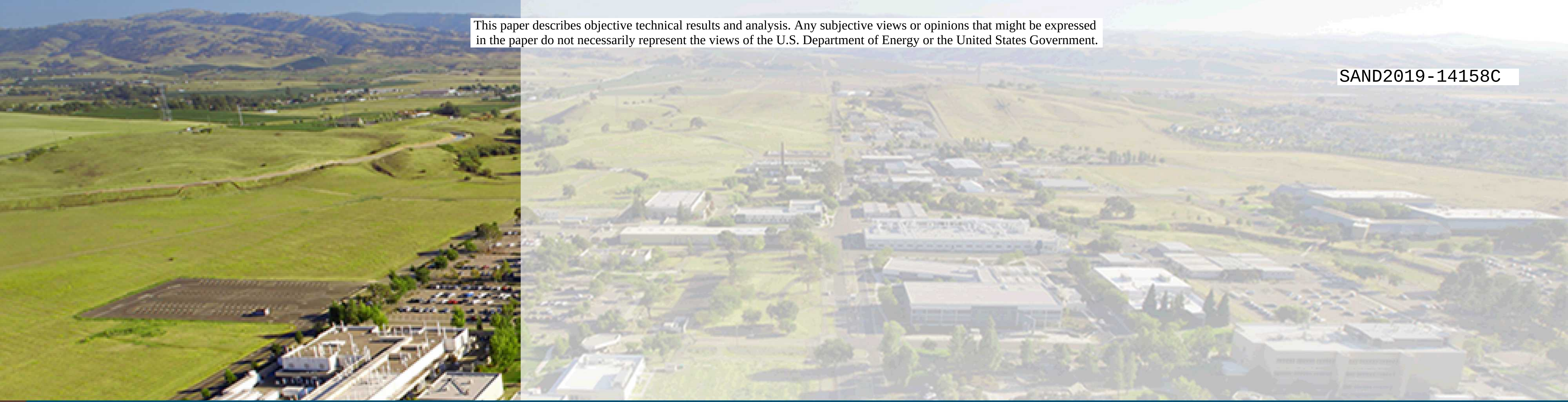
SAND2019-14158C



Experimental and Computational Aspects of Ductile Failure for Structural Engineering Alloys

Jake Ostien, Jay Foulk, Helena Jin, Andy Stershic, Brandon Talamini, Sharlotte Kramer, Bill Scherzinger, Edmundo Corona, Tim Shelton

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Integrating multiple efforts

Motivation: crash and impact environments (abnormal mechanical)
- In the spirit of safety we consider drop/crush/impact and pressurization
- Every scenario requires ductile failure modeling
- Explicit dynamics simulations with lots of technical complexity: Preload, Contact, Large deformation, Local temperature rise, Fracture/Failure

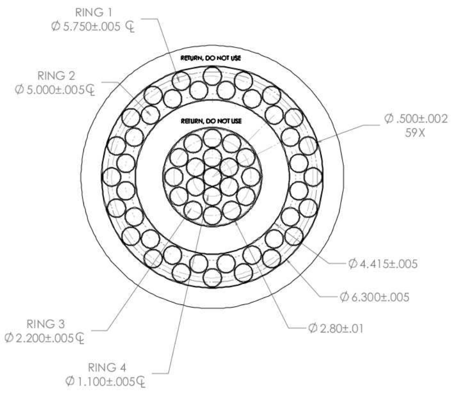
Objectives and Principles
- Improve ductile failure capability for system model analysis
  - Materials, environments, examples, benchmarks (QoIs)
  - Focus on structural alloys SS304L, Al6061-T6
- Make data informed decisions
  - Generate experimental discovery and characterization data for relevant alloys
  - Probe numerical techniques and study applicability to system analyses
- Improve our fundamental understanding
  - Probe failure surface of relevant alloys comprehensively in terms of rate, temperature, and stress state
  - Develop tools to decipher and understand system response in nuclear safety scenarios

Operations
- Integrate a collection of projects spanning multiple programs to develop understanding and deliver tools for system analysis

Research driven by Sandia's mission

Material: stainless steel 304L-VAR

- Vacuum Arc Remelting (VAR) typically minimizes anisotropy
- Hardens tremendously, high ductility
- Sensitive to strain rate and sensitive to temperature changes
- Produces temperature changes at even moderate strain rates



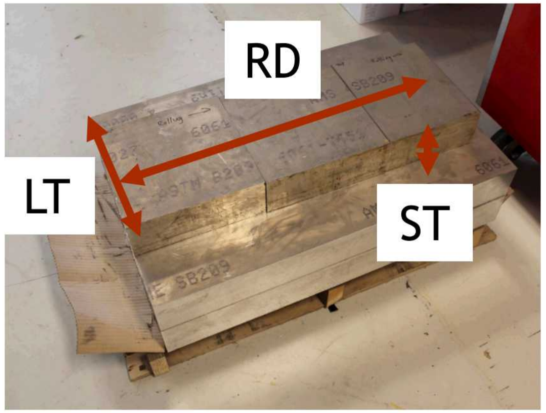
SS 304L-VAR Bar

Material: aluminum 6061-T6

- System aluminum parts produced by first forging to net shape with heat treatment, then final machining
- Process is expected to produce preferential gran flow leading to mechanical anisotropy
- Not nearly as ductile as 304L-VAR, sensitive to defect structures from manufacturing process
- Less sensitive to strain rate at moderate strains (< 1000/sec)
- Higher thermal conductivity leads to less local temperature production from plastic work

Environment (abnormal mechanical)

- Primarily of interest are crash or drop safety scenarios
- Crush and large deformation from impact loading at various velocities
- Temperature, initially at room
- Strain rate up to 1000-10000 / sec
- Multiaxial stress states



Al 6061-T6 Plate Stock

Current ductile failure capabilities in abnormal mechanical environments

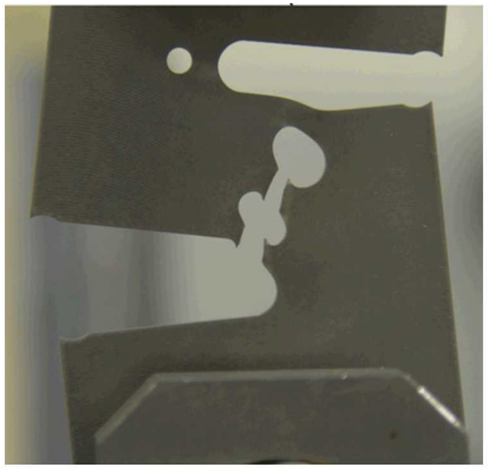
Solid mechanics simulations of impact or crash scenarios
- Explicit transient dynamics capability in SIERRA/SM

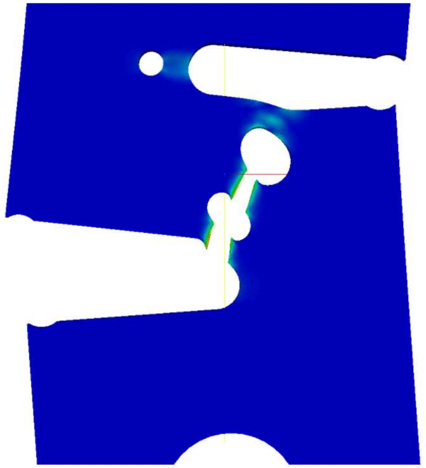
Ductile constitutive model
- Typically isotropic J2 plasticity with nonlinear hardening, possibly rate and/or temperature dependence
- Pursuing modular rate and temperature dependent anisotropic plasticity
- Pursuing calibration methods applicable to a broad class of models and data sets

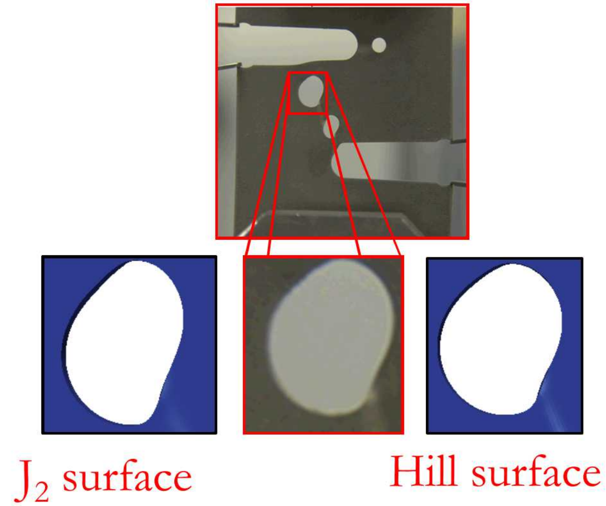
Failure model
- Typically a local measure of material damage or criteria
- Pursuing more advances theories and implementations of ductile failure methodologies

Regularization method
- Typically none – lack of regularization leads to grid dependent results, lack of confidence and rigor
- Pursuing phase field fracture and nonlocal regularization applicable for explicit transient dynamics

Surface Creation method
- Typically element death|deletion|erosion
- Working towards XFEM|GFEM|remeshing (out of scope)







SFC2 – Ti-6Al-4V lessons learned included the need for anisotropic viscoplasticity & temperature

Current ductile failure capabilities in abnormal mechanical environments

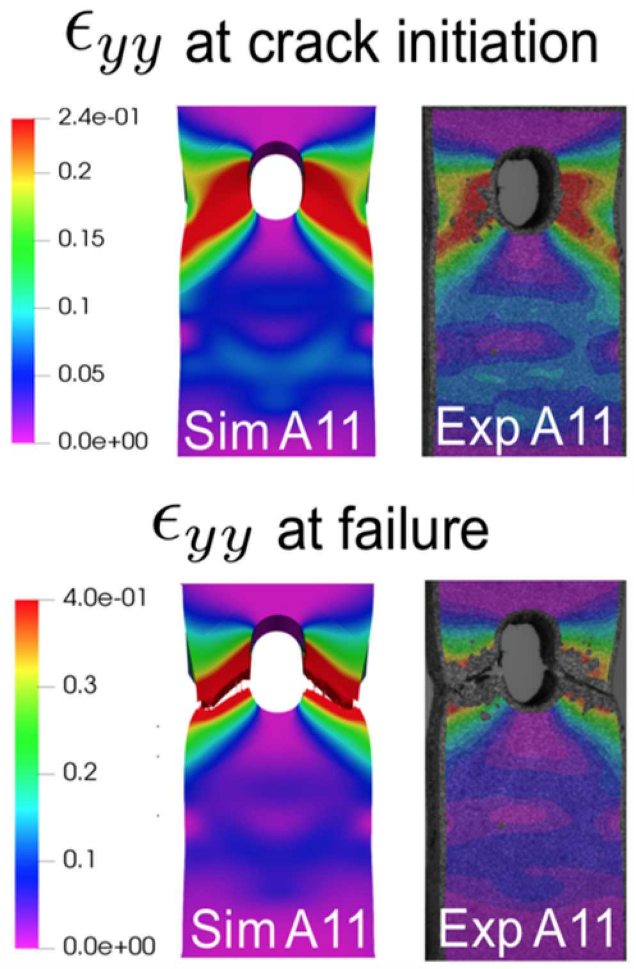
Solid mechanics simulations of impact or crash scenarios
- Explicit transient dynamics capability in SIERRA/SM

Ductile constitutive model
- Typically isotropic J2 plasticity with nonlinear hardening, possibly rate and/or temperature dependence
- Pursuing modular rate and temperature dependent anisotropic plasticity
- Pursuing calibration methods applicable to a broad class of models and data sets

Failure model
- Typically a local measure of material damage or criteria
- Pursuing more advances theories and implementations of ductile failure methodologies

Regularization method
- Typically none – lack of regularization leads to grid dependent results, lack of confidence and rigor
- Pursuing phase field fracture and nonlocal regularization applicable for explicit transient dynamics

Surface Creation method
- Typically element death|deletion|erosion
- Working towards XFEM|GFEM|remeshing (out of scope)



SFC3 – AM SS 316L lessons learned include value in geometry, ICs, modularity

Activities

Contributions

- Ductile Failure looking a regularization strategies and integrated project oversight
- Constitutive model development for modular plasticity
- Damage model development for anisotropy
- Calibration tool development (MatCal)
- Exploration of ductile failure in shear environments
- Code development and implementation into production analysis code SIERRA/SM
- Experimental support for Ductile Failure characterization and validation data

Operations

- Ductile Failure Working Group meetings held quarterly
- Ductile Failure Advisory Panel meeting held occasionally
- Leveraging the Sandia Fracture Challenges and teams

Activities

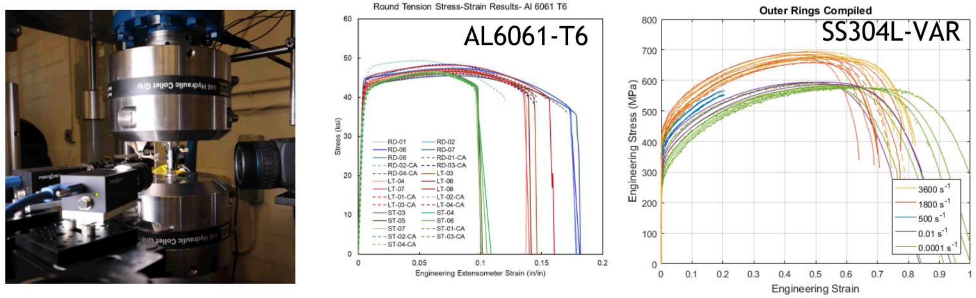
Contributions

- Ductile Failure looking a regularization strategies and integrated project oversight - Talamini
- Constitutive model development for modular plasticity - Scherzinger
- Damage model development for anisotropy
- Calibration tool development (MatCal)
- Exploration of ductile failure in shear environments - Corona
- Code development and implementation into production analysis code SIERRA/SM
- Experimental support for Ductile Failure characterization and validation data - Jin

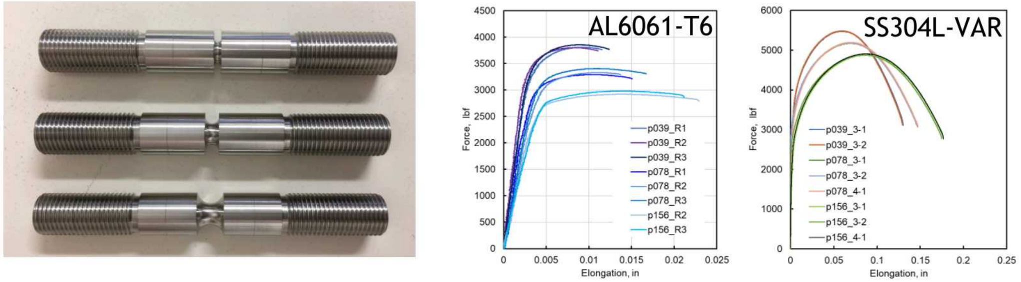
Operations

- Ductile Failure Working Group meetings held quarterly
- Ductile Failure Advisory Panel meeting held occasionally
- Leveraging the Sandia Fracture Challenges and teams

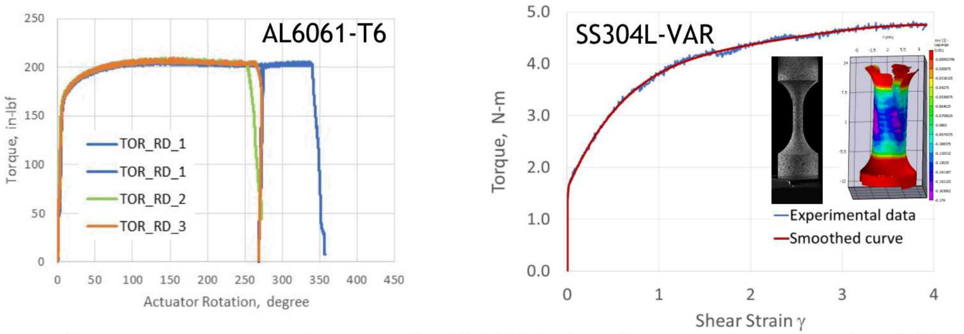
Technical highlights – Experimental Characterization



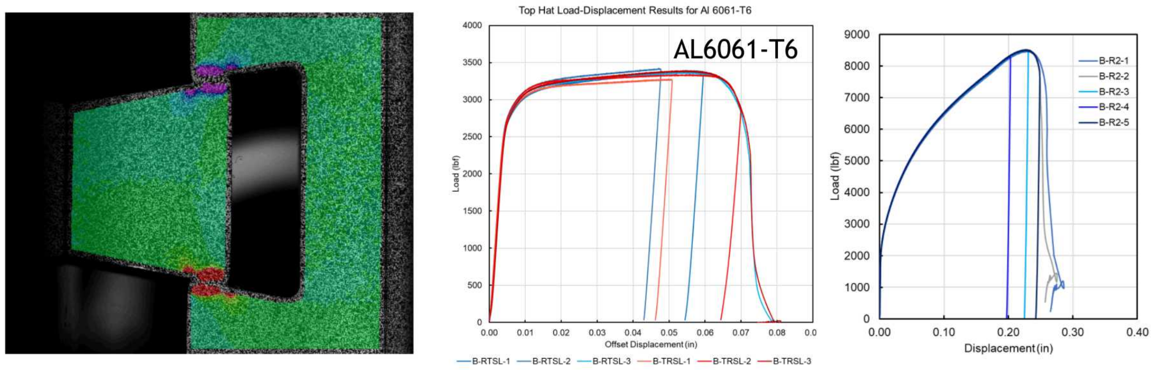
Tension setup and load versus displacement plots, colors correspond to material orientation for the aluminum, and strain rates for the steel



Notched tension specimens and load versus displacement plots



Solid bar torsion torque versus rotation curve for AL6061 in the rolling direction orientation (left), torque versus shear strain curve with inset speckled specimen and 3D DIC shear strain contours for 304L (right)

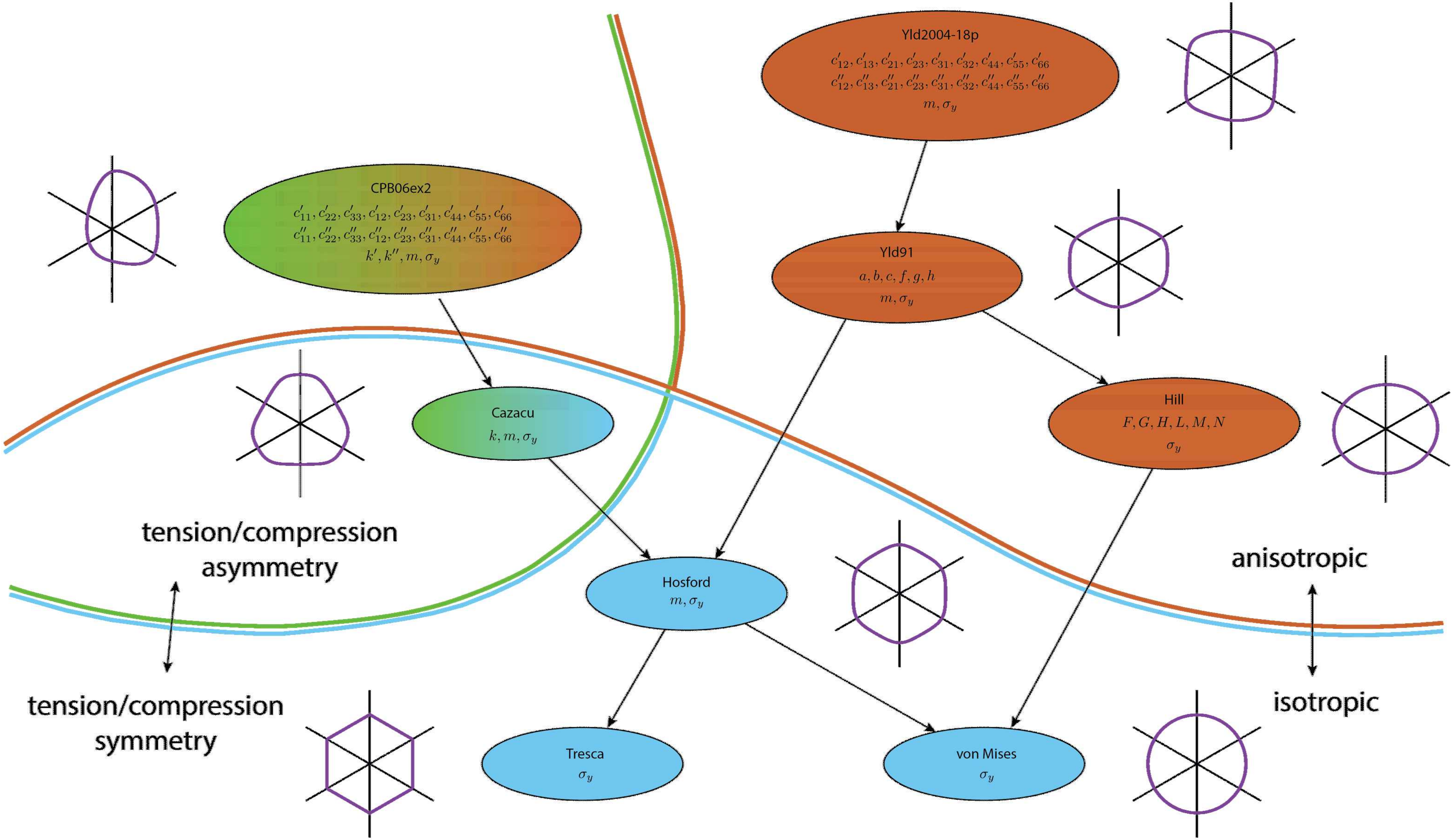


Top-hat shear deformed specimen with shear strain contours from DIC and load versus displacement plots

Mechanical characterization of SS304L-VAR and AL6061-T6

Objective: generate a body of characterization data, deliver modelers and analysts

Technical highlights – Modular Plasticity



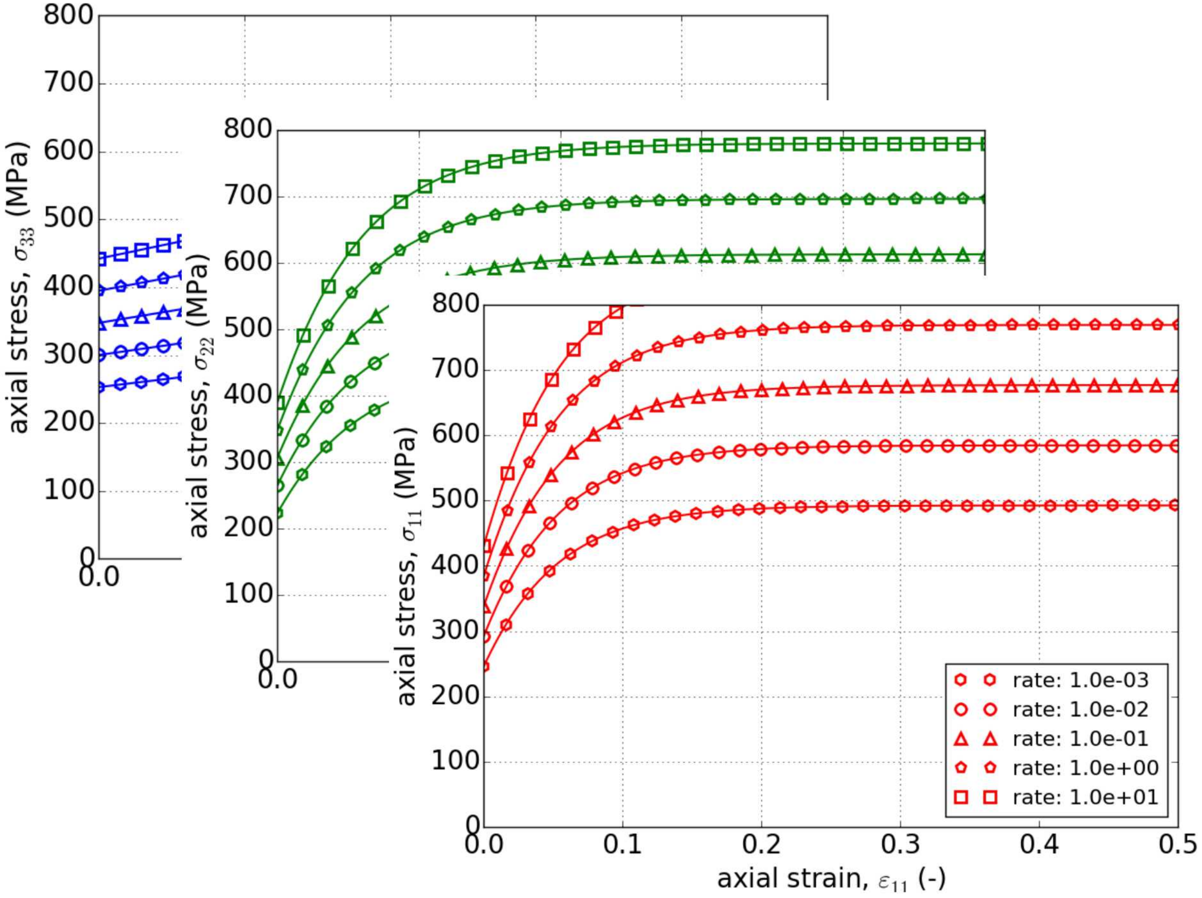
A family of yield surfaces implemented in LAMÉ provides the basis for a flexible modeling of plastic deformation

Scherzinger and Lester

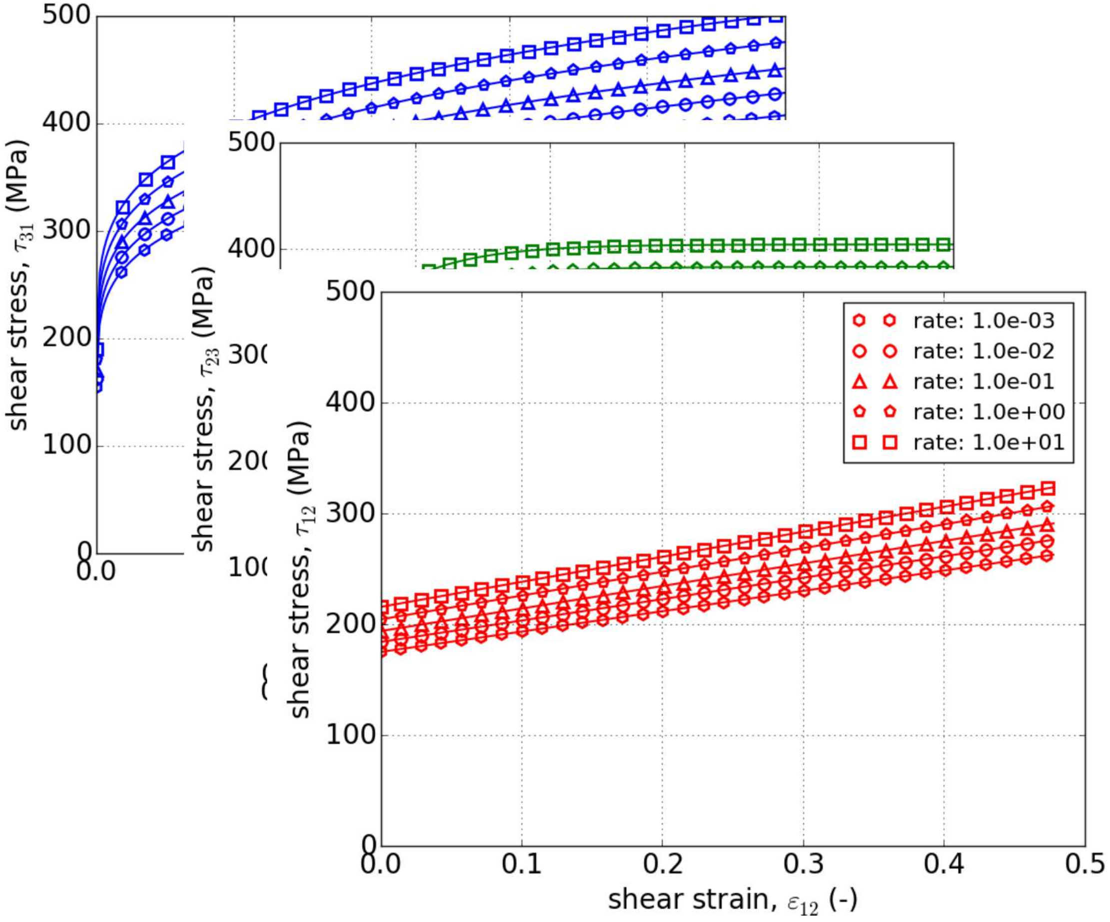
Technical highlights – Modular Plasticity

Hundreds of analytical, automated tests

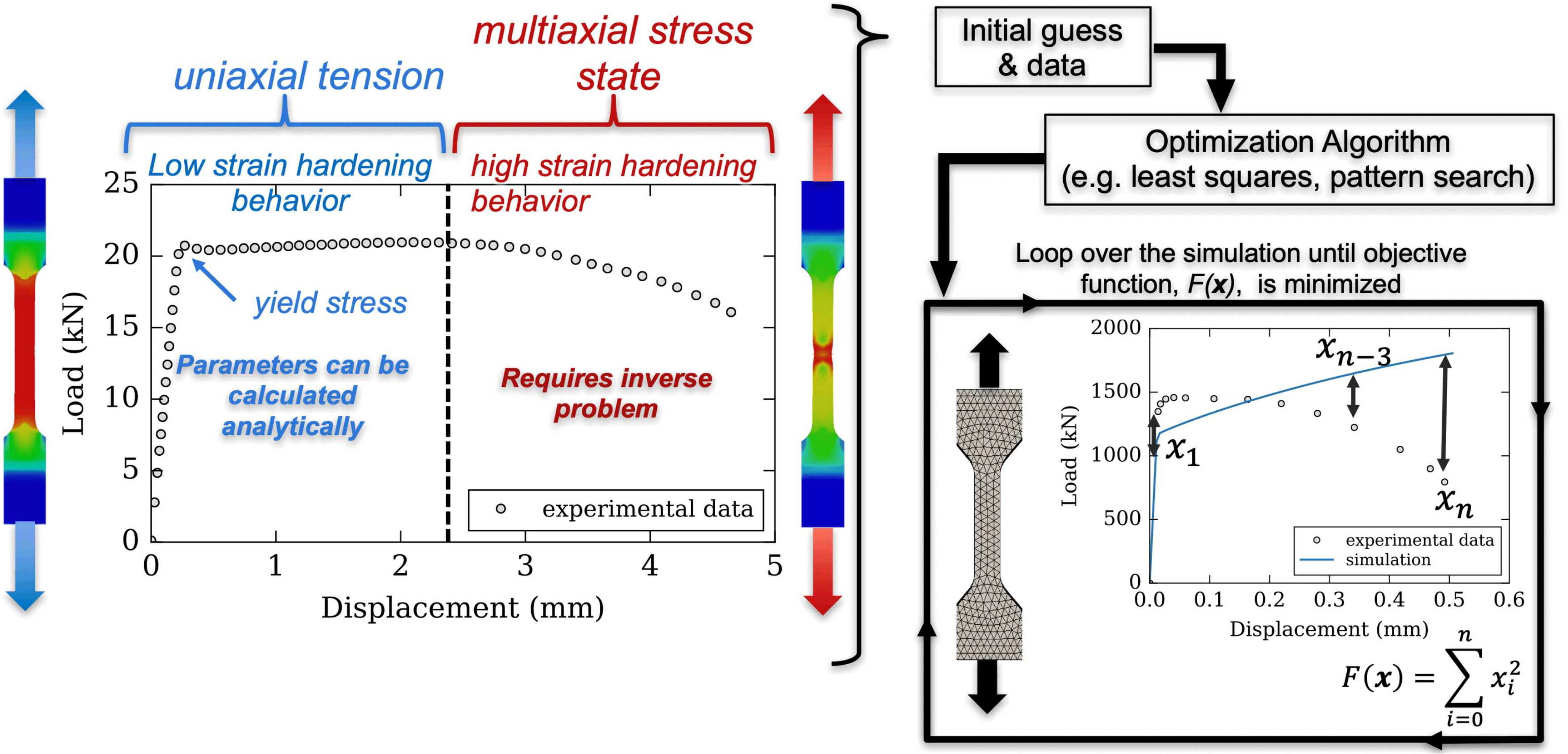
Uniaxial – Barlat (Yld2004-18p)



Pure Shear - Hill



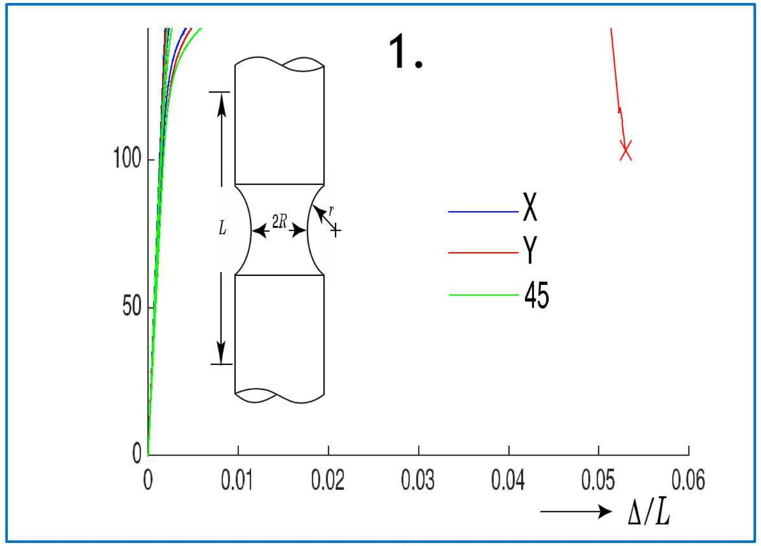
Technical highlights – Calibration

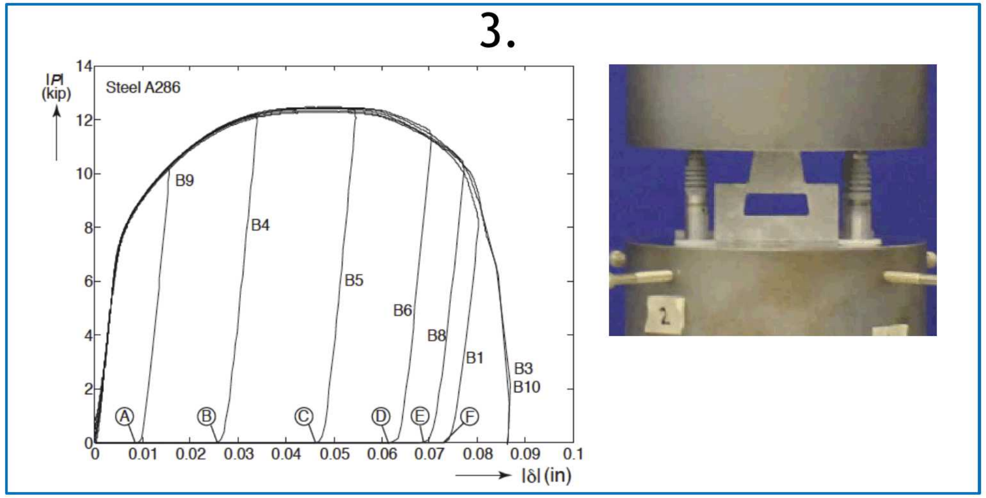


MatCal – calibration tool that uses SIERRA/SM and Dakota to identify model parameters

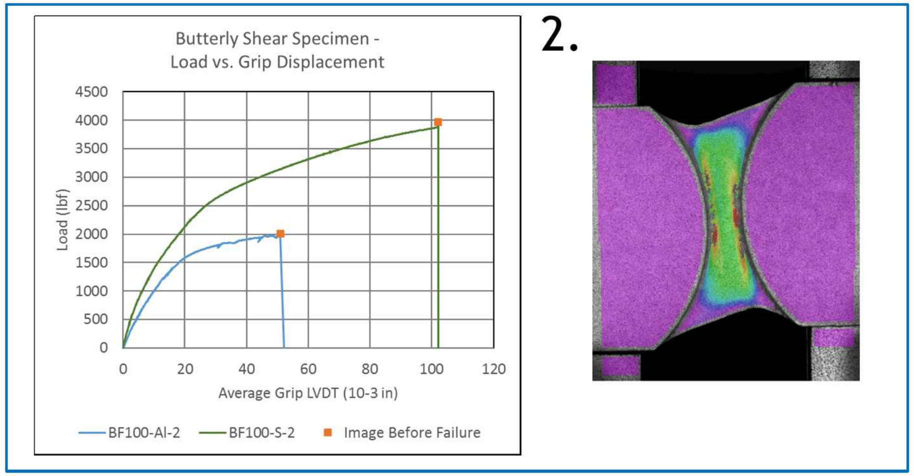
Technical highlights – Shear Failure

Exploration of material behavior in low triaxiality, or shear dominated environments

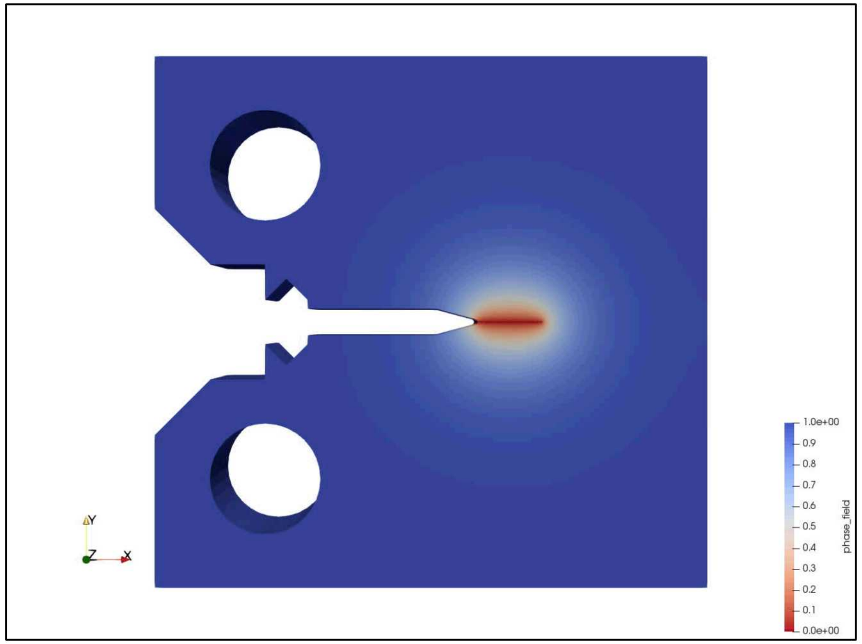


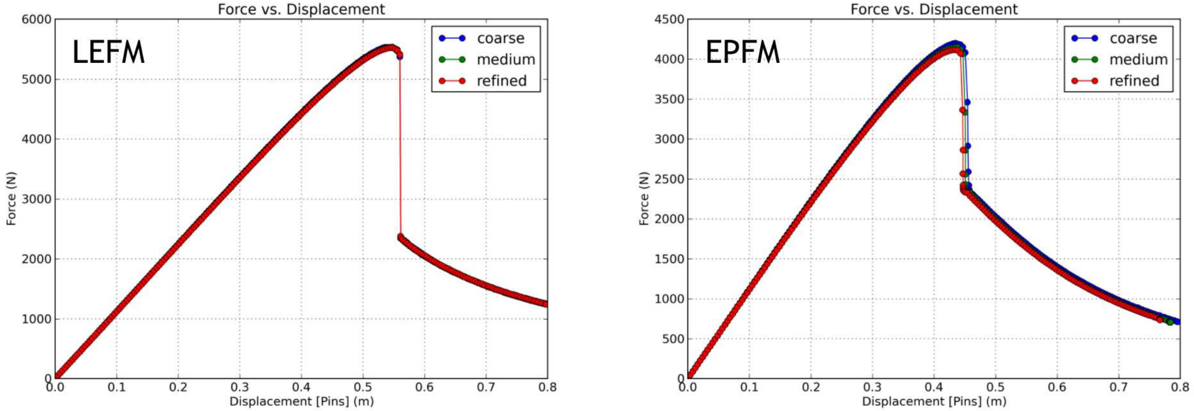


1. Four Notched Tension Tests
2. Butterfly shear test
3. Compression hat specimen

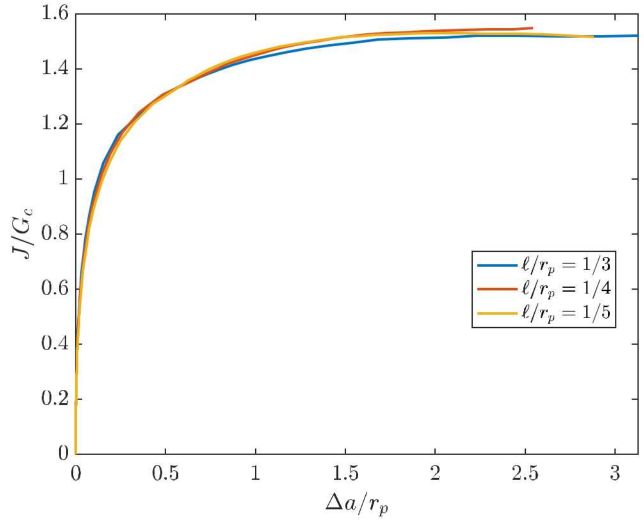


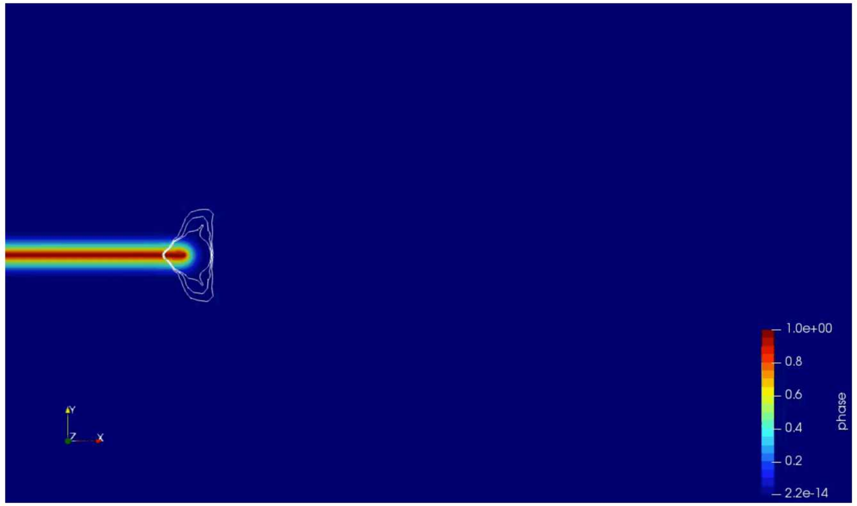
Technical highlights – Phase Field Regularization





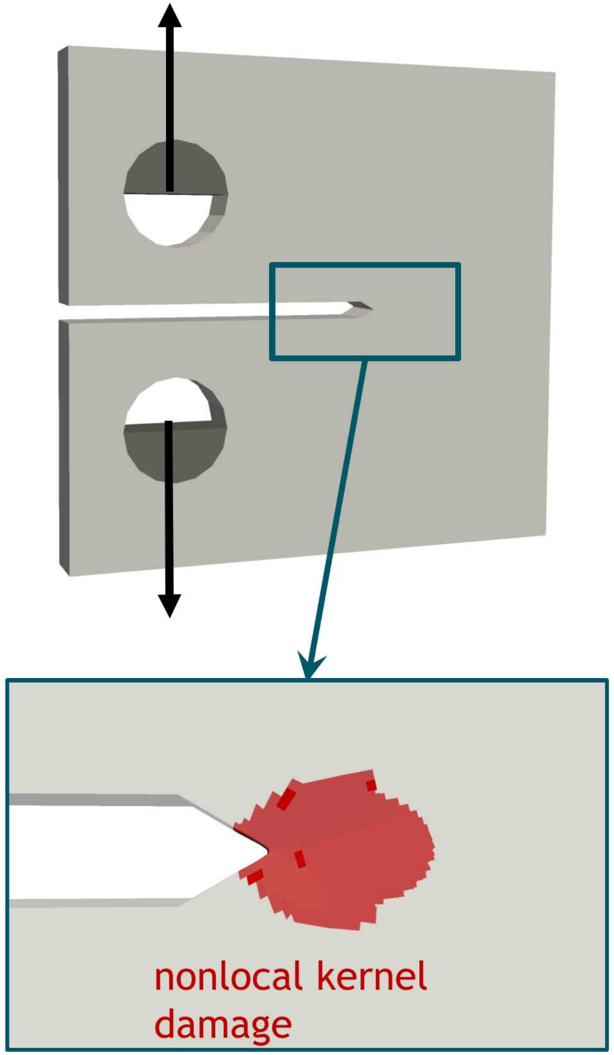
Phase field fracture methodology, as implemented in SIERRA/SM, a promising mesh independent failure capability

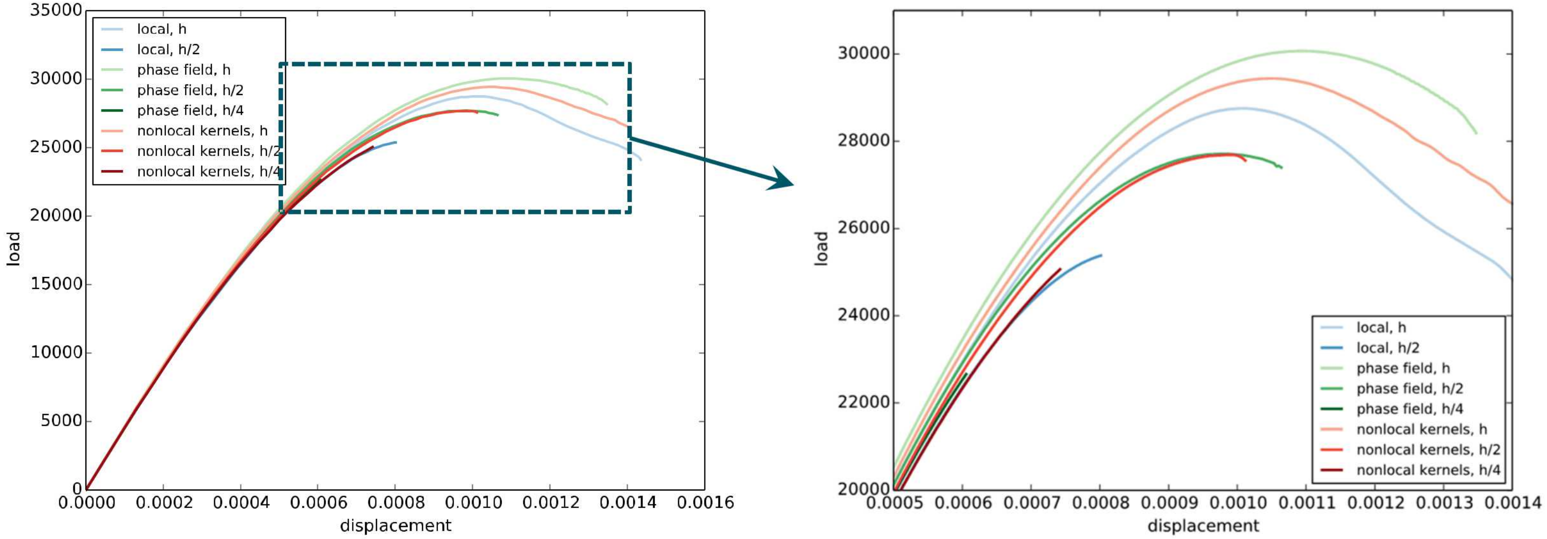




What can we say about R-curve behavior?

Technical highlights – Nonlocal Regularization





Nonlocal regularization strategy in SIERRA/SM

Nonlocal average of a local state variable, such as damage

Comparison here to phase field approach for verification

Conclusions and Future Work

Ductile Failure is a challenging and important research topic for the mechanics communities

- Alloys exhibit a broad range of behaviors
- Physical mechanisms governing plasticity and failure vary by material system
- Physical mechanisms governing plasticity and failure vary by environment (rate, temperature, stress state)
- Modeling and simulation with targeted discovery, characterization, and validation experiments can help us increase our understanding of the dominant physical mechanisms for a given application

Next steps

- Constitutive modeling – anisotropic hardening, integration and implementation improvements, how to partition energy in storage and dissipation during large inelastic deformation
- Failure modeling – anisotropic failure, how does this fit into the phase field and nonlocal approaches
- Experiments – development of techniques to extract more information from experiments via surface (DIC) or volume (DVC) measurements, also how to get more value from current testing techniques and diagnostics
- Numerical methods – how to generally introduce adaptivity to modify meshes in front of, and also behind, crack fronts, local remeshing/enrichment

Thank you for your attention!

- Boyce, B. L., et al. "The second Sandia Fracture Challenge: predictions of ductile failure under quasi-static and moderate-rate dynamic loading." *International Journal of Fracture* 198.1-2 (2016): 5-100.
- Karlson, Kyle N., et al. "Sandia fracture challenge 2: Sandia California's modeling approach." *International Journal of Fracture* 198.1-2 (2016): 179-195.
- Kramer, Sharlotte LB, et al. "The third Sandia Fracture Challenge: predictions of ductile fracture in additively manufactured metal." *International Journal of Fracture* 218.1-2 (2019): 5-61.
- Karlson, Kyle N., et al. "Sandia Fracture Challenge 3: detailing the Sandia Team Q failure prediction strategy." *International Journal of Fracture* 218.1-2 (2019): 149-170.