FEATURES OF FRACTURE DISTRIBUTION AROUND A TUNNEL CAUSED BY BLAST WAVES

D.L. Sulsky, L. Xu and H.L. Schreyer

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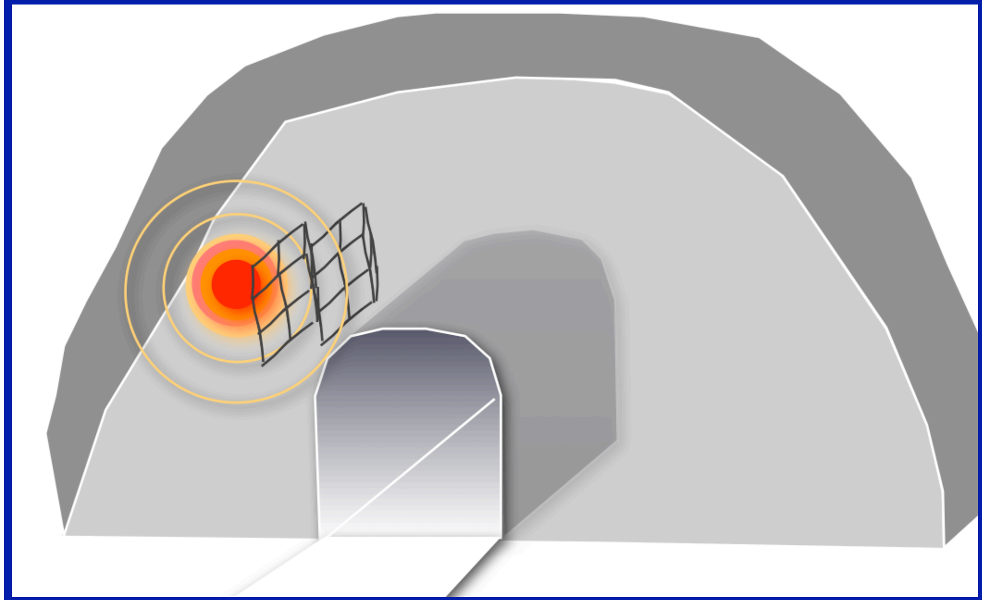
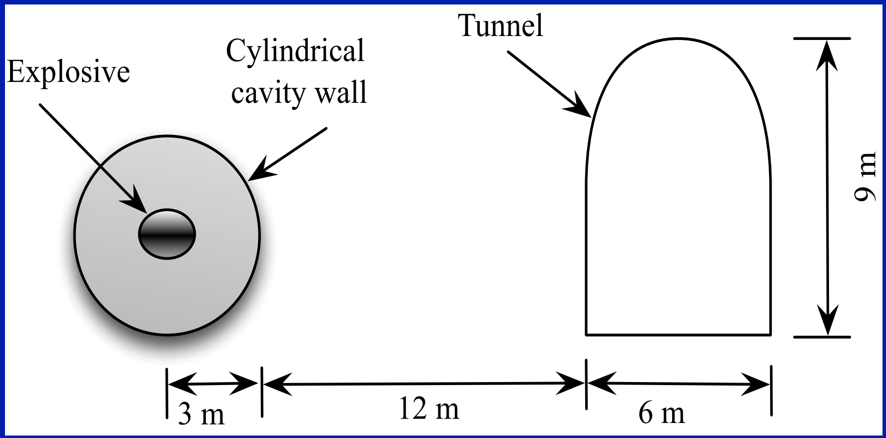
OUTLINE

THE UNIVERSITY of NEW MEXICO

1. The Problem





Simplifying Assumptions:

1. Blast source is cylindrical – plane strain

2. Blast source replaced by a larger cylinder
   (excludes region with plasticity, massive failure and thermal effects)

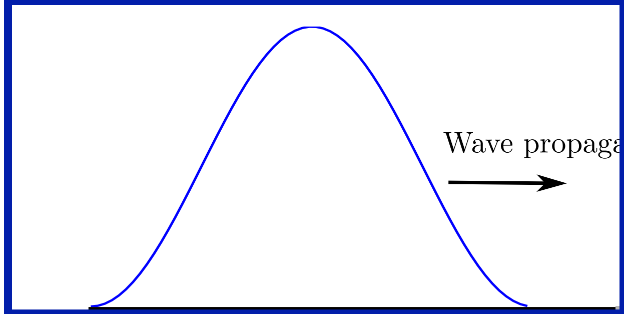
3. Forcing term is a single compressive pulse.

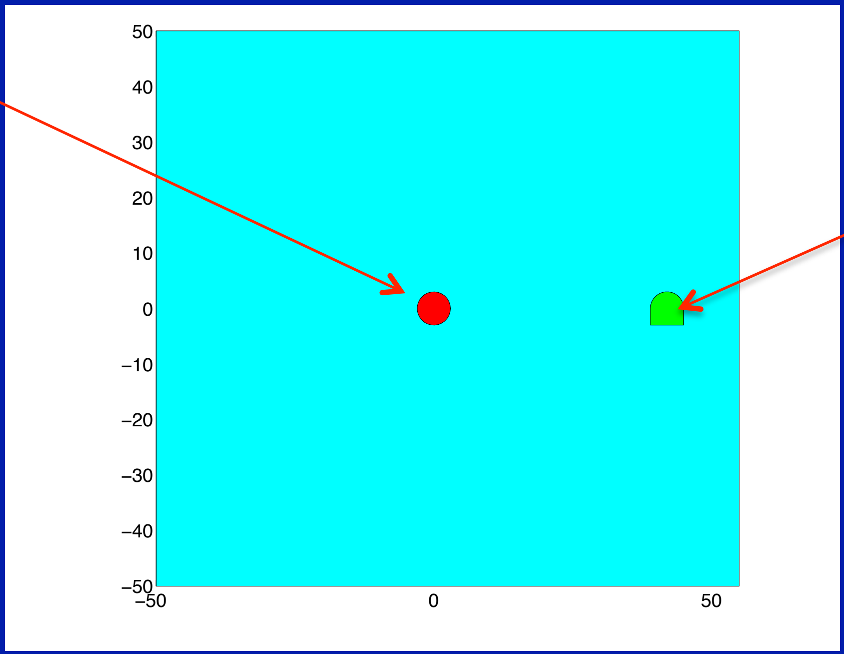
4. Rock modeled as elastic-decohesive failure.

1. The Problem

Wave source

Radial stress
On surface
Of cylinder



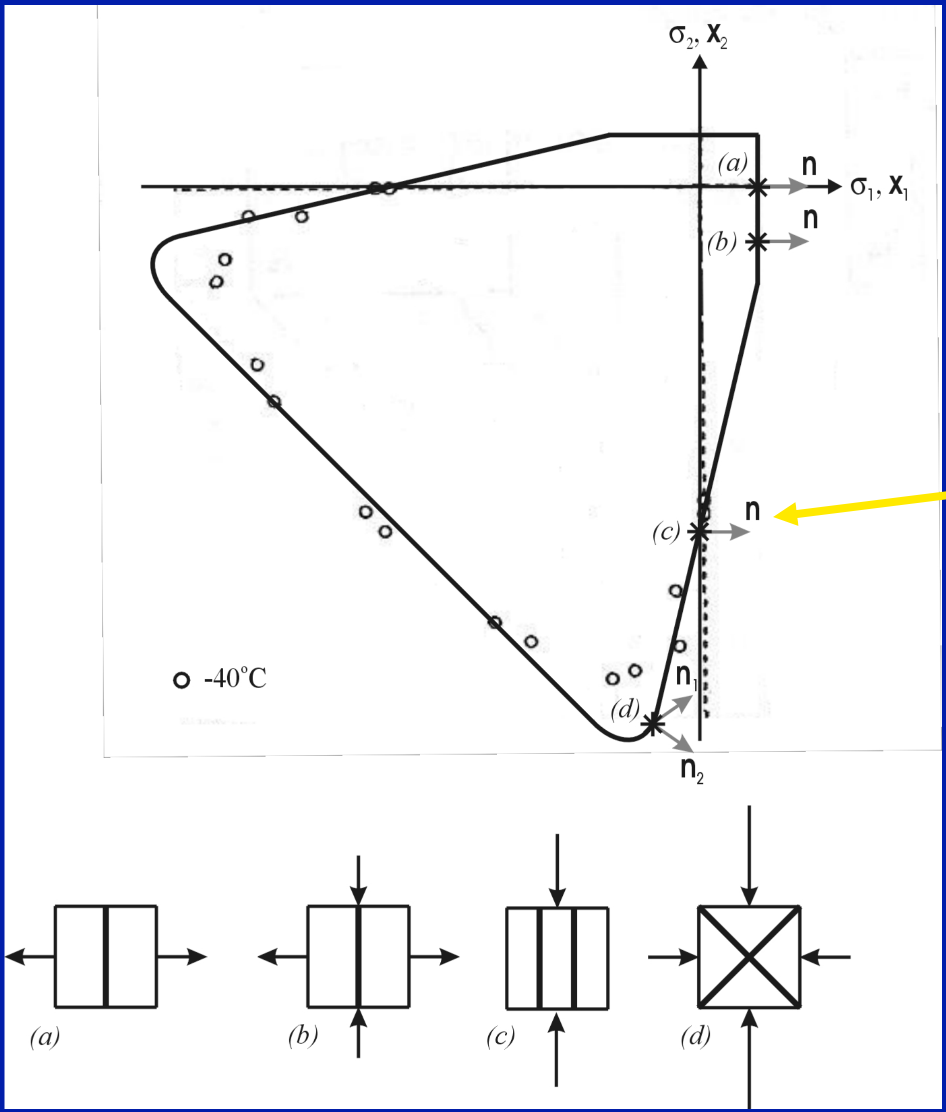


Tunnel

$$\sigma_{rr}(t)\Big|_{r=3m} = -H[t]H[t_d - t]\frac{\sigma_0}{2}\left\{1-\cos\left(\frac{2\pi t}{t_D}\right)\right\}$$

$$v_{max}\Big|_{r=3m} = 3m/s$$

2. Decohesive Failure - Experimental Features



Experimental Data -

Sea-ice (anisotropic)

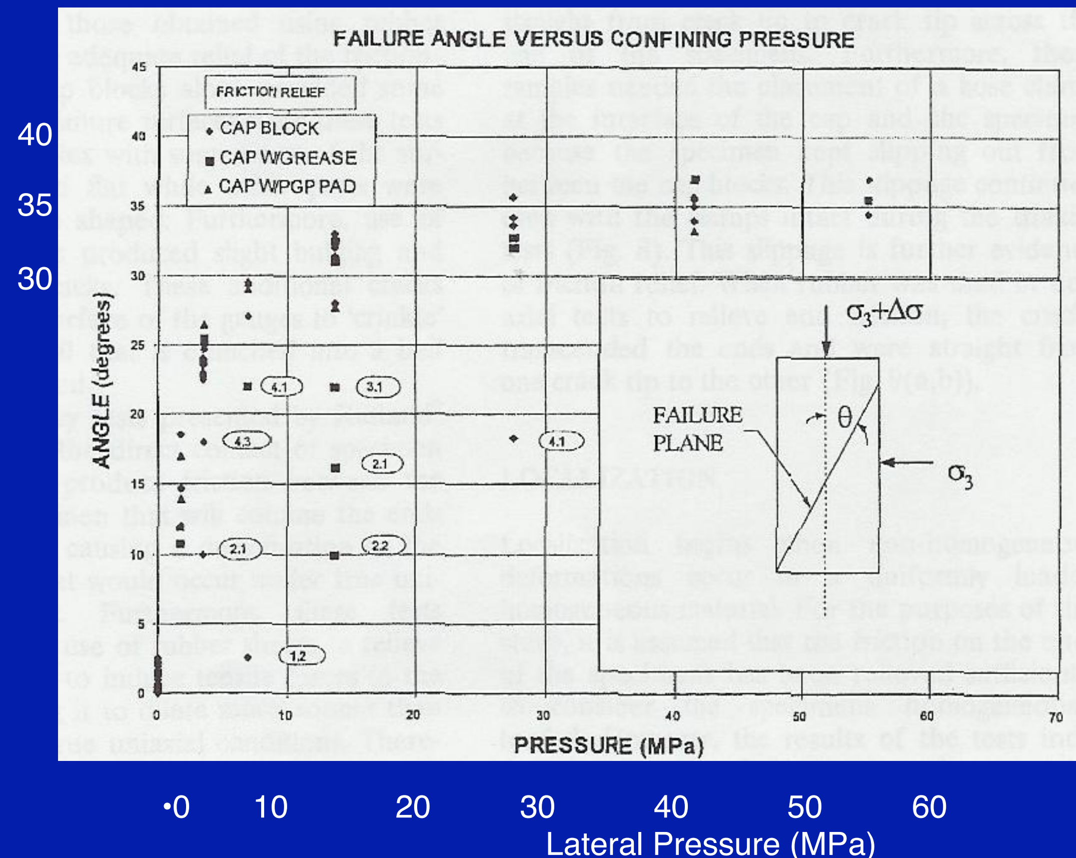
Plane stress:

From Schulson

(c) Axial splitting

2. Decohesive Failure- Experimental Features

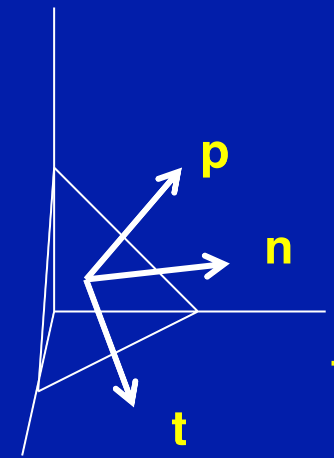
Triaxial Compression



Ref: Rutland, C.A., 1994, The Effects of Confinement on the Failure Mechanisms in Cementitious Materials, Ph.D. Dissertation, Dept. of Civil Eng'g, Univ. of New Mexico.

2. Decohesive Failure - CLASSICAL MODELS

Surface defined by normal - n



triad - **n**, **t**, **p**

t, **p** - in tangent plane

Stress - $\boldsymbol{\sigma}$

Traction: $\boldsymbol{\tau} = \boldsymbol{\sigma} \cdot \mathbf{n}$

Components of traction:

$$\tau_n = \boldsymbol{\tau} \cdot \mathbf{n} = \sigma_{nn}$$

$$\tau_t = \boldsymbol{\tau} \cdot \mathbf{t} = \sigma_{nt}$$

$$\tau_p = \boldsymbol{\tau} \cdot \mathbf{p} = \sigma_{np}$$

Magnitude of shear on surface:

$$\tau_s^2 = \tau_t^2 + \tau_p^2$$

Components of stress not used: $\sigma_{tt}, \sigma_{pp}, \sigma_{tp}$

2. CLASSICAL MODELS

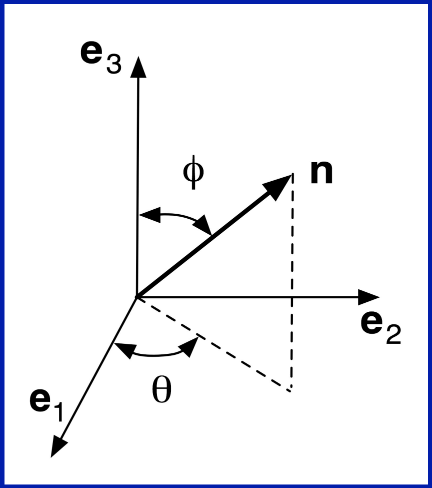
Failure: $F = 0$ $\quad F = \max_{n} F^{n}$

$$\mathbf{n} = \mathbf{e}_1 \sin\phi \cos\theta + \mathbf{e}_2 \sin\phi \sin\theta + \mathbf{e}_3 \cos\phi$$

$$F = \max_{\theta,\, \phi} F^{n}$$

$$F = \max_{\theta_i,\, \phi_j} F^{n}$$

Discrete values of polar angles



Maximum Principal Stress Criterion (Rankine): $F_R^n = \dfrac{\tau_n}{\tau_{nf}} - 1$

Maximum Shear Stress Criterion (Tresca): $F_T^n = \dfrac{\tau_s^2}{\tau_{sf}^2} - 1$

Maximum Coulomb Friction Criterion (Mohr-Coulomb): $F_{MC}^n = \dfrac{|\tau_s|}{\tau_{sf}} + c\tau_n - 1$

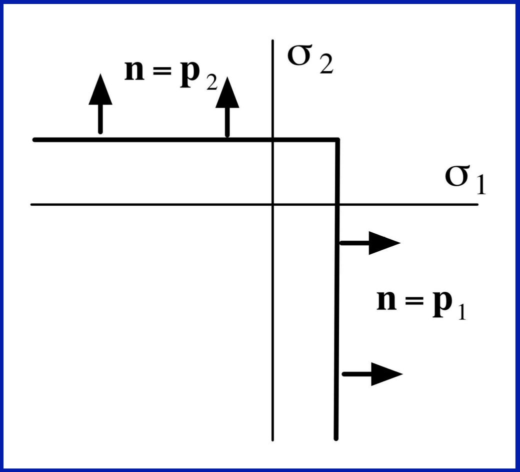
2. CLASSICAL MODELS - Application to plane stress

Principal directions - stress: p_1, p_2, p_3

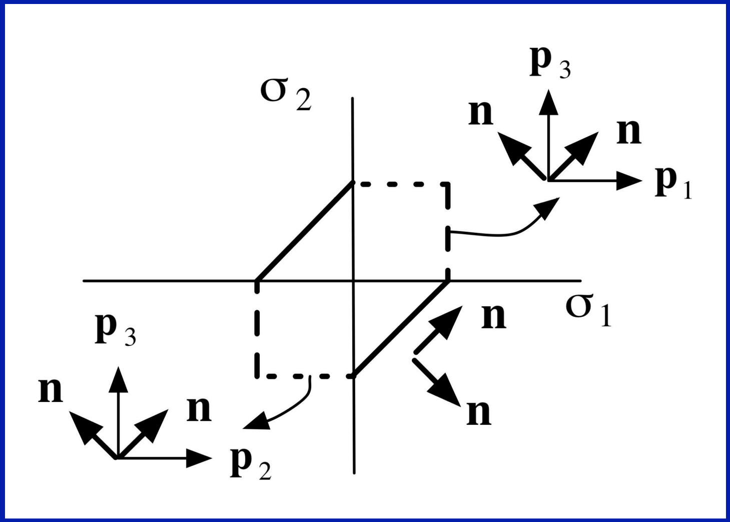
Some aspects:

Wrong shape of failure surface

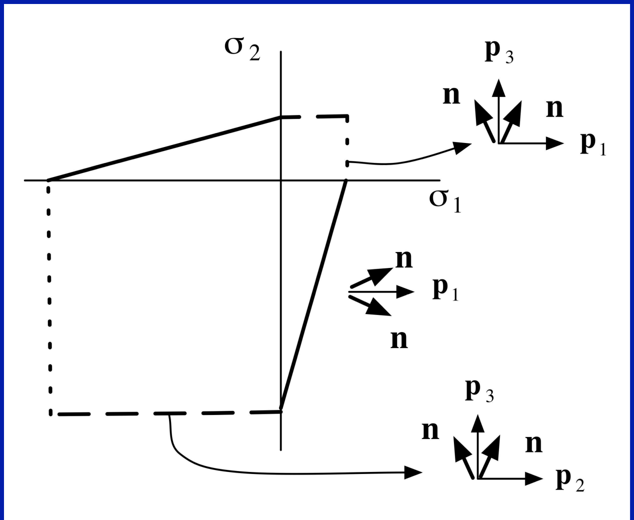
Wrong orientation of failure plane



Rankine (Mode I)



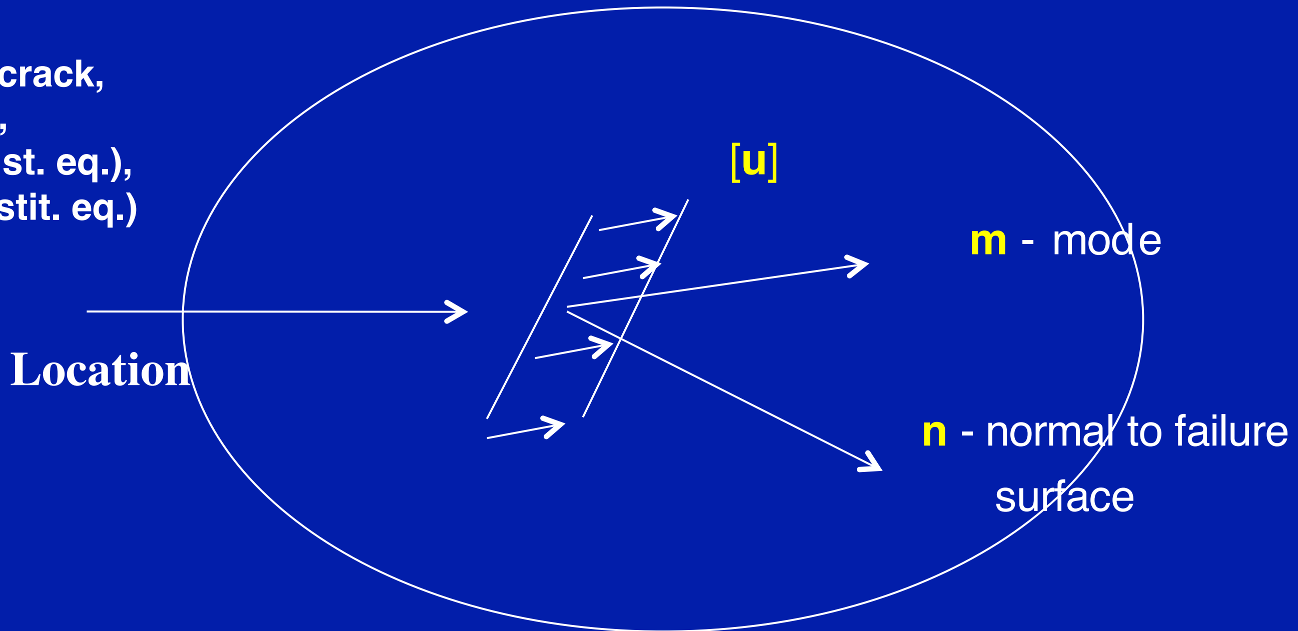
Tresca (shear)

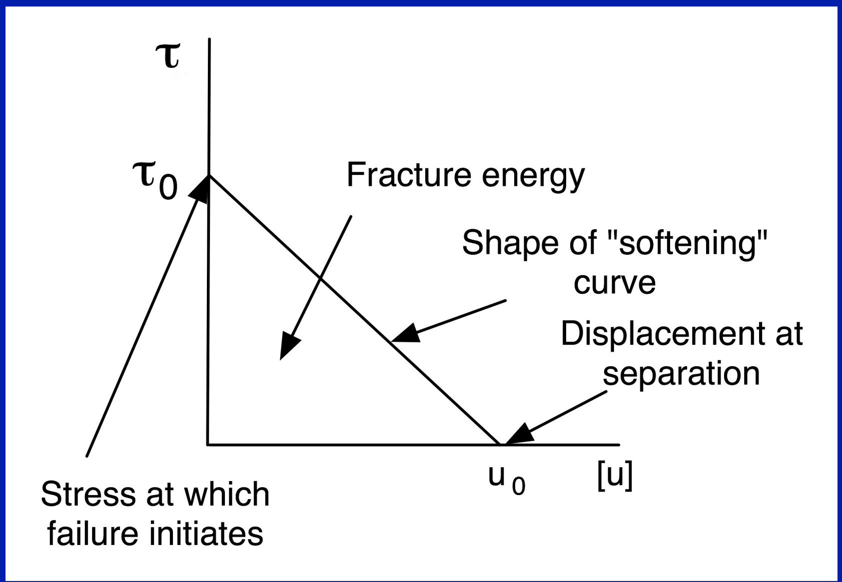


Mohr-Coulomb

3. DECOHESIVE PROPOSED MODEL - Assumption

Assumption - cohesive crack,
(decohesive),
(discrete const. eq.),
(discontinuum constit. eq.)





2. DECOHESIVE PROPOSED MODEL - General Approach

Decohesion Function: $F[\{\sigma, \mathbf{n}\}; \{f(\mathbf{n})\}]$ or $F_n[(\sigma), f_n]$

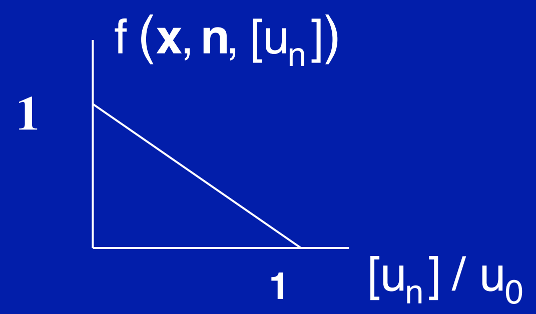
$F < 0$ - decohesion not occurring

$F = 0$ - decohesion may be occurring

- also called the failure surface

$F > 0$ - not allowed

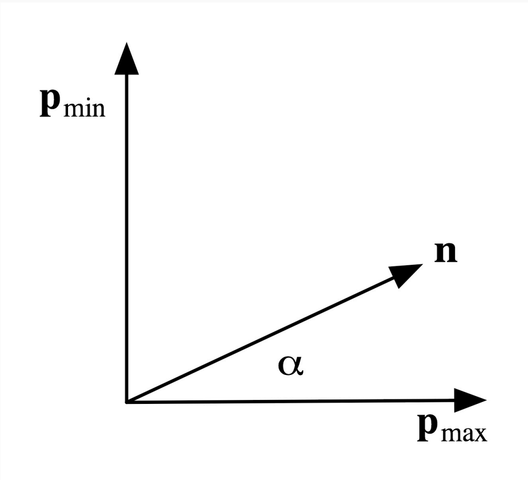
Softening Function $f(\mathbf{x}, \mathbf{n})$



2. Decohesive Failure

$$F = \max_n F_n \qquad F_n = \frac{\tau_s^2}{(s_m \tau_{sf})^2} + e^{B_n} - 1$$

$$B_n = \kappa \left[\frac{\tau_n}{\tau_{nf}} + \frac{\langle -\sigma_{tt}^* \rangle^2}{(f_c')^2} - f_n \right] \qquad f_n = 1 - \frac{[u]_n}{[u]_0}$$



$$\text{"Brittle failure"}$$

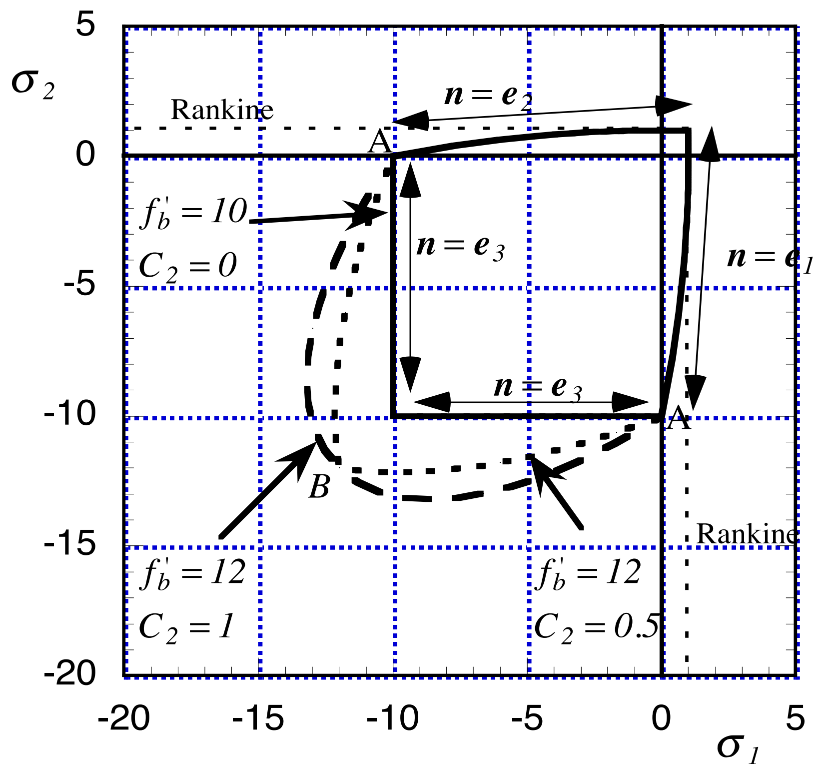
$$\alpha = 0 \qquad \frac{\tau_{sf}}{\tau_{nf}} > 0.35$$

Orientation of failure –
Principal directions of stress

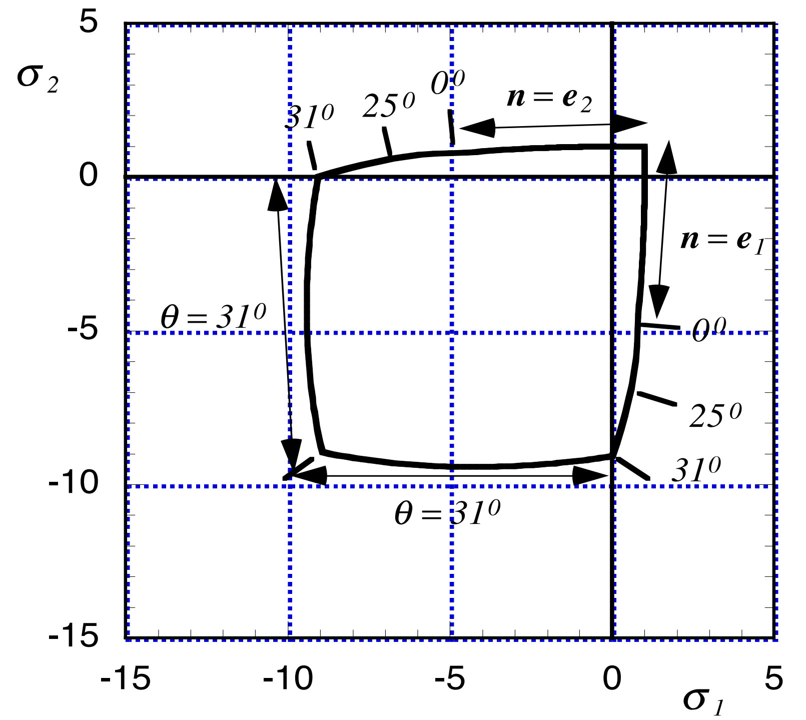
2. Decohesive Failure

Plane stress failure surface

Dimensionless Parameters



$$\tau_{nf} = 1, \tau_{sf} = 3.5, f_c' = 10, s_m = 4$$



$$\tau_{nf} = 1, \tau_{sf} = 2.4, f_c' = 10, f_b' = 12, s_m = 4, C_2 = 1$$

2. Decohesive Failure

ALGORITHM

1. **Does a crack or do cracks already exist?**

   If yes, allow decohesion to evolve for each until F = 0

2. **Check to see if an additional crack starts, i,e., search for worst orientation.**

   If yes, store orientation, n, and provide storage for discontinuity variables.

Represent effect of discontinuity through a smeared crack-

result is an algorithm closely related to plasticity.

2. Decohesive Failure

"Choice of material parameters"

$$Y = 50{,}000\ MPa \qquad \rho = 2660 kg/m^3$$

$$c = 4{,}300\ m/s \qquad f_c' = Y/1000 = 50 MPa$$

$$\tau_{nf} = f_c'/10 = 5 MPa$$

$$G_f = K_c^2/Y = 80\ Pa \cdot m$$

$$[u_0] = 2G_f/\tau_{nf} = 3 \times 10^{-5}\ m$$

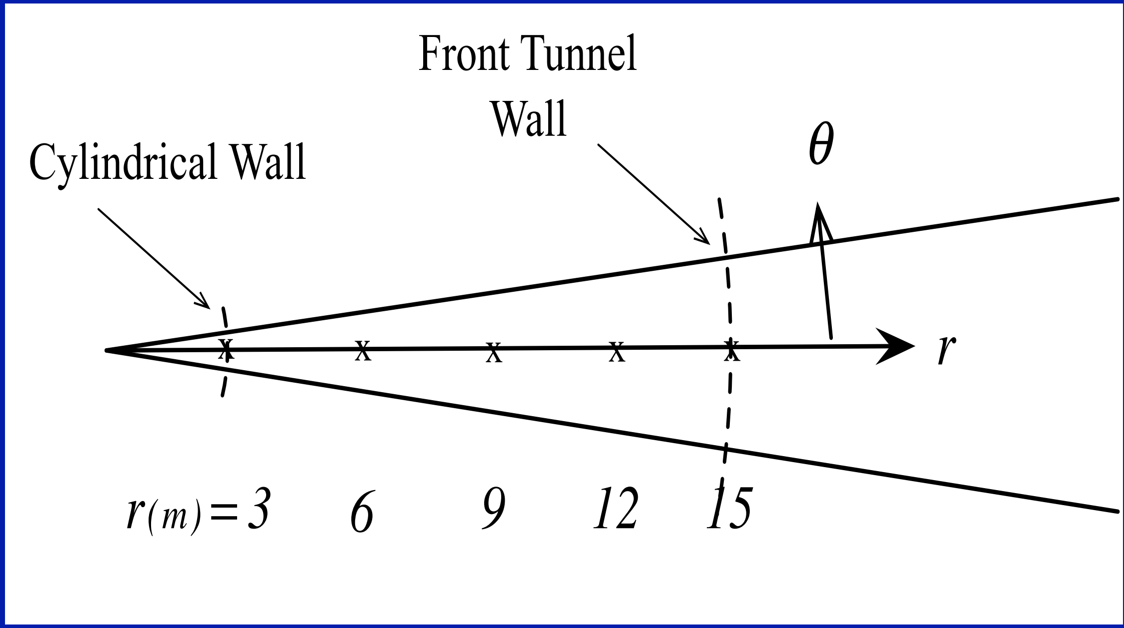
$$h_{cr} \approx [u_0]\frac{Y}{\tau_{nf}} = 10{,}000[u_0] = 0.3m$$

Force stress amplitude $\sigma_0 = f_c'$

Pulse duration $t_D = 3ms$

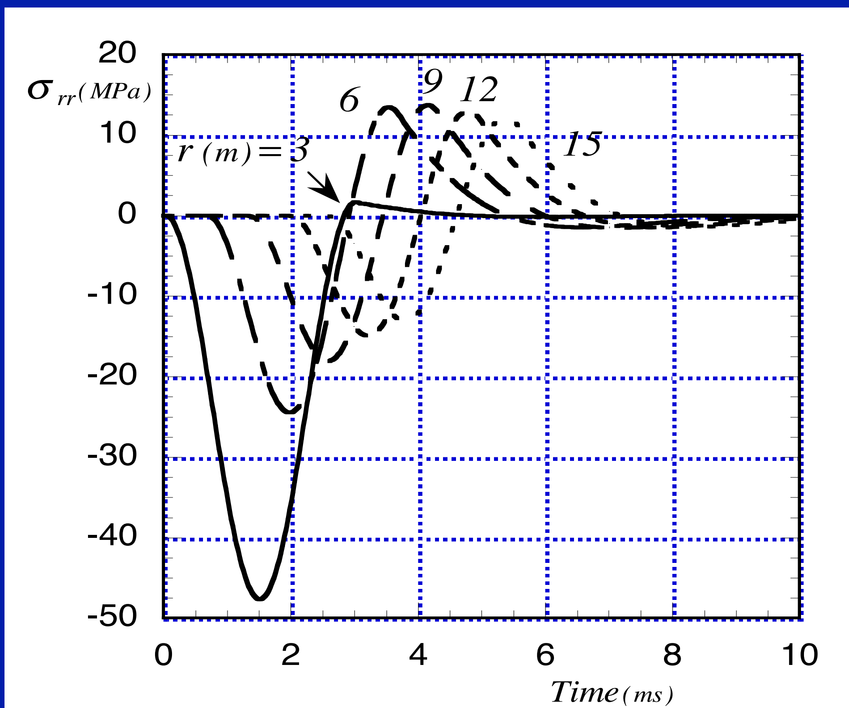
Mesh size $h = 0.25\ m$

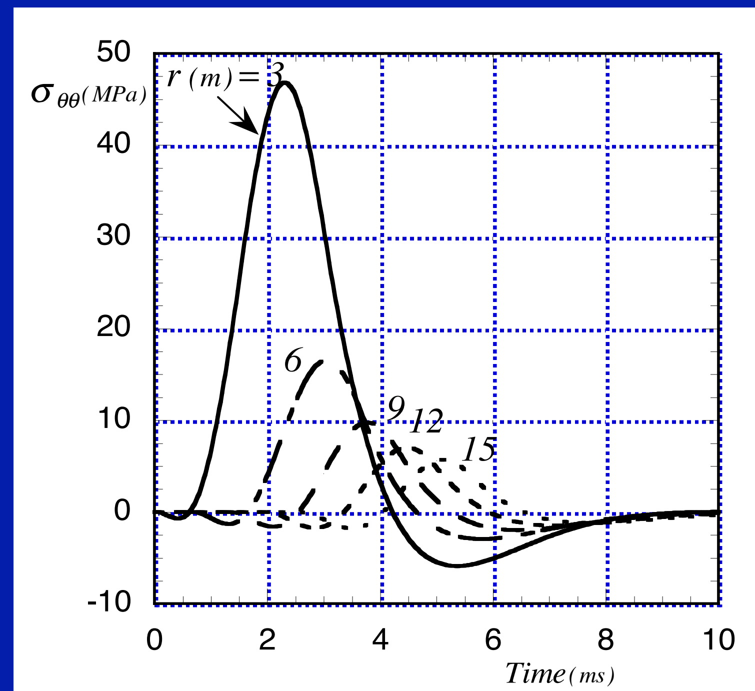
3. One-Dimensional Cylindrical Wave Propagation



$$\sigma_{rr}(t)\Big|_{r=3m} = -H[t]H[t_d - t]\frac{\sigma_0}{2}\left\{1-\cos\left(\frac{2\pi t}{t_D}\right)\right\}$$

3. One-Dimensional Cylindrical Wave Propagation

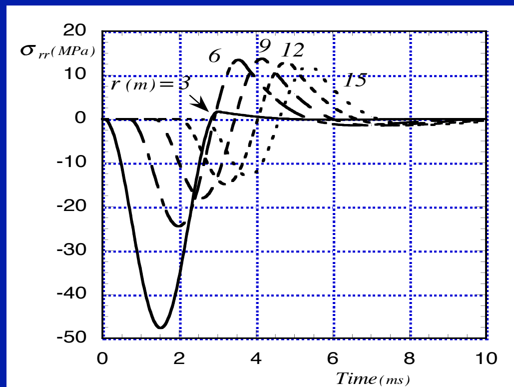


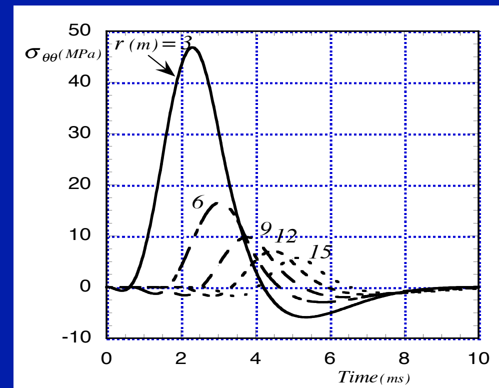


Radial and circumferential stress as functions of time at various radii

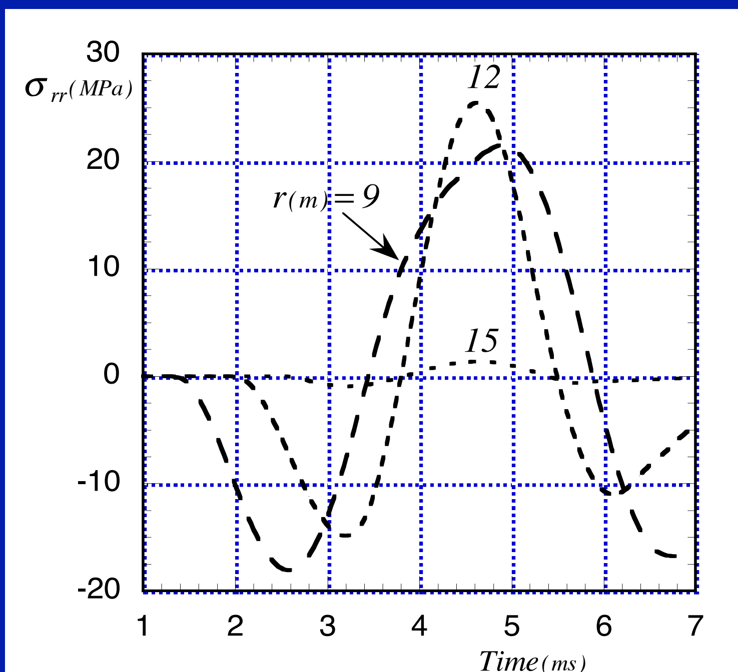
- no tunnel (simple wave propagation)

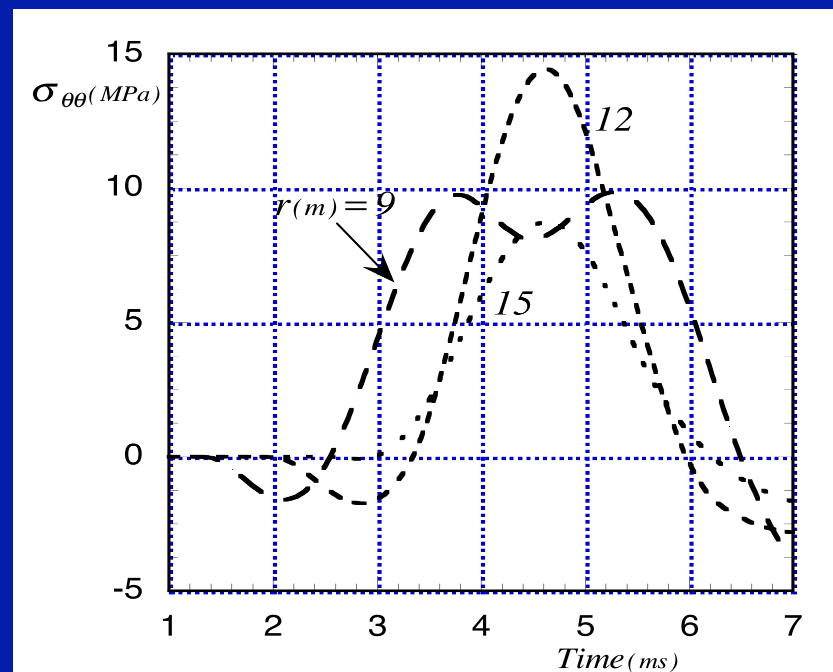
3. One-Dimensional Cylindrical Wave Propagation





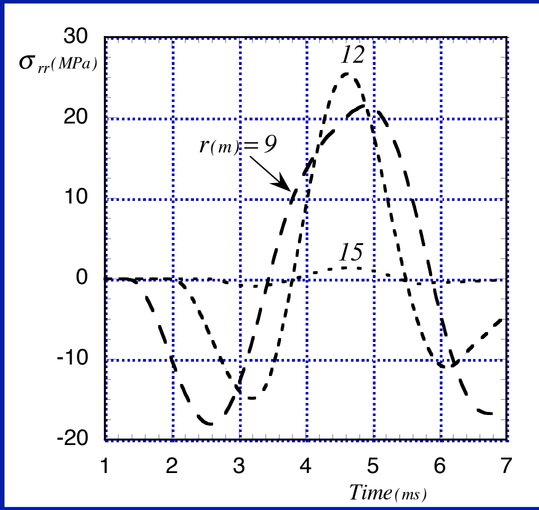
Free wave solution

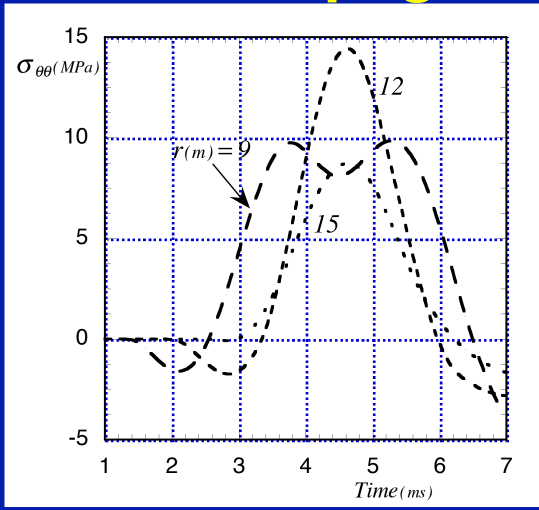




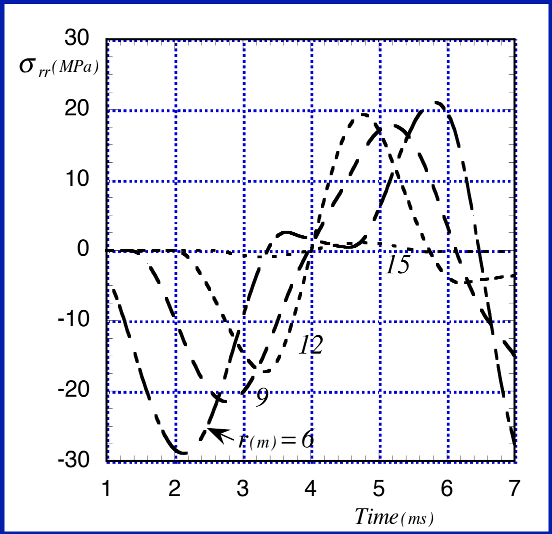
Radial and circumferential stress as functions of time at various radii with effect of free surface at r = 15 m

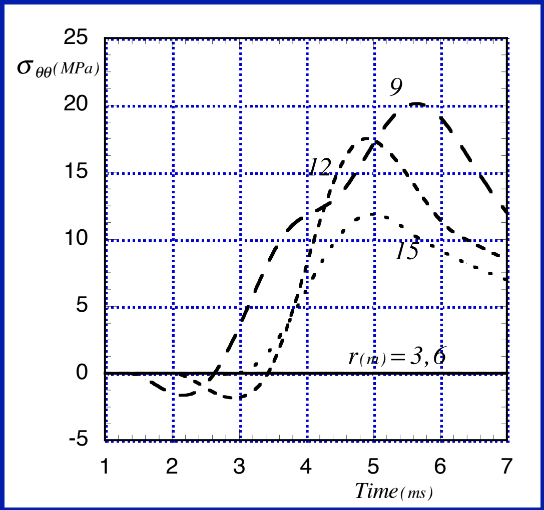
3. One-Dimensional Cylindrical Wave Propagation





No radial crack



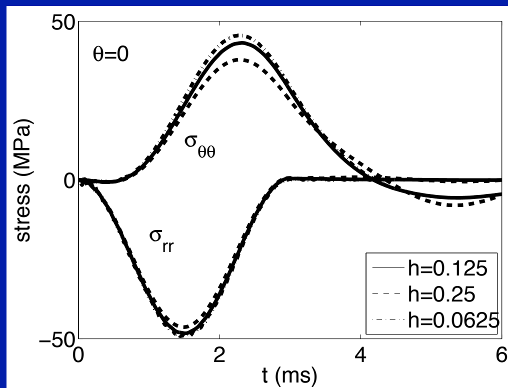


With radial crack

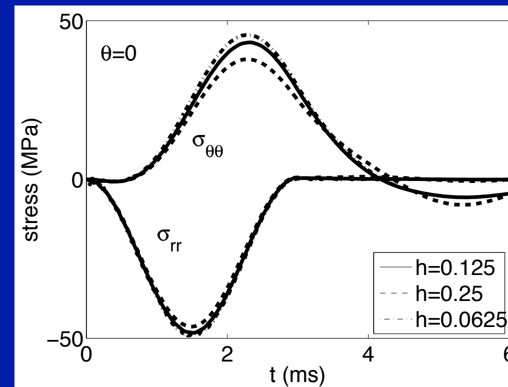
Radial and circumferential stress as functions of time at various radii with effect of free surface at r = 15 m and pre-existing radial cracks from 3 < r < 9 m

4. Two-Dimensional Solutions of Free Waves with MPM-Elastic

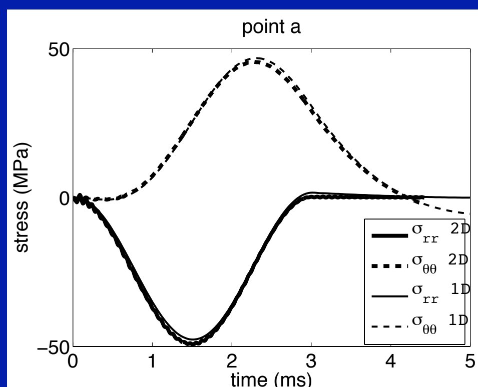
R = 3 m



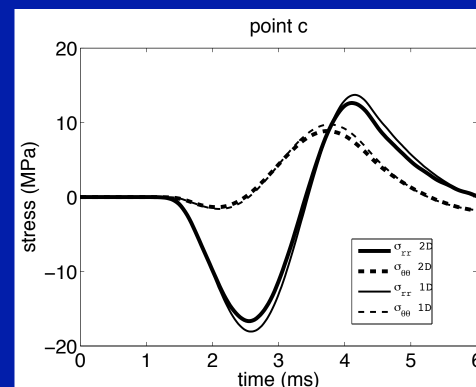
Mesh refinement

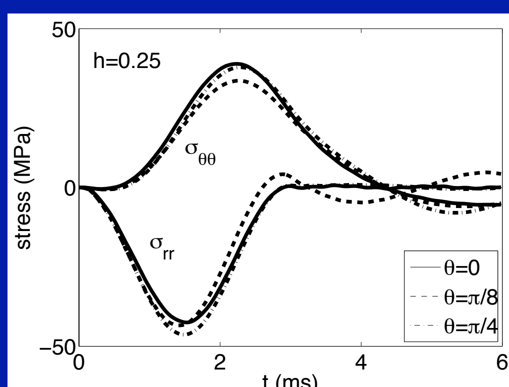


R = 6 m

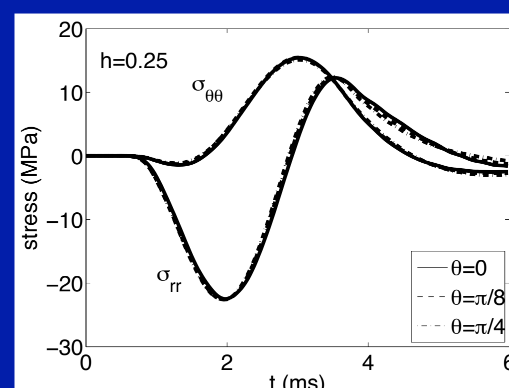


Comparison with 1-D Solution



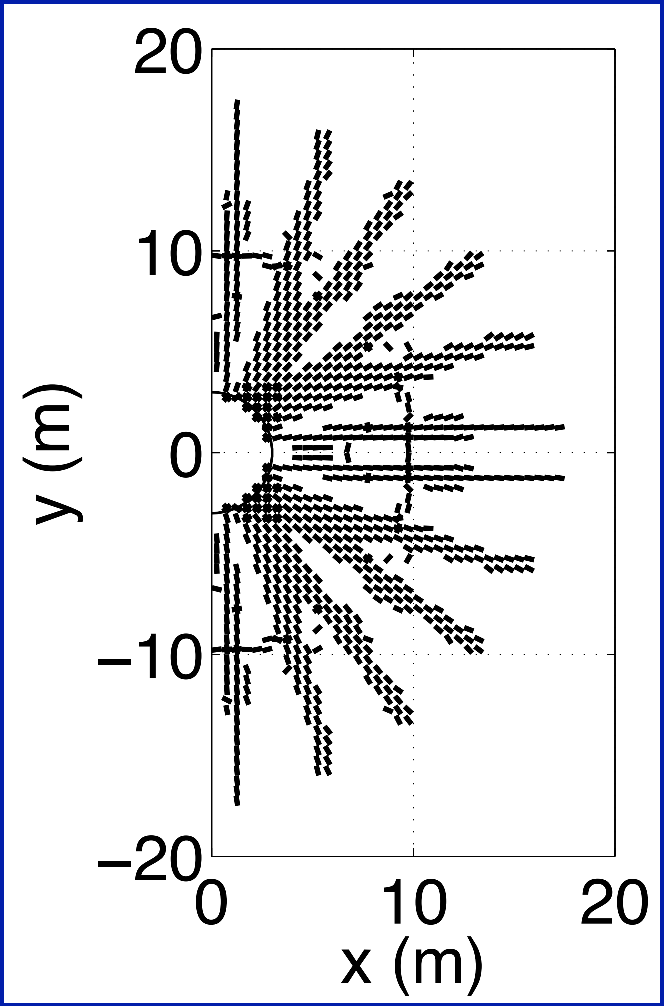


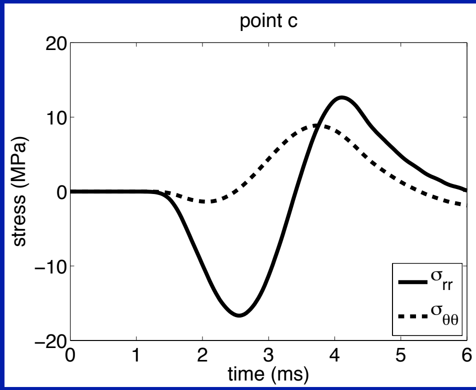
Effect of mesh orientation



4. Two-Dimensional Solutions of Free Waves with MPM-Failure

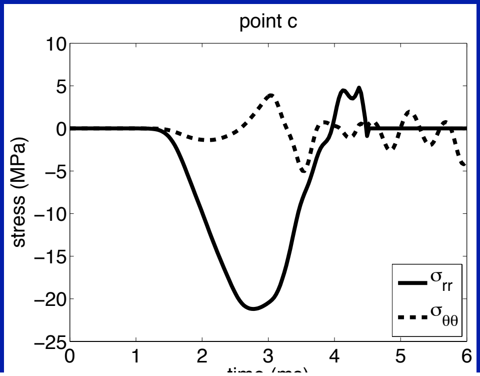
Crack distribution at t = 6 ms.





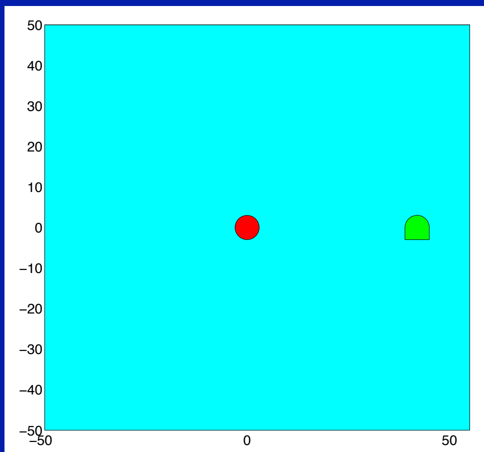
No cracking

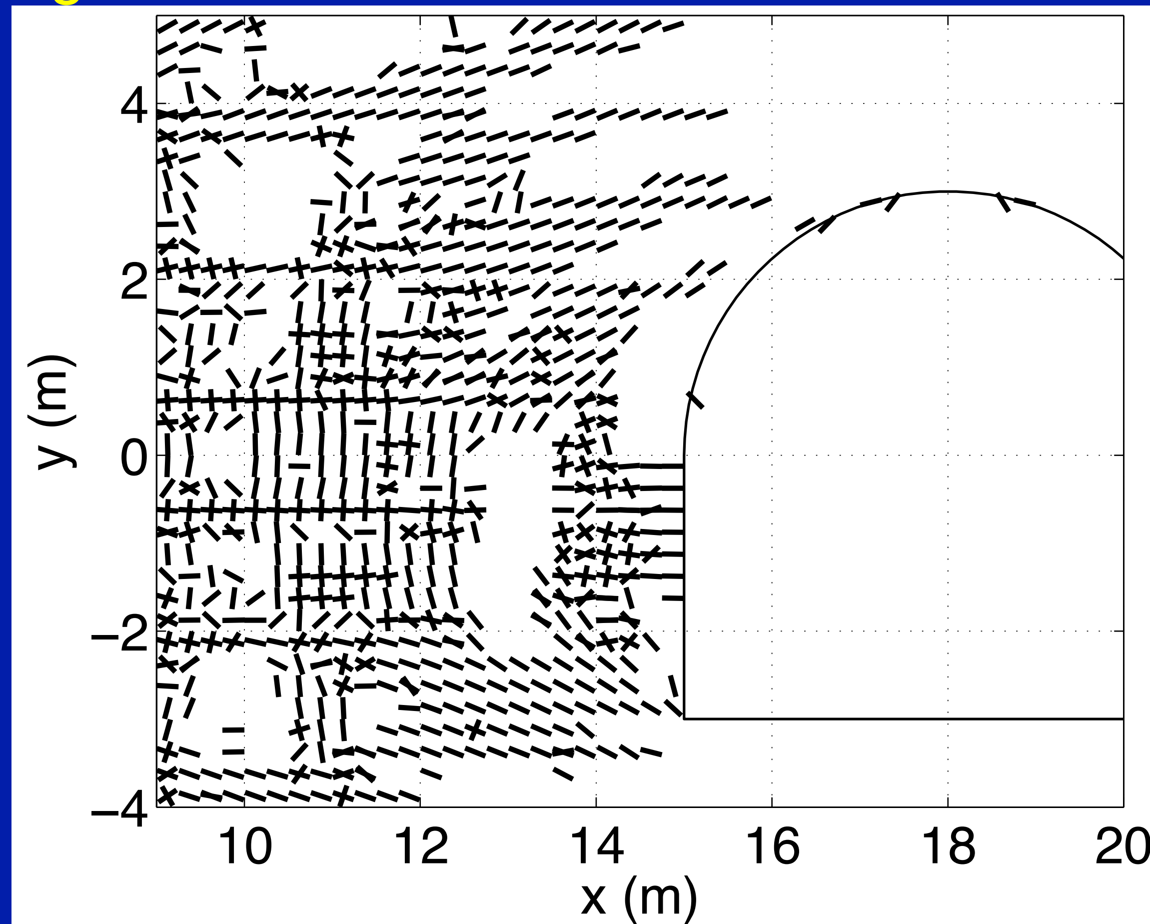
Stress as function of time at r = 9 m.



With cracking

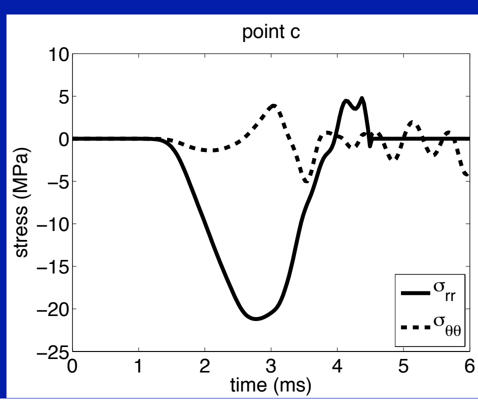
5. Solutions with Cracking around Tunnel



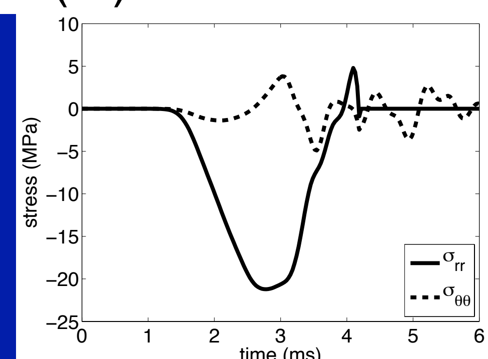


Crack distribution at t = 7 ms.

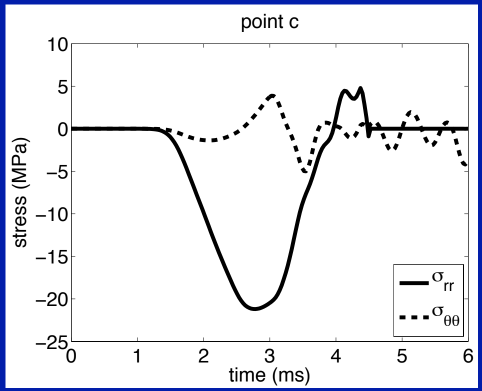
Free-field cracking



Stress as function of time at r = 9 m.

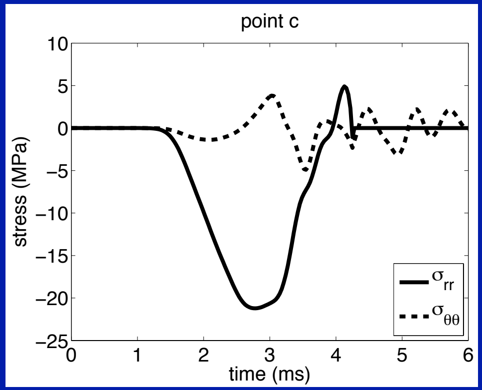


5. Solutions with Cracking around Tunnel that is Turned

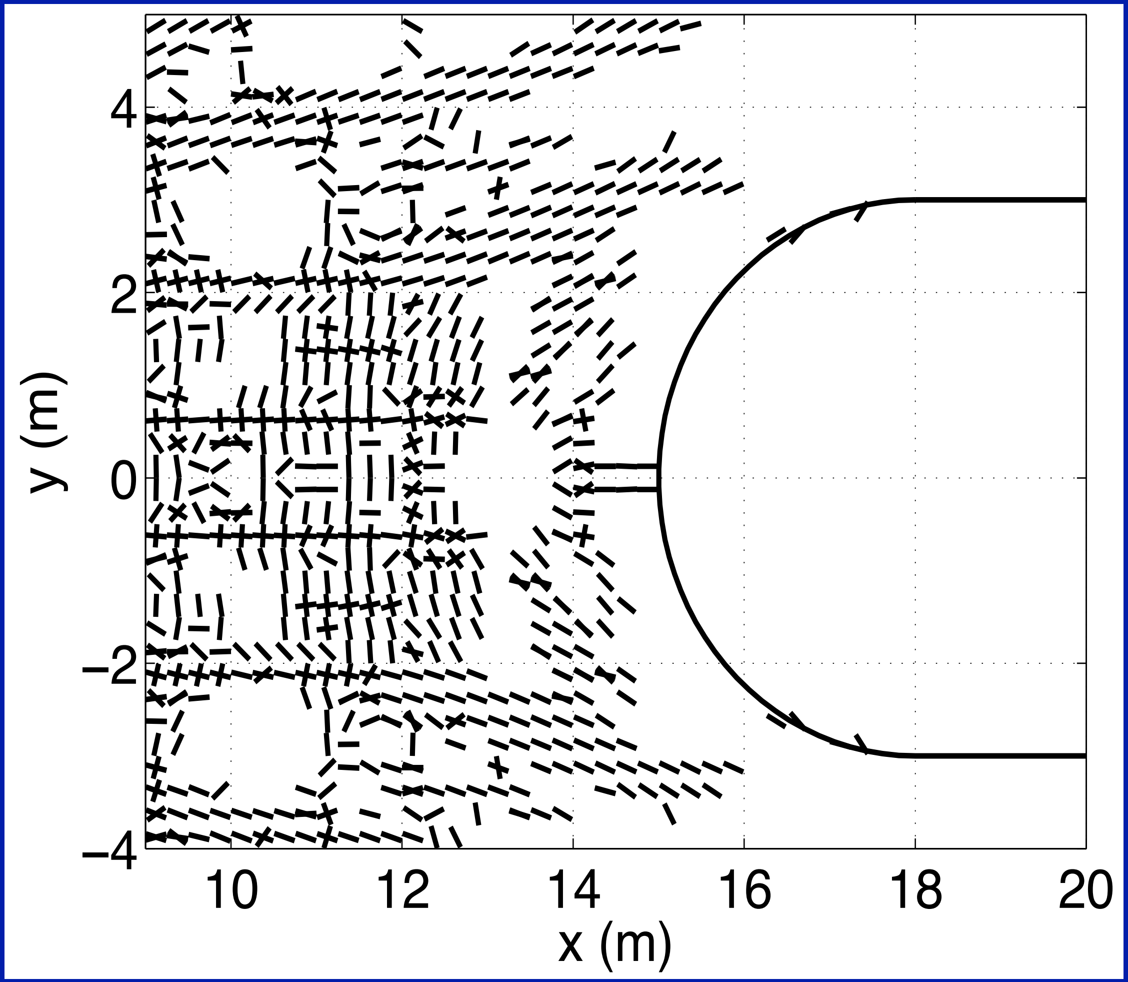


Free-field cracking

Stress as function of time at r = 9 m.

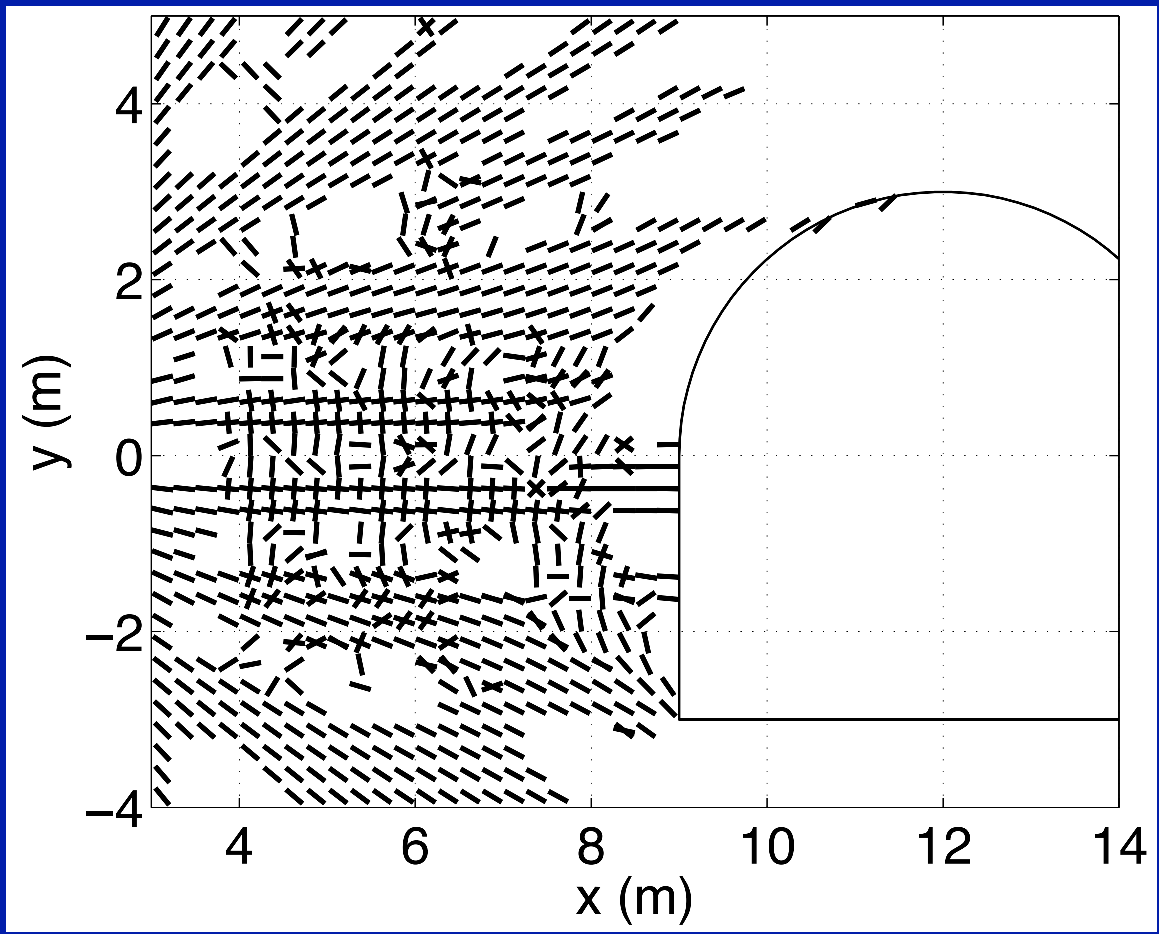


Cracking with tunnel



Cracking with tunnel **Crack distribution at t = 7 ms.**

5. Solutions with Cracking around Tunnel closer to Source



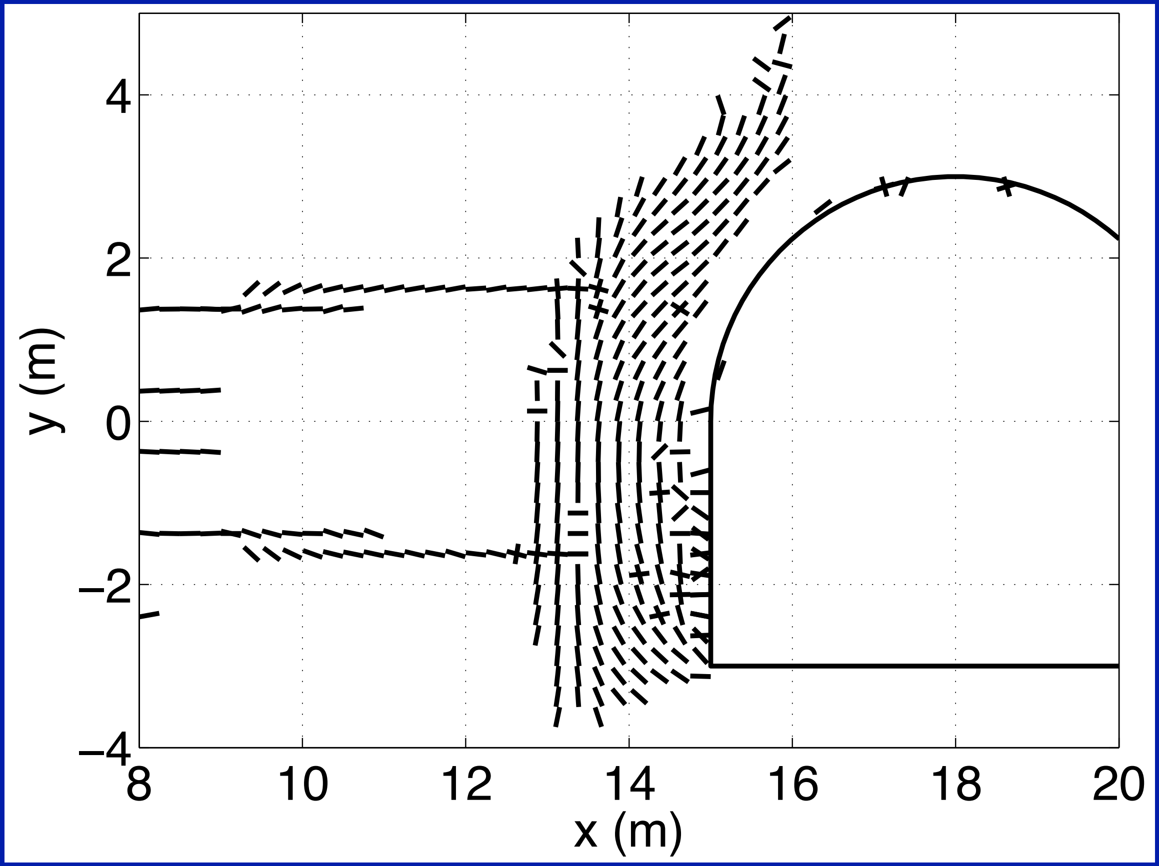
Crack distribution at t = 4 ms.

5. Solutions with Cracking around Tunnel with short duration

Short-duration pulse, t_d =0.2ms

provides vertical cracks

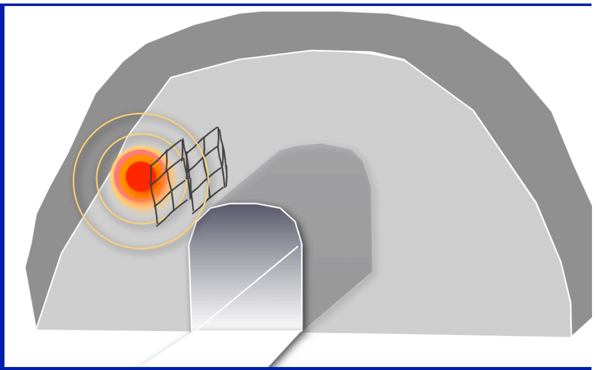
much closer to front face



Crack distribution at t = 7 ms.

With t_d = 0.5 ms

6. SUMMARY



1. Several simplifying assumptions

2. Cylindrical (and spherical) waves –
    large tensile radial tails and circumferential component

3. Reflections off free surface

    - initial compressive part enhances tensile radial component

    - region of large tensile circumferential stress enhanced

  Result –
    Region of significant radial and circumferential cracks adjacent to front face

4. Multiple cracking handled “straight-forwardly” with MPM

5. Axial splitting –
    source of additional cracks tangent to tunnel walls –possible source of slabbing