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*Title:* Damage Initialization for Modeling of Dynamic Shear Banding


*Author(s):* Michael B. Prime, ESA-EA
Rick L. Martineau, DX-5
Carl R. Necker, Jr., MST-6



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# Damage Initialization for Modeling of Dynamic Shear Banding

**Michael B. Prime, Rick L. Martineau, Carl R. Necker, Jr.**
prime@lanl.gov
Los Alamos National Laboratory, Los Alamos, NM, 87545

Abstract:

This research combines experiments and finite element modeling to predict the development of shear bands in rapidly expanding thin shells. Magnetic flux compression generators rely on the expansion of thin ductile shells to generate magnetic fields. This presentation focuses on the use of a microvoid damage model in order to model these shear bands and on the strong effect of the damage initialization on the timing of the shear band formation. It is proposed that the most physically realistic model of initial void volume fraction is a random variation with a characteristic length corresponding to the material grain size.

Thin cylindrical copper shells were subjected to internal explosive detonations and expanded outwardly at strain-rates on the order $10^4$ $s^{-1}$. The outer surface of the shell was photographed using a fast framing camera. At approximately 150% strain, multiple plastic instabilities were visible on the surface of these shells in a quasi-periodic pattern. Recovered fragments were metallographically examined to provide quantitative information on shear bands.

A viscoplastic constitutive model was formulated to model the high strain-rate expansion and provide insight into the development of shear bands. The model used the Mechanical Threshold Stress (MTS) constitutive model, the Mie-Grüneisen equation of state, and a modified Gurson yield surface. The model was implemented as a user material subroutine into the ABAQUS/Explicit commercial finite element code.

Predictions with a purely homogeneous material failed to predict shear banding correctly. The model predictions predicted the onset of shear banding too late and predicted the final thickness of fragments as too thin. It was realized that on the grain size scale the material is not homogeneous. The athermal stress term in the MTS model is known to vary with grains size. Modeling a variation in this term on the grain size scale greatly improved the prediction of shear banding.

A method for initializing the athermal stress variation using a physical length scale was developed. A set of random numbers varying over a specified range was generated and assigned to a rectangular grid with the spacing equal to the material grain size. Using spline interpolation and 2-D numerical integration, this grid was used to calculate the initial VVF for the elements in the model. This method was found to result in a different value for the shear band initiation strain than with the random numbers applied directly to each element. However, the convergence is slow, requiring about 4 elements per grain in a 2-D model.

# Modeling of Dynamic Shear Banding

Michael B. Prime[1], R. L. Martineau[2], & C. R. Necker, Jr[3].

[1] Engineering Sciences & Applications Division
[2] Dynamic Experimentation Division
[3] Materials Science & Technology Division

Los Alamos National Laboratory
Los Alamos, New Mexico, USA

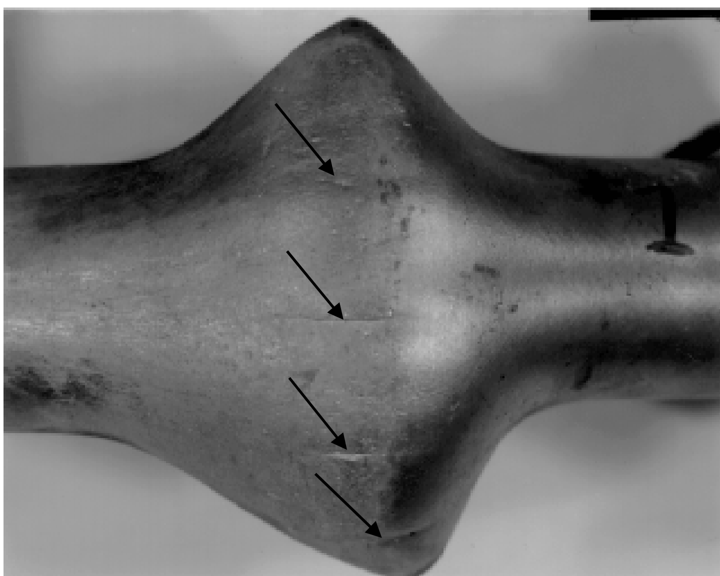
- Introduction
- Experiments
- Analysis

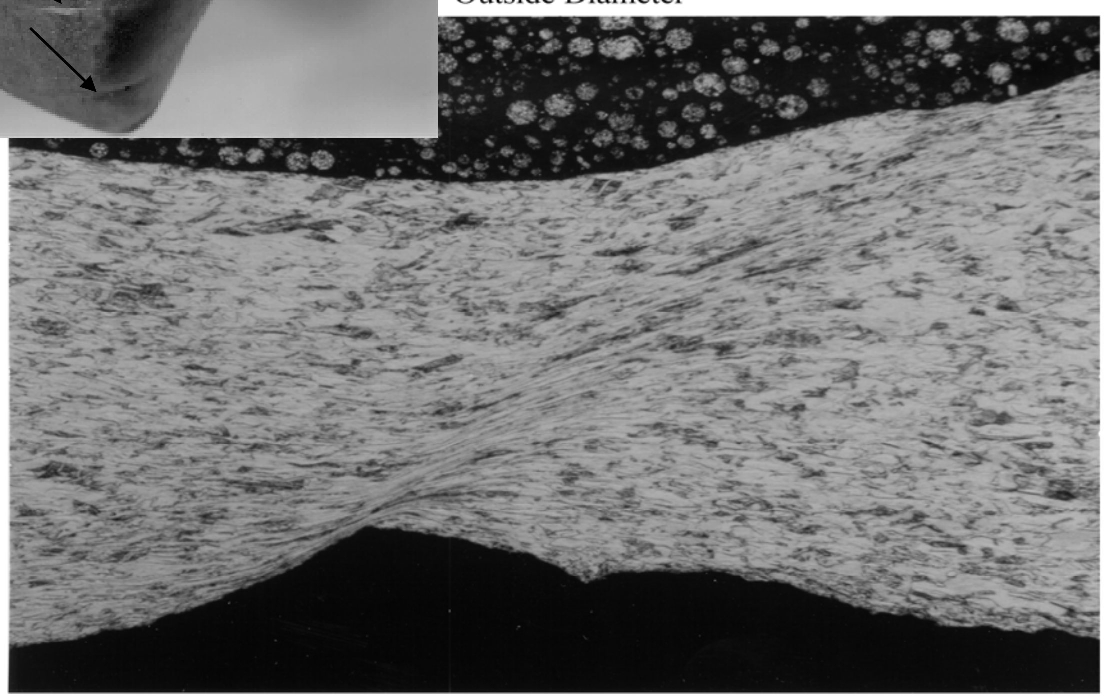
# Introduction



- 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





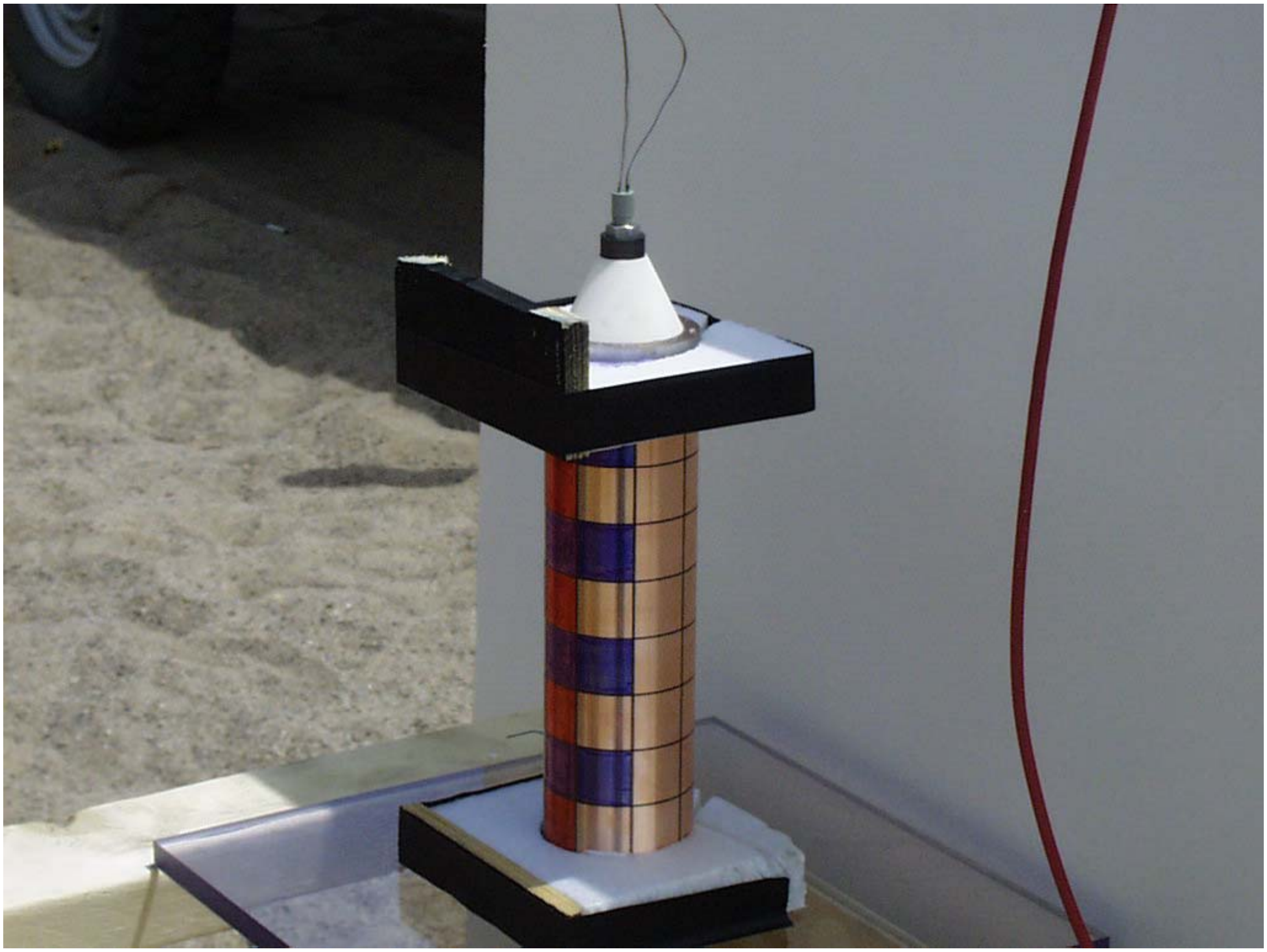
# Introduction



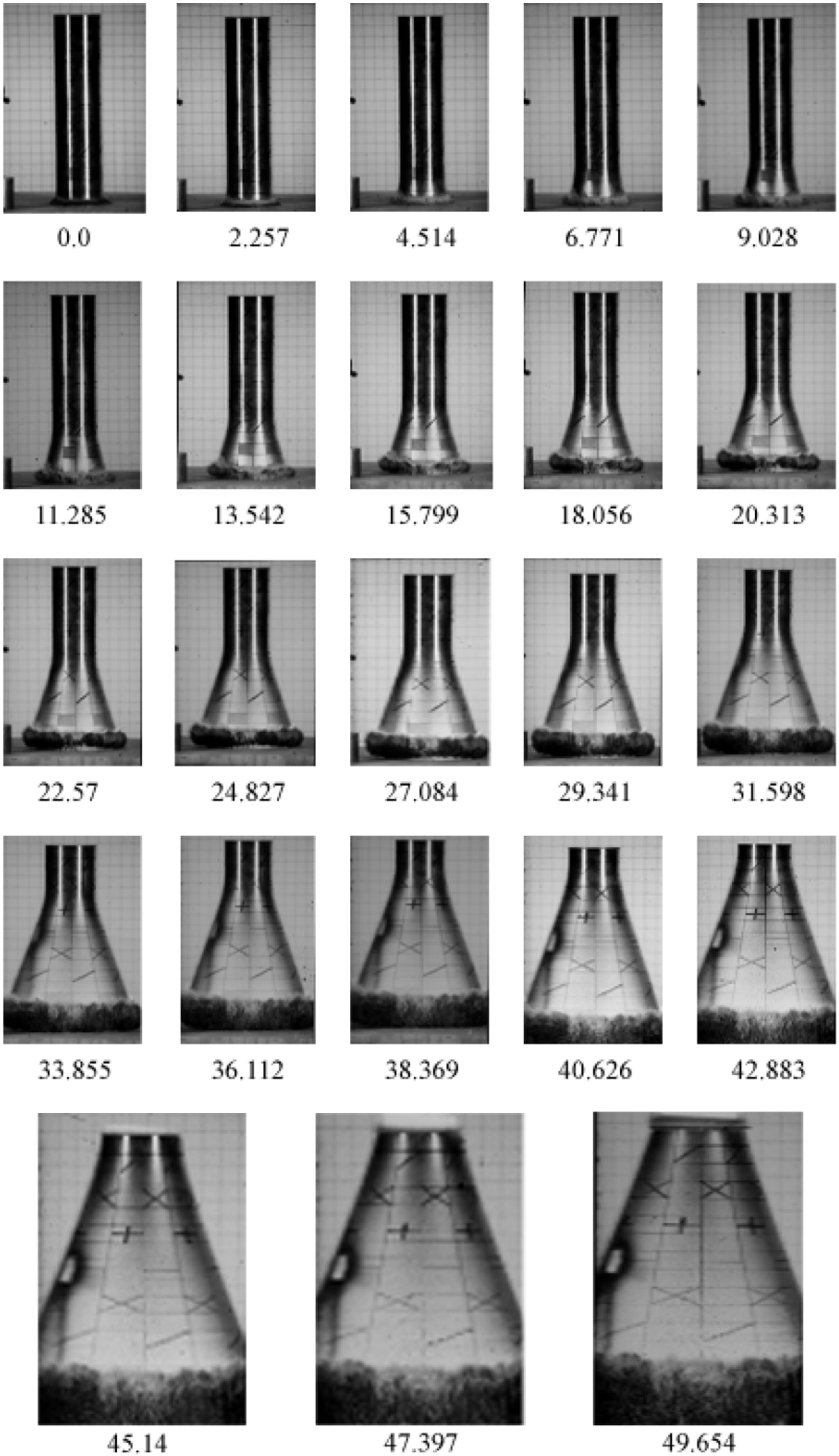
- Shear Banding in Dynamically Expanding Shells
  - Flux compression generators
  - Explosive Forming
  - Explosive Containment vessels
  - Explosive Bonding
- Desire to Predict Timing & Evolution
  - Finite element modeling (explicit)

# Cylinder Experiments



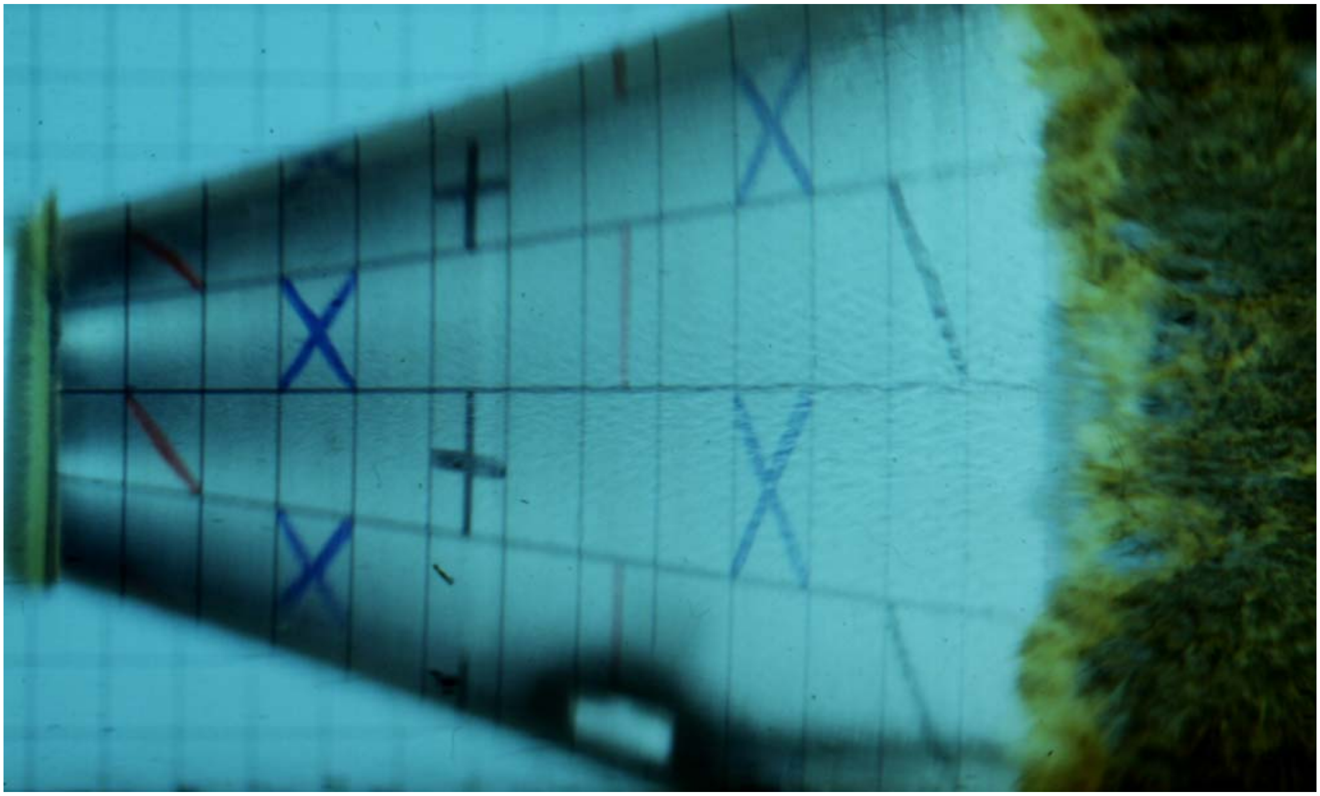


- Explosively-loaded, end-detonated
- Copper: grainsize: 40µm (large cylinders), ~100µm (small)
- 2 tests: 4" (100mm) ID, 16" (400mm) long, PBX-9501 (energetic HE) filled, 0.1" & 0.2" (2.5 & 5mm) wall
- 2 tests: 2" (50mm) OD, 8" (200mm) long, ~ 0.25" (6mm) annulus of nitromethane, 0.3 " & 0.36 " (7.6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

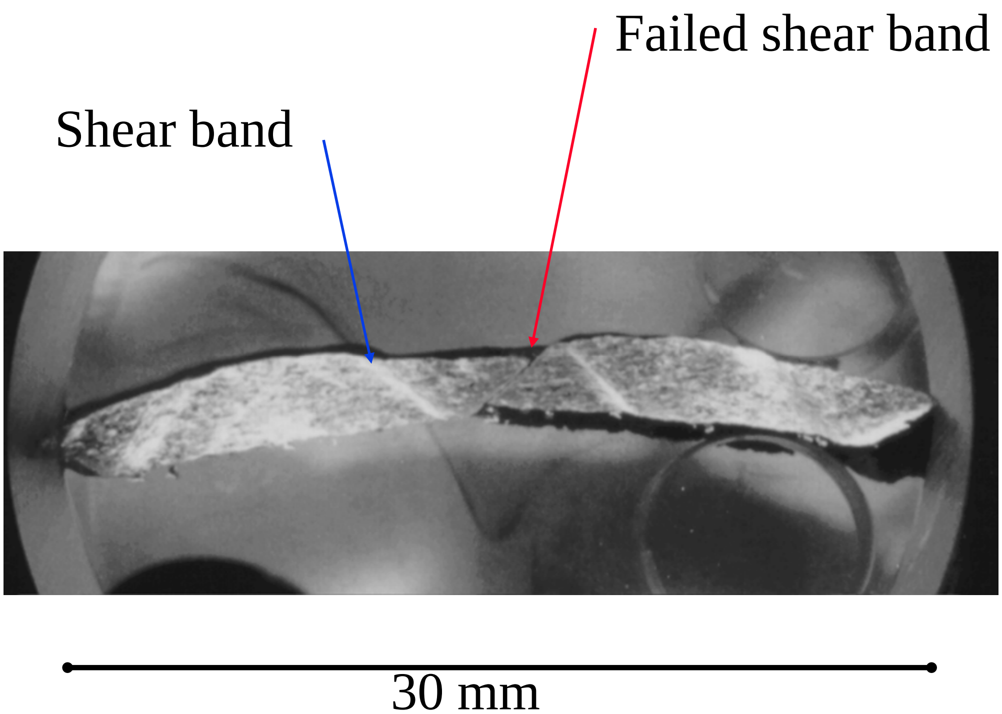




- **Diagnostics:**
  - Fast framing camera (used 3-5 μs frame time)
  - Visar/Fabry-Perot interferometry
- **Uses:**
  - Validate finite element model with disps, velocities
  - Observe shear banding formation on surface, final fracture

# Experiments - Recovered Fragments

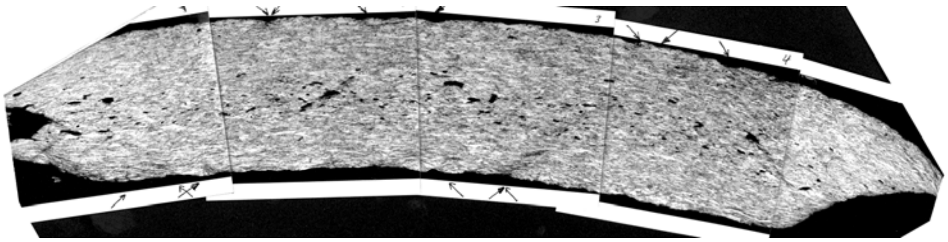





- **Cross-Section of soft-catch fragment, smaller cylinders only**
- **Many Shear bands evident**
- **Data**
  - **Shear band spacing**
  - **fragment thickness gives upper bound on final failure**

# Experiments - Recovered Fragments

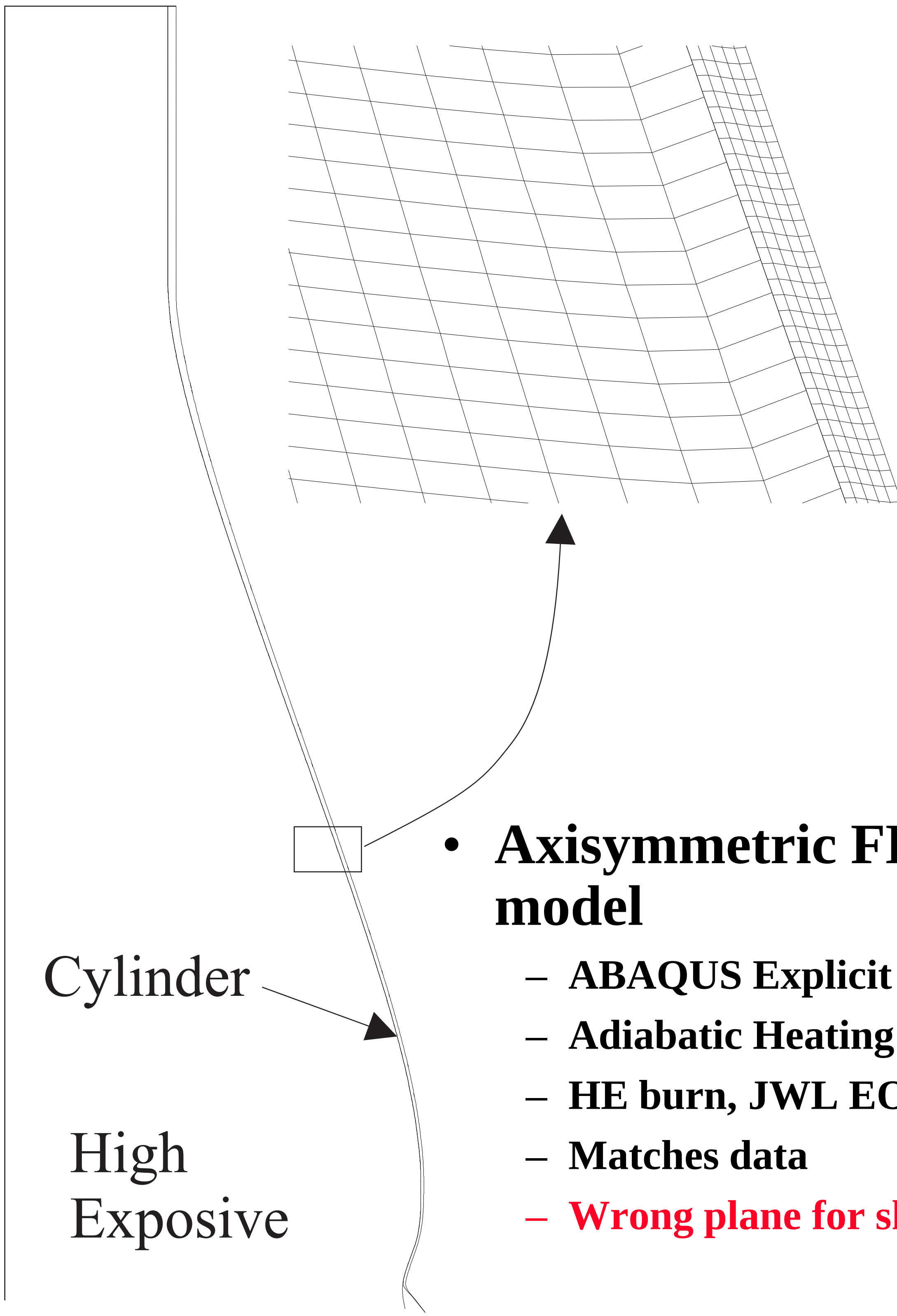




- Same test, 20% thicker cylinder
- Void plane
- Less developed shear bands
- lower strain at failure

# Modeling Approach

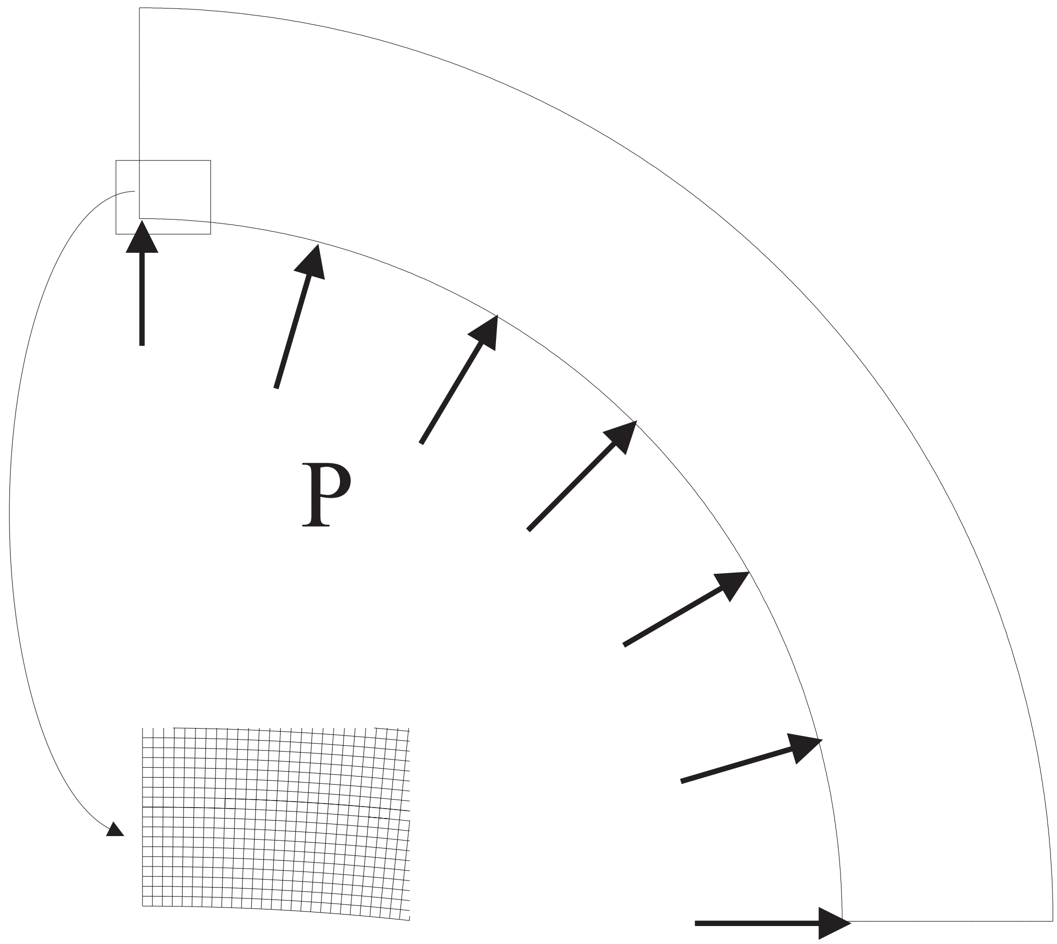





- **Axisymmetric FEM model**
  - **ABAQUS Explicit + VUMAT**
  - **Adiabatic Heating**
  - **HE burn, JWL EOS**
  - **Matches data**
  - **Wrong plane for shear bands**

# Plane Strain Model

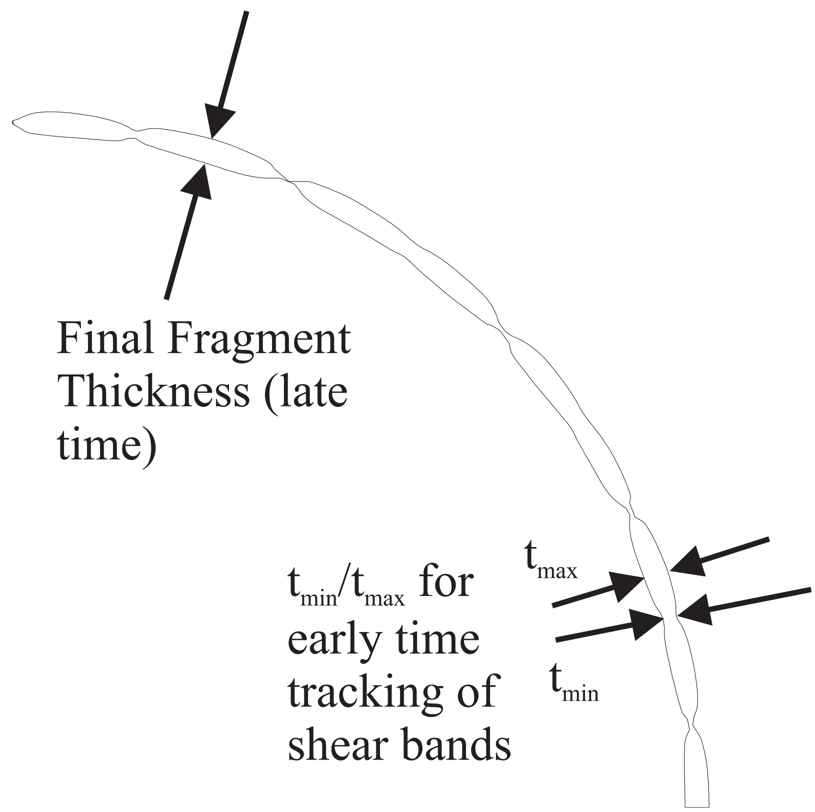





- Pressure load instead of HE elements
  - carefully extracted from axisymmetric contact forces
- Refined mesh to capture shear banding

# Quantifying Model Results

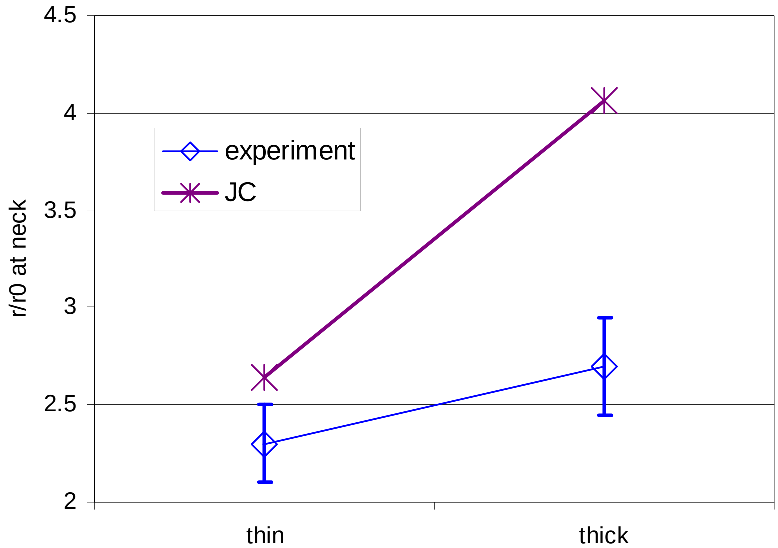





- Track final fragment thicknesses
  - Plateaus quickly
  - Unambiguous
  - No fragments for energetic shots
- $t_{min}/t_{max} = 0.9$
  - Compare with optical record of perturbation appearance

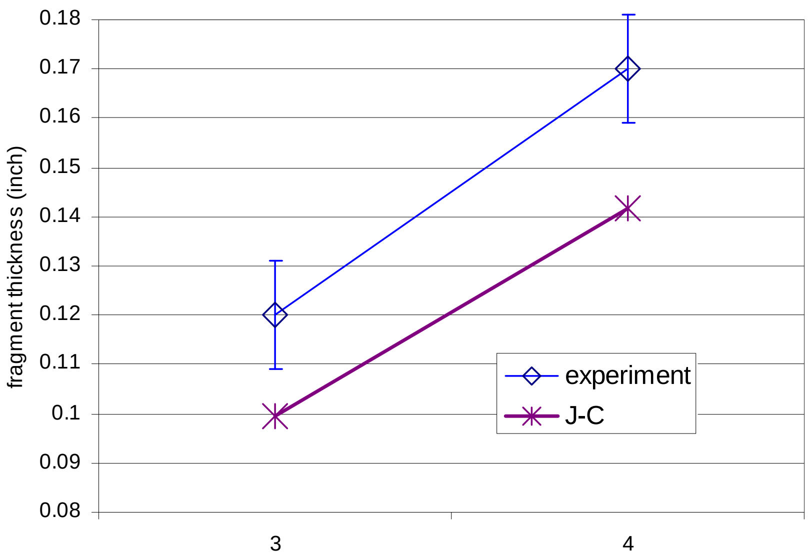
# Model Predictions - Johnson-Cook






<u>Big cylinders</u>

necking too late




<u>Small Cylinders</u>

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)*
$\sigma_a$ is athermal, rate independent term (interaction of dislocations with long-range barriers, like g.b.'s)

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

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

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

$\varepsilon =$ strain-evolving
- Dislocation accumulation (strain hardening)
- Dislocation annihilation (recovery)
- Rate sensitivity

# MTS model

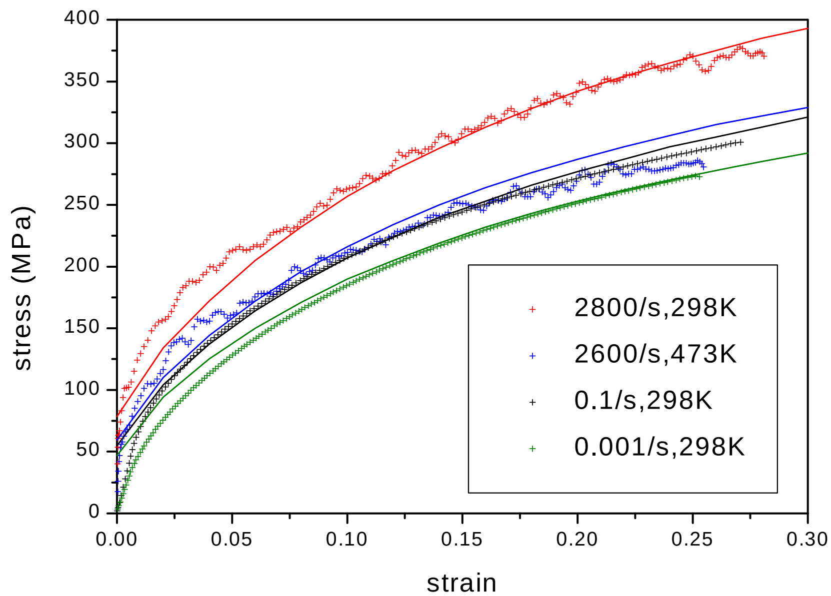


- 4 tests with our Copper
  - 2 low rate, $T_{room}$ tensile
  - 2 high rate Hopkinson bar, $T_{room}$ & 200 C

MTS fit excellent

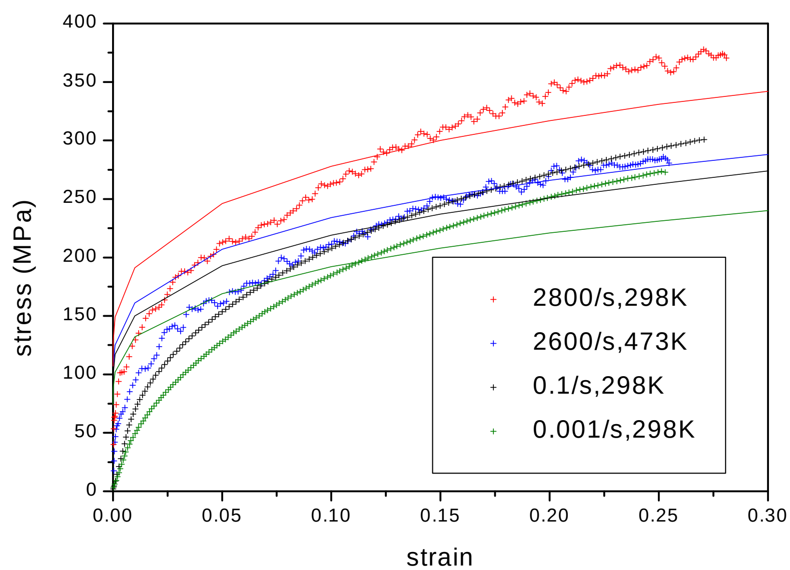
• Use well-studied Copper parameters, slight changes only for our material

• Well calibrated for higher strains



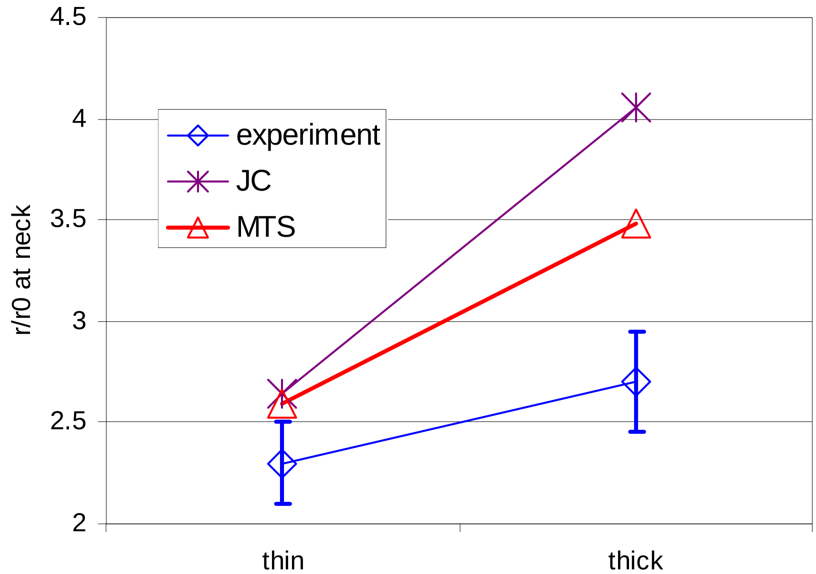

Johnson-Cook fit poor

• Does not capture physical behavior



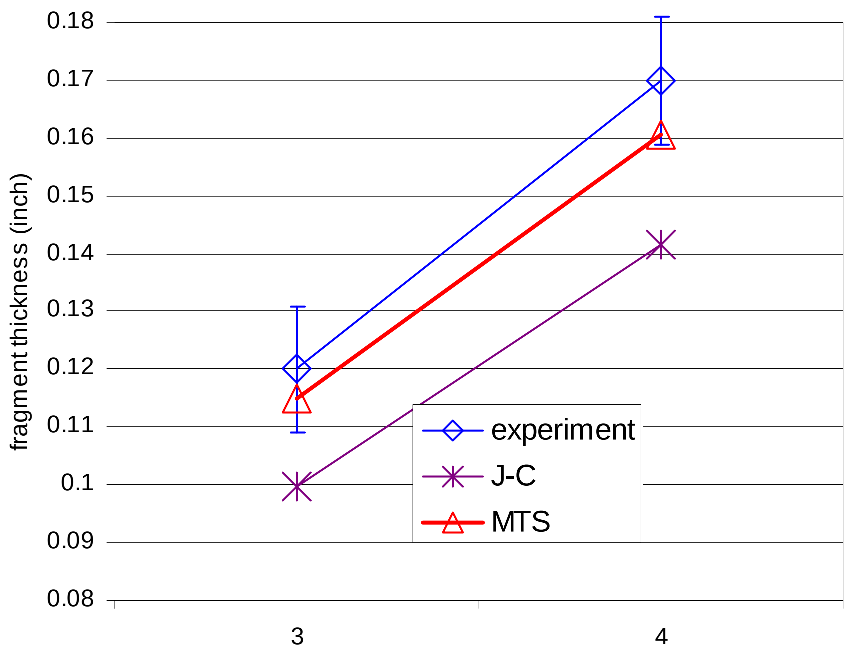
# MTS model






<u>Big cylinders</u>

necking too late




<u>Small Cylinders</u>

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)

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

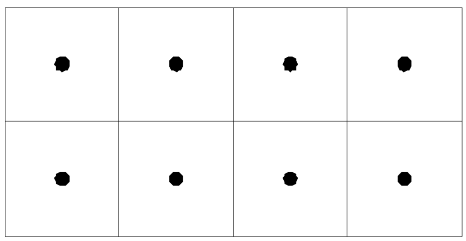
Initialize with $\sigma_a$ variation on grain size scale

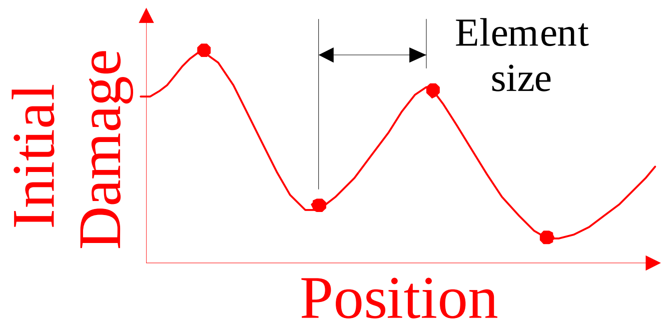
# Initializing Random Damage



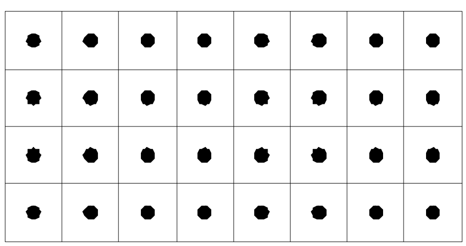
## RANDOM NUMBERS BY ELEMENT

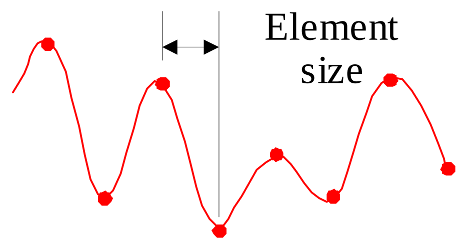
• = Element Integration Point



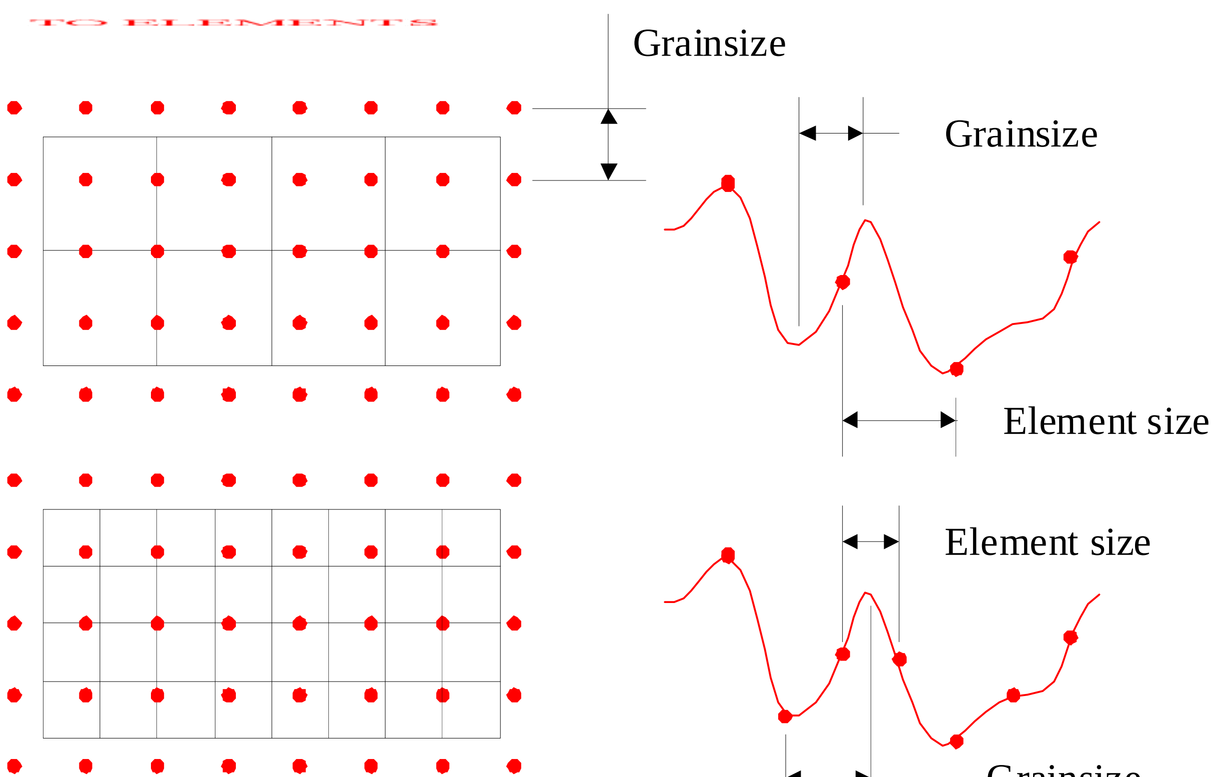



Refined Mesh



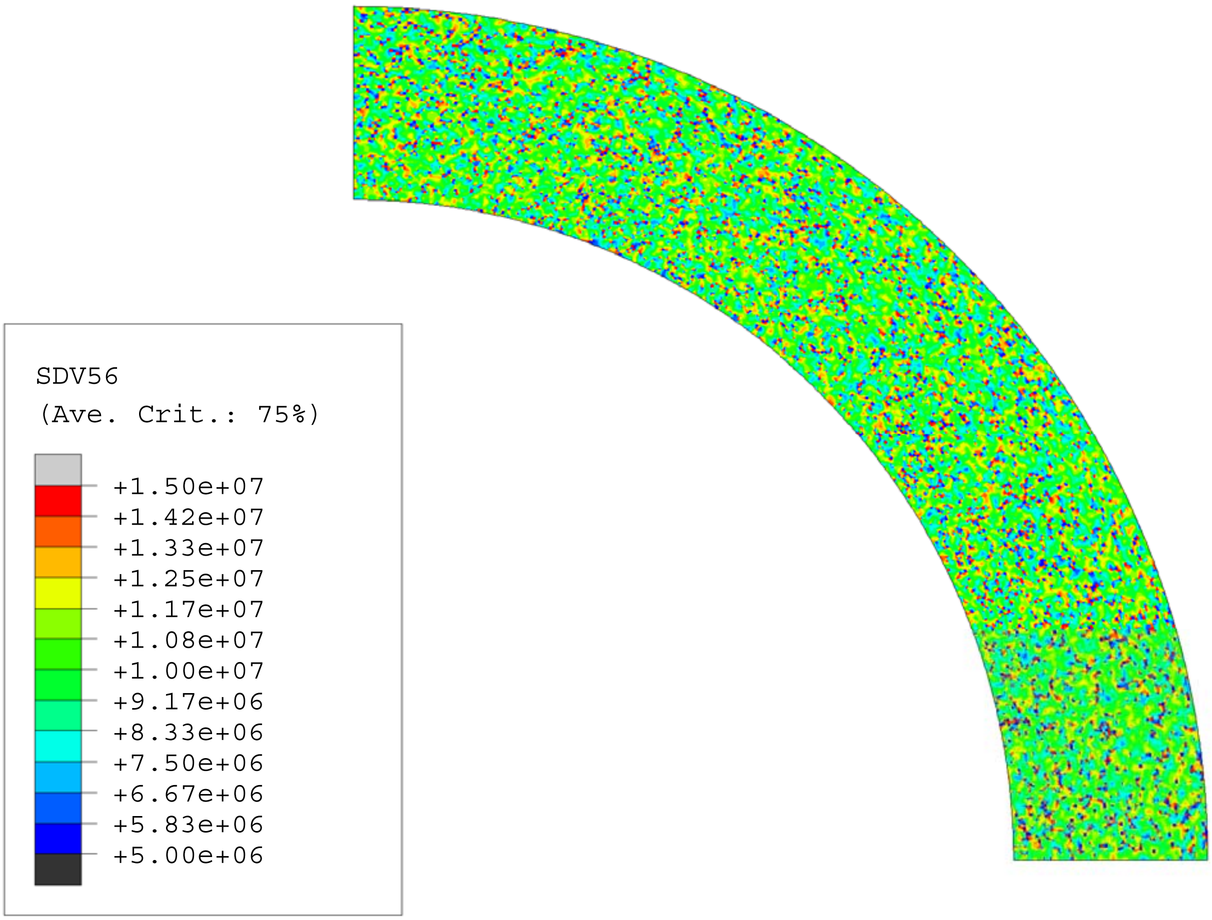



BACKGROUND GRID INTEGRATED TO ELEMENTS



# Initialized Athermal Stress

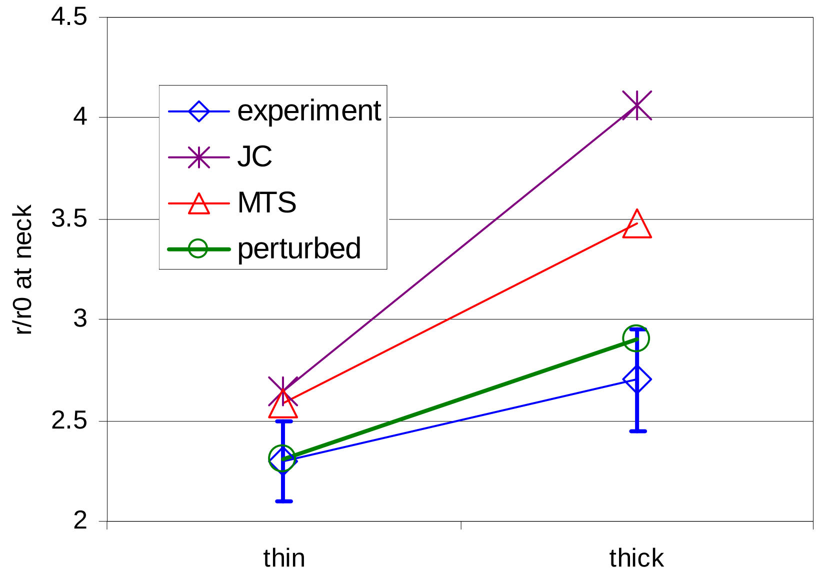


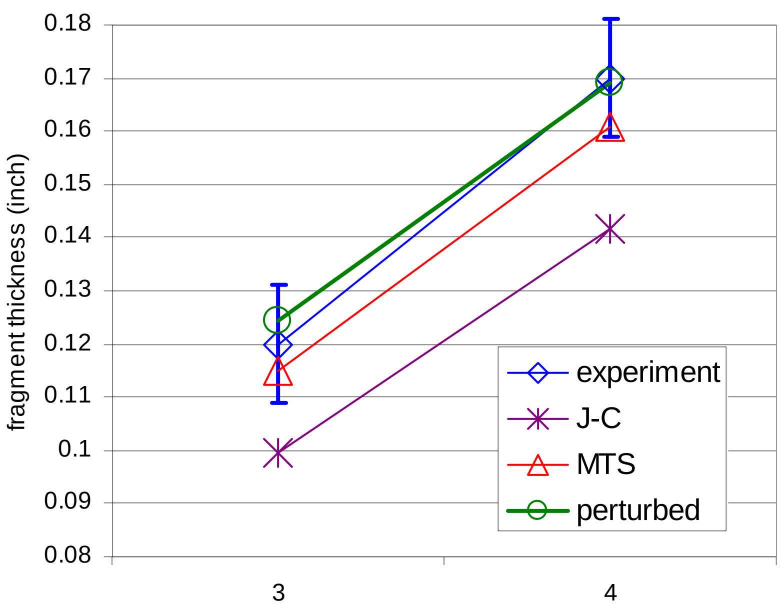



- Randomly initialized $\sigma_a$
- Element size = 90 μm
- 5MPa to 15MPa

# Predicted fragment sizes





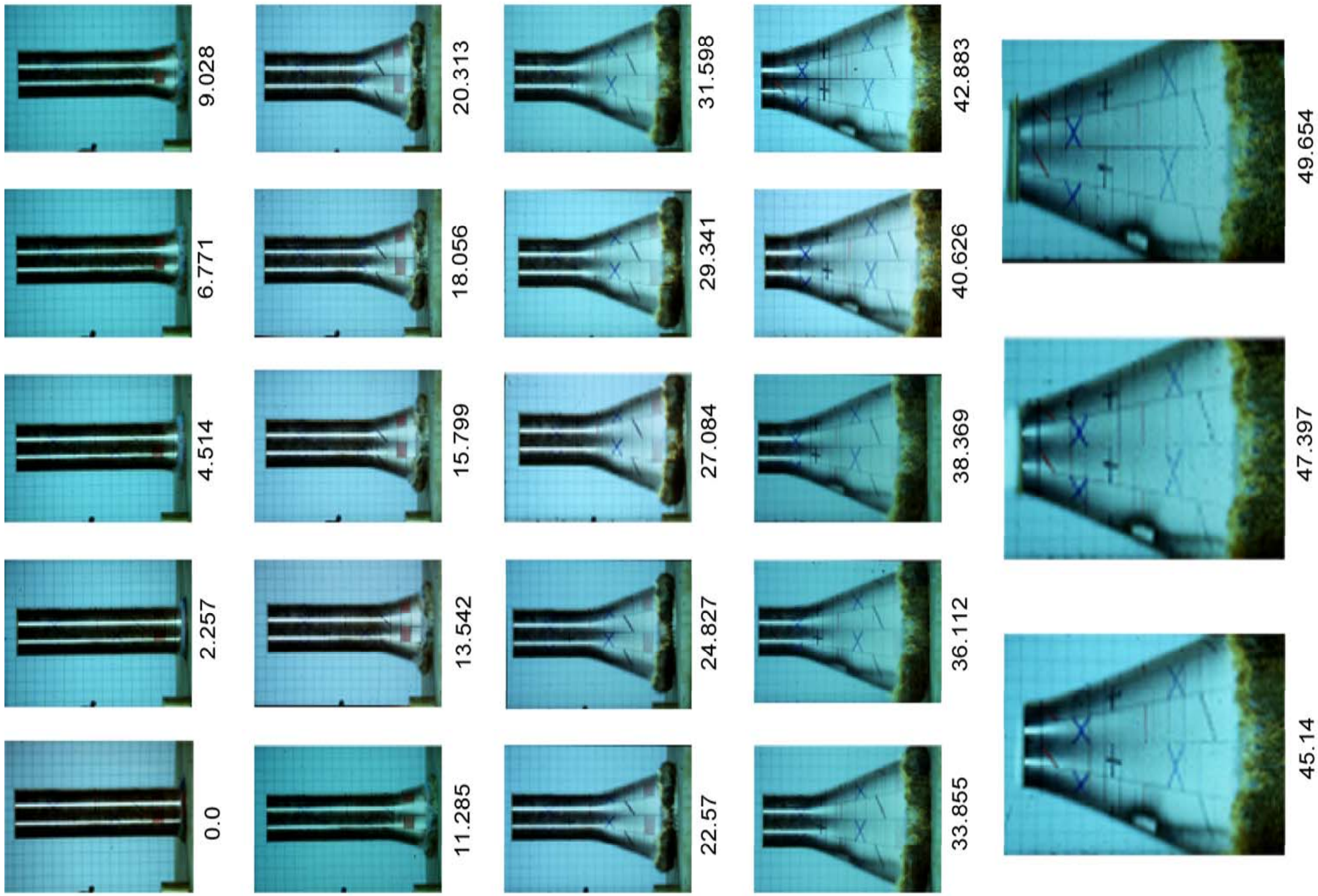




"perturbed" = random spatial variation in strength

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

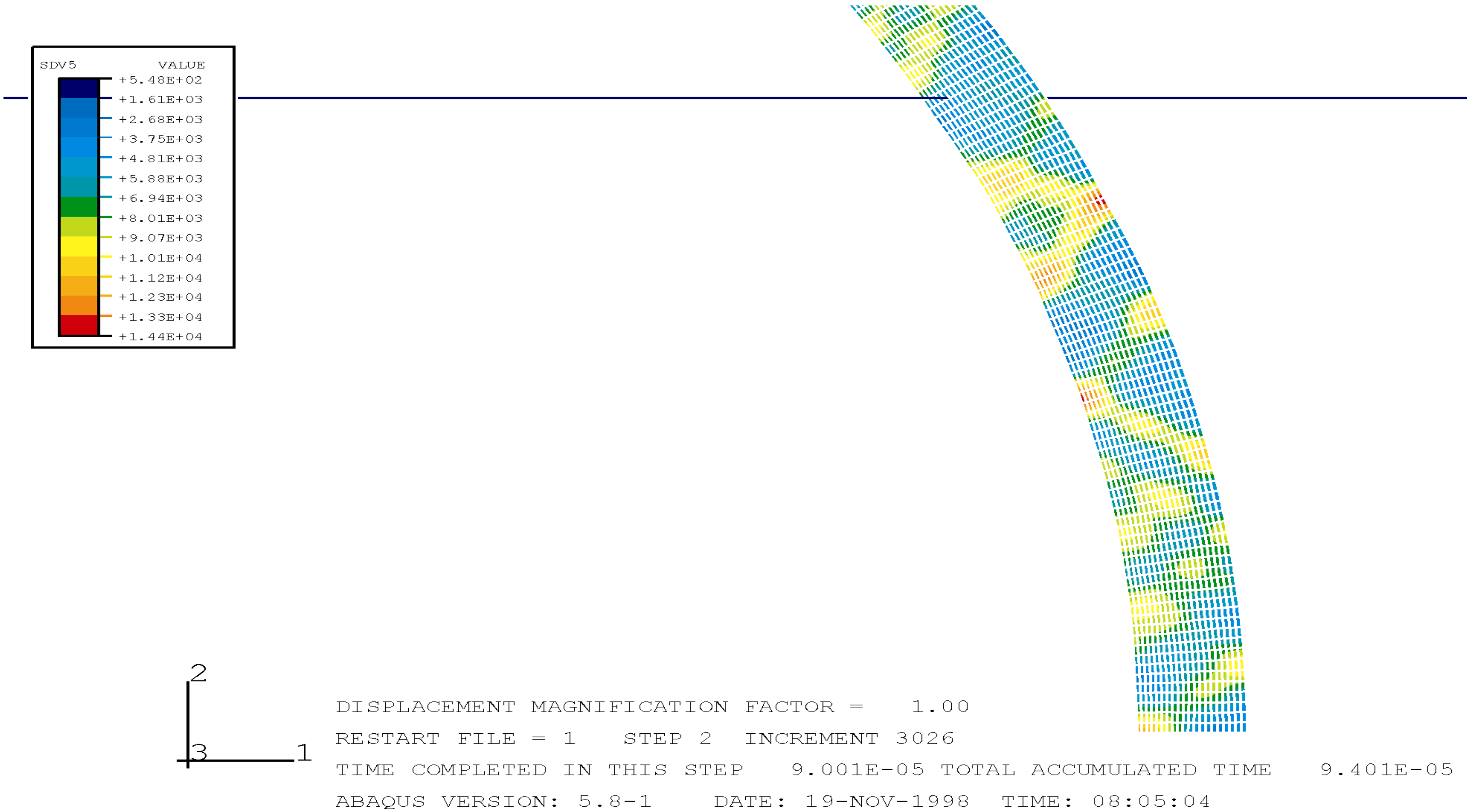
# Framing Camera Pictures





# Plane Strain Model

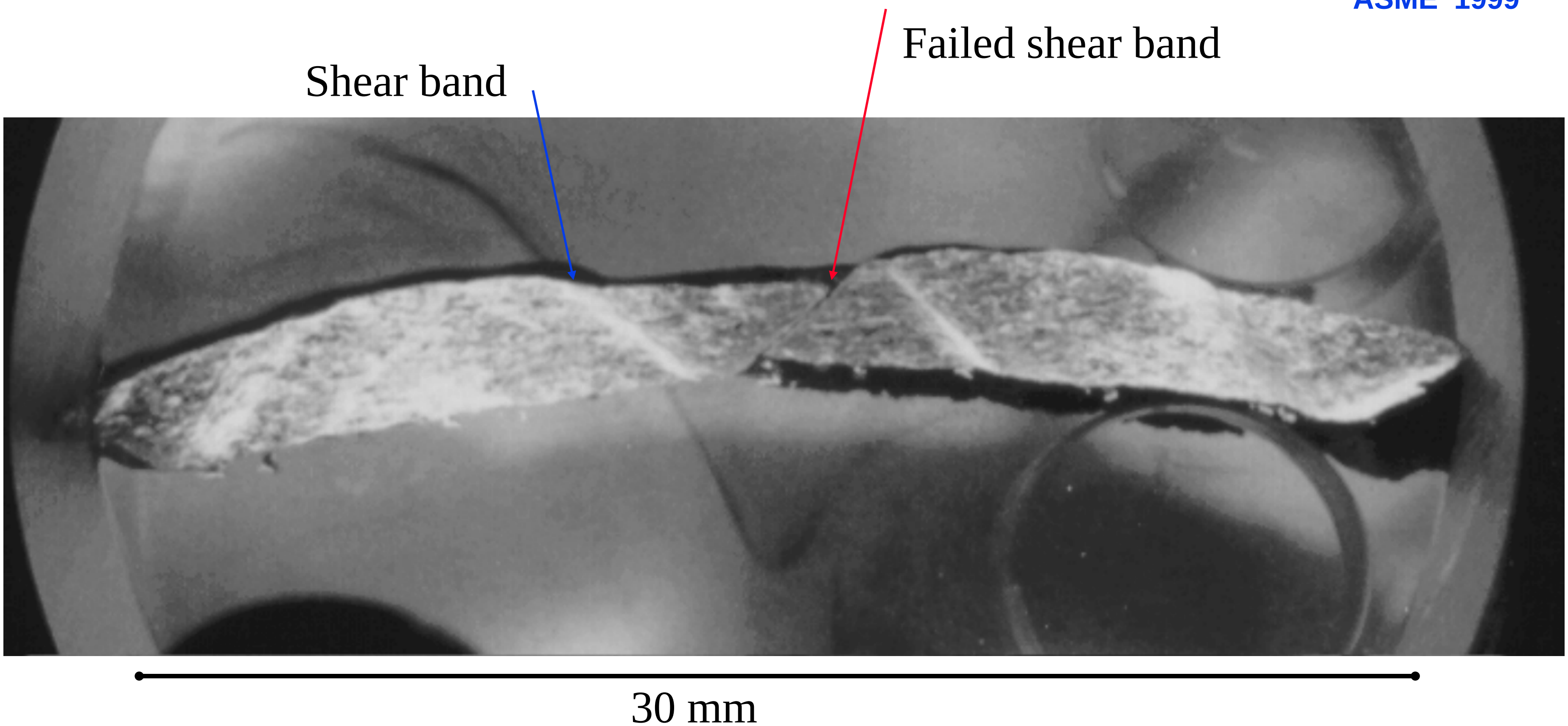





- Beginning of shear localization
- Equivalent plastic strain rate plotted here

# 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**