A Comparative Study of Penetration Codes for Brittle Materials

Dr. Sikhanda Satapathy, Anthony Dawson, Dr. Gregory Rodin

International Ballistics Symposium

New Orleans, Louisiana

September 23, 2008

Overview

Objective

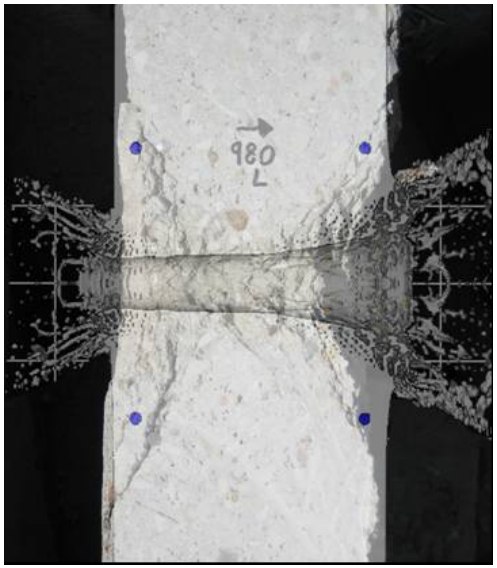
- Identify and exercise computational tools for modeling penetration of concrete targets, and compare with IAT experiments

Back Ground

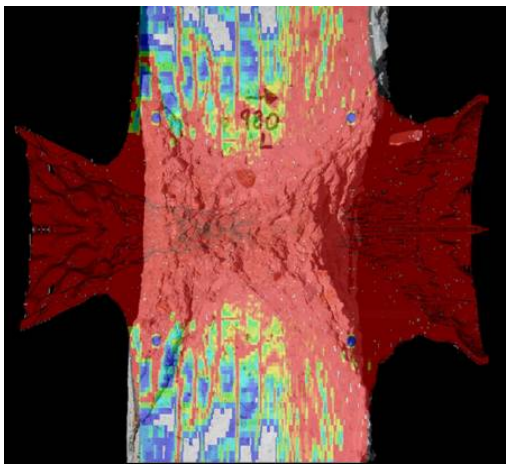
- Earlier comparisons (reported in 2007 HVIS) were not satisfactory
- A non-local peridynamic approach (EMU) was identified for comparison with continuum method (CTH.)

Approach

- Evaluate peridynamics as an alternative approach and compare with CTH's BFK and HJC models.
- Benchmark CTH and EMU with Cavity Expansion Analysis
- Validate with low velocity deceleration data



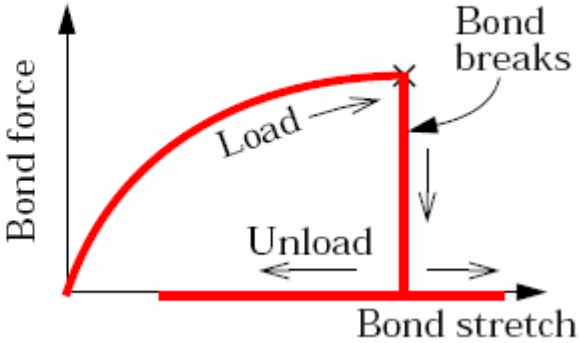
CTH (BFK) model compared with experiment

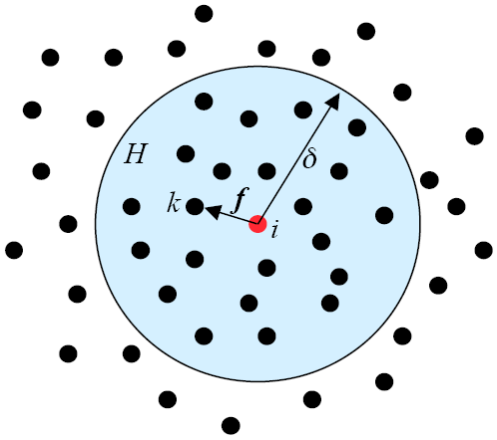


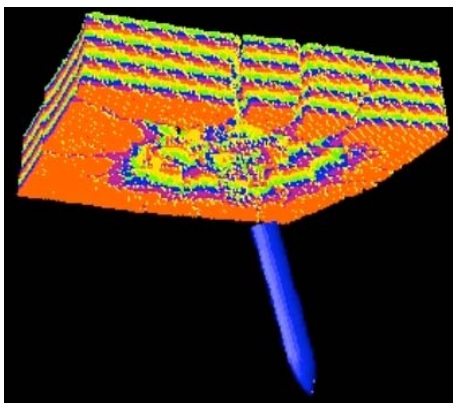
CTH (HJC) model compared with experiment

Peridynamic Method

- Classical Continuum Mechanics uses partial differential equations. However, spatial derivatives may not exist everywhere in the body (i.e. fractures)
- Peridynamic method* uses integral equations which hold everywhere in the body, regardless of any discontinuities
- Cracks form by breaking bonds irreversibly.
- Meshless Lagrangian method





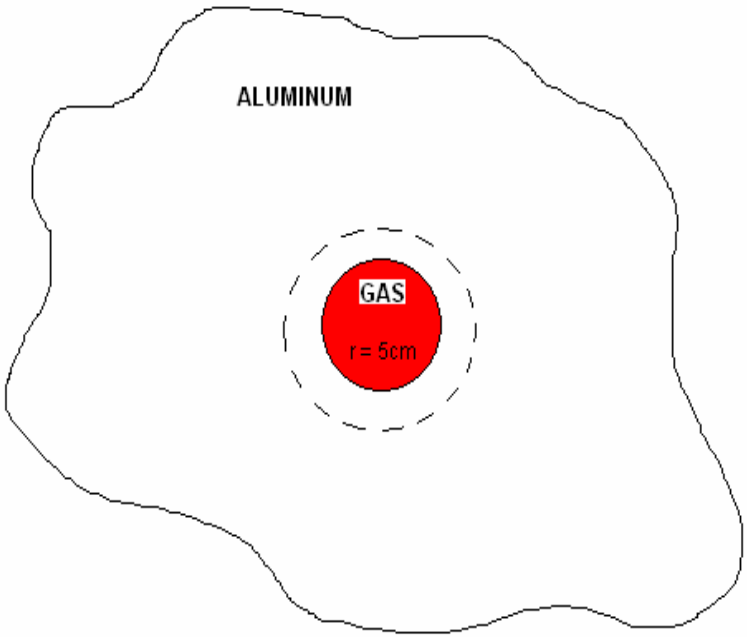


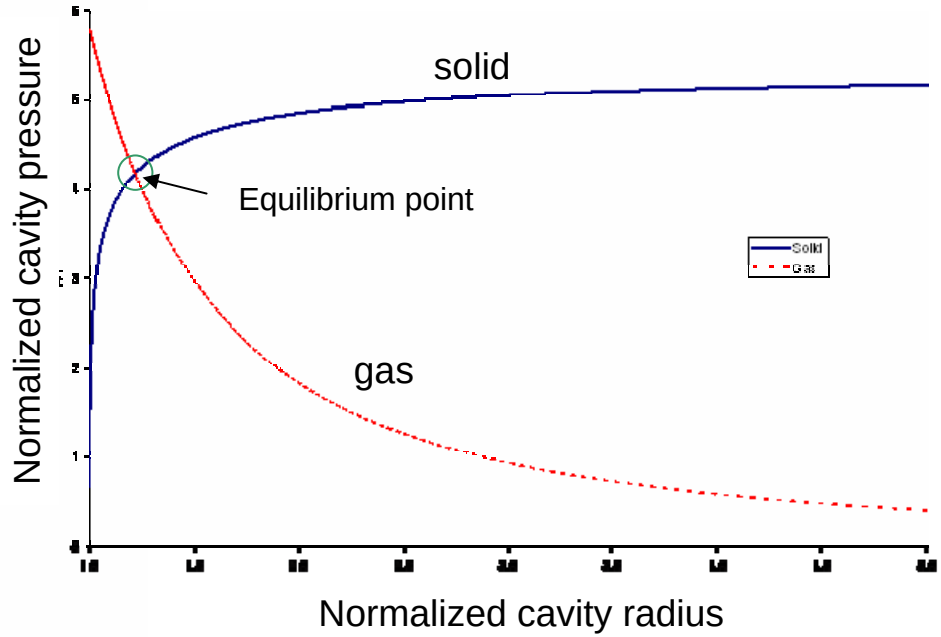
$$\rho\, \ddot{\boldsymbol{u}}_i^n = \sum_{k \in H} \boldsymbol{f}(\boldsymbol{u}_k^n - \boldsymbol{u}_i^n, \boldsymbol{x}_k - \boldsymbol{x}_i)\Delta V_i + \boldsymbol{b}(\boldsymbol{x}_i, t)$$

* Ref. Silling and Askari,Comp. Struct., 2005

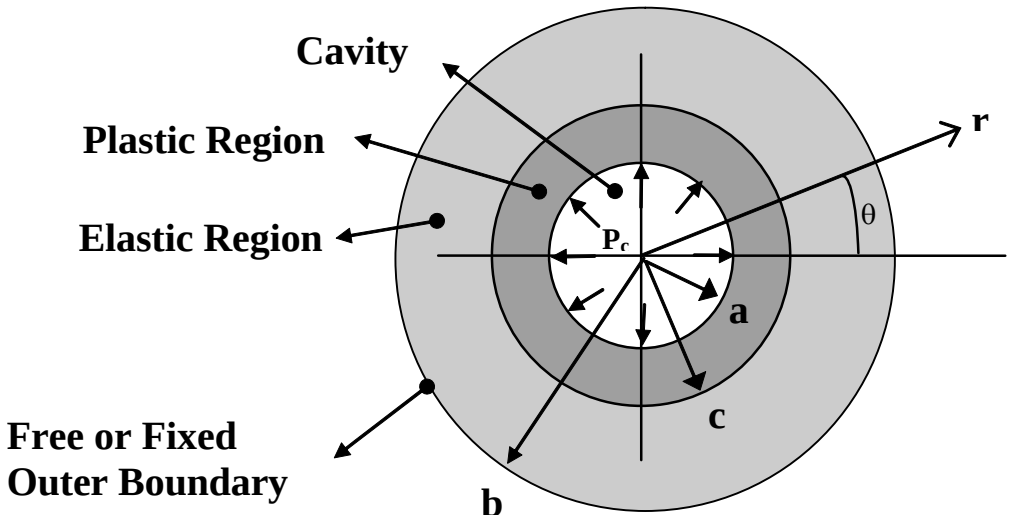
Verification Problem

- Cavity expansion problem was chosen for verification purposes.
- Since traction boundary conditions couldn't be imposed easily neither in CTH nor in EMU, a surrogate problem was chosen
- Cavity was filled with high pressure gas that expanded in an infinite body of aluminum until it reached equilibrium.





Cavity Expansion Theory



Cavity Expansion Pressure

$$\frac{P_c}{Y} = \int_0^\infty \frac{f(X)}{\exp\,(3X/2) - 1}\,dX$$

<u>P < 2Y/3:</u>

Elastic stress field (r > a)

$$s_r = -P\left(\frac{a_0}{r}\right)^3 \text{ and } u_r = \frac{Pa_0^3}{4mr^2}$$

<u>P > 2Y/3:</u>

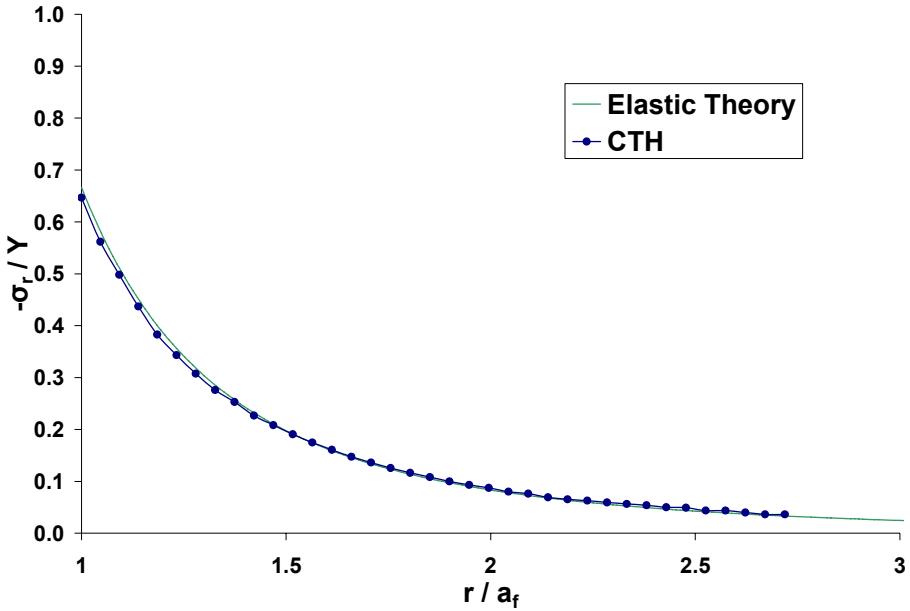
Elastic field (r > c)

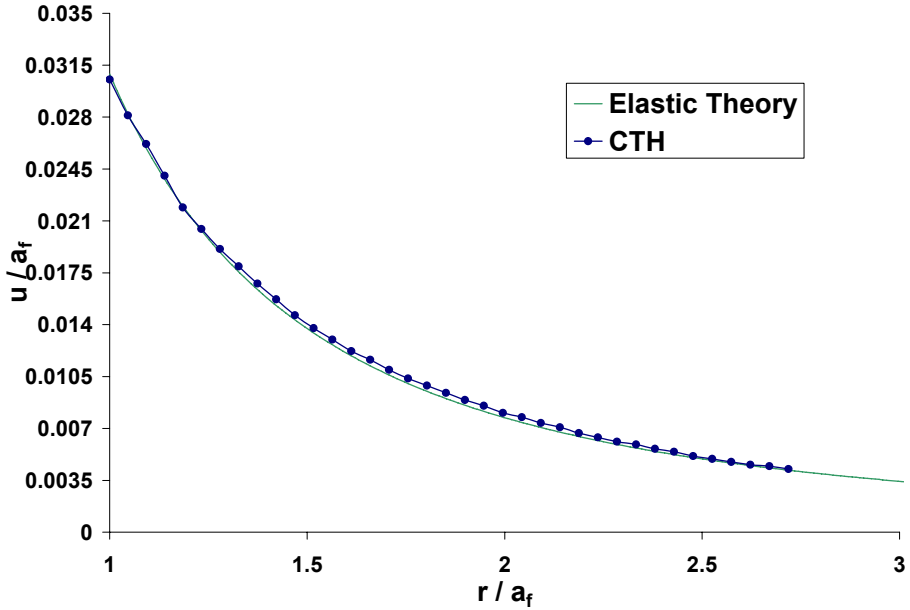
$$\sigma_r = -\left[\frac{2Y}{3}\left(\frac{c}{r}\right)^3\right] \text{ and } u_r = \frac{Yc^3}{6\mu r^2}$$

Plastic field (a <r <c)

$$\sigma_r = -\left[\frac{2Y}{3} + 2Y\ln\left(\frac{c}{r}\right)\right] \text{ and } u_r = r\left\{1 - \left[1 - \left(\frac{c}{r}\right)^3\left(1 - e^{\frac{-Y}{2\mu}}\right)\right]^{\frac{1}{3}}\right\}$$

CTH: P = 2Y/3 (elastic case)

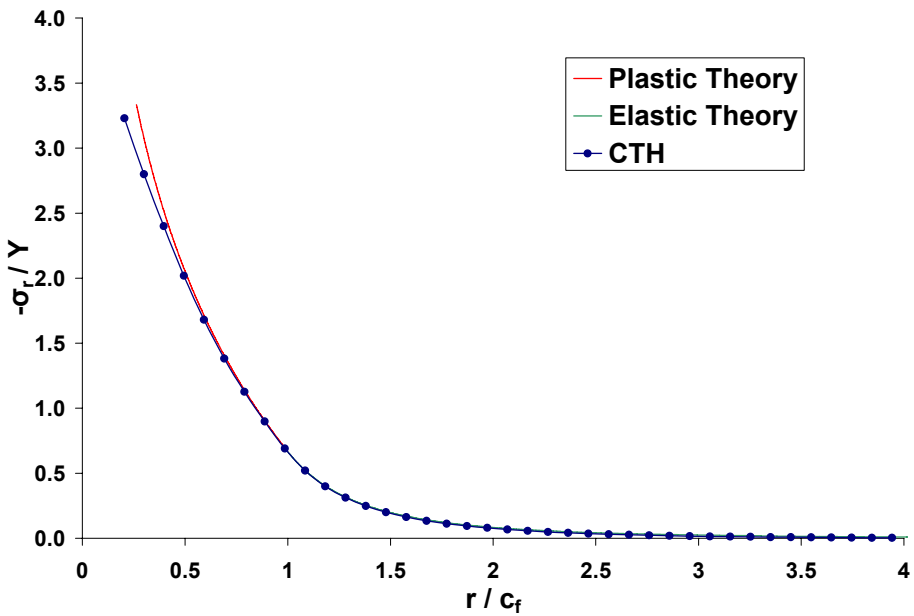


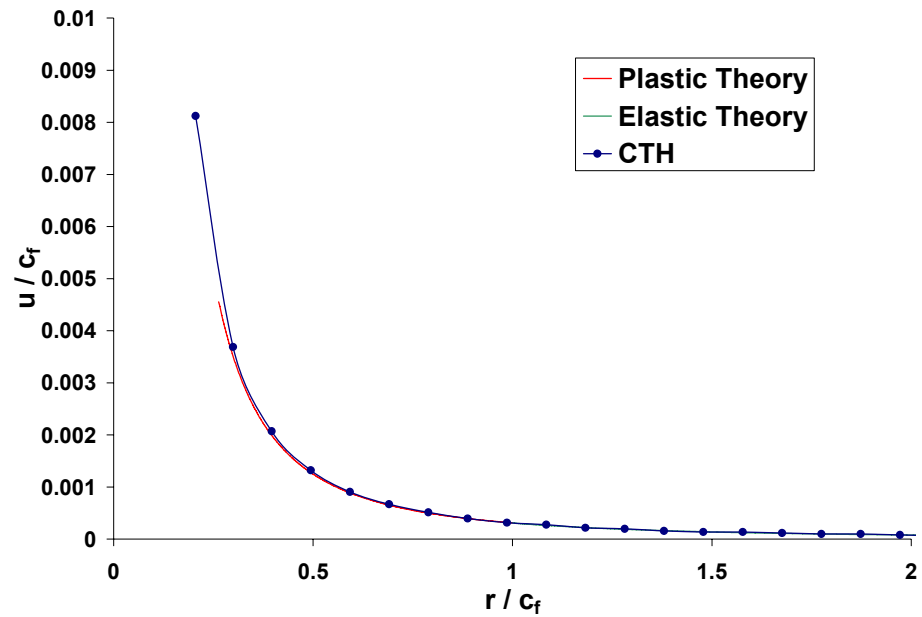


Radial stress and Displacement vs. radius for nominally elastic case

CTH calculation used a linear equation of state and an elastic-plastic strength model

CTH: P > 2Y/3 (elastic-plastic case)

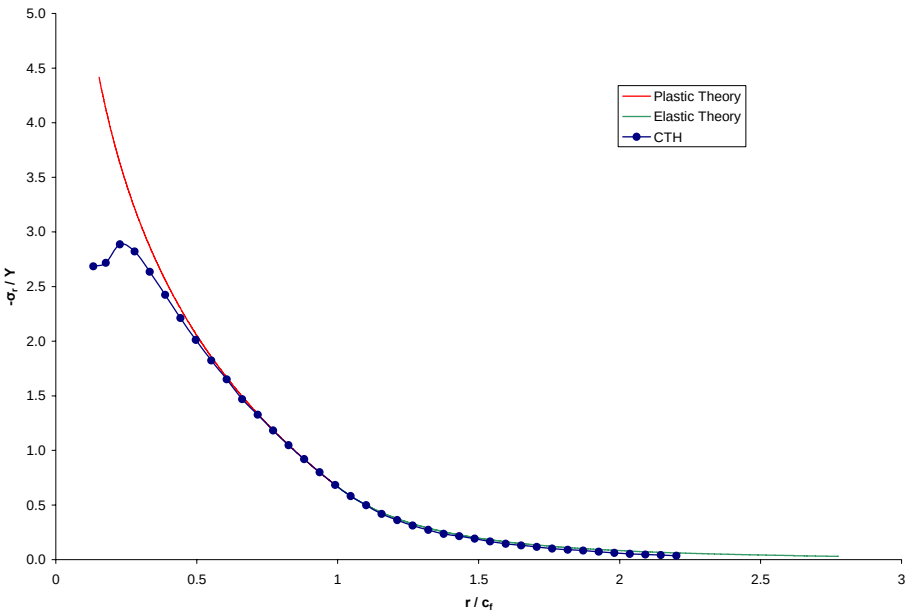


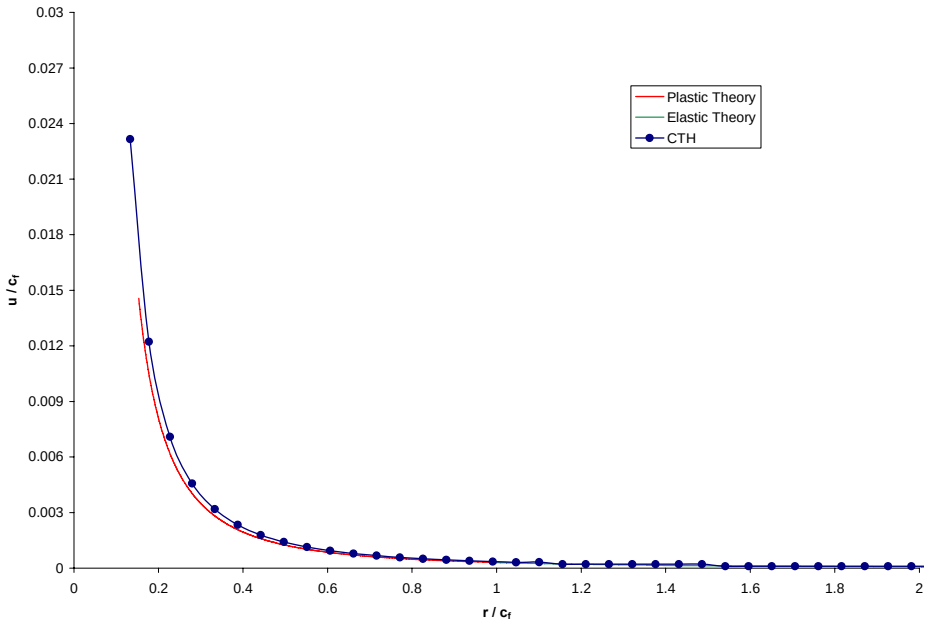


Radial stress and Displacement vs. radius for nominally elastic-plastic case.

Notice the departure of numerical solution from theory near the cavity wall.

CTH: P >> 2Y/3 (elastic-plastic case)





Radial stress and Displacement vs. radius for significant plastic yielding case.

Notice the departure of numerical solution from theory near the cavity wall.

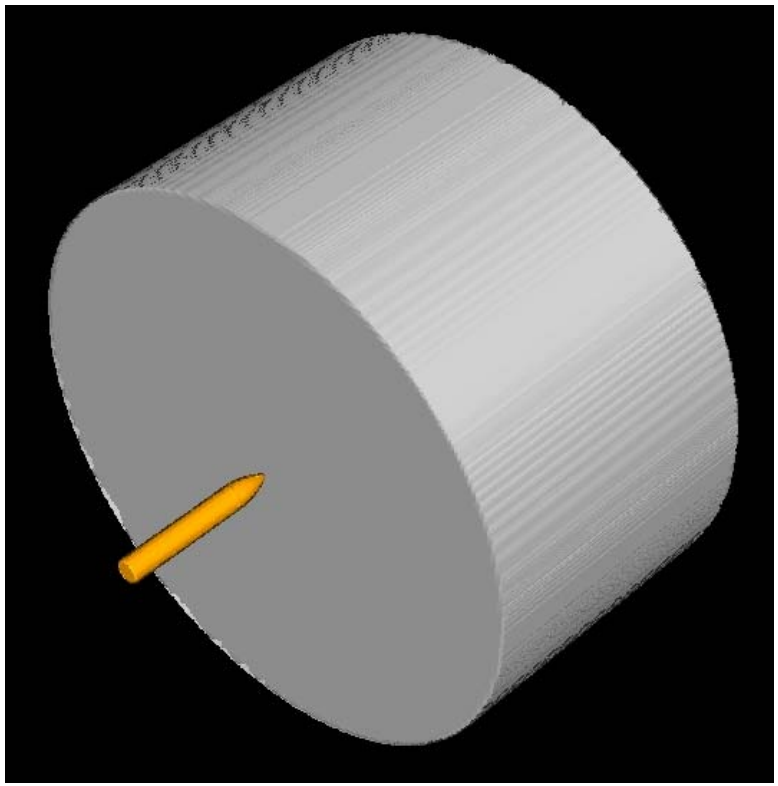
Dynamic Cavity Expansion: $P_0 \left(\frac{a_0}{a}\right)^{3g} - \left(\frac{2Y}{3}\right) + 2Y \ln\left(\frac{c}{a}\right) = b_2 \ddot{a} + b_1 \dot{a}^2$

Verification summary

- CTH produced satisfactory results when dynamic effects were not significant.
- EMU implementation did not produce the desired solution since gas diffusion into solid couldn't be prevented.
- Code modification needed to complete the verification process for EMU.

Validation Problem

- Rigid penetration into Concrete (1.83 m radius, 23 MPa f'_c)
- Steel Penetrator of 80 mm dia, 13 kg at 380 m/s
- Penetration depth and deceleration measurements taken with accelerometer



Ref: Forrestal et al.,IJIE, 2003

BFK Model

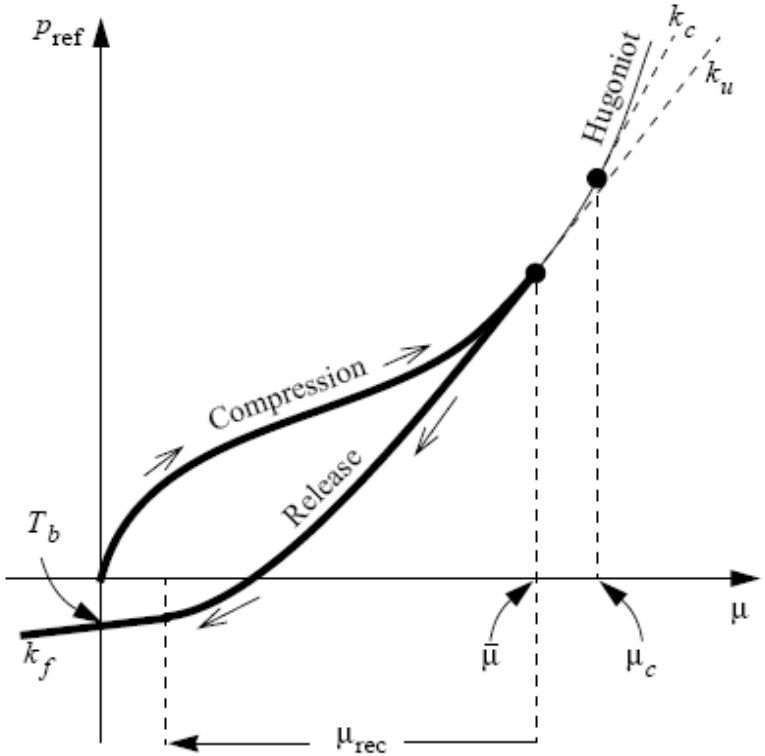


Figure 2.2. Compression (loading) followed by release (unloading) along a reference curve. (Not all the void space is crushed out in this path, $\bar{v} > v_c$.)

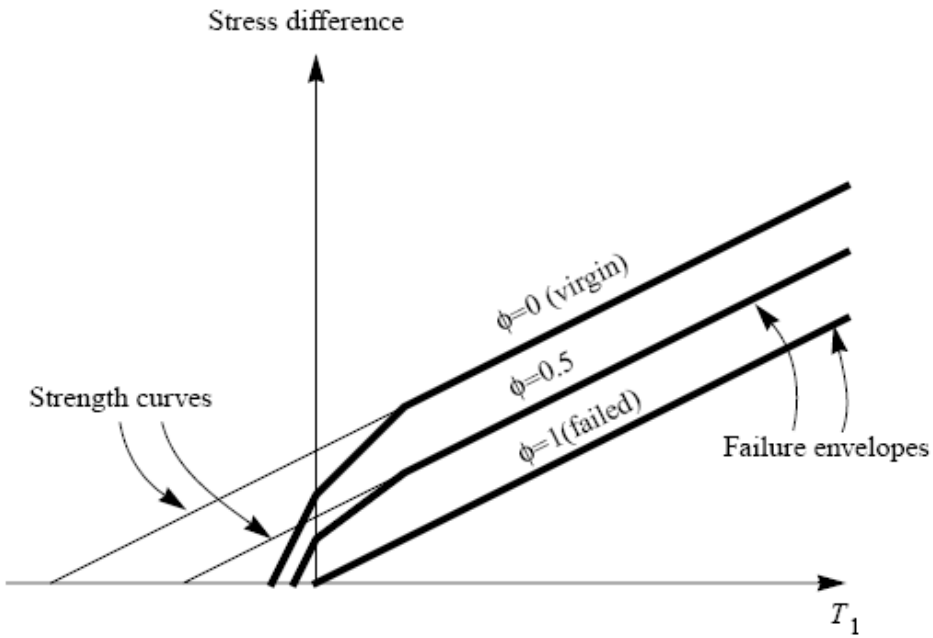
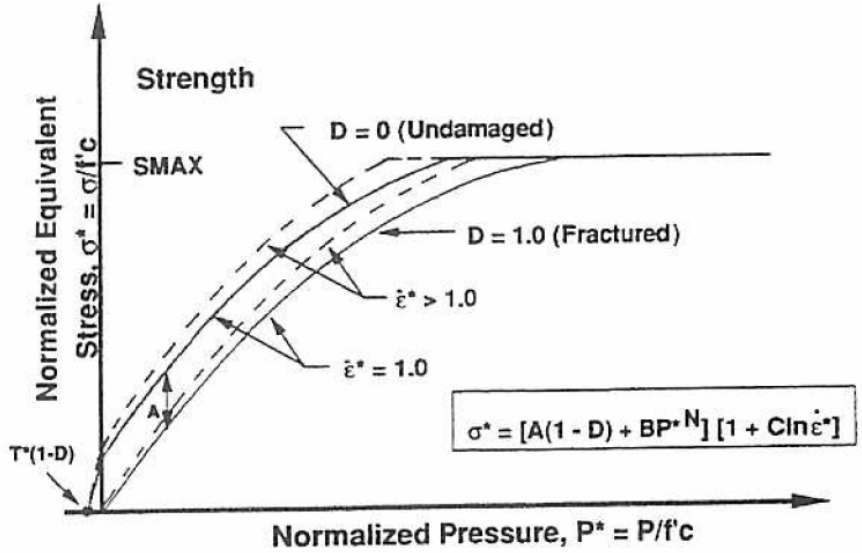
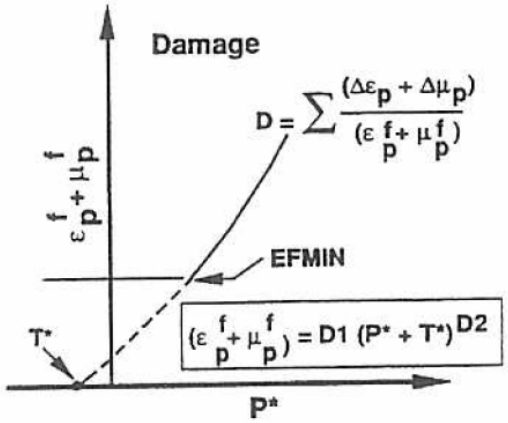


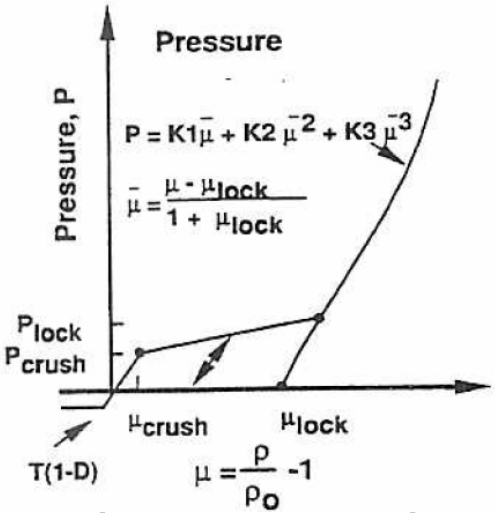
Figure 2.5. Evolution of the failure envelope.

- Scalar damage model explicitly dependent on time
- Damage has three components: brittle, ductile and compressive

HJC Model

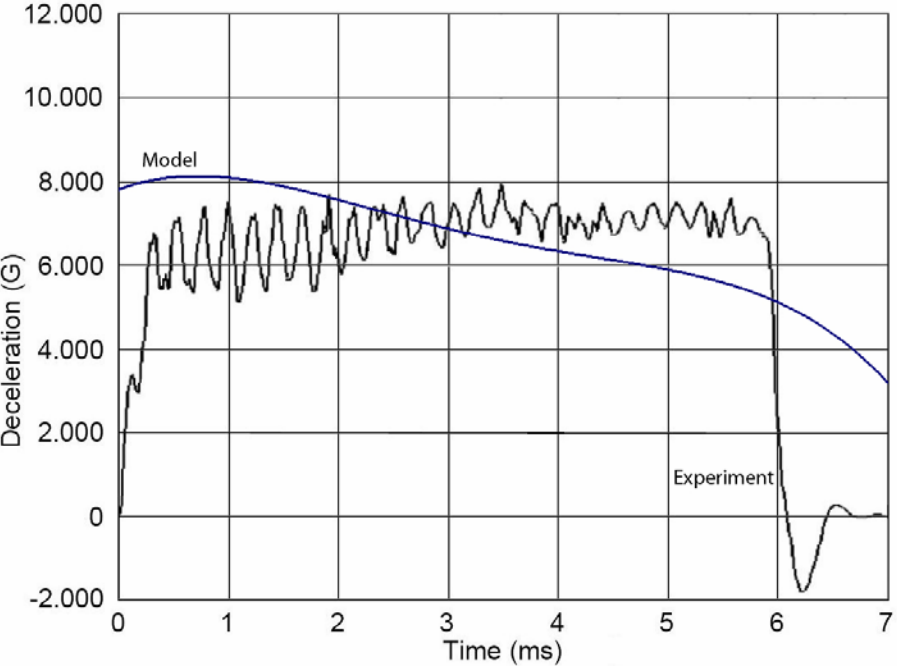






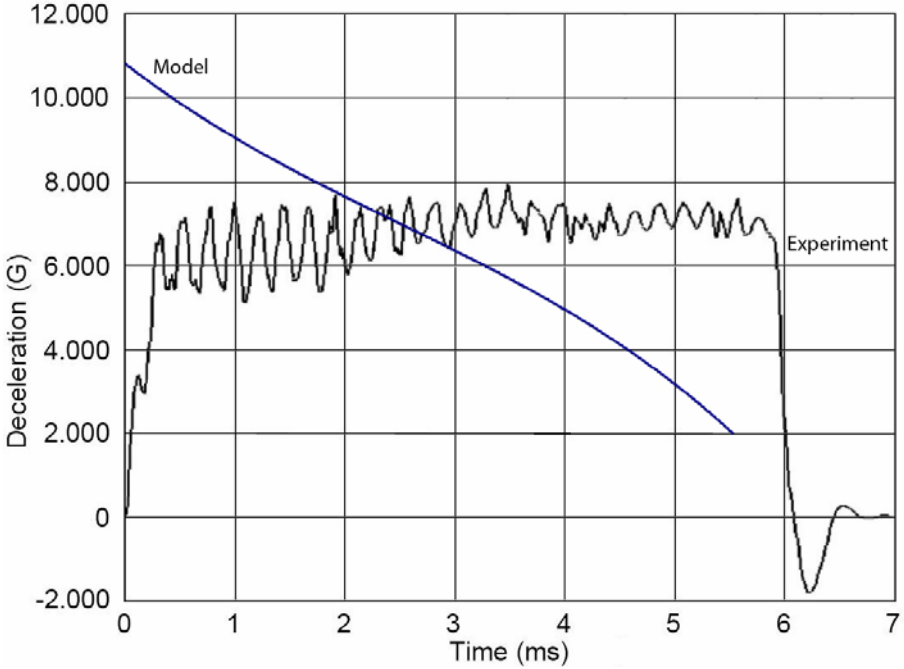
- Damage accumulated from both equivalent plastic strain and plastic volumetric strain (majority from EPS)

CTH Validation Results



BFK

Depth Under-predicted by 5.1%



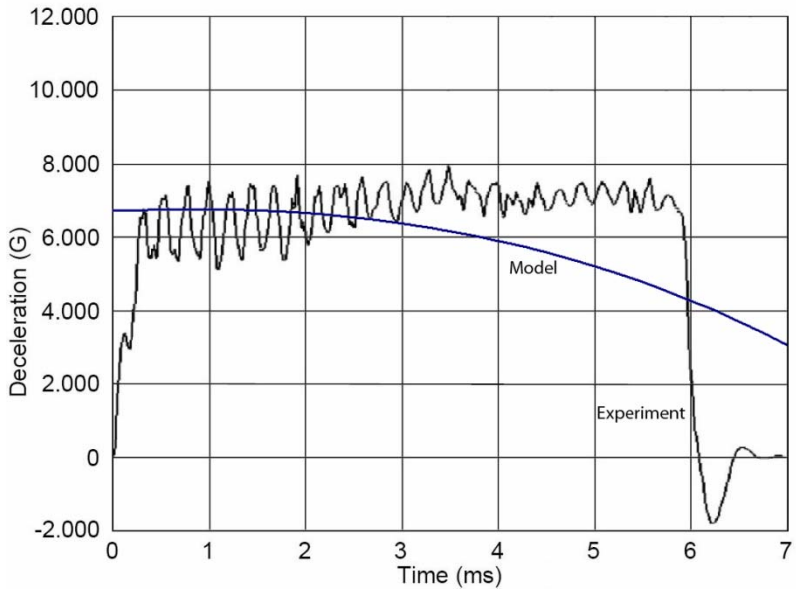
HJC

Depth Under-predicted by 23%

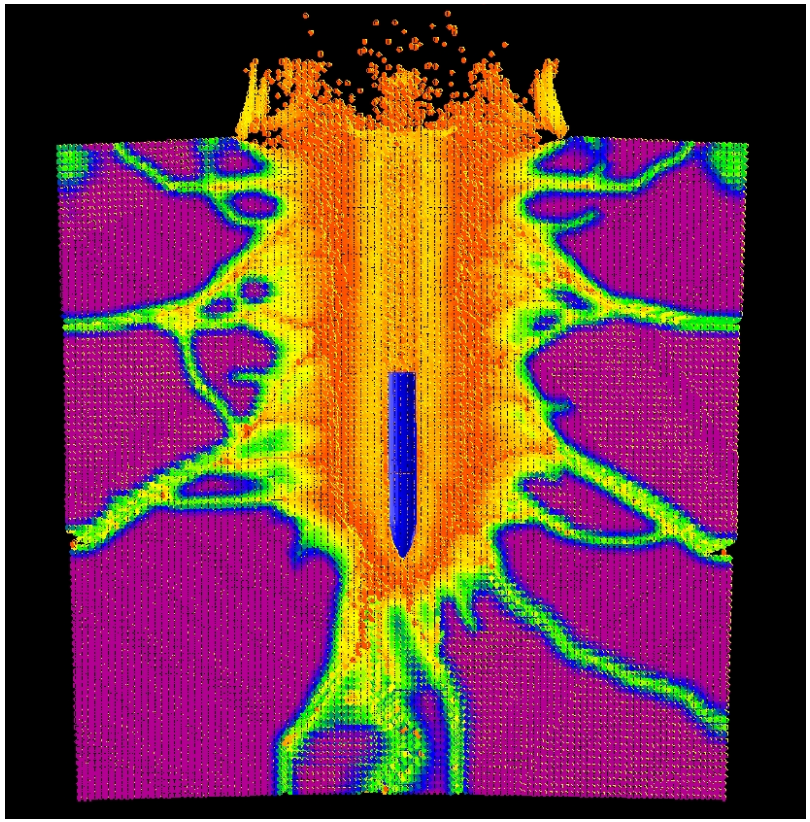
BFK simulation is in much closer agreement with test results than HJC simulation.

Ref: Forrestal et. al. IJIE, 2003

EMU Validation Results



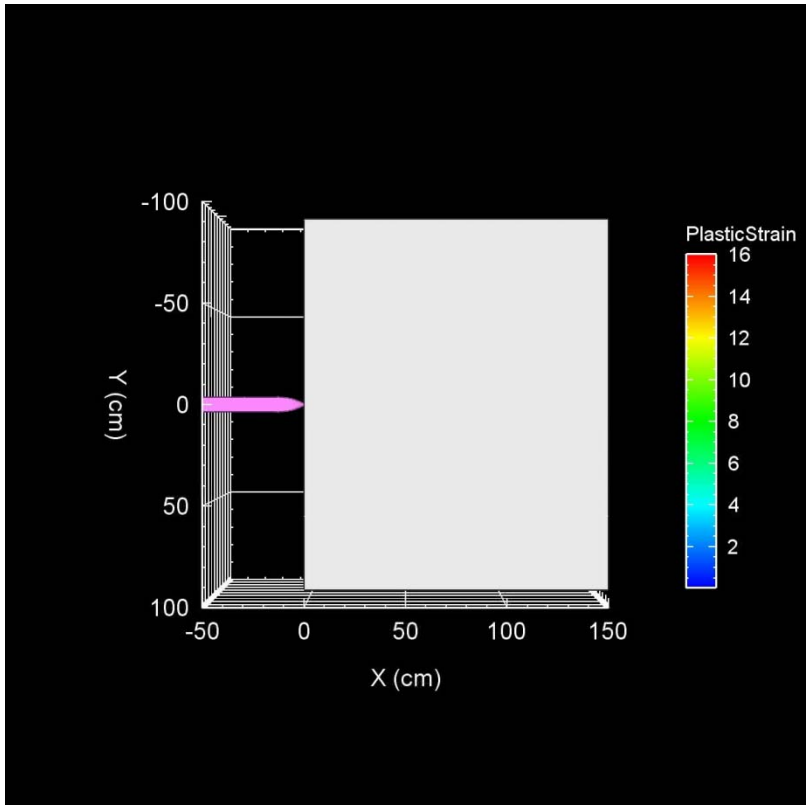
Depth Over-predicted by 0.5%



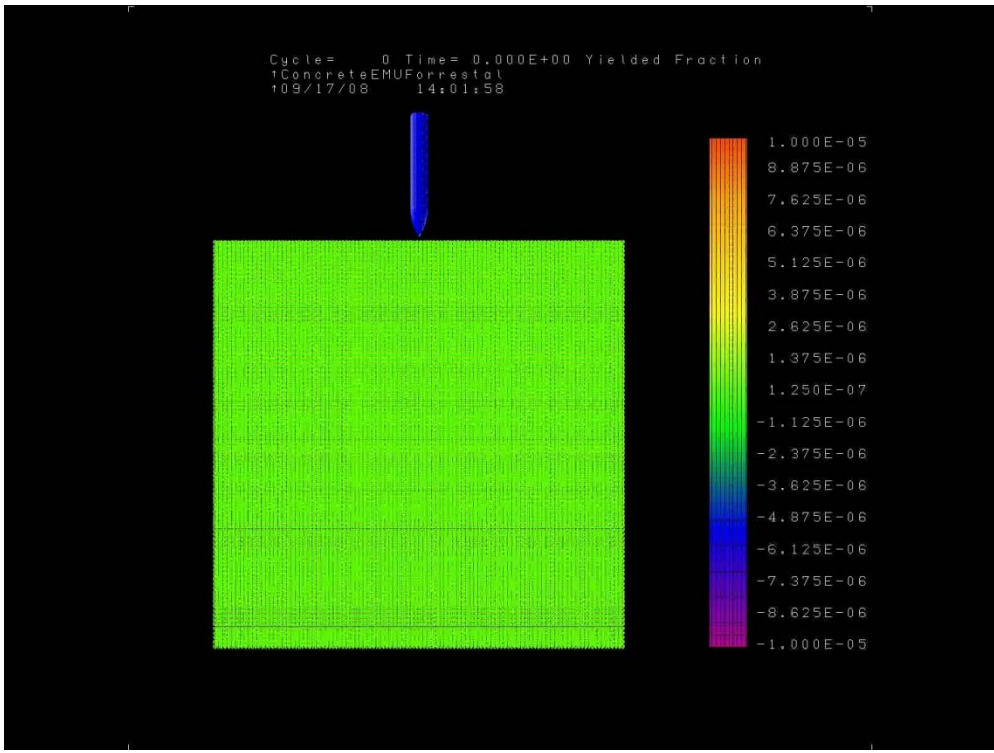
EMU accurately modeled the deceleration

Cracks in target were similar to experimental observations

Simulation Comparison



CTH



EMU

Summary

- CTH verification with cavity expansion solution for elastic-plastic materials was satisfactory when dynamic effects were not significant.
- CTH-BFK model produced reasonable agreement with deceleration data.
- EMU verification couldn’t be completed due to code limitations.
- EMU agreed with deceleration data very well.
- EMU produced fracture patterns similar to that observed in experiments.

Questions?