Combining Cracks and Contact with Constitutive and Cohesive laws for Complete Calculations of Cutting

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MPM Workshop
14-15 March 2013, Salt Lake City, Utah

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and a Carnot Cycle and Caoutchouc Compression

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...if the Clock Consents

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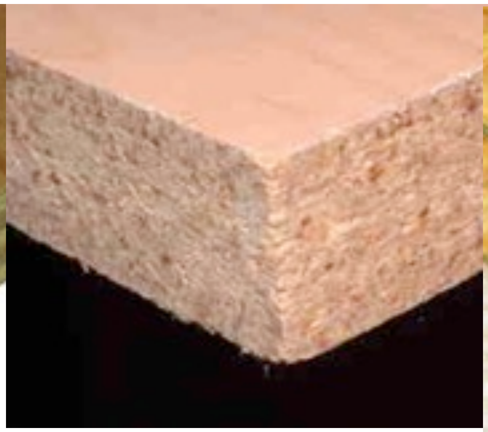
Motivation

- Cutting of solid wood and wood-based composites
  - Historically done by empirical methods (Koch, 1950s)
  - Almost no analysis for wood-based composites
    - Plywood
    - Particle Board
    - Oriented Strand Board



    - Wood Plastic Composites

"You can cut *Trex* just like regular wood."

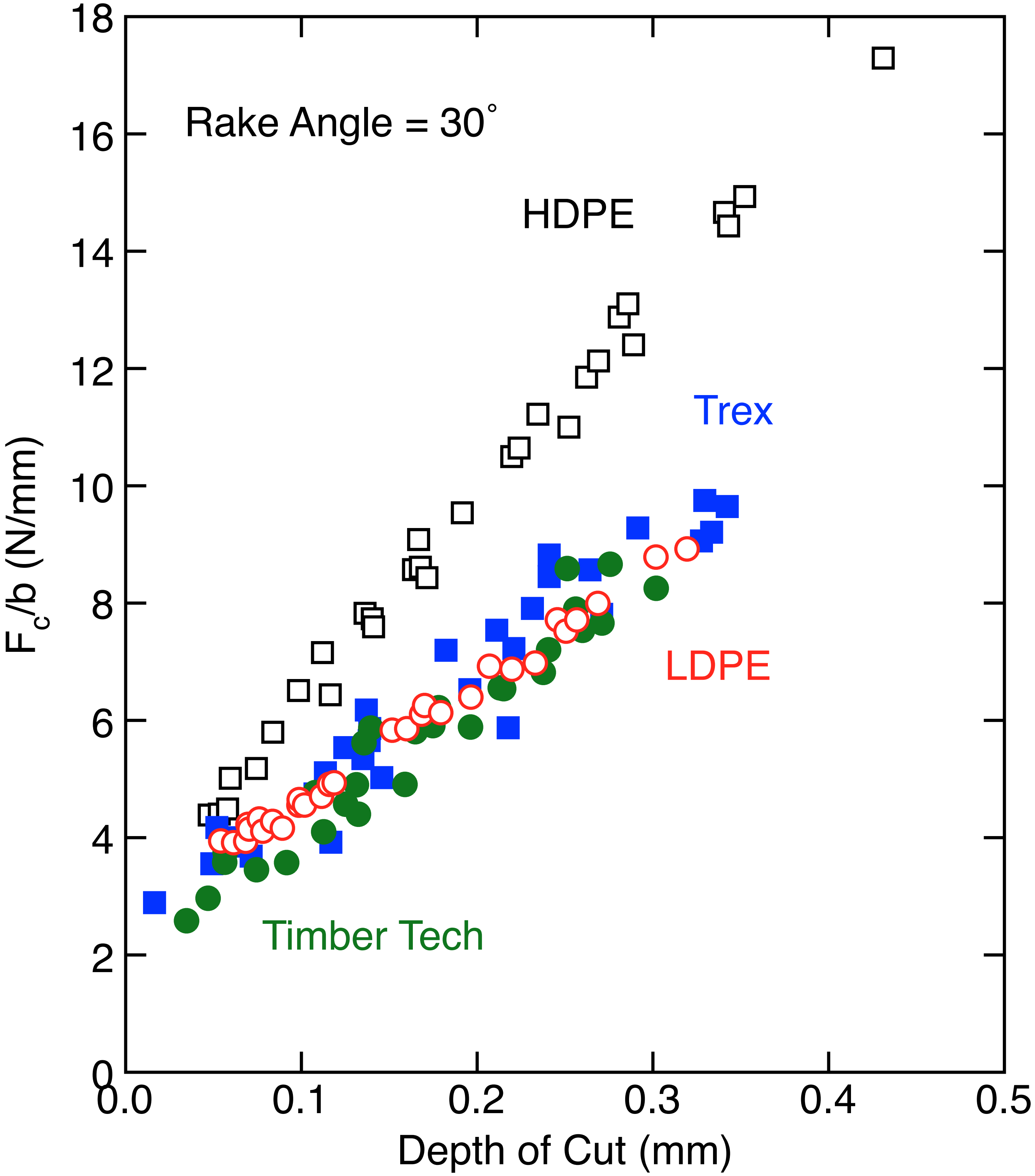
- Should be able to do better
  - *e.g.*, Atkins, Williams, *etc*.

Experiments Too

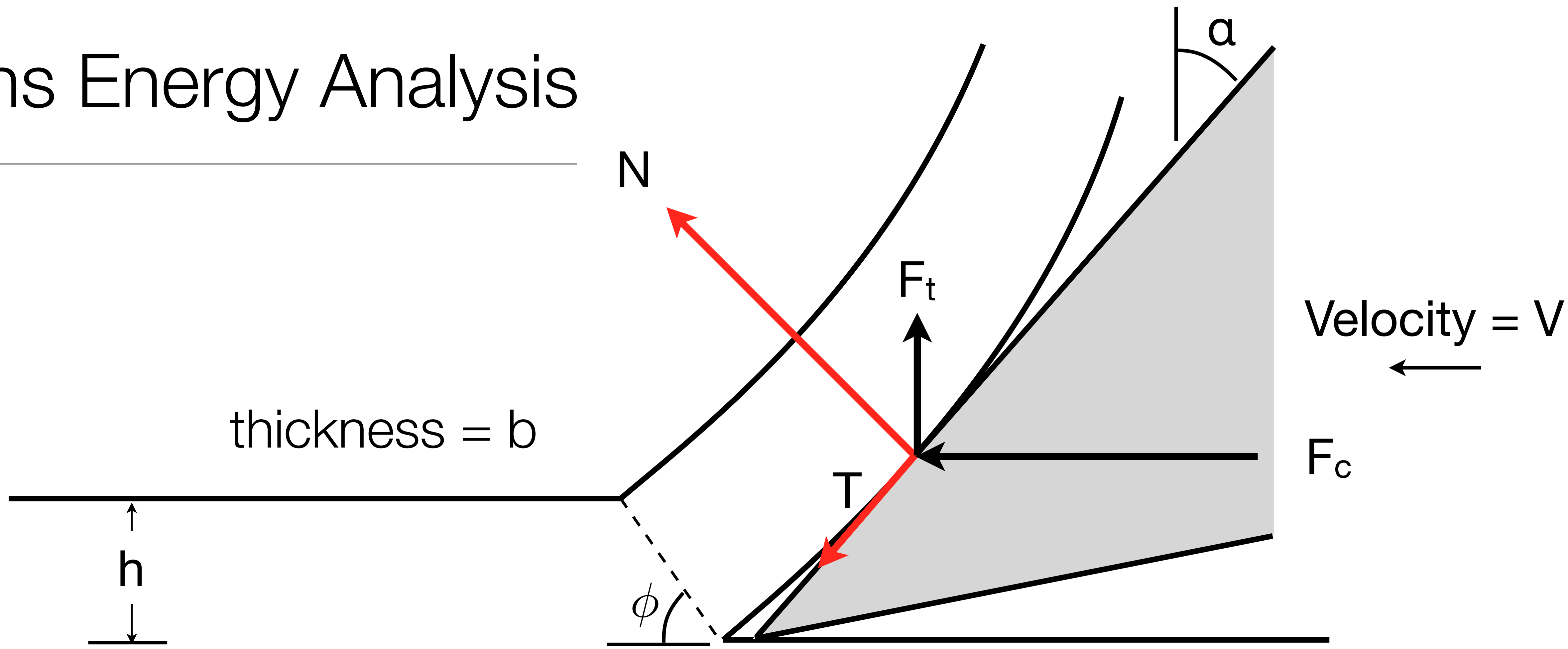
- Build apparatus for cutting experiments
  - Based on Patel, Blackman, and Williams (from 5th ESIS TC4 meeting)
- New experiments and analysis
  - HDPE and LDPE
  - Trex (WPC)
  - Timber Tech (WPC)
  - Wood
- Theory and Numerical modeling
  - Material Point Method (MPM)

Experiments

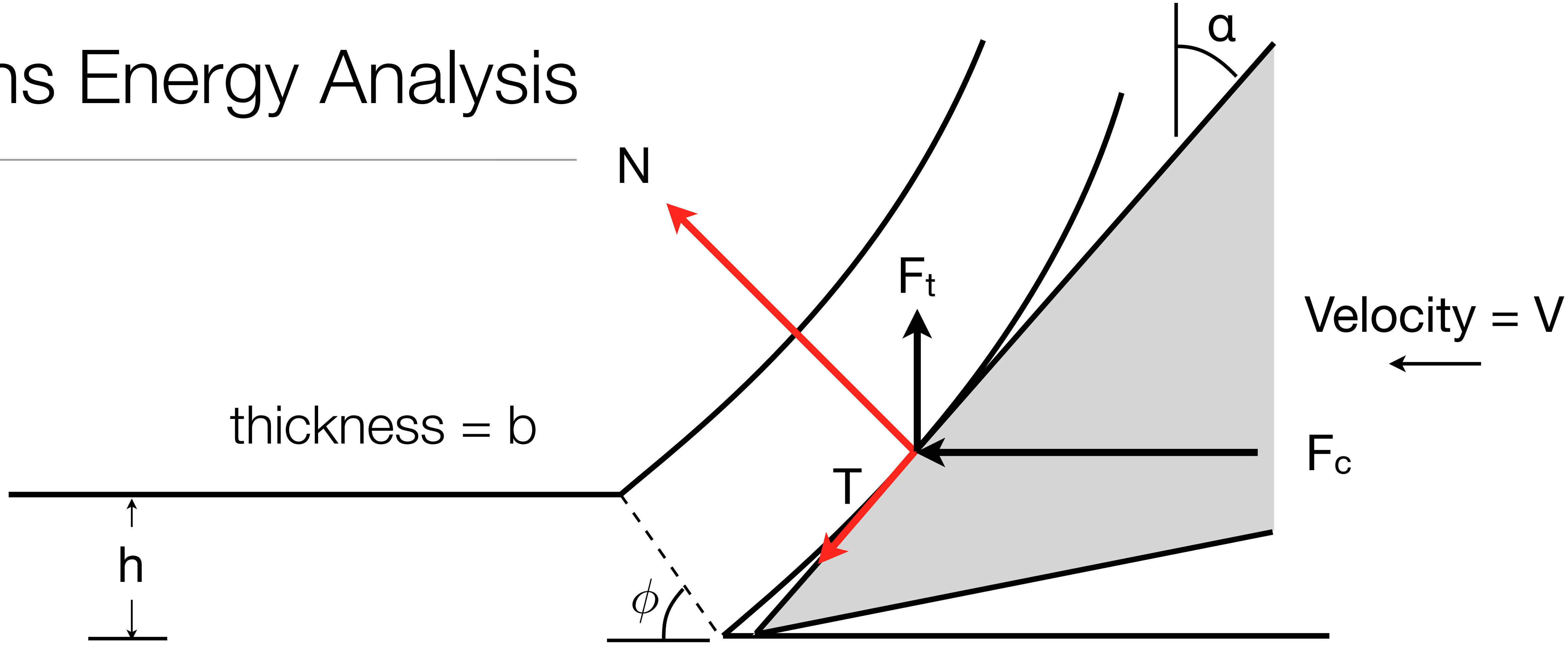
- Four materials - HDPE, LDPE, Trex, and Timber Tech
- Rake Angles 15, 20, 22.5, 25, 30, 35, 40, 45, 50, and 55
- Depth of cut up 0.006 mm to 0.59 mm
- Semi-automatic data acquisition
- Most likely, the non-zero intercept relates to a “cutting toughness,” but how it is best determined?



Atkins Energy Analysis



Atkins Energy Analysis

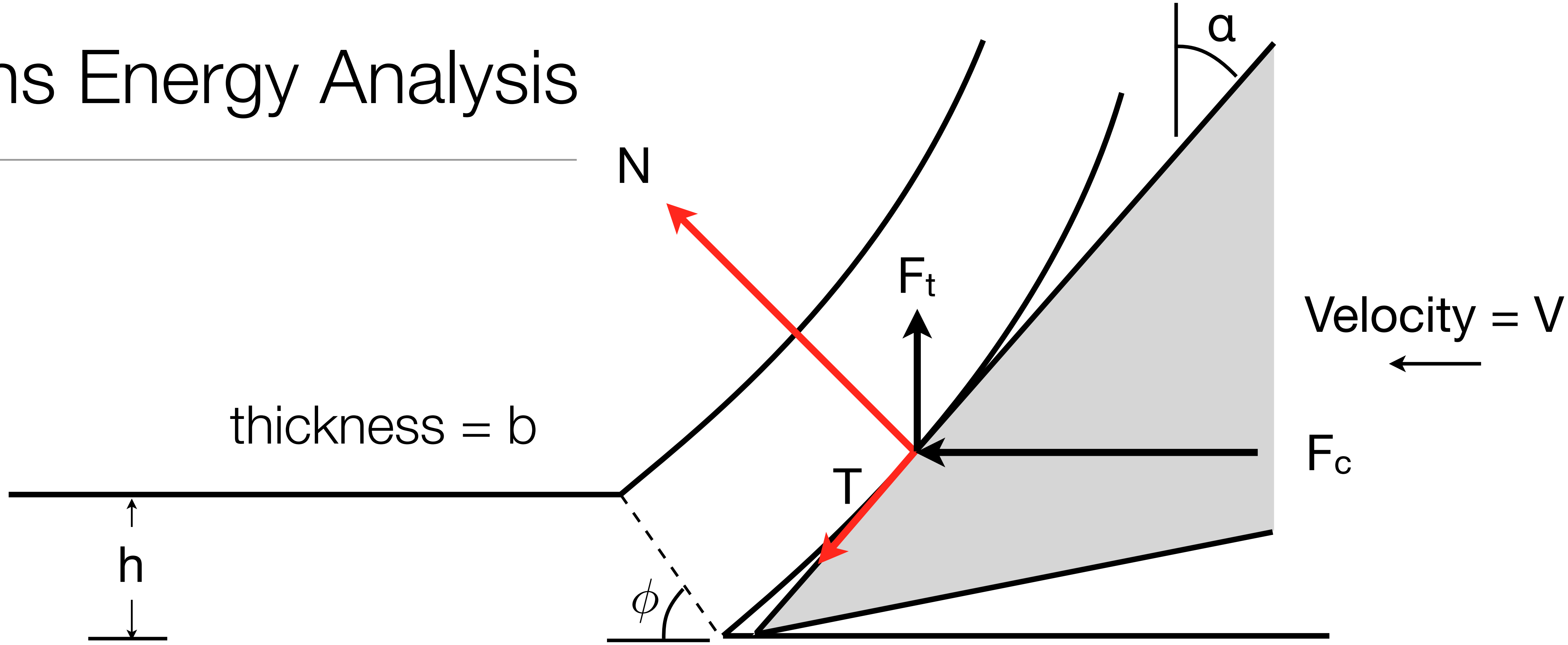


Griffith-Like Energy Balance (from Atkins)

$$F_c V = \tau_y \gamma (hbV) + T\left(\frac{V \sin\phi}{\cos(\phi - \alpha)}\right) + G_c bV$$

Work = Plastic Energy + Frictional Work + Fracture Work

Atkins Energy Analysis



Griffith-Like Energy Balance (from Atkins)

New Term

$$F_c V = \tau_y \gamma (hbV) + T \left(\frac{V \sin\phi}{\cos(\phi - \alpha)} \right) + G_c bV$$

Work = Plastic Energy + Frictional Work + Fracture Work

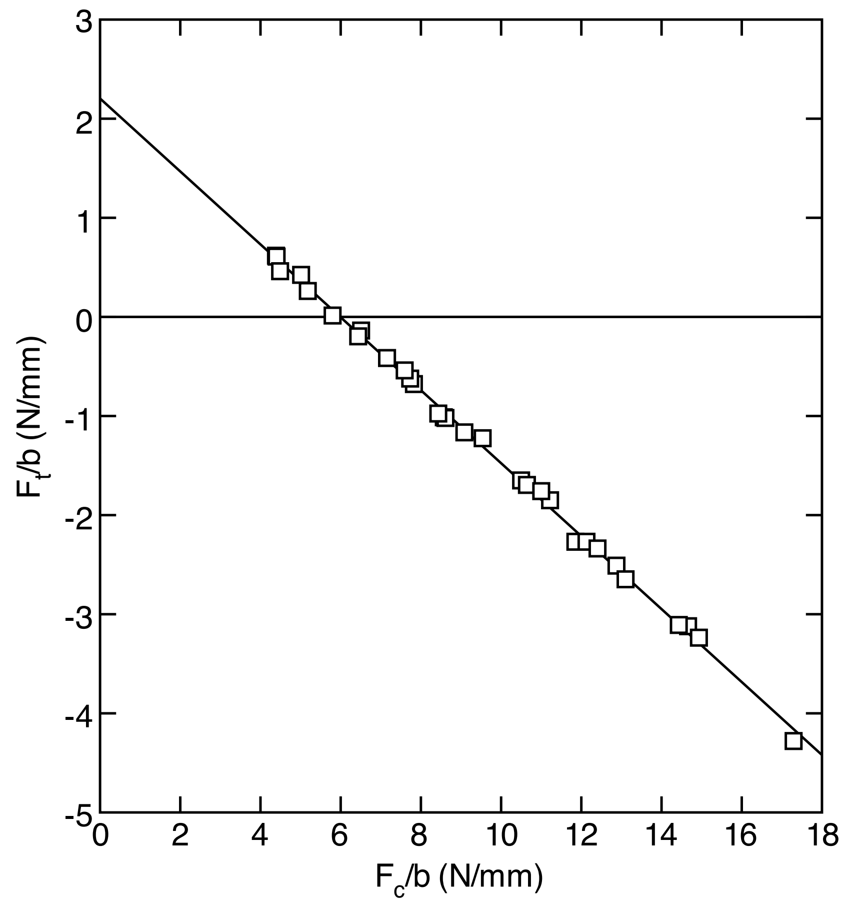
Williams/Atkins Analysis — Chip Force Method

- Energy balance to forces, energy release rate, yield stress, and shear angle

$$\frac{\sigma_y}{2}\frac{h}{\sin\phi} = \left(\frac{F_c}{b} - G_c\right)\cos\phi - \left(\frac{F_t}{b} + G_c\tan\alpha\right)\sin\phi$$

- Observations show that $T \neq \mu N$, Williams tried:

$$T = G_a + \mu N \quad \Rightarrow \quad \frac{F_t}{b} = Z\frac{F_c}{b} + \frac{G_a}{\cos\alpha + \mu\sin\alpha}$$

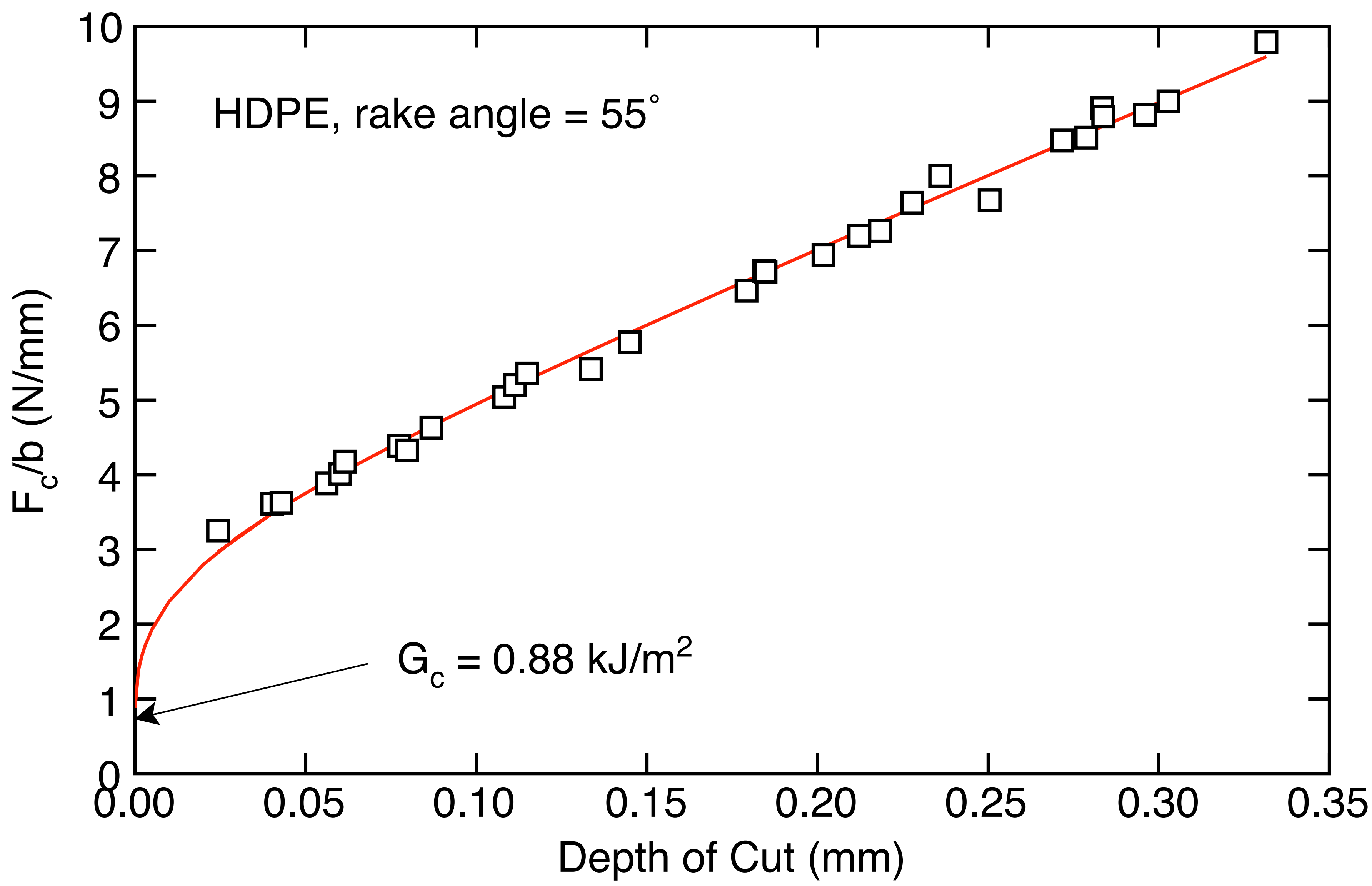


- Minimize work (to eliminate φ)

$$\frac{F_c}{b} = G_c + \sigma_y h\left(Z + \sqrt{1 + Z^2 + H}\right)$$

$$H = \frac{2}{\sigma_y h}\left(\frac{G_a}{\cos\alpha + \mu\sin\alpha} + G_c(Z + \tan\alpha)\right)$$

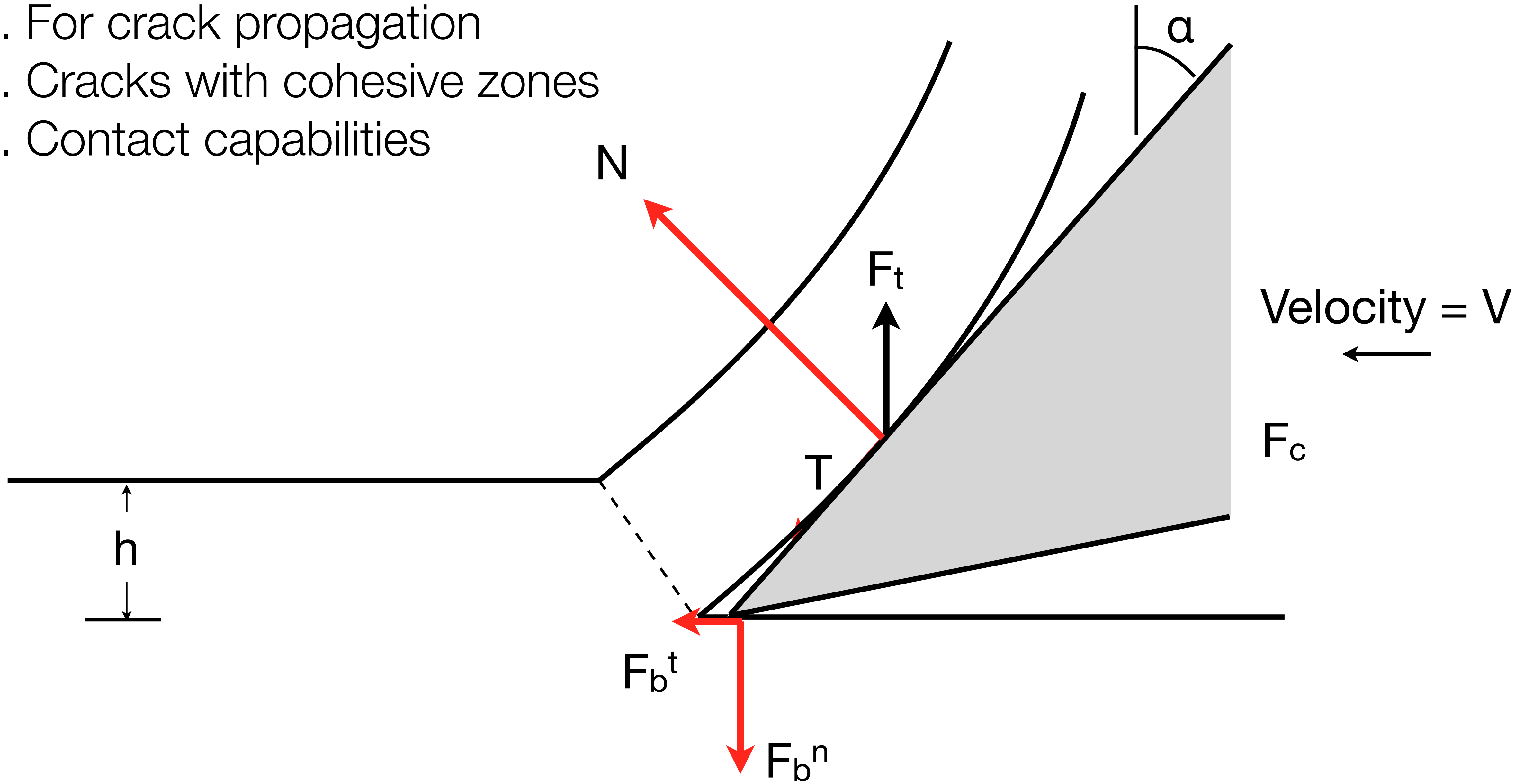
Sample Extrapolation



“Multiphysics” Numerical Modeling

Material Point Method (MPM) Modeling

1. For crack propagation
2. Cracks with cohesive zones
3. Contact capabilities

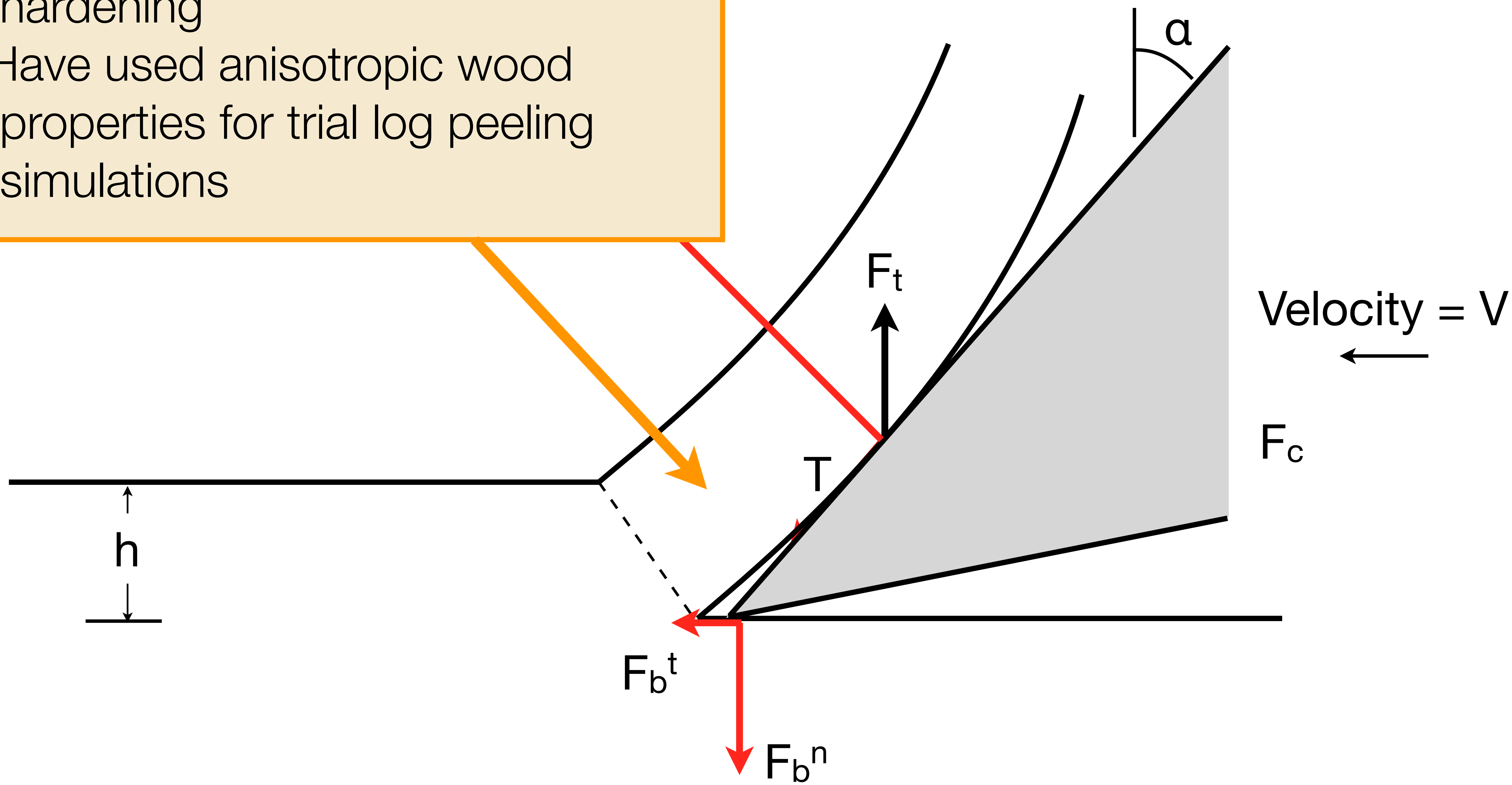


Modeling

) Modeling

Material Model

- Any option implemented in code
- Used elastic/plastic with work hardening
- Have used anisotropic wood properties for trial log peeling simulations



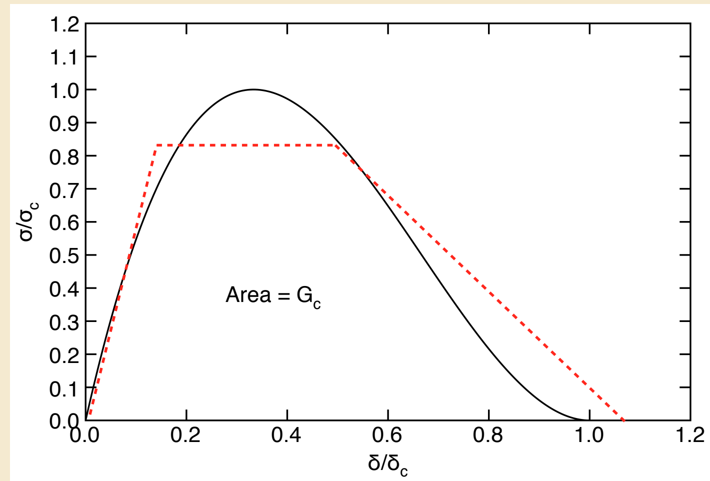
“Multiphysic

Material Poin

1. For crack pro
2. Cracks with c
3. Contact capa

Fracture Mechanics

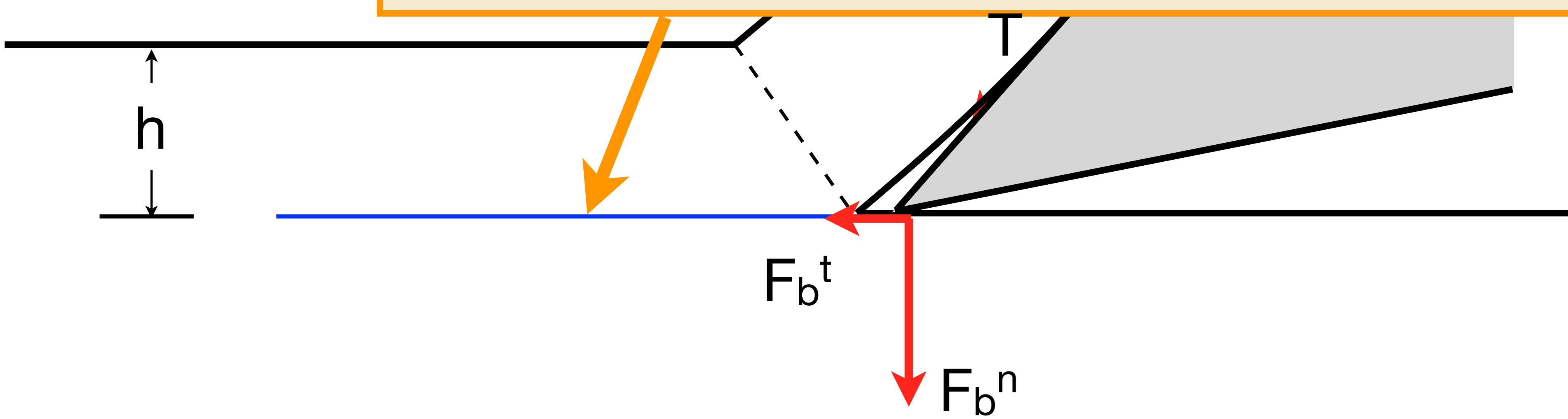
- Cohesive law (cubic)



$$G_c,\ \sigma_c,\ \delta_c$$

- Mixed mode fracture (found 90% opening mode)

$$\left(\frac{G_I}{G_{Ic}}\right)^n + \left(\frac{G_{II}}{G_{IIc}}\right)^n = 1 \qquad n,\ G_{Ic},\ G_{IIc}$$

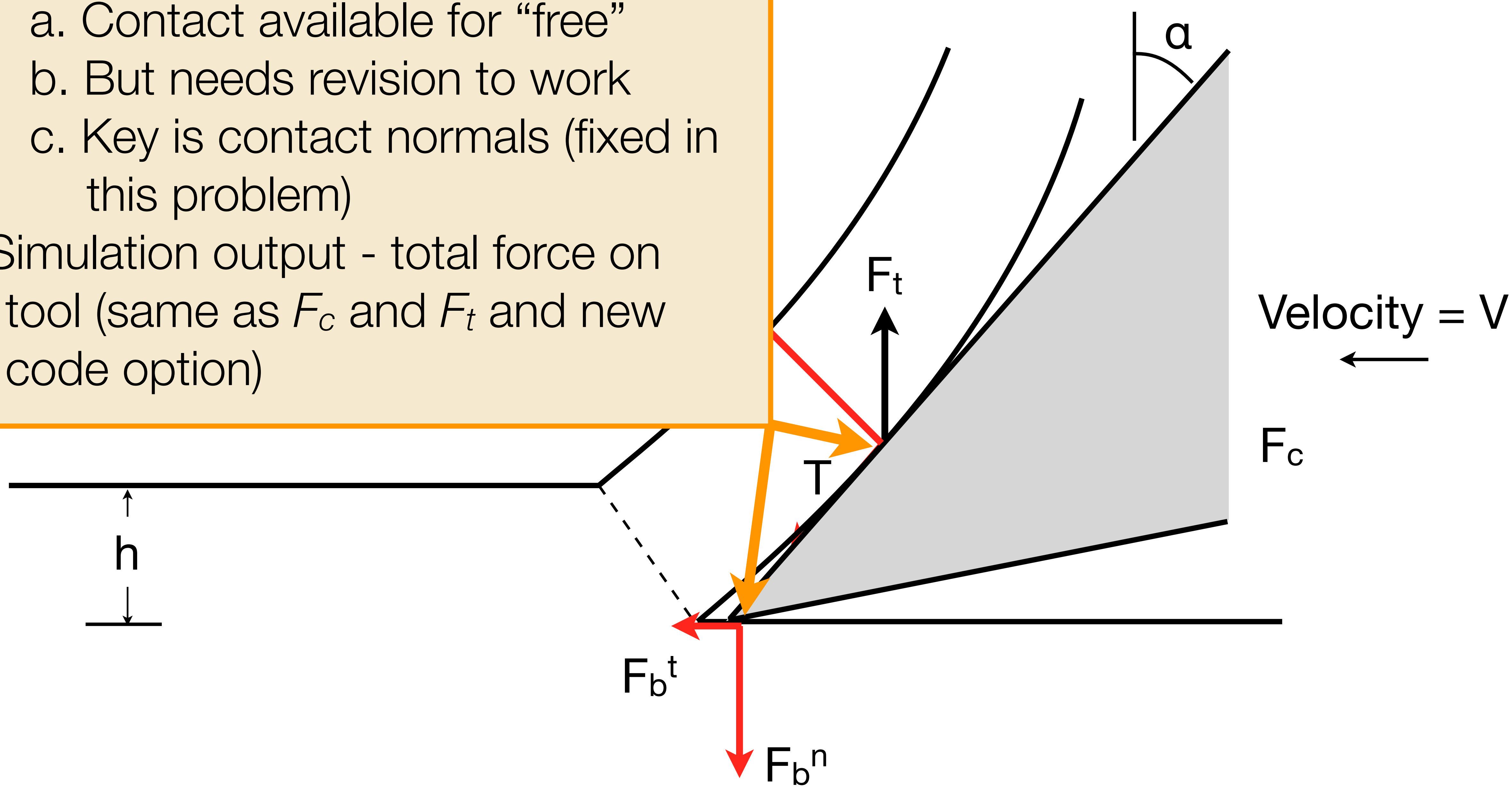


Contact Physics

- Tool = Rigid Material
- Coulomb Friction on chip and on bottom
- MPM Contact
    a. Contact available for “free”
    b. But needs revision to work
    c. Key is contact normals (fixed in this problem)
- Simulation output - total force on tool (same as F_c and F_t and new code option)

lodeling

Modeling



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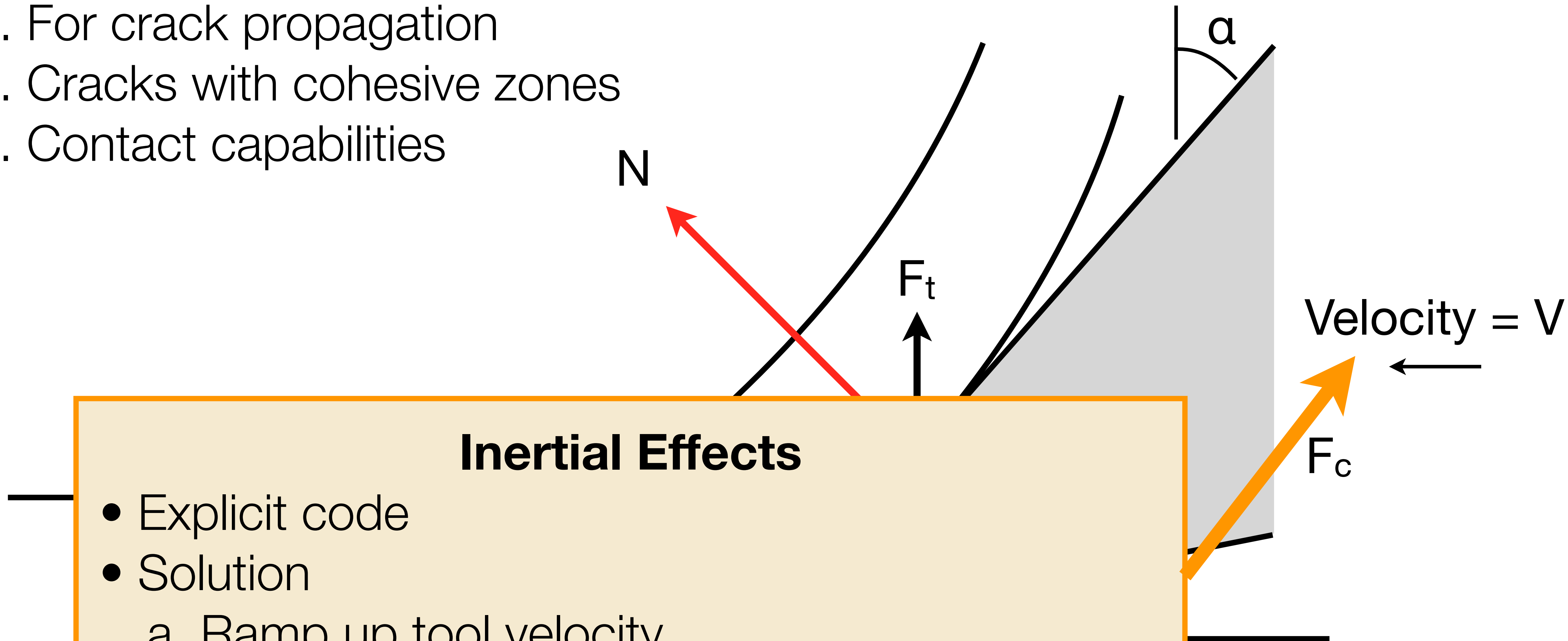


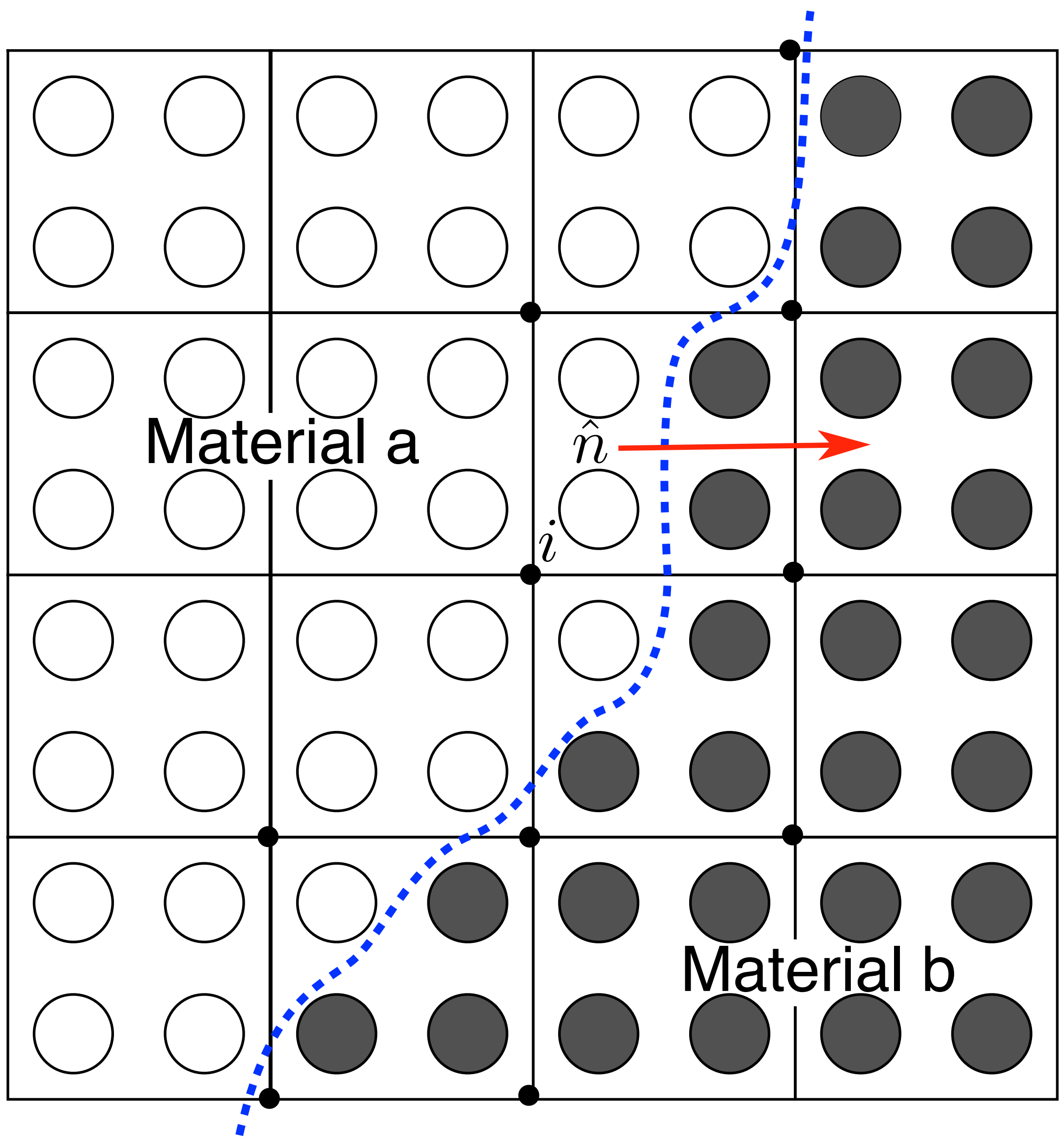
Inertial Effects

- Explicit code
- Solution
  a. Ramp up tool velocity
  b. Kinetic energy “thermostat”
  c. If damping controlled, good results, otherwise failed simulation
  d. Good results gave steady state forces

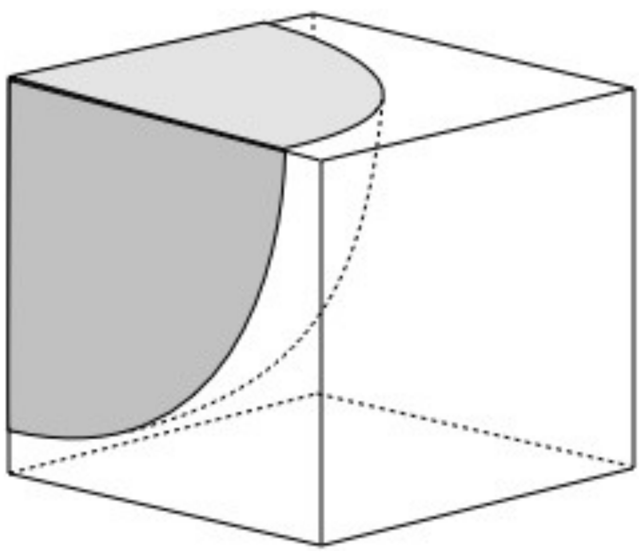
MPM Contact

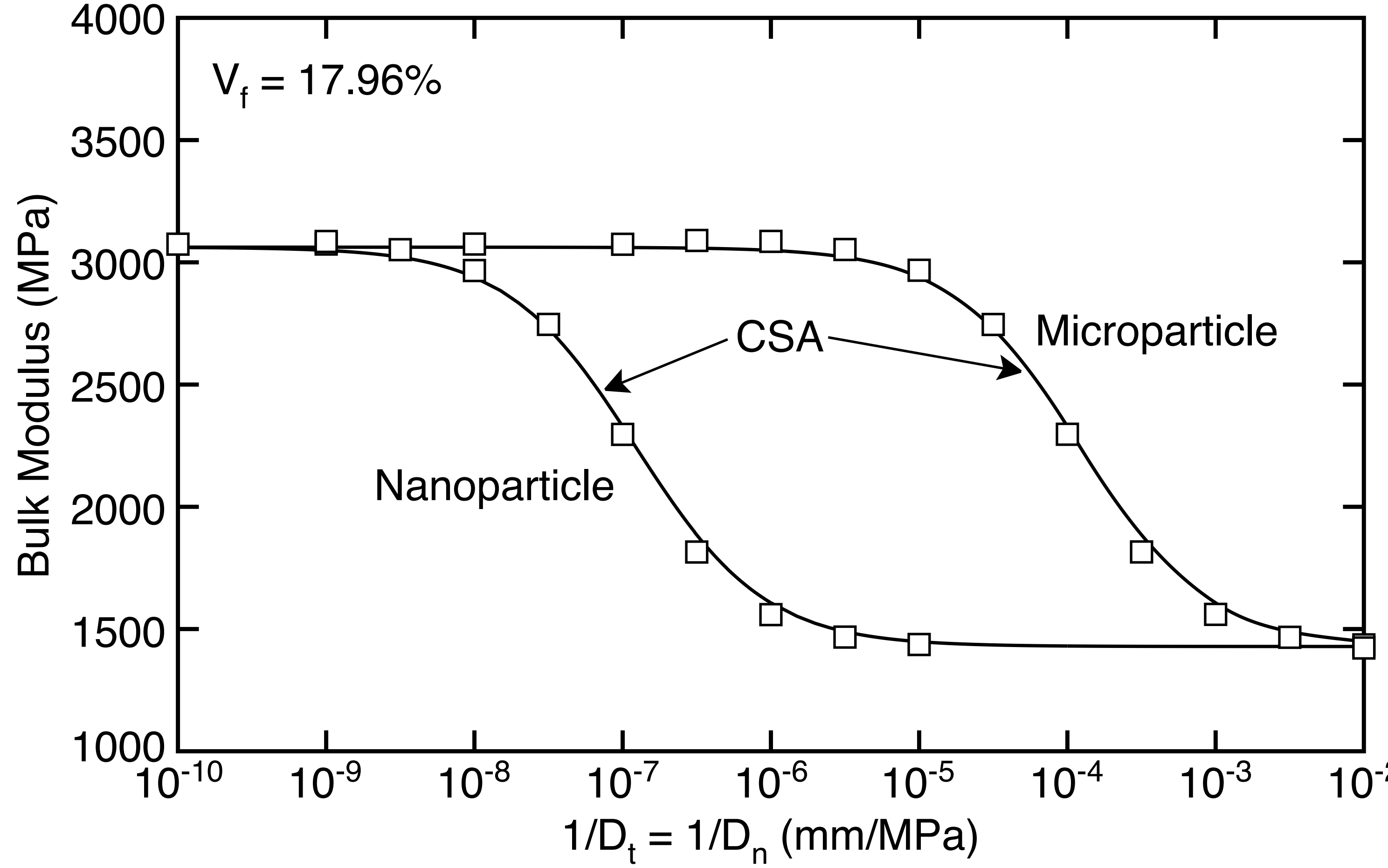
- Contact Detection
  - Volume Screening: $V_{total} > V_c$
  - Approaching: $\Delta\vec{p}_{i,a} \cdot \hat{n} < 0$
  - Overlap: $\vec{\delta}_i \cdot n - \delta_{contact} < 0$
- Normal Vector Calculation Options
  - MVG: maximum volume gradient
  - AVG: average volume gradient
  - SN: Specify the normal
- Extension of Contact to Model Interfaces

$$T_n = D_n[u_n] \quad \text{and} \quad T_t = D_t[u_t]$$



One Imperfect Interface Result





Challenges

1. Finding contact area for arbitrary interface orientation
2. Working with stiff interfaces $D_n,\ D_t \to \infty$

J.A. Nairn, "Modeling Imperfect Interfaces in the Material Point Method using Multimaterial Methods," Computer Modeling in Eng. & Sci., in press (2013) — http://www.cof.orst.edu/cof/wse/faculty/Nairn/papers/MMInterfaces.pdf

15°

30°

45°

15°

30°

45°

15°

30°

45°

15°

30°

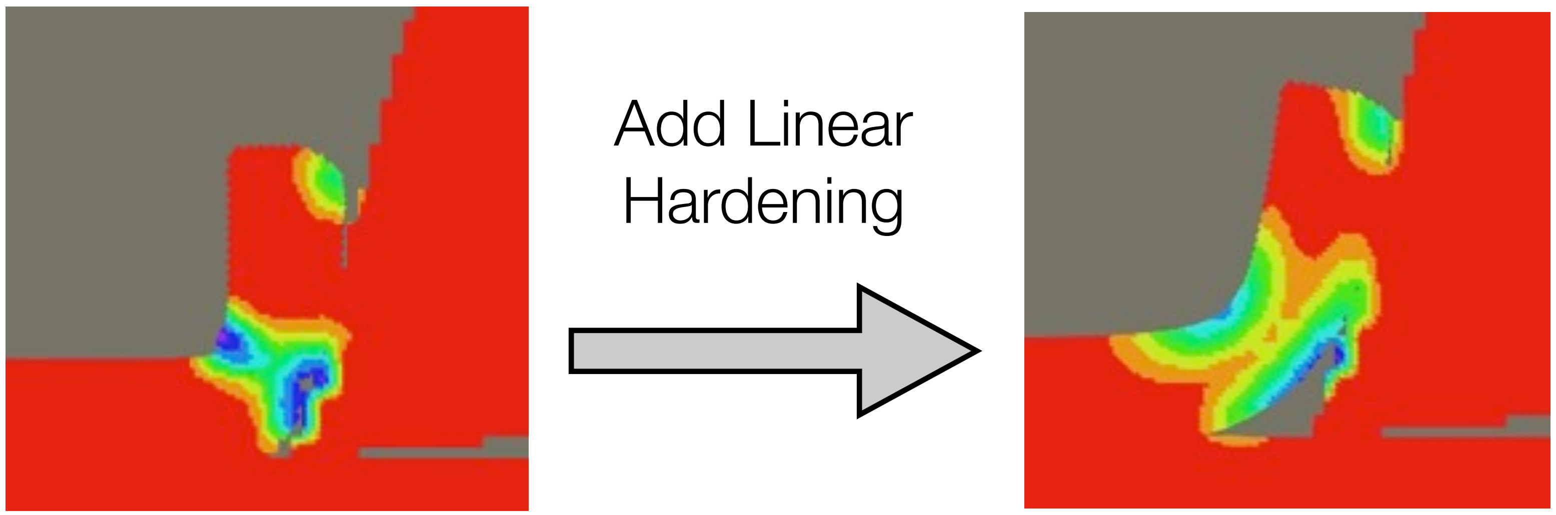
45°

Model Verification

- Elastic, perfectly-plastic material
  - E = 1000 MPa, ν = 0.33, σ_y = 25 MPa
  - Plane strain analysis
- Simple fracture law
  - $n = 1$, $G_{Ic} = G_{IIc} = G_c$ = 2000 J/m^2 (constant G_c regardless of mode)
  - Cubic traction law, σ_c = 40 MPa
- Frictionless contact
- Compare to analytical model
  - J. G. Williams, *Eng. Fract. Mech.*, **77**, 293-308 (2010).

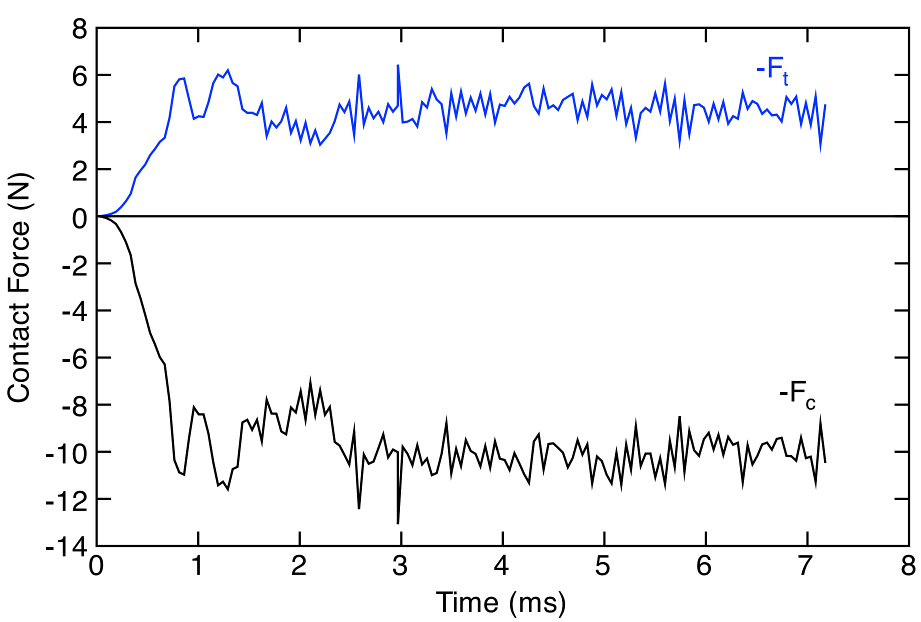
Simulations Problems

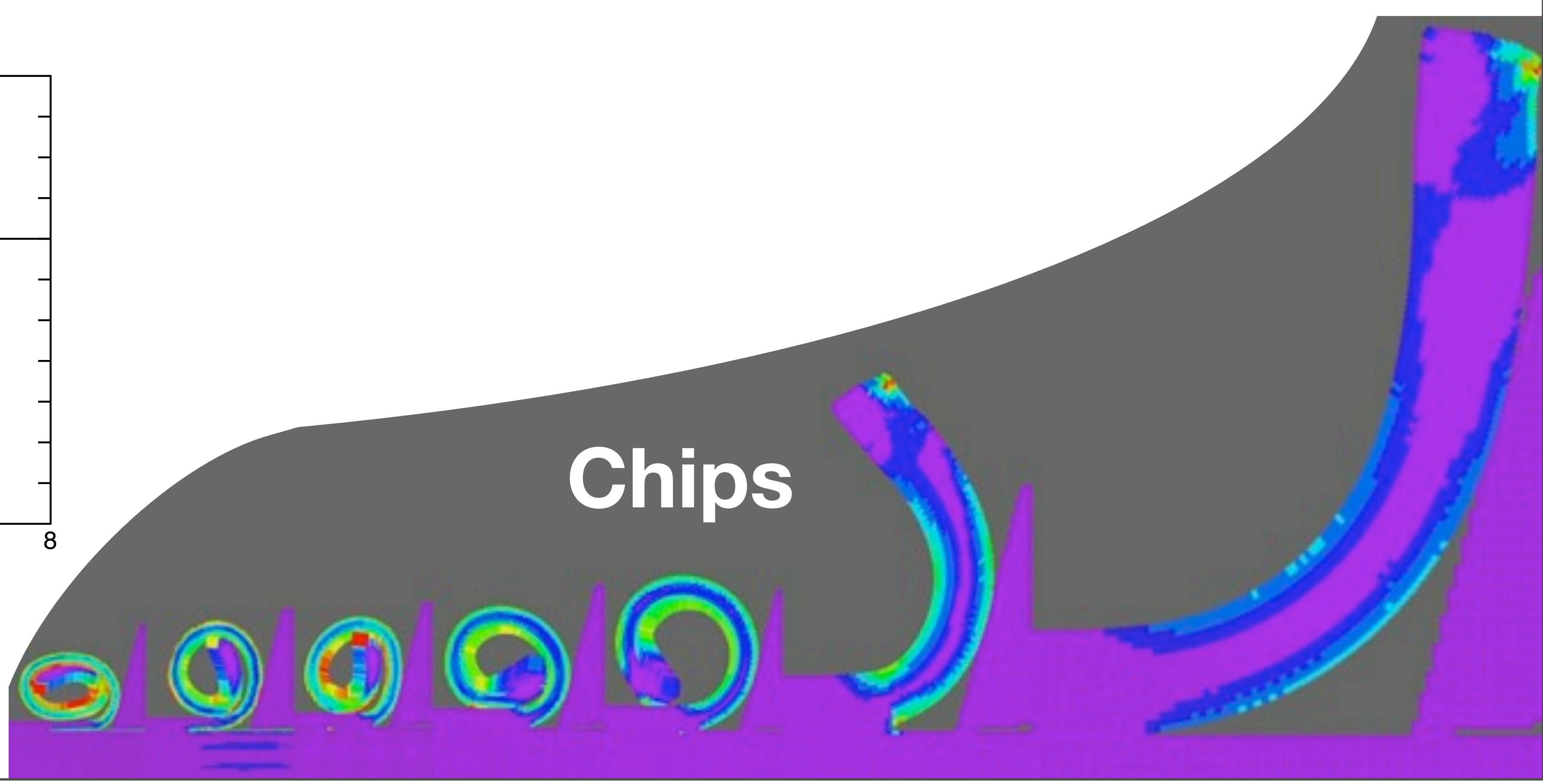
- Numerical difficultly resolving contact at the tool tip



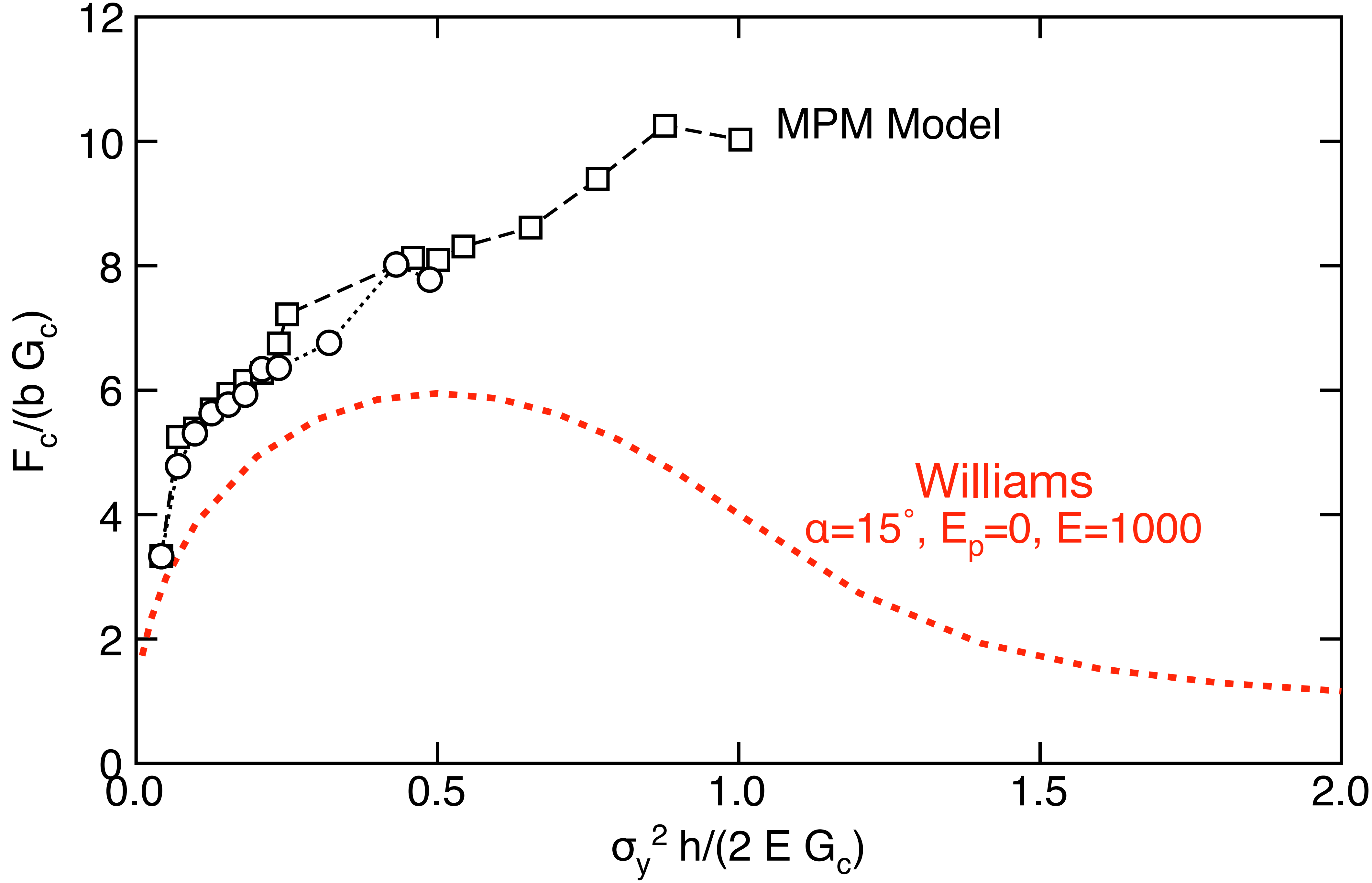
“Elastic-plastic bending”

- Simulation Forces





Simulations *vs*. Plastic Bending Analysis



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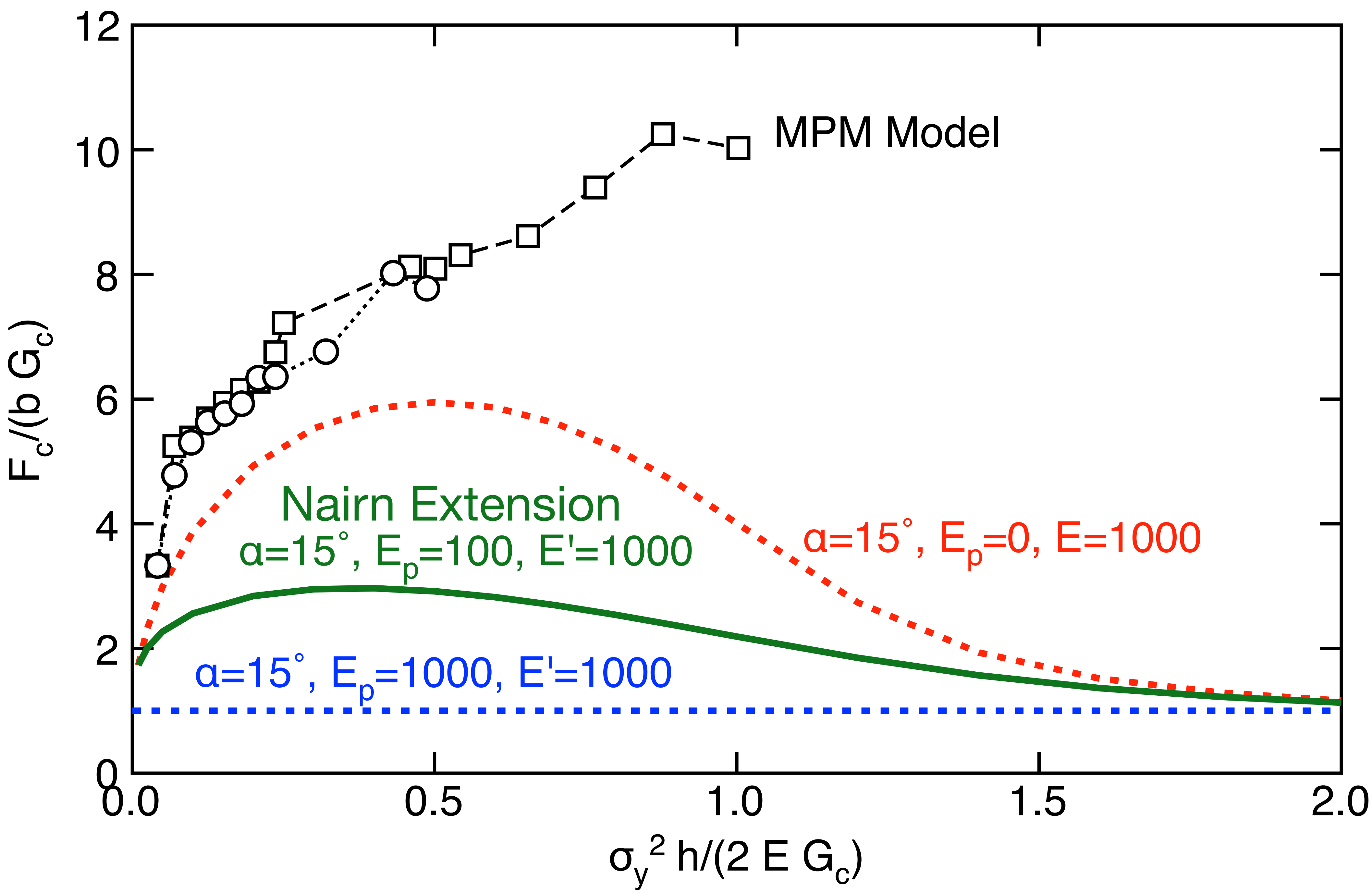
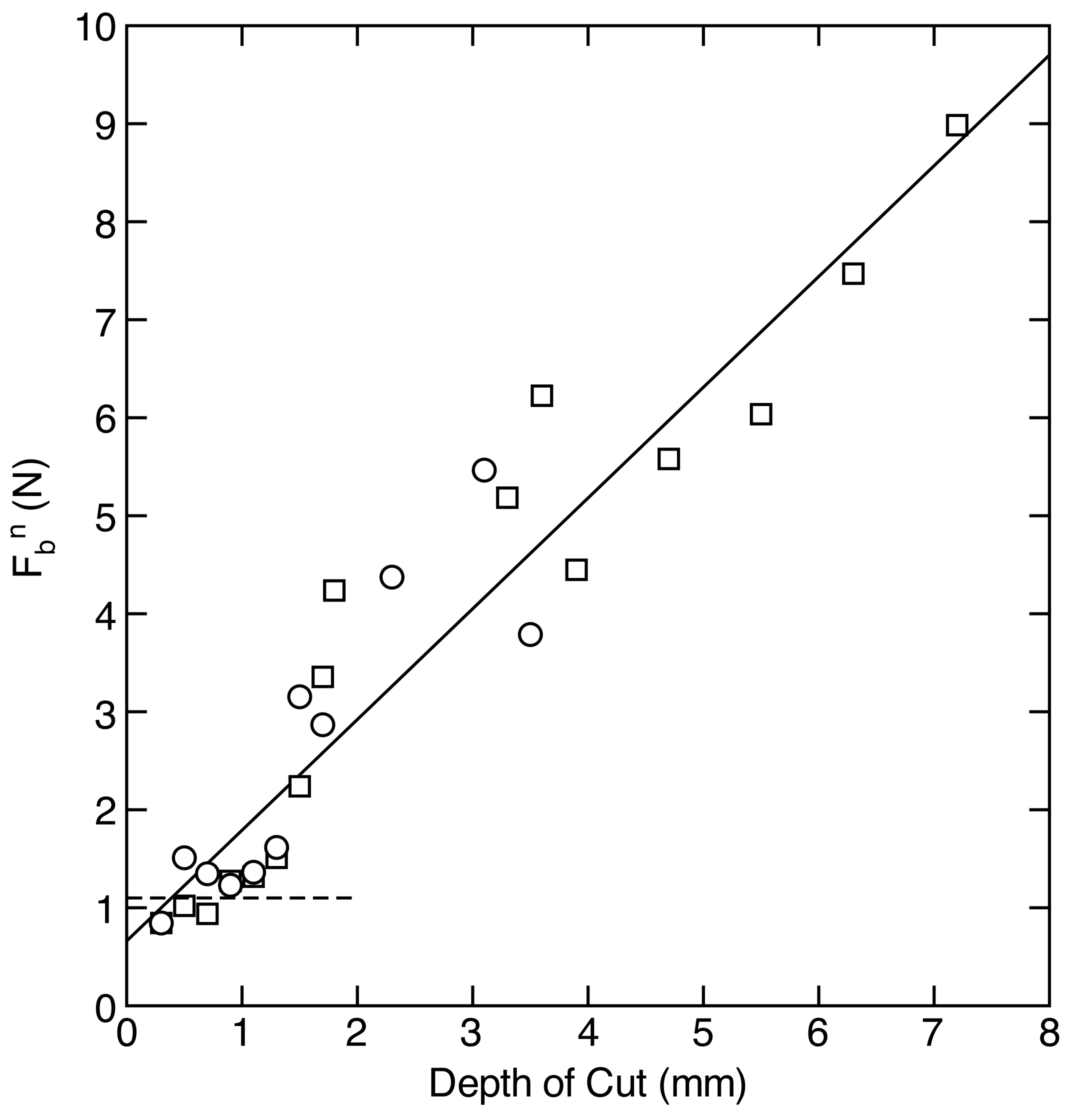
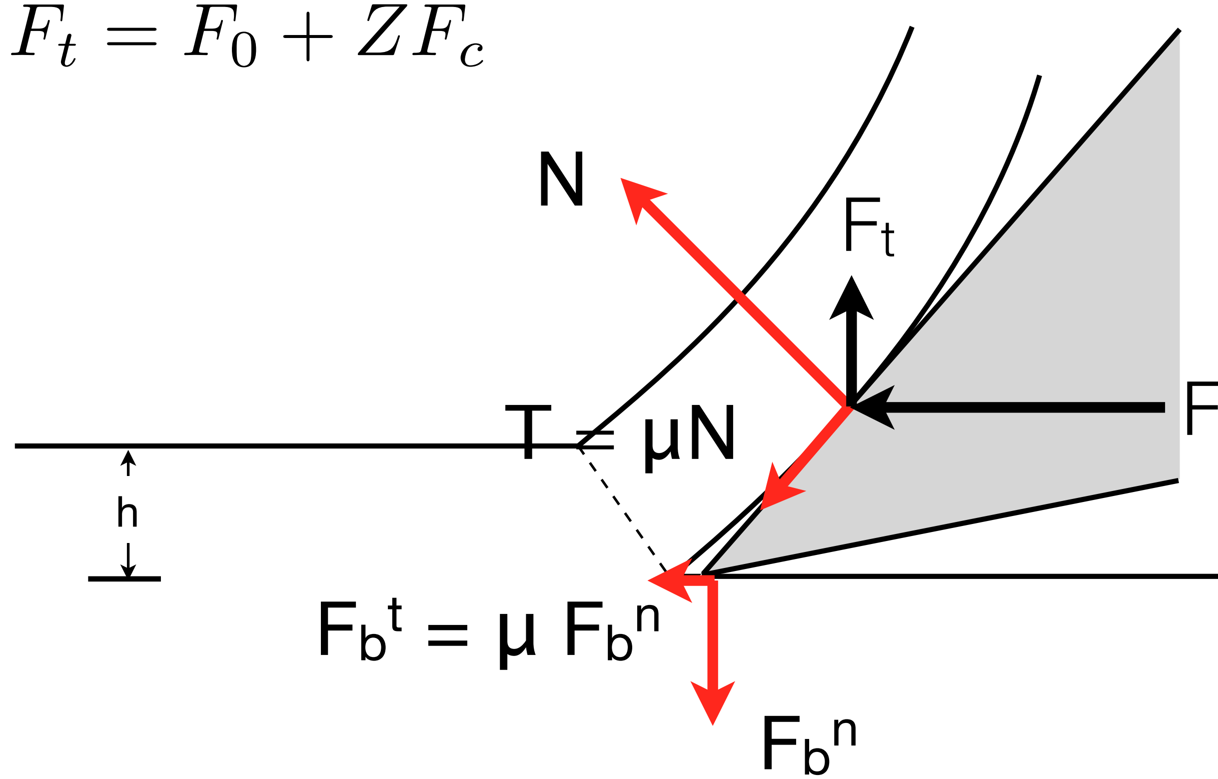


Simulations Reveal Non-Negligible Bottom Force



$$F_t = F_0 + ZF_c$$

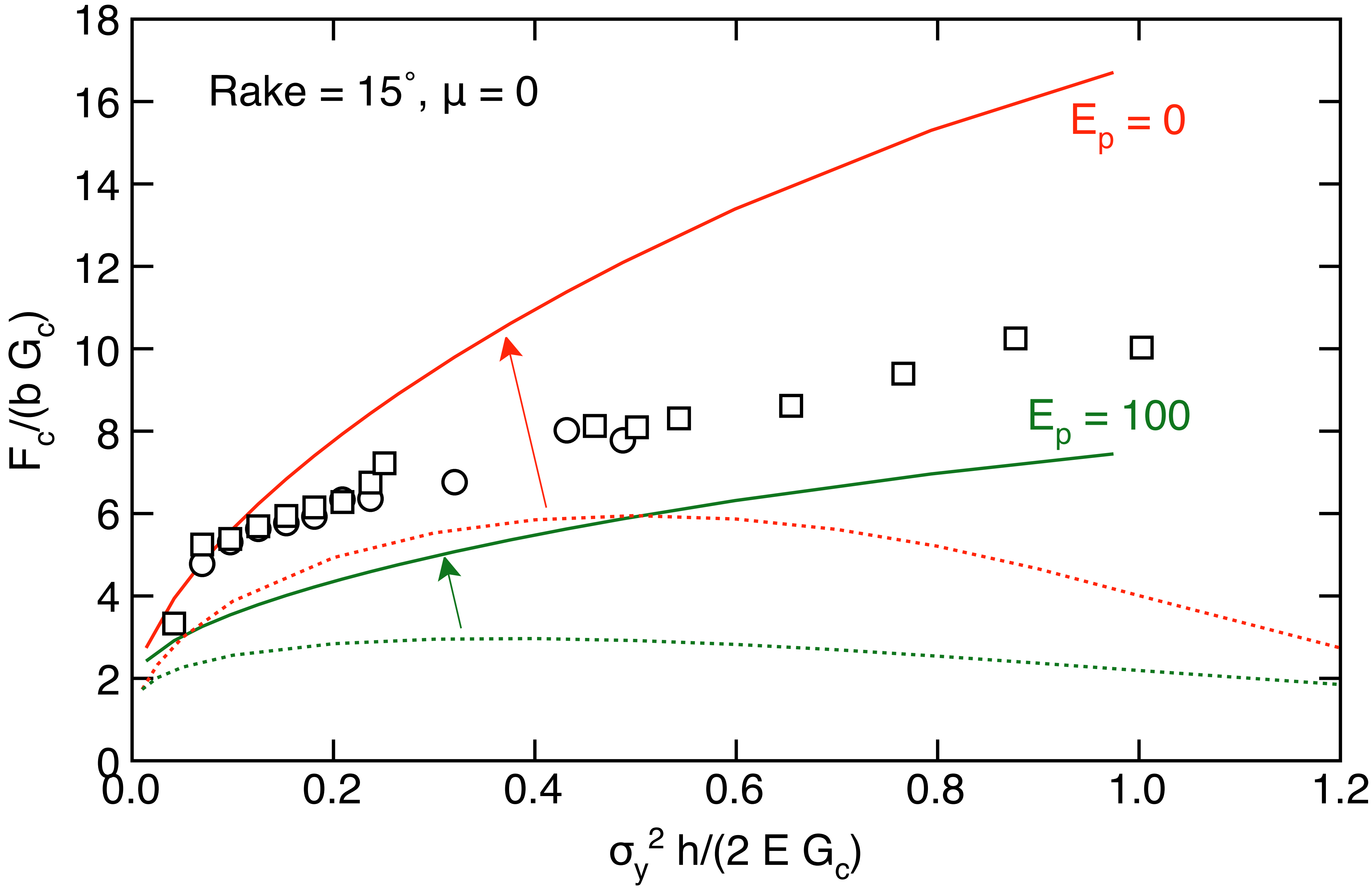


Semi-Analytical Model

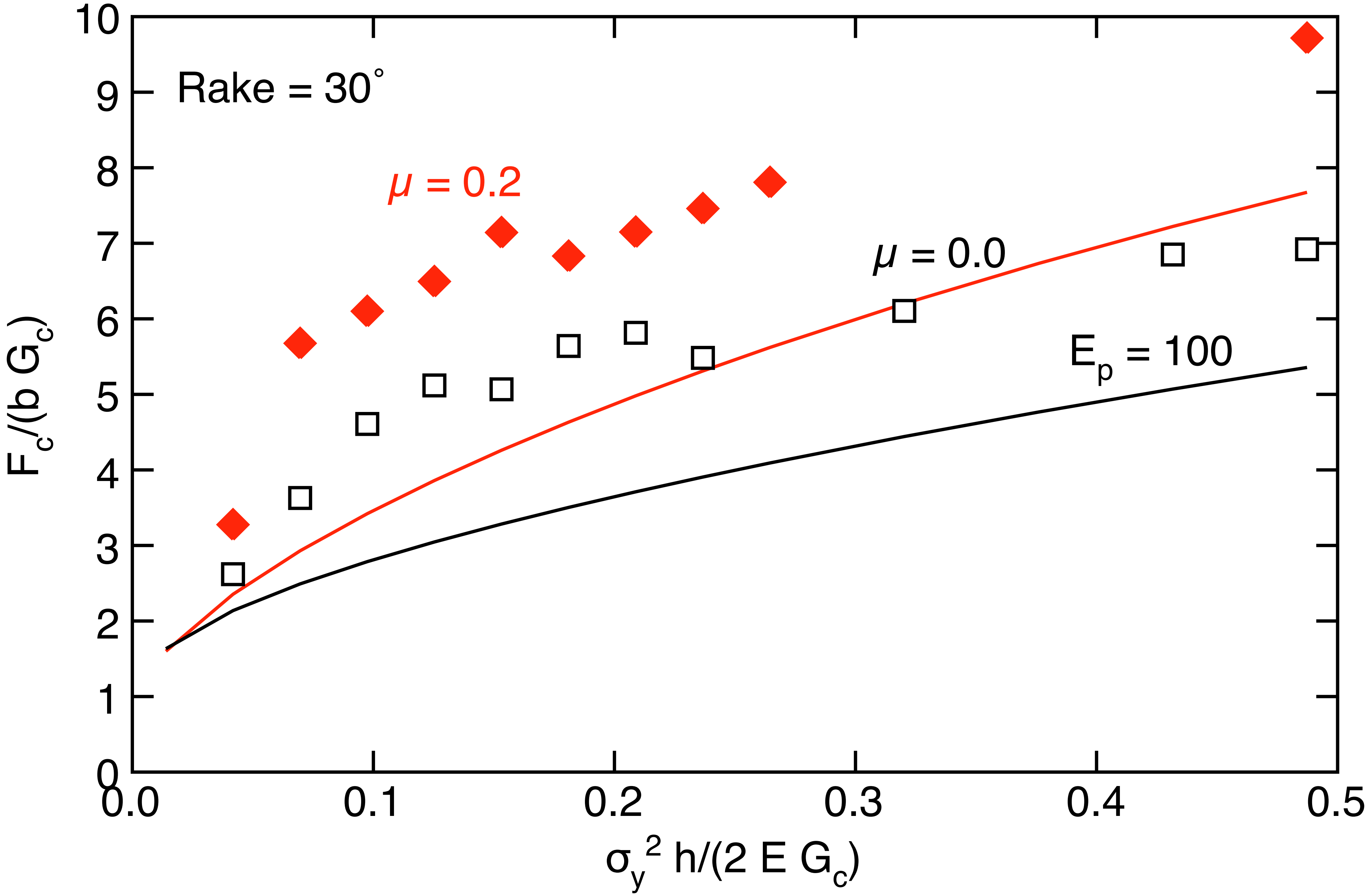
- Revise elastic-plastic bending for F_b^n
- Insert F_b^n from simulation results

$T \neq G_a + \mu N$ but instead: $T = \mu N$, $F_b^t = \mu F_b^n$ ⇒ $\dfrac{F_t}{b} = Z\dfrac{F_c}{b} + (1-\mu Z)\dfrac{F_b^n}{b}$

Semi-Analytical Model

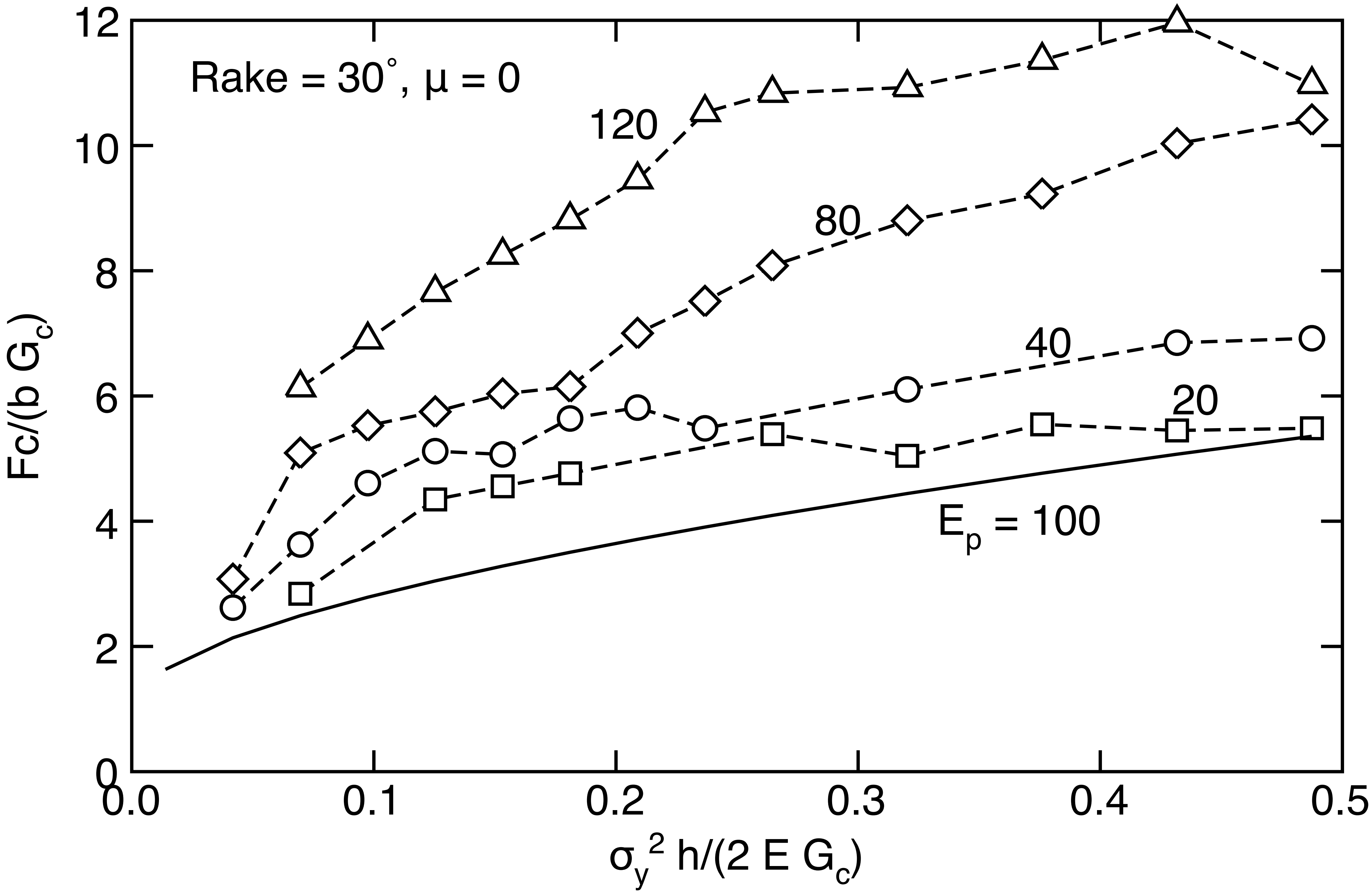


Simulations/Modeling with Friction

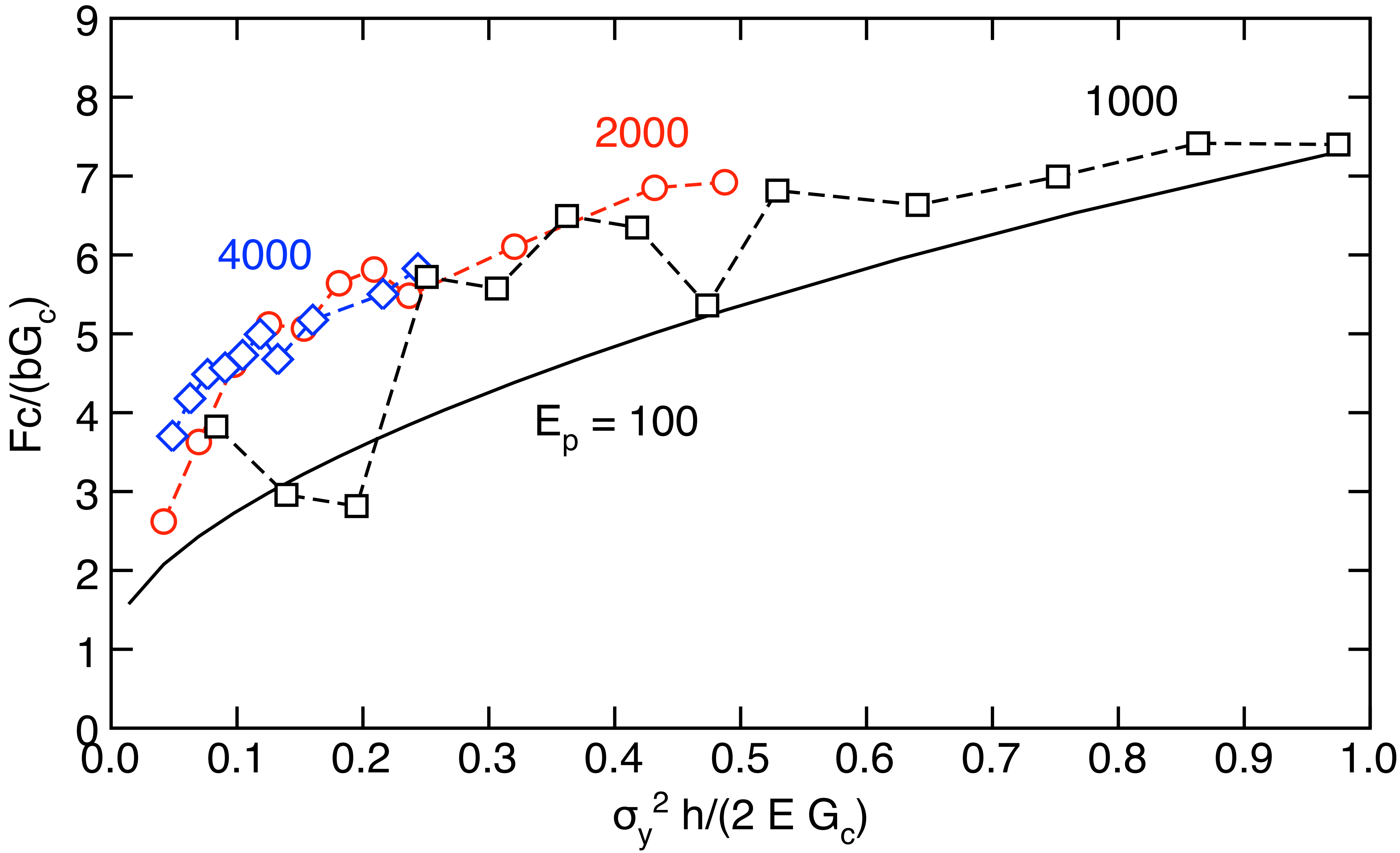


"Virtual Experiments"

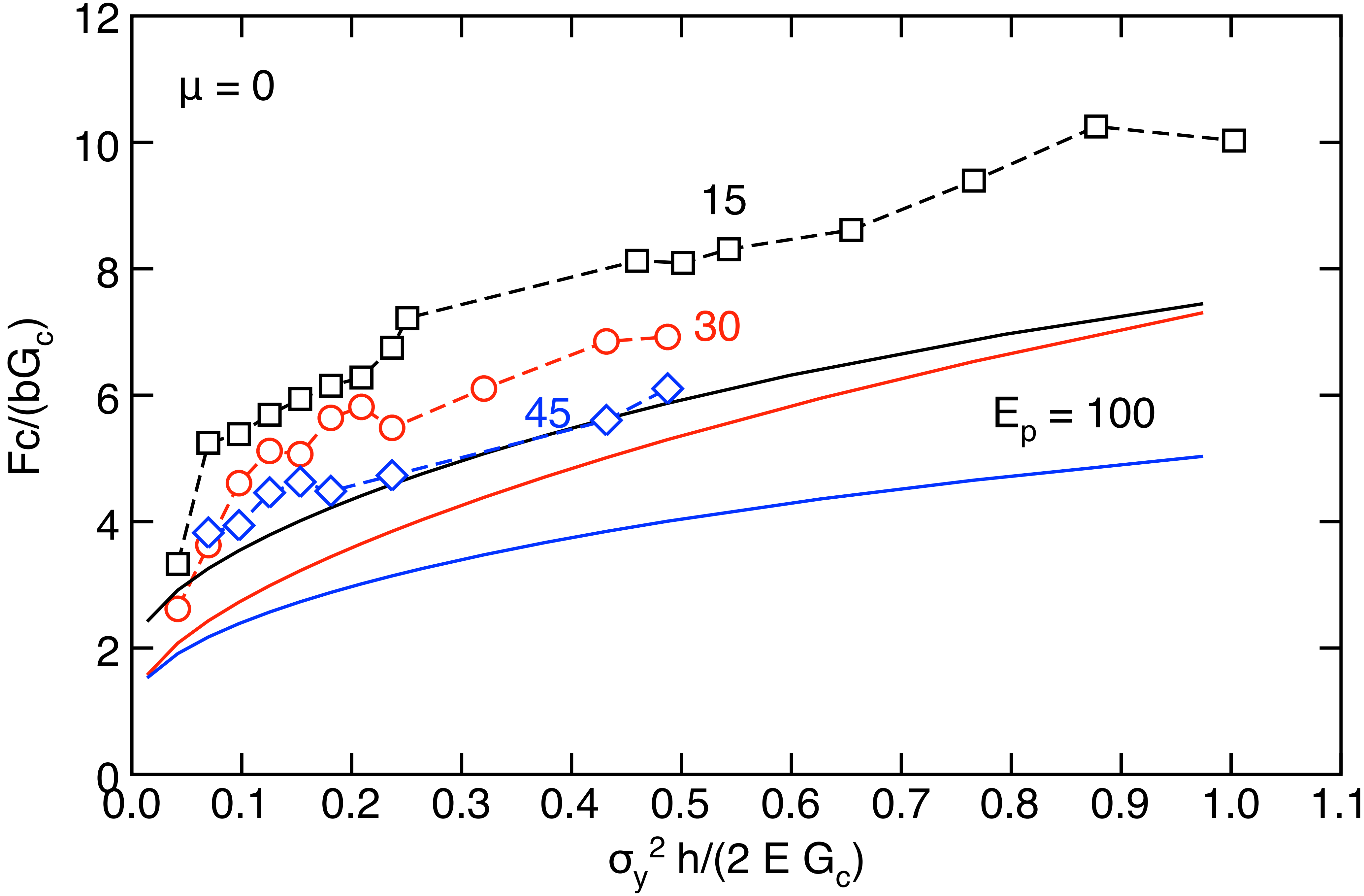
Effect of Cohesive Stress



Effect of Toughness



Effect of Rake Angle



Hyperelastic-Plastic, Large Strain Material

Hyperelastic

Hypoelastic

Cumulative Plastic Strain

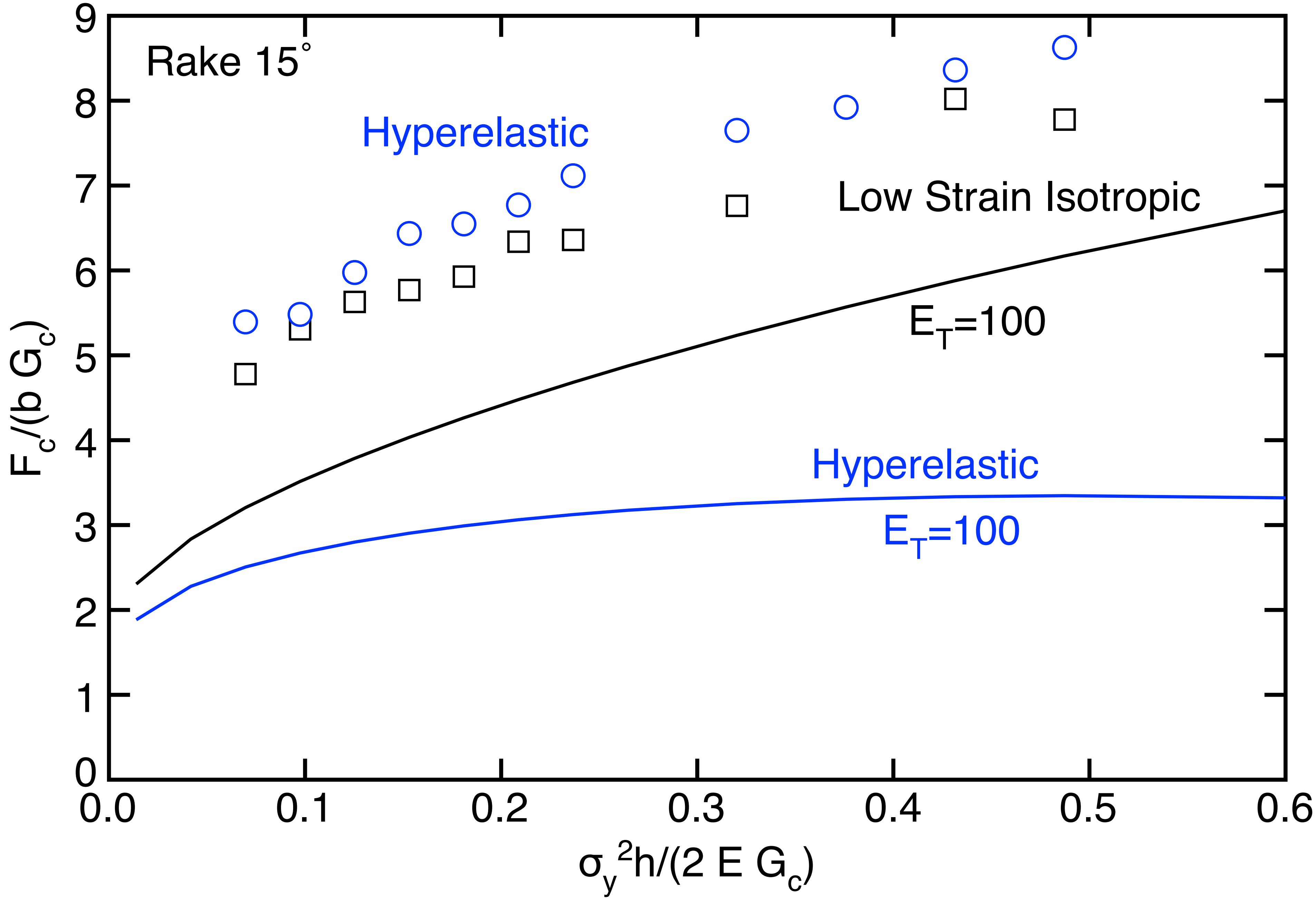
Hyperelastic-Plastic, Large Strain Material

Hyperelastic

Hypoelastic

Equivalent Stress

Cutting Forces



In-conclusions

- HDPE, LDPE, Trex, and Timber Tech Experiments
  - Works reasonable well, but answer depends on interpretation of the F_t *vs*. F_c intercept.
  - New results for Trex and Timber Tech Wood Plastic Composites
- Numerical simulations (by MPM) are working
  - Uncertain validation
  - Potential simulations (*e.g.*, veneer peeling) may be useful
- Forces on bottom of tool
  - How to handle it?
  - Related to sharpness
  - Essential to theory and to modeling

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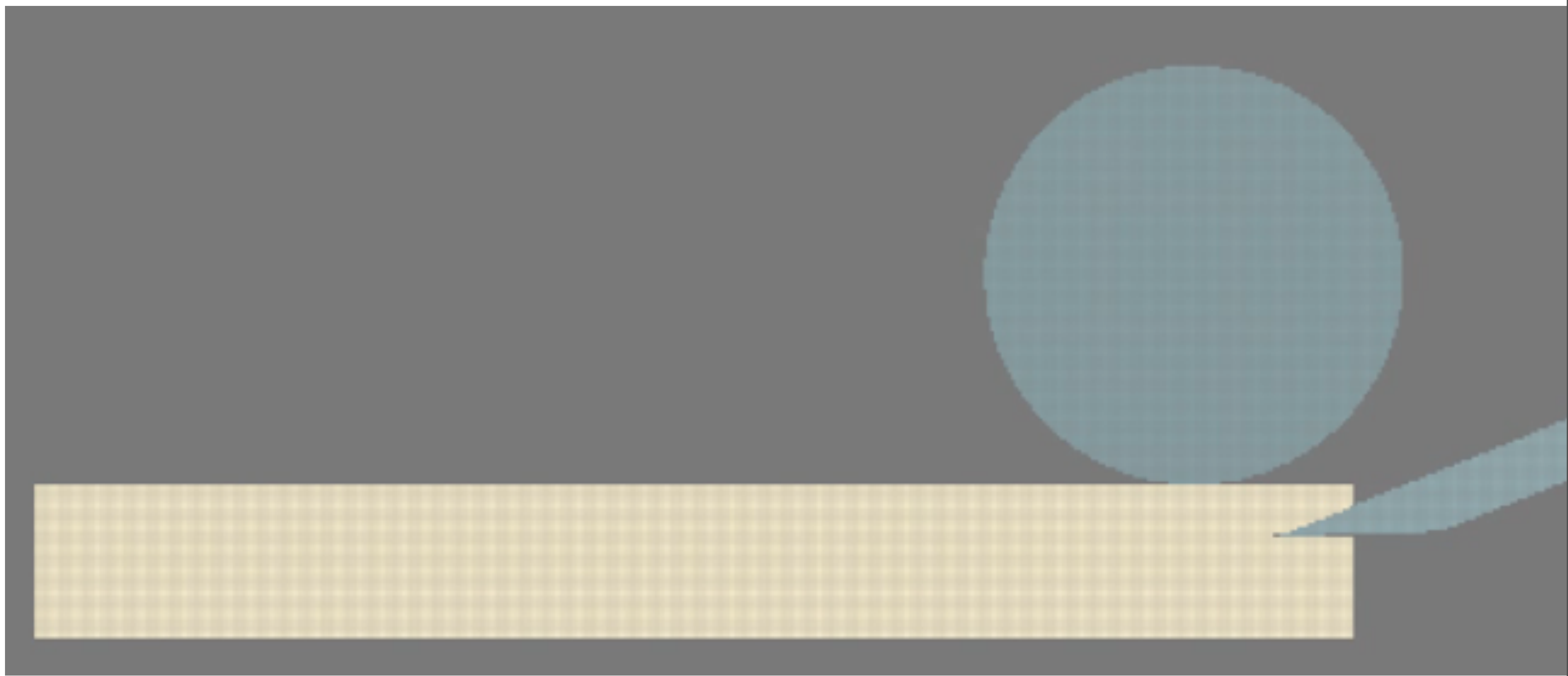
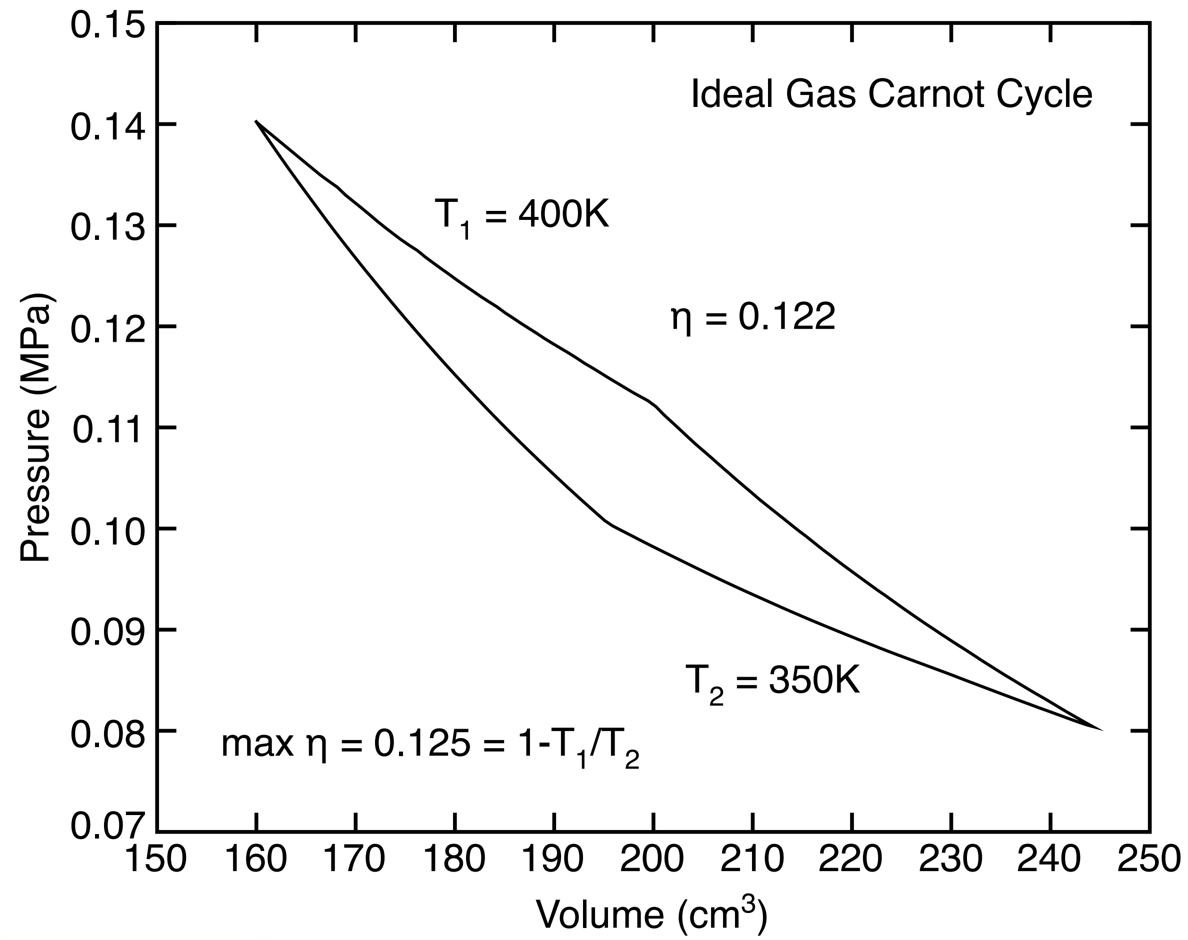
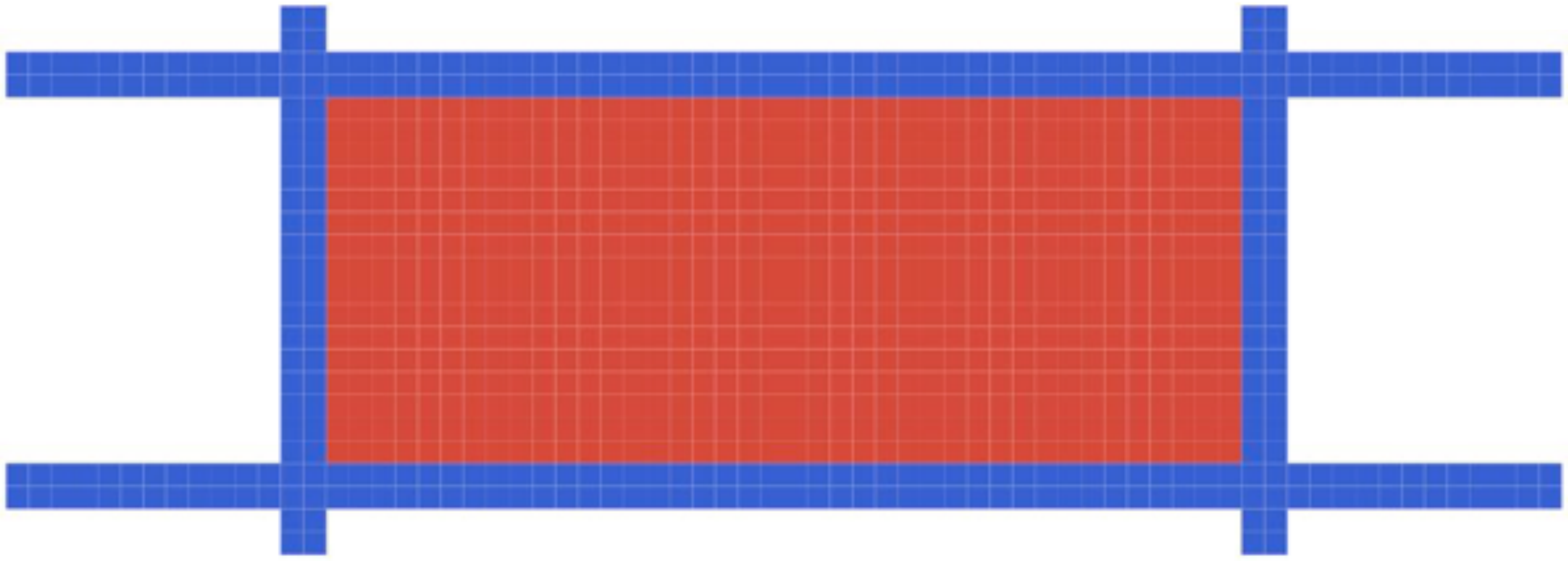


Carnot Cycle or an MPMgine™

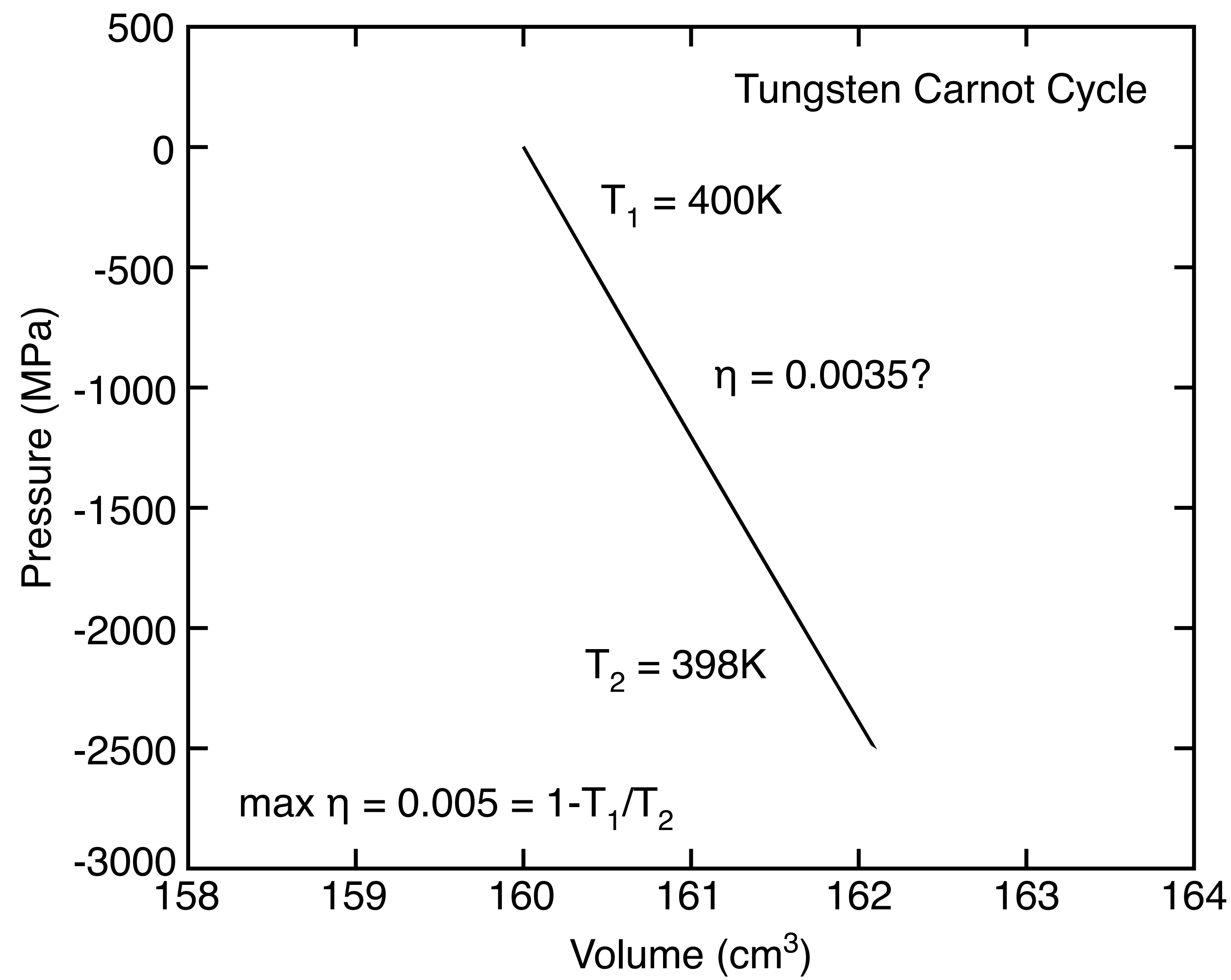
- Ideal Gas as Hyperelastic Material
- Custom boundary conditions
- Trick is when to switch on returning
- Why not other materials
    - Carnot claimed general result





Carnot Cycle on Other Materials?

- First step is cooling on isothermal expansion
  - True in coupled conduction-elasticity
  - Small effect, usually neglected
- Example
  - Tungsten with MG EOS
  - But plasticity always heats?
  - Eliminate yielding



Ideal Rubber Elastic Material

- In 1805, John Gough described a series of experiments on caoutchouc or Indian rubber:

> "For the resin evidently grows warmer the further it is extended; and the edges of the lips possess a high degree of sensibility, which enables them to discover these changes with greater facility than other parts of the body."

- Mooney-Rivlin Hyperelastic Material
- "Ideal Rubber" from Flory

$$\left(\frac{\partial U}{\partial L}\right)_T = 0 \qquad \text{therefore} \qquad dq = -dw$$

$$dS = \frac{dq}{T} = -\frac{dw}{T}$$

Isothermal Loading of Ideal Rubber