SAND2011-8466P

Modeling Techniques for Localization and Failure

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2011 TCG Fall Rodeo
November 16, 2011
Monterrey, CA

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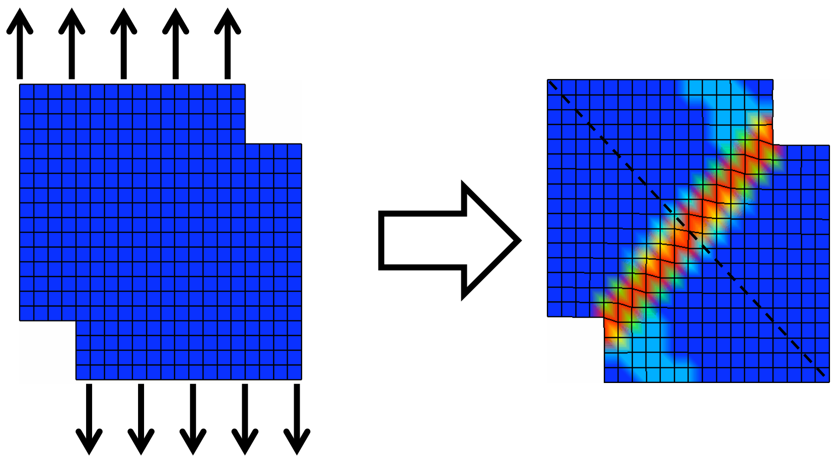
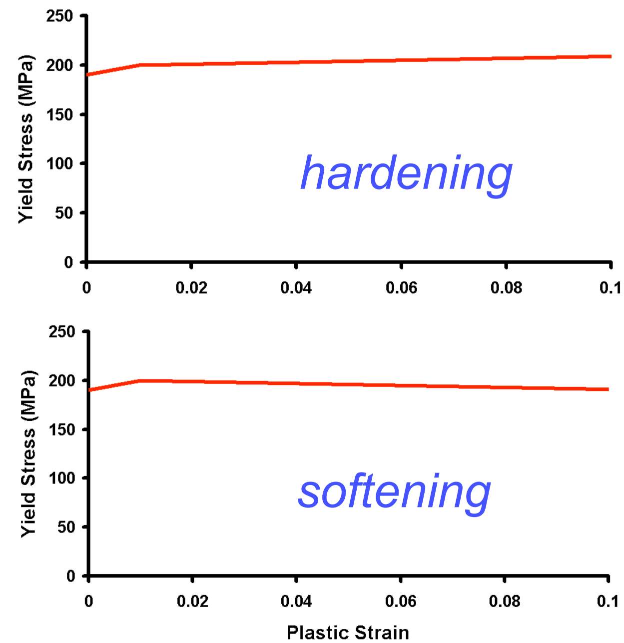
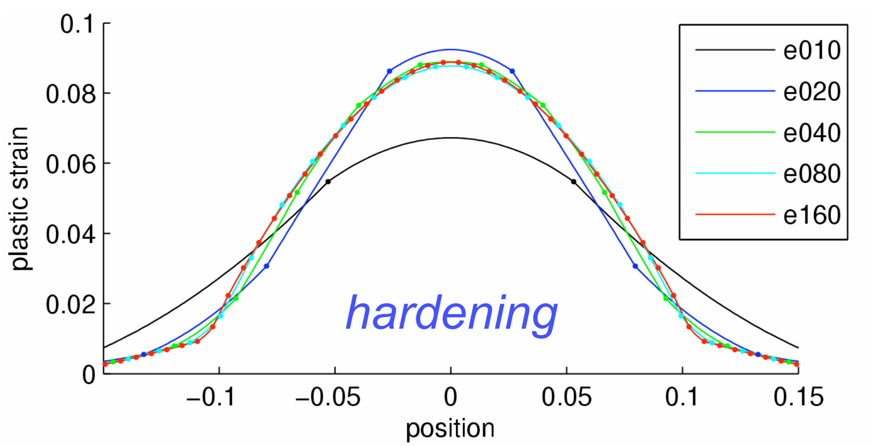
Softening Response (due to Heating, Damage, etc.) Leads to Mesh Dependence

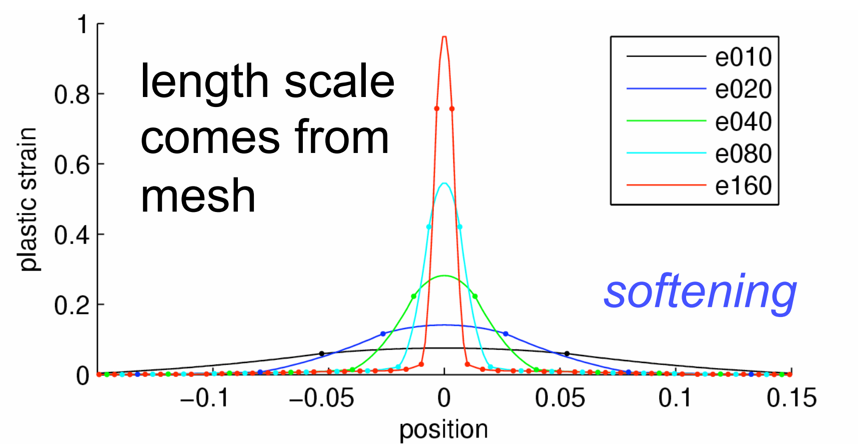
softening (loss of ellipticity) behavior corrupts the PDE and results in mesh dependent results

(Tim Kostka)









need to separate numerical issues from physics issues

Localization and Failure (TRL 1-3)

What are you trying to do?

- Provide techniques for the modeling of localization and failure (ductile fracture, shear bands, compaction bands, etc.) that are not mesh dependent:
  - localization elements
  - variational non-local method

What makes you think you can do it?

- Follow multiple modeling techniques at different maturity levels → reduce risk
- Significant experience in development and implementation of localization techniques

What difference will it make?

- DoD and DOE have continued need for ability to perform predictive simulations of munitions behavior
- Failure and localization are inevitably the most critical aspects of munitions simulations

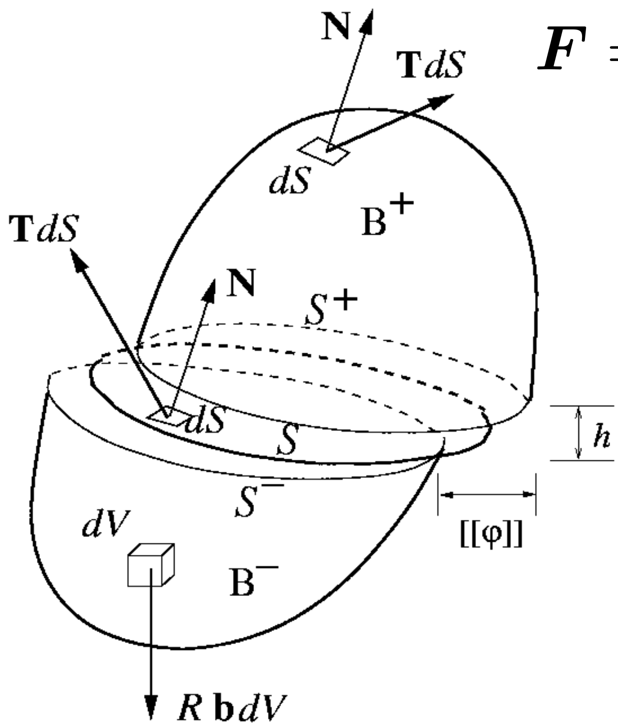
What / When / To Whom Will You Deliver?

- Verify localization elements
- Implement, verify, and validate adaptive insertion
- Develop variational mixed formulation
- Implement into Sierra when appropriate

Q4-FY13 - Demonstrate the capability to obtain a mesh independent solution involving failure for a problem of realistic complexity.

Localization Elements
(similar to cohesive elements)

IDEA: Use ANY bulk constitutive model (σ–ε) to drive surface separation



$$\boldsymbol{F} = \boldsymbol{F}^{\parallel}\boldsymbol{F}^{\perp}$$

h = band thickness

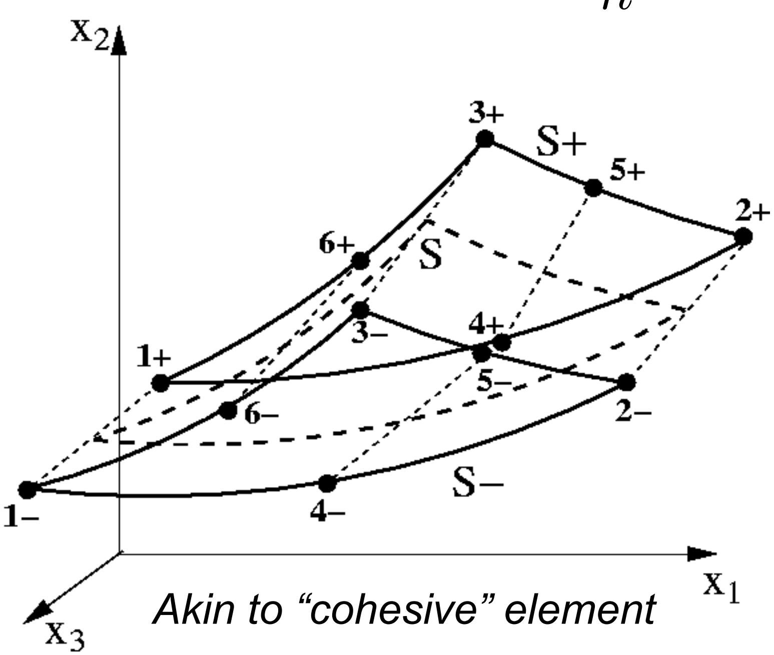
$$\boldsymbol{F}^{\parallel} = \boldsymbol{g}_i \otimes \boldsymbol{G}^i$$

$$\boldsymbol{F}^{\perp} = \boldsymbol{I} + \frac{[\![\boldsymbol{\Phi}]\!]}{h} \otimes \boldsymbol{N}$$

$$\boldsymbol{F} = \boldsymbol{F}^{\parallel} + \frac{[\![\boldsymbol{\varphi}]\!]}{h} \otimes \boldsymbol{N}$$

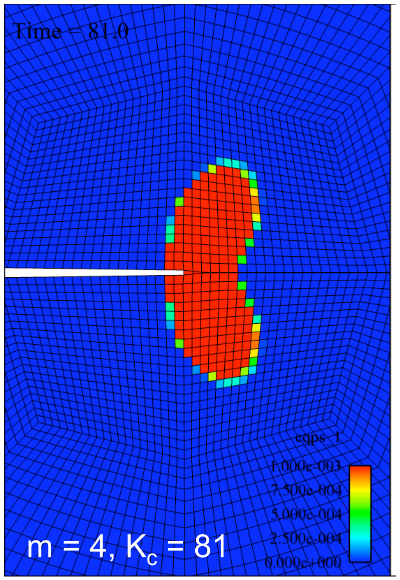
- Finite-deformation kinematics.
- Simulation of strain localization.
- No additional constitutive assumptions

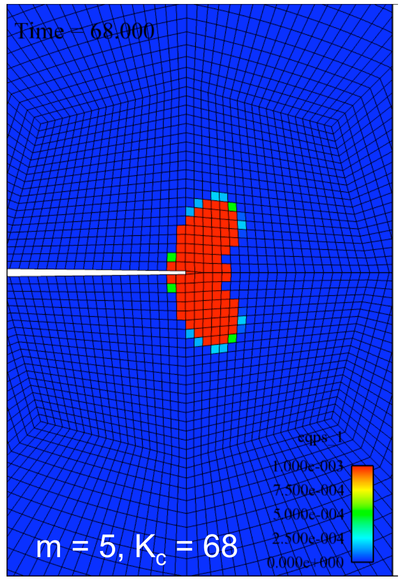
Yang, Mota and Ortiz, IJNME, 2005

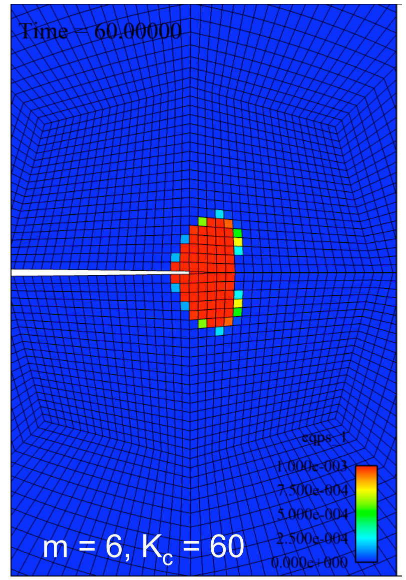


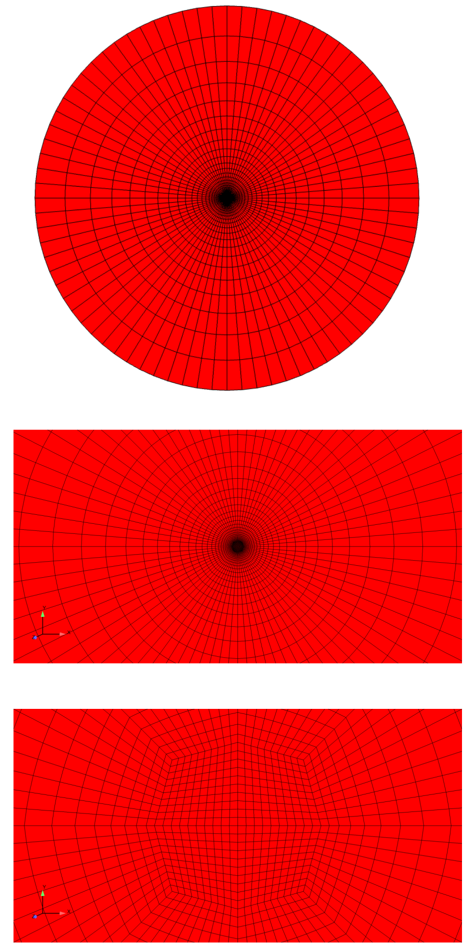
Akin to "cohesive" element

Resolution and lumping dissipation





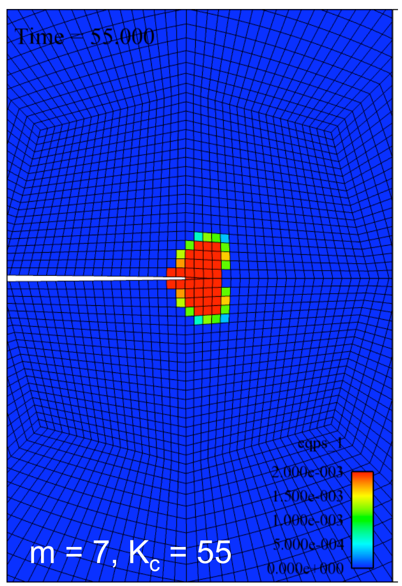


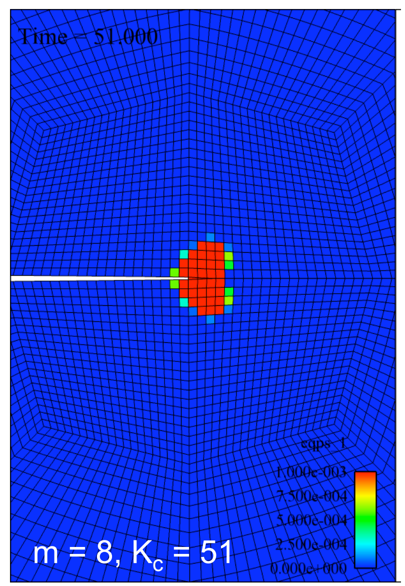


K-field boundary condition

The size of the plastic zone at propagation, Da = 60 μm, The mesh size s is 30 μm.

K_{Ic} = 70 MPa-m$^{0.5}$
h = 30 μm

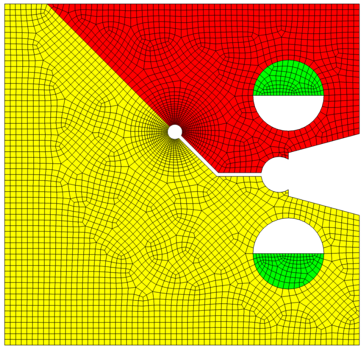




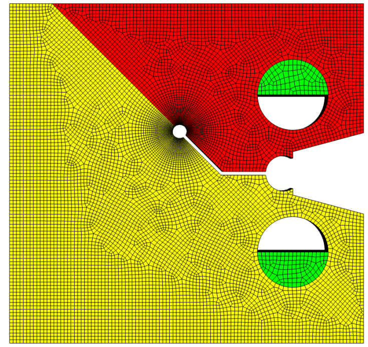
Quasi-statics with SierraSM

Damage is Convergent

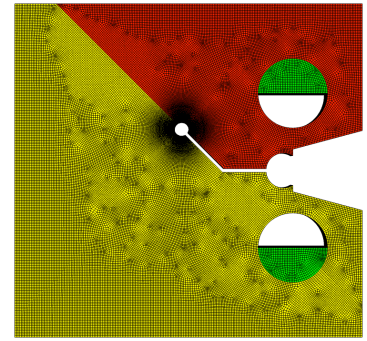
Mesh: 02
Label: Medium
Nodes: 30k
Elem: 24k
s ~ 120 μm

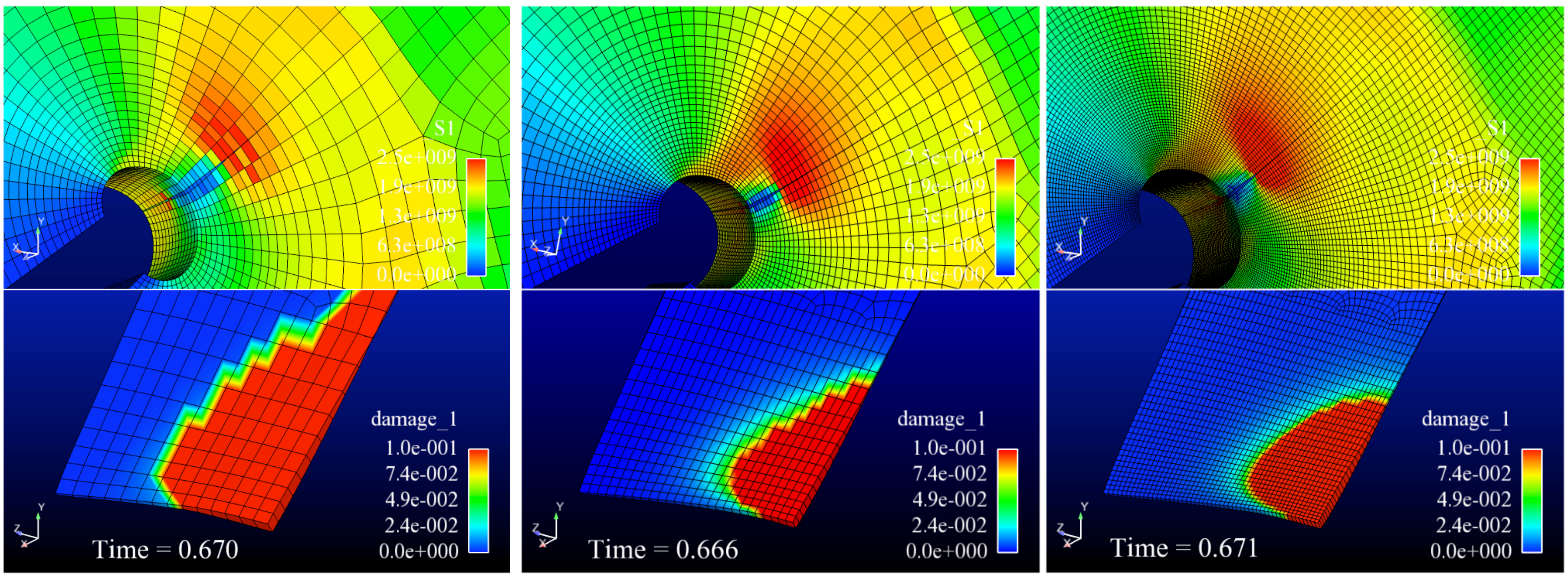


Mesh: 03
Label: Fine
Nodes: 142k
Elem: 126k
s ~ 60 μm



Mesh: 04
Label: Finest
Nodes: 1M
Elem: 1M
s ~ 30 μm

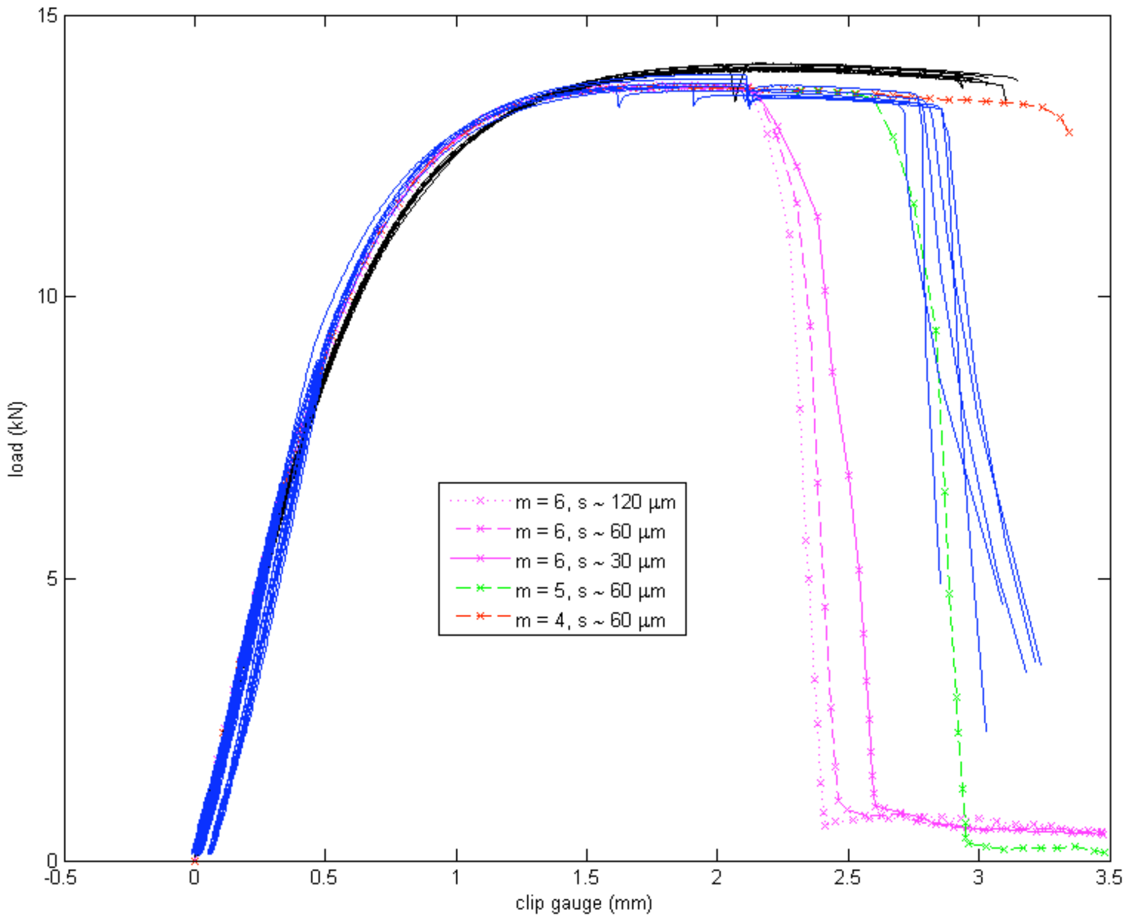


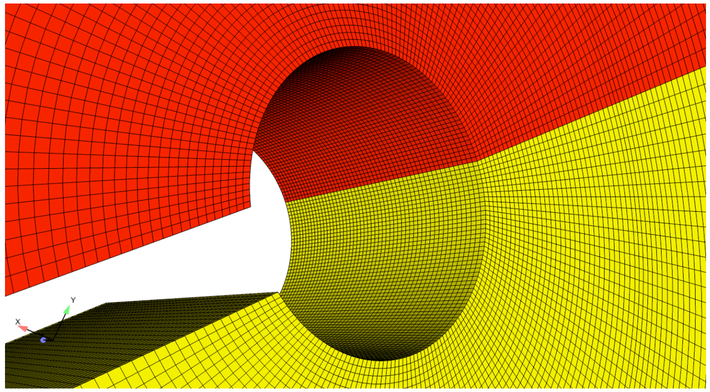


Although at slightly different times, the evolution of damage is comparable for 03 & 04.

Quasi-statics with SierraSM NOTE: Smooth notch – the specimen was not pre-cracked.

Load-Displacement Is Convergent





Boyce's lab:

- *Load line rate is 0.0127 mm/s*

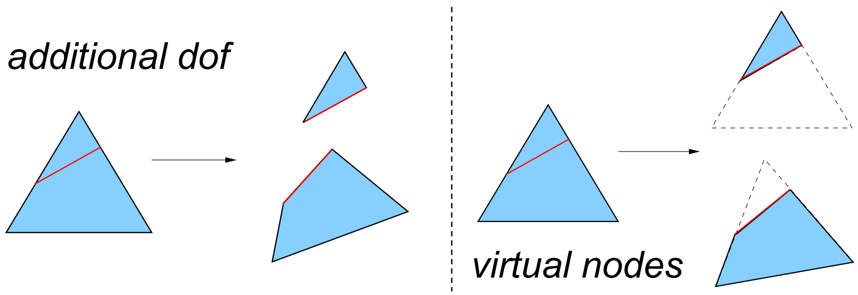
Cordova's lab

- *Load line rate before 2.03 mm is 0.0027 mm/s*
- *Load line rate after 2.03 mm is 0.00025 mm/s*

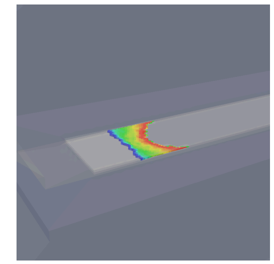
blind predictions differed somewhat from experimental data but showed correct trend

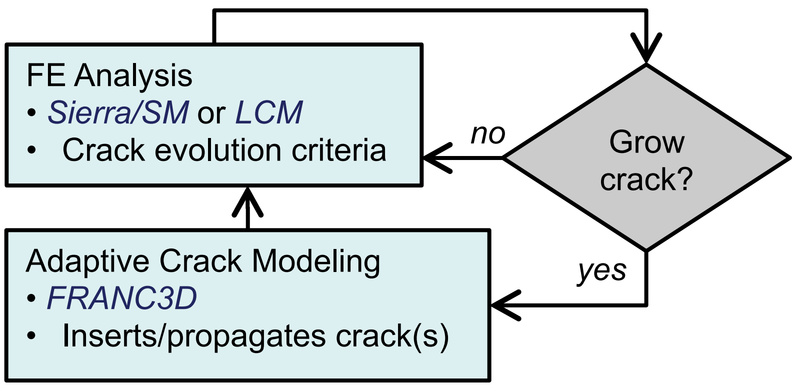
Moving the Discontinuity

X-FEM through virtual node method in SierraSM

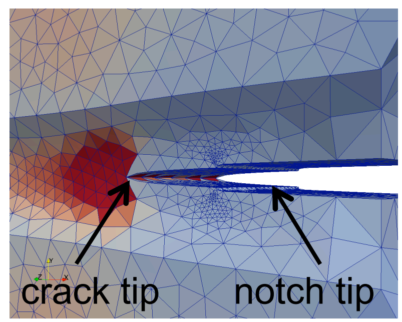


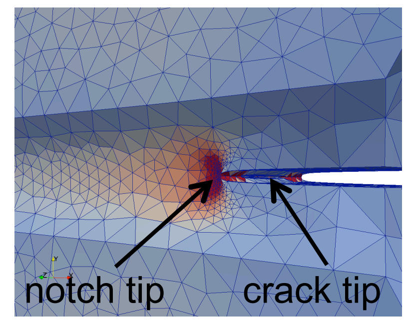
- Virtual node method enriches displacement field elements by duplicating cut elements
- Results in same number of degrees of freedom as Heaviside-enriched XFEM
- Two approaches shown to be equivalent



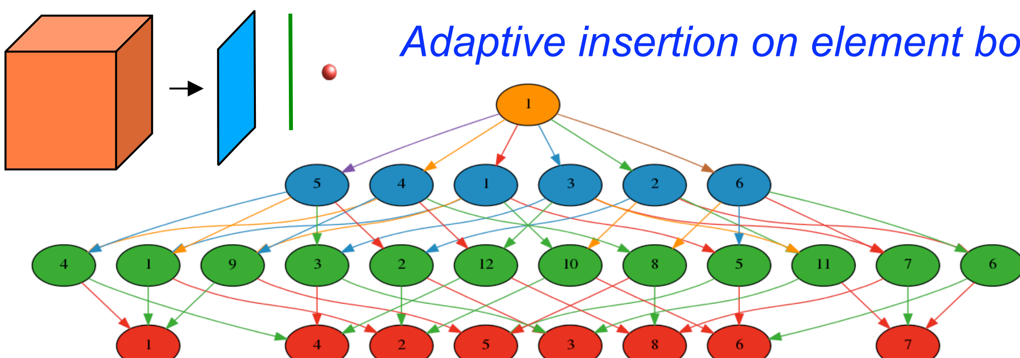


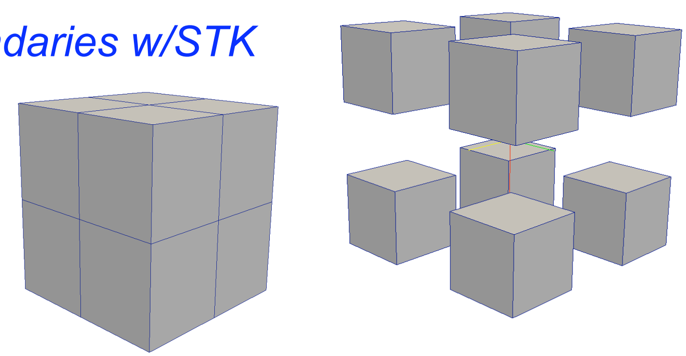
Adaptive remeshing with refinement/coarsening





Adaptive insertion on element boundaries w/STK



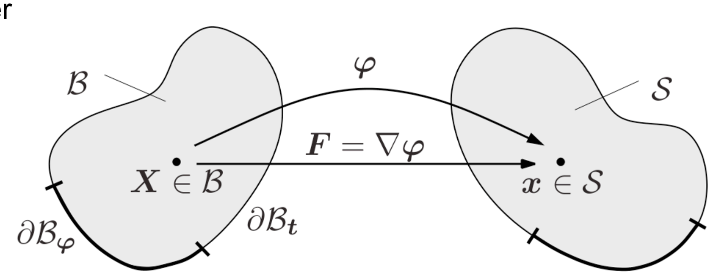


Variational Nonlocal Method

IDEA: Derive nonlocality optimized for parallel computation for ANY bulk (σ−ε) model

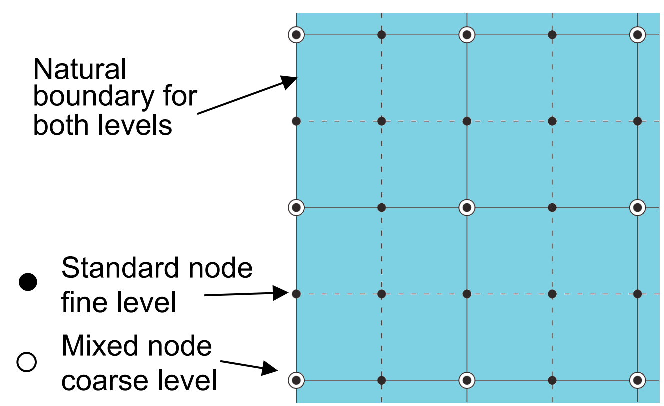
$$\Phi[\boldsymbol{\varphi}, \bar{\boldsymbol{Z}}, \bar{\boldsymbol{Y}}] := \int_B W(\boldsymbol{F}, \bar{\boldsymbol{Z}}, \boldsymbol{Q}, T)\, dV + \int_B \bar{\boldsymbol{Y}} \cdot (\bar{\boldsymbol{Z}} - \boldsymbol{Z})\, dV - \int_B \rho_0 \boldsymbol{B} \cdot \boldsymbol{\varphi}\, dV - \int_{\partial_T B} \boldsymbol{T} \cdot \boldsymbol{\varphi}\, dS$$

Deformation Mapping — Helmholtz Free Energy — Nonlocal Internal Variable — Constraint Enforced by Lagrange Multiplier



Deformation Mapping

- Motivated through studies of non-locality
- Fully variational approach that by-passes ad hoc assumptions.
- No modifications to constitutive models.
- Nonlocal domain is defined.
- Natural parallelization by domain decomposition of coarse discretization.
- Does not require cut-off approaches at boundary.



Mesh Dependence in Baseline Case

Simple finite-deformation elastic model with damage:

$$W(\boldsymbol{C}, \zeta) = (1 - \zeta) W_0(\boldsymbol{C})$$

$$\boldsymbol{\epsilon} = \frac{1}{2} \log(\boldsymbol{C})$$

$$\bar{\boldsymbol{\epsilon}} = \mathrm{dev}(\boldsymbol{\epsilon}), \quad \theta = \mathrm{tr}(\boldsymbol{\epsilon}),$$

$$W_0(\boldsymbol{C}) = W_0^{\mathrm{vol}}(\theta) + W_0^{\mathrm{dev}}(\bar{\boldsymbol{\epsilon}}),$$

$$W_0^{\mathrm{vol}}(\theta) = \frac{\kappa}{4} \left[\exp(2\theta) - 1 - 2\theta \right],$$

$$W_0^{\mathrm{dev}}(\bar{\boldsymbol{\epsilon}}) = \frac{\mu}{2} \left[\mathrm{tr}(\exp \bar{\boldsymbol{\epsilon}}) - 3 \right].$$

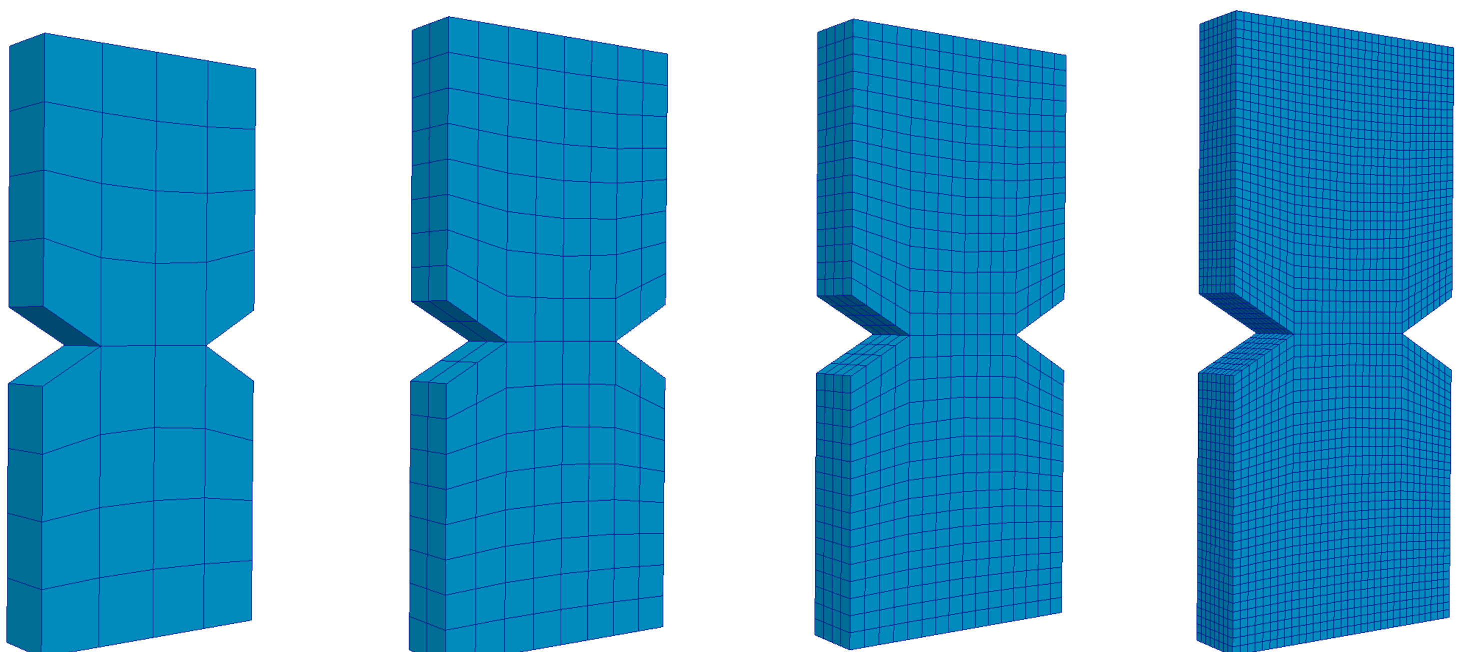
$$\zeta(\alpha) := \zeta_\infty [1 - \exp(-\alpha / \iota)]$$

$$\alpha(t) := \max_{s \in [0,t]} W_0(s)$$

ζ_∞: maximum possible damage

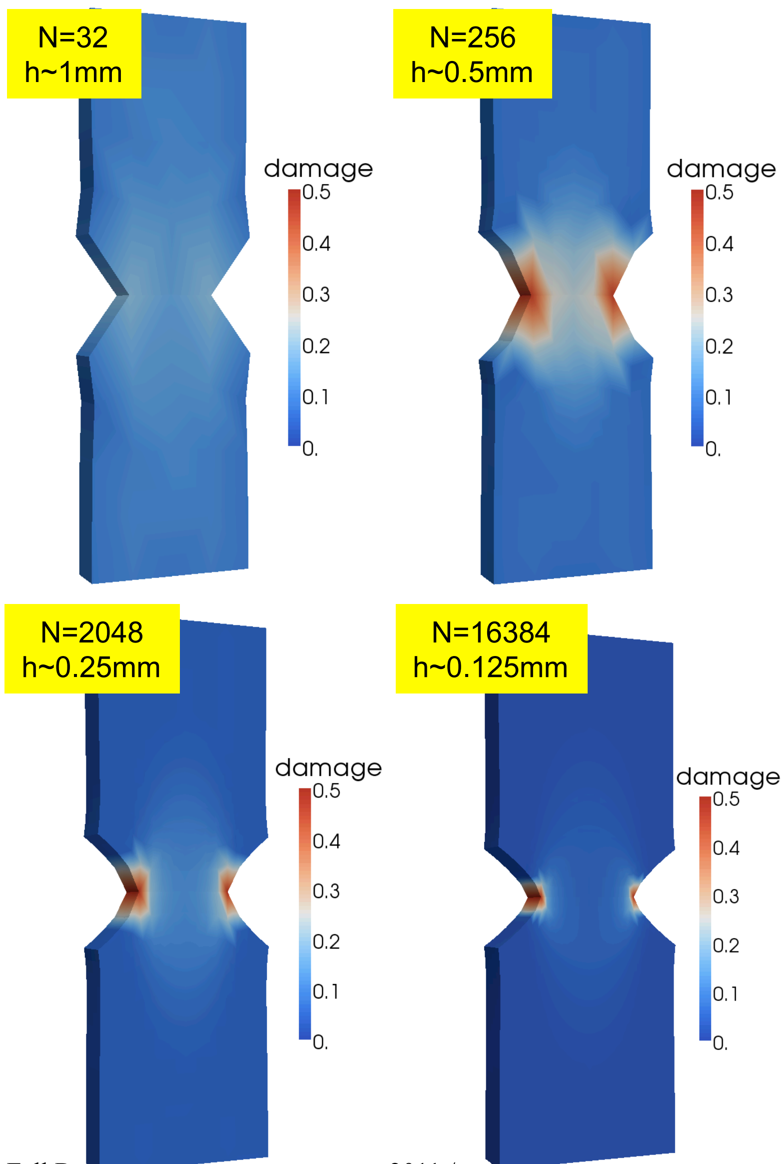
ι: damage saturation parameter

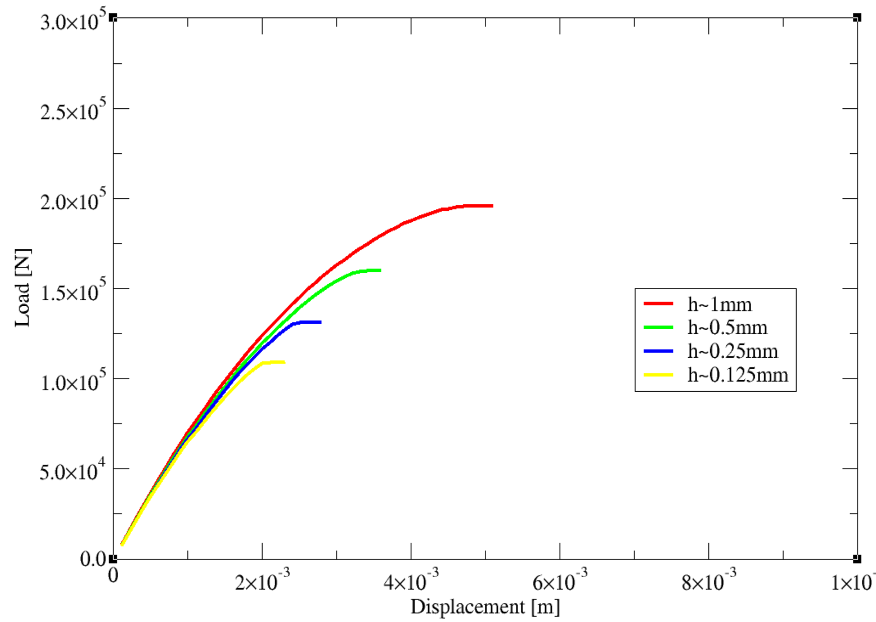
$$E = 200\mathrm{GPa}$$
$$\nu = 0.25$$
$$\kappa = 133\mathrm{GPa}$$
$$\mu = 80\mathrm{GPa}$$
$$\zeta_\infty = 1.0$$
$$\iota = 100\mathrm{GJm}^{-3}$$



N=32 h~1mm | N=256 h~0.5mm | N=2048 h~0.25mm | N=16384 h~0.125mm

Mesh Dependence in Baseline Case (2)





damage zones and load-displacement curves display mesh dependent behavior: as mesh is refined damaged region shrinks and failure load drops

Mesh Partitioning Tools Used to Provide Coarse Scale

$$\bar{\boldsymbol{Y}} = \frac{1}{\mathrm{vol}(D)} \int_D \boldsymbol{Y} \; dV,$$

$$\bar{\boldsymbol{Z}} = \frac{1}{\mathrm{vol}(D)} \int_D \boldsymbol{Z} \; dV,$$

$$\mathrm{vol}(\bullet) := \int_{(\bullet)} dV,$$

Constant interpolation leads to decoupling and simple averaging:

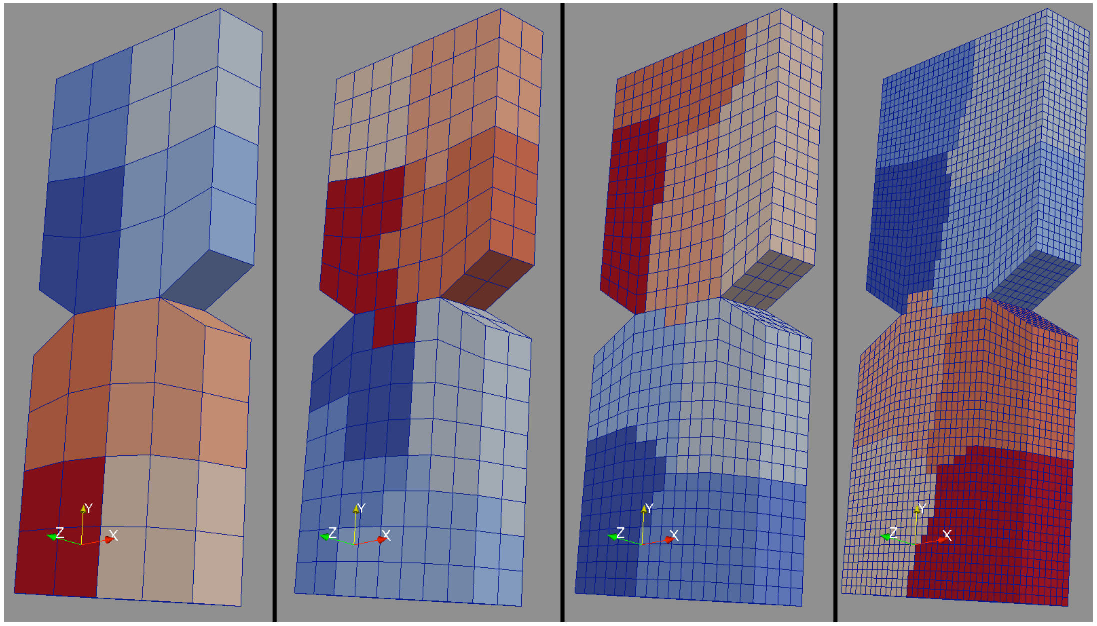
$$\mathrm{vol}(D) = \sum_{i=0}^{n} \mathrm{vol}(E_i),$$

$$\int_D \boldsymbol{Y} \; dV = \sum_{i=0}^{n} \int_{E_i} \boldsymbol{Y} \; dV,$$

$$\int_D \boldsymbol{Z} \; dV = \sum_{i=0}^{n} \int_{E_i} \boldsymbol{Z} \; dV.$$

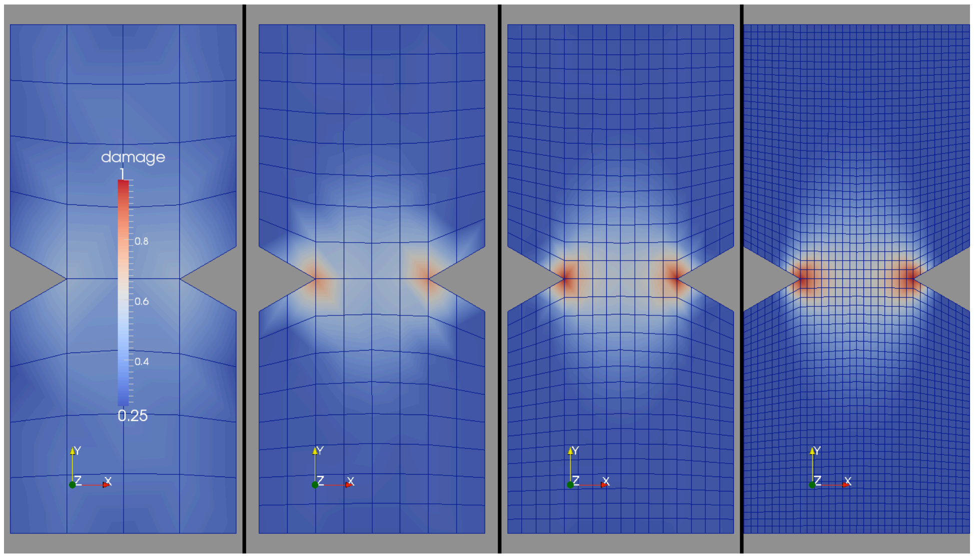
use mesh partitioner (Zoltan in Sierra) to create domains *D*

vol(*D*)=(length scale)^3=(1.6mm)^3



N=32	N=256	N=2048	N=16384
h~1mm	h~0.5mm	h~0.25mm	h~0.125mm

Variational Nonlocal Technique is Convergent



N=32
h~1mm

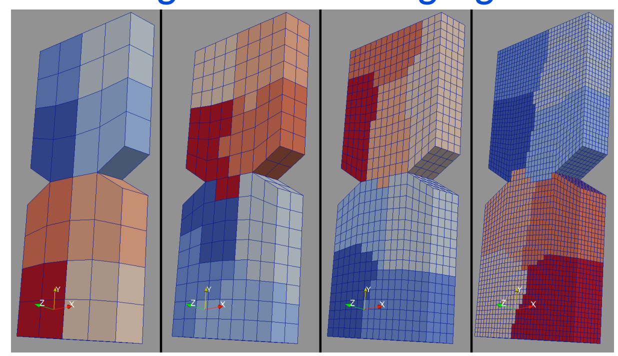
N=256
h~0.5mm

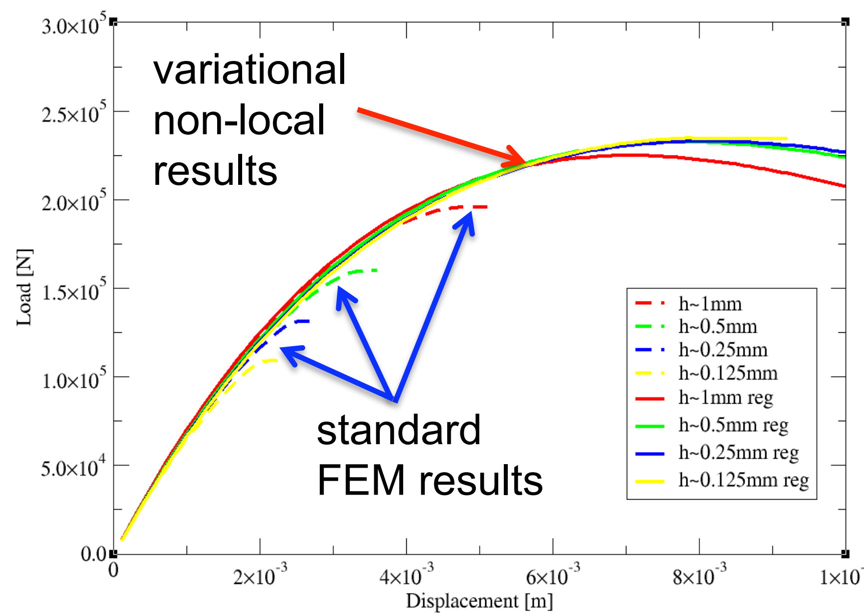
N=2048
h~0.25mm

N=16384
h~0.125mm

- Regularization effective
- Derived naturally from variational principle
- No special boundary considerations
- Simple form with unit interpolation functions

Initial studies in 3-D confirm 1-D findings, the fields are damage are converging





Conclusions

- Developing multiple methods to reduce mesh dependence in problems involving failure and localization, but there is no silver bullet!
- Methods are convergent and have a space of applicability
- Localization elements have broad applicability (leverage bulk response) and provide the regularization needed
  - issues when element size is of order of h
  - robust insertion techniques
- Variational non-local technique establishes length that is natural to the FEM mesh
  - derived naturally from variational principle
  - no special boundary considerations
  - simple form with unit interpolation functions.

We measure success by analyst adoption and not by model development or implementation.