

# Recent Advances in Continuum Anisotropic Plasticity

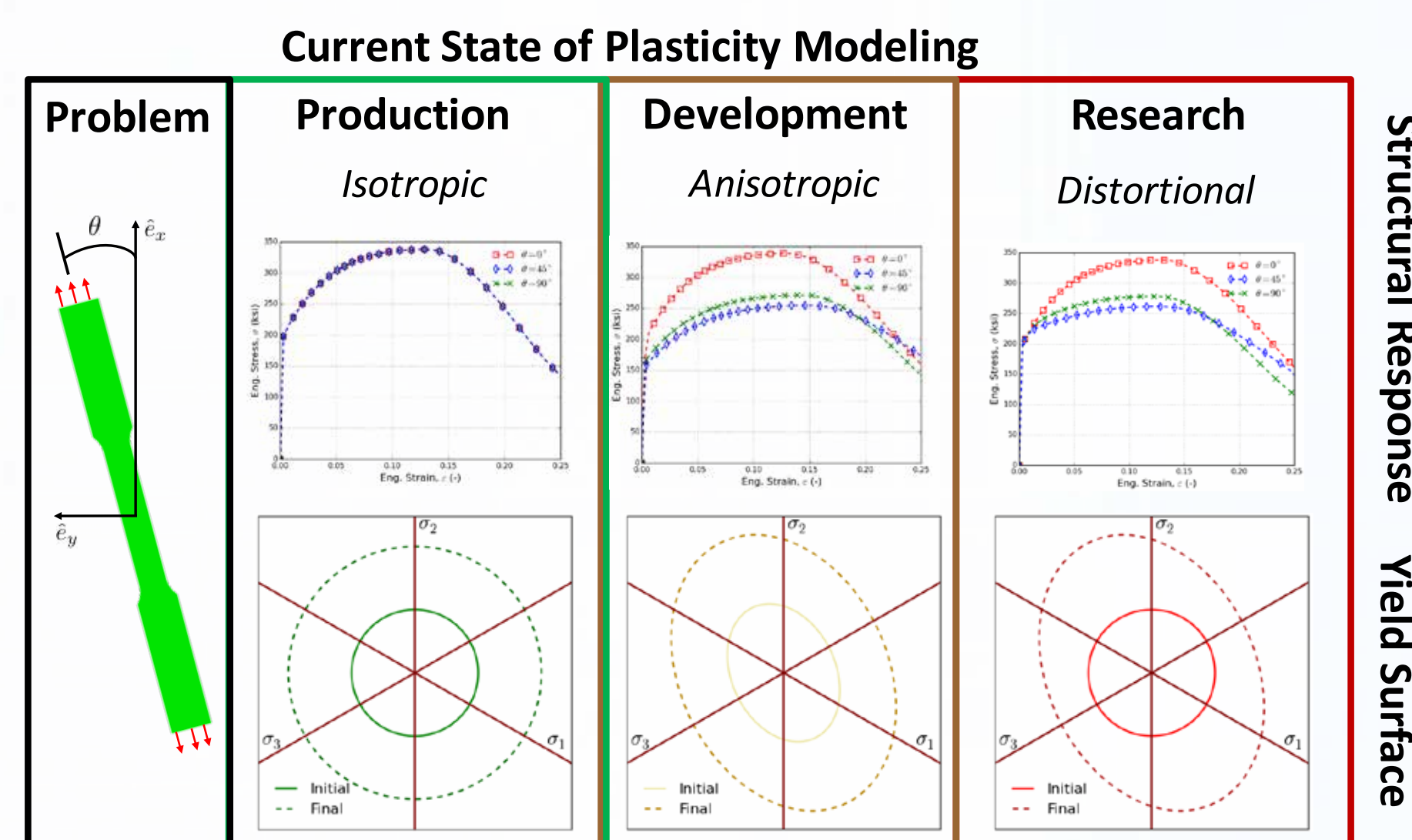
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## Macroscale Plasticity Modeling

- Seek to transform the state of practice for anisotropic plasticity models
  - Continuum, engineering scale structural analysis rely upon efficient, accurate material models
  - Currently, production level analysis relies upon isotropic descriptions
  - Many structural metals of interest exhibit anisotropic responses and behaviors
  - Objective is to improve capabilities in Sierra/Solid Mechanics for analysts

• Current efforts include:

- Development: Robust numerical implementations
- Development: Novel calibration methods
- Research: New distortional hardening models



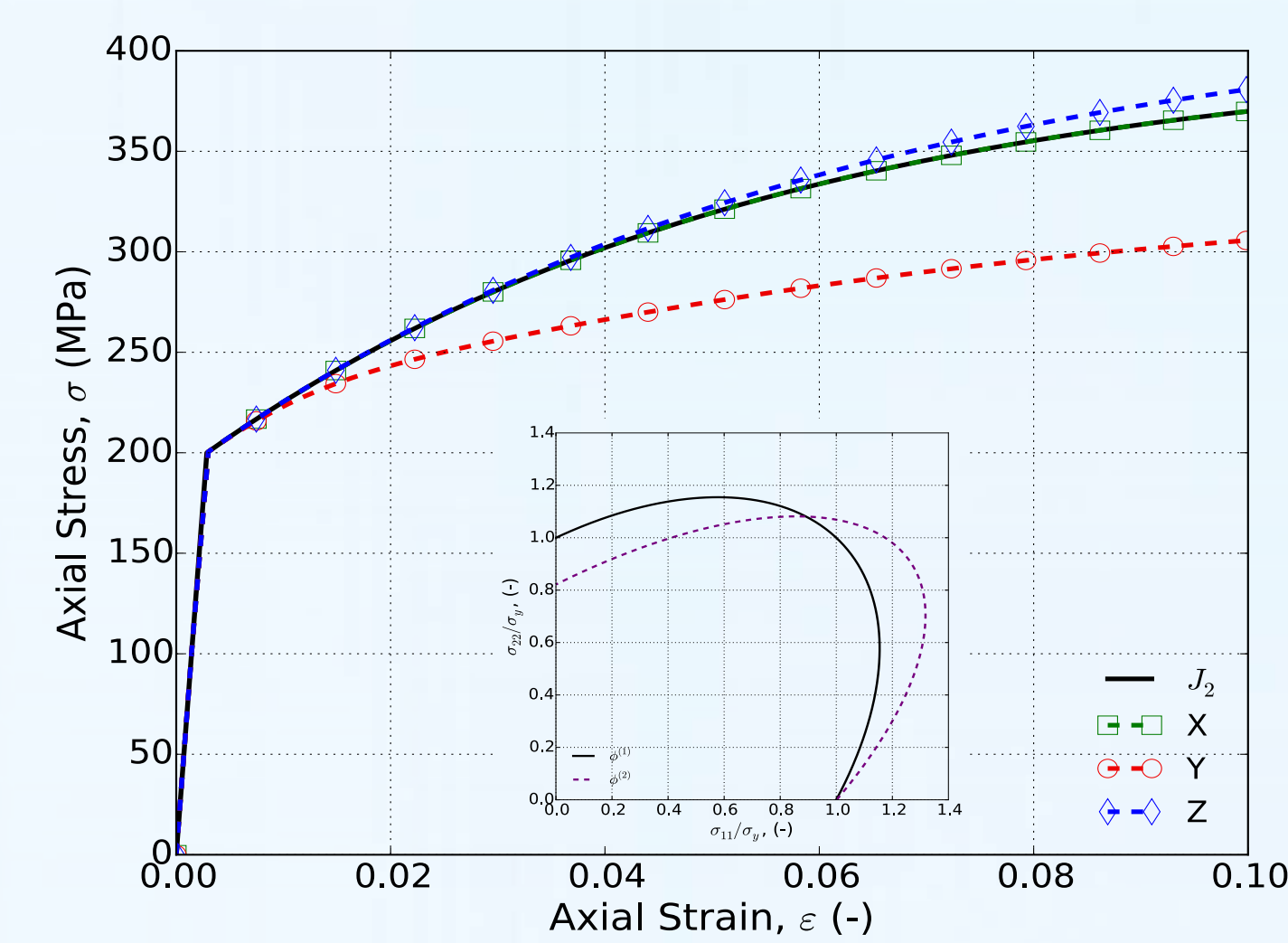
## Yield Surface for Distortional Hardening

- Distortional hardening captures change of yield surface shape with plastic deformation

- Directional hardening
- Existing methods computationally expensive and/or thermodynamically inconsistent

- Propose new mix and match yield surface framework for distortional hardening

- Introduce single internal state variable,  $\eta$
- Use of associated flow rules ensures thermodynamic consistency



Example responses with different directional responses

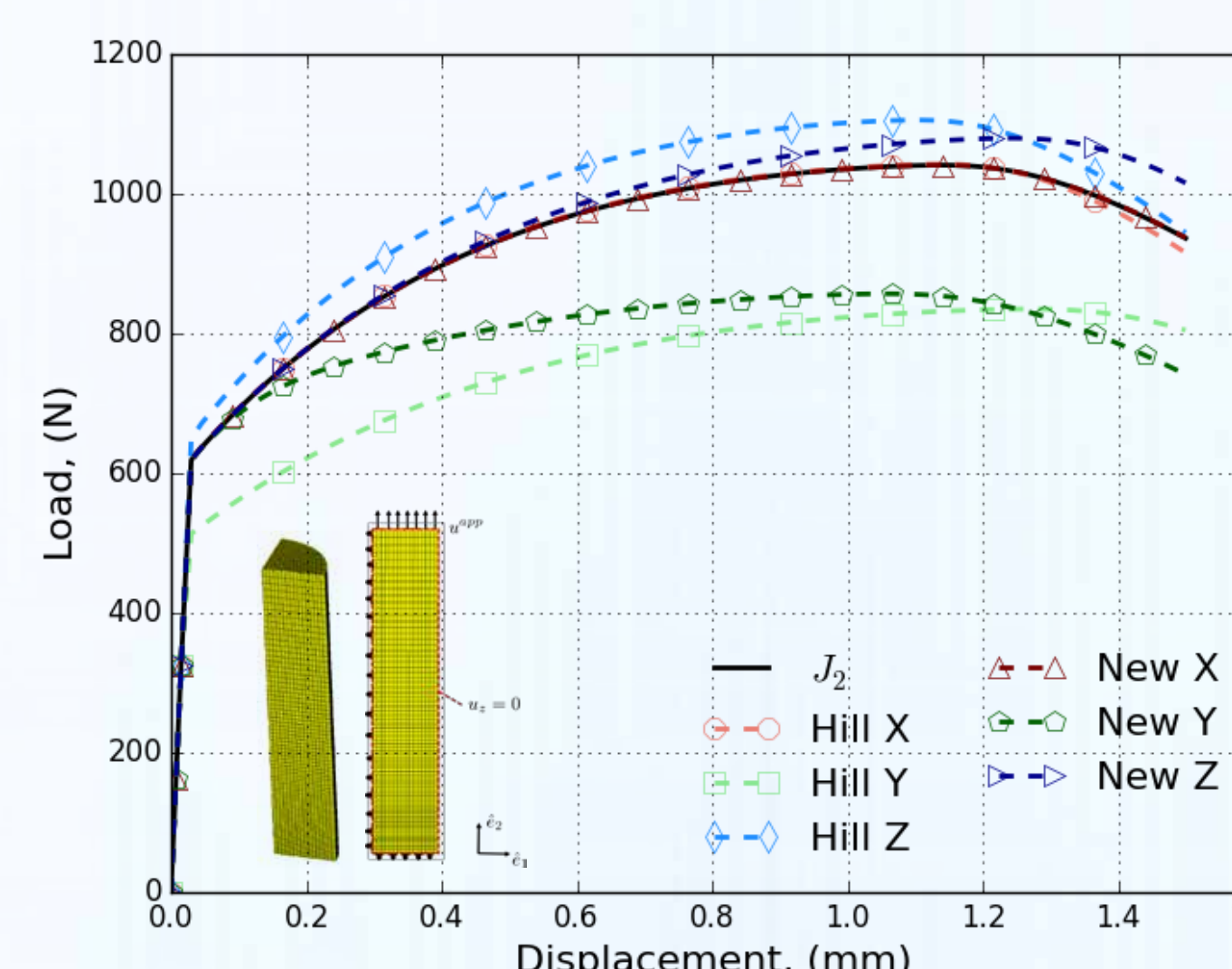
- Model implemented in Sierra/Solid Mechanics and used to solve series of boundary value problems

- Difference in hardening, shape evolution show impact of anisotropic plastic flow
- Reasonable cost increase

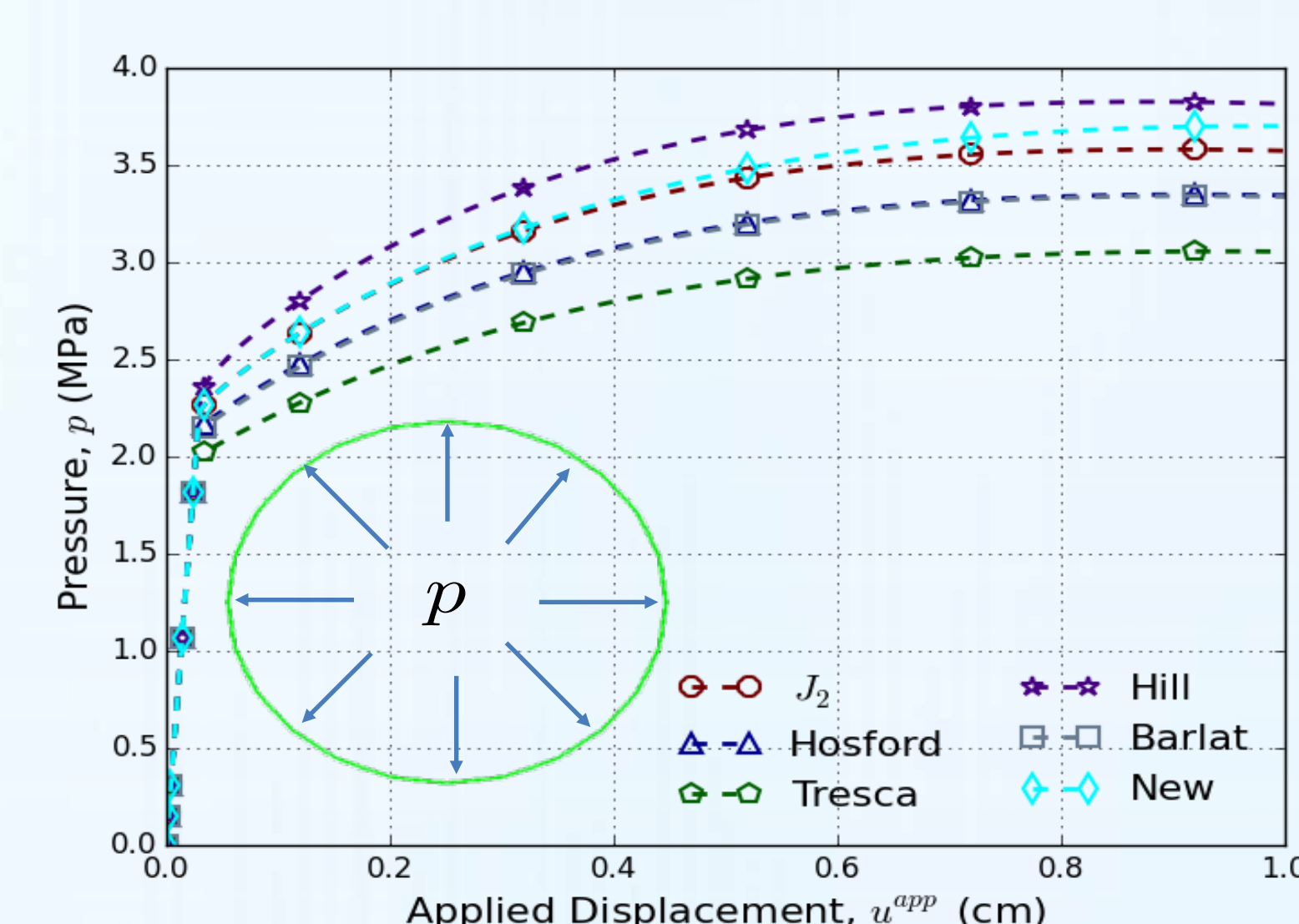
Traditional, isotropic yield surface  $f(\sigma_{ij}, \kappa) = \phi(\sigma_{ij}) - \sigma_y^0 - K(\kappa)$

New mix and match yield surface  $f(\sigma_{ij}, \kappa, \eta) = \phi(\sigma_{ij}, \eta) - \sigma_y^0 - K(\kappa)$

$$\phi(\sigma_{ij}, \eta) = \sum_{r=1}^n \zeta^{(r)}(\eta) \phi^{(r)}(\sigma_{ij}) \quad \sum_{r=1}^n \zeta^{(r)}(\eta) = 1$$



Load-displacement of a round tensile bar loaded in different directions



Response of internally pressurized cylinder with different material models

## Trust-Region (TR) Based Return Mapping Algorithm

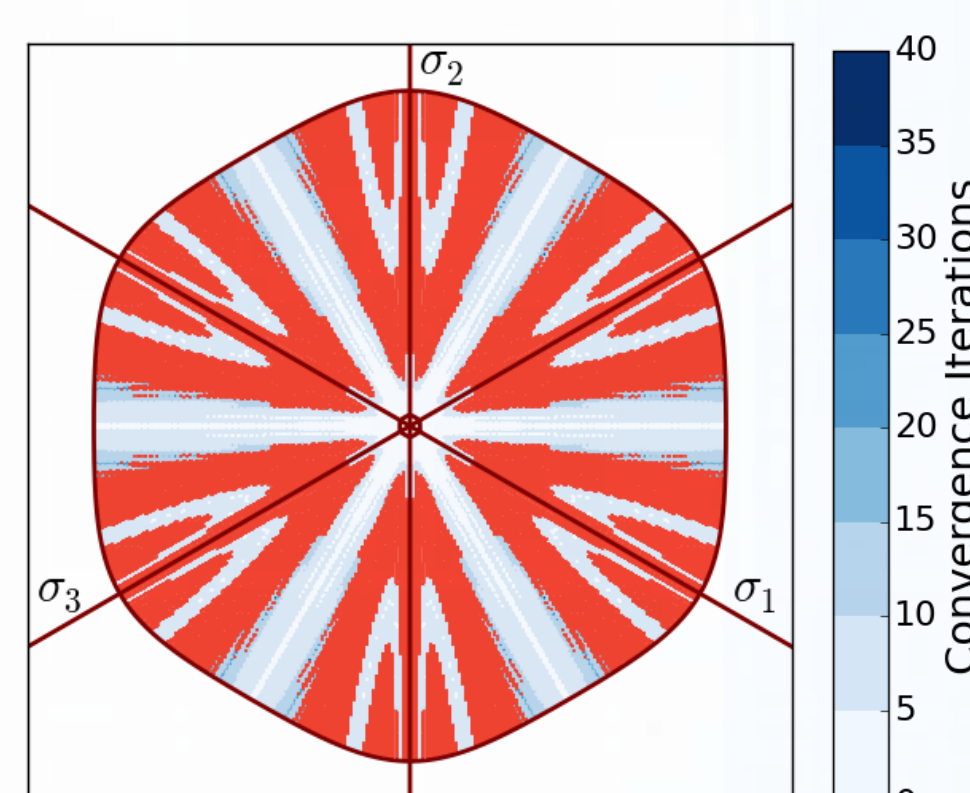
- Current constitutive integration routines rely on Newton-Raphson (NR) solution scheme
  - Lose guaranteed convergence with anisotropy
  - Need sufficiently robust algorithms to enable convergence; decrease cost

- Develop new trust-region based approach based on non-linear optimization theory

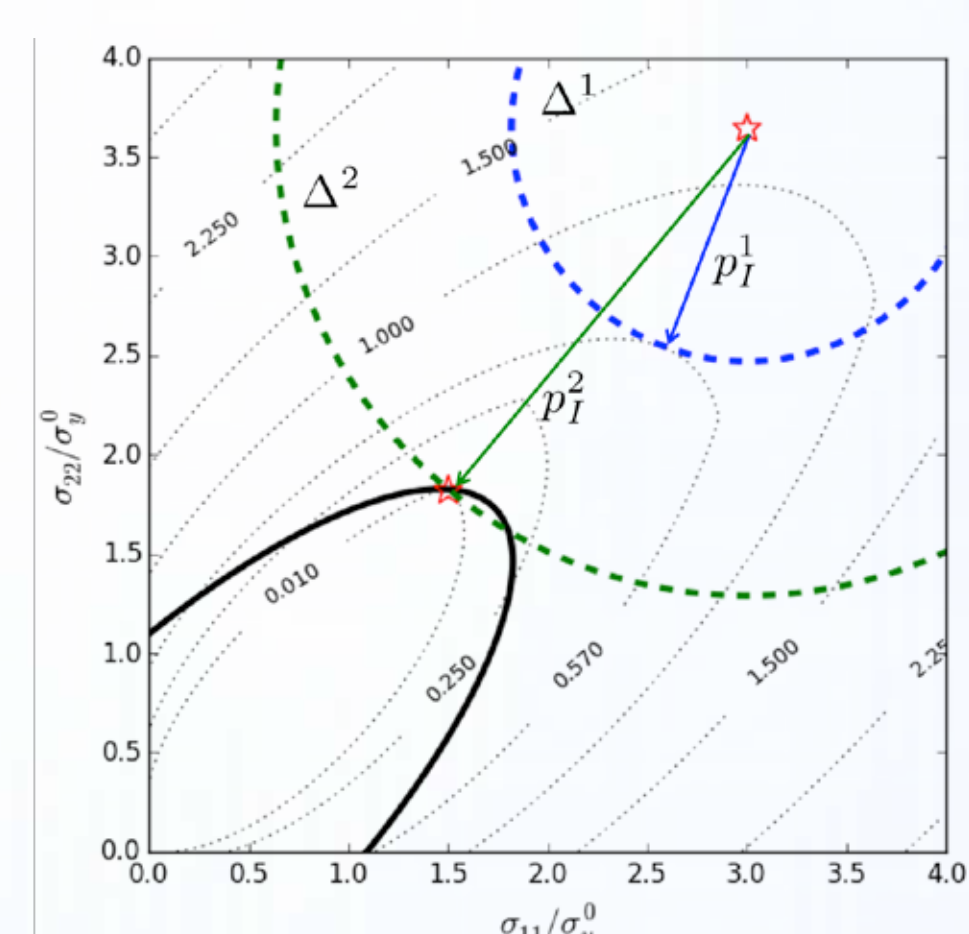
- Iterative technique based on solving approximate model problem in trusted domain
- Scaling of residual and solution vector important

- New TR based approach shows greatly improved robustness over traditional NR scheme

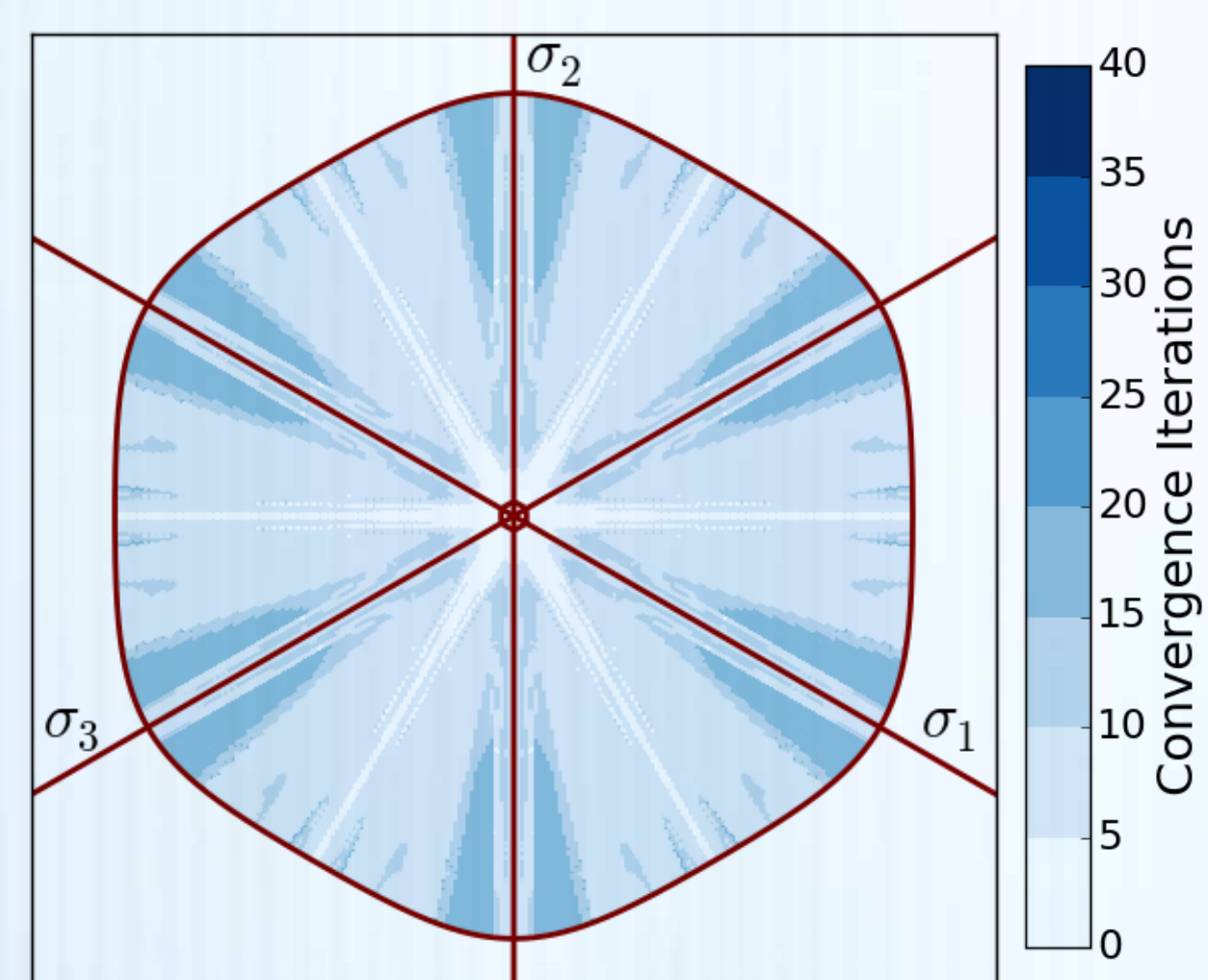
- Convergence observed at large input deformations
- Modest cost increase vs. NR (~5-10%)



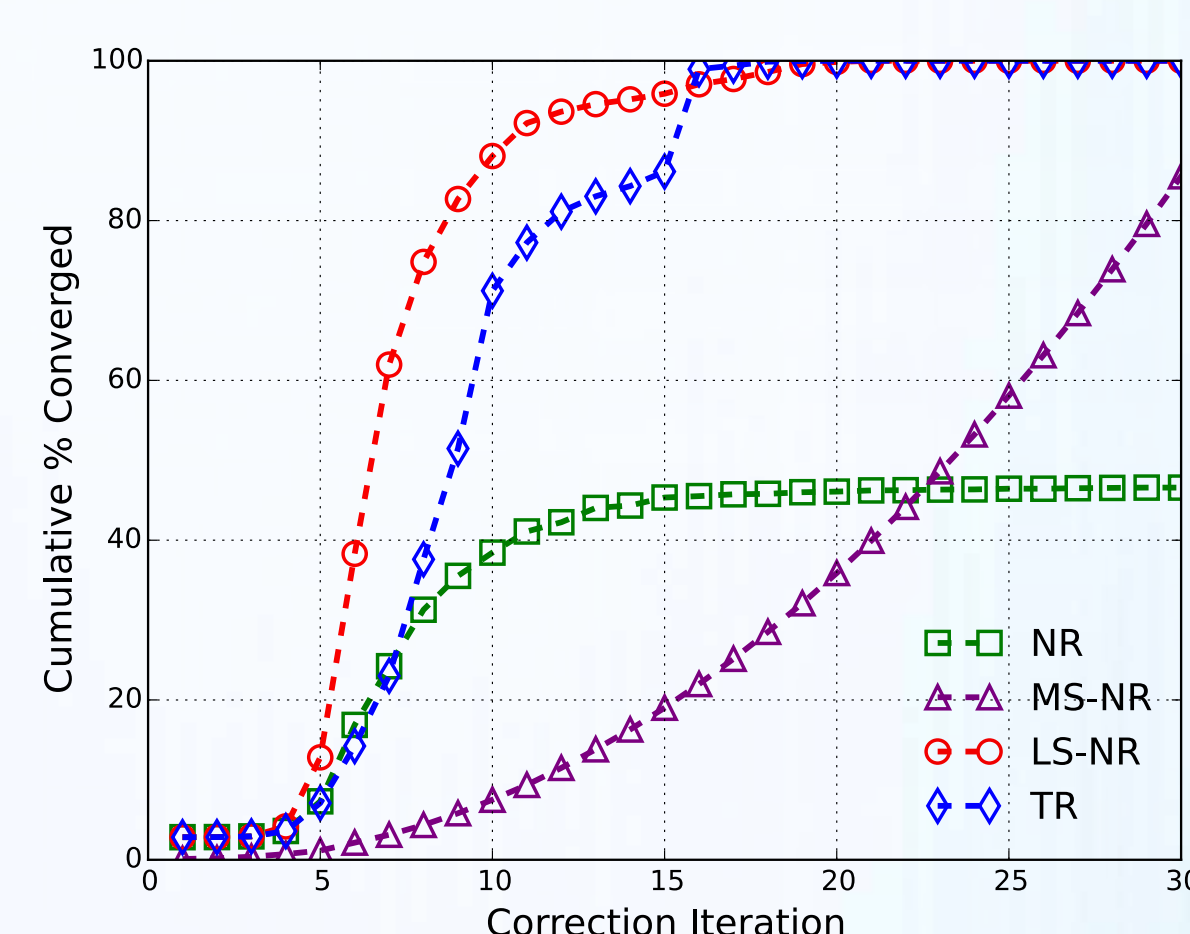
Convergence maps for Hosford yield surface using NR scheme



Schematic of new trust-region based solution technique



Convergence maps for Hosford yield surface with new solver



Cumulative convergence distributions for new TR, NR, multistage NR (MS-NR), and line search NR (LS-NR) based solvers

## Conclusions

- Pursued variety of research and development activities to advance state of practice of anisotropic continuum plasticity
  - Developed new trust-region based return mapping algorithm for robust constitutive model integration
  - Created and implemented new mix and match yield surface for efficient, thermodynamically consistent description of anisotropic, distortional hardening
  - Current techniques implemented in Sierra/Solid Mechanics but easily portable to other finite element frameworks
- Continued efforts needed to expand distortional hardening, increase ease of use of anisotropic plasticity (calibration; cost), and investigate model form error

## References

1. Lester and Scherzinger, 2017, "Trust-Region Based Return Mapping Algorithm for Implicit Integration of Elastic-Plastic Constitutive Models", IJNME, In Press
2. Scherzinger, 2017, "A return mapping algorithm for isotropic and anisotropic plasticity models using a line search method", CMAME, 317, 526-553