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Effect of Fracture Toughness Testing Geometry on Opening Style: Implications for Subsurface Crack Propagation

Alex Rinehart

E&ES (NMT) and Geomechanics (SNL)

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New Mexico Tech
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Acknowledgements

Co-authors
Thomas Dewers and Joseph Bishop

Laboratory Collaborators
Alex Urquhart, Scott Broome and Greg Flint

Advisor
Glenn Spinelli

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To Begin....

Mechanical strength of Lower Tuscaloosa Injection Horizon at CO2 injection reservoir conditions.

Effect of fracture toughness testing geometry on opening style.

Automatic overlapping phase arrival picker: Picking P&S waves from acoustic emissions.

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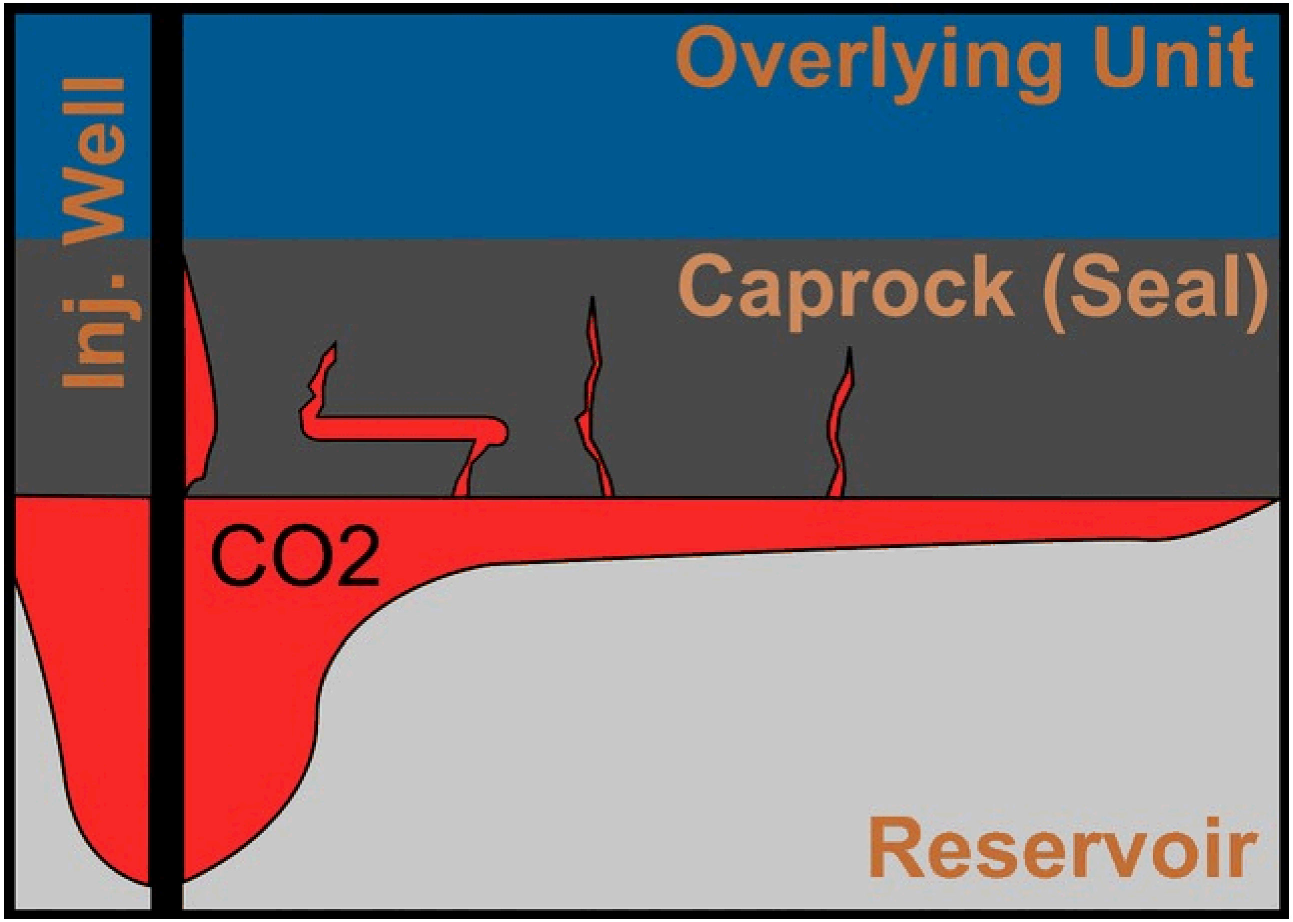
Why Care About Fractures?

Fractures are a fast flow path in tight rocks.



Subsurface CO2 storage leakage pathway.

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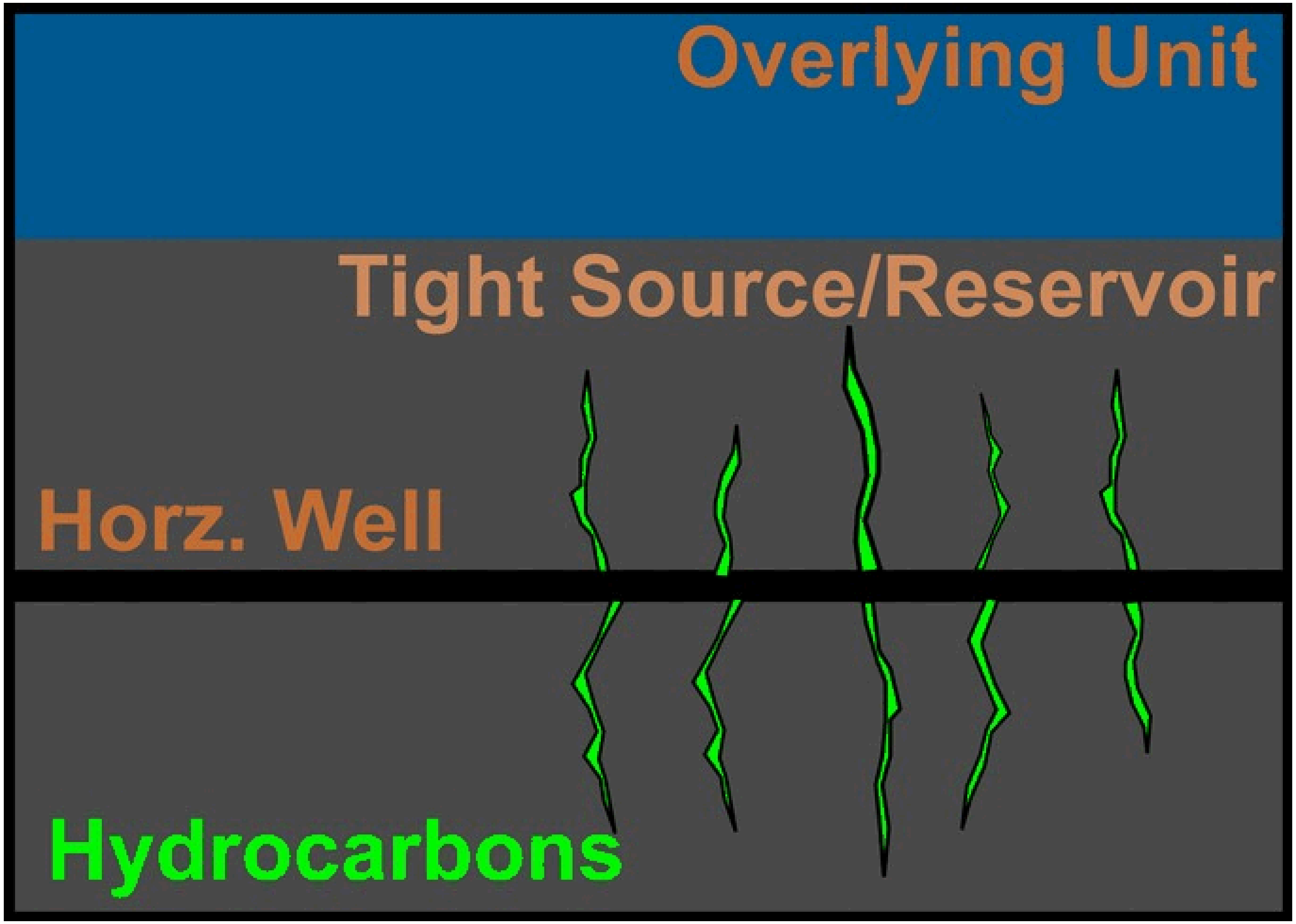
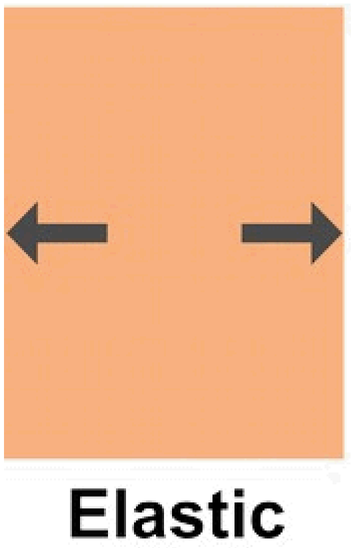
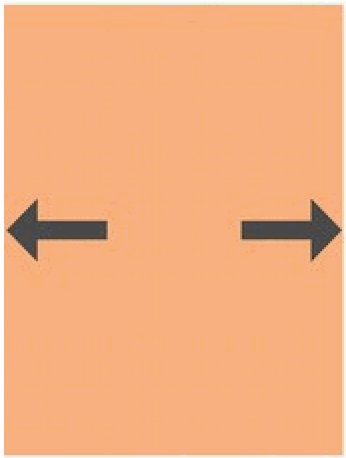


Natural Gas Release in Shales

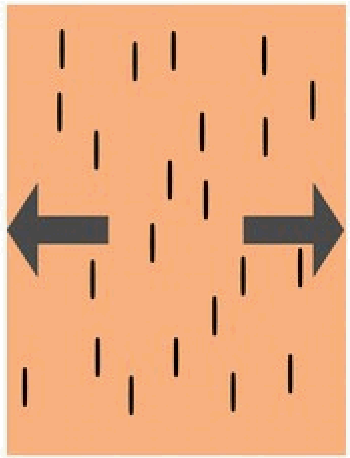
Fractures Defined



Fractures Defined

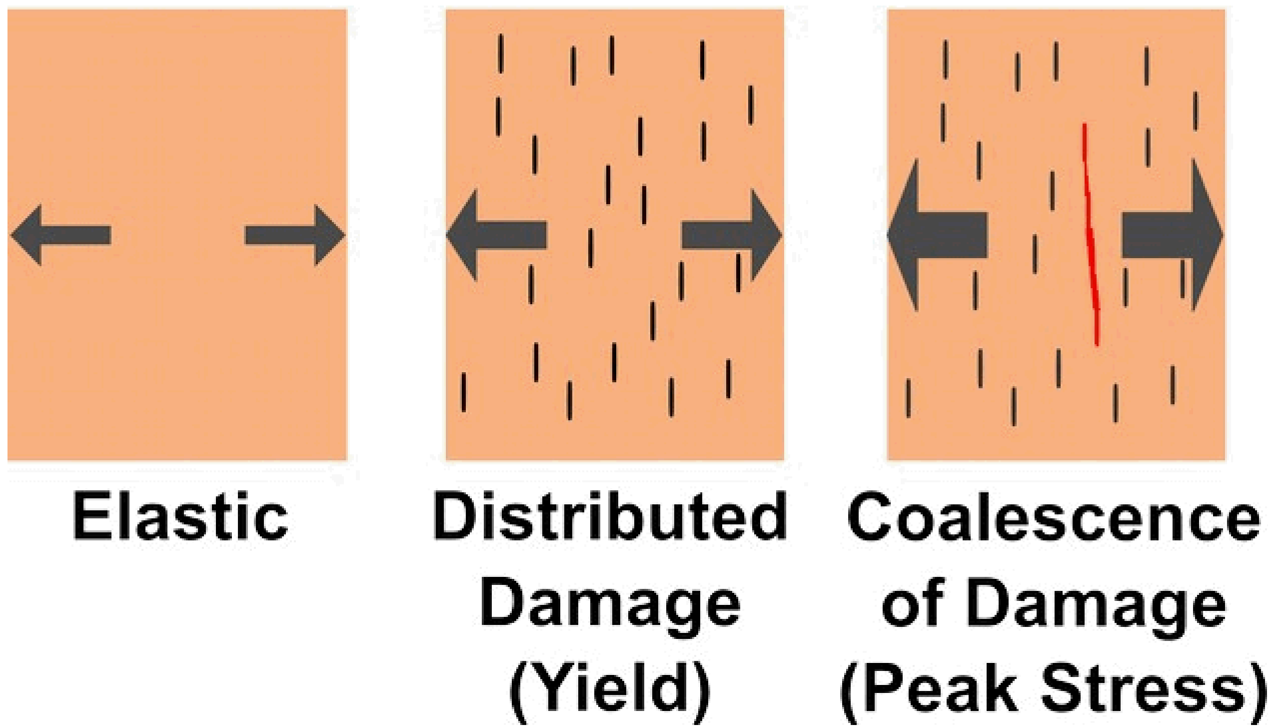


Elastic

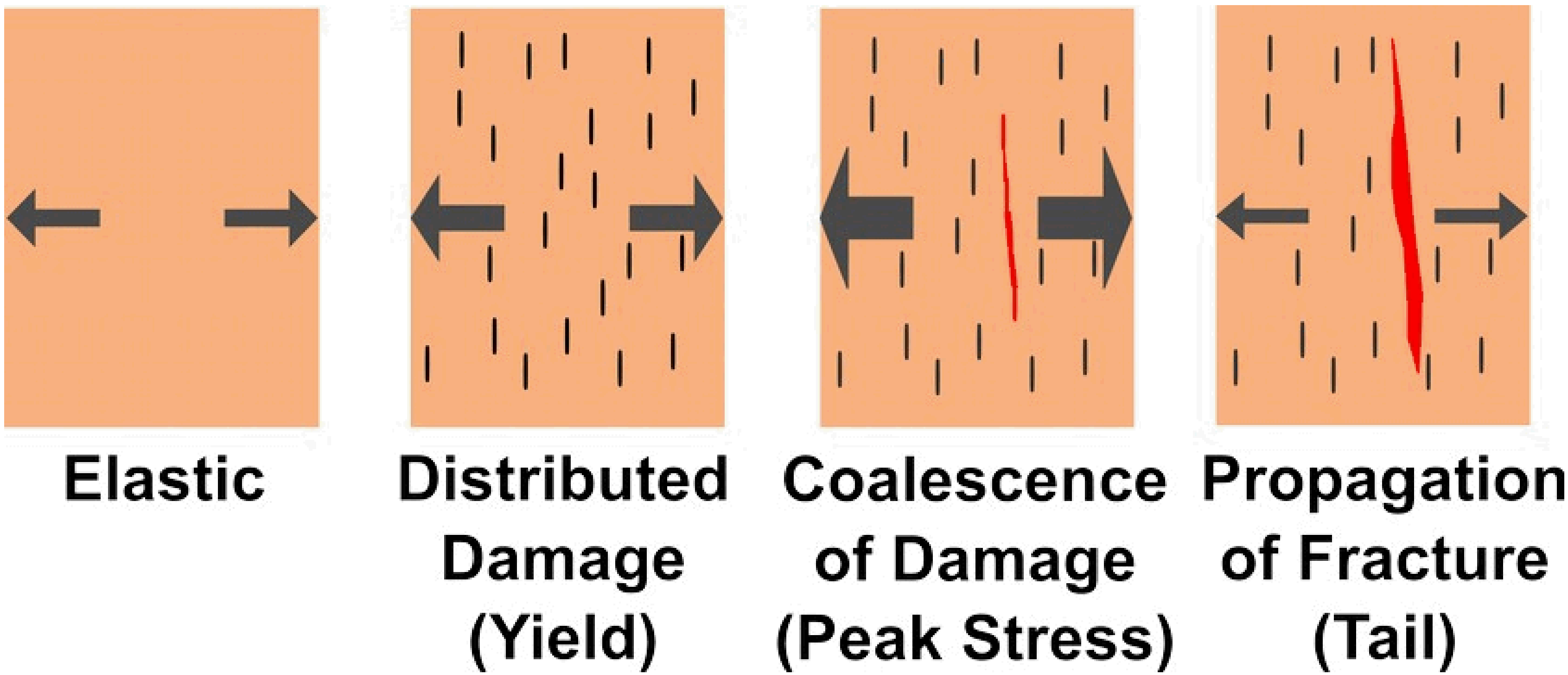


Distributed Damage (Yield)

Fractures Defined

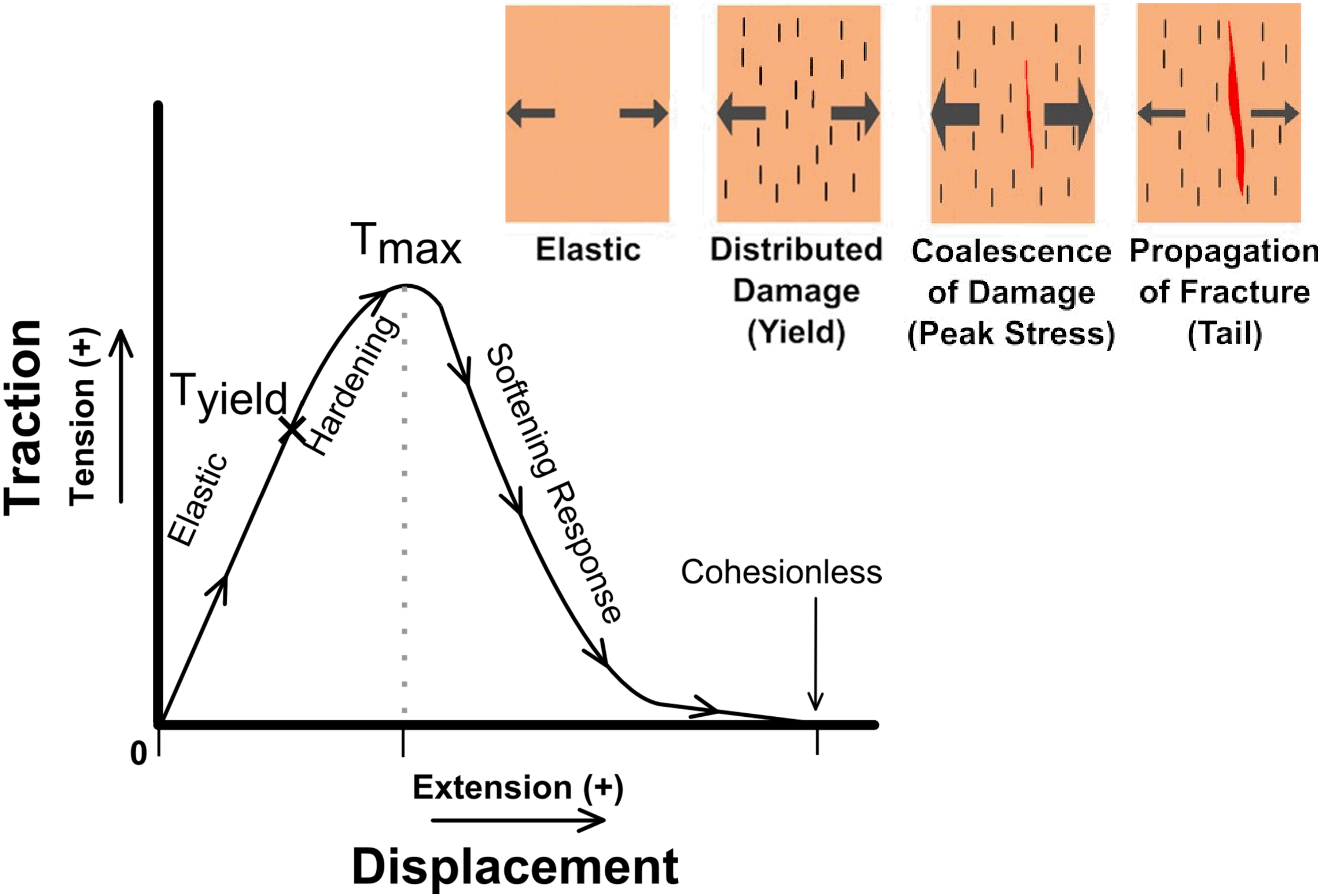


Fractures Defined

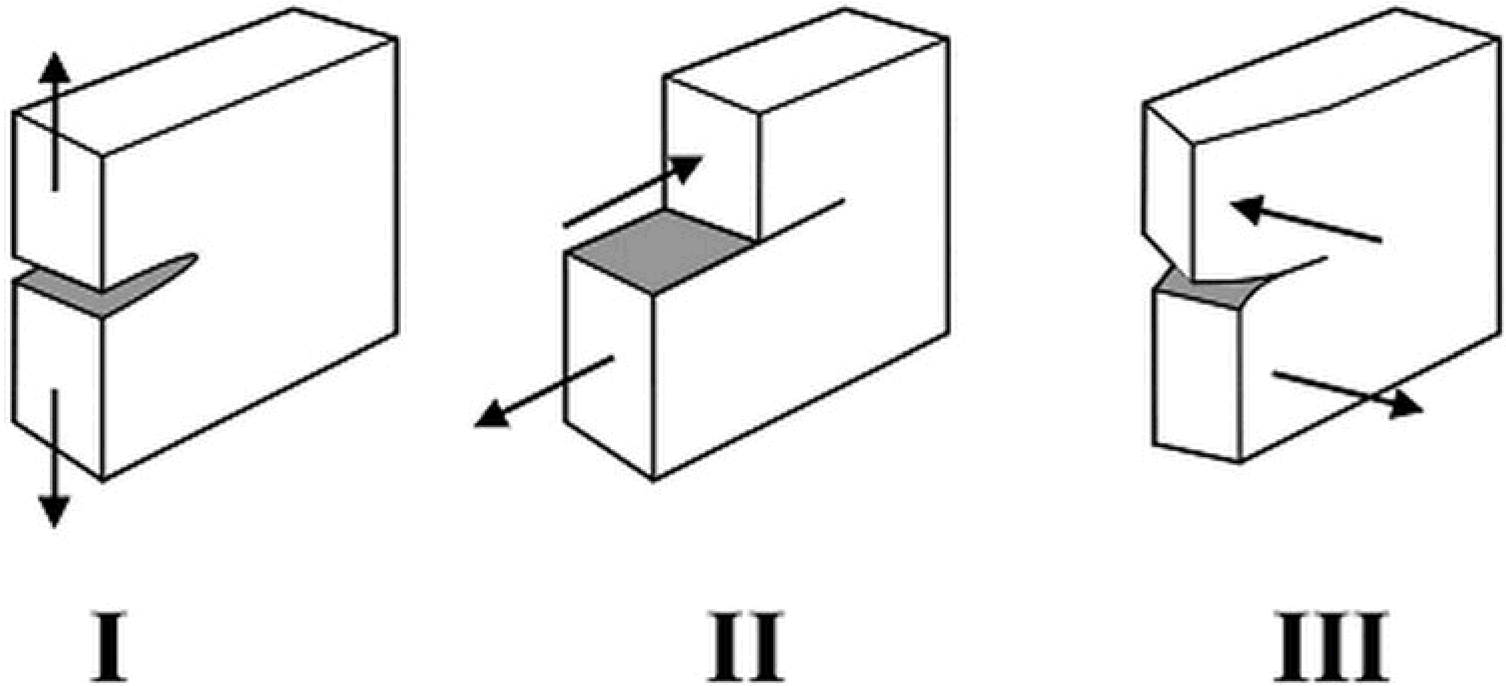


The coalescence of damage into a single roughly planar opening with limited surrounding damage.

Fractures Defined



Modes: Opening vs. Shear



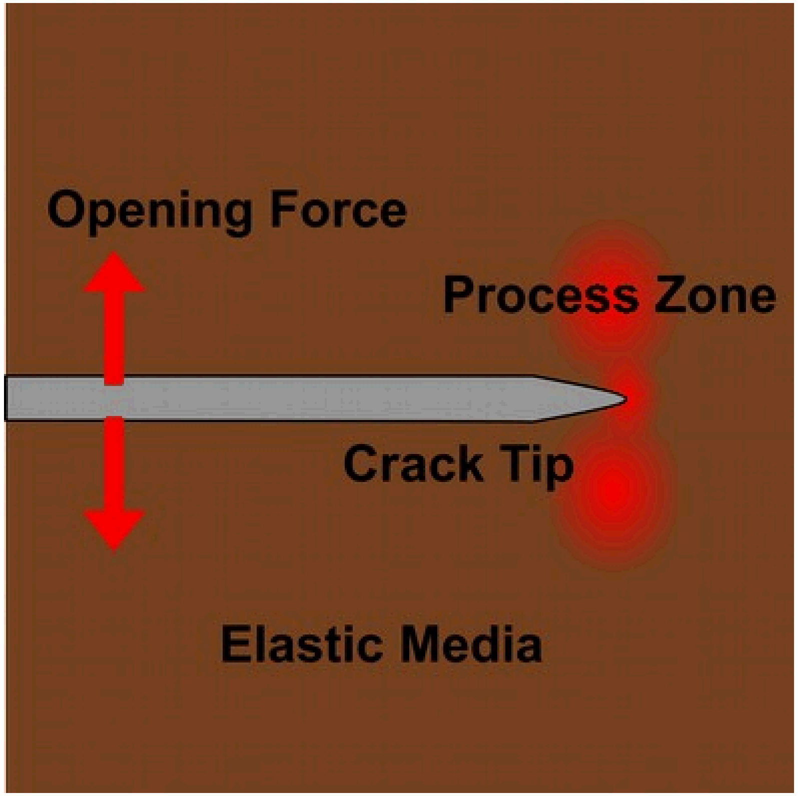
Opening

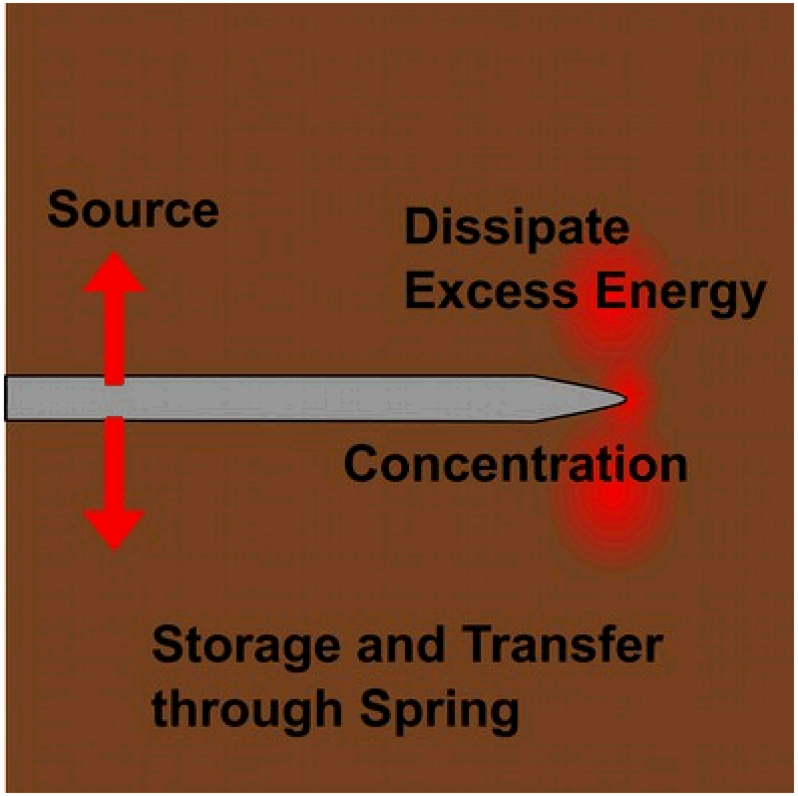
Shear

For rocks, shear mode is often to 5x stronger than opening mode

http://www.doitpoms.ac.uk/tlplib/brittle_fracture/same.php

The Parts of a Fracture

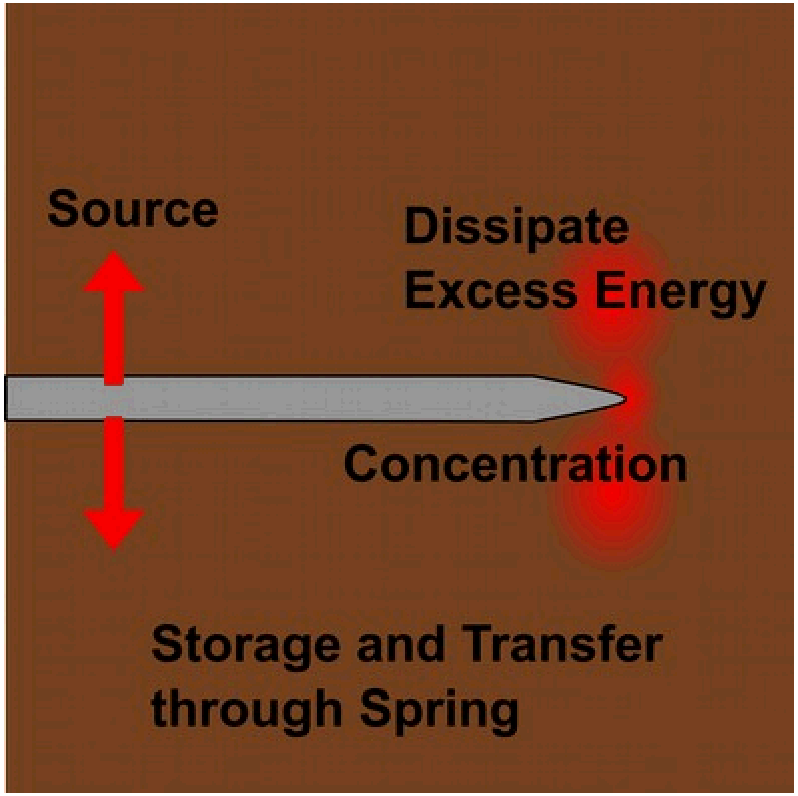




The Energy Balance

Softer the spring, the more displacement needed to get enough force (energy) to propagate fracture.

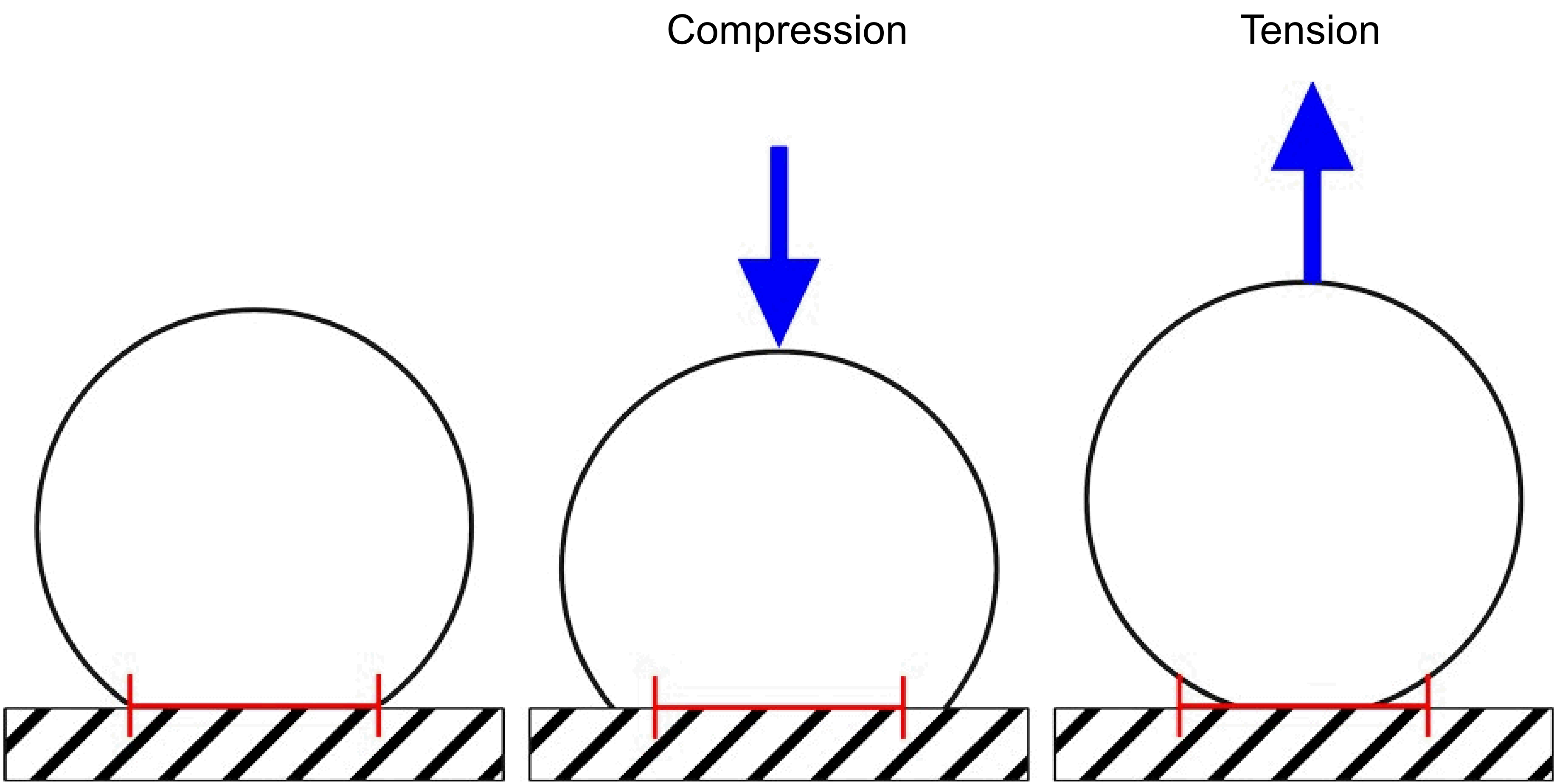
'Spring compliance' controlled by inherent material properties and tension/compression stress state.



Magnitude of excess energy controlled by fracture mode:

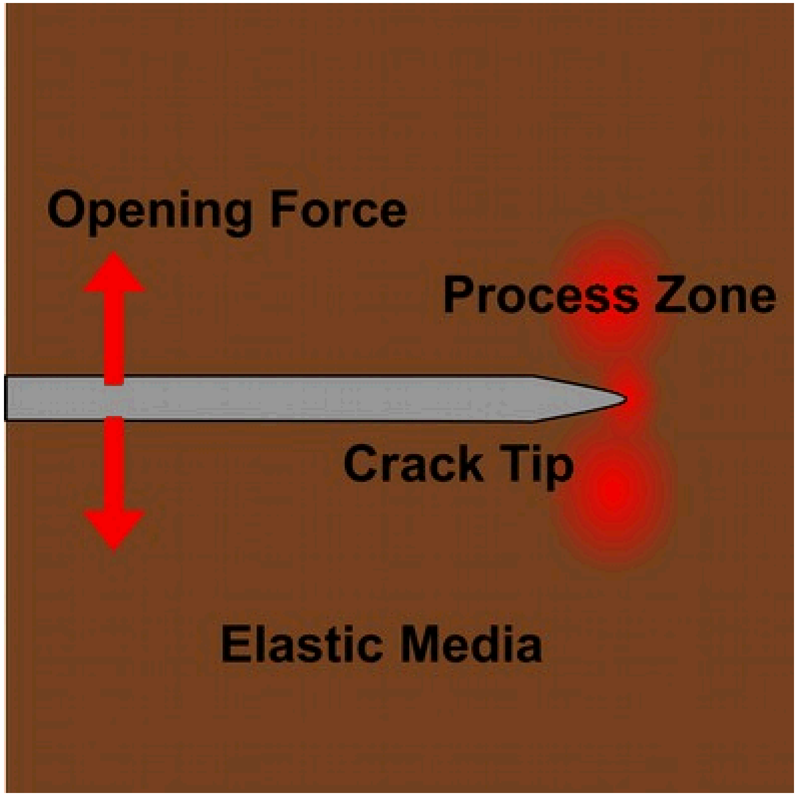
Shear Strength > Opening Strength

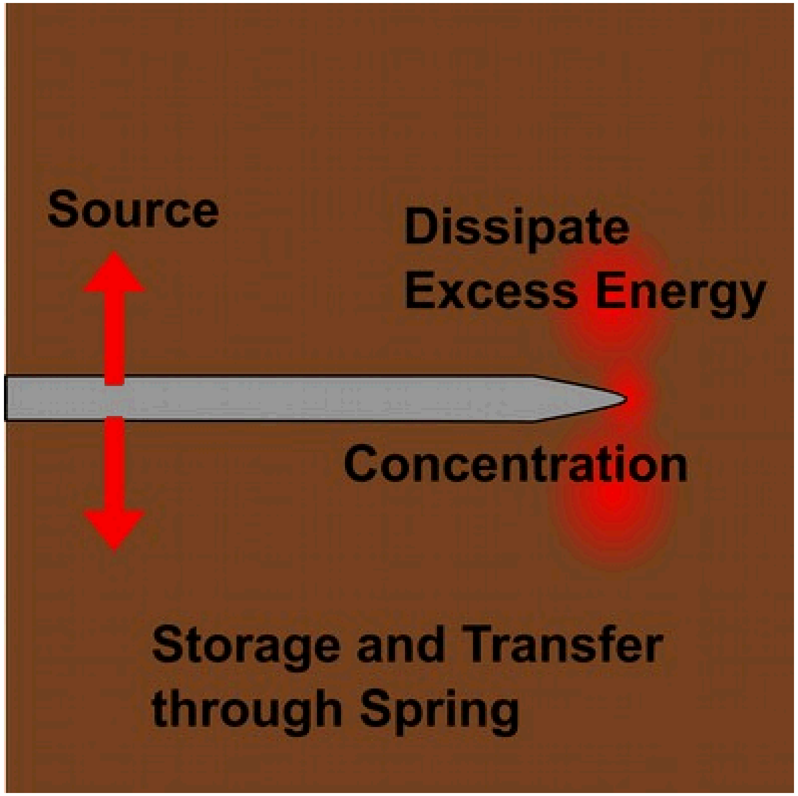
Tension vs. Compression



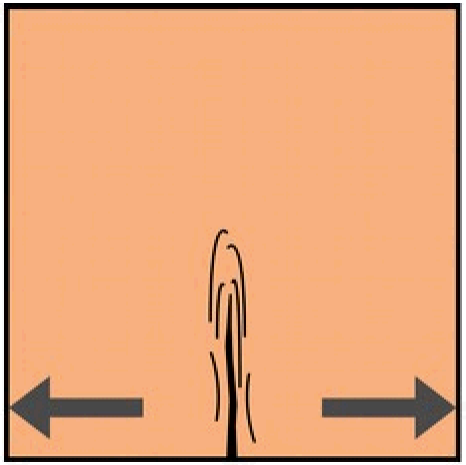
Both b/c of pores closing and grain contacts, elastic modulii are less stiff in tension than in compression.

The Parts of a Fracture

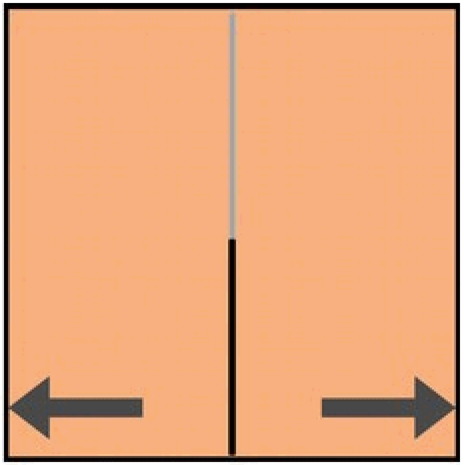




Cohesive Fracture Approach



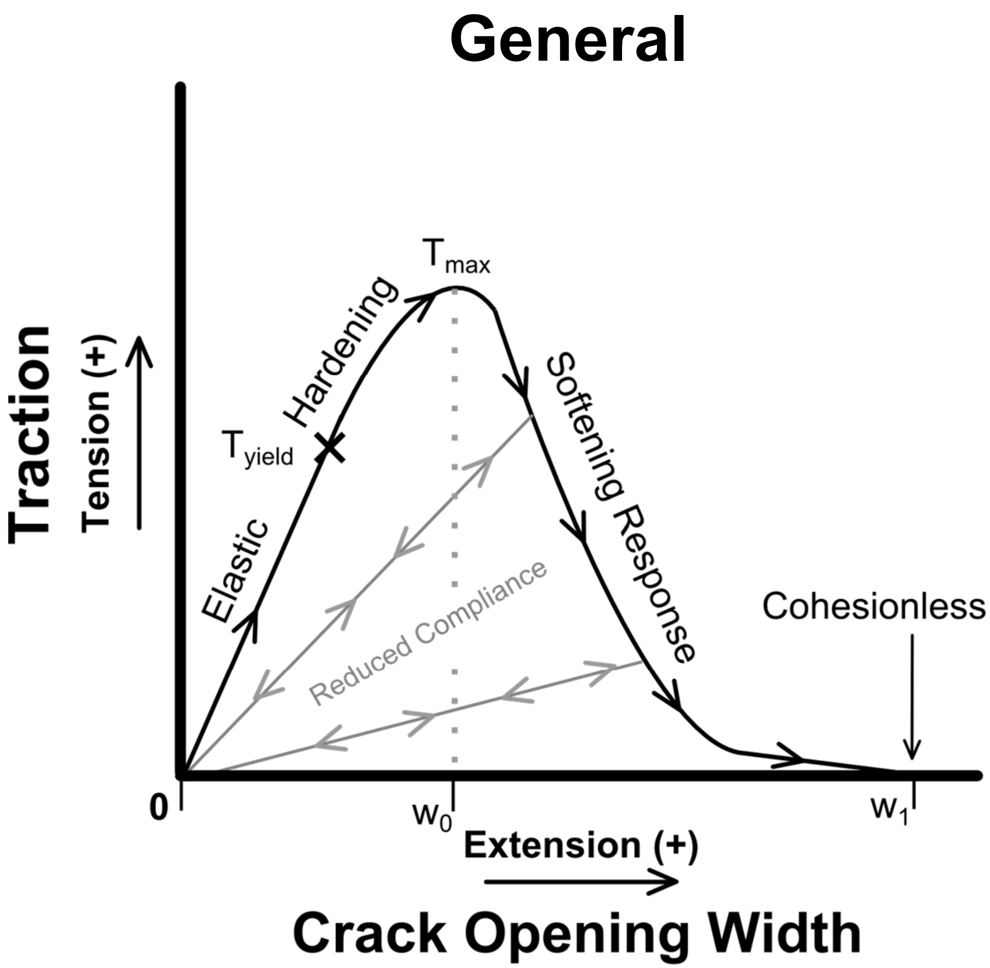
'Real' Fracture w/ Distributed Damage and Complex Geometry



Cohesive Fracture w/ Finite Defined Zone of Damage

Cohesive fracture lumps all inelastic deformation into thin finite zone.

Cohesive Fracture Approach



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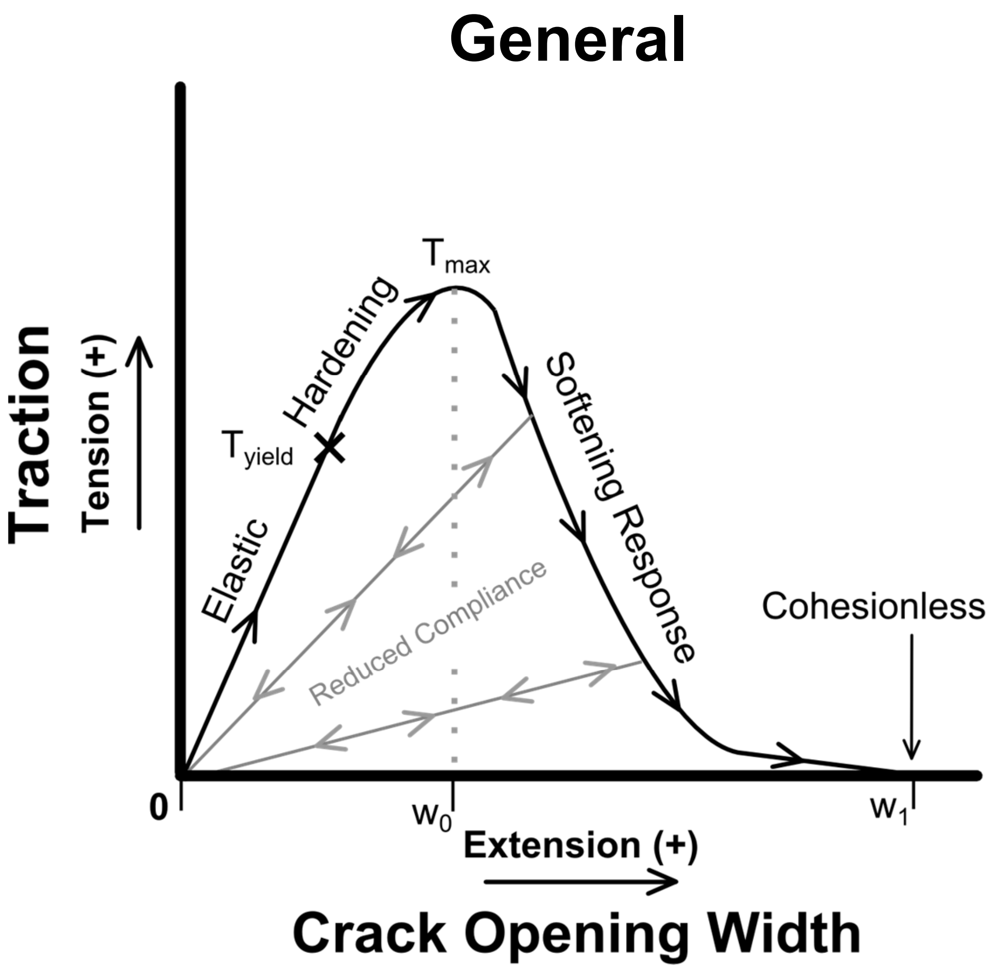
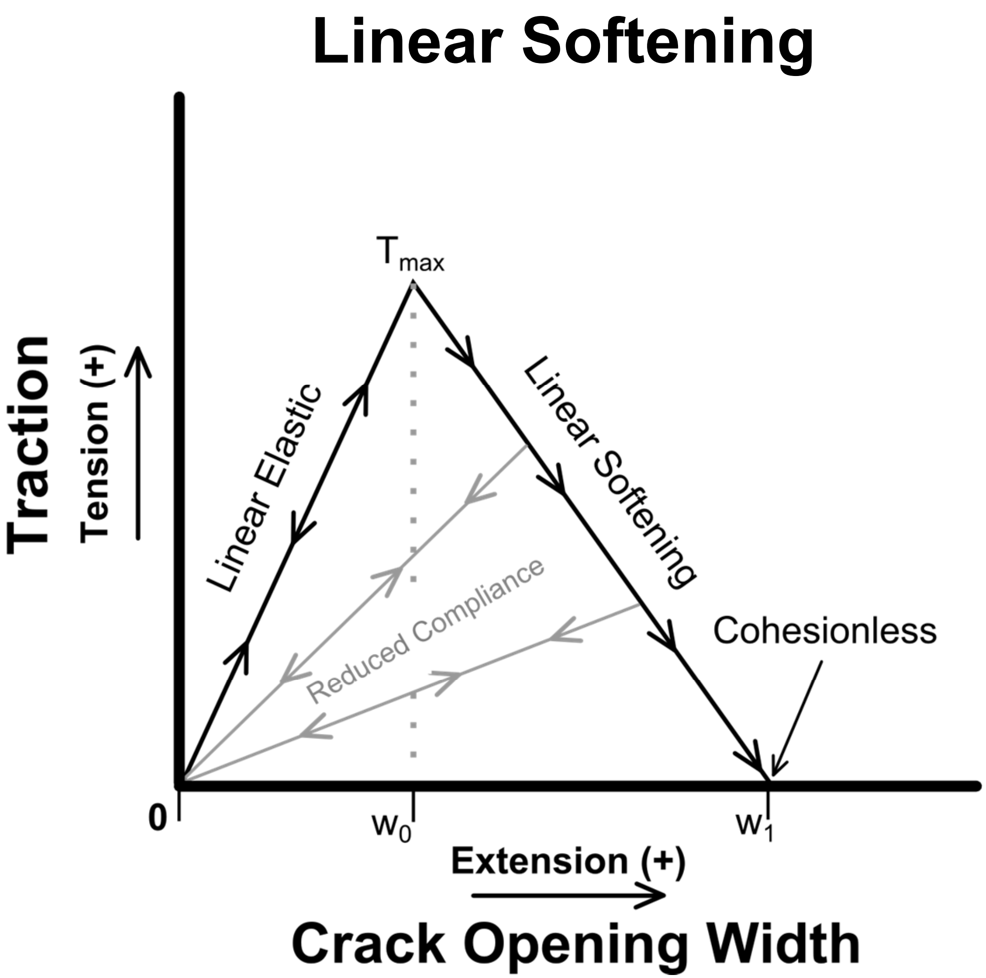
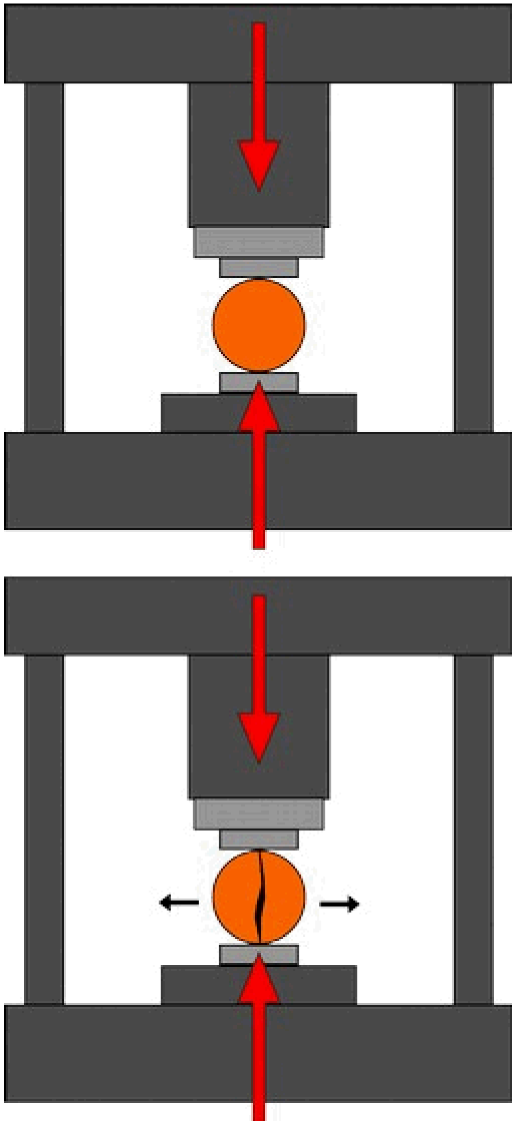


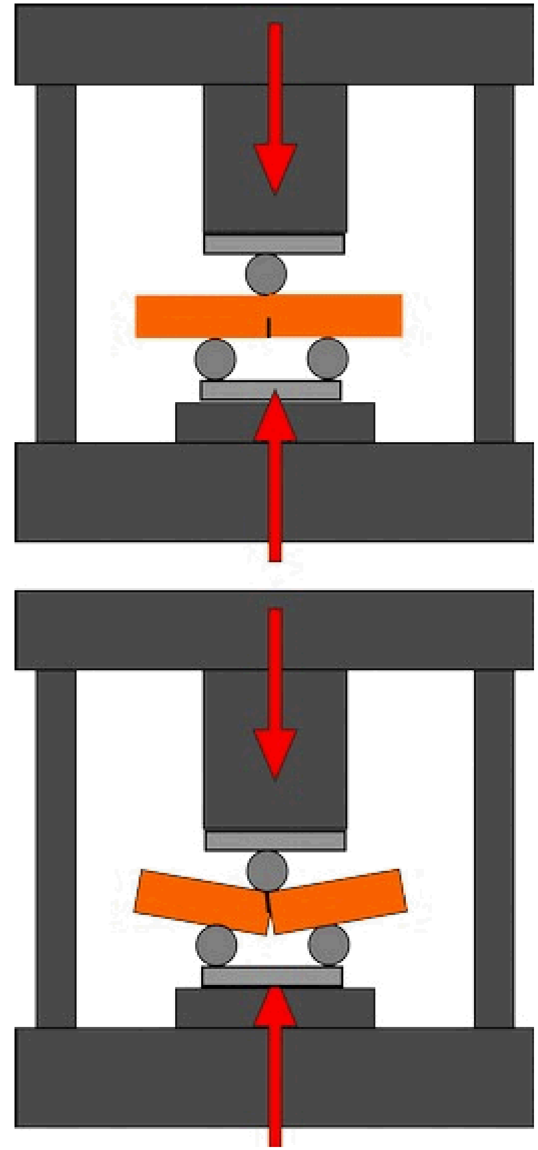


Posited in geomaterials, but little work systematically confirming approach.

Approaches to Fractures (Testing)



Brazil Test
Tensile Splitting Stress



Notched 3-Point-Bend
Fracture Toughness

Approaches to Fractures (Testing)

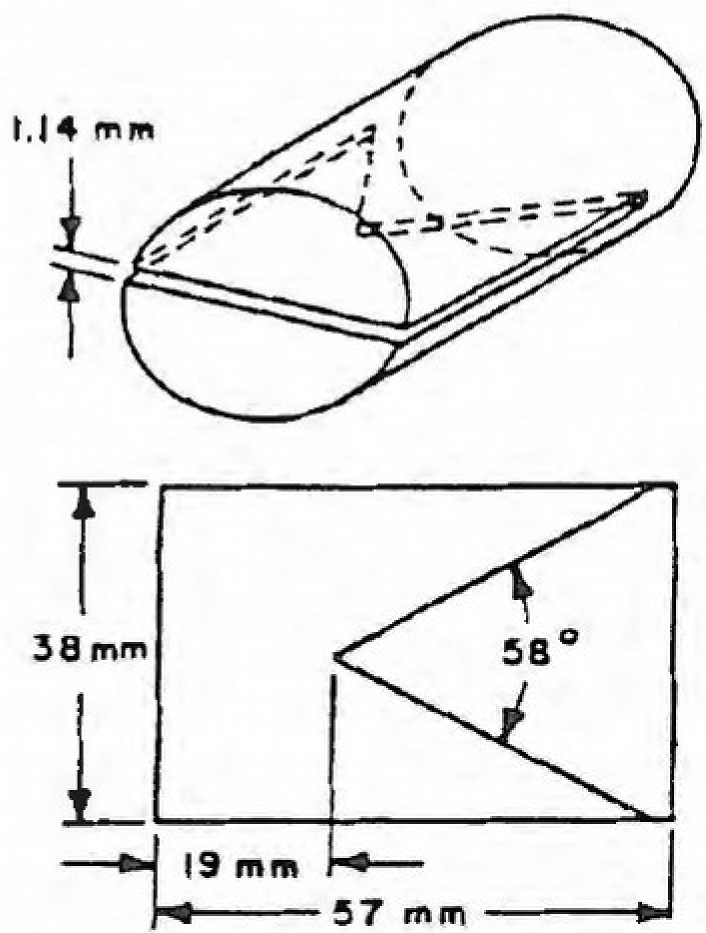
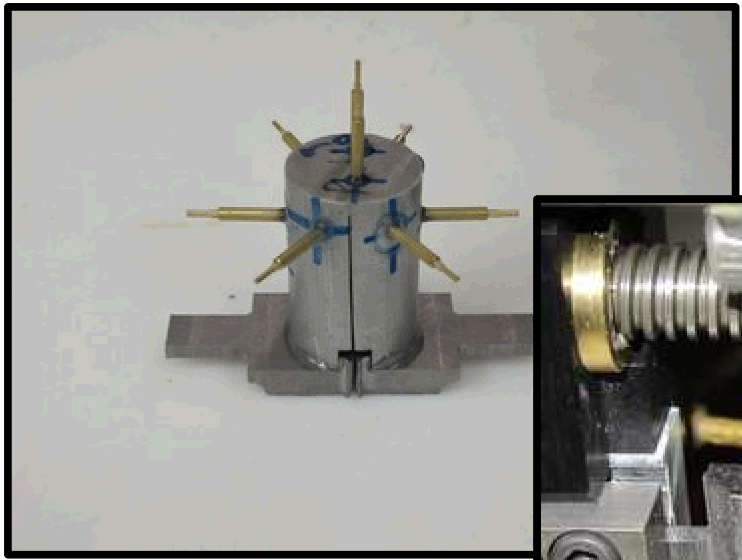


Fig. 1 Specimen Geometry.

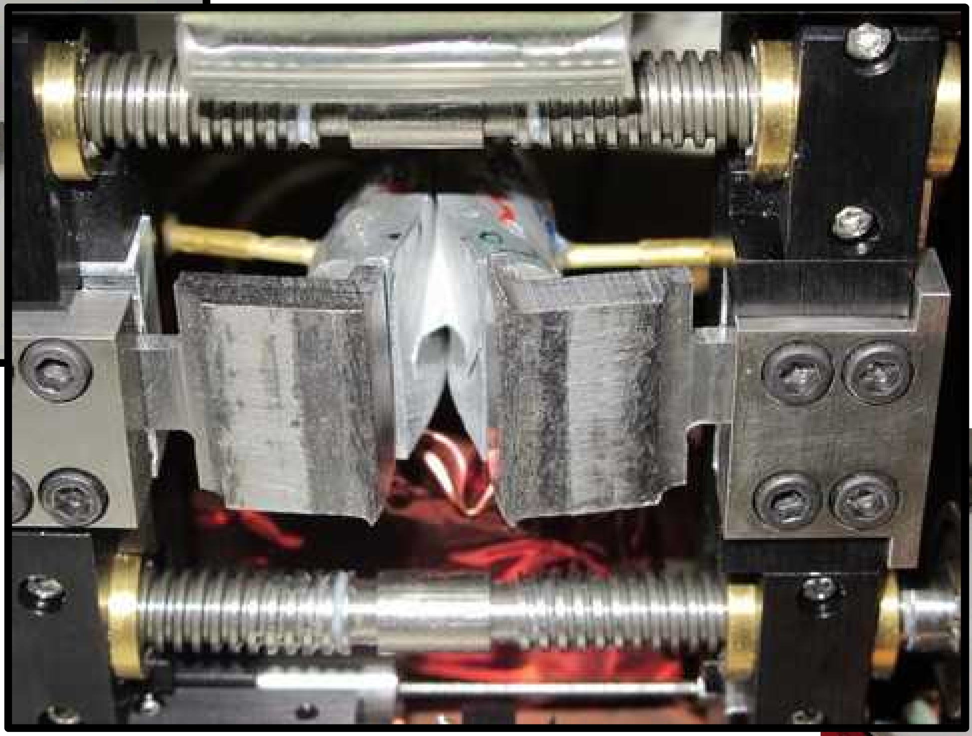
Short-Rod
Fracture Toughness

Senseny and Pfeifle (1987)

Approaches to Fractures (Testing)

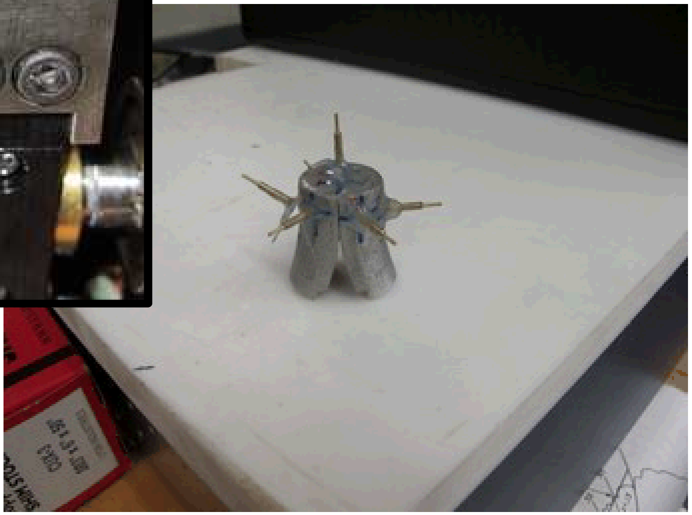


Pre-Test



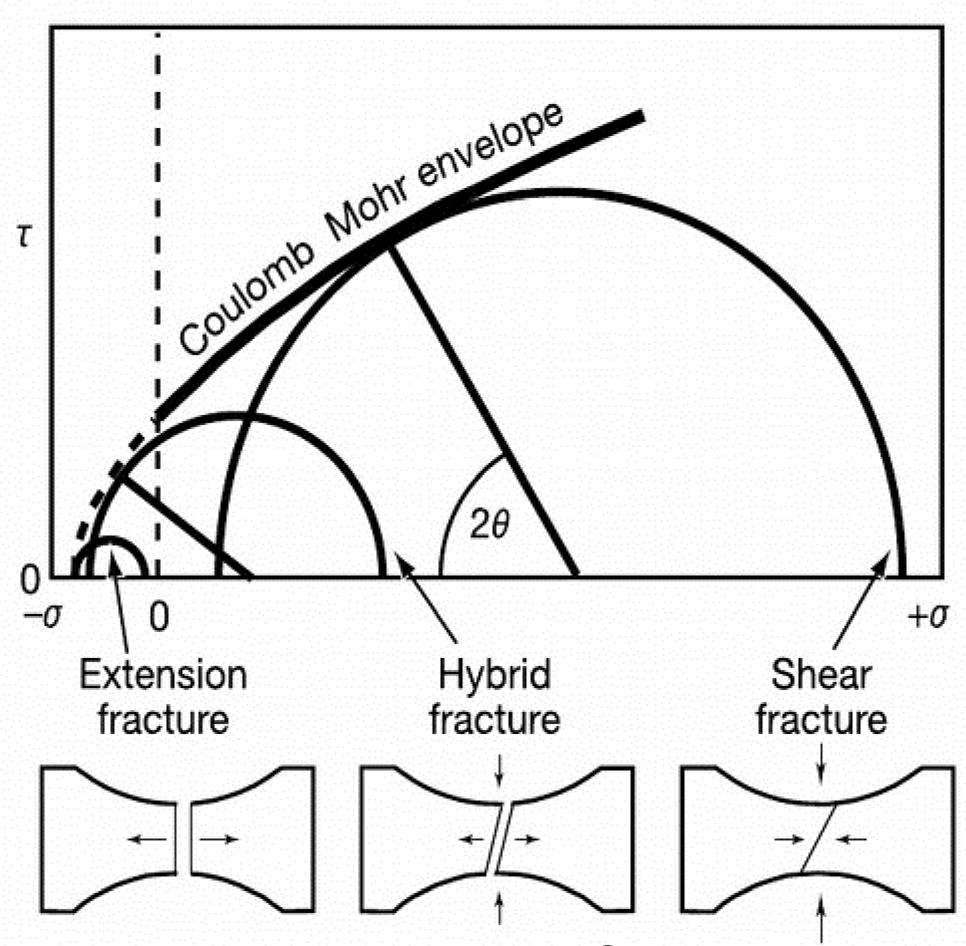
During Test

Post-Test



Short-Rod
Fracture Toughness

Subsurface Fractures in the Field



Mixed-mode fractures predominate fracture propagation deep (3,000 m depth).

Extension (Mode I) fractures dominate at shallow depths (<1,000 m depth).

Ramsey and Chester (2004), Nature

The Big Question....

How sensitive are cohesive fracture model parameters to changes in geometry?

Do changing processes or simply changing stresses cause geometry dependence?

Which testing geometry is appropriate for parameterizing models for subsurface applications?

Calibration and Confirmation Outline

Notched 3-point bend (N3PB) geometry, mesh and experiments.

Short-rod geometry, mesh and experiments.

Short-rod cohesive fracture modeling and calibration.
Qualitative observations of deformation.

N3PB confirmation of cohesive fracture model.
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Summary of pros and cons of cohesive fracture modeling for parameterizing fracture propagation.

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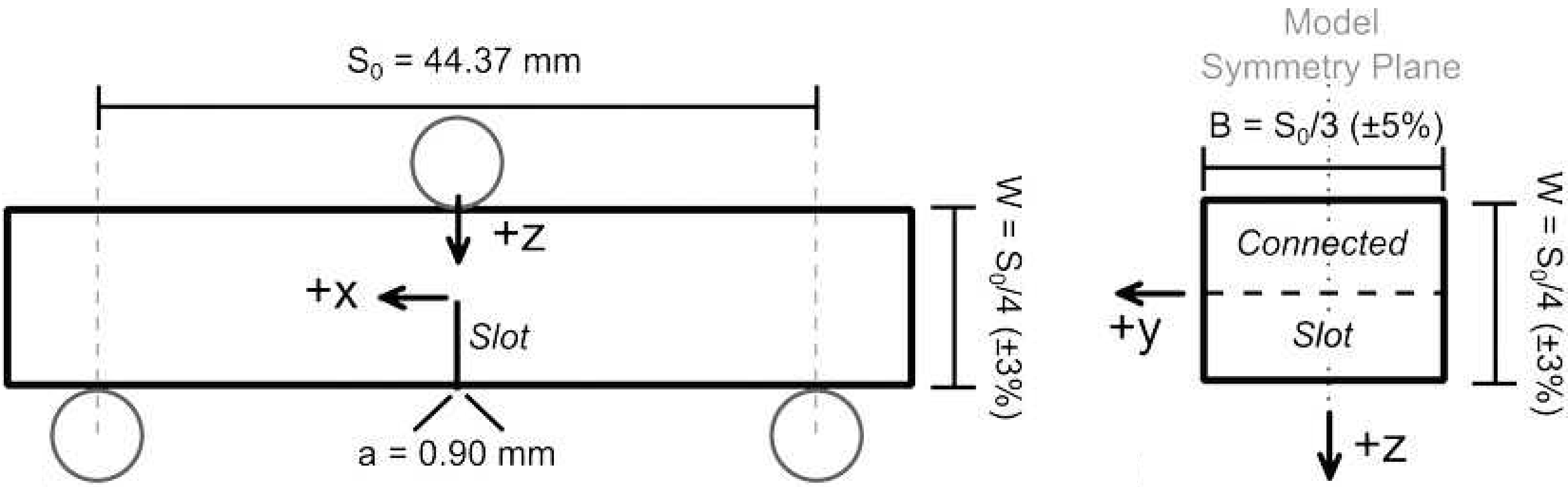
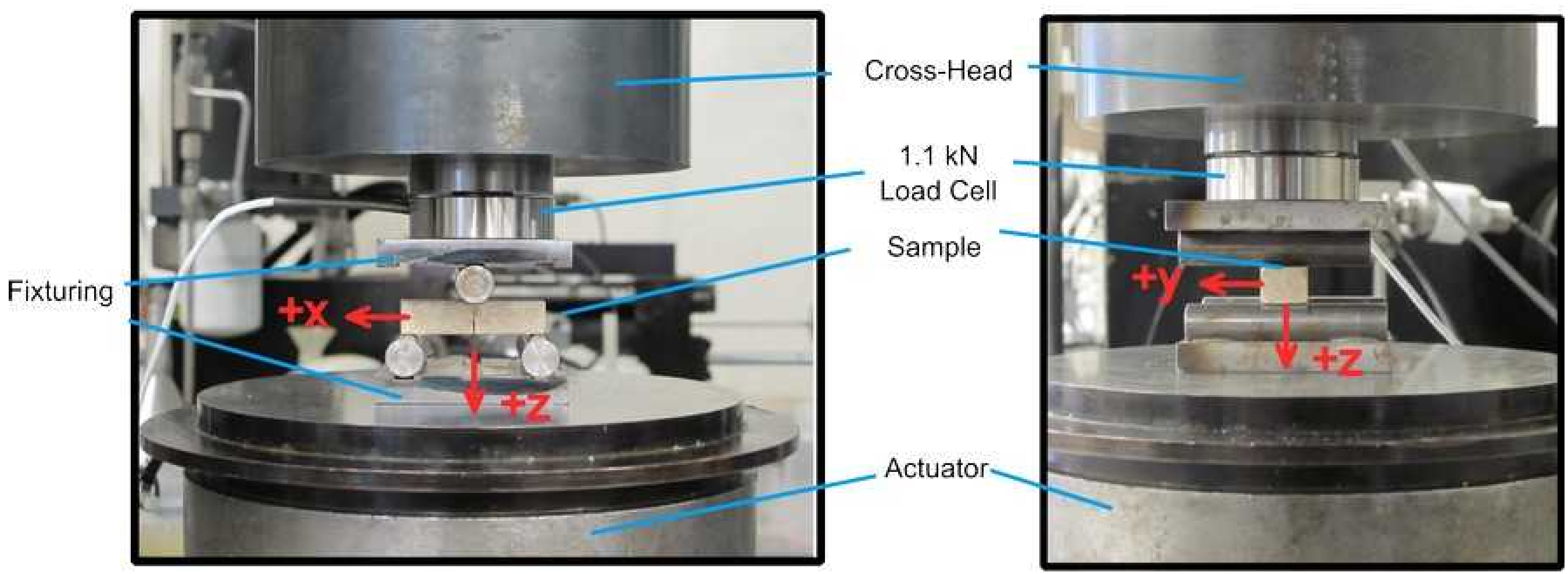
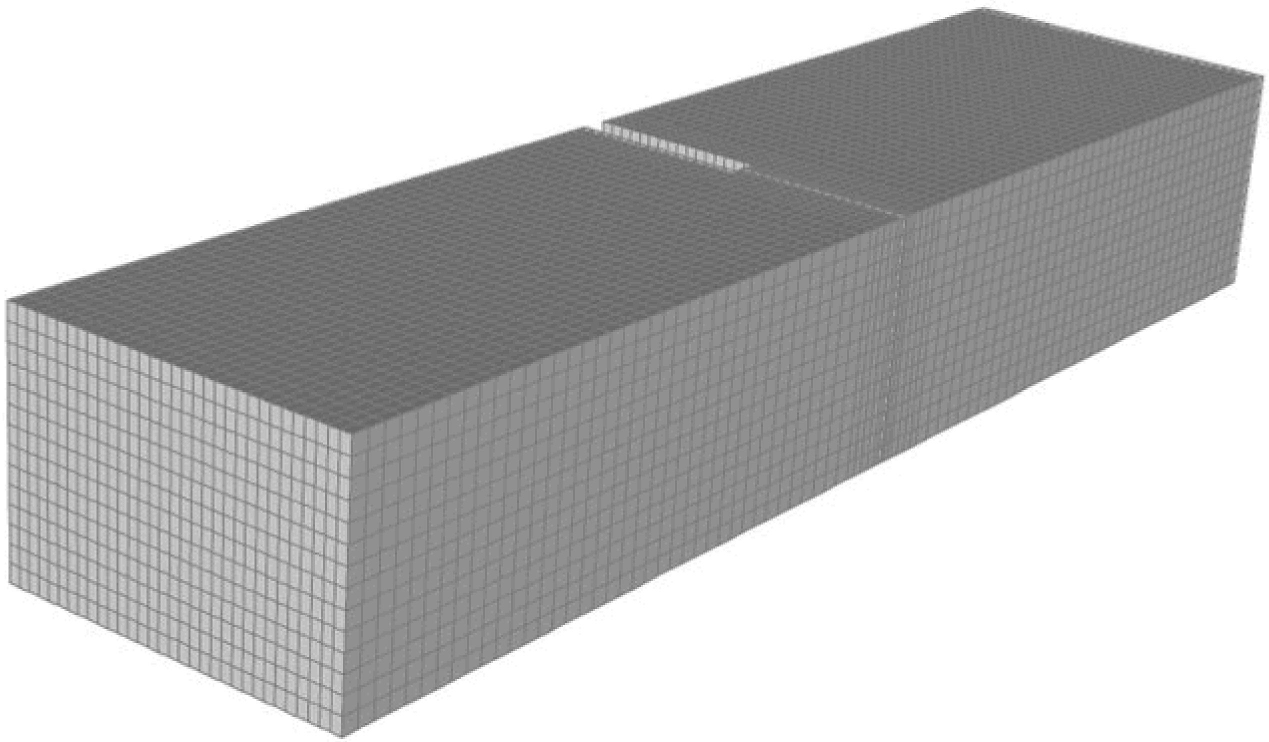
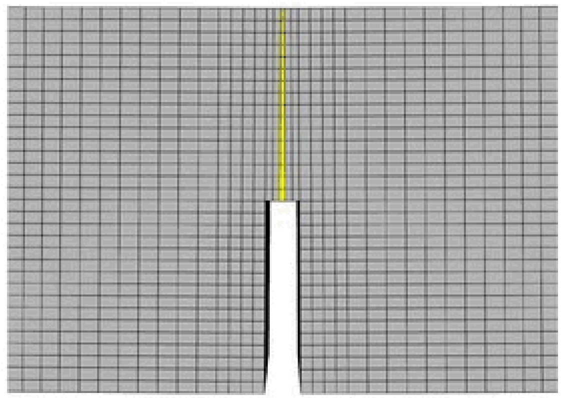
3PB Tests and Geometry

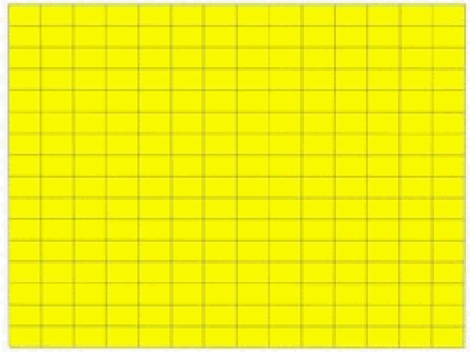




N3PB Mesh







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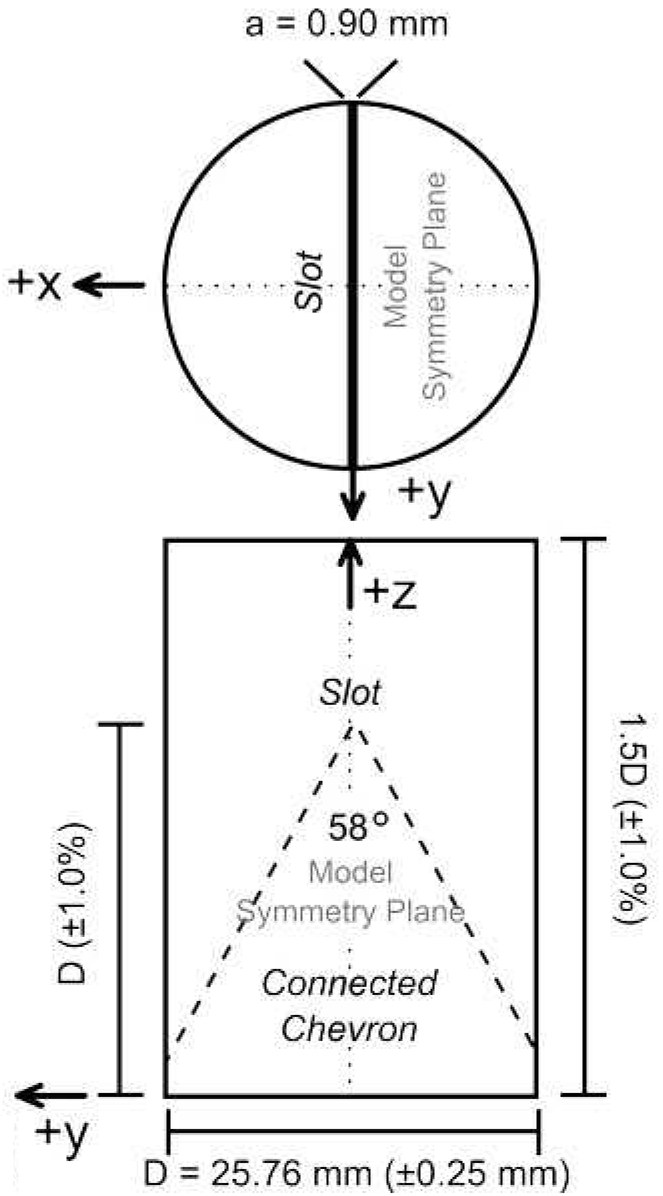

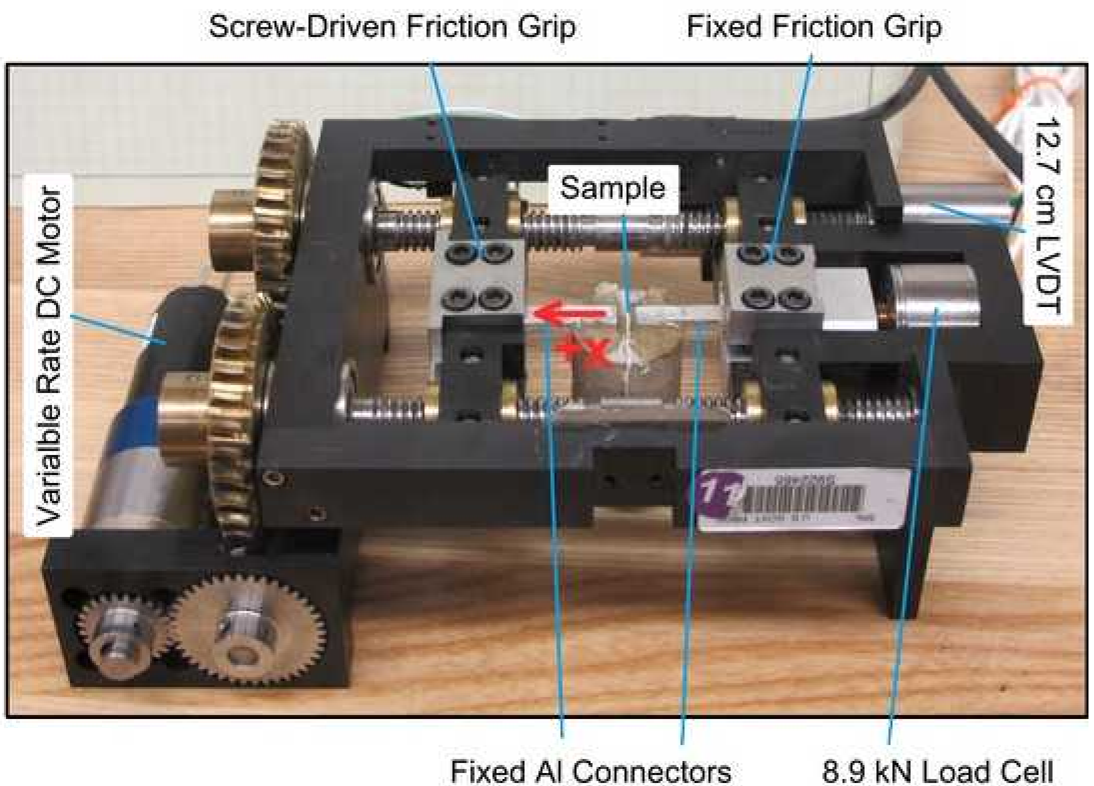

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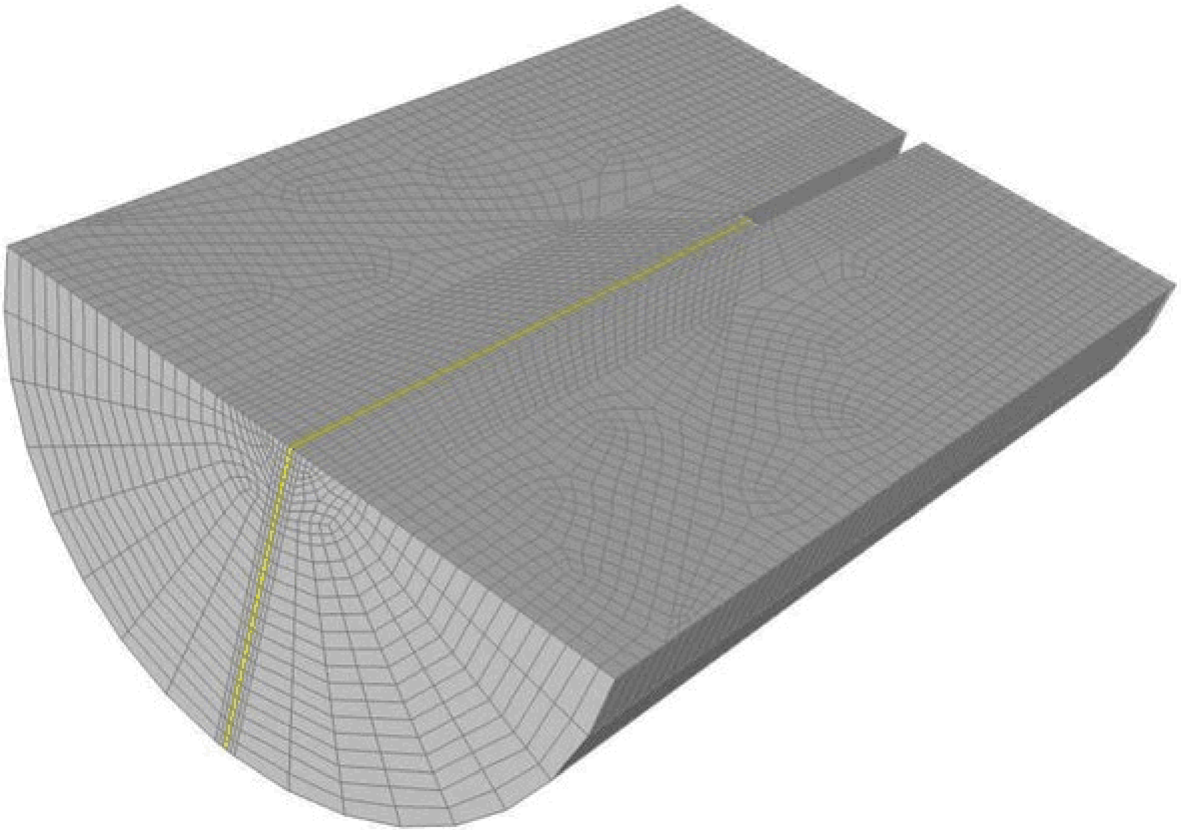

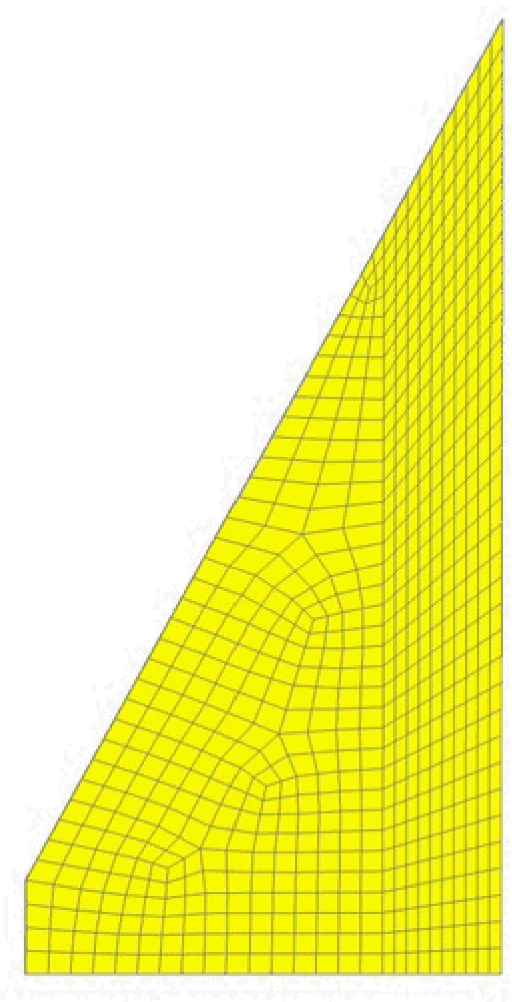

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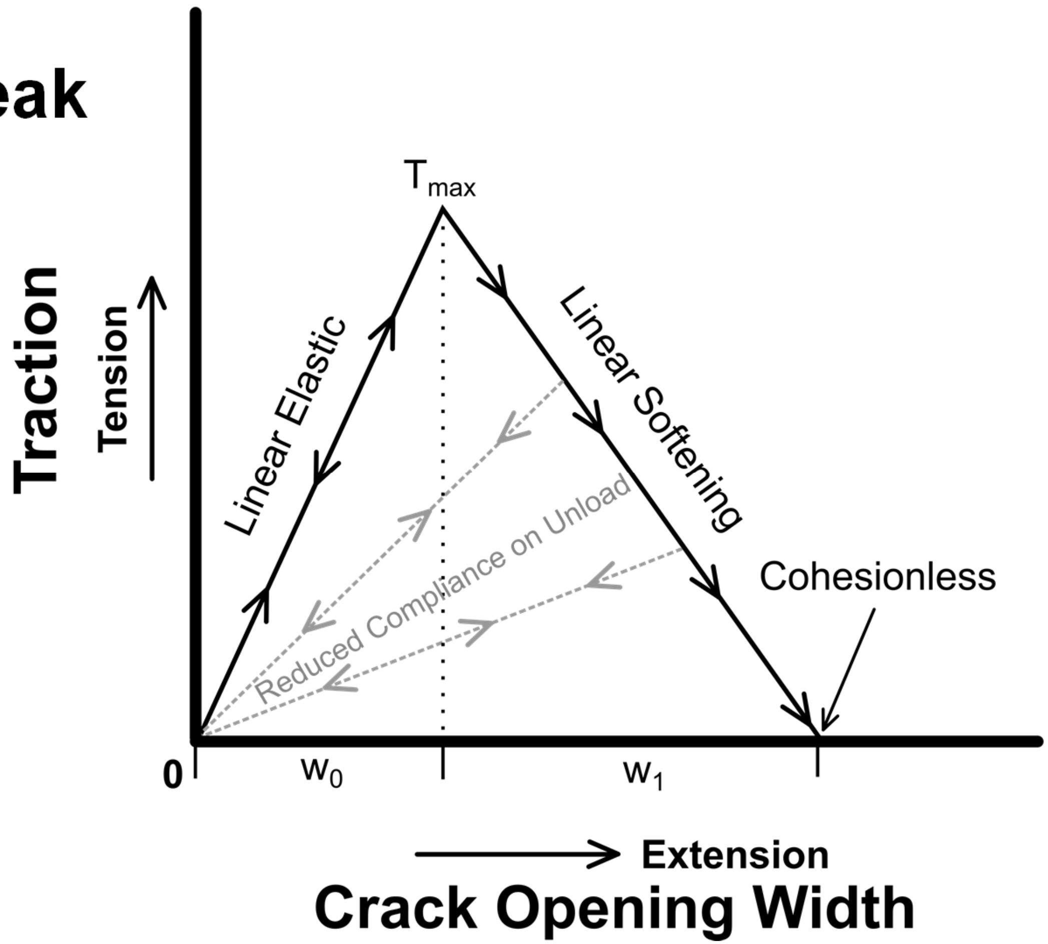
Calibration Strategy

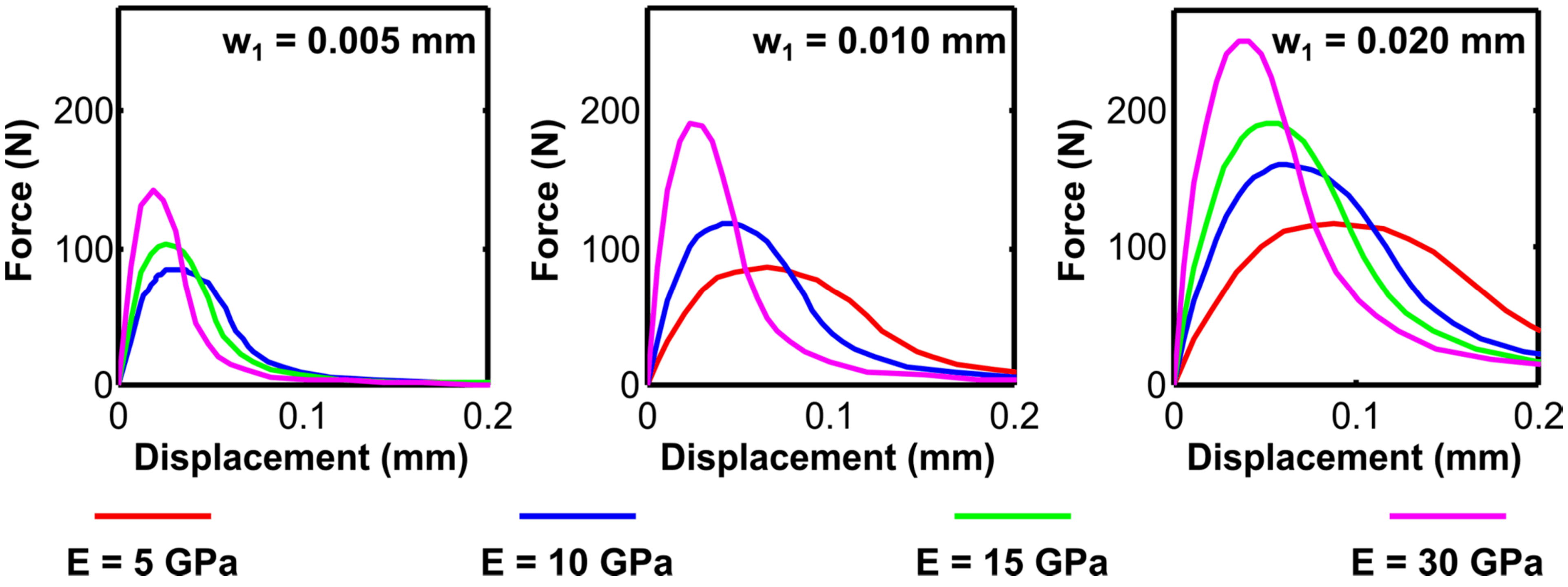
Fix σ_t = 5.9 MPa from Brazil tests.

Begin with E=39 GPa from UCS tests, vary to calibrate elastic response.

Vary w_1 to match peak and softening.



Parameters and Sensitivity



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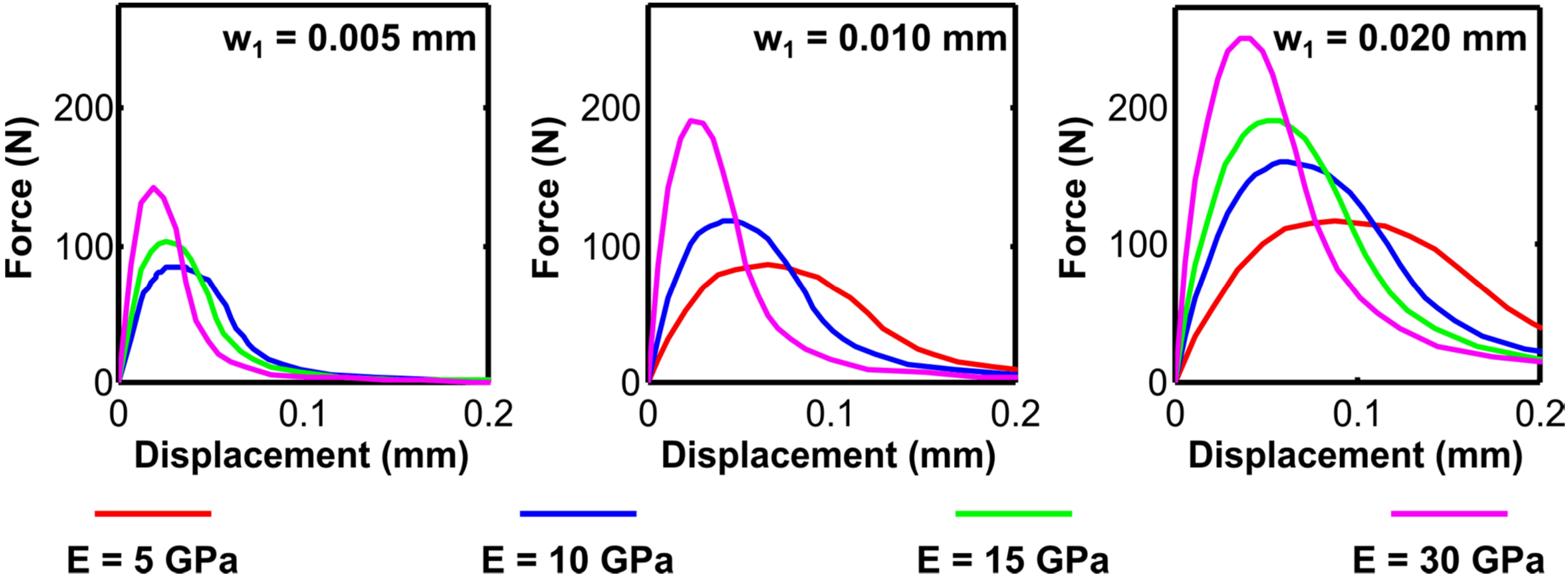
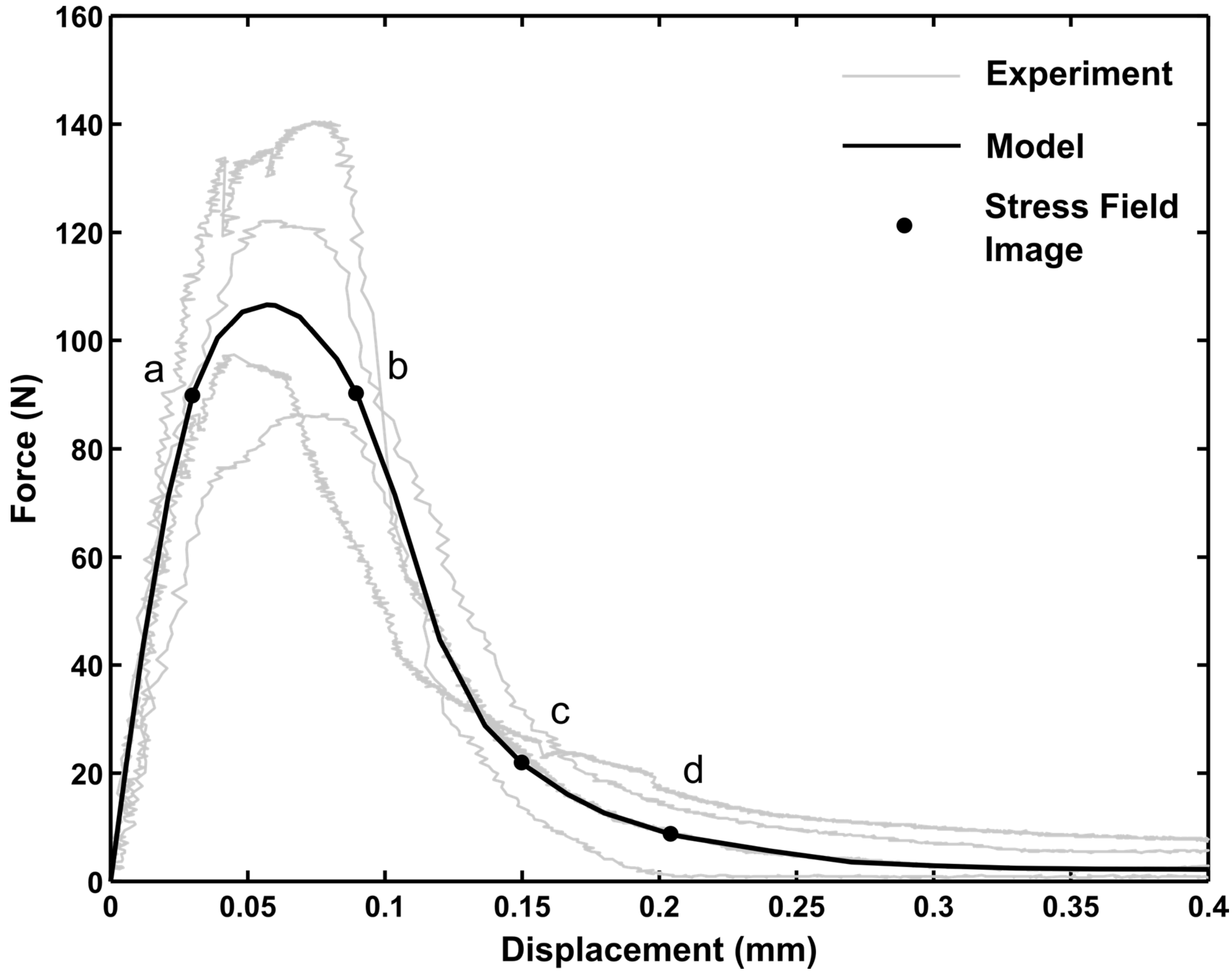


σ_t = 5.9 MPa fixed.

E = 7.0 GPa

W_1 = 0.0115 mm

Calibration Results



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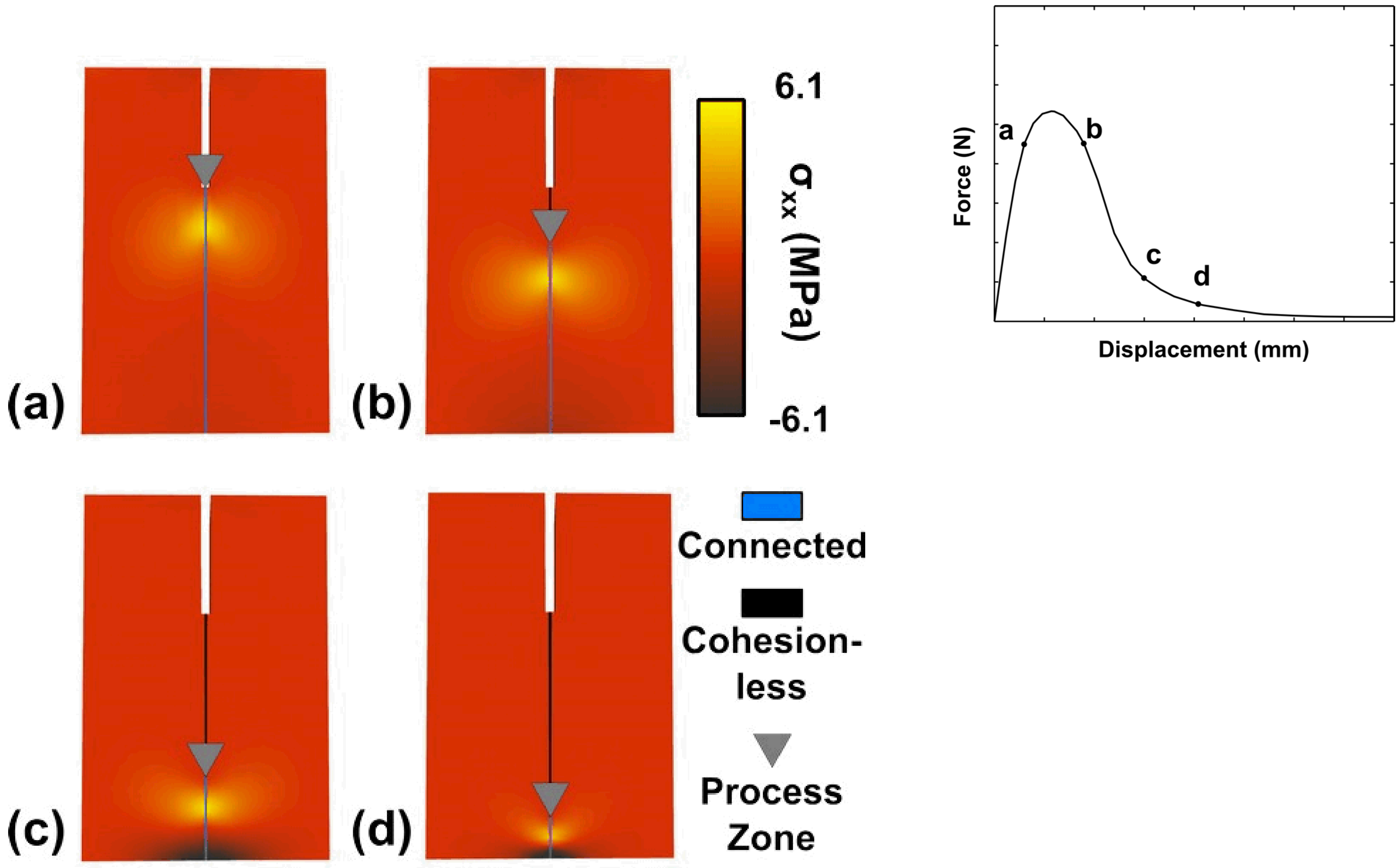

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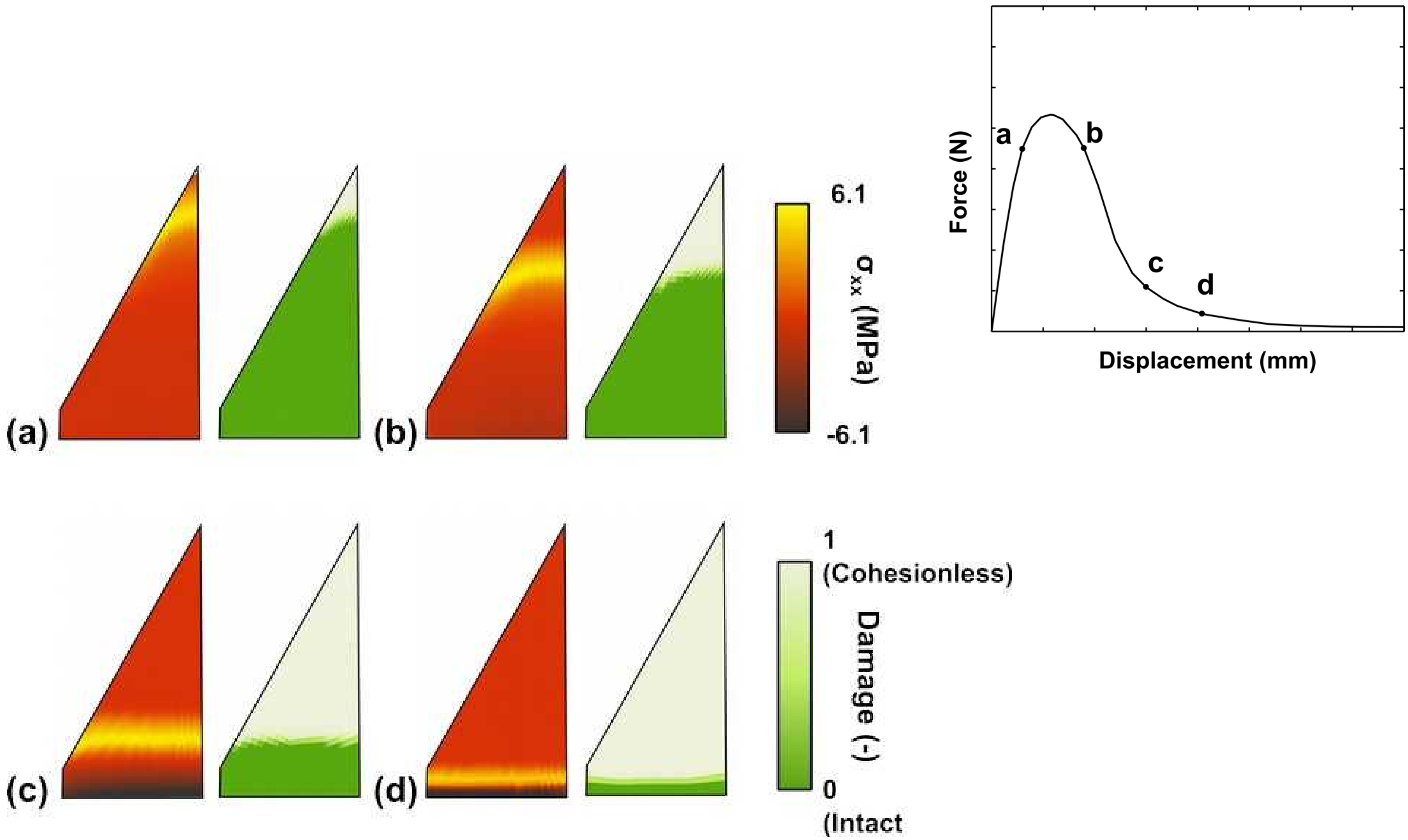
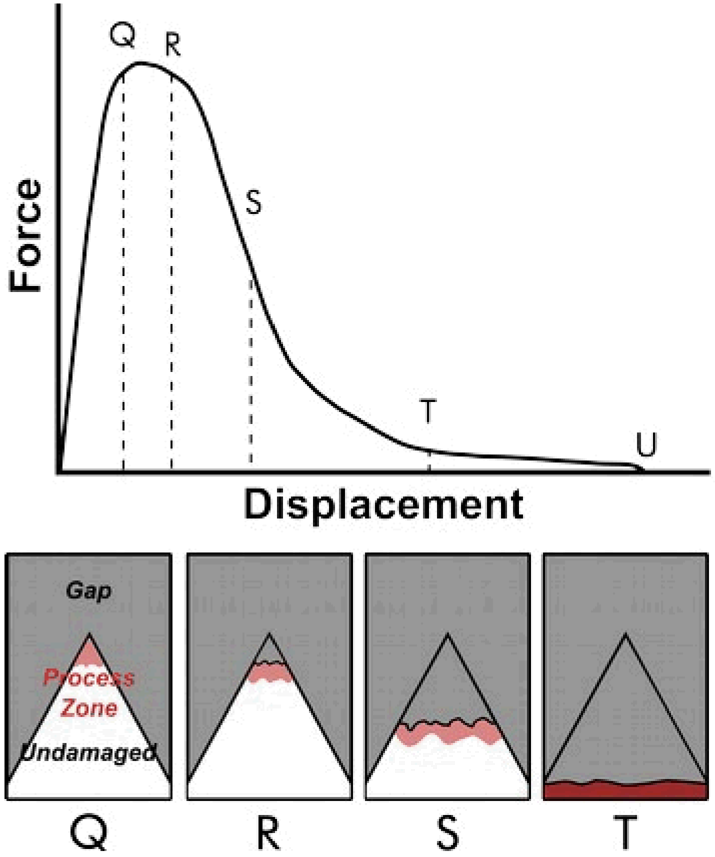


Process Cartoon

Short-Rod



Calibration Summary

Cohesive fracture model can be calibrated to match elastic loading, yield, peak and **softening behavior** by

Fixing maximum tensile stress with Brazil tests.
Varying E and w_1 in order to calibrate.

Qualitative model fracture propagation similar to observed fracture propagation.

Matching softening behavior uncommon in other test geometries. May imply test geometry 'best at' separating Mode 1 behavior.

Large difference in elastic properties (E = 7 GPa in tension vs. E = 39 GPa in compression).

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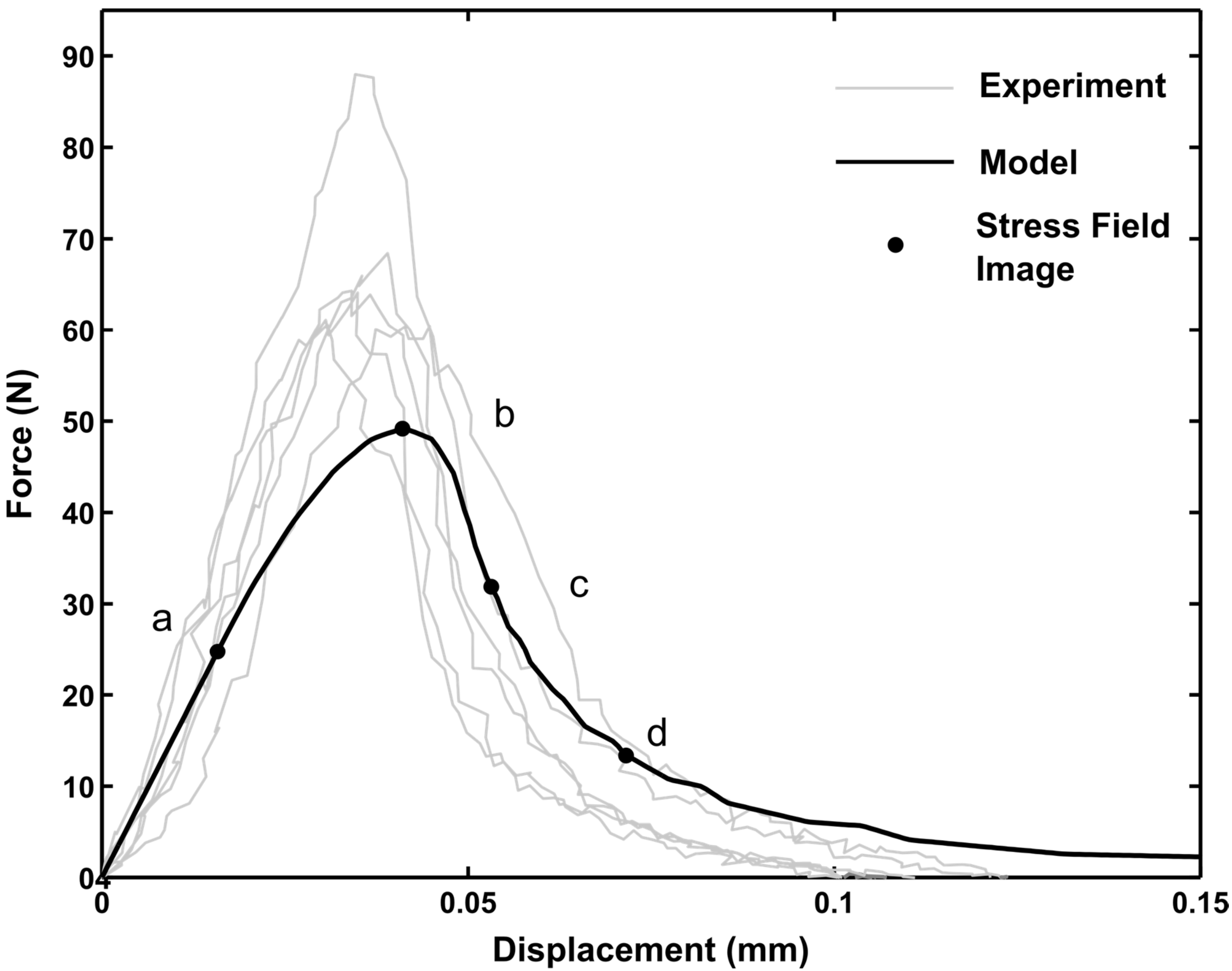

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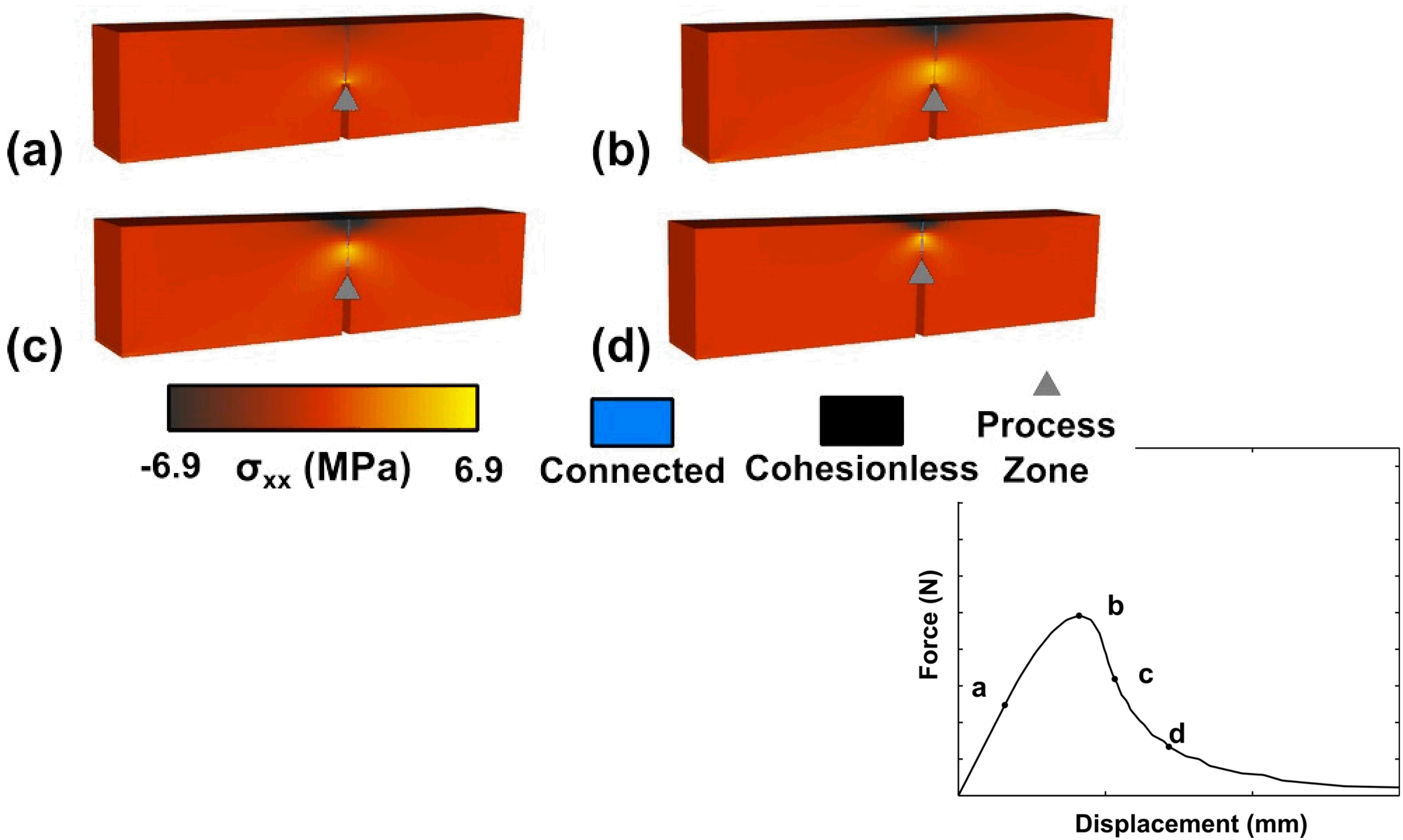

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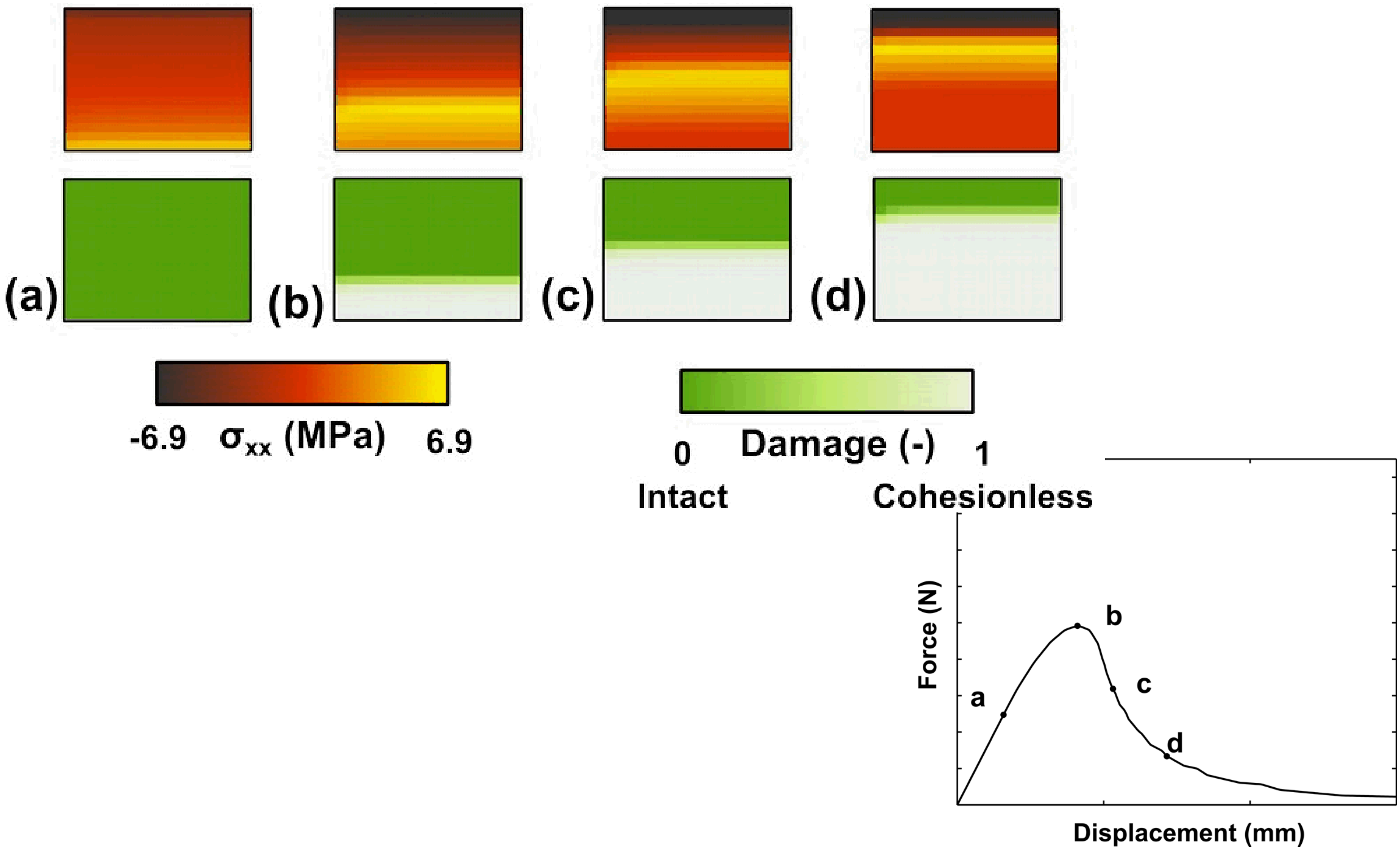

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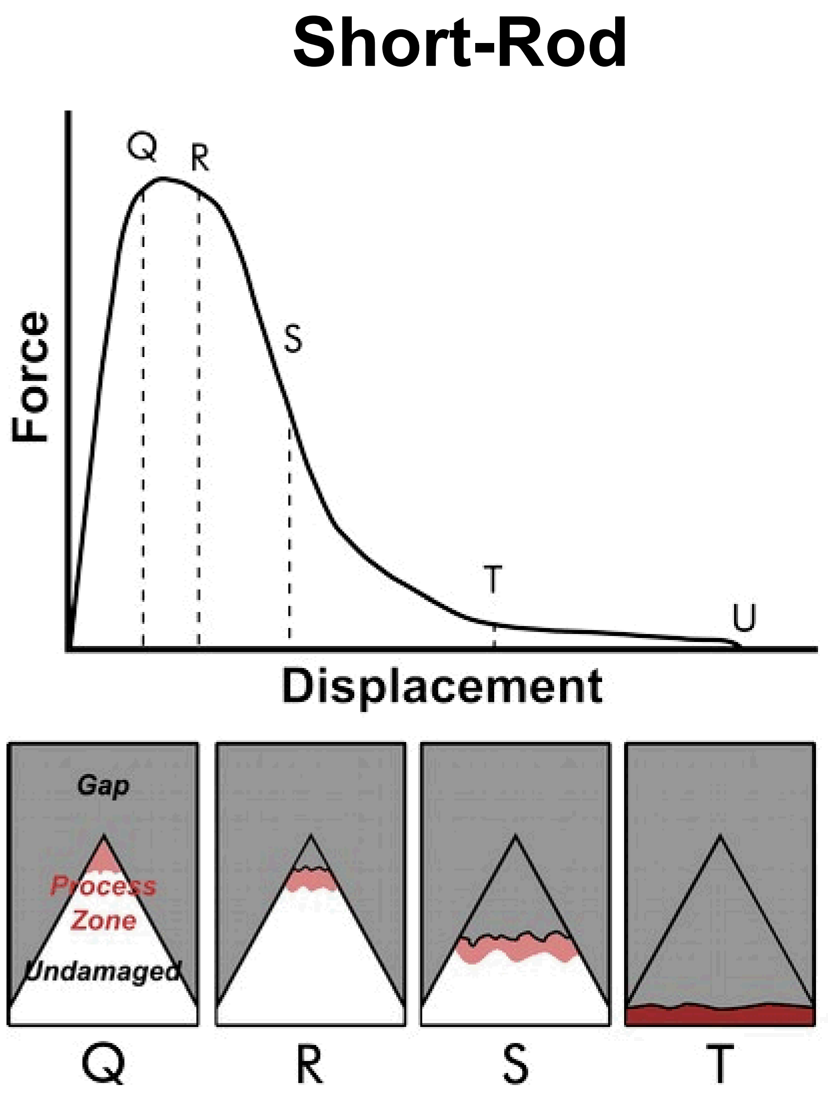
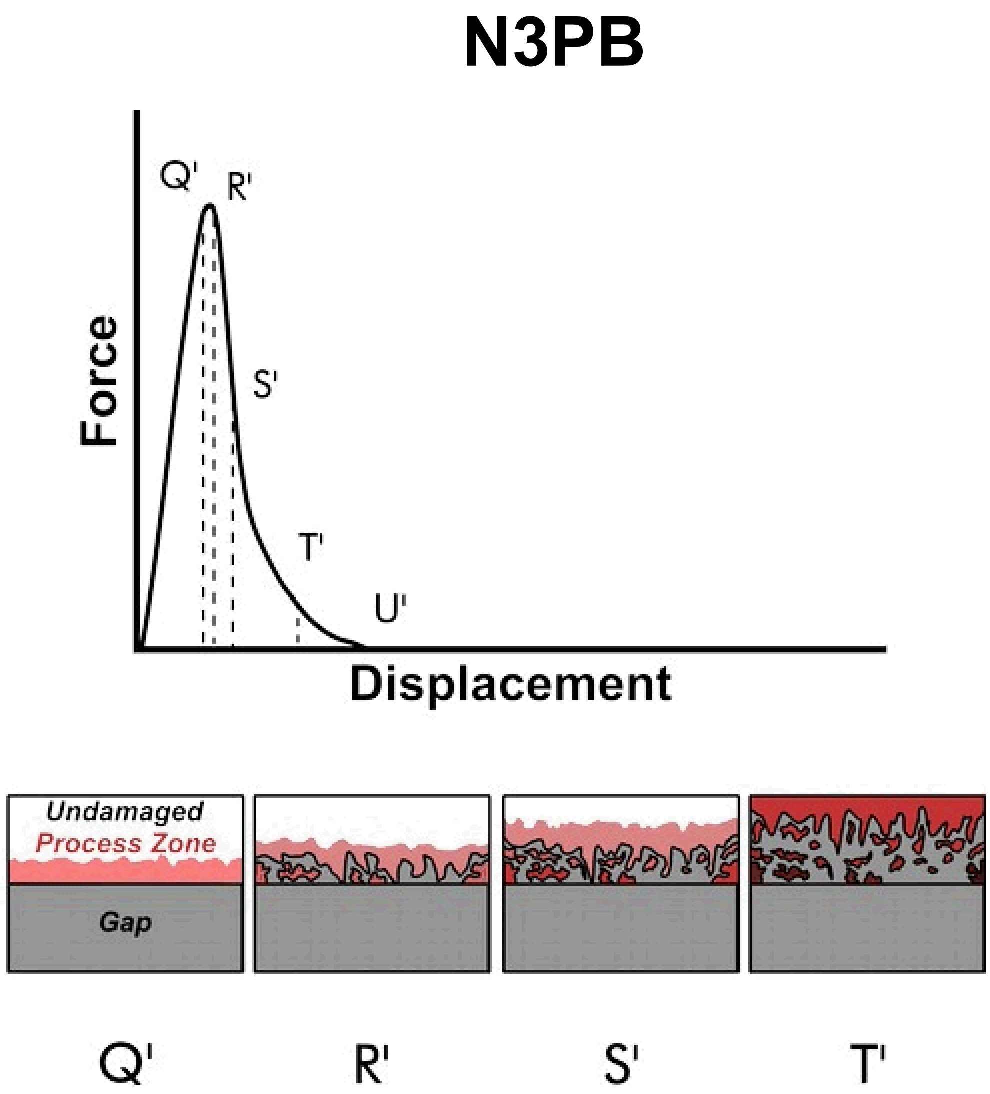




Confirmation Summary

Calibrated cohesive fracture model fell within uncertainty for peak stress and initial softening.

N3PB model initial elastic response 'softer' than measured.

N3PB response showed yielding pre-peak not observed.

N3PB model does not accurately depict large-displacement behavior.

Qualitative diffuse fracture pattern does not match modeled fracture propagation pattern.

More volume immediately in compression and likely predominant shear failures in fracture both control change in response with geometry.

Conclusions

Cohesive elements can, within O(1), be used to predict crack propagation in different geometries.

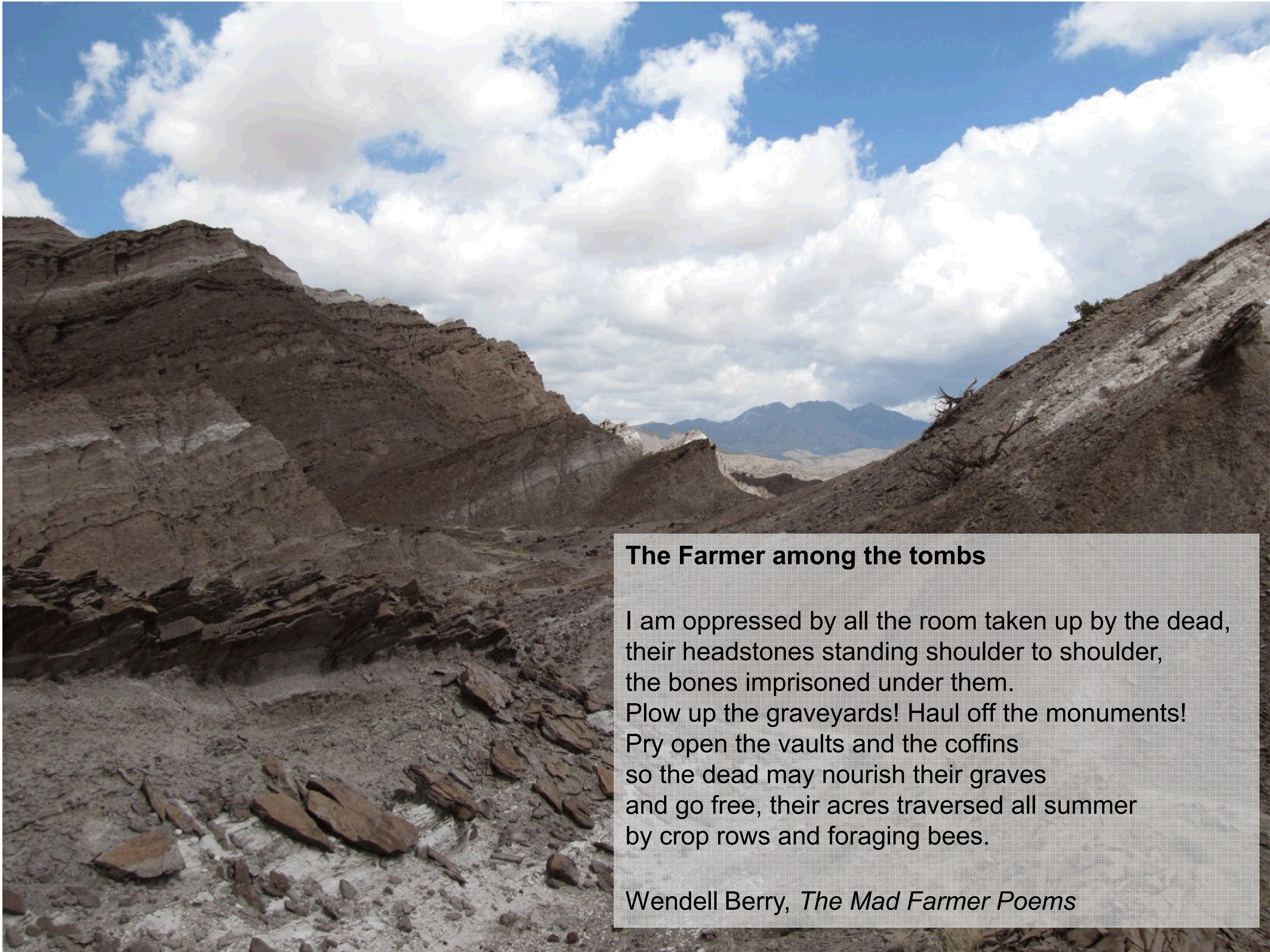
Varying stress state in Indiana limestone significantly affects effective elastic properties between short-rod and 3pb simulations.

Short-rod provides a more accurate Mode 1 fracture geometry than N3PB.

Bulk plasticity or microcracking along edge of fracture needed to portray propagation.

Cohesive crack mimics tail in short-rod, not N3PB.

'Cold-runs' of 3pb fall within uncertainty, but display yielding before any of experiments.



The Farmer among the tombs

I am oppressed by all the room taken up by the dead,
their headstones standing shoulder to shoulder,
the bones imprisoned under them.
Plow up the graveyards! Haul off the monuments!
Pry open the vaults and the coffins
so the dead may nourish their graves
and go free, their acres traversed all summer
by crop rows and foraging bees.

Wendell Berry, *The Mad Farmer Poems*