THREE APPROACHES TO COMPUTATIONAL FRACTURE OF DUCTILE STRUCTURAL METALS

1) **Critical plastic strain:**
   - damage-free plasticity used until critical strain is attained
   - some form of element deletion is used upon attainment of critical strain
   - critical plastic strain may depend on hydrostatic stress
   - critical strain *and* element size must be calibrated for material and/or structural element
   - predicts onset of cracking and crack advance

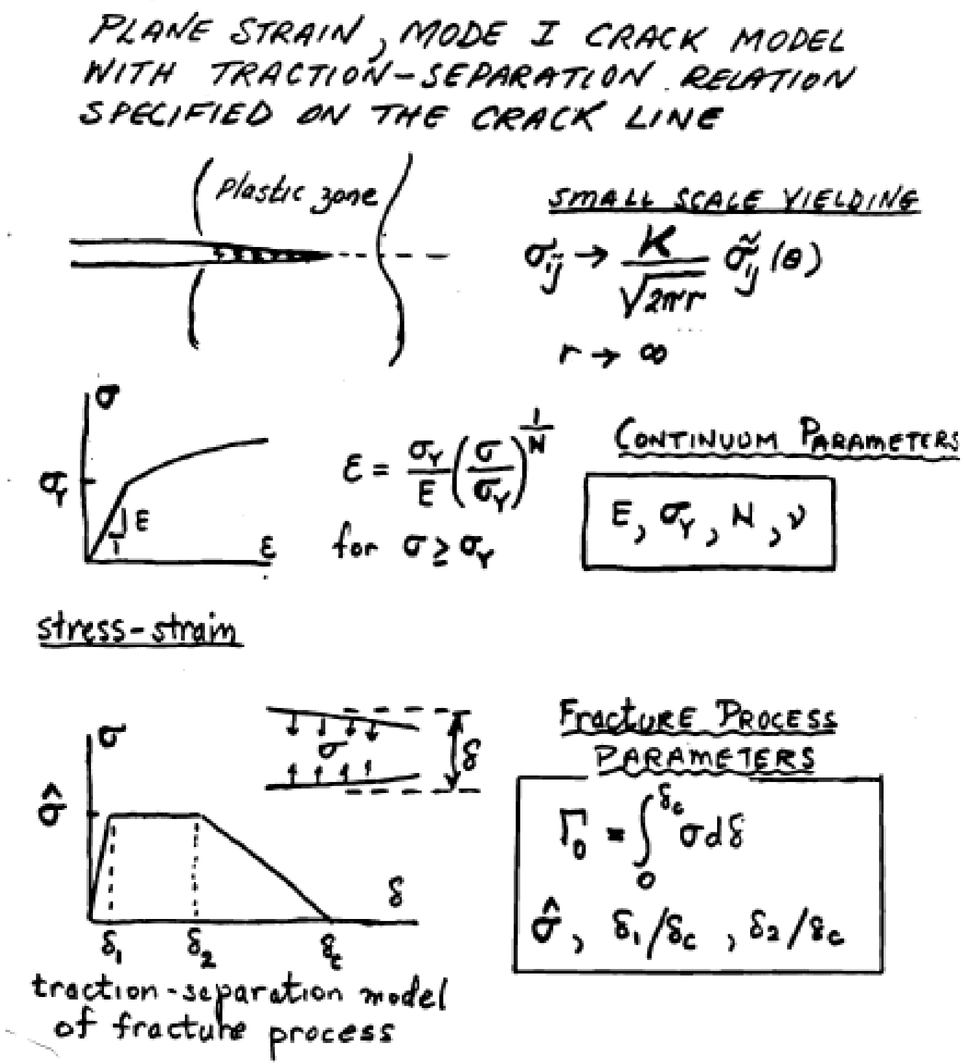
2) **Cohesive zone models:**
   - either fracture plane is assumed or cohesive zones are required between all elements across potential fracture planes
   - parameters characterizing cohesive zone (at least 2, generally more) must be calibrated for material and/or structural element
   - open issues when cohesive zones inserted between all elements
   - so far, only demonstrated convincingly for pre-existing cracks

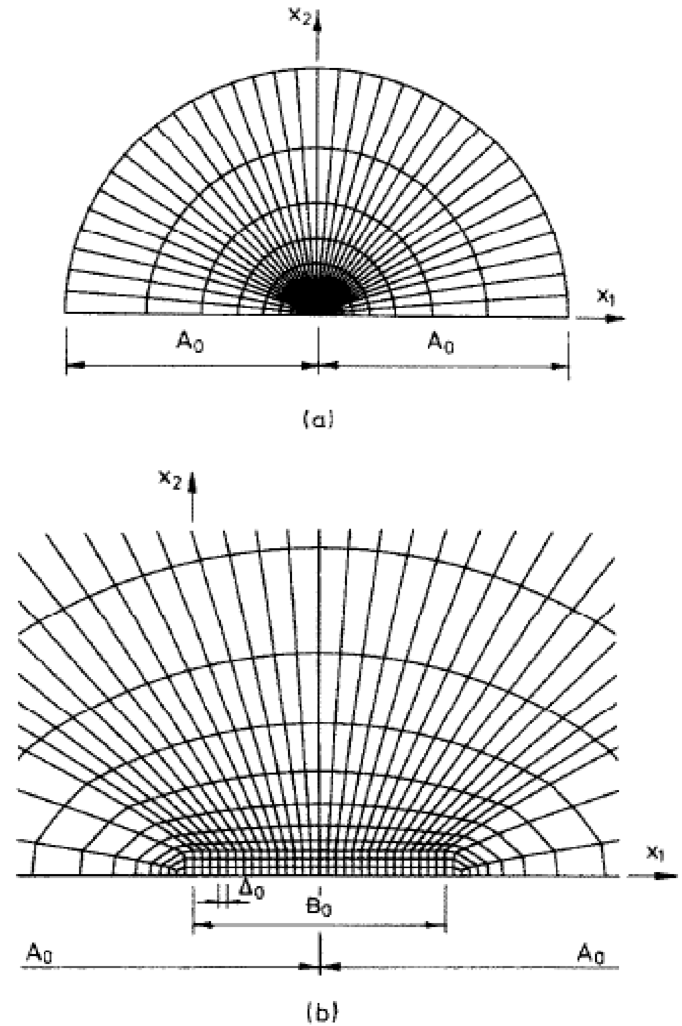
3) **Damage constitutive models incorporating fracture:**
   - Gurson-type models (or French versions) of void damage include softening, localization and fracture.
   - damage parameters in the models (at least 1, generally more) *and* element size must be calibrated.
   - predicts onset of cracking and crack advance

Computational models of ductile fracture: Illustrated by Mode I cracking

“Generic” Cohesive zone models:

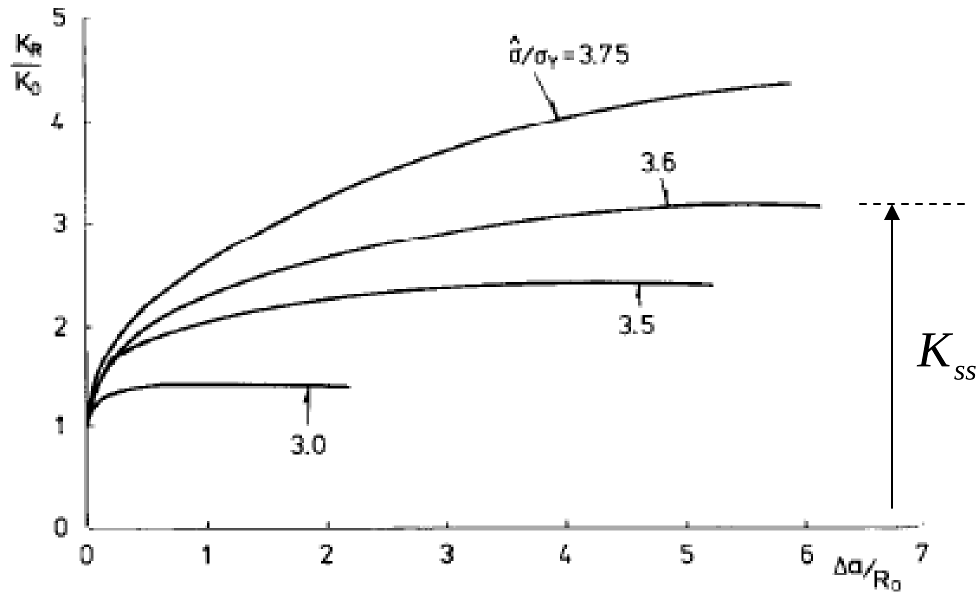
Tvergaard & Hutch JMPS 40, 1377-1397 (1992)





Finite element model with high resolution
along the separation line

Cohesive zone models (continued)



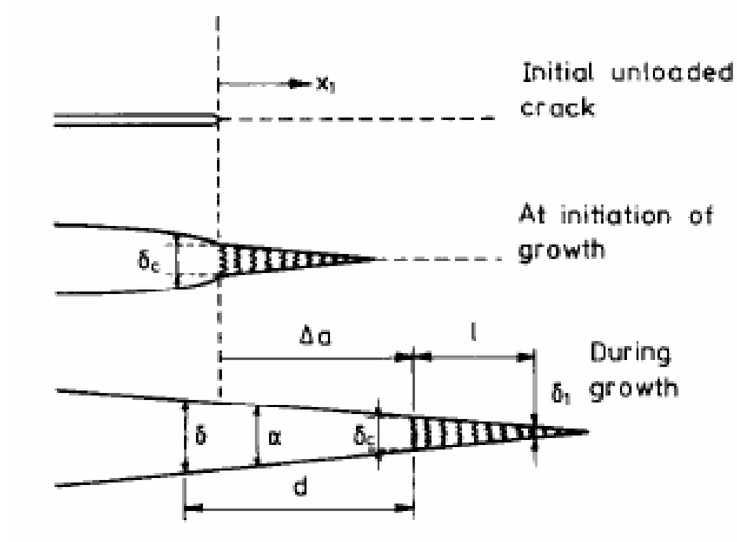


FIG. 4. Crack tip quantities.

Crack growth resistance curves with $\sigma_Y/E = 0.003$, $N = 0.1$, $\nu = 0.3$, $\delta_1/\delta_c = 0.15$ and $\delta_2/\delta_c = 0.5$.

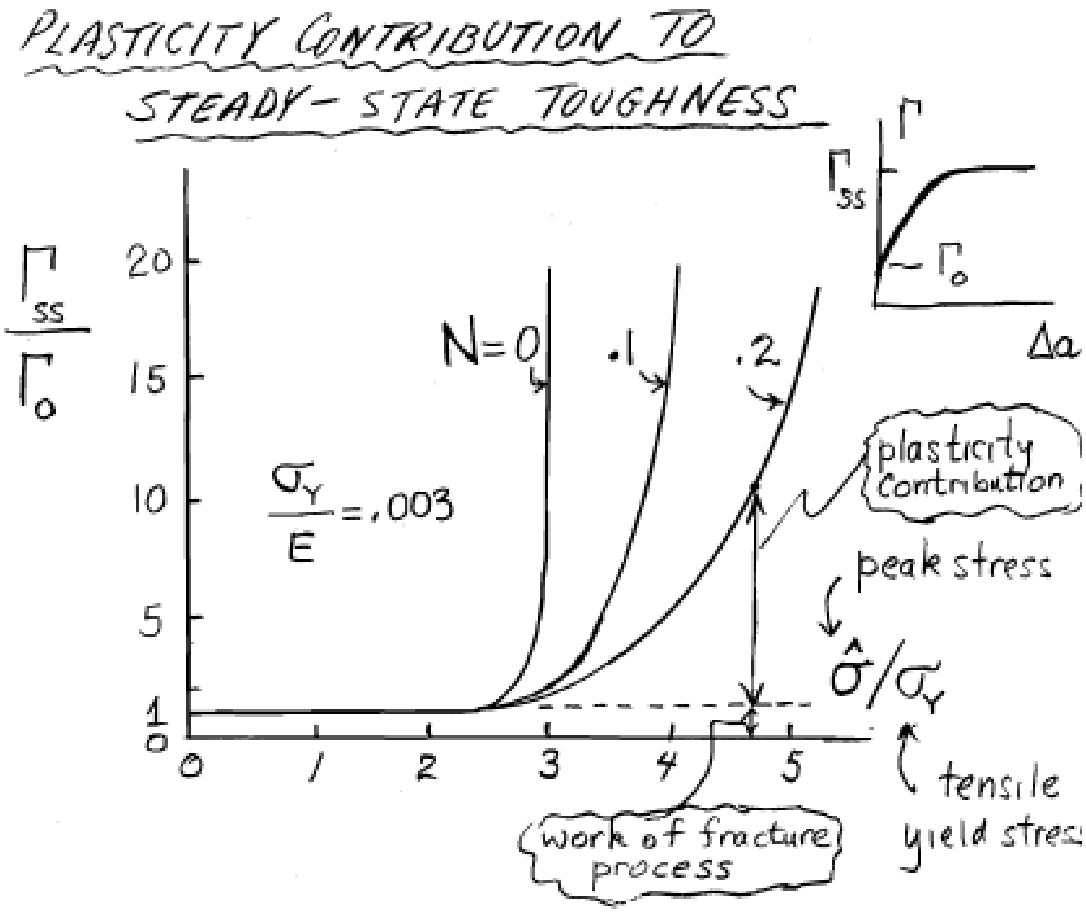
J-integral applies prior to crack growth

$$J = \int_\Gamma [W\, dx^2 - T^i u_{i,1}\, ds], \quad W = \int_0^{\eta_{ij}} \tau^{ij} \delta\eta_{ij},$$

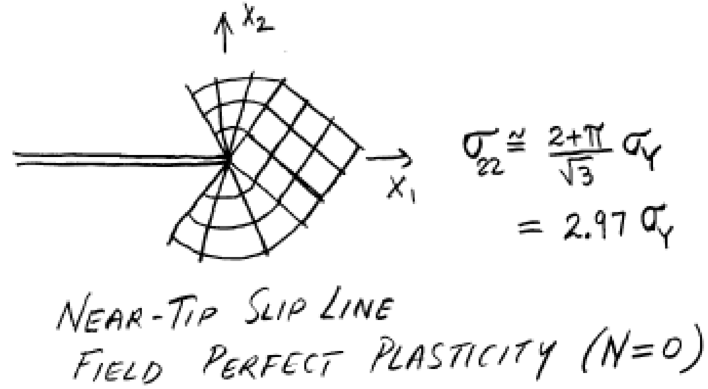
At initiation:

$$J = \int_0^{\delta_c} \sigma(\delta) d\delta = \Gamma_0 \quad \Rightarrow \quad K_{iniation} = K_0 = \sqrt{\bar{E}\Gamma_0}$$

Cohesive zone models (continued)

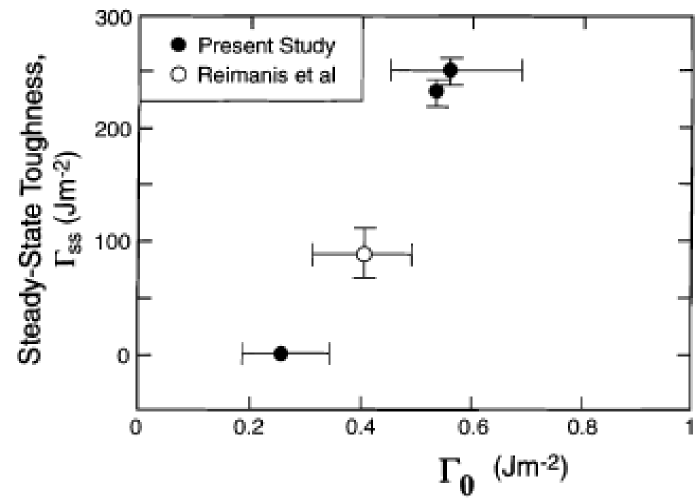


$$\Gamma_{ss} = K_{ss}^{\ 2} / \bar{E}$$



Max normal stress cannon exceed

$$2.97\,\sigma_Y \quad \text{for } N = 0$$

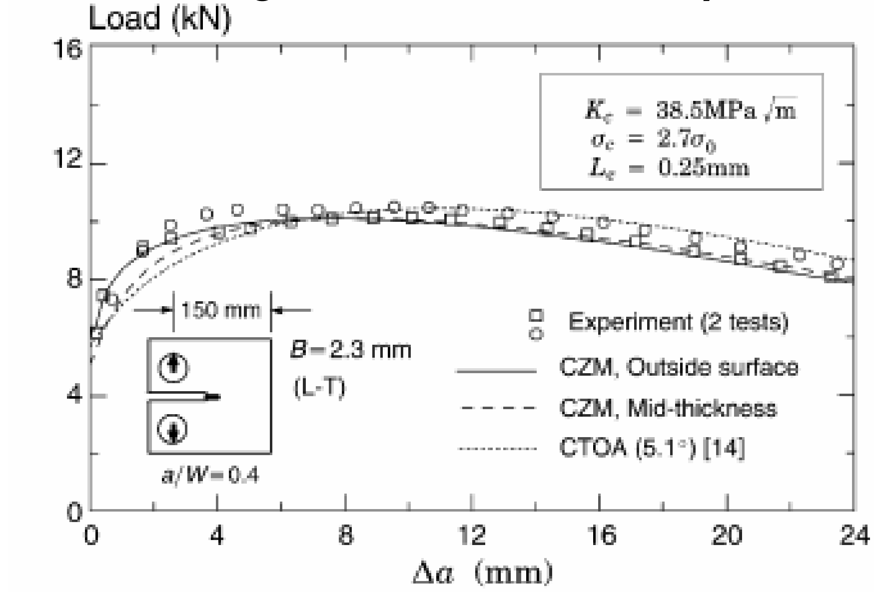


Experimental data of Evans, et al for a Au/Al2O3 interface. The separation energy (and probably the peak separation stress) is varied by incorporating a fraction of an atomic layer of carbon.

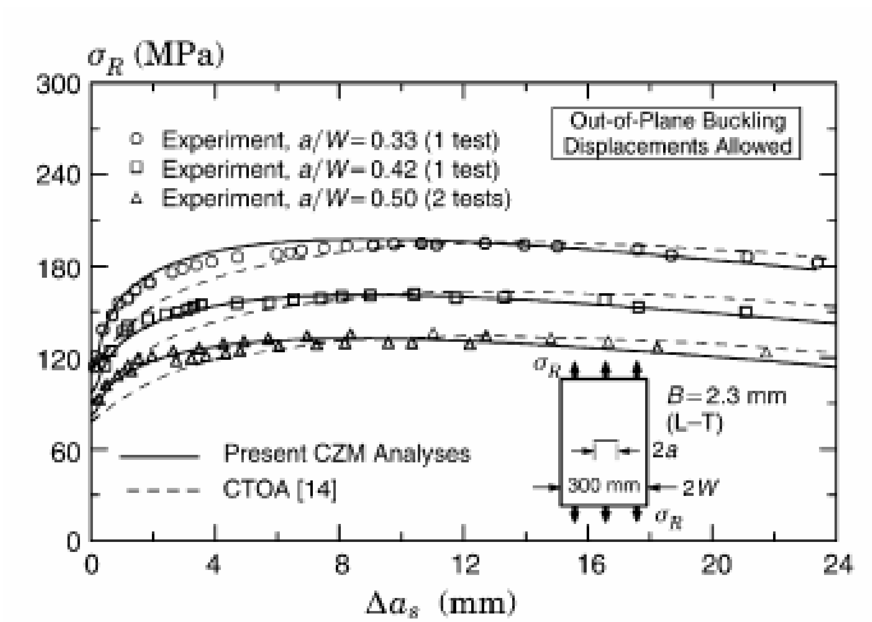
APPLICATION OF COHESIVE ZONE FOR MODE I GROWTH IN THIN PLATES

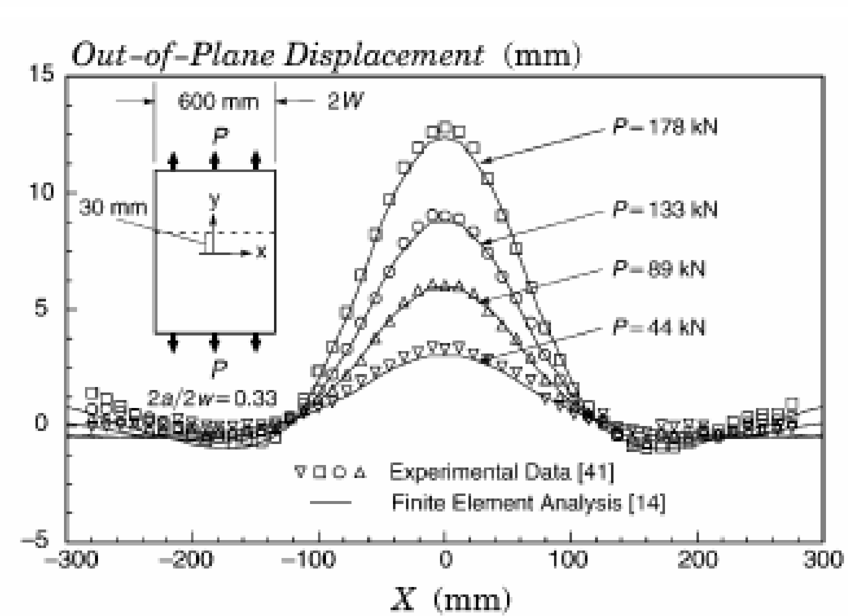
2.3mm thick Al 2024-T3 sheets (Dodds, et al. Eng. J. Fract. Mech. 2002)

Calibration: Compact tension specimen

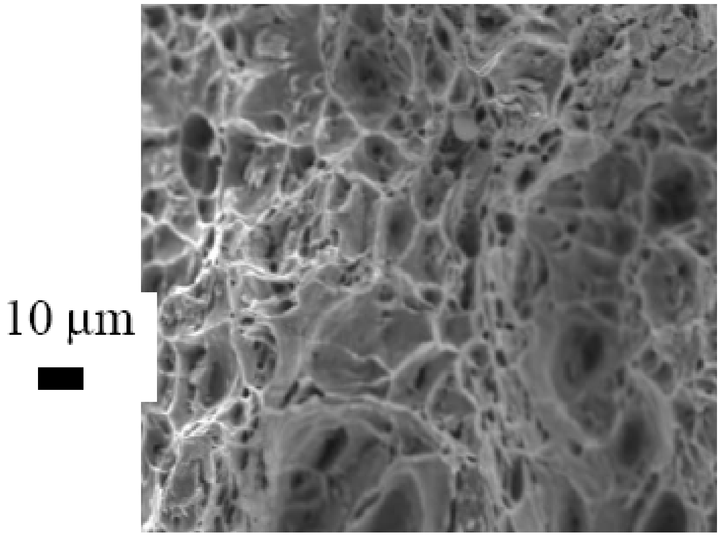


Application: Center cracked specimen which buckles out of plane





Mechanism of ductile fracture—void nucleation, growth & coalescence



Fracture surface of Weldox steel (Faleskog, 2006)

Gurson Model of Plasticity with void nucl., growth & coal.

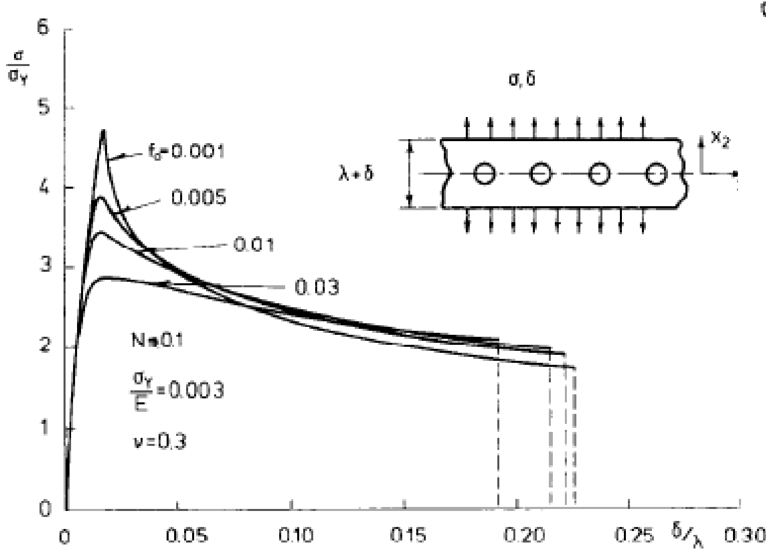
Y.F.

$$\left(\frac{\sigma_e}{\bar{\sigma}}\right)^2 + 2q_1 f\cosh\left(\frac{3q_2\sigma_m}{2\bar{\sigma}}\right) - \left(1 + q_1^2 f^2\right) = 0$$

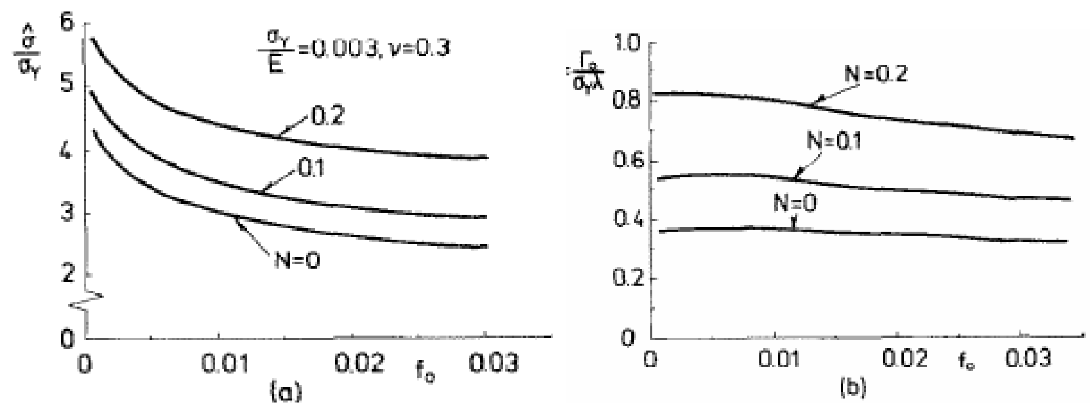
State Variables

$$\dot{f} = (1-f)\dot{\epsilon}^p_{kk} + \mathcal{A}\dot{\bar{\epsilon}} + \mathcal{B}(\dot{\bar{\sigma}} + \dot{\sigma}_m)$$

$$\dot{\bar{\epsilon}} = \frac{\dot{\sigma} : \dot{\epsilon}^p}{(1-f)\bar{\sigma}}$$



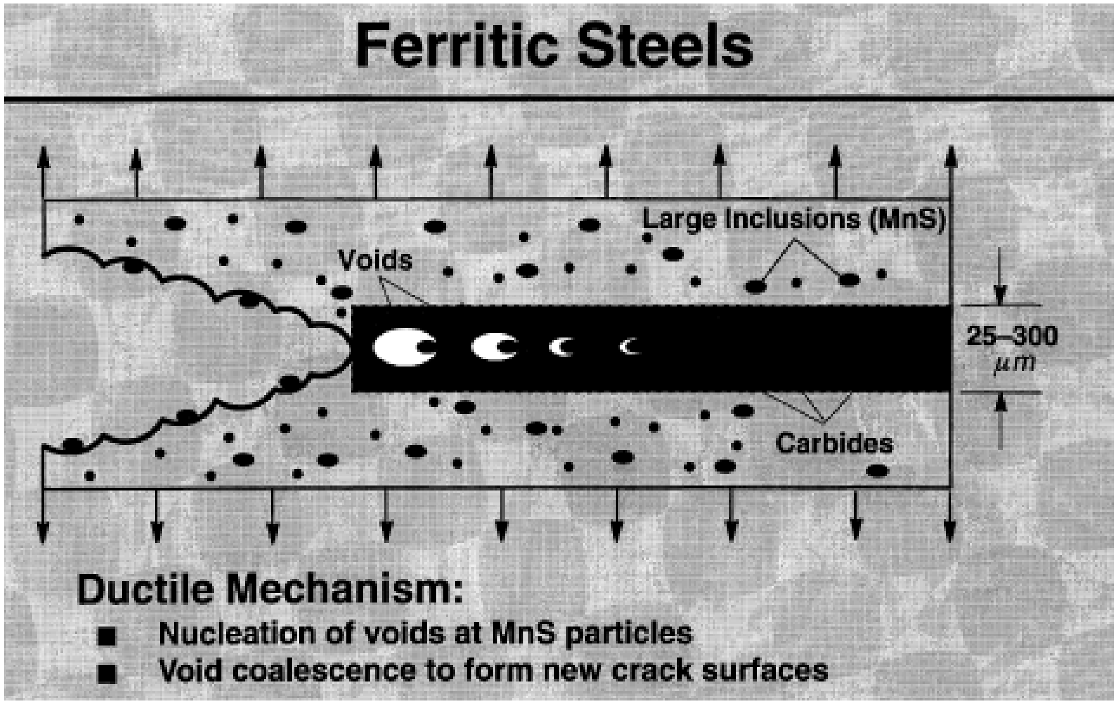
Computation of traction-separation relation using Gurson Model

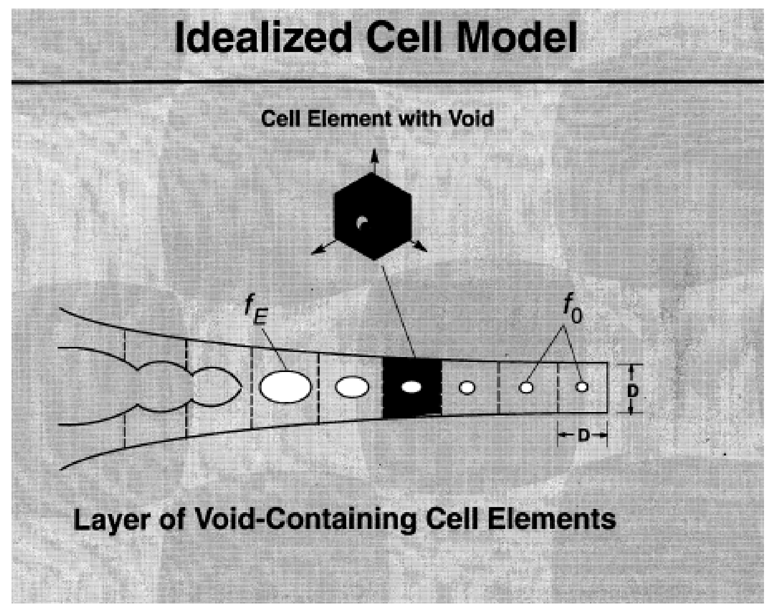


Peak stress and work of separation as predicted by Gurson Model as a function of initial void volume fraction for various levels of strain hardening.

Void-Damage Plasticity approach (Gurson model)

Acknowledgment: This general approach was developed by groups in France, Germany, UK and US. In the US, C.F. Shih and R.H. Dodds were the lead developers. I am using selected material from a set of slide they prepared.





Damage parameters in model :

D ~ spacing between voids

f ~ void vol. fraction;

f_0 ~ initial void vol. fraction

f_E ~ void vol. fraction at onset of coalescence

Void-Damage Plasticity approach--continued

GT Porous Plasticity Model

Y.F. $$\left[\frac{\sigma_e}{\bar{\sigma}}\right]^2 + 2q_1 f \cosh\left[\frac{3q_2\sigma_m}{2\bar{\sigma}}\right] - \left[1 + q_1^2 f^2\right] = 0$$

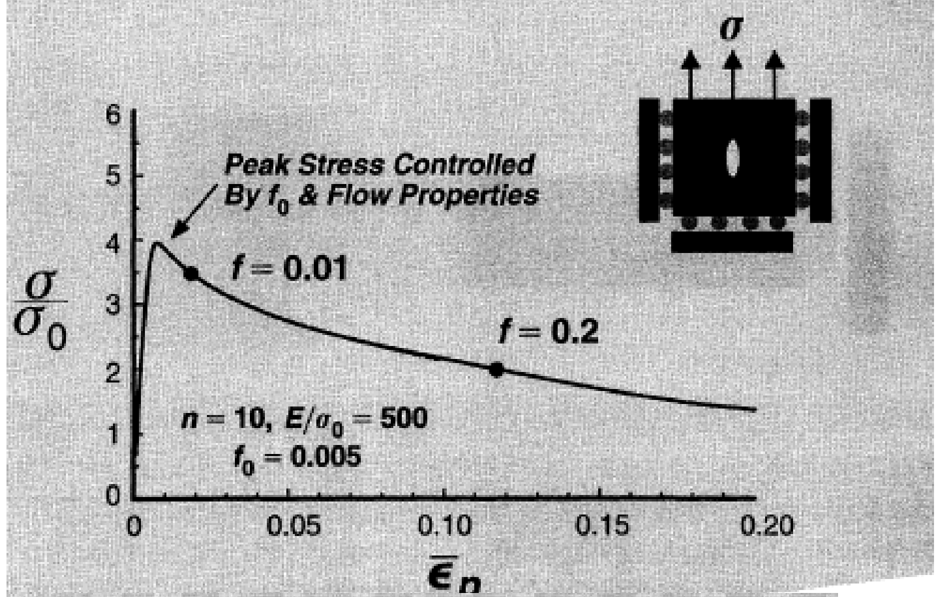
State Variables $$\dot{f} = (1-f)\dot{\epsilon}^p_{kk} + \mathcal{A}\dot{\bar{\epsilon}} + \mathcal{B}(\dot{\bar{\sigma}} + \dot{\sigma}_m)$$

$$\dot{\bar{\epsilon}} = \frac{\boldsymbol{\sigma} : \dot{\boldsymbol{\epsilon}}^p}{(1-f)\bar{\sigma}}$$

Numerical Implementation (Finite Strains)

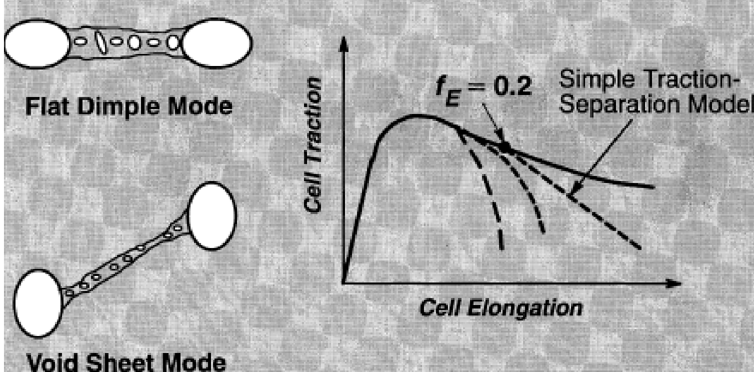
- Elastic–Predictor, Radial Return
- Consistent Tangent Operator
- Multiple Hardening Models for Matrix Material
- Viscoplastic Matrix Response

Isolated Cell Response



Micromechanics Parameters

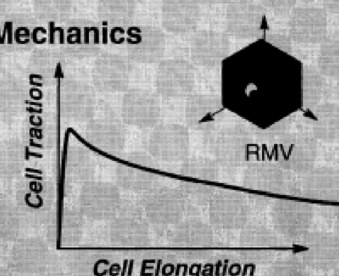
Coalesence Mechanics



Micromechanics Parameters

Hole Growth Mechanics

Adjust q_1 and q_2 in GT to best fit the RMV results over range of triaxialities



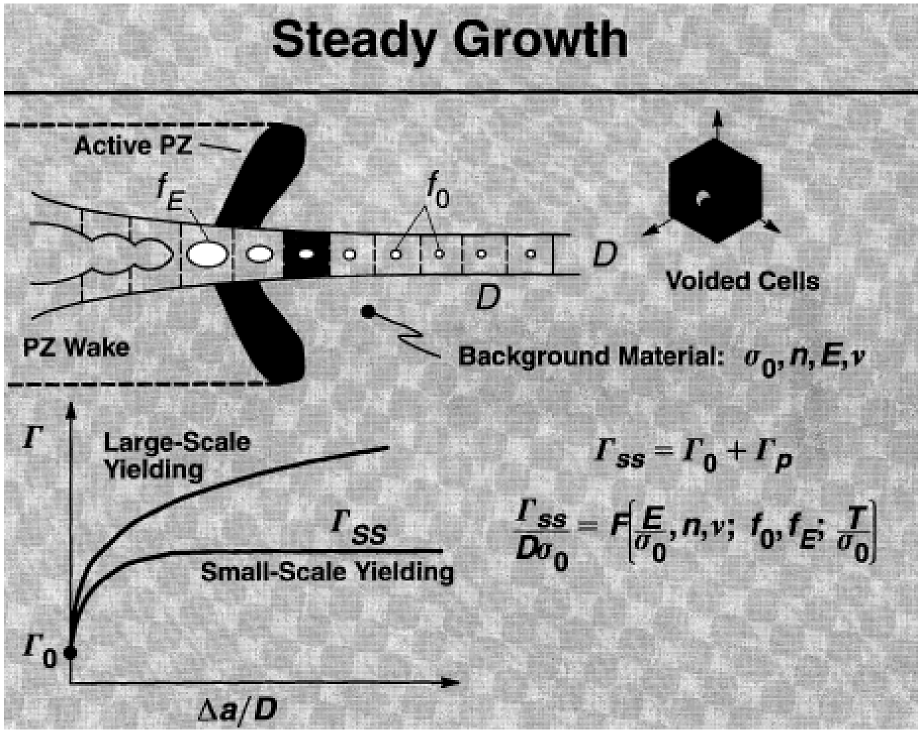
$E/\sigma_0 = 500$

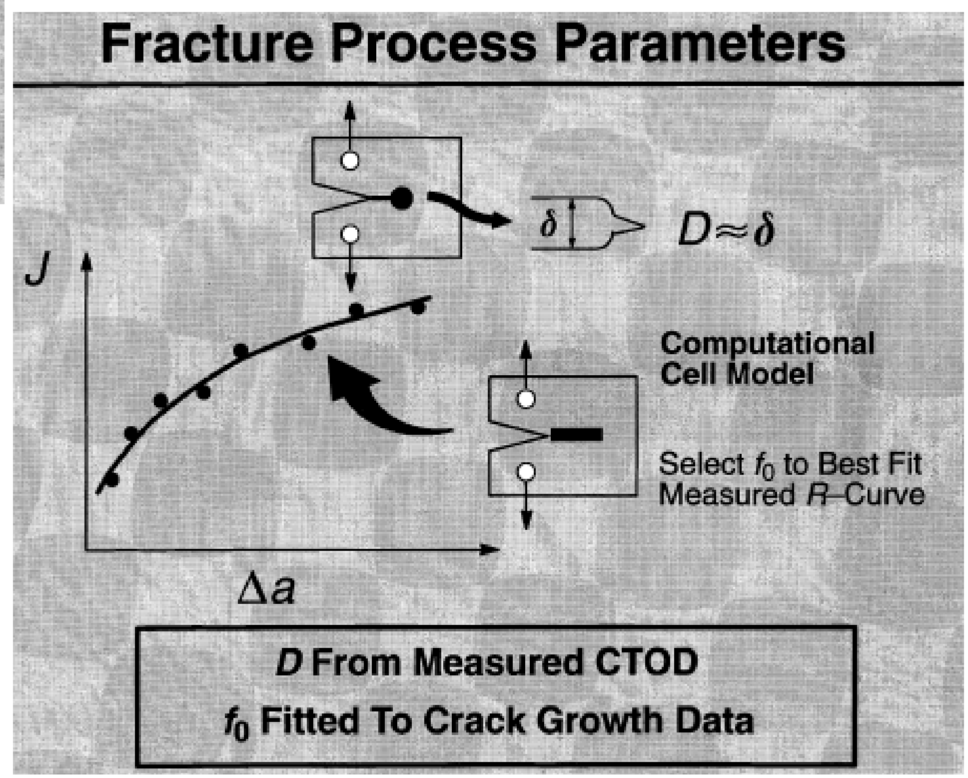
$n = 5$: $q_1 = 1.62$, $q_2 = 0.835$

$n = 10$: $q_1 = 1.35$, $q_2 = 0.953$

$n = 40$: $q_1 = 1.20$, $q_2 = 1.056$ ← ≈Tvergaard's elastic, perfectly–plastic values

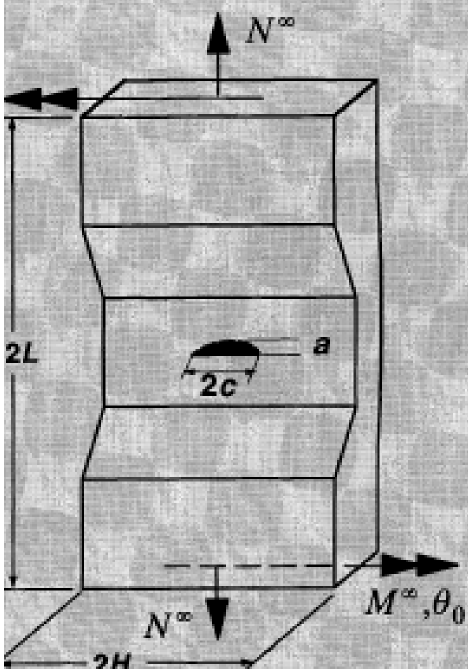
Void-Damage Plasticity approach--continued

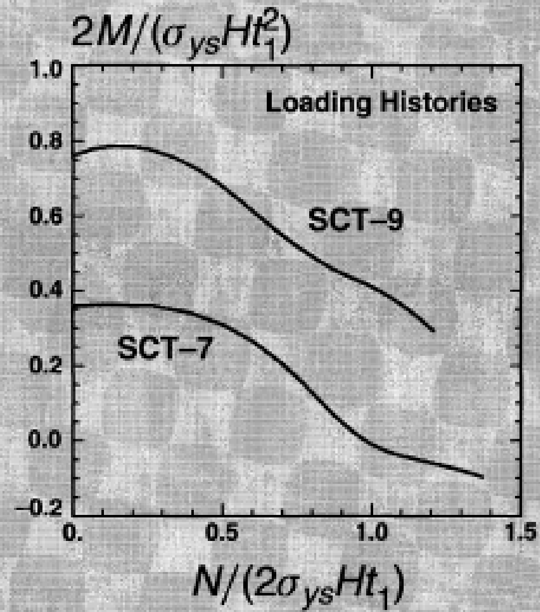




Void-Damage Plasticity approach—continued: Application to 3D surface crack

Specimen Geometry & Loading

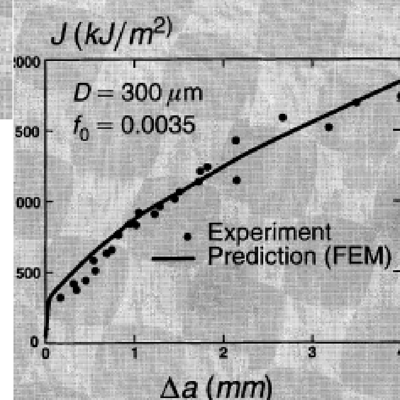


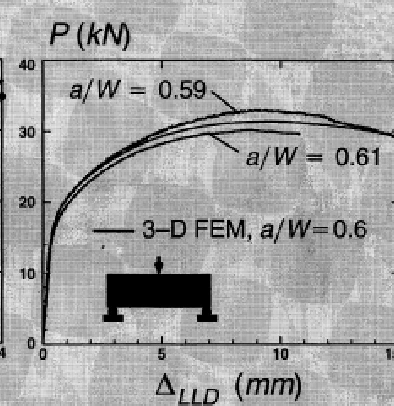


Plates with Surface Cracks

- ***Material:*** **2 1/4 Cr 1 Mo Steel (Press. Vessels)**
  - ***Yield Stress:*** **255 MPa**
  - ***Ultimate Stress:*** **495 MPa**
  - ***n:* 4–5 (high hardening)**
- ***Micromechanics Parameters***
  - **$q_1 = 2.0$, $q_2 = 0.77$**
  - **$f_E = 0.2$ (Linear traction–separation)**
- ***Fracture–Process Parameters***
  - **$D = 300\ \mu m$ ($\approx$ CTOD)**
  - **Calibrate f_0 Using 2-D and 3-D Analyses of SE(B) Specimen [plane sided]**

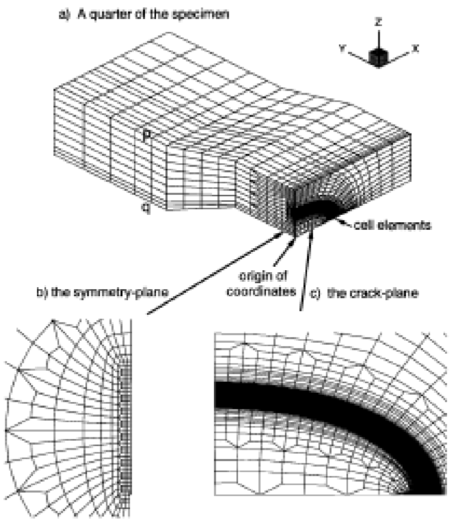
f_0 Calibration



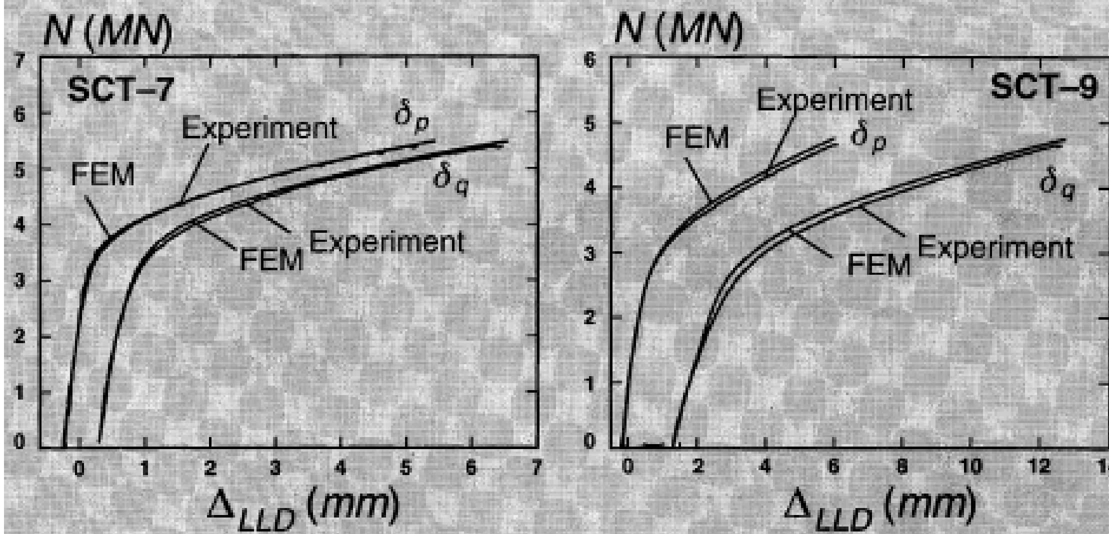


Void-Damage Plasticity approach—continued: Application to 3D surface crack

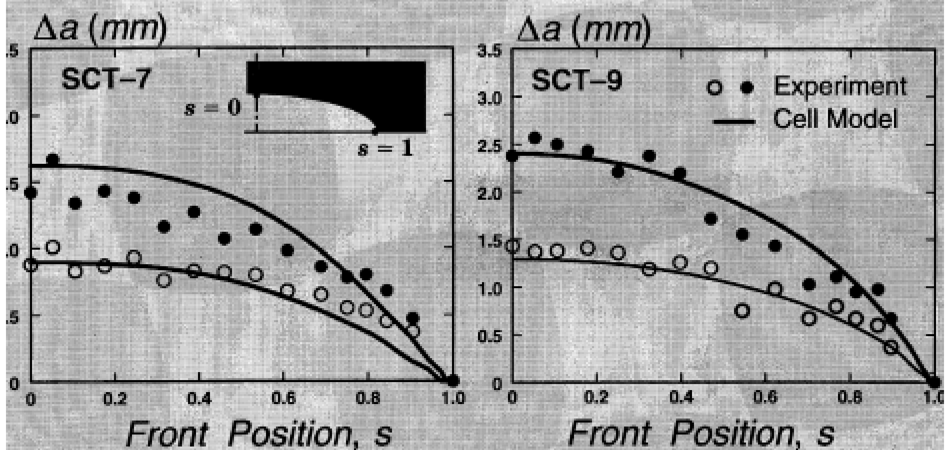
Surface Crack Model



Load-Displacement Response



Ductile Tearing



Modeling void as individual entities—plane strain model

Two types of crack growth: void by void & multiple void interaction

Tvergaard & Hutchinson IJSS (2002)

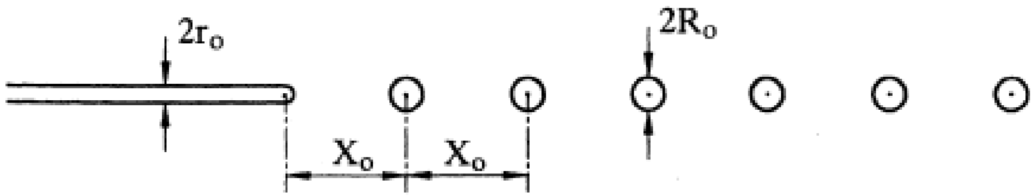
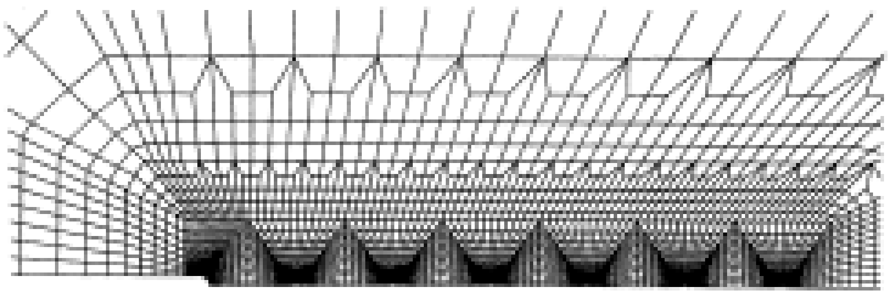
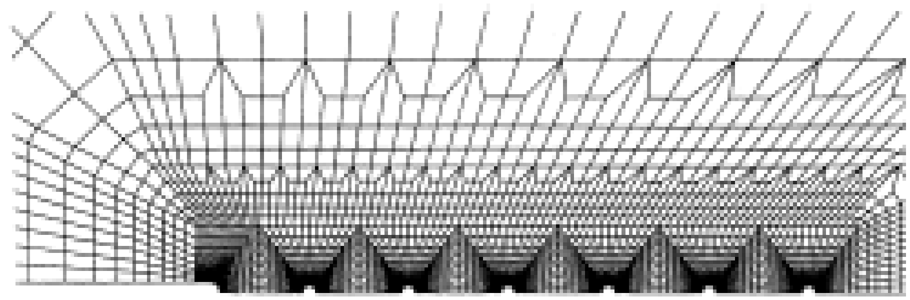


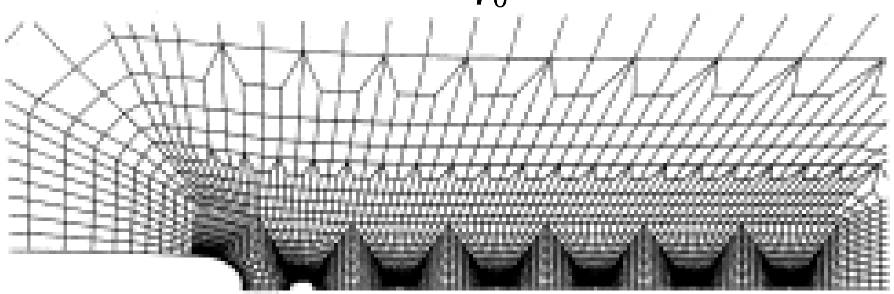
Fig. 1. Geometry of the two-dimensional, plane strain small scale yielding model.



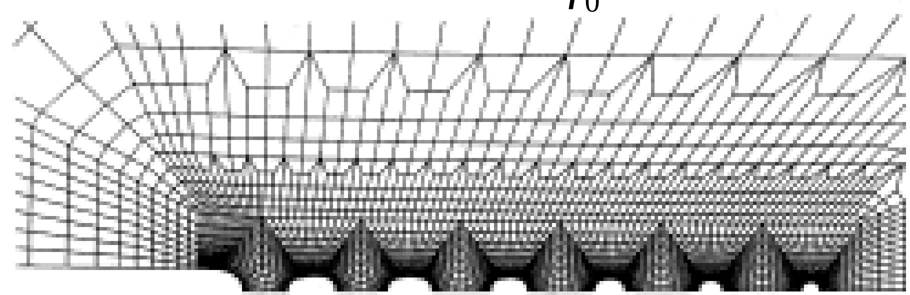
(a) $f_0 = 0.00087$ **undeformed**



(a) $f_0 = 0.014$



(b)



(b)

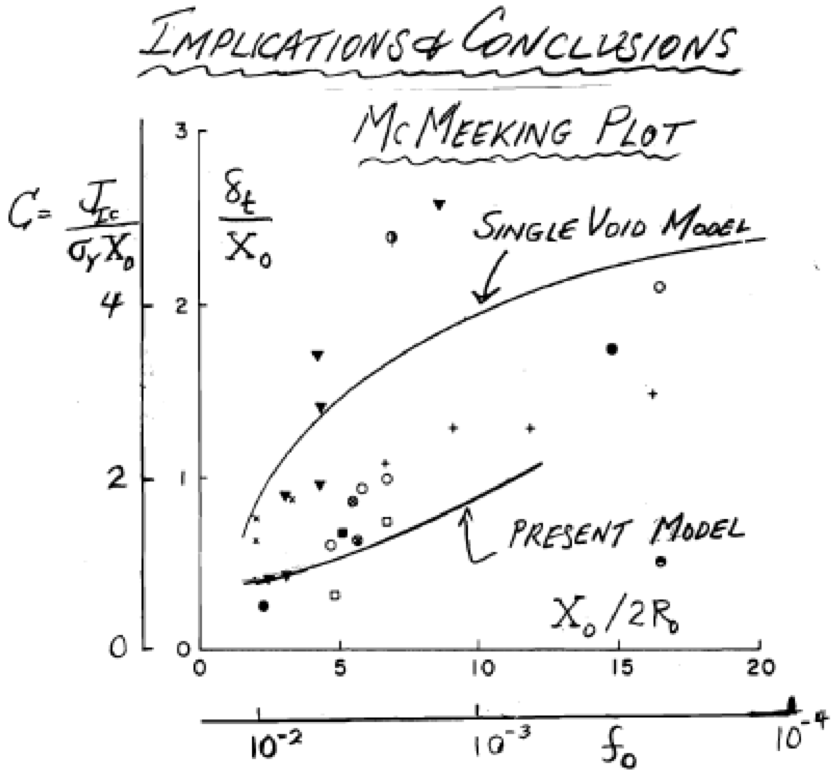
Void-by-void

deformed—prior to failure of first ligament

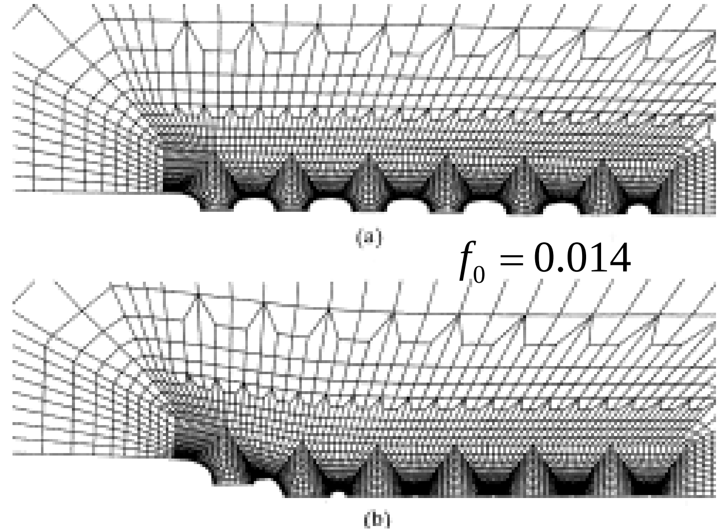
Multiple void interaction

Modeling void as individual entities—plane strain model

Two types of crack growth: void by void & multiple void interaction



- STRONG MULTIPLE VOID INTERACTION : $f_0 > .001$
- IS SINGLE VOID EVER "CORRECT" ?
- CALIBRATED GURSON–TYPE MODELS SHOULD CAPTURE ENTIRE RANGE OF BEHAVIORS



(a) $f_0 = 0.014$

(b) $f_0 = 0.00087$