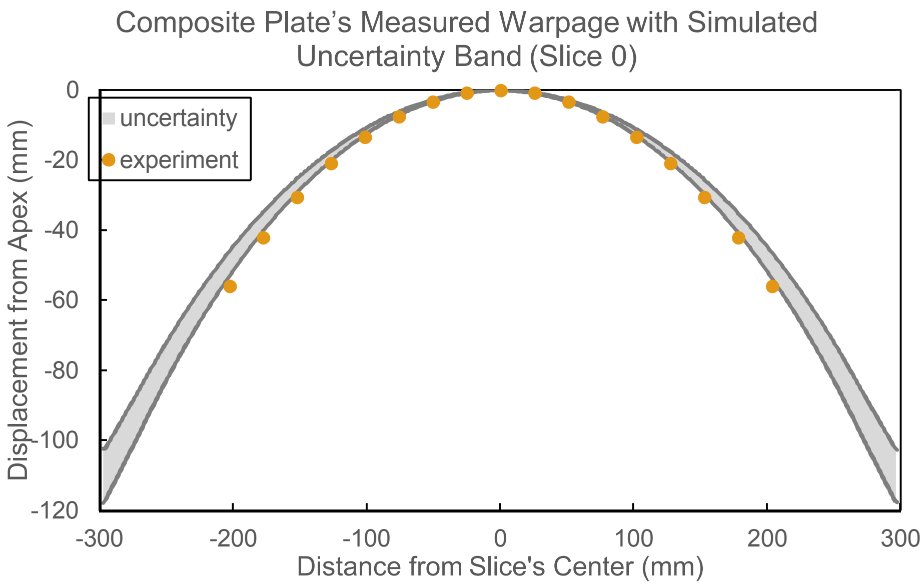
Uncertainty Quantification with SIERRA/V&V

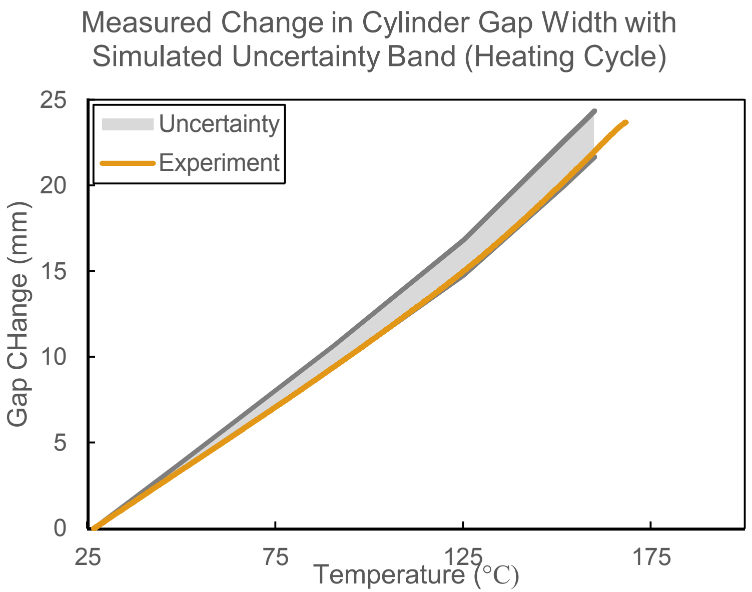
- Sensitive parameters were rigorously characterized as ***distributions with uncertainty***
- ***Uncertainty quantification*** was used to propagate input parameter ranges through the simulation
  - A distribution is defined for each parameter
  - Each distribution is sampled many times and processed through a simulation
    - ***LHS sampling*** is used to ensure complete coverage of the distributions
  - A distribution of output responses is the result



UQ Results and Validation

- Predicted distributions match well with experimental data
  - Improvements might be seen with the inclusion of temperature dependent material properties
- ***It is more accurate to represent the residual stress predictions as distributions, instead of as single values, as there are variations in the material property data that must be accounted for in the reported solutions***



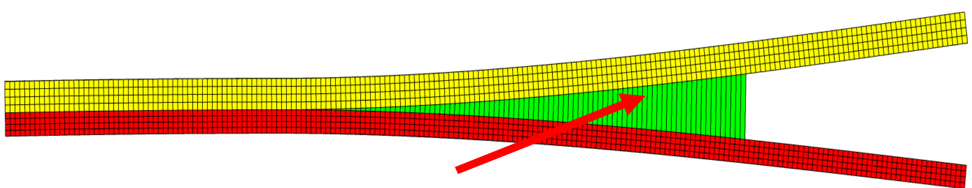


Case Study 3

Interlaminar Fracture in Composite Structures Exhibiting Residual Stresses

Interlaminar Fracture Modeling with SIERRA

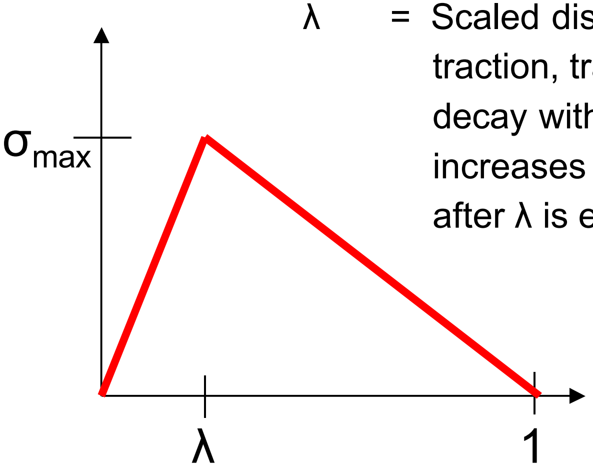
- Interlaminar delamination is simulated in SIERRA with ***cohesive zone elements***
  - Collapsed solid elements representing the cohesive forces resisting separation are defined between "bonded" composite plies
  - Behaviors are defined with traction-separation laws
- ***SIERRA material model library supports cohesive zone laws with and without mode mixing***
  - Mode I vs. Mode II
  - Tvergaard-Hutchison
  - Thouless-Parmigiani



Cohesive zone elements expand to indicate separation governed by traction-separation law

σ_{max} = Peak traction

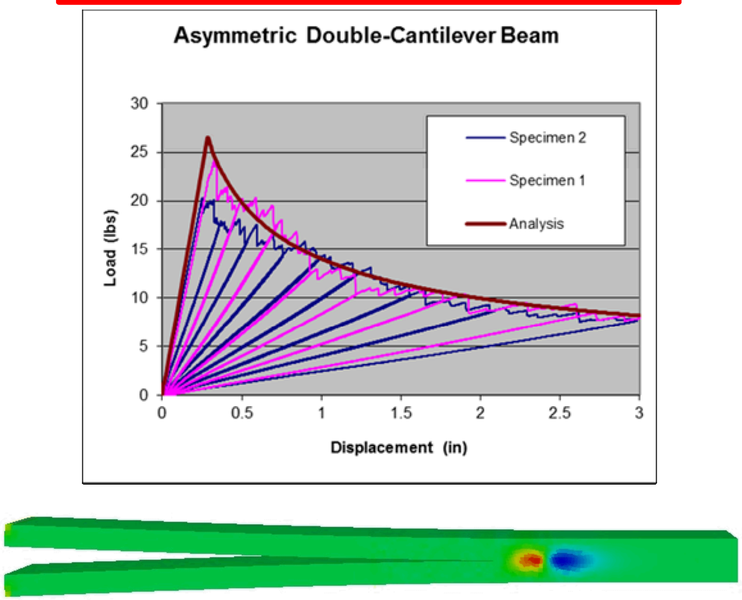
λ = Scaled distance to peak traction, traction will decay with additional increases in separation after λ is exceeded



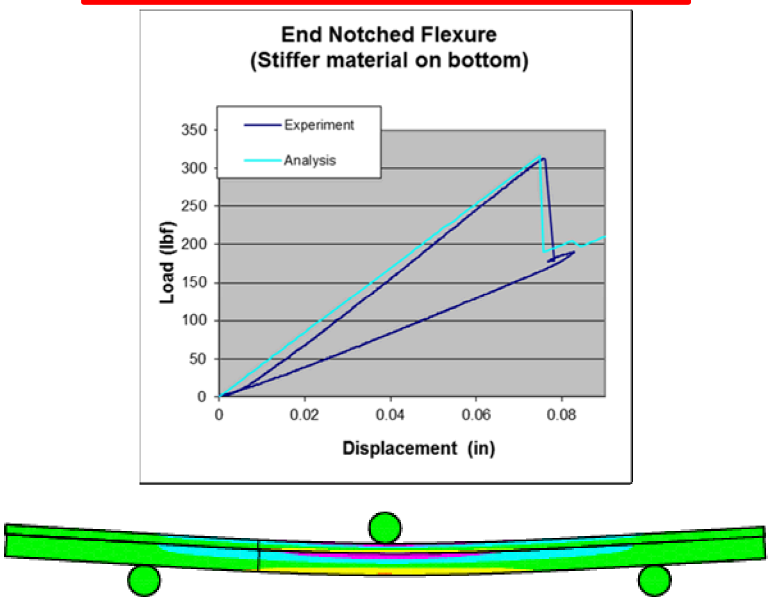
CZM Predictions without Residual Stresses

- ***SIERRA's CZM predictions of interlaminar delamination are accurate in the absence of residual stresses***

Mode I Fracture/DCB Simulation

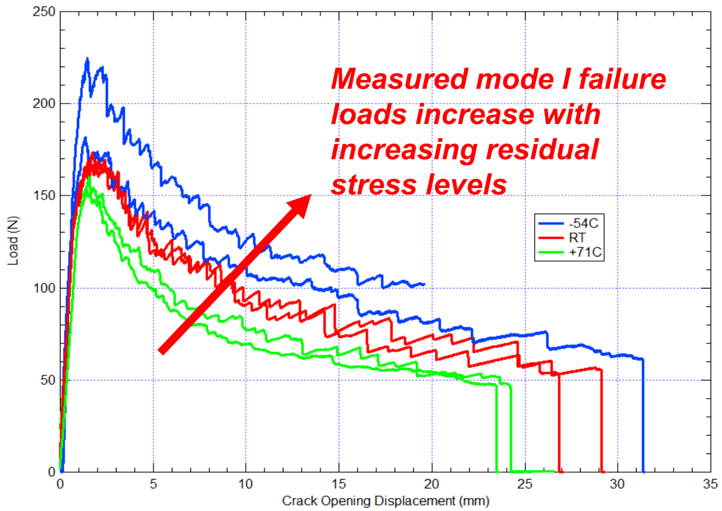


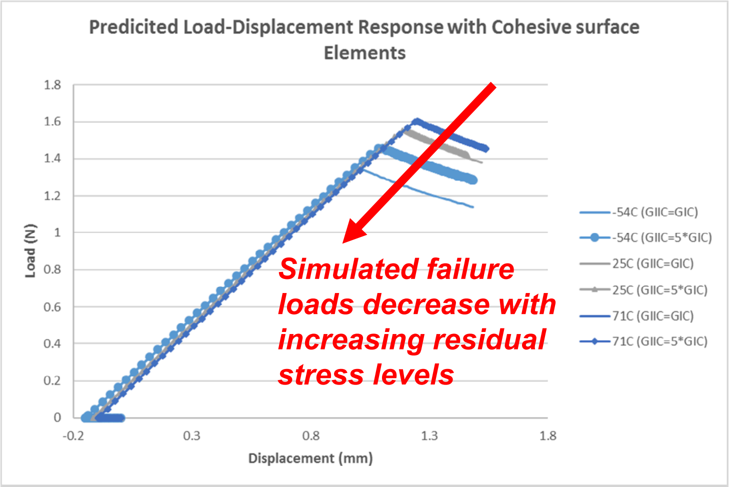
Mode II Fracture/ENF Simulation



CZM Predictions with Residual Stresses

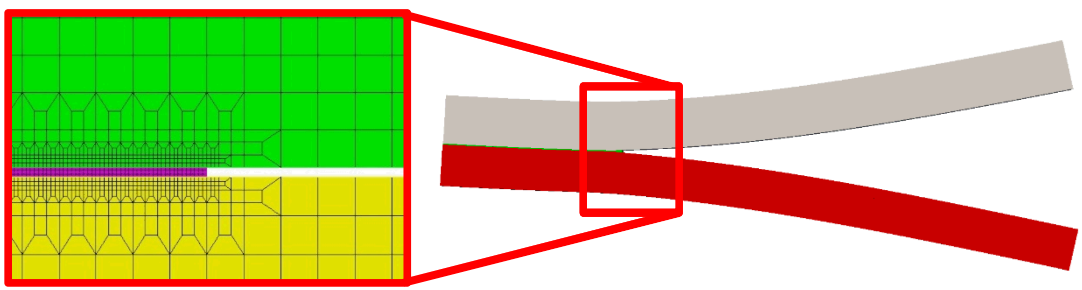
- ***SIERRA's CZM predictions of interlaminar delamination are NOT accurate in the presence of residual stresses***
  - Mode I fracture toughness was experimentally observed to increase with increasing residual stress levels
  - Simulations show opposite trend, but imply importance of mode mixing
    - Increasing mode II fracture toughness increases predicted peak loads

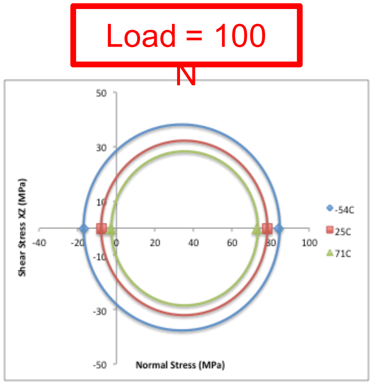




High-Fidelity Delamination Modeling

- ***High fidelity DCB simulations are being used to better understanding the experimentally observed behaviors***
  - Bondline modeled with solid elements
    - 3D Stress state at crack tip can be examined
- Detailed models indicate that ***bondline stresses evolve "faster" at lower residual stress levels***
  - Residual stresses cause large shear strains, which deform bondline and must be overcome by mechanical loading to promote crack growth
- This work is informing development of new CZM material model





Case Study 4

Low Velocity Impact Damage of Carbon Fiber Laminates

Composite Failure Modeling in SIERRA

- The ***Orthotropic-Elastic-Failure model*** requires the definition of 77 material parameters
  - Elastic, damage initiation, damage evolution, post-failure softening, strain rate dependency

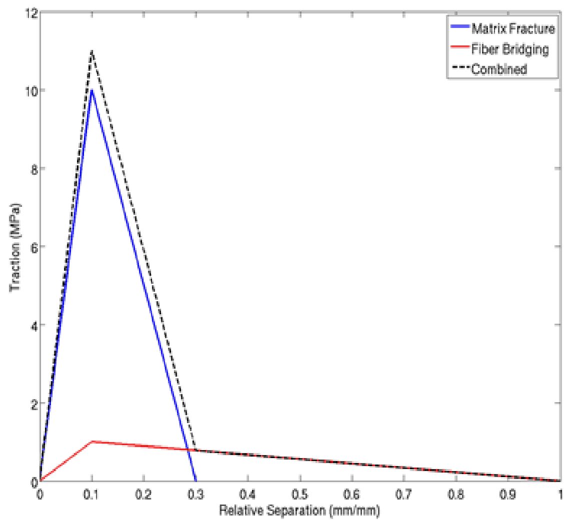
Elastic Properties
E11, E22, E33
NU12, NU13, NU23
G12, G13, G23
Initial Failure Properties
TENSILE_MATRIX_STRENGTH_11, _22, _33
COMPRESSIVE_MATRIX_STRENGTH_11, _22, _33
TENSILE_FIBER_STRENGTH_11, _22, _33
COMPRESSIVE_FIBER_STRENGTH_11, _22, _33
SHEAR_MATRIX_STRENGTH_12, _23, _13
SHEAR_FIBER_STRENGTH_12, _23, _13
Post-Failure, Damage Evolution Properties
TENSILE_FRACTURE_ENERGY_11, _22, _33
COMPRESSIVE_FRACTURE_ENERGY_11, _22, _33
SHEAR_FRACTURE_ENERGY_12, _23, _13
CHARACTERISTIC_LENGTH
MAXIMUM_COMPRESSIVE_DAMAGE_11, _22, _33
COMPRESSION_COUPLING_FACTOR_11, _22, _33
TENSILE_DAMAGE_MODULUS_11, _22, _33
COMPRESSIVE_DAMAGE_MODULUS_11, _22, _33
SHEAR_DAMAGE_MODULUS_12, _23, _13
HARDENING_EXPONENT_11, _22, _33
HARDENING_EXPONENT_12, _23, _13

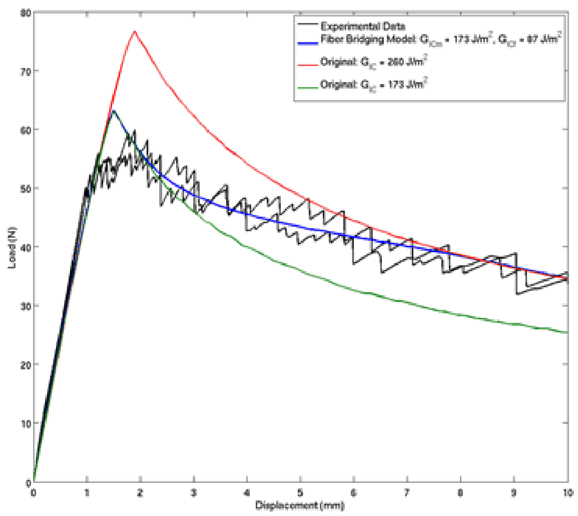
Strain Rate Dependency Properties
REFERENCE_STRAIN_RATE
ELASTIC_RATE_COEFFICIENT_11, _22, _33
ELASTIC_RATE_COEFFICIENT_12, _23, _13
FIBER_STRENGTH_RATE_COEFFICIENT_11, _22, _33
FIBER_STRENGTH_RATE_COEFFICIENT_12, _23, _13
MATRIX_STRENGTH_RATE_COEFFICIENT_11, _22, _33
MATRIX_STRENGTH_RATE_COEFFICIENT_12, _23, _13
FIBER_STRENGTH_RATE_COEFFICIENT_12, _23, _13
MATRIX_STRENGTH_RATE_COEFFICIENT_11, _22, _33

- Only 30 of the 77 parameters required definition for LVI simulations
  - Strain rate sensitivity is neglected
  - Characteristic length is a mesh dependent variable

Fiber Bridging Model (in-development)

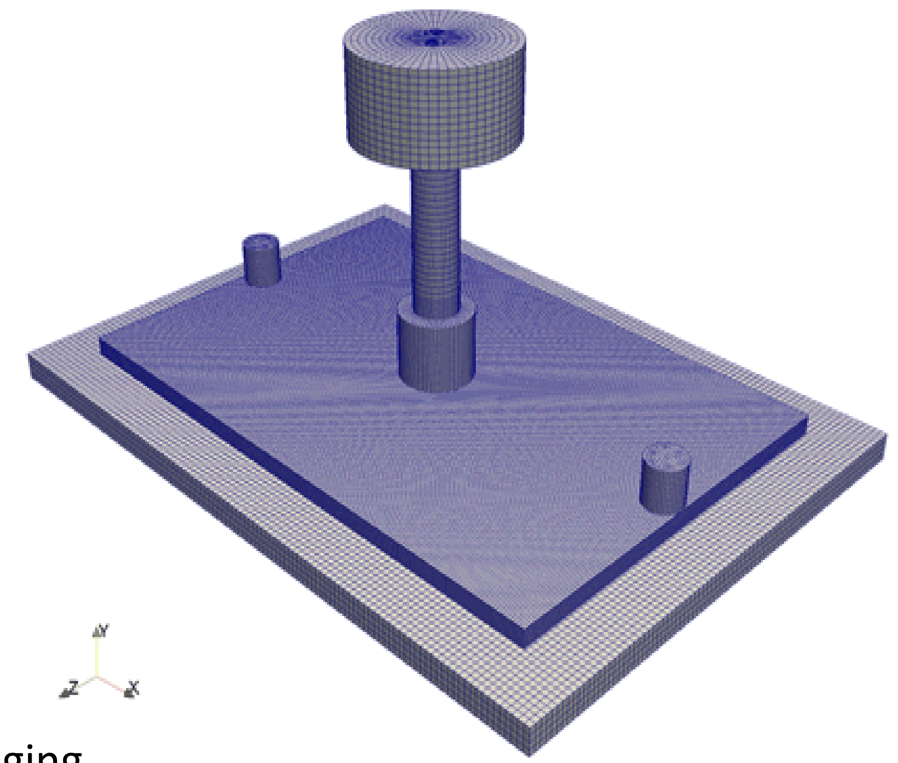
- ***Fiber bridging has been observed in carbon fiber laminates***
  - "Pulling of fibers from one side of delamination plane to the other"
- ***A fiber bridging model is under development for SIERRA***
  - Will account for the extrinsic toughening mechanisms behind the crack tip that is common in fiber-reinforced composites
  - Conceptualized as the summation of two traction-separation laws, one for matrix fracture and one for fiber pull-through/bridging
- The model was validated with DCB test data





LVI Experiment and Model

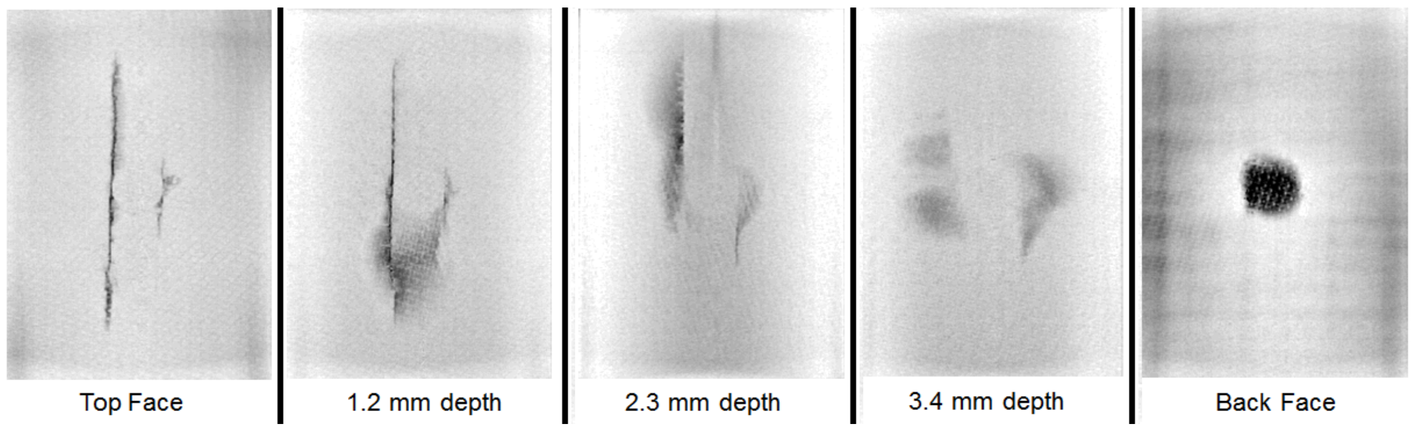
- Experiment:
  - Carbon composite
  - Flat Rectangular specimens
  - Specimens were clamped with and unsupported central section
  - Specimens were impacted with flat, cylindrical indenters
  - 50J impact
- Model:
  - Fully explicit
  - Hexahedral, reduced order, high quality solid elements
  - Composite response modeled with orthotropic-elastic-failure and fiber bridging models
  - Boundary conditions mimic test
    - Indenter initial velocity and angle of incidence



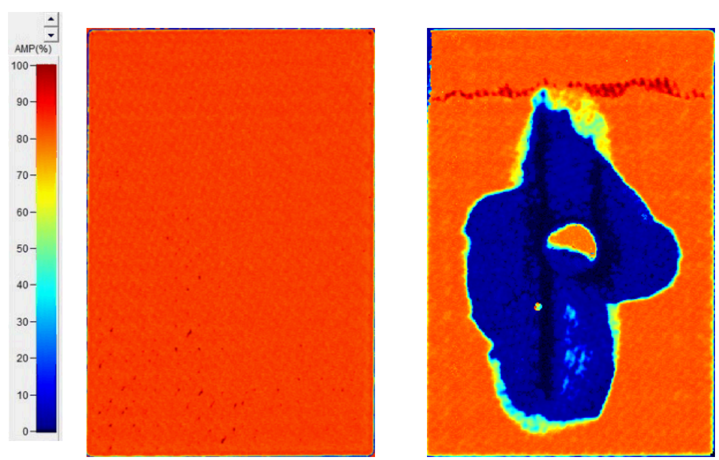
Experimental Data for Validation

- Ultrasonic scans and 3D computed tomography were used after testing to visualize damage form and location

<u>CT Scans</u>
Spatial/through-the-thickness distribution of damage



<u>Ultrasonic Scans</u>
Area and regions of delamination

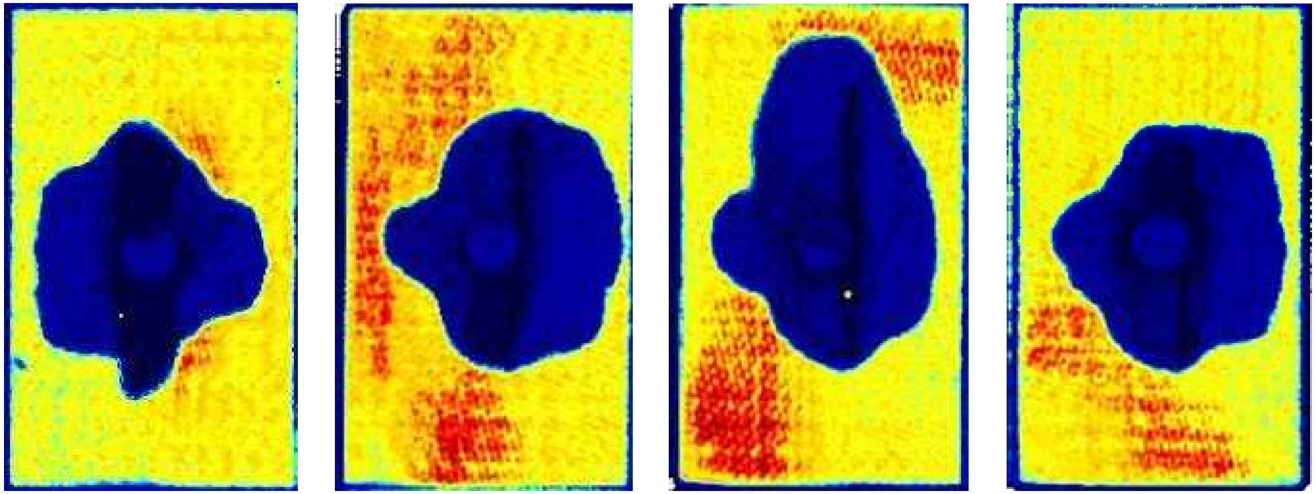


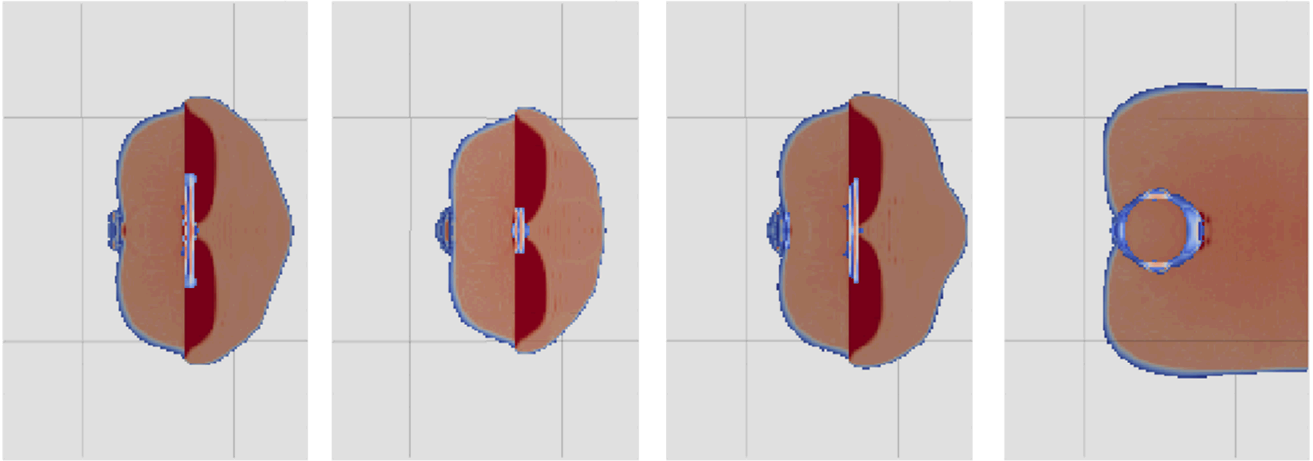
The ultrasonic scans provide better imaging of delamination since the CT scans will not show delaminated regions that are still in contact

Predicted Regions of Delamination

- ***UQ was completed to understand effect of parameter uncertainty***
- Random comparison of delaminated areas show agreement

Ultrasonic scans of four tested panels (delamination is generally contained within the panel)





Predicted delamination regions from randomly selected simulations

FY17 and Future Work

Modeling Path Forward

- FY17-FY18:
  - Develop a ***new fracture mechanics (cohesive zone) model***, which will account for residual stress effect on fracture toughness, within the SIERRA framework
- FY18-FY20:
  - Develop a ***new orthotropic, NLVE model*** for the SIERRA framework
- FY19-FY22:
  - Develop a ***new damage mechanics model*** for the SIERRA framework