Potential-Based Dynamic Fracture Simulation with Adaptive Topological Operators

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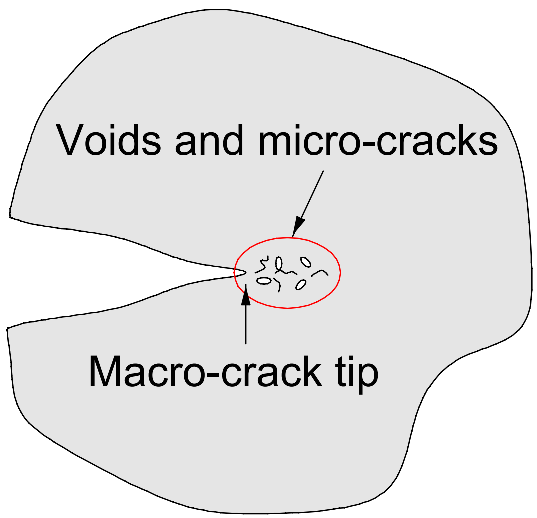
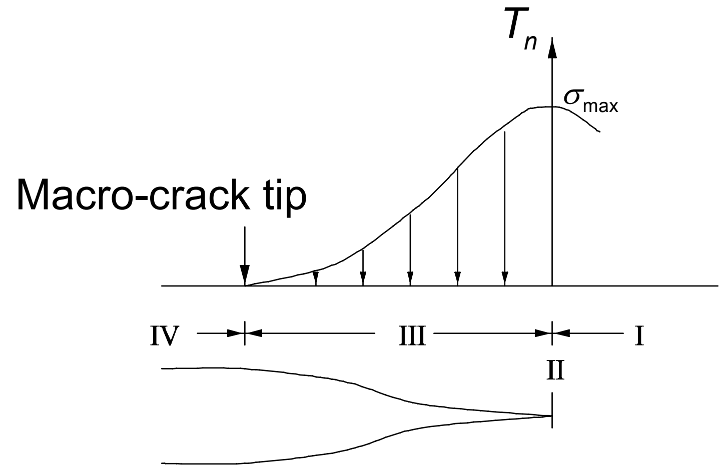
Outline

- Cohesive Zone Modeling
- Potential-Based Cohesive Model
- Adaptive Topological Operators
- Computational Examples
  - Mode I pre-defined crack path
  - Mixed-mode fracture problem
  - Micro-Branching
- Summary

Cohesive Zone Modeling





- **Constitutive Relationship of Cohesive Fracture**
  - Non-potential based-model vs. Potential based-model
- **Computational Methods**
  - Cohesive surface elements, enrichment functions, embedded discontinuities

Previous Potentials for Fracture

- **Needleman A. (1987)**
  - Polynomial potential / linear shear interaction
- **Needleman A. (1990)**
  - Exponential potential / periodic dependence
- **Beltz G.E. and Rice J.R. (1991)**
  - Generalized the potential (Exponential + Sinusoid)
- **Xu X.P. and Needleman A. (1993)**
  - Exponential potential (Exponential + Exponential)

- Needleman A. 1987, A continuum model for void nucleation by inclusion debonding, Journal of Applied Mechanics, 54, 525-531
- Needleman A. 1990, An analysis of tensile decohesion along an interface, Journal of the Mechanics and Physics of Solid, 3, 289-324
- Beltz GE and Rice JR, 1991, Dislocation nucleation versus cleavage decohesion at crack tip, Modeling the Deformation of Crystalline Solids, 457-480.
- Xu XP and Needleman, 1993, Void nucleation by inclusion debonding in a crystal matrix, Modeling Simulation Material Science Engineering, 1, 111-132.

PPR: Unified Mixed Mode Potential

$$\Psi(\Delta_n, \Delta_t) = \min(\phi_n, \phi_t) + \left[\Gamma_n \left(1 - \frac{\Delta_n}{\delta_n}\right)^{\alpha} \left(\frac{m}{\alpha} + \frac{\Delta_n}{\delta_n}\right)^{m} + \langle \phi_n - \phi_t \rangle\right] \left[\Gamma_t \left(1 - \frac{|\Delta_t|}{\delta_t}\right)^{\beta} \left(\frac{n}{\beta} + \frac{|\Delta_t|}{\delta_t}\right)^{n} + \langle \phi_t - \phi_n \rangle\right]$$

- **Energy Constants: Γ_n and Γ_t**
- **Exponents: *m* and *n***
- **Characteristic length scales: δ_n and δ_t**
- **Shape parameters : α and β**

- **Fracture energy**
- **Cohesive strength**
- **Cohesive interaction shape**
- **Initial slope**

USNCCM10: Sunday Technical Session 10, 9:30AM, Rm D144

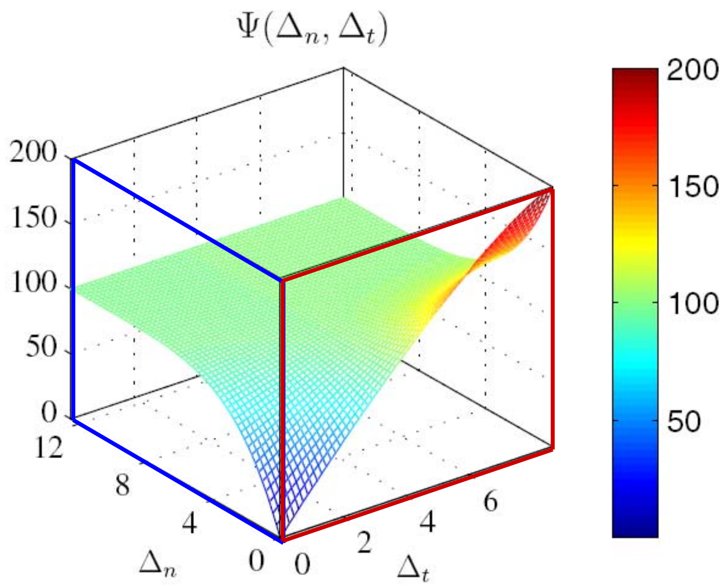
K. Park, GH. Paulino, JR. Roesler, 2008, A unified potential-based cohesive model of mixed-mode fracture, *Journal of the Mechanics and Physics of Solids* 57, 891-908.

Extension for the *EXTRINSIC* Model

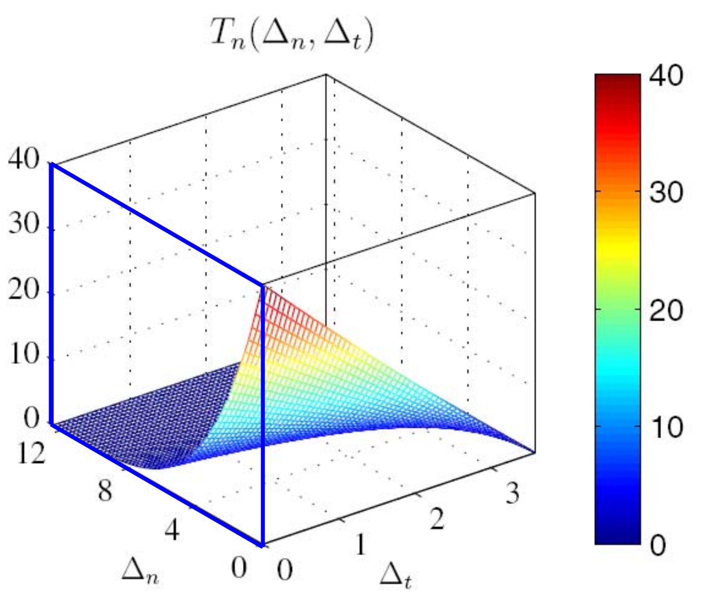
- **Correct Limit Procedure**
  - Limit of initial slope indicators in the potential

$$\Psi(\Delta_n, \Delta_t) = \min(\phi_n, \phi_t) + \left[\Gamma_n \left(1 - \frac{\Delta_n}{\delta_n}\right)^{\alpha} + \langle \phi_n - \phi_t \rangle\right] \left[\Gamma_t \left(1 - \frac{|\Delta_t|}{\delta_t}\right)^{\beta} + \langle \phi_t - \phi_n \rangle\right]$$

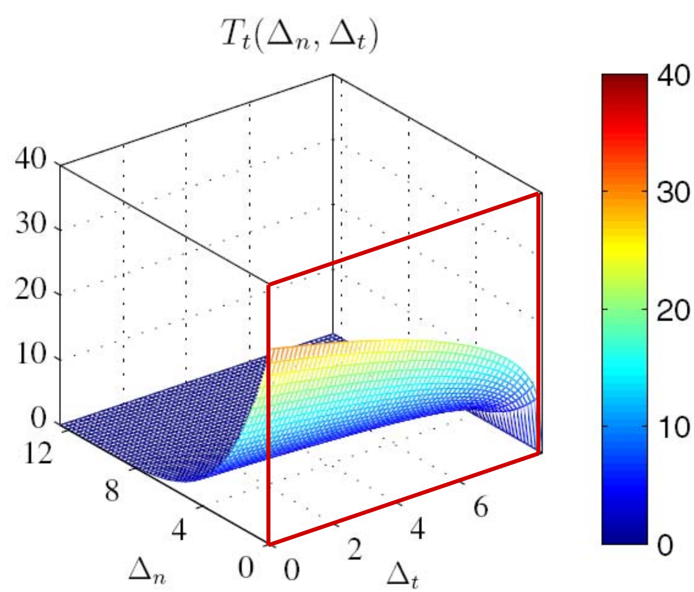
  - Energy constants: Γ_n and Γ_t
  - Characteristic length scales: δ_n and δ_t
  - Shape parameters: α and β
- **Exclude elastic behavior → Extrinsic model**
- **Consider different fracture energy:** ϕ_n, ϕ_t
- **Describe different cohesive strength:** σ_{max}, τ_{max}
- **Represent various cohesive shape:** α, β



$\phi_n = 100\,N/m$	$\phi_t = 200\,N/m$
$\sigma_{\max} = 40\,MPa$	$\tau_{\max} = 30\,MPa$
$\alpha = 5$	$\beta = 1.3$



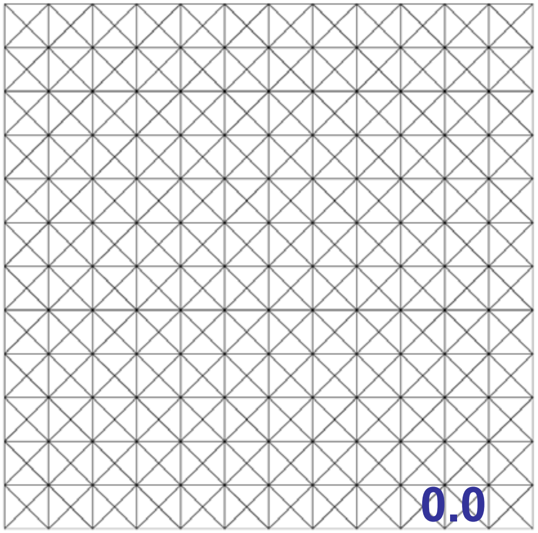
Mode I

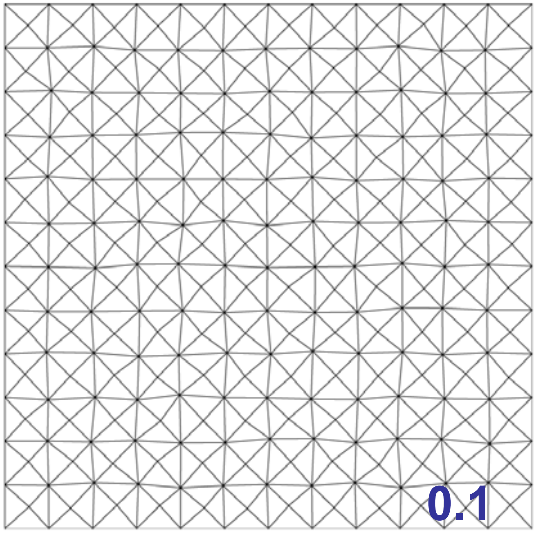


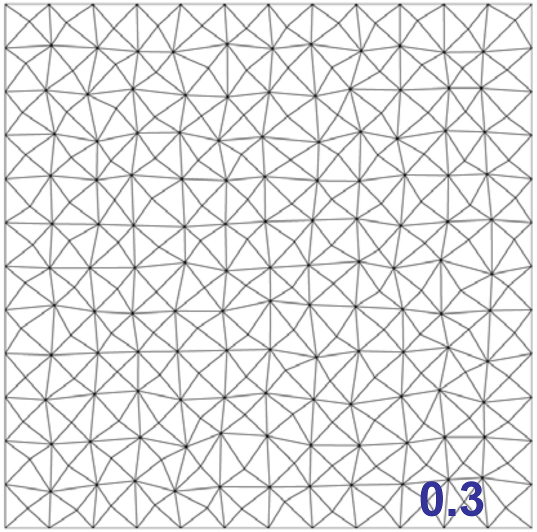
Mode II

Topological Operators

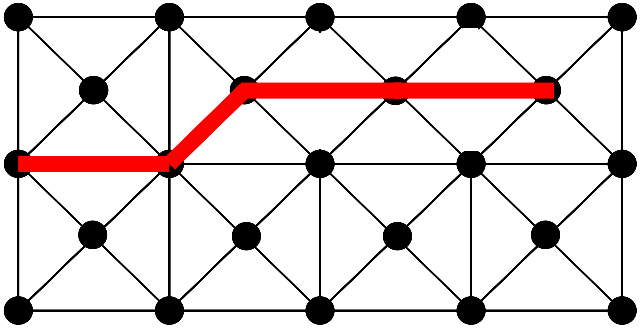
- Nodal Perturbation





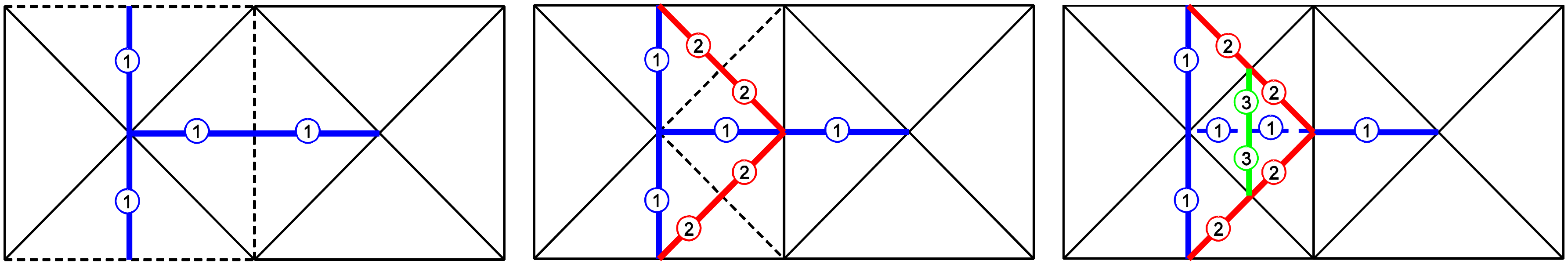


- Edge-Swap

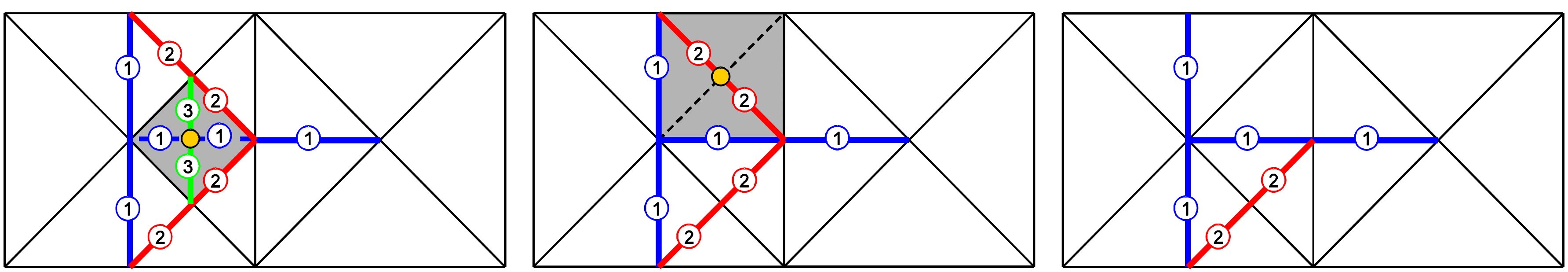


Topological Operators

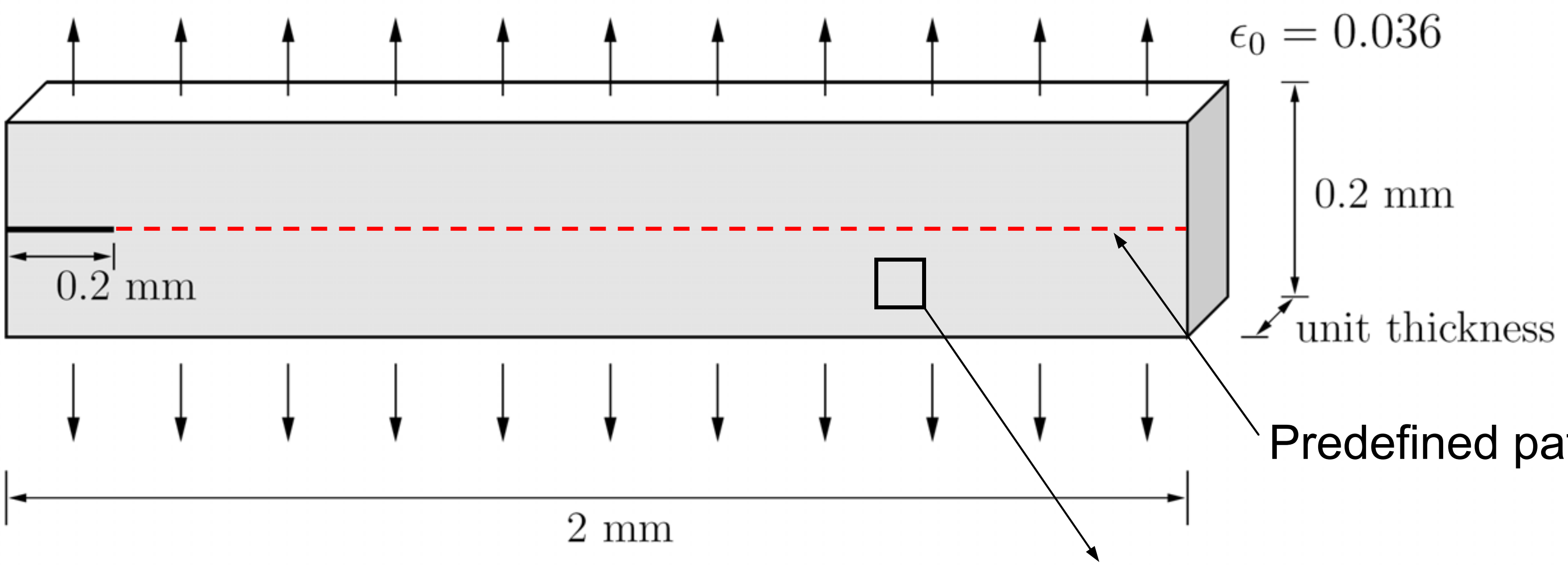
- **Edge-Split**
  - Adaptive mesh refinement based on *a priori* knowledge



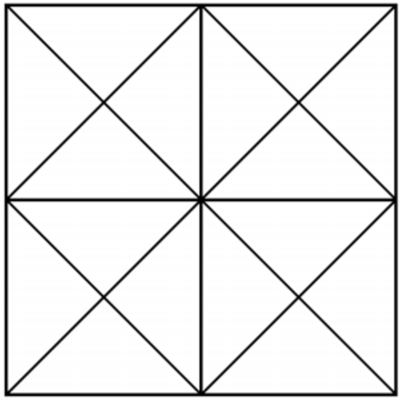
- **Vertex-Removal (or Edge-Collapse)**
  - Adaptive mesh coarsening based on *a posteriori* error estimation, i.e. root mean square of strain error



Mode I Pre-defined Crack Propagation



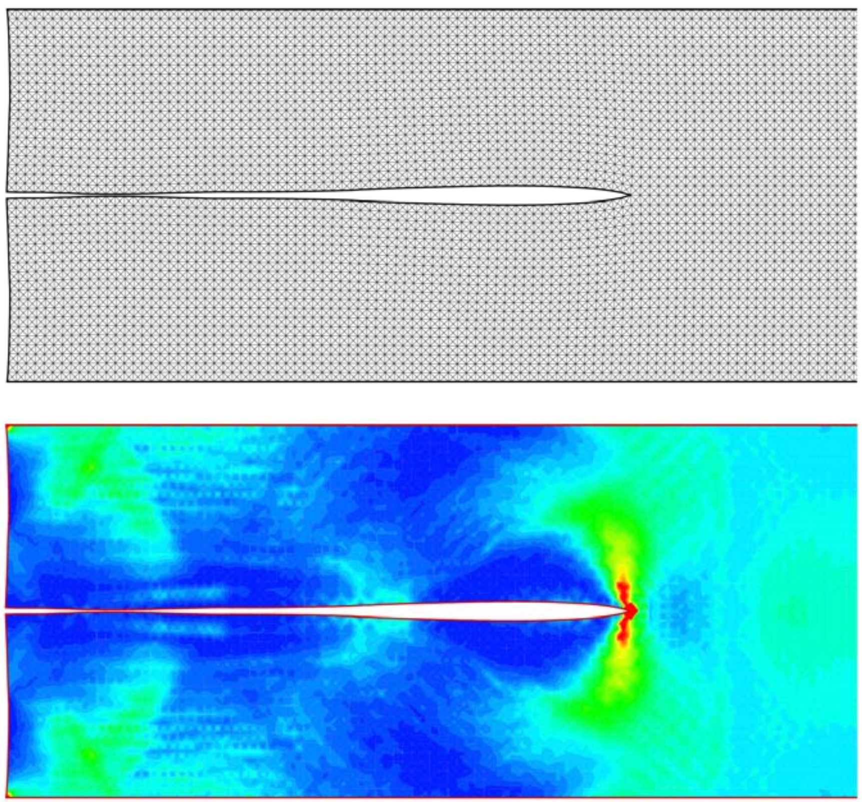
E	v	ρ	G_I	T_{max}
3.24 GPa	0.35	1190 kg/m³	352 N/m	324 MPa

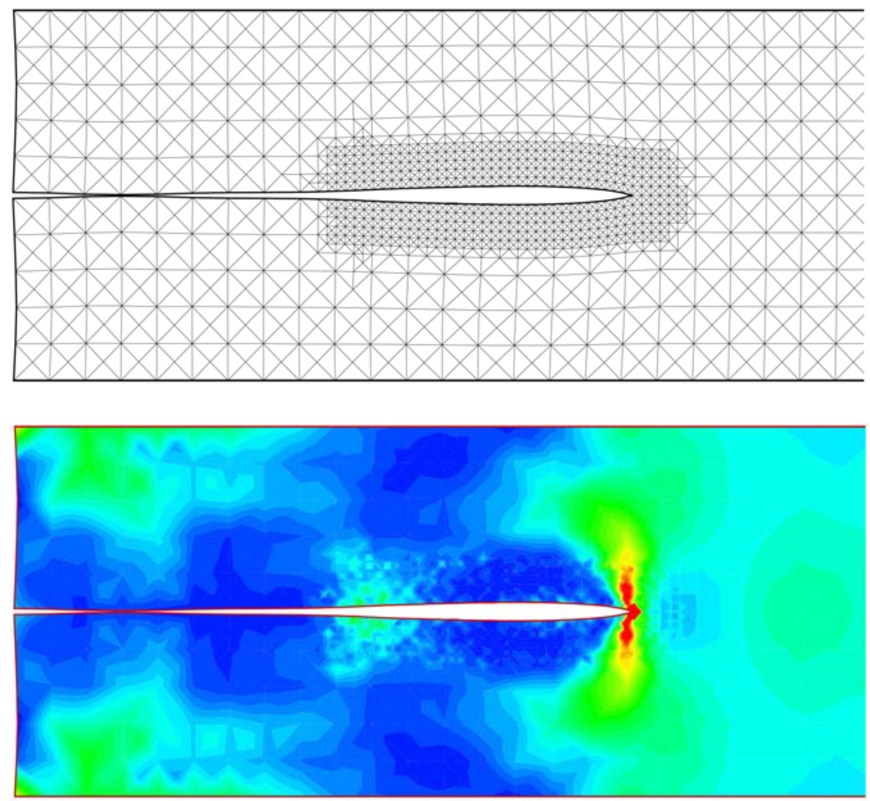


4k mesh

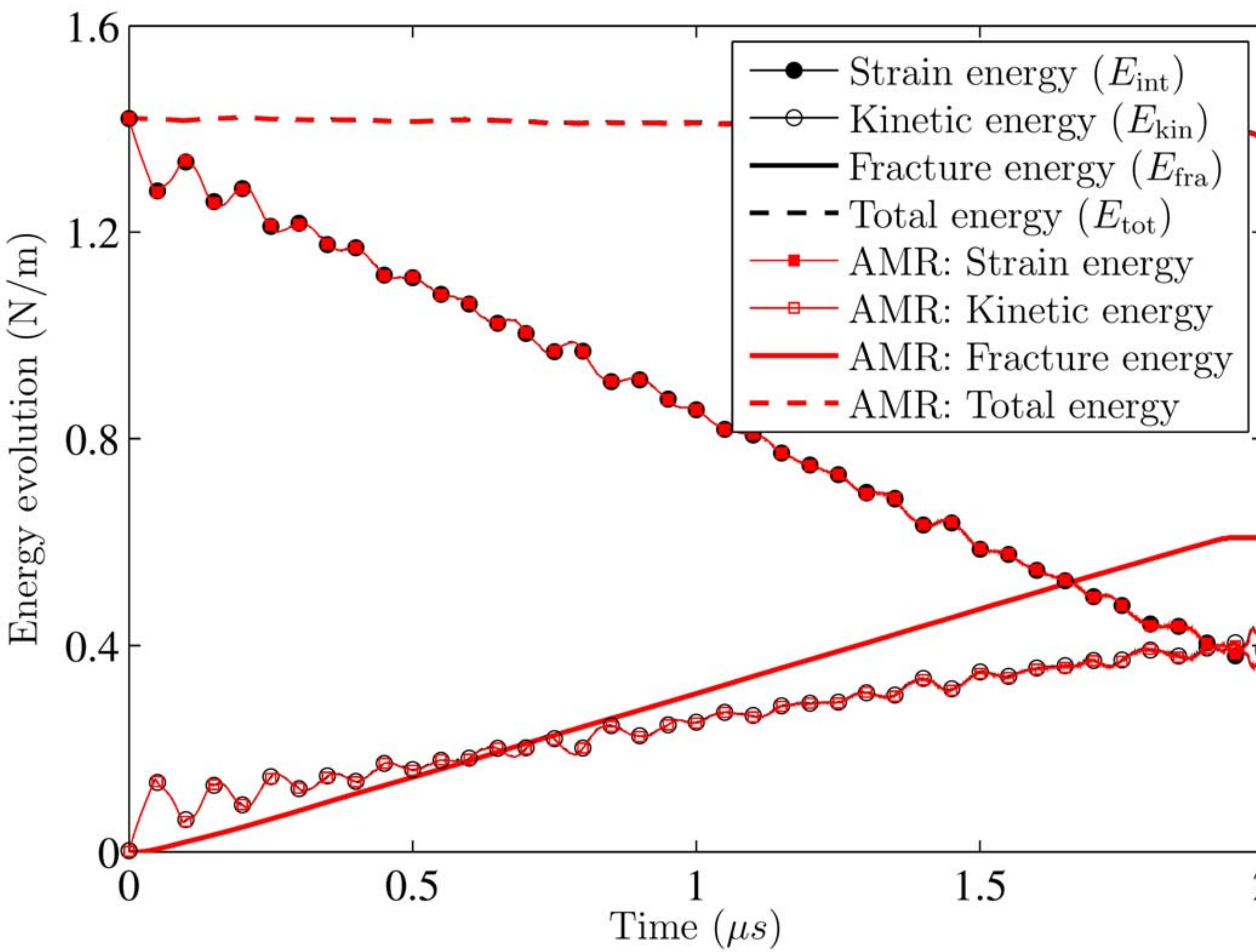
Computational Results

- **Uniform Mesh Refinement**
  - 400x40 mesh grid
  - Element size: 5μm
  - 64000 elements, 128881 nodes
- **Adaptive Mesh Refinement**
  - 100x10 mesh grid
  - Element size: 20~5μm
  - 4448 elements, 9147 nodes

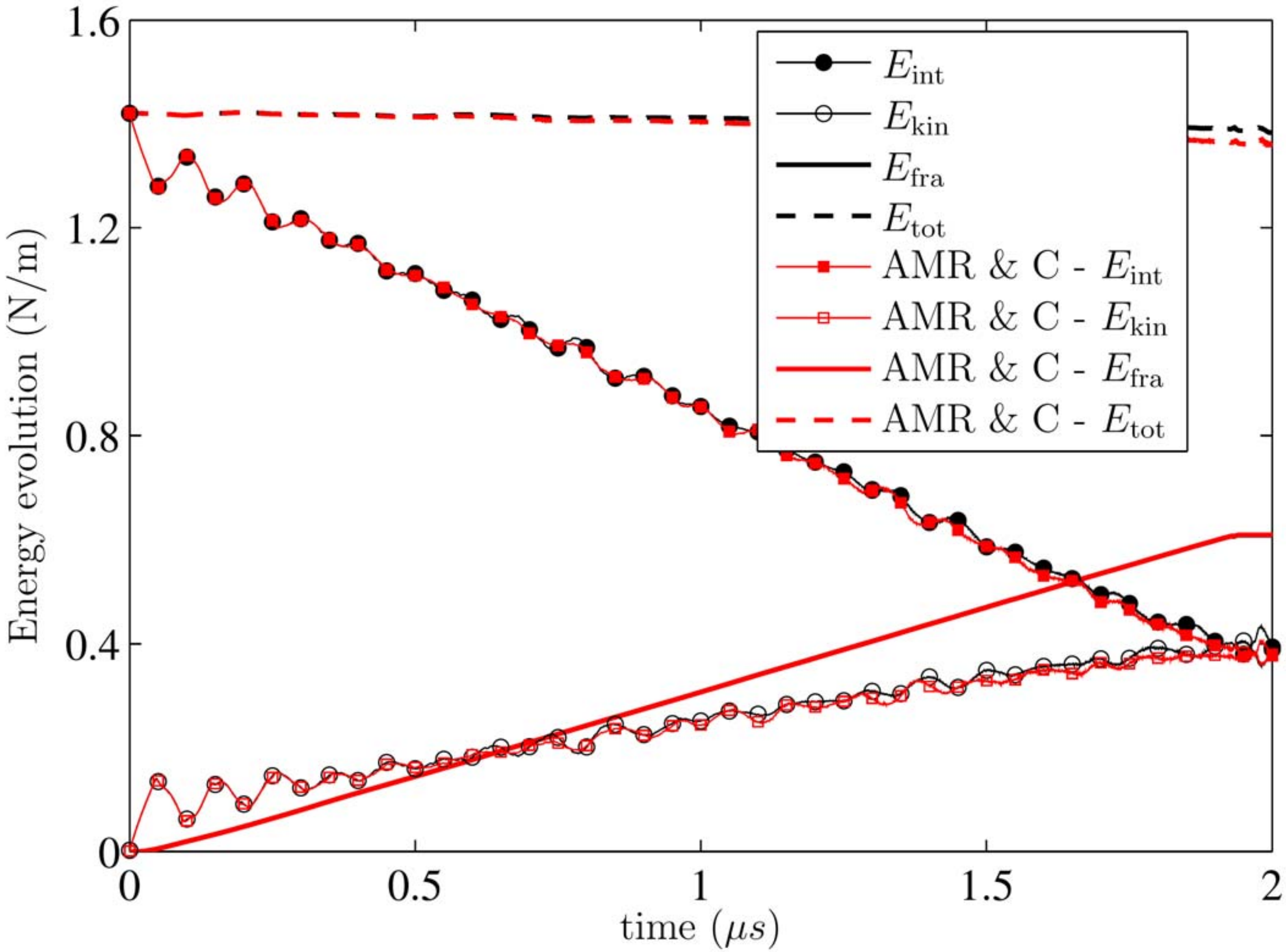




Computational Results (AMR)

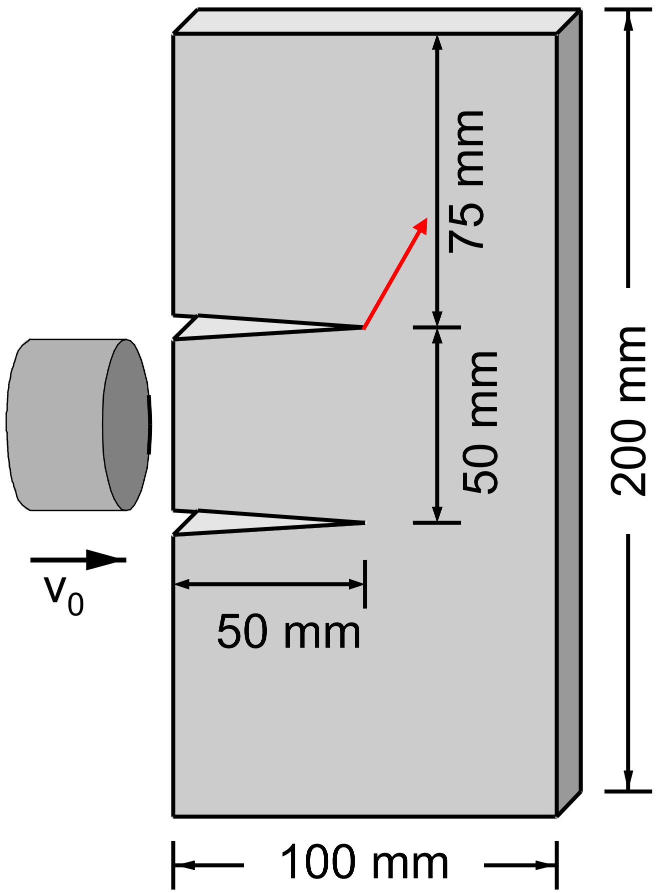


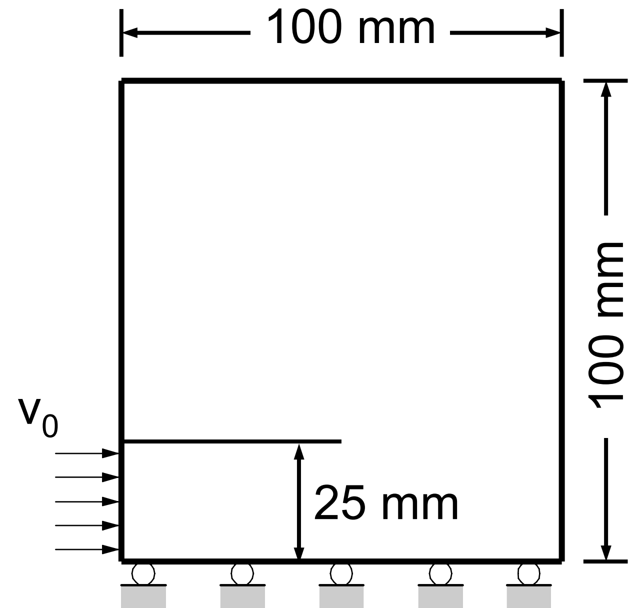
Computational Results (AMR+C)



Mixed-Mode Crack Propagation

▫ Kalthoff-Winkler's Experiments

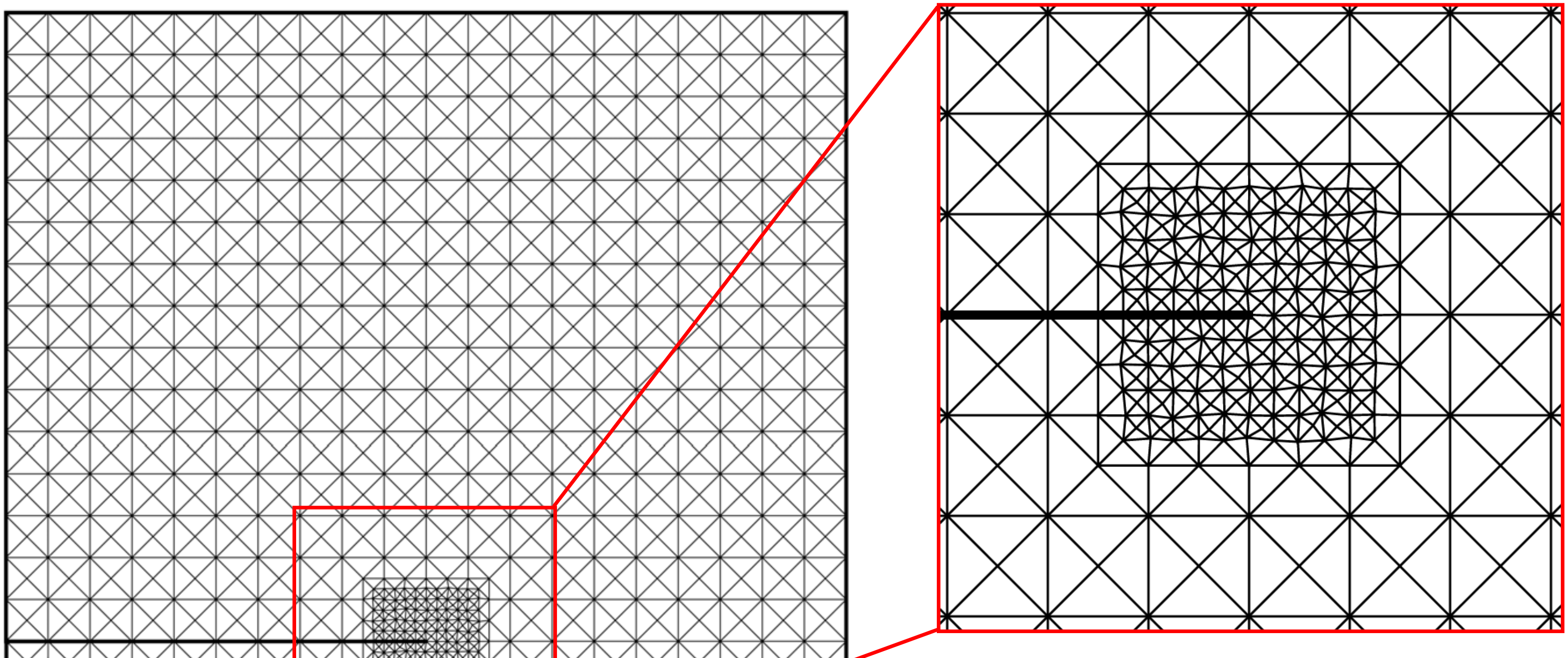


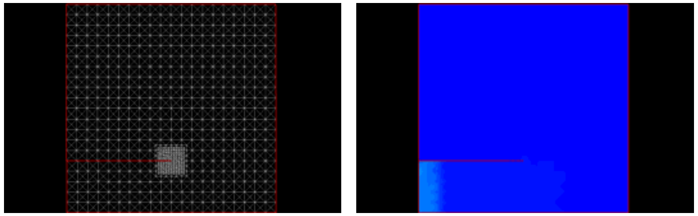


Kalthoff, J. F., Winkler, S., 1987. Failure mode transition at high rates of shear loading. International Conference on Impact Loading and Dynamic Behavior of Materials 1, 185–195.

Finite Element Mesh

- **Initial Discretization**

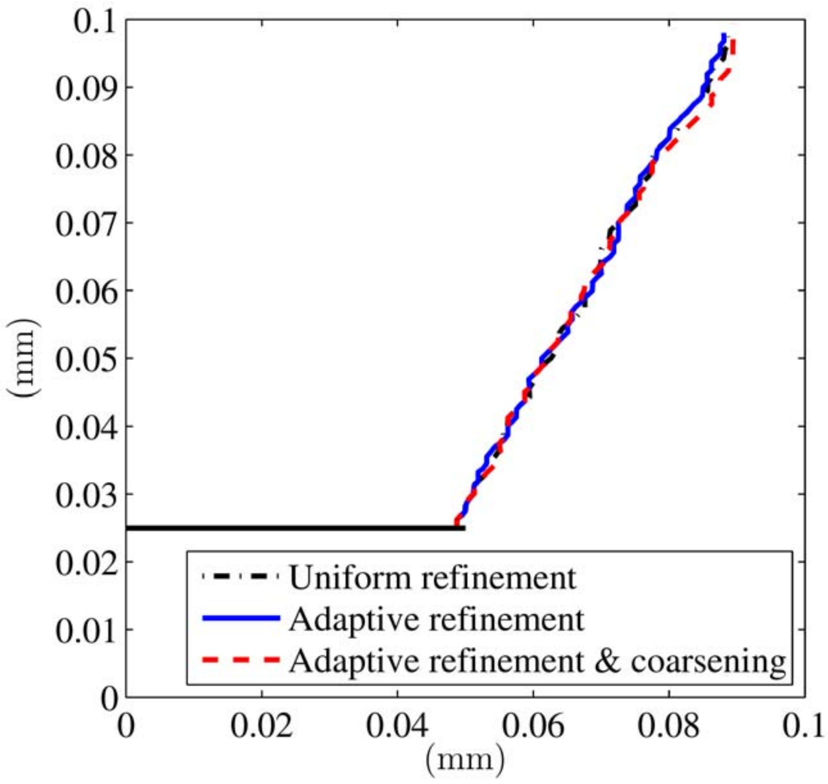




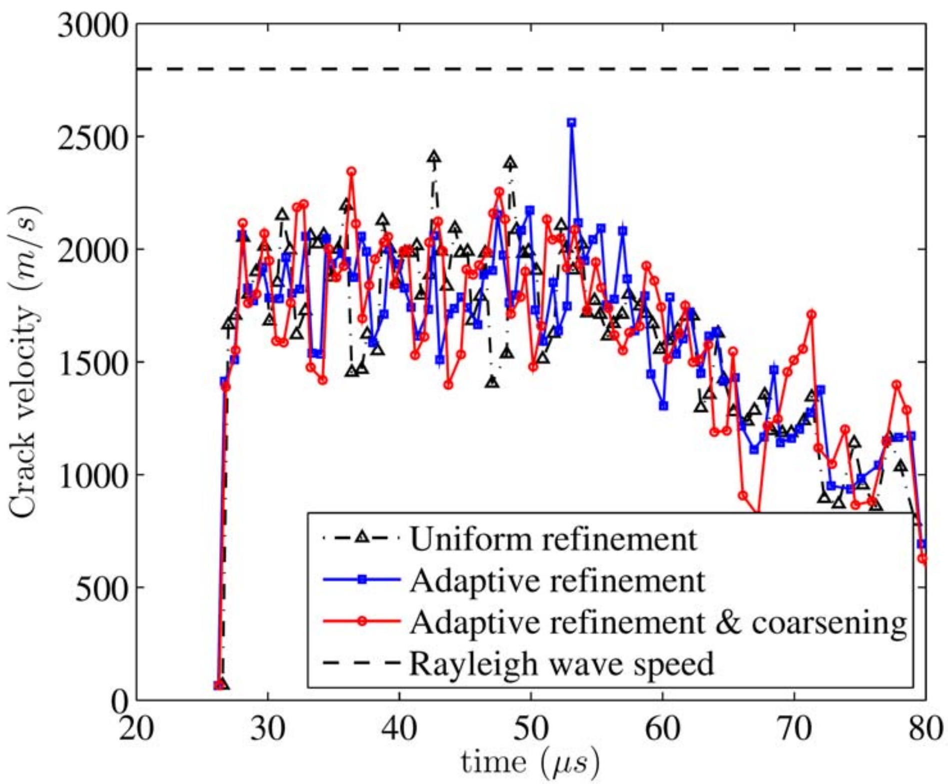
Animations (FE Mesh & Strain energy)

Computational Results

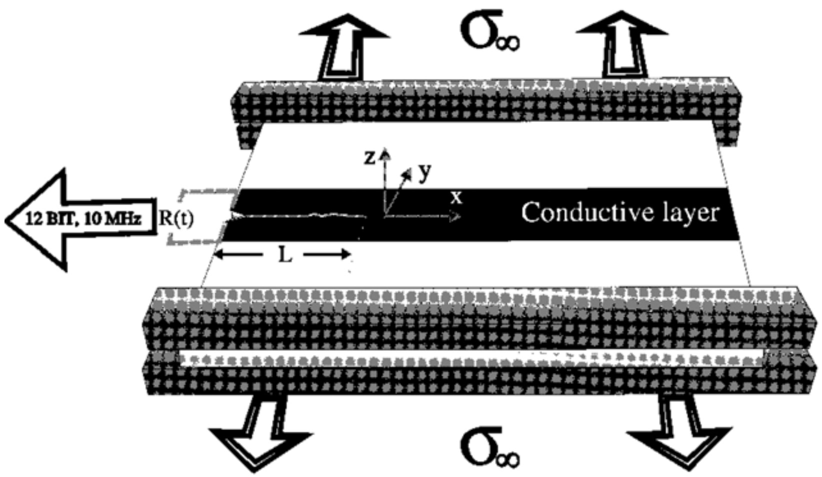
- Crack Path



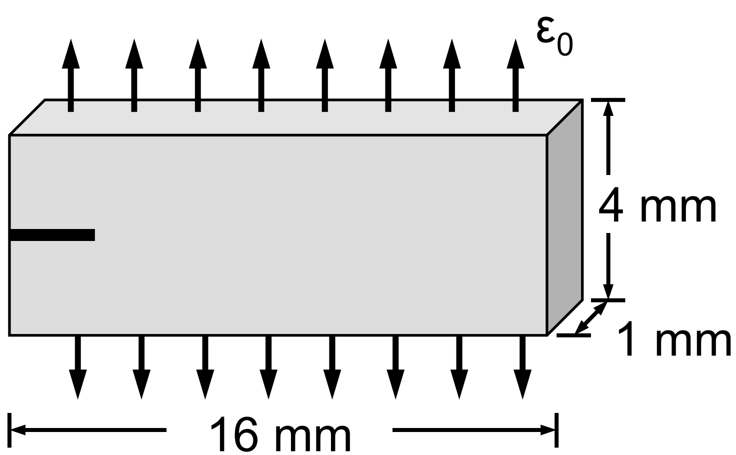
- Crack Velocity

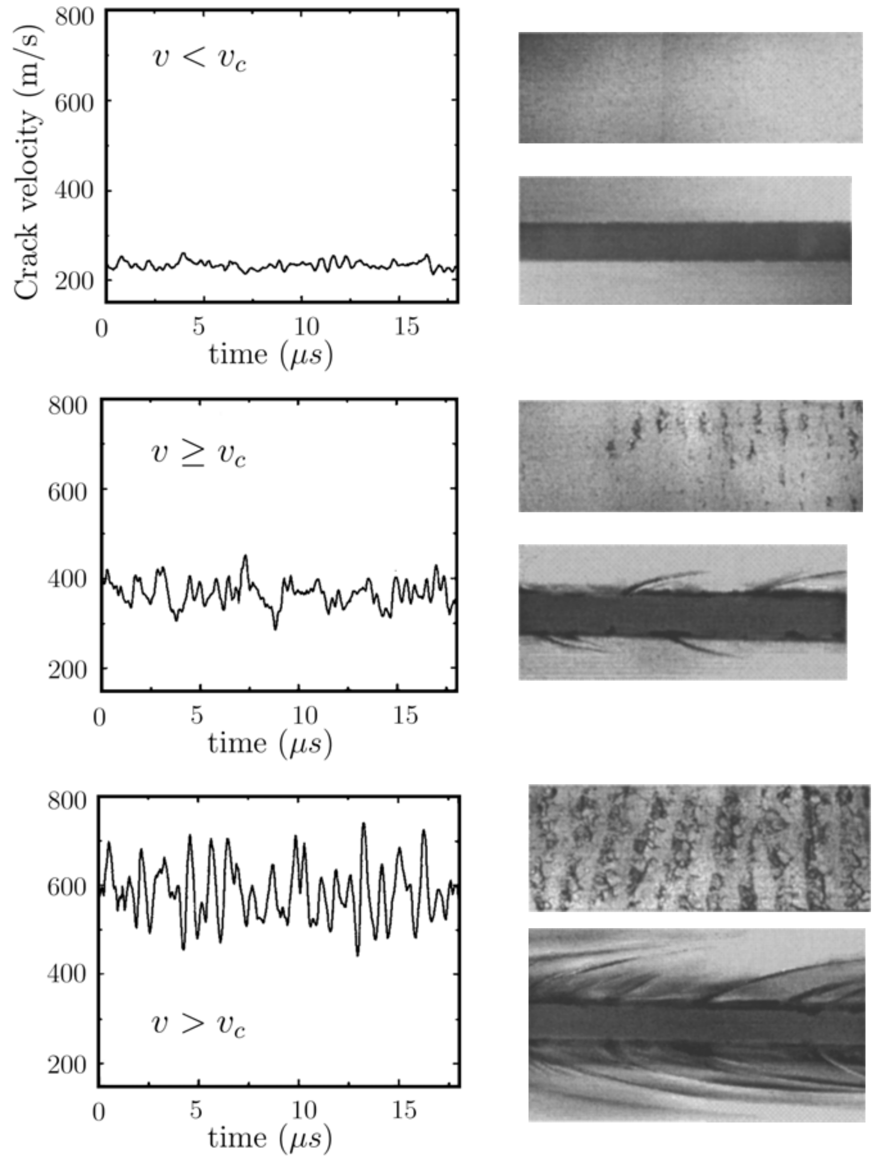


Micro-Branching Experiment

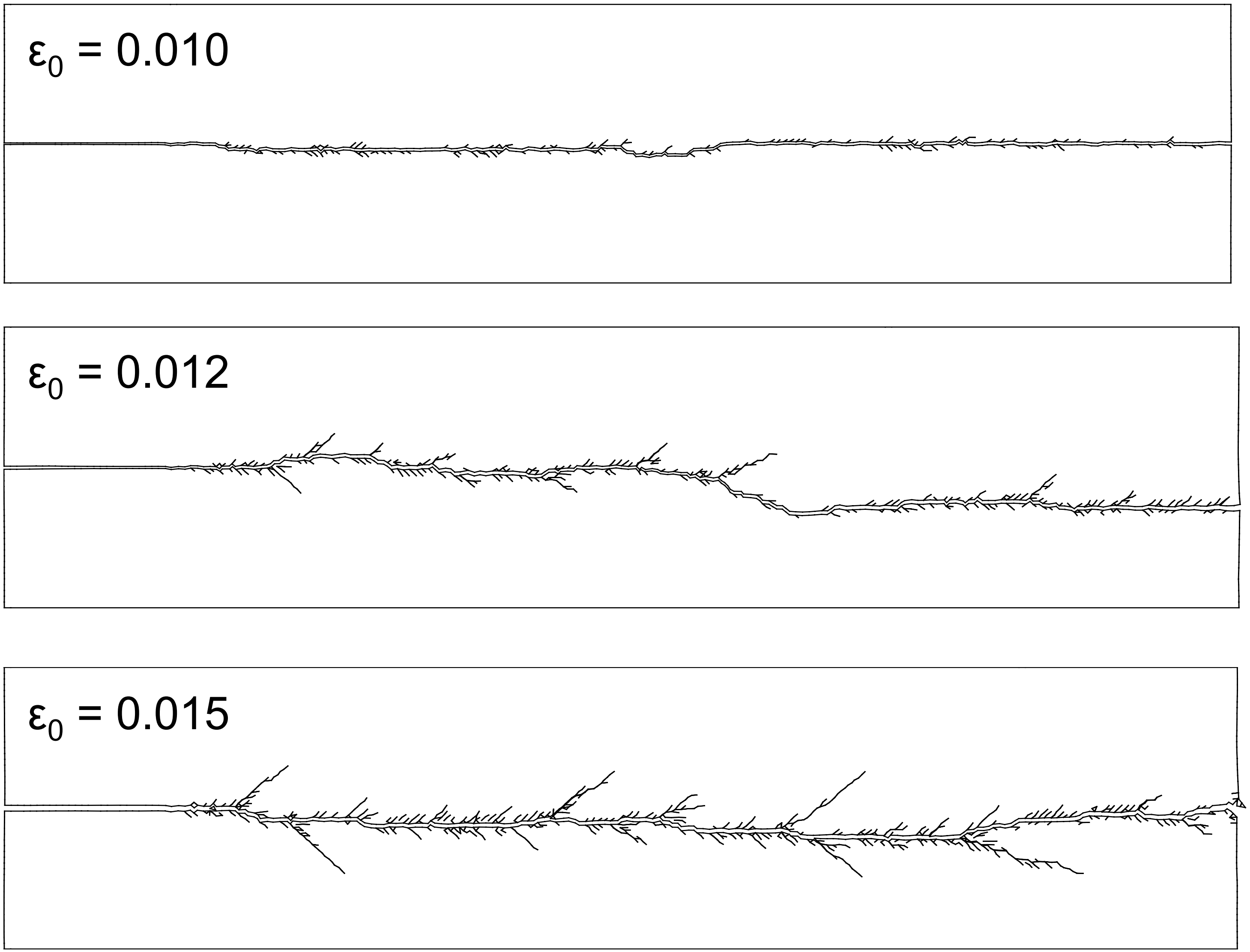


Sharon E, Fineberg J. Microbranching instability and the dynamic fracture of brittle materials. Physical Review B 1996; 54(10):7128–7139.



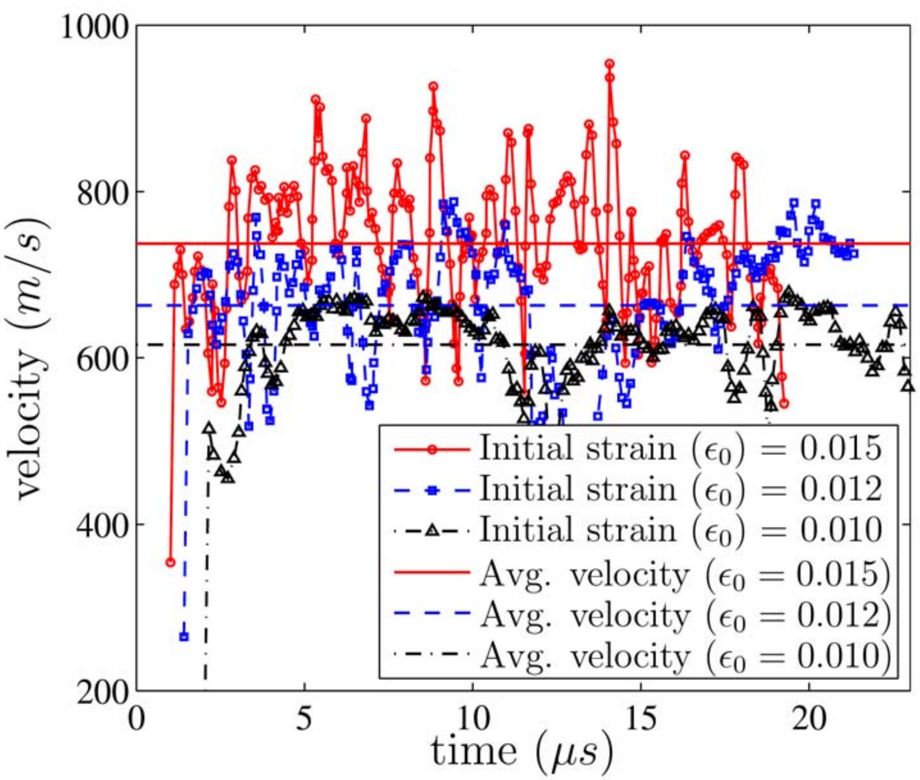


Computational Results

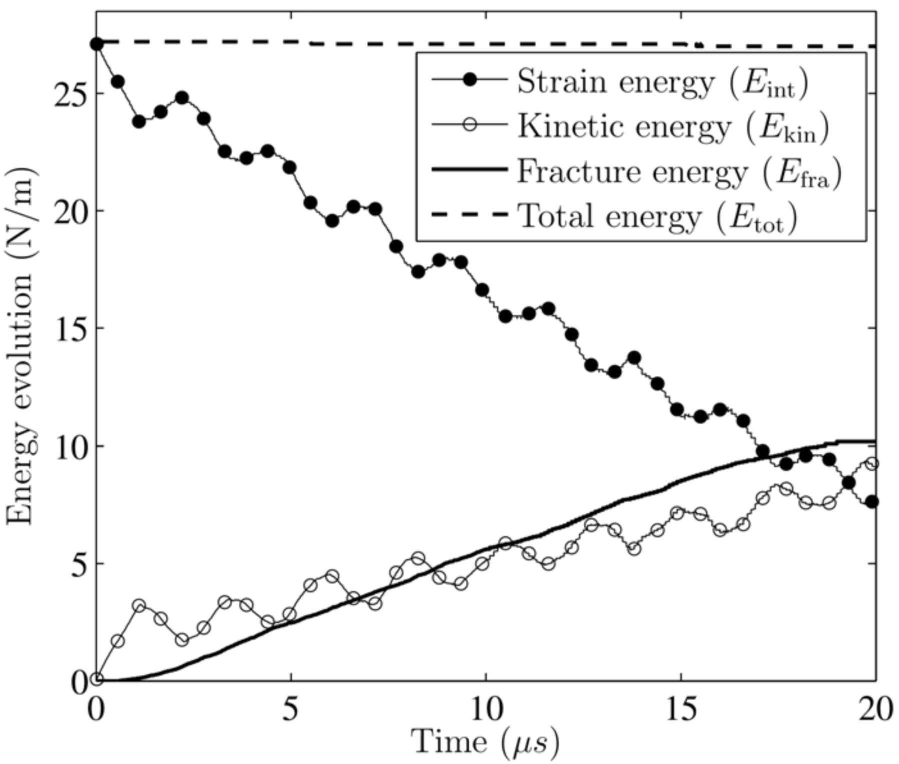


Computational Results

- Crack Velocity



- Energy Evolution (ε_0=0.015)



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Summary

- **The potential-based constitutive model**
- **Adaptive operators**
  - Nodal perturbation, Edge-swap
  - Edge-split, Vertex-removal
- **Effective and efficient computational framework to simulate physical phenomena associated with fracture.**
- **The computational results of the adaptive mesh refinement and coarsening is consistent with the results of the uniform mesh refinement.**

Thank you for your attention !