Solid Dynamics
Dynamic fracture and fragmentation
Modeling and Simulation

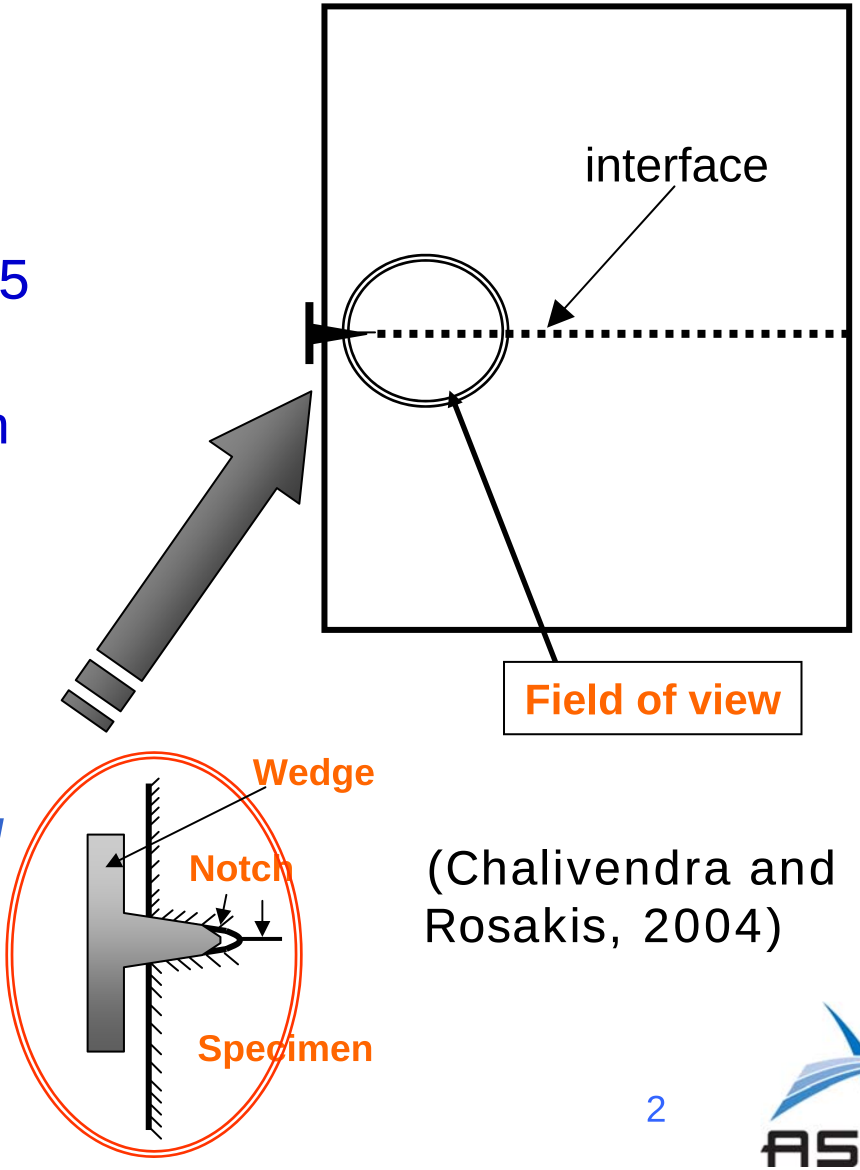
M. Ortiz (Caltech) Group leader
I. Arias, J. Knap, A. Mota

A.J. Rosakis, V. Chalivendra, S. Hong

Caltech ASC Center – Midyear review
April 13-24, 2005

Description of experiment (IV)

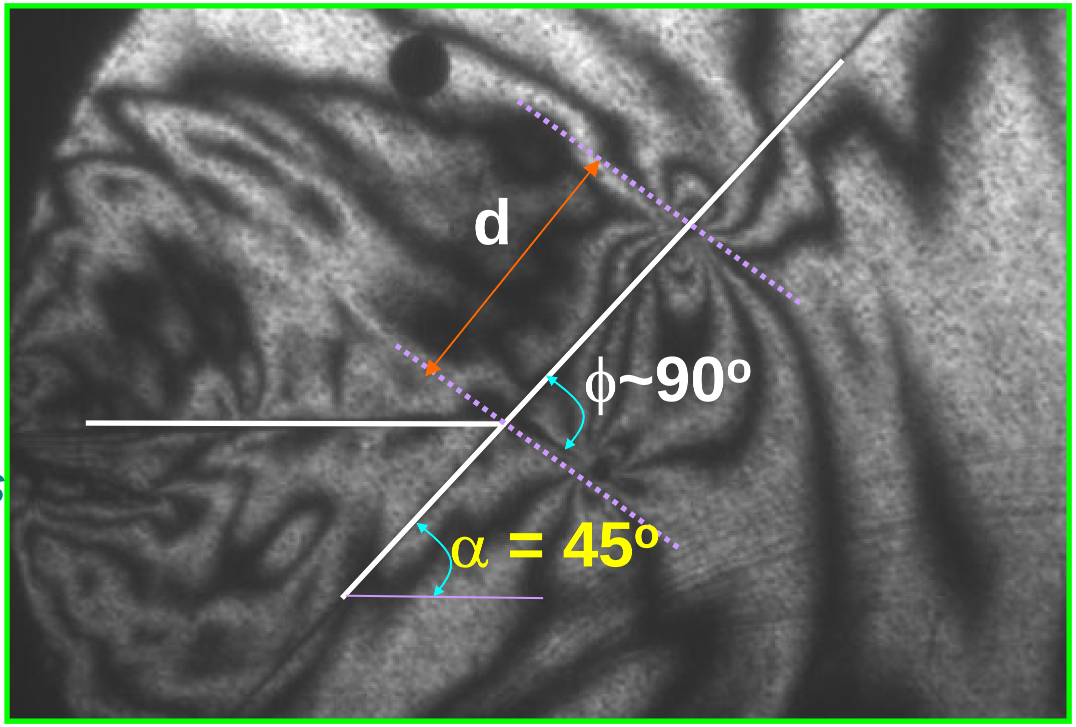
- Horizontal interface: Loctite 384
- Material: Homalite-100
- Sample size: 450 x 375 x 9.5 (mm)
- Boundary conditions: traction free
- Loading:
  - *Experiment: Hopkinson bar*
  - *Simulation: distributed tractions on notch surfaces*
- Linear cohesive law (*material properties from experiment*)
- l_c= 1.267 [mm]=1267 [μm]



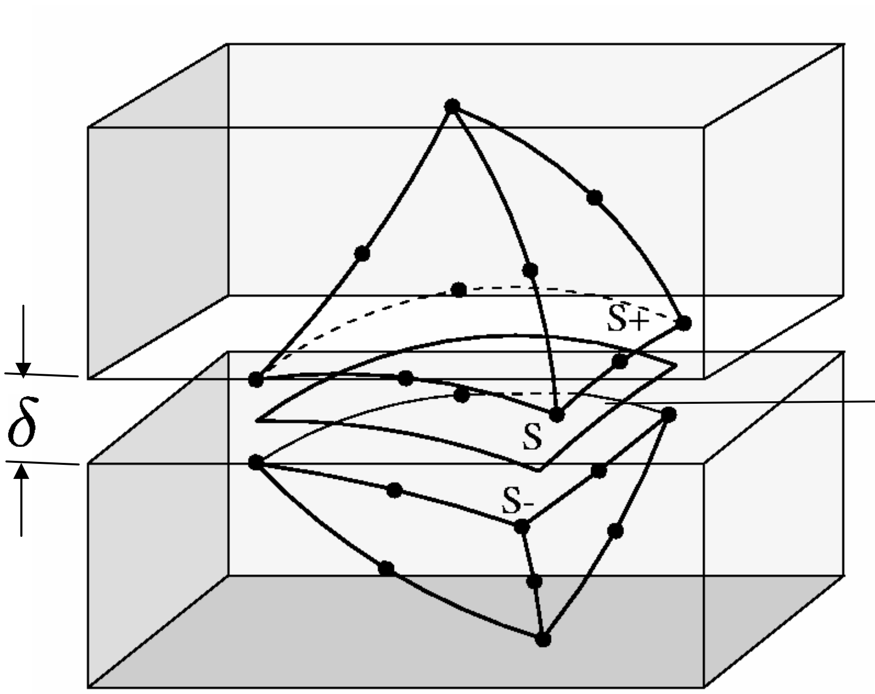
(Chalivendra and Rosakis, 2004)

Validation metrics

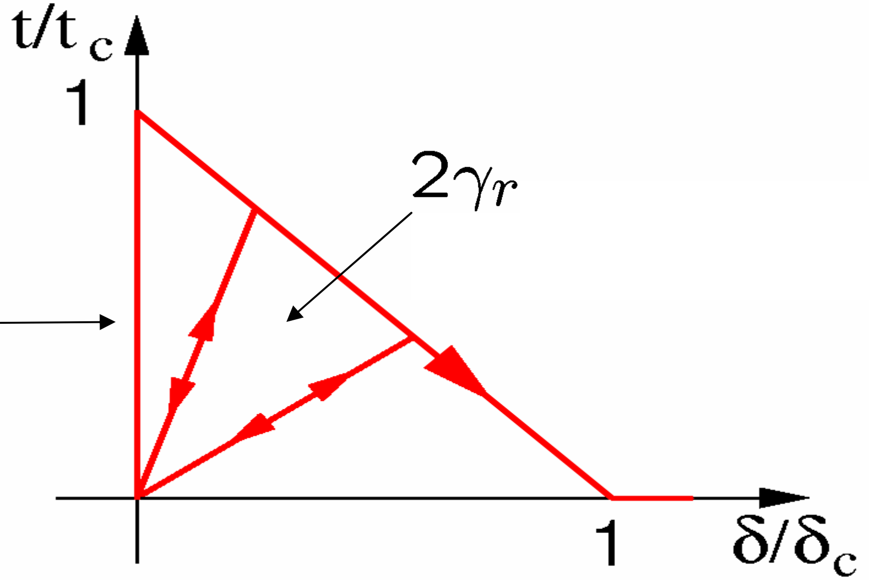
- Crack initiation time
- Crack tip arrival time at the interface
- Crack speed
- Crack length
- Deflection length (d)
- Penetration angle (ϕ)
- Fracture parameters
  - *Mode-I/II stress intens*
    factors
  - *Mode mixity*
  - *Non-singular stress*



Approach – Cohesive elements

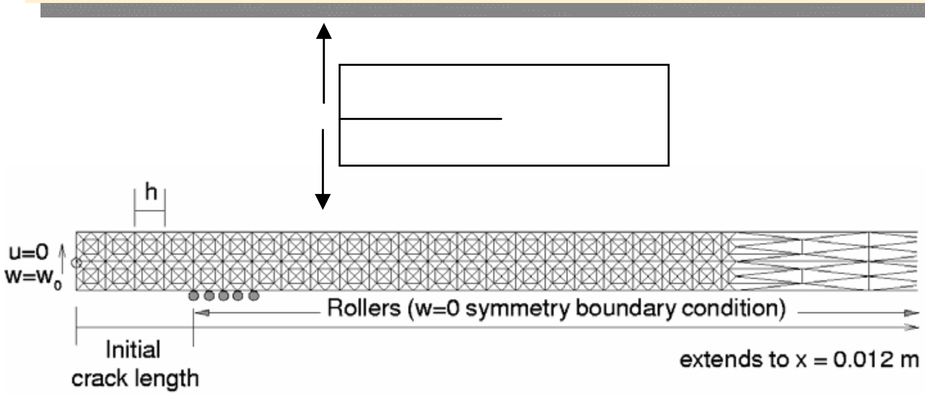


Quadratic cohesive element
(Ortiz and Pandolfi '99)



Cohesive law
(Camacho and Ortiz '96,
Nguyen and Ortiz '02,
Hayes, Ortiz and Carter '04)

Approach – Cohesive elements



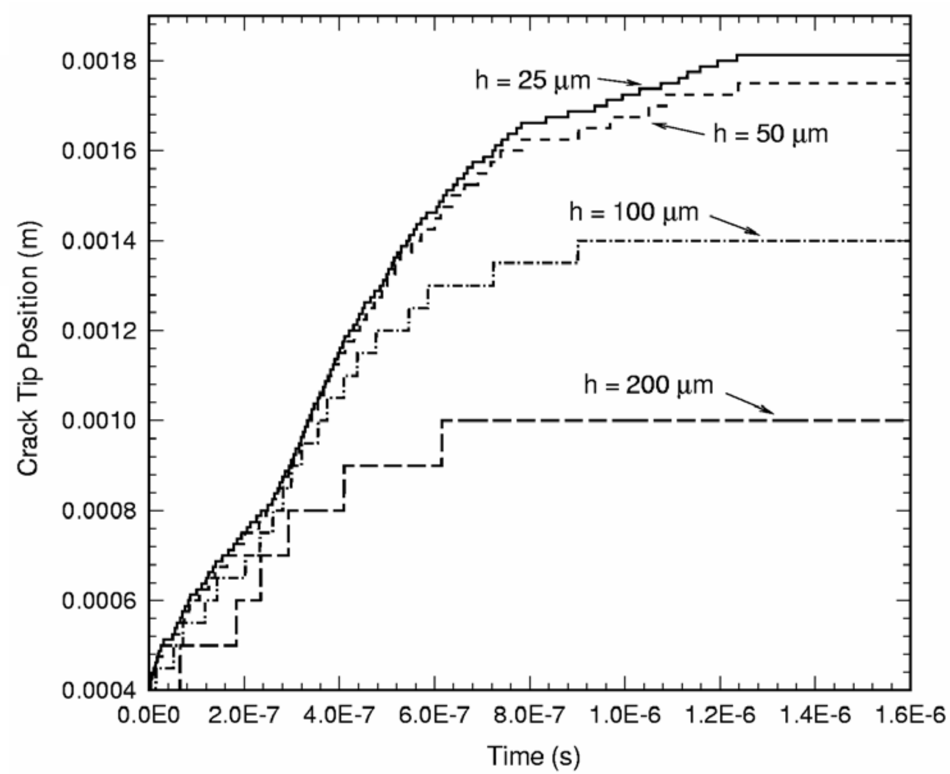
Double cantilever specimen

- Characteristic size:

$$l_c = \frac{\pi}{8}\frac{E}{1-\nu^2}\frac{G_c}{\sigma_c^2}$$

- Characteristic time:

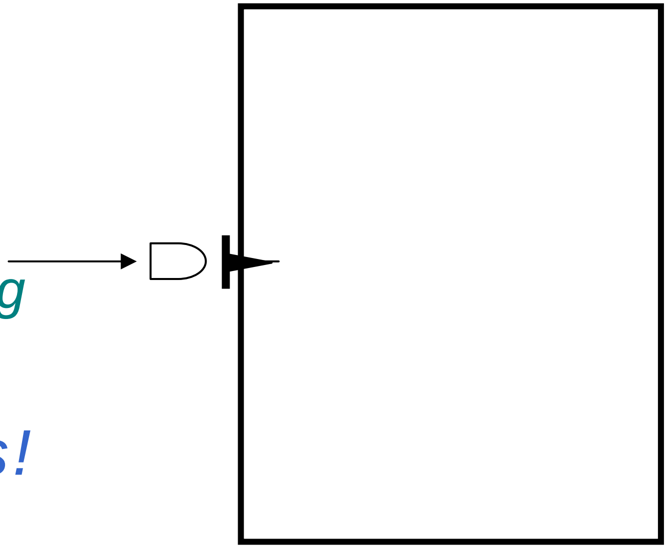
$$t_c = \frac{l_c}{c_R}$$



Crack-tip trajectory
as a function of element size
(Camacho and Ortiz, 1996)

Fracture model-Implementation issues

- Conflicting requirements:
  - *Experiment: need* large *sample size for proper instrumentation*
  - *Simulation: need* small *number of elements to reduce computational cost*
- Possible solutions
  - ☑ *Adaptive Mesh Refinement*
  - *Massively parallel computing*
- Model size:
  2D - *100 million elements!*
  3D - ?

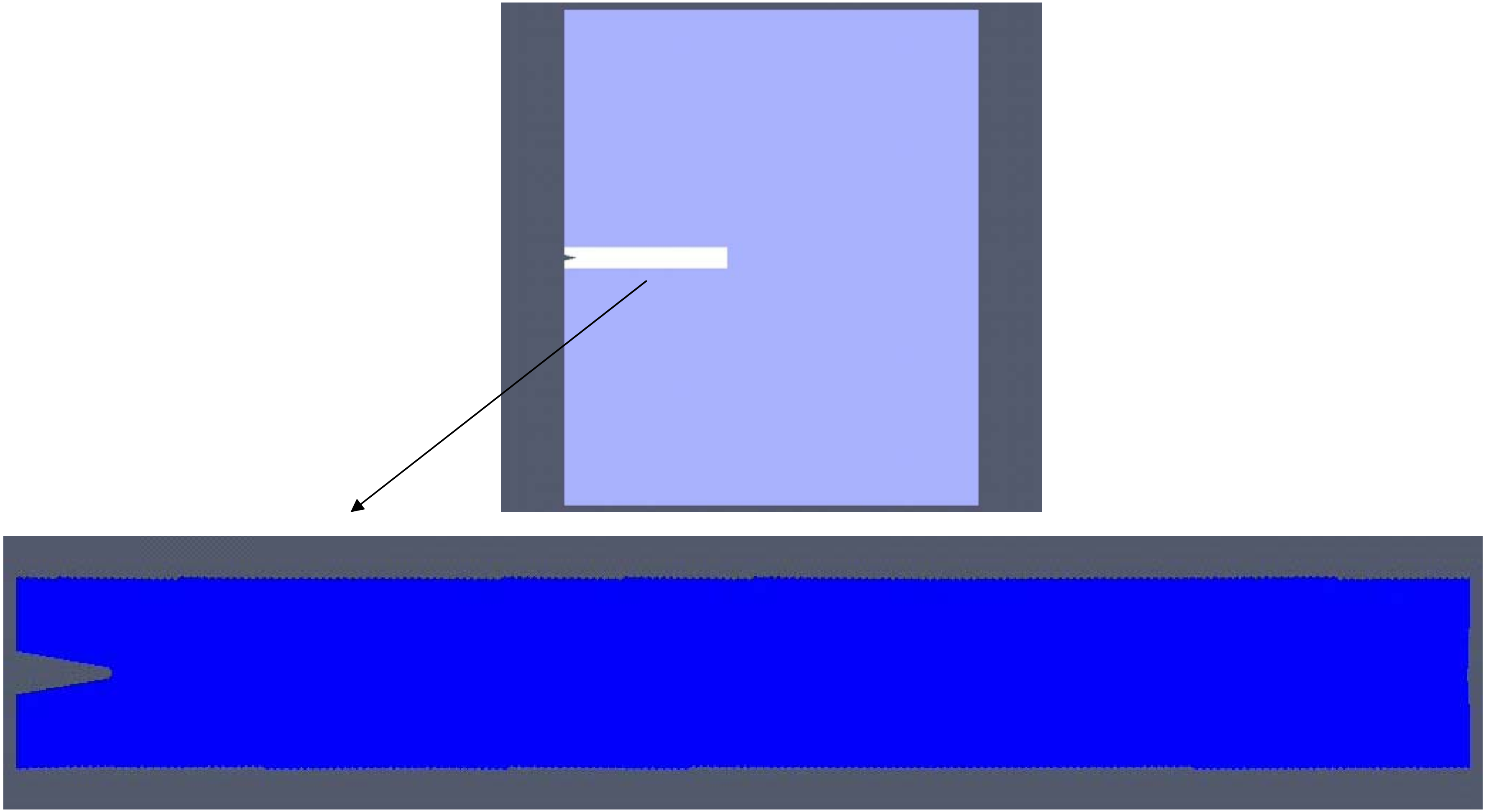


508 x 154 x 6 (mm)

Brittle fracture - Latest runs

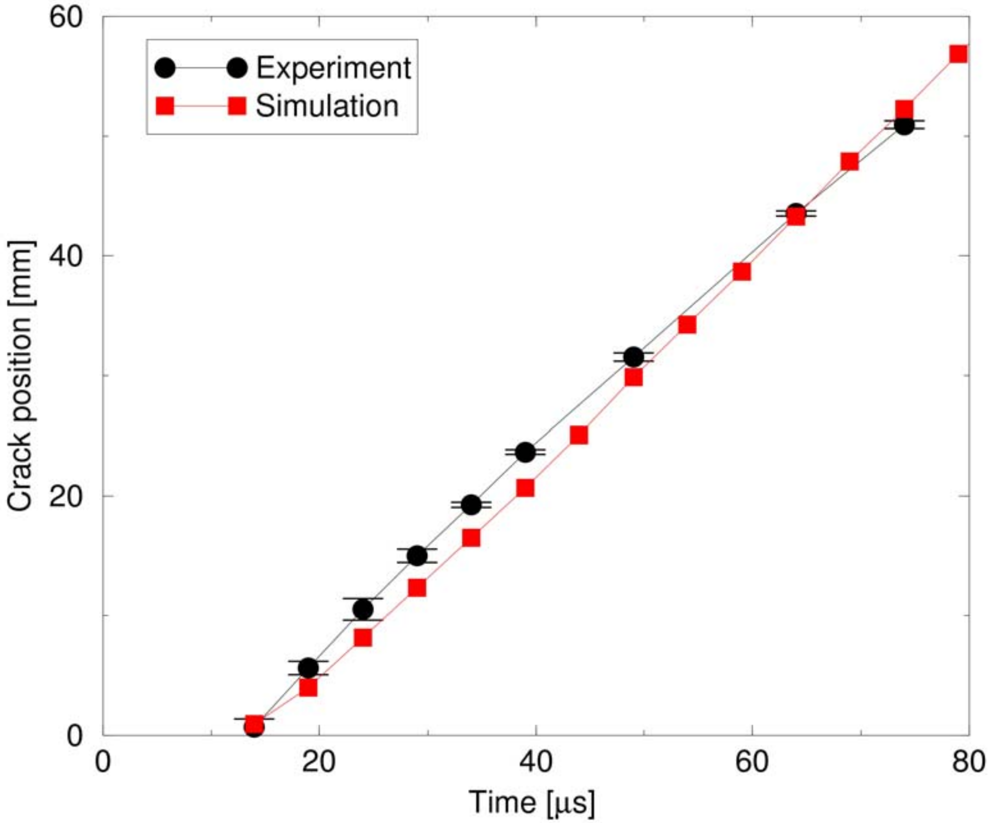
- Two dedicated weekends of 450 ALC nodes (900 processors):
  - *Level 5 subdivision (~33 million elements) for 60 hours*
  - *Level 4 subdivision (~8 million elements); exploring parameter space; each run 12 hours*
- One dedicated weekend of 900 ALC nodes (1,800 processors):
  - *Level 6 subdivision (~133 million elements) for 60 hours (only 15μs mark reached)*
- Batch queues 256-450 ALC nodes (512-900 processors):
  - *Level 4 subdivision (~8 million elements) for 12-24 hours*
- Need lots of storage:
  - *checkpoints every 1μs i.e. 150-200 checkpoints per run*
  - *each checkpoint ~100MB/processor*
- ALC – great environment and outstanding level of technical support for these large runs.

Brittle fracture - Latest runs



(Knap and Ortiz, 2005)

Metrics-Comparison (III)

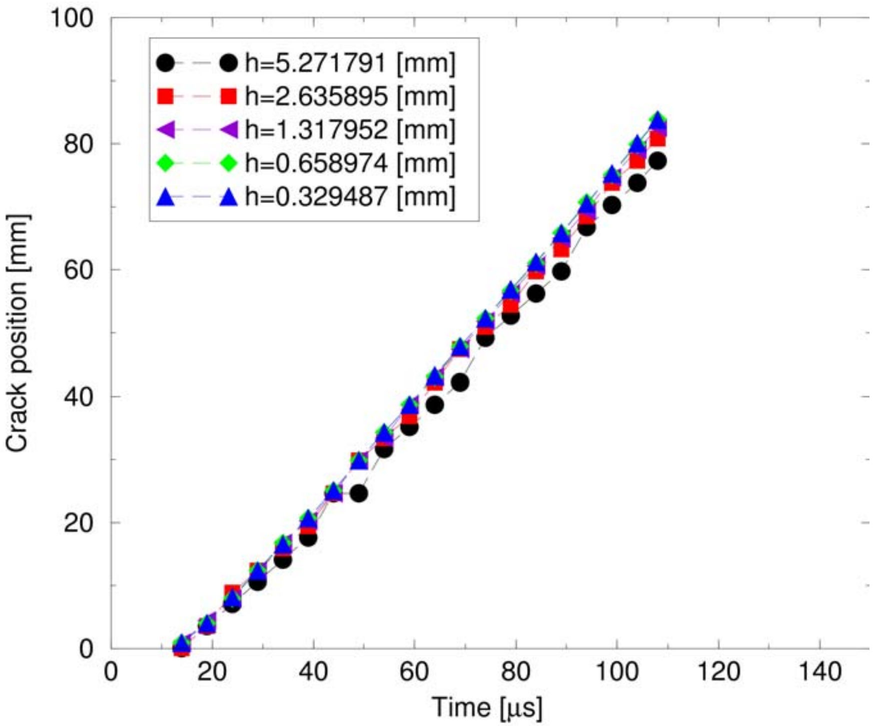


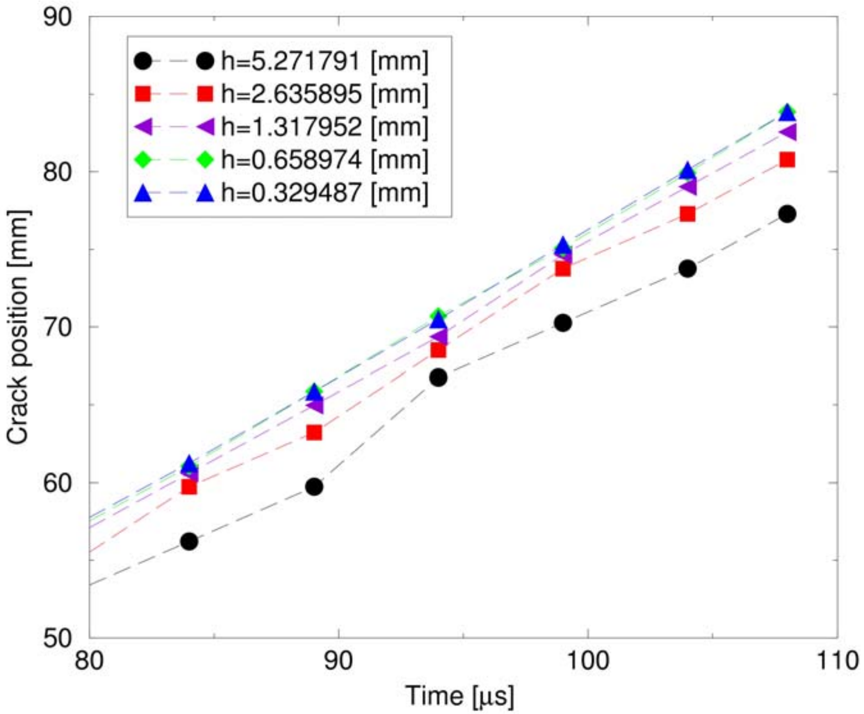
- Experimental velocity 832 [m/s]
- Simulation velocity 893 [m/s]
- Experimental crack initiation time: 13 µm
- Simulation crack initiation time: 13-14 µm

(Knap and Ortiz, 2005)

Convergence analysis

$l_c = 1.267$ [mm]

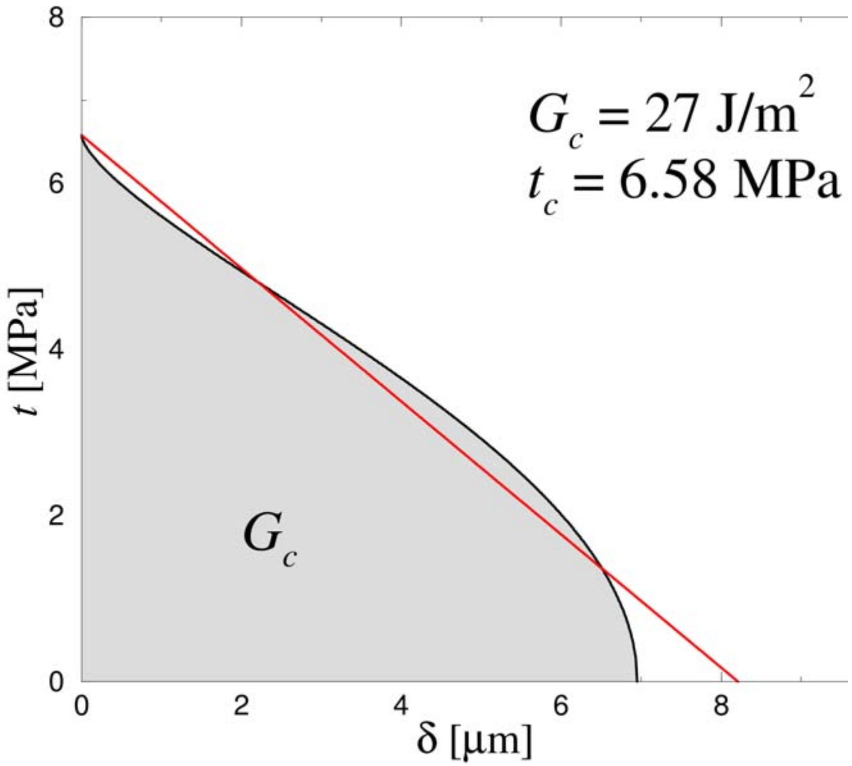


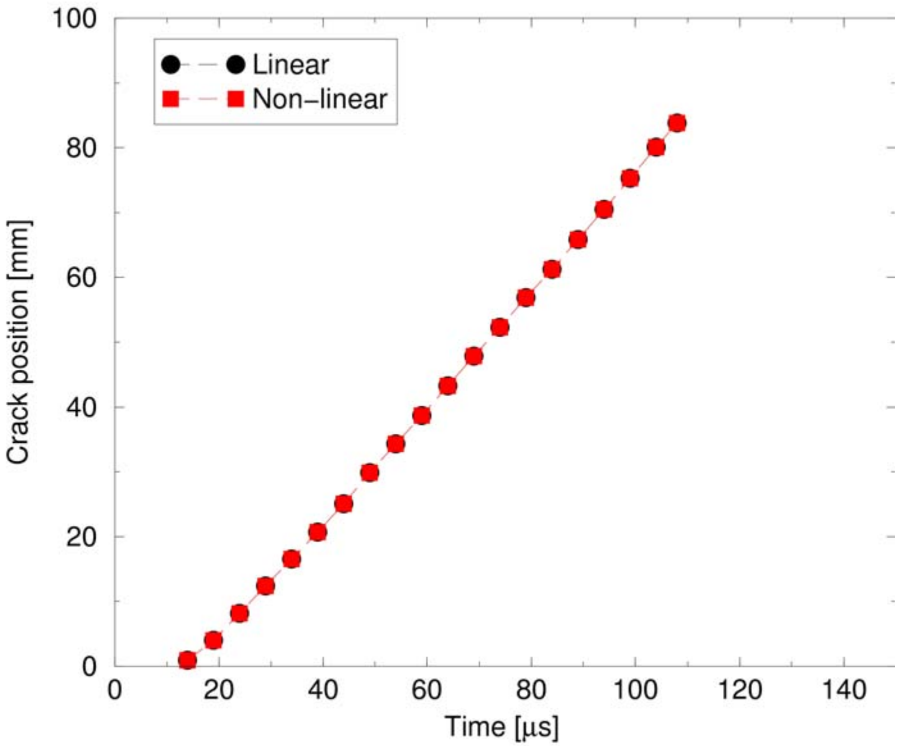


(Knap and Ortiz, 2005)

Sensitivity to cohesive law

Level 4 subdivision (h=0.3295 [mm])

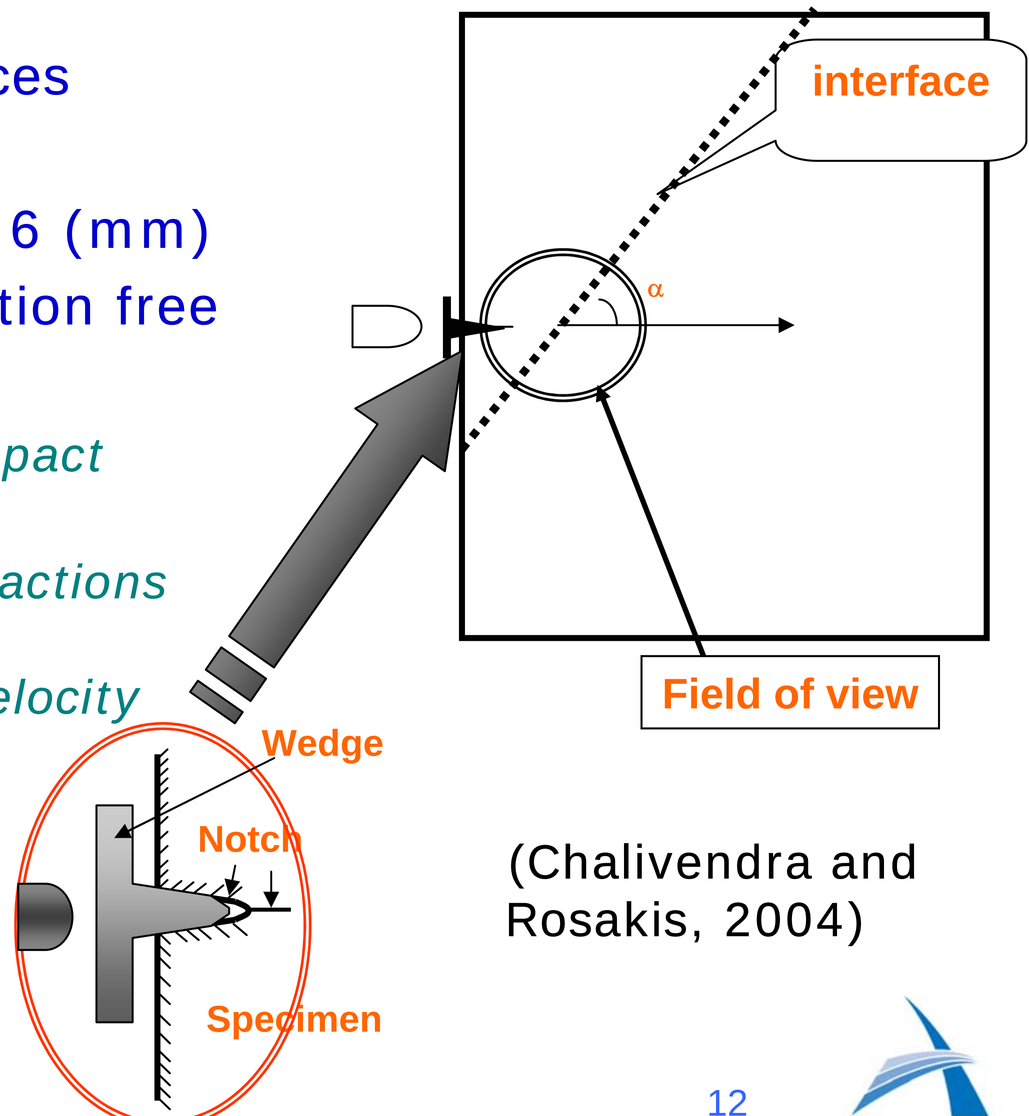




(Knap and Ortiz, 2005)

Path forward - Experiments

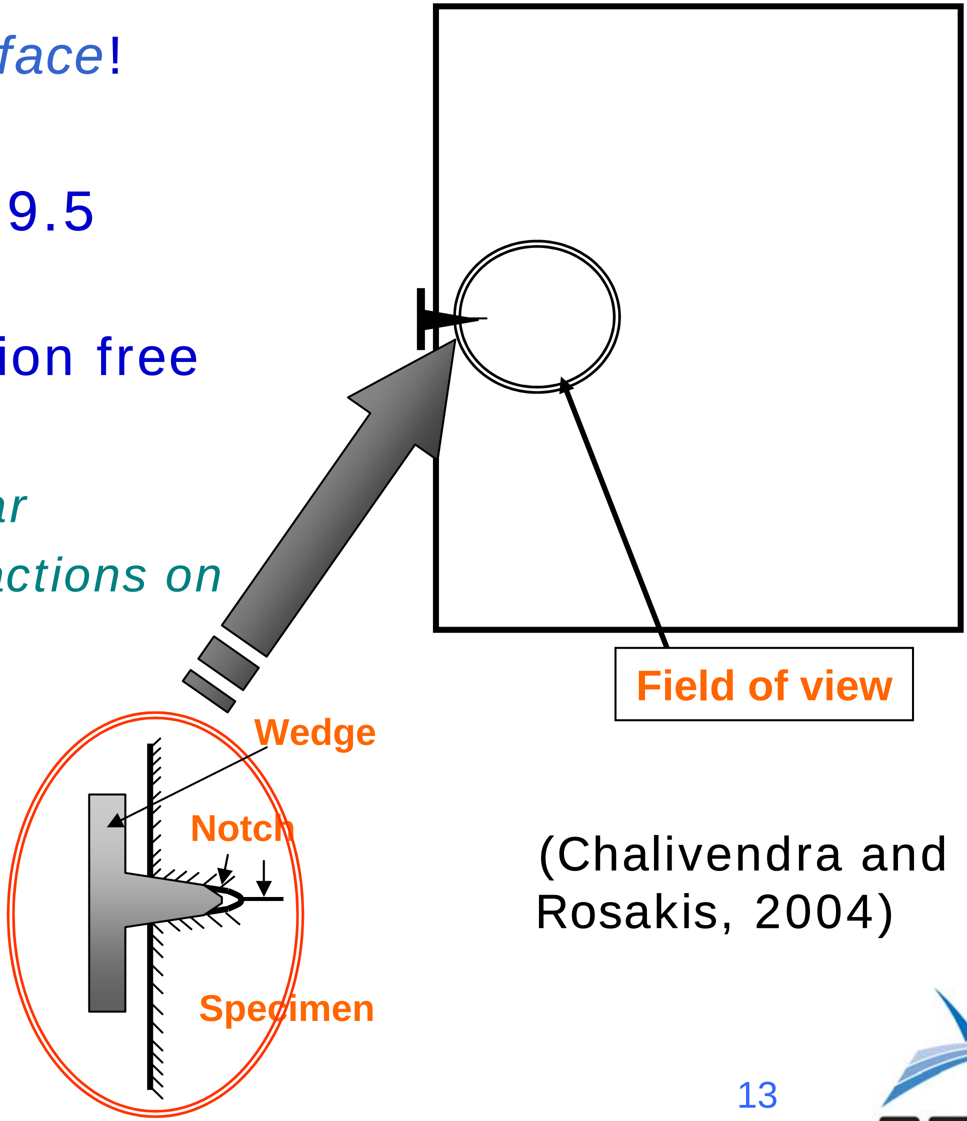
- 45° and 60° weak interfaces
- Material: Homalite-100
- Sample size: 508 x 154 x 6 (mm)
- Boundary conditions: traction free
- Loading:
  - *Experiment: projectile impact velocity*
  - *Simulation: distributed tractions on notch surfaces (impact velocity dependent)*
- Linear cohesive law



(Chalivendra and Rosakis, 2004)

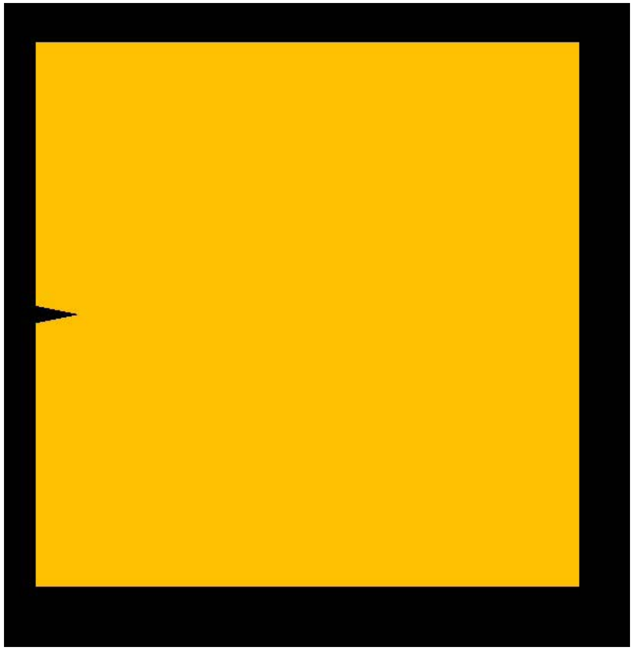
Path forward - Experiments

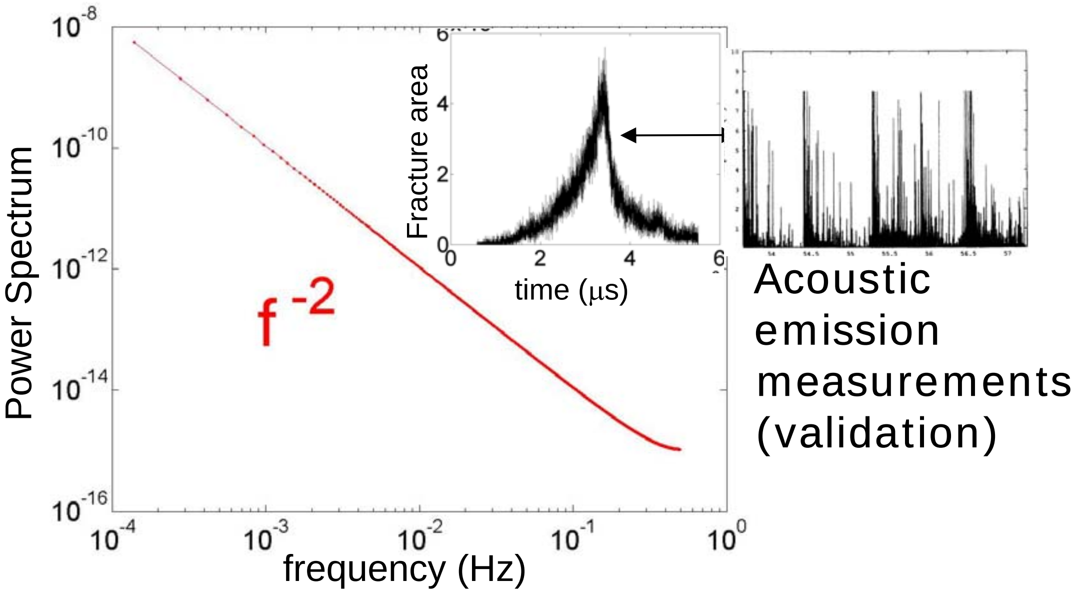
- Monolithic sample-*no interface*!
- Material: Homalite-100
- Sample size: 450 x 375 x 9.5 (mm)
- Boundary conditions: traction free
- Loading:
  - *Experiment: Hopkinson bar*
  - *Simulation: distributed tractions on notch surfaces*
- Linear cohesive law
- l_c = 0.094 [mm] = 94 [μm]



(Chalivendra and Rosakis, 2004)

Path forward – Highly driven systems

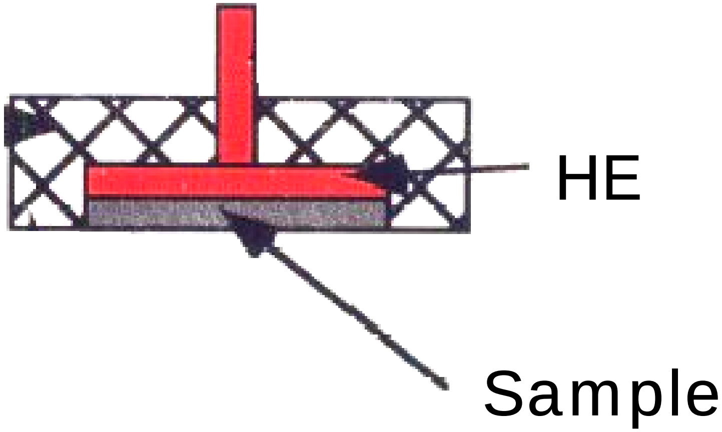




- Power spectrum $1/f^2$ characteristic of diffusion!
- Results suggest that highly driven branching is governed by a diffusion equation
- Validation from acoustic emission measurements

(I. Arias, J. Knap and M. Ortiz '04)

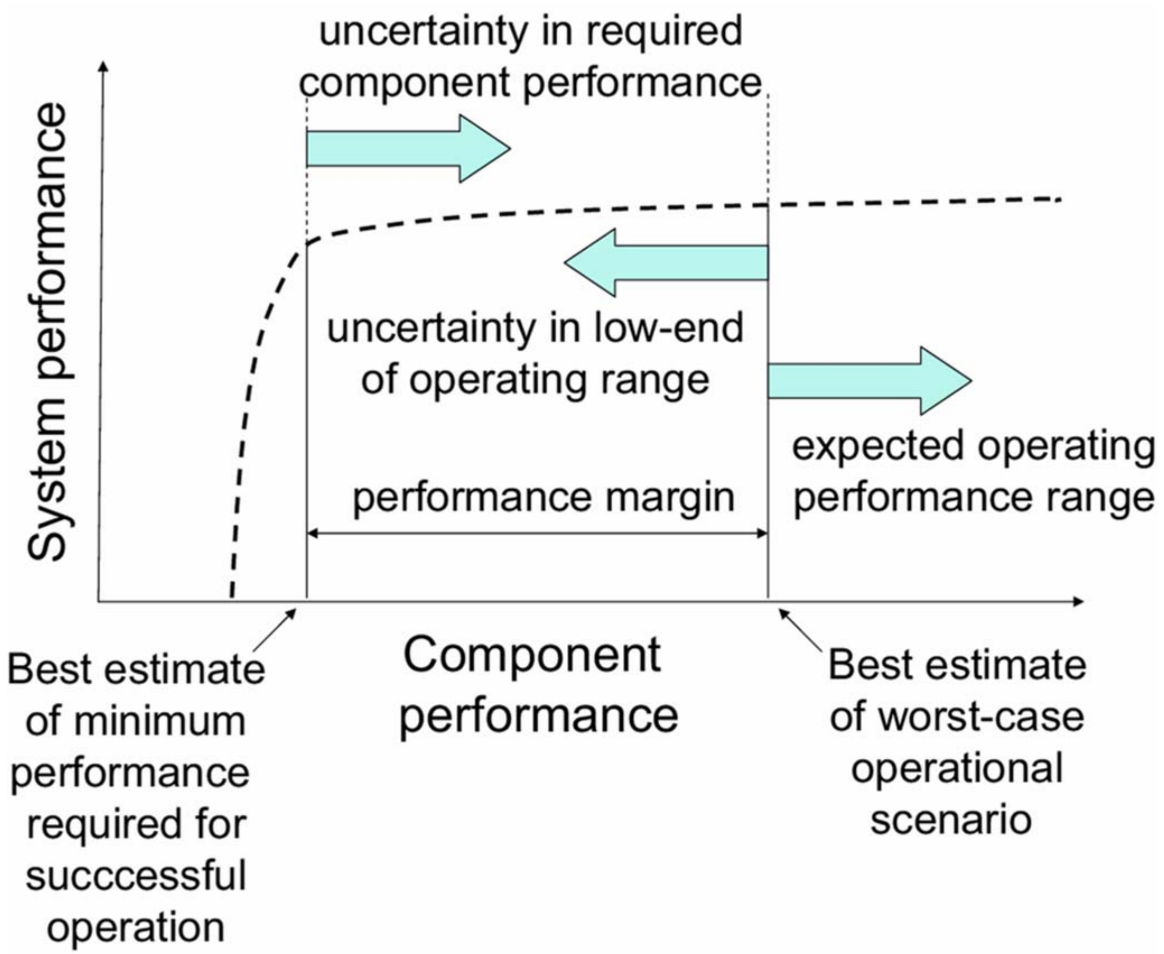
Path forward – Highly driven systems



(Donald L. Griswold, LLNL)

Parth forward – Uncertainty Quantification

- Assess uncertainties in performance measures

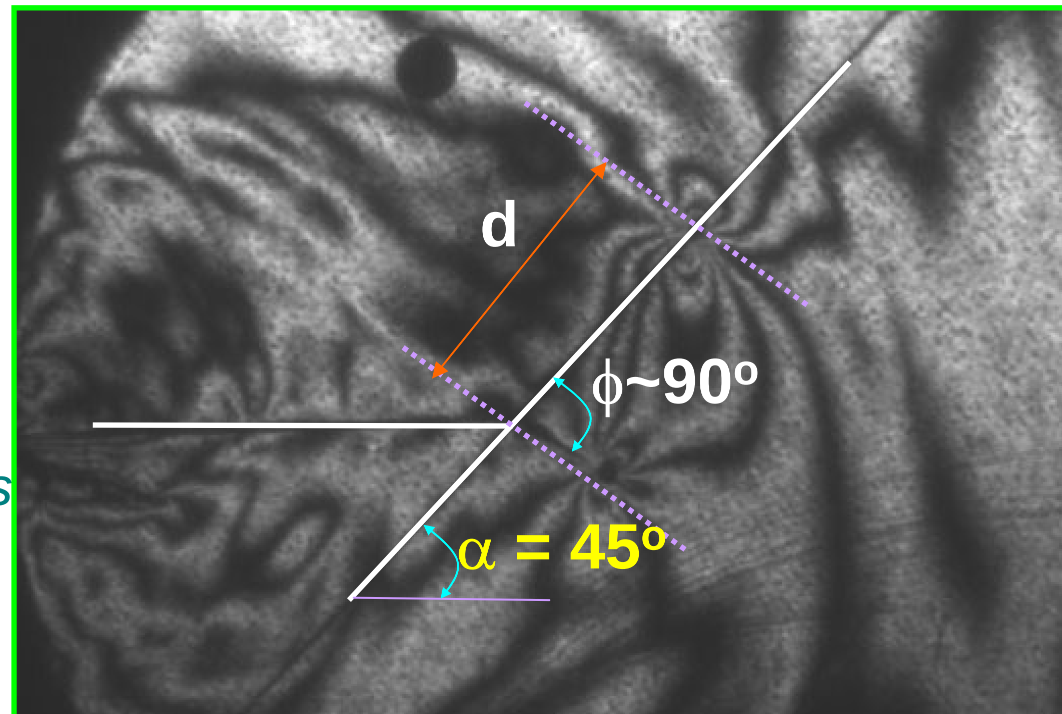


Uncertainty Quantification – Input

- Finite element model:
  - *Sample dimensions (width x height x thickness)*
  - *Notch radius*
  - *Pre-crack length*
  - *Mesh size*
  - *Loading data*
- Bulk material data (Homalite):
  - *Constitutive relation (Neo-hookean)*
  - *Mass density*
  - *Young's modulus*
  - *Poisson's ratio*
- Interface material data (Loctite 384)
  - *Functional form of the cohesive law*
  - *Fracture strength* t_c
  - *Critical strain-energy release rate* G_c
  - *Shear/tension coupling coefficient* β

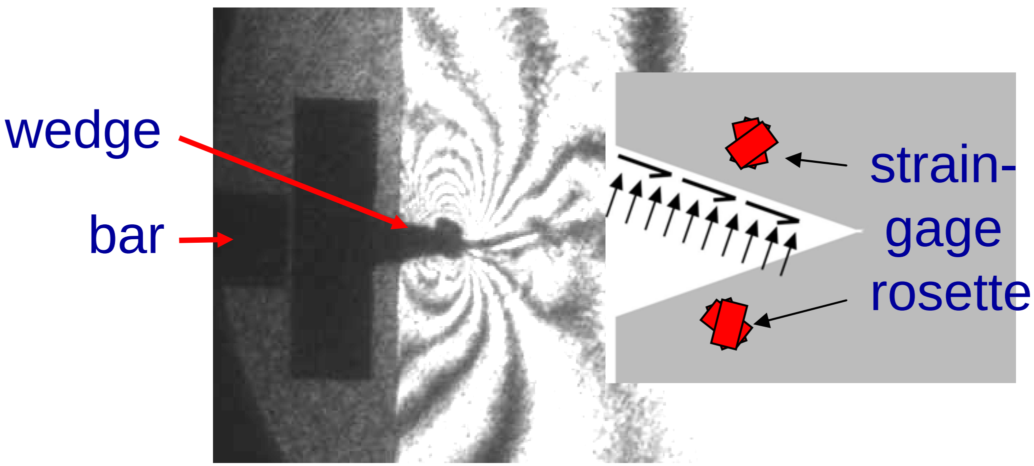
Uncertainty Quantification - Measures

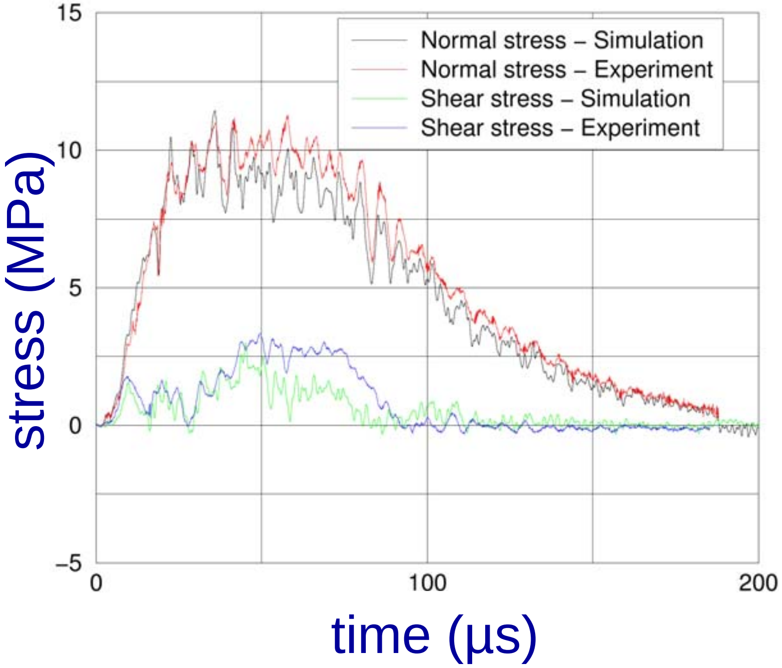
- Crack initiation time
- Crack tip arrival time at the interface
- Crack speed
- Crack length
- Deflection length (d)
- Penetration angle (ϕ)
- Fracture parameters
  - *Mode-I/II stress intens factors*
  - *Mode mixity*
  - *Non-singular stress*



Uncertainty Quantification - Loading

Direct loading measurements





Notch and fatigue pre-crack included in geometrical model, finite-element mesh

Uncertainty Quantification – Resolution

- Homalite-100 characteristic length – l_c= 0.094 [mm]
- Element sizes - *uniform subdivision*

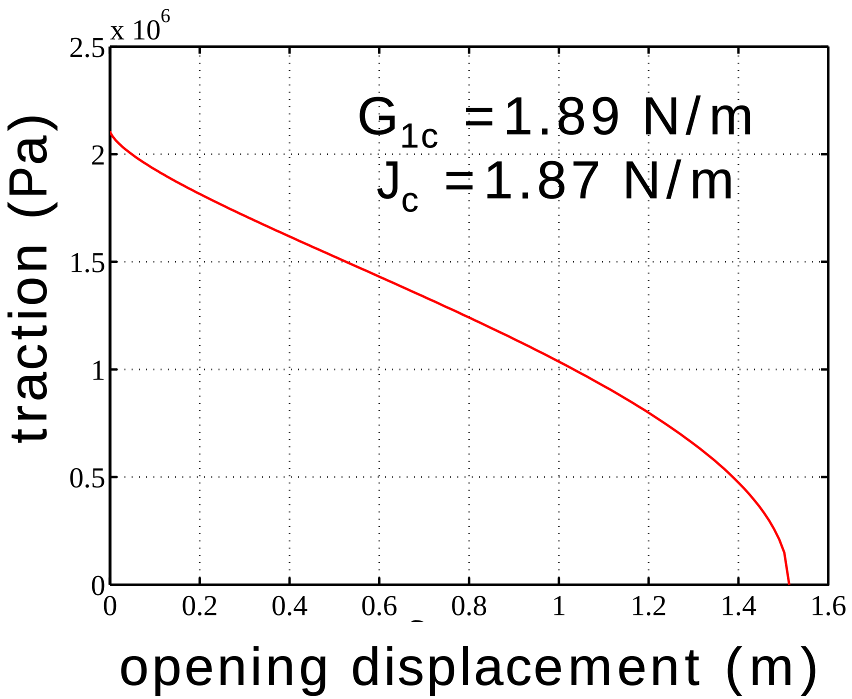
Subdivision level	Element size [mm]	Number elements
0	5.271	32,440
1	2.636	129,760
2	1.318	519,040
3	0.659	2,076,160
4	0.329	8,304,640
5	0.165	33,218,560
6	0.082	132,874,240

Uncertainty Quantification – Resolution

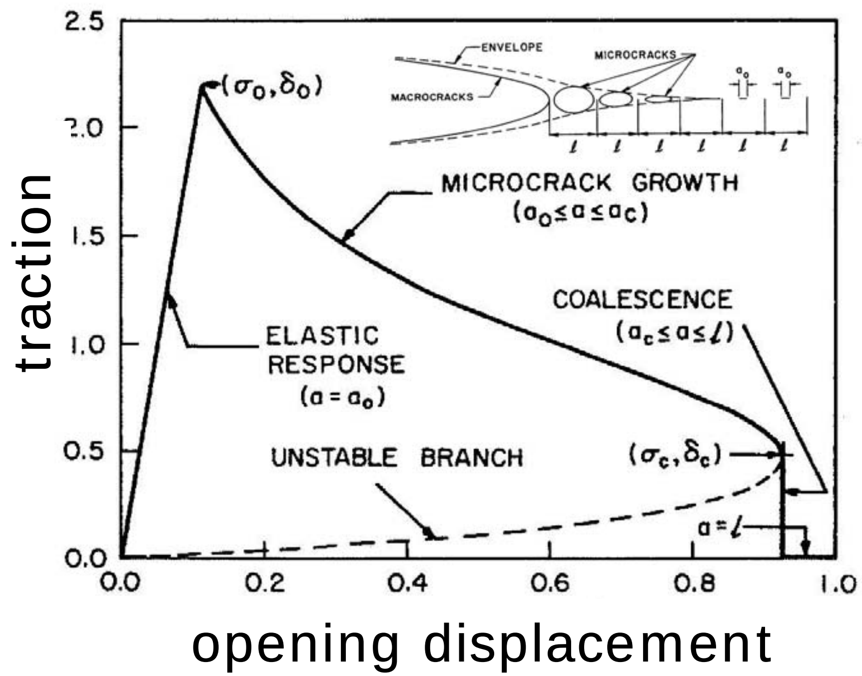
- Level 4 subdivision – *unresolved mesh*!
- Need to run level 6 subdivision (132 million elements) for ~100 μs.
- 1,800 CPUs of *ALC* (LLNL) – 15μs per 48h!
- Substantial performance improvements necessary (performance analysis and tuning in progress- S. Brunett).
- Modify the experimental setup to allow for changes in the material fracture properties- increase l_c.

Uncertainty Quantification - Physics

- Identification of cohesive law:



(S. Hong and A.J. Rosakis)



(M. Ortiz, *IJSS*, 1988)

Uncertainty Quantification – TODO list

Regard performance measures as dynamical system:

$$\dot{\mathbf{x}}(t,\boldsymbol{\omega}) = \mathbf{f}(\mathbf{x}(t,\boldsymbol{\omega}),\boldsymbol{\omega}).$$

- Stochastic Galerkin, Polynomial Chaos:

$$\mathbf{x}(t,\boldsymbol{\omega}) = \sum_{m=1}^{M} \hat{\mathbf{x}}_m(t)\phi_m(\boldsymbol{\omega}),$$

- Equation-free stochastic Galerkin projection

$$\hat{\mathbf{f}}_m = \frac{1}{\langle \phi_m^2(\boldsymbol{\omega})\rangle} \left\langle \mathbf{f}\left(\sum_{m=1}^{M} \hat{\mathbf{x}}_m(t)\phi_m(\boldsymbol{\omega}),\boldsymbol{\omega}\right), \phi_m(\boldsymbol{\omega}) \right\rangle .$$

- Optimal sampling of parameters.