LA-UR- 99-3435

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Title: Damage Initialization for Modeling of Dynamic Shear Banding

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Submitted to: ASME Mechanics and Materials Conference June 27-30, 1999, Blacksburg, Virginia USA

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Form 836 (10/96)

Modeling of Dynamic Shear Banding

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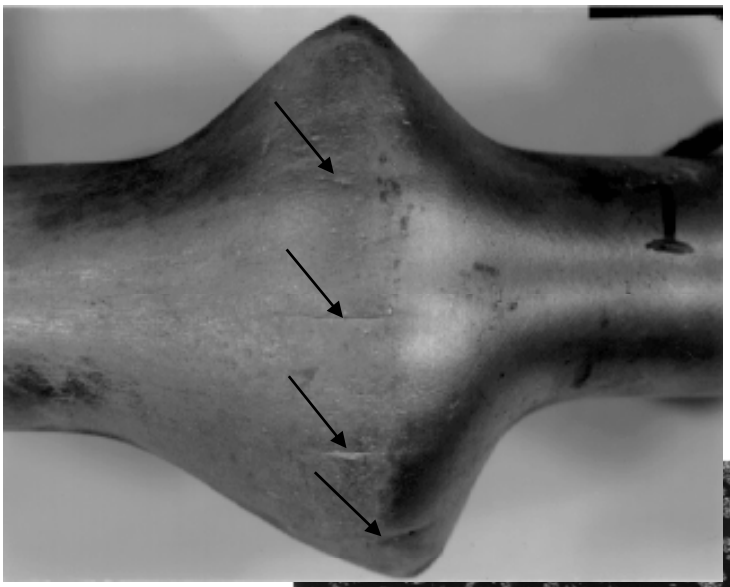
Los Alamos, New Mexico, USA

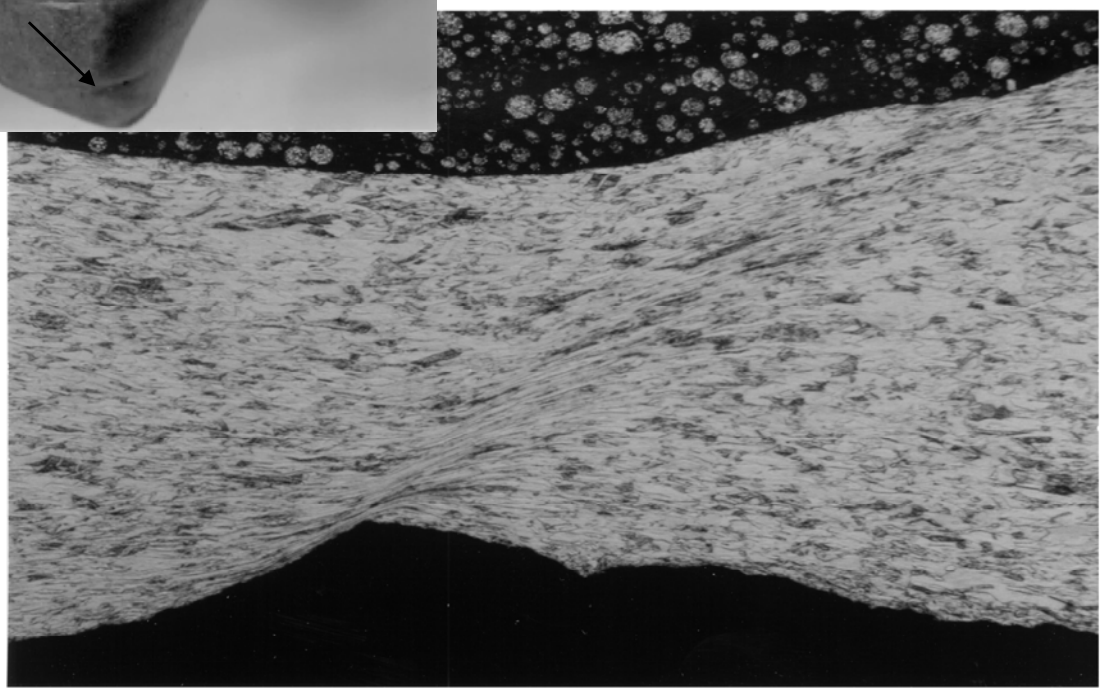
- **Introduction**
- **Experiments**
  - **Analysis**

Introduction

- Adiabatic shear banding
  - Adiabatic: high rate = no heat transfer
  - Plastic work: $\Delta T = \frac{1}{\rho C_p} \int_0^{\varepsilon} \bar{\sigma} d\bar{\varepsilon}_p$
  - If thermal softening > strain hardening

    localization ----> shear banding

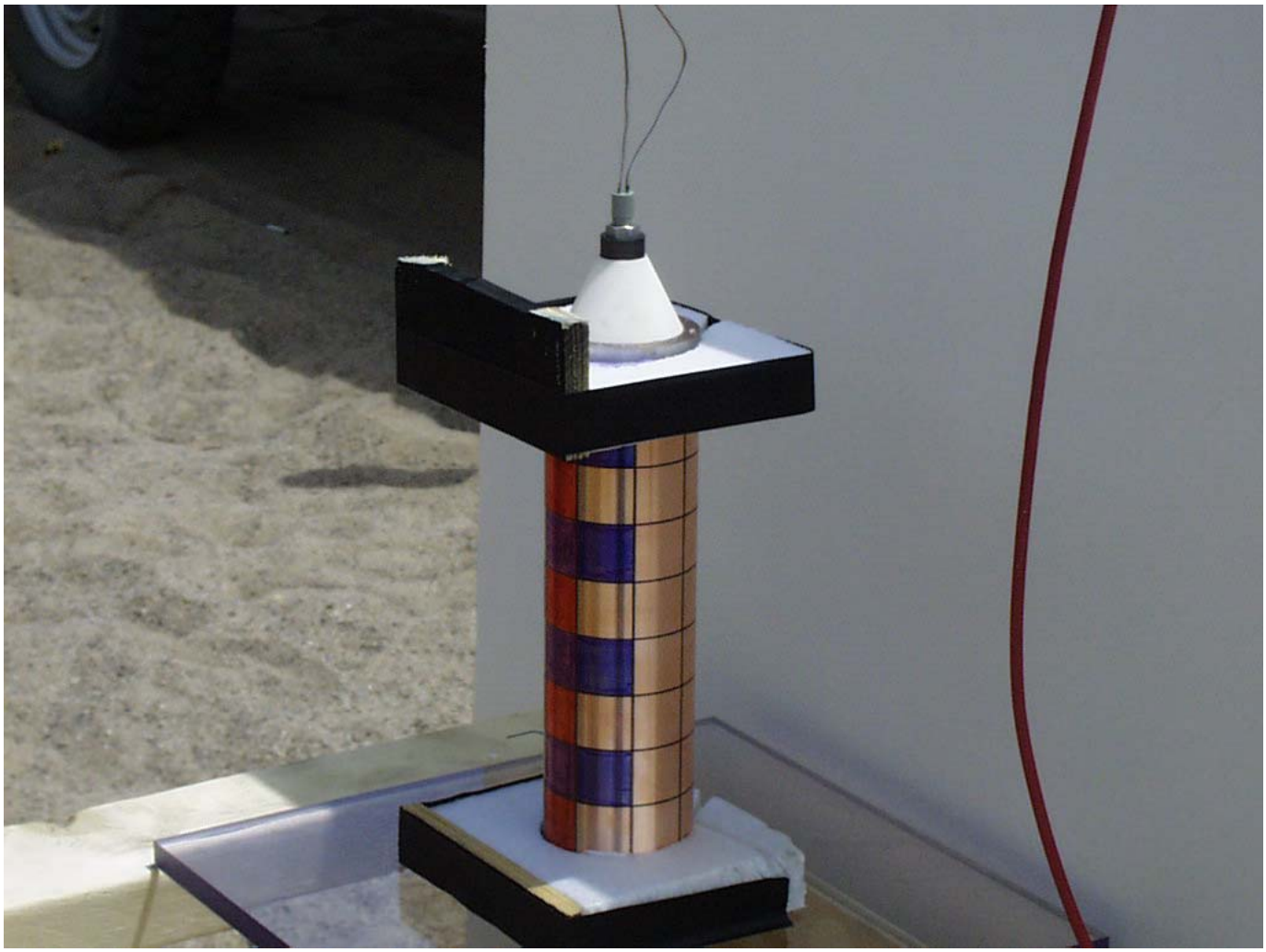




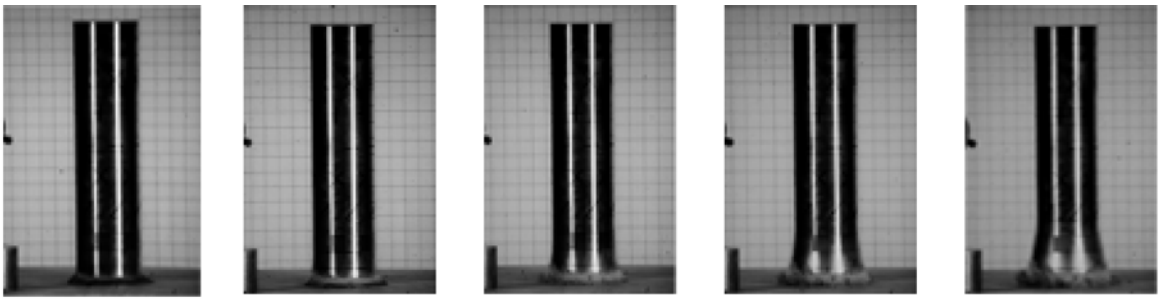
Introduction

- Shear Banding in Dynamically Expanding Shells
  - Flux compression generators
  - Explosive Forming
  - Explosive Containment vessels
  - Explosive Bonding
- Desire to Predict Timing & Evolution
  - Finite element modeling (explicit)

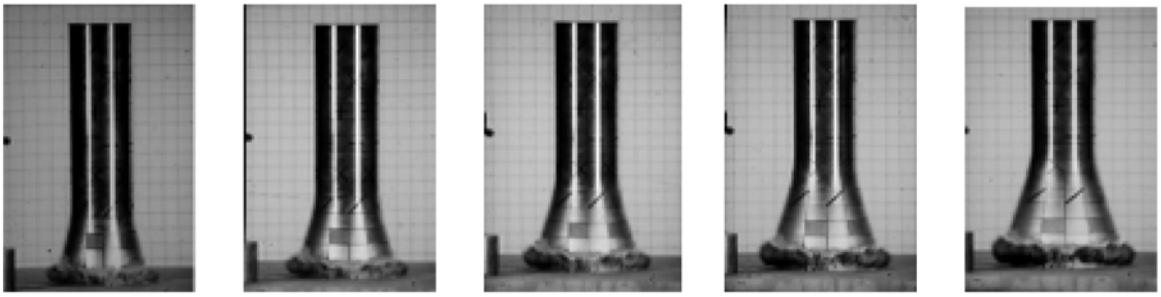
Cylinder Experiments



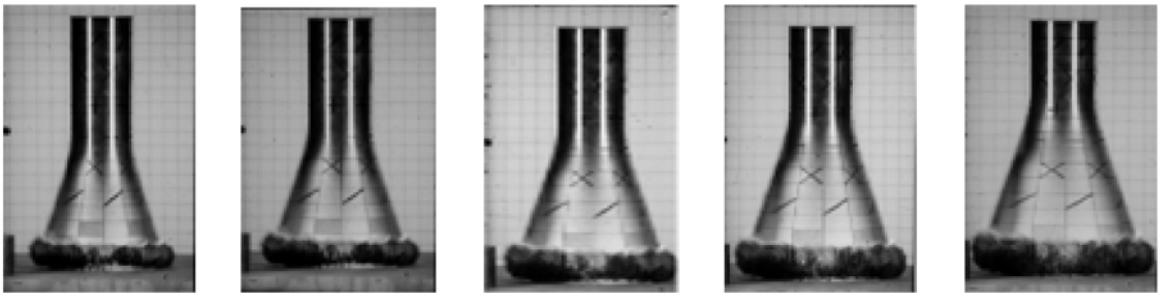
- Explosively-loaded, end-detonated
- Copper: grainsize: 40μm (large cylinders), ~100μm (small)
- 2 tests: 4" (100mm) ID, 16" (400mm) long, PBX-9501 (energetic HE) filled, 0.1" & 0.2" (2.5 & 5mm) wall
- 2 tests: 2" (50mm) OD, 8" (200mm) long, ~ 0.25" (6mm) annulus of nitromethane, 0.3 ” & 0.36 ” (7.6 & 9.2 mm) wall, inner copper cylinder



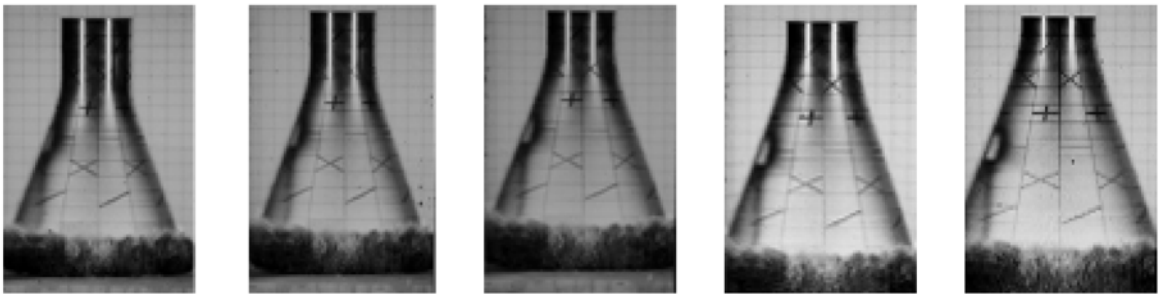
0.0 2.257 4.514 6.771 9.028



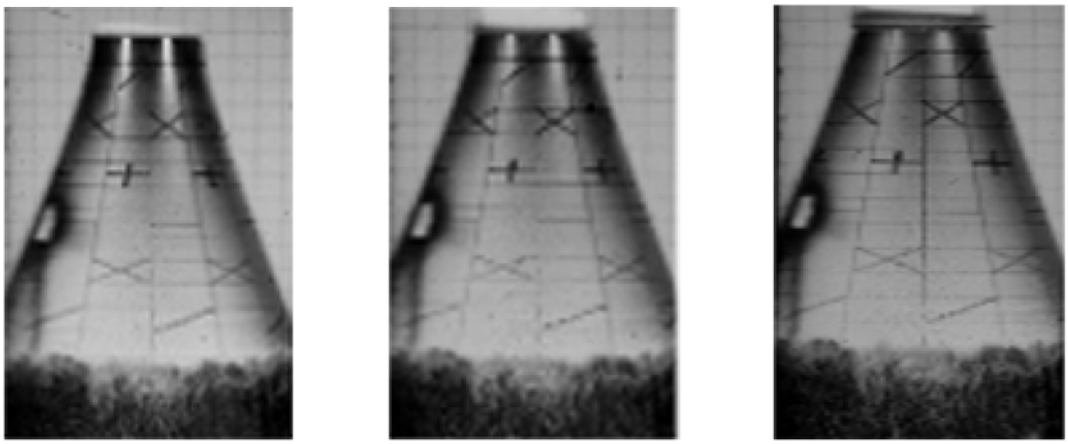
11.285 13.542 15.799 18.056 20.313



22.57 24.827 27.084 29.341 31.598

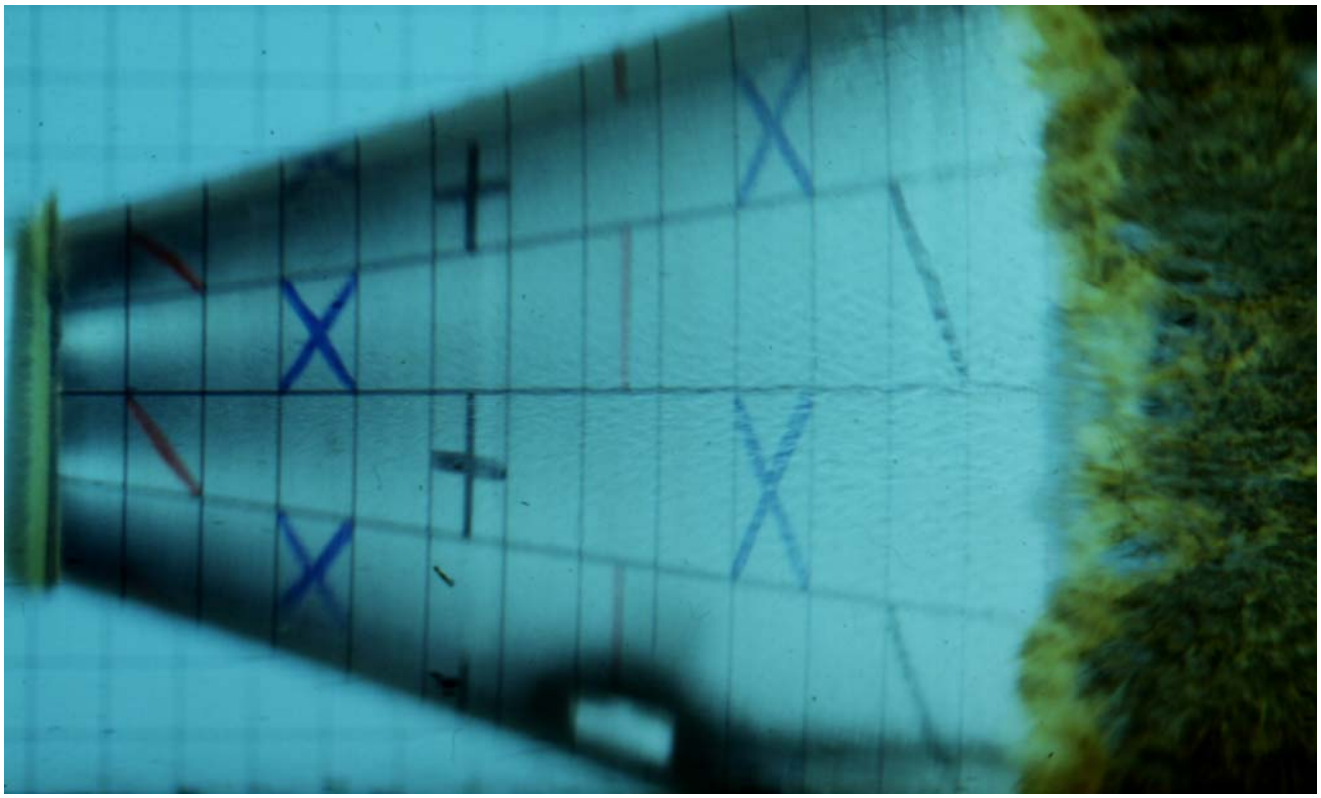


33.855 36.112 38.369 40.626 42.883



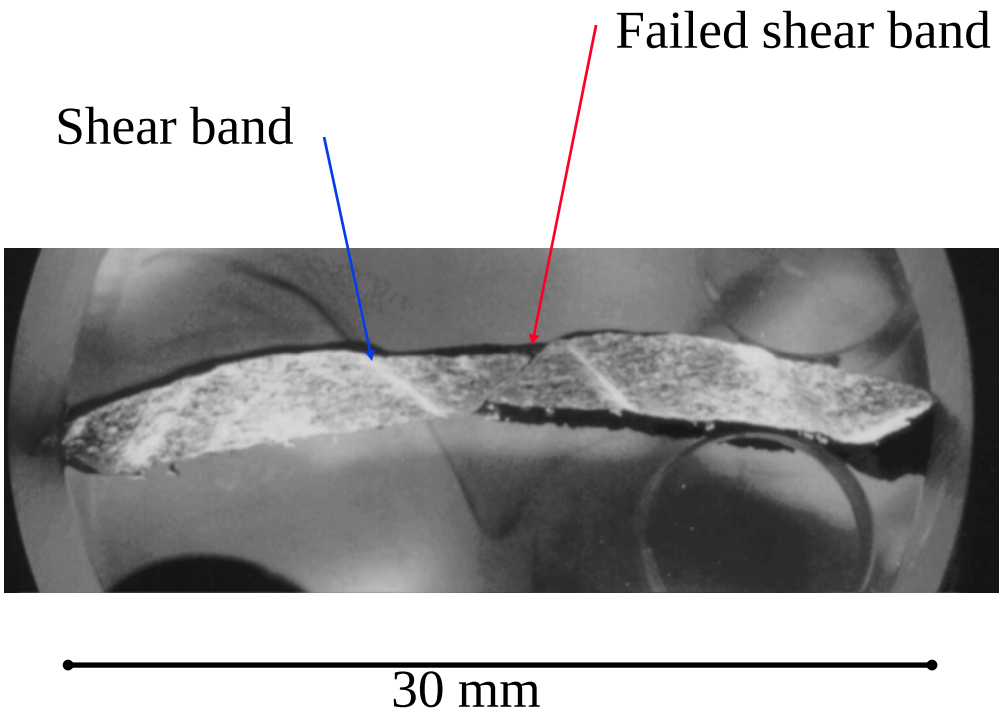
45.14 47.397 49.654

Experiments - Diagnostics



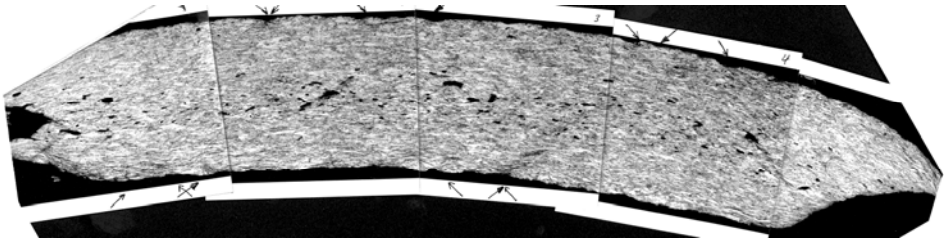
- **Diagnostics:**
  - Fast framing camera (used 3-5 μs frame time)
  - Visar/Fabry-Perot interferometry
- **Uses:**
  - Validate finite element model with disps, velocities
  - Observe shear banding formation on surface, final fracture

Experiments - Recovered Fragments



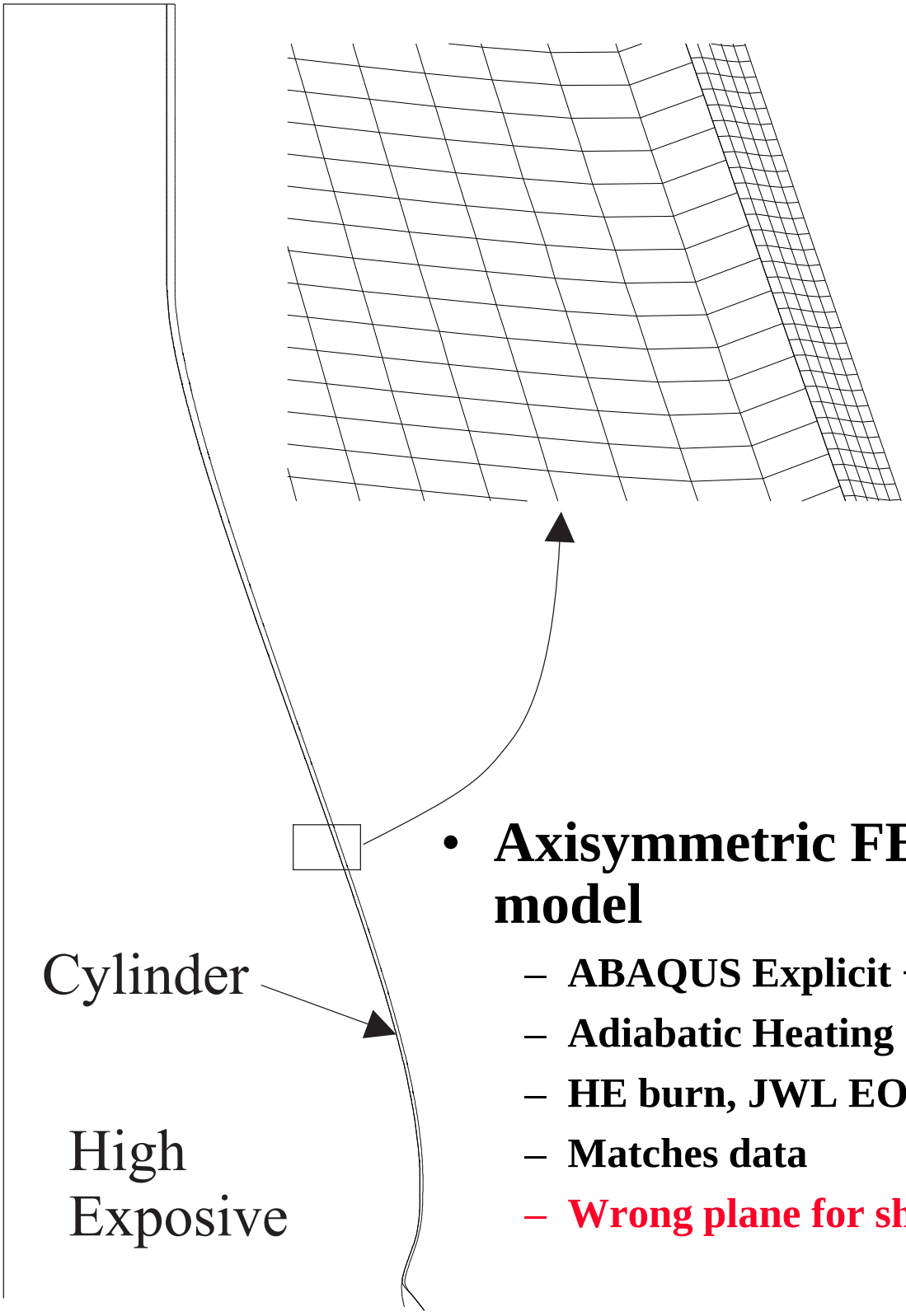
- **Cross-Section of soft-catch fragment, smaller cylinders only**
- **Many Shear bands evident**
- **Data**
  - **Shear band spacing**
  - **fragment thickness gives upper bound on final failure**

Experiments - Recovered Fragments



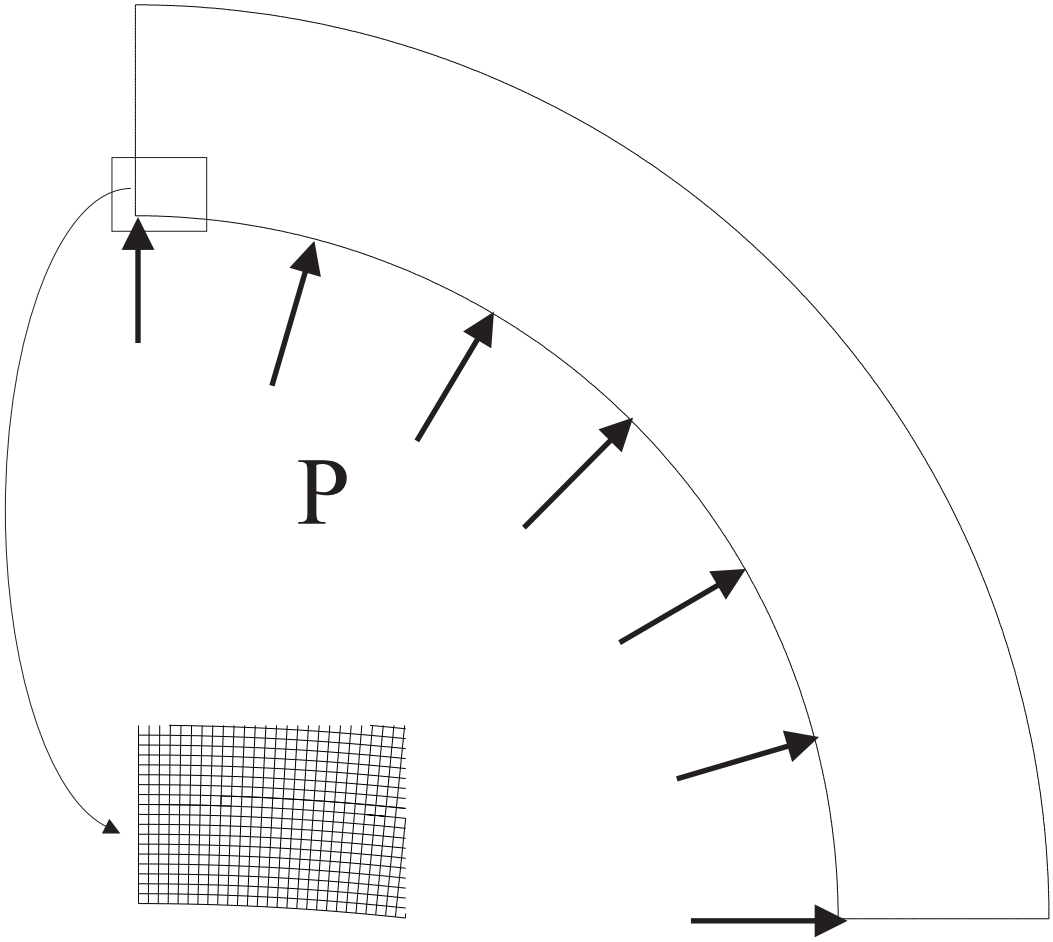
- **Same test, 20% thicker cylinder**
- **Void plane**
- **Less developed shear bands**
- **lower strain at failure**

Modeling Approach



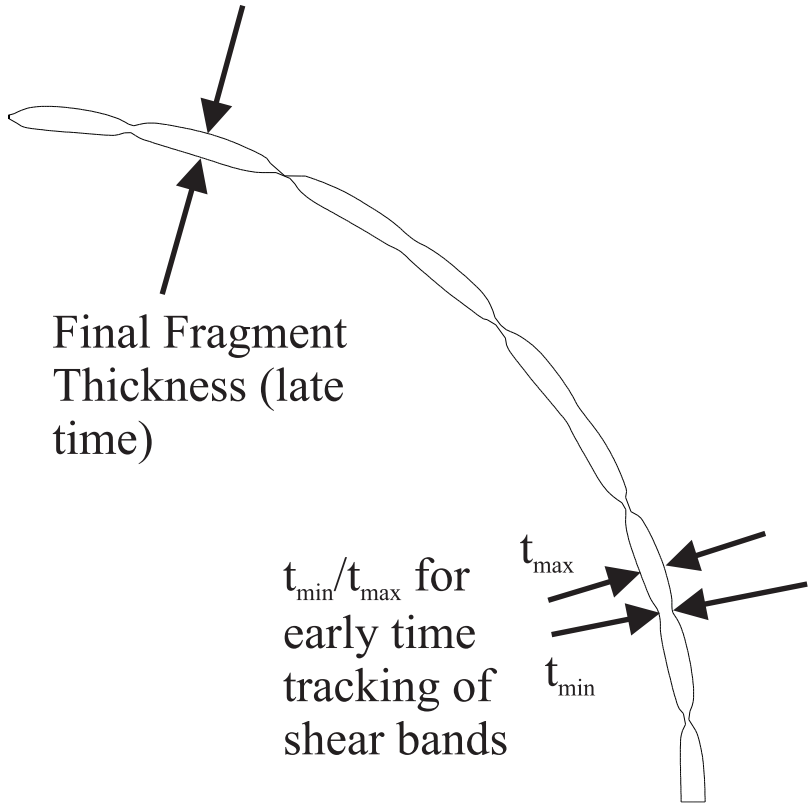
- **Axisymmetric FEM model**
  - **ABAQUS Explicit + VUMAT**
  - **Adiabatic Heating**
  - **HE burn, JWL EOS**
  - **Matches data**
  - **Wrong plane for shear bands**

Plane Strain Model



- Pressure load instead of HE elements
  - carefully extracted from axisymmetric contact forces
- Refined mesh to capture shear banding

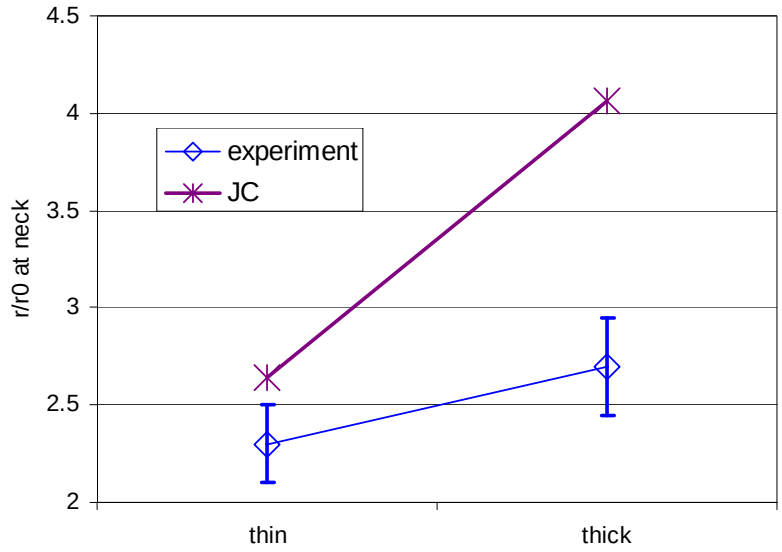
Quantifying Model Results



- Track final fragment thicknesses
  - Plateaus quickly
  - Unambiguous
  - No fragments for energetic shots
- t_{min}/t_{max} = 0.9
  - Compare with optical record of perturbation appearance

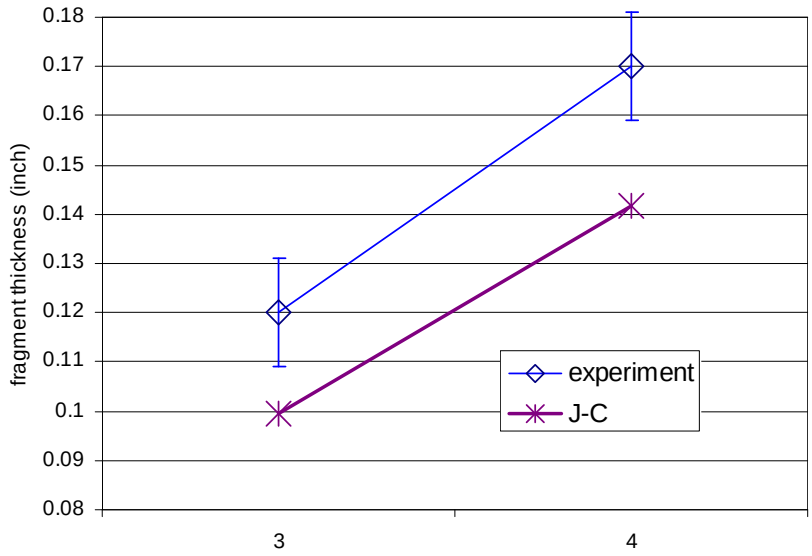
Model Predictions - Johnson-Cook

ASME 1999



Big cylinders

necking too late



Small Cylinders

fragments too thin (=necking too late)

FEM with Johnson-Cook constitutive law predicts shear banding too late in time

MTS constitutive model

- **Physically realistic**
- Mechanical Threshold Stress is internal state variable (as compared to just strain, strain rate, temperature)
- Evolution controlled by thermally activated interaction of dislocations with obstacles

$$\frac{\sigma}{\mu} = \frac{\sigma_a}{\mu} + S_i(\dot{\varepsilon},T)\frac{\hat{\sigma}_i}{\mu_0} + S_\varepsilon(\dot{\varepsilon},T)\frac{\hat{\sigma}_\varepsilon}{\mu_0}$$

μ is shear modulus = *f(T)*
σ_a is athermal, rate independent term (interaction of dislocations with long-range barriers, like g.b.'s)

$$S_i(\dot{\varepsilon},T) = \left\{1 - \left[\frac{kT}{\mu b^3 g_{0i}}\ln\left(\frac{\dot{\varepsilon}_{0i}}{\dot{\varepsilon}}\right)\right]^{1/q_i}\right\}^{1/p_i}, \sigma_i = \text{constant}$$

$\imath$ = intrinsic barriers (e.g. Peierls stress), non-evolving

$$\frac{d\hat{\sigma}_\varepsilon}{d\varepsilon} = \theta_0(\dot{\varepsilon},T)\left[1 - \frac{\tanh\left(\alpha\frac{\hat{\sigma}_\varepsilon}{\hat{\sigma}_{es}(\dot{\varepsilon},T)}\right)}{\tanh(\alpha)}\right]$$

ε = strain-evolving
- Dislocation accumulation (strain hardening)
- Dislocation annihilation (recovery)
- Rate sensitivity

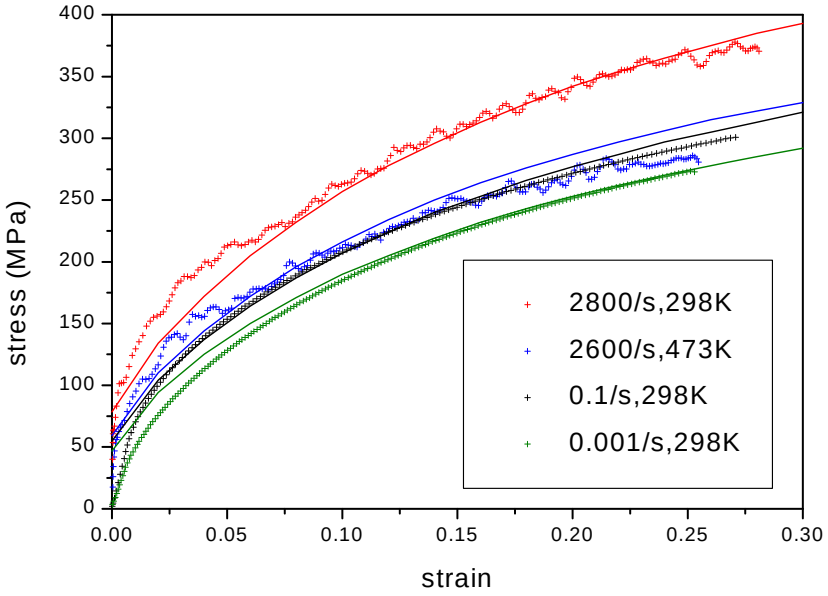
MTS model

- 4 tests with our Copper
  - 2 low rate, T_{room} tensile
  - 2 high rate Hopkinson bar, T_{room} & 200 C

MTS fit excellent

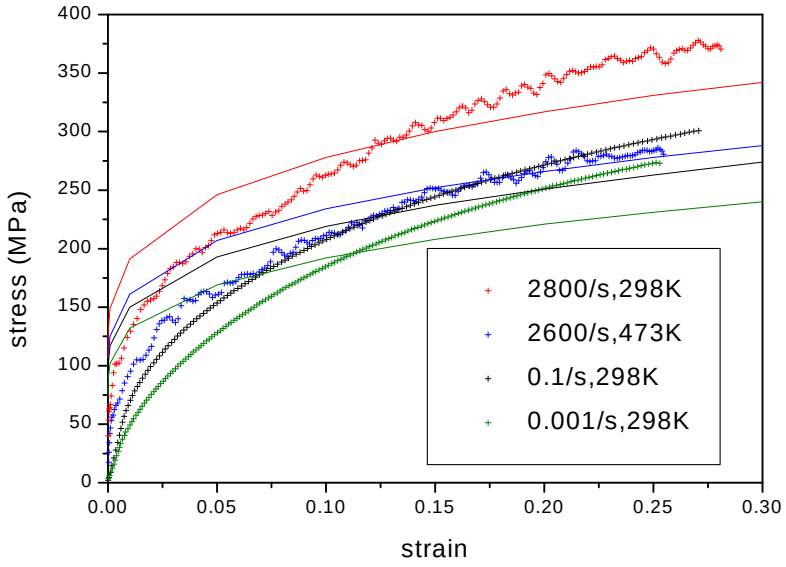
• Use well-studied Copper parameters, slight changes only for our material

• Well calibrated for higher strains

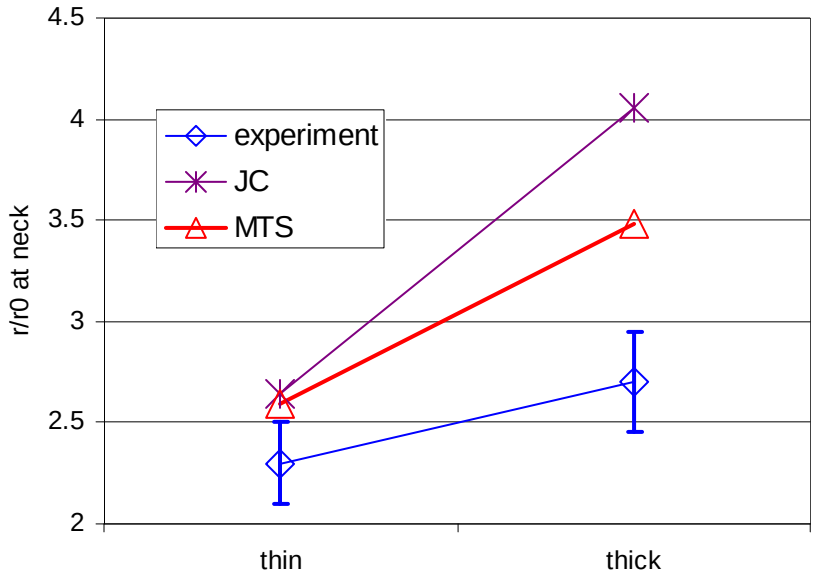


Johnson-Cook fit poor

• Does not capture physical behavior

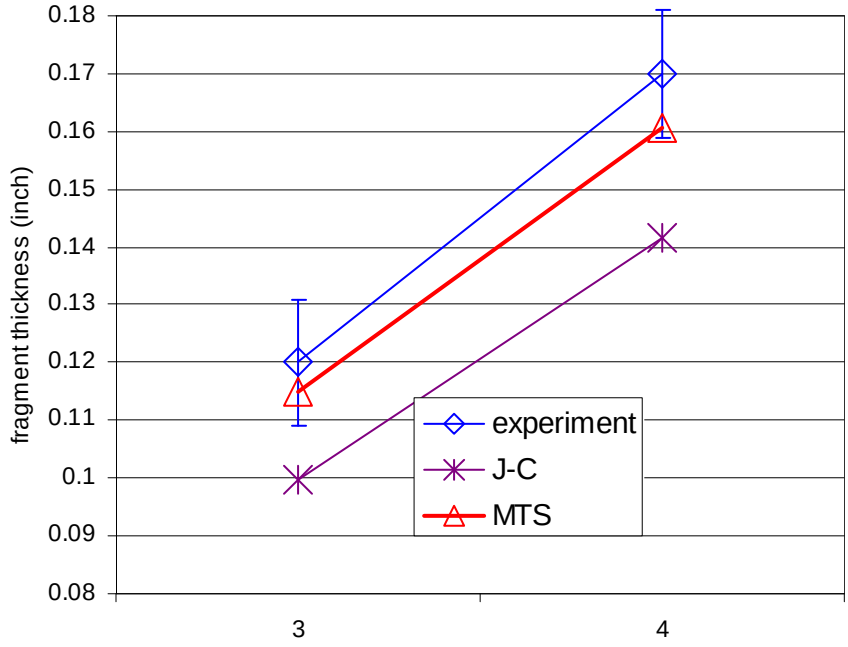


MTS model



Big cylinders

necking too late



Small Cylinders

fragments only slightly too thin

Better - but not quite

Modeling Approach

Homogeneous Models Don't Work

- **Shear bands come later than observed**

Initial Approach

- **Void growth model (Gurson)**
- **Predictions good *if* use random spatial variation in initial void volume fraction**
- **Voids not observed experimentally**

Mechanisms (Meyers; Curran, Seaman, & Shockey)

- **Second phase particles & carbides form voids**
- **Dislocation pileup & release at grain boundaries**
- **Grain size inhomogeneity**
- **Textural localization**

ALL HAVE GRAIN SIZE LENGTH SCALE

MTS athermal stress

- **Long range (i.e., grain size) interactions**
- **depends on grain size** (Gourdin & Lassilla 1991)

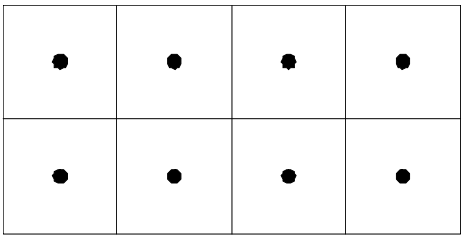
$$\sigma_a = \frac{0.278}{d^{1/2}}, d \text{ in m}, \sigma \text{ in MPa}$$

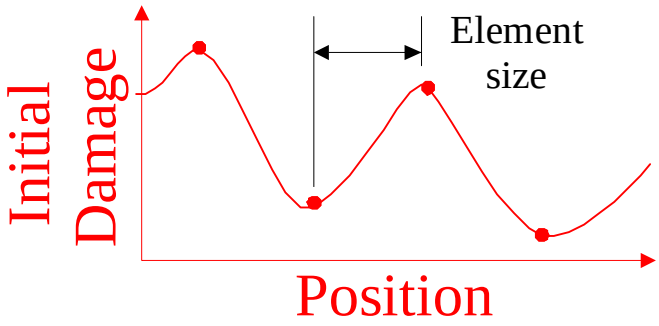
Initialize with σ_a variation on grain size scale

Initializing Random Damage

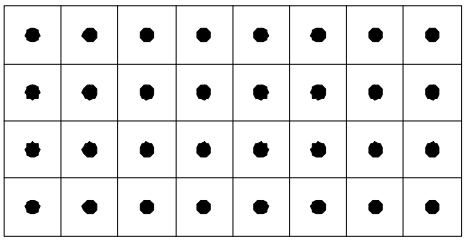
RANDOM NUMBERS BY ELEMENT

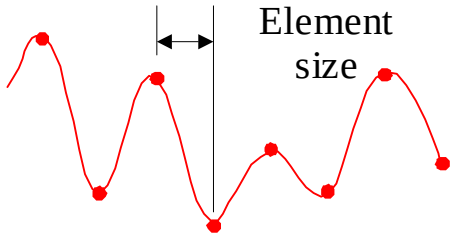
- = Element Integration Point



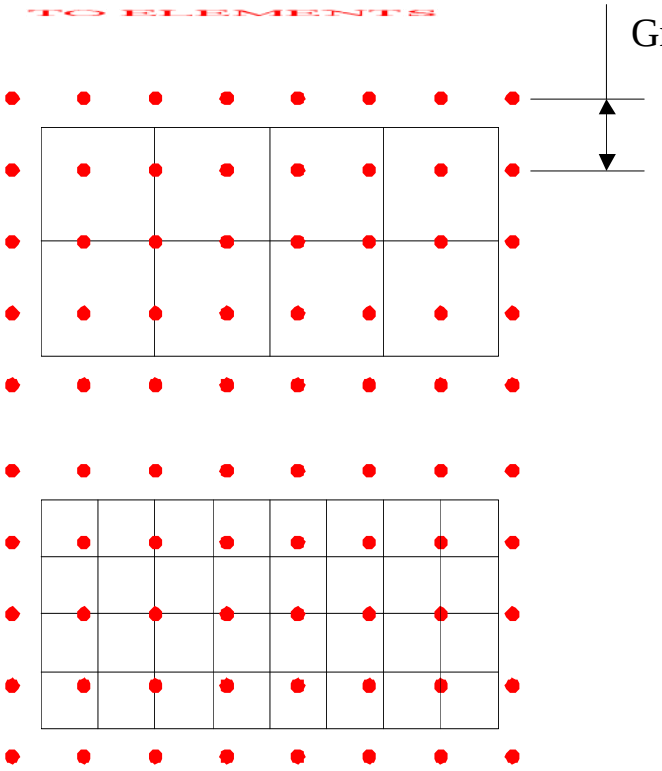


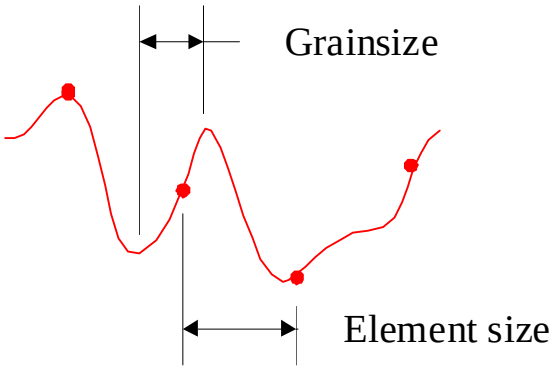
Refined Mesh

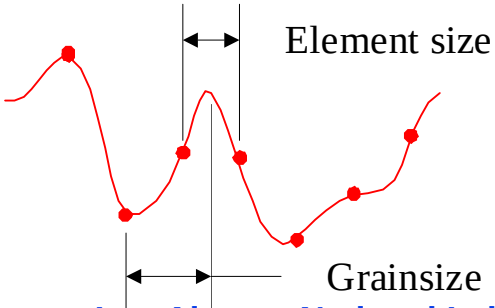




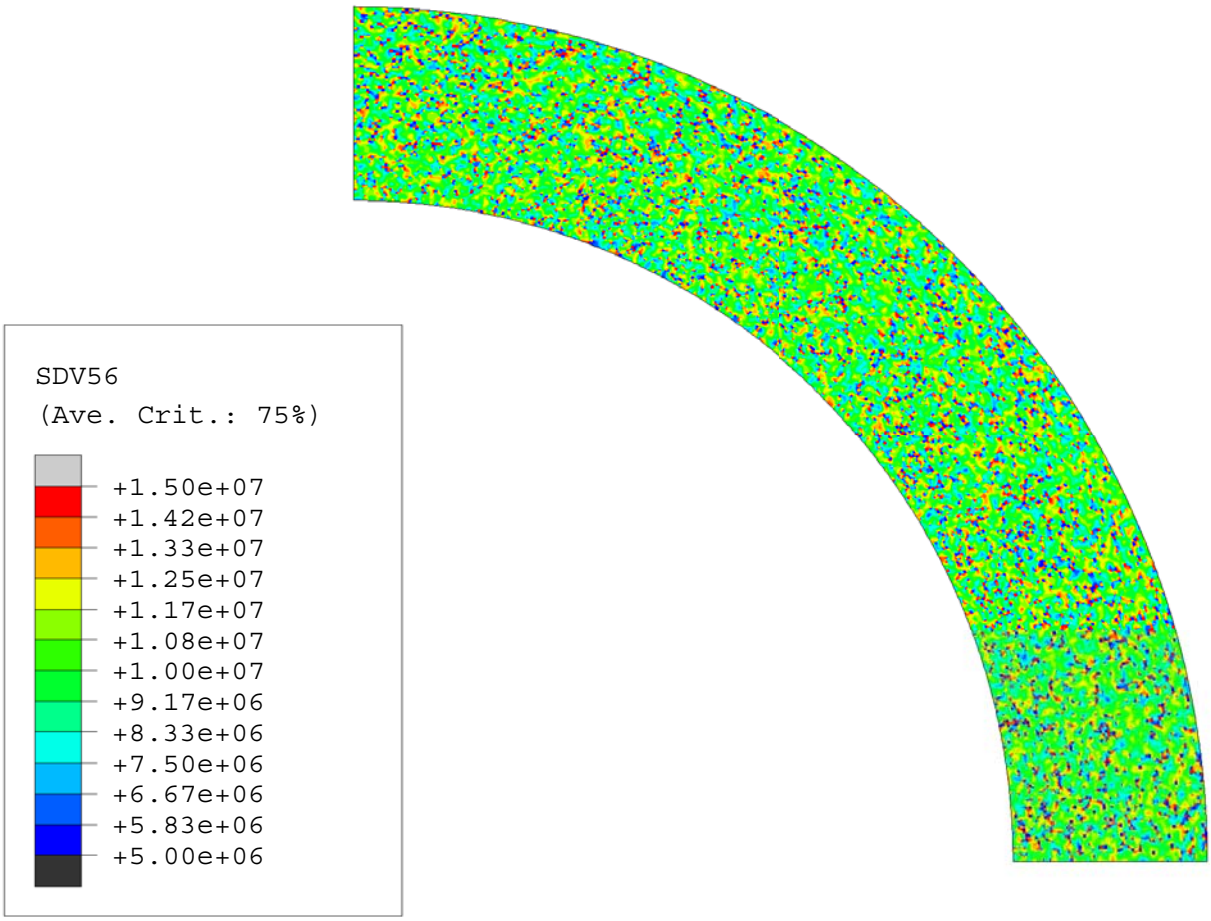
BACKGROUND GRID INTEGRATED TO ELEMENTS





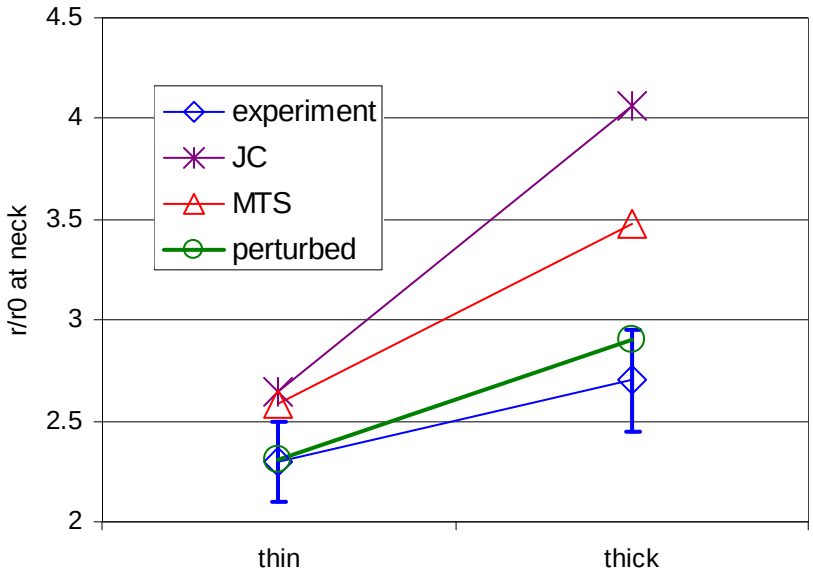


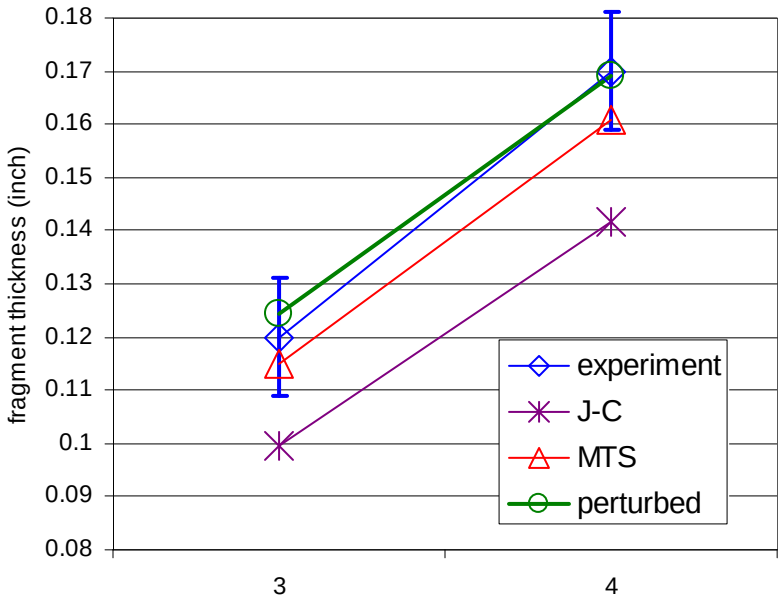
Initialized Athermal Stress



- Randomly initialized σ_a
- Element size = 90 μm
- 5MPa to 15MPa

Predicted fragment sizes

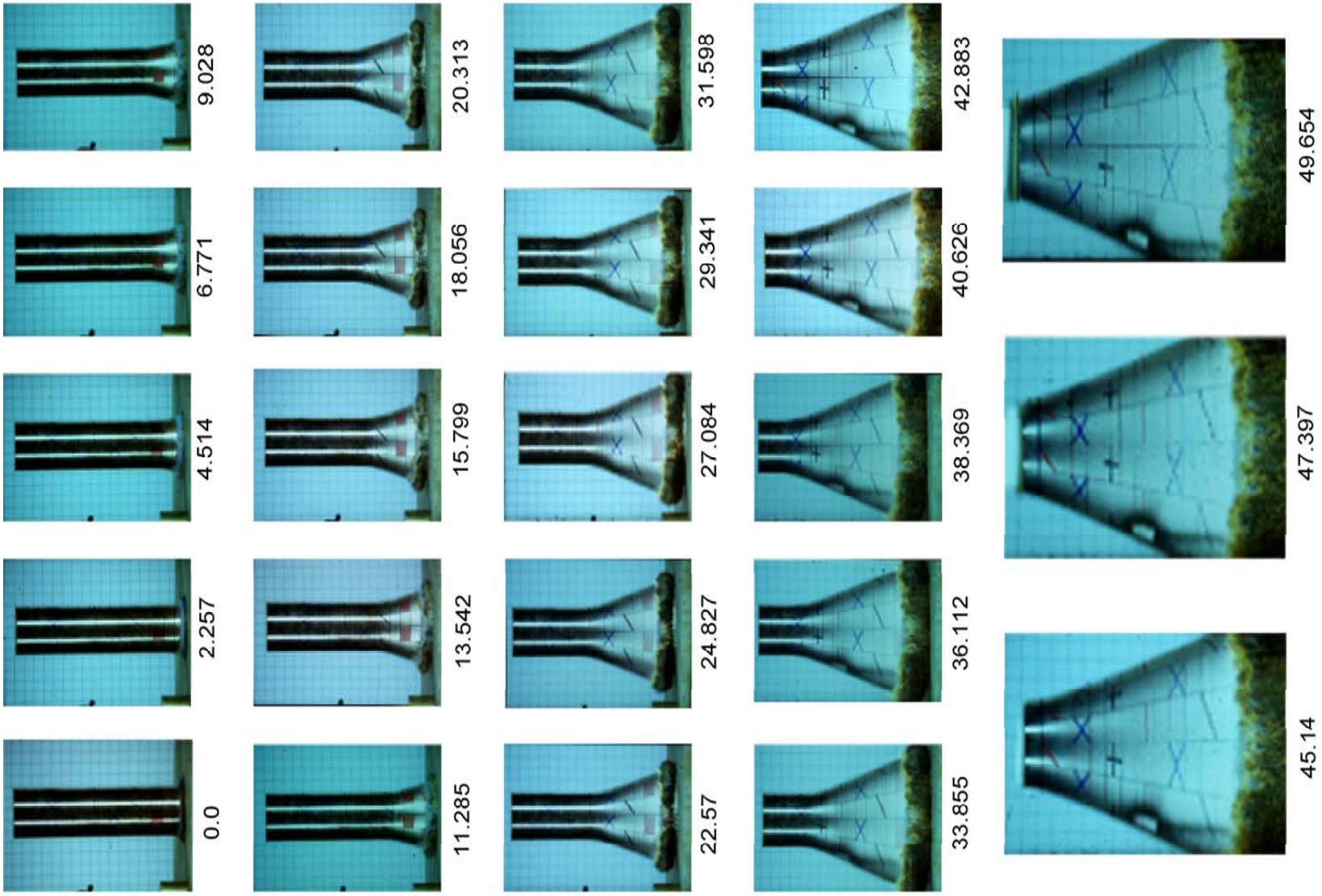




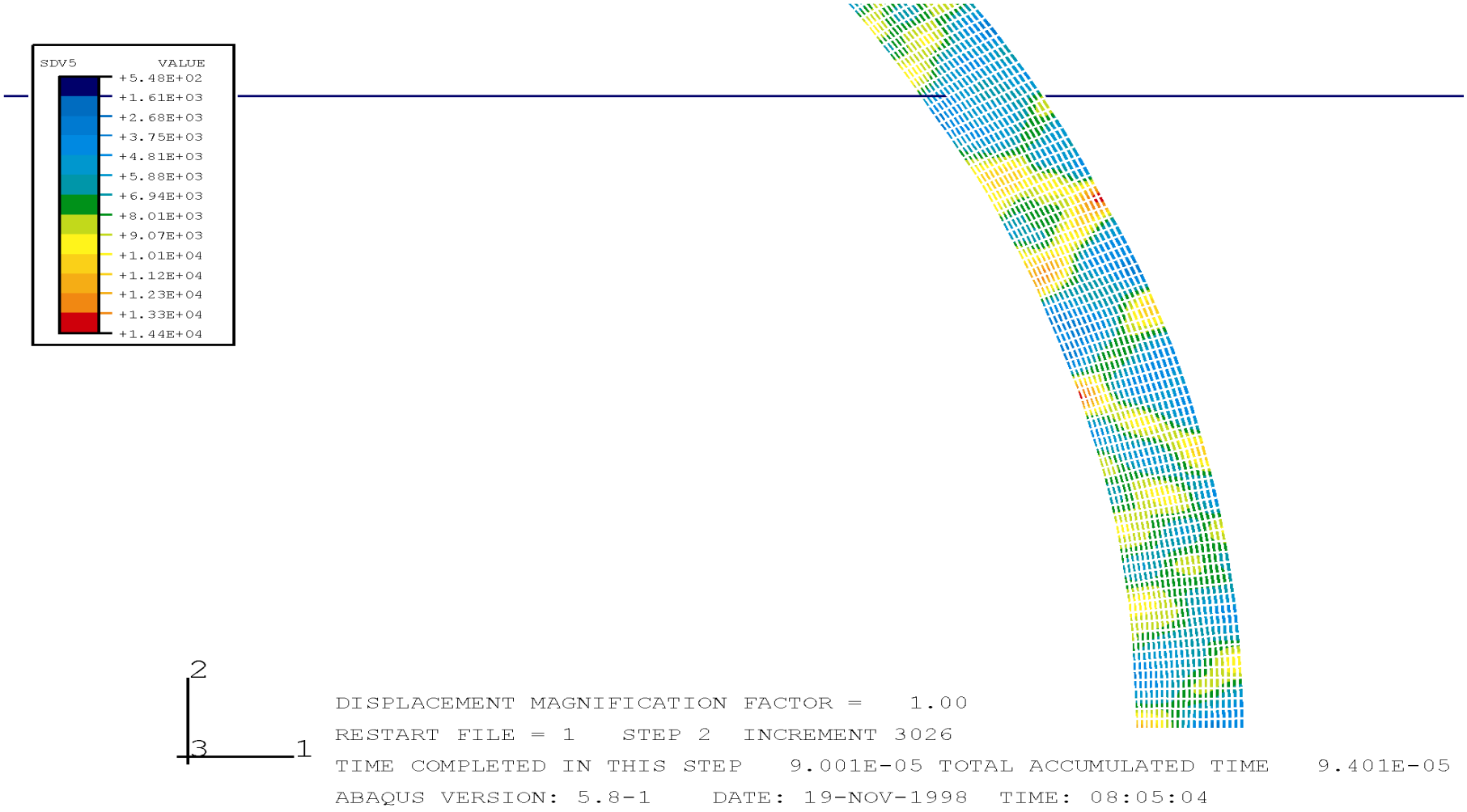
"perturbed" = random spatial variation in strength

- Conclusion: perturbations important, probably grain-sized
- Very speculative: much more work needed

Framing Camera Pictures

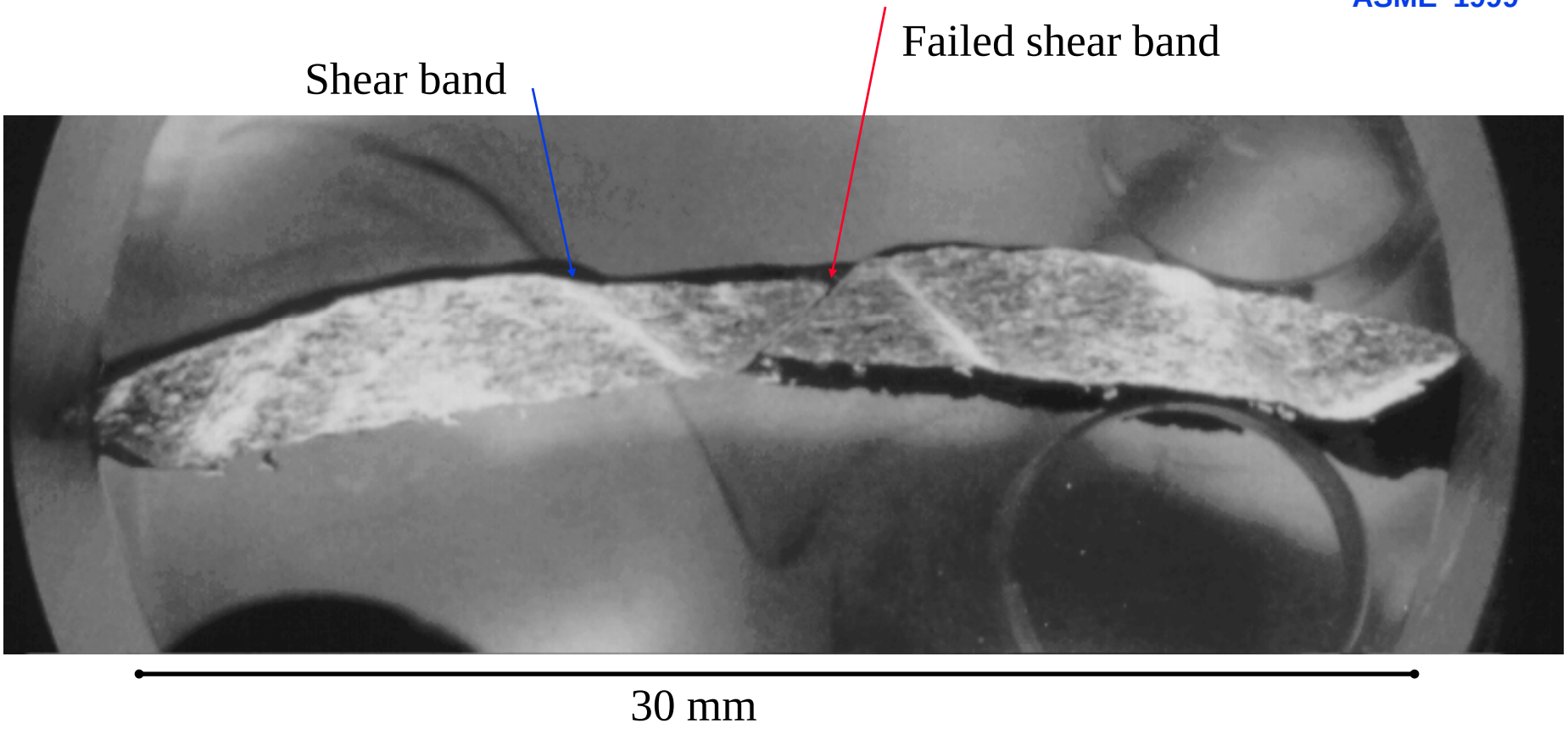


Plane Strain Model



- Beginning of shear localization
- Equivalent plastic strain rate plotted here

Experiments - Recovered Fragments



- **Cross-Section of soft-catch fragment, smaller cylinders only**
- **Many Shear bands evident**
- **Data: Shear band spacing, fragment thickness gives upper bound on final failure**