Mechanics of Creping in Tissue Making

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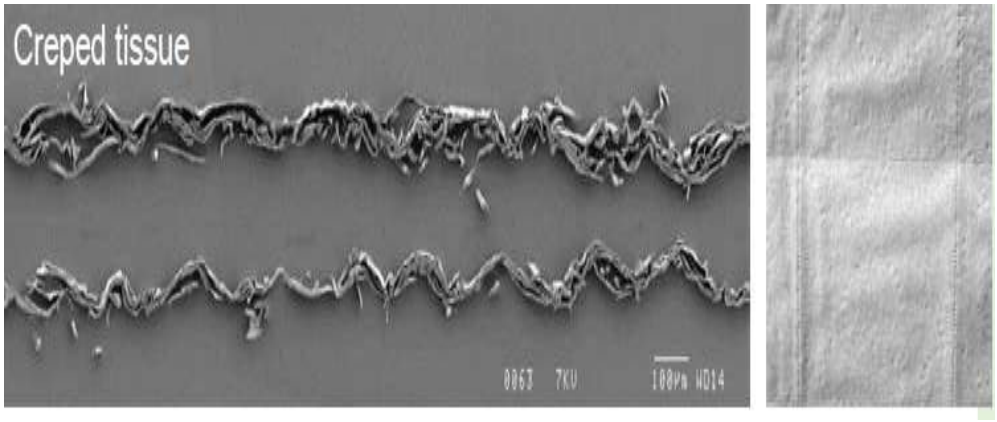
Outline

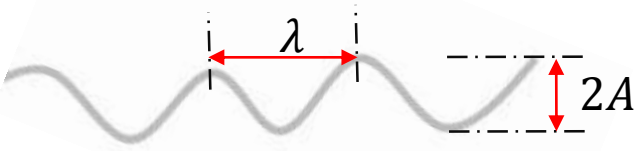
- Background
- Research Objectives
- Methodology and Results
- Conclusion

Creping Influences Tissue Properties



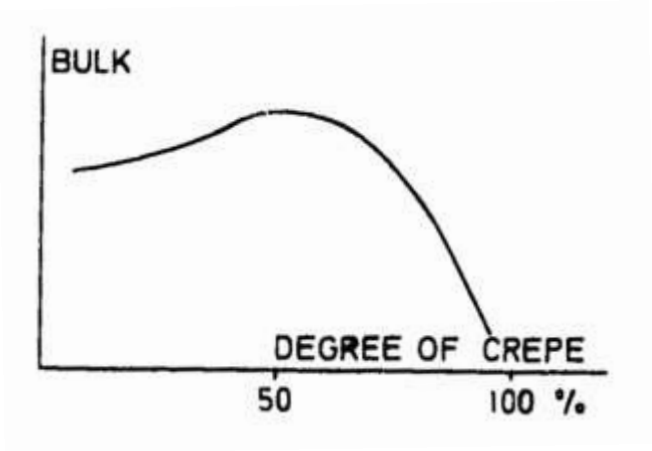
SEM cross-sectional image of tissue

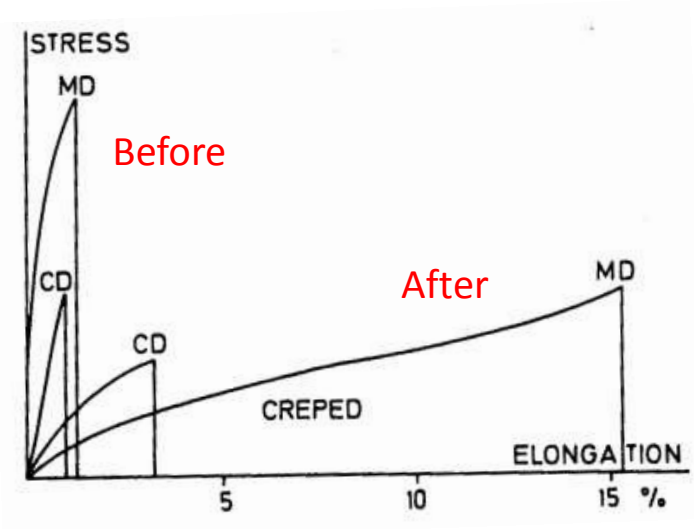
H.F. Jang, FPI, 2013



Schematic of tissue structure

Wavelength: λ ~ 0.3mm
Amplitude: A ~ 0.1mm

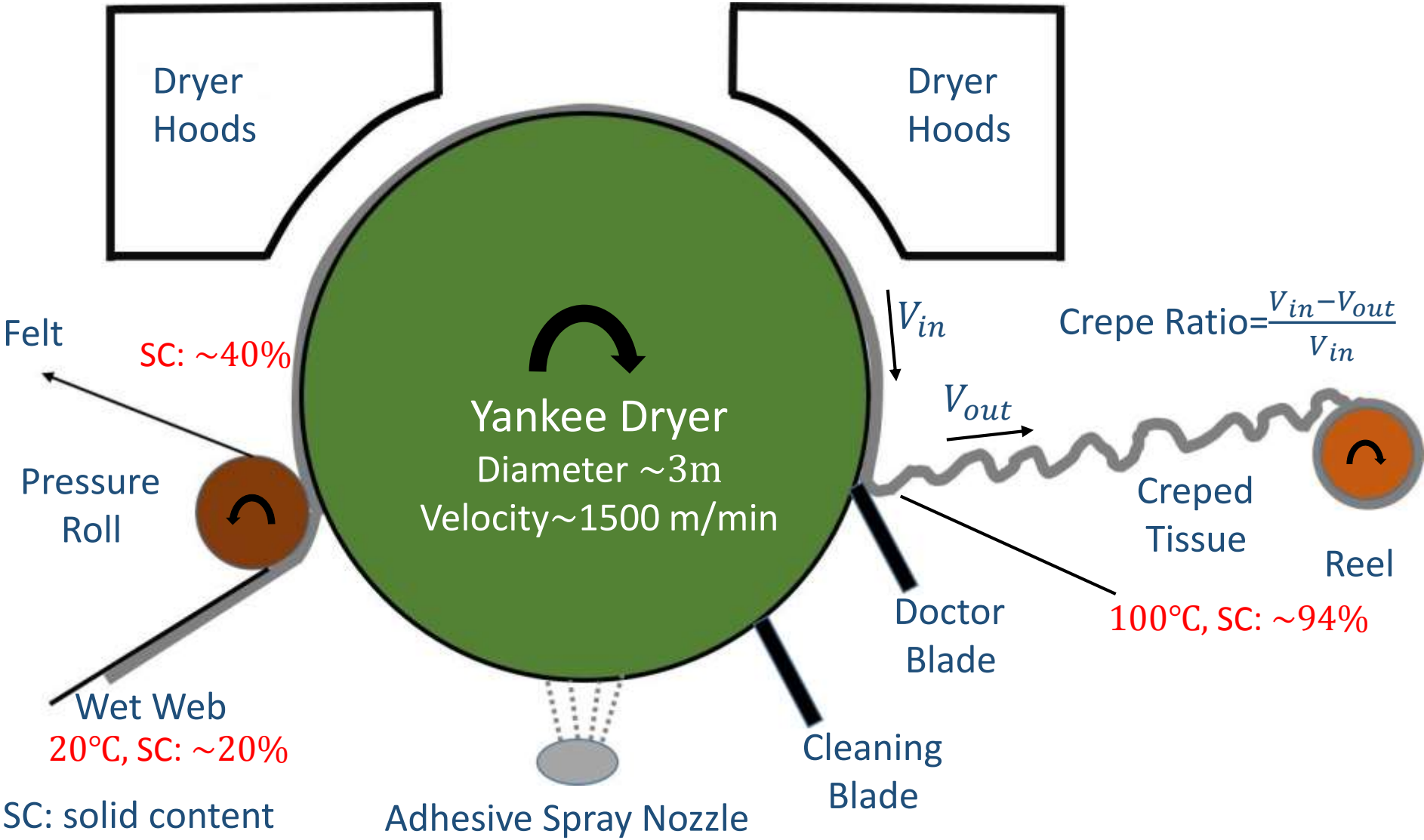




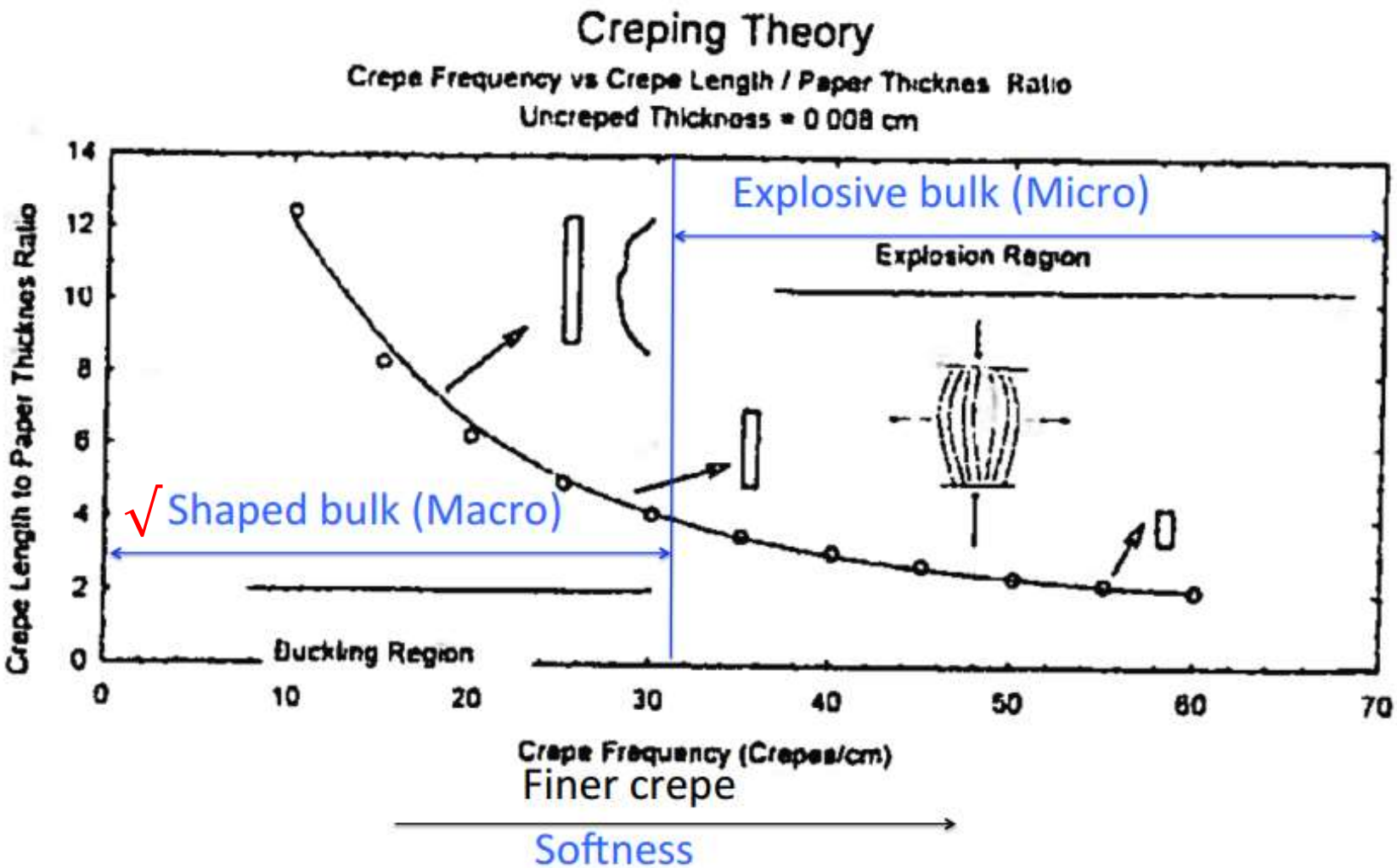
MD: machine direction; CD: cross direction.

Creping: a de-densification process

Dry-Creping Process

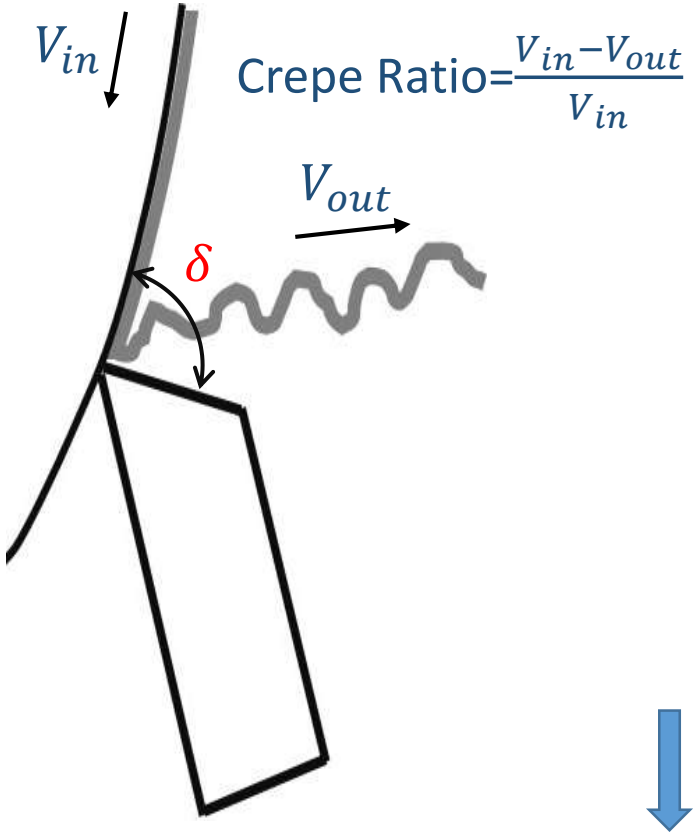


Creping Regimes



W. McConnel, The science of creping. 2004.

Governing Parameters



δ: Creping angle

Typical Control Parameters:

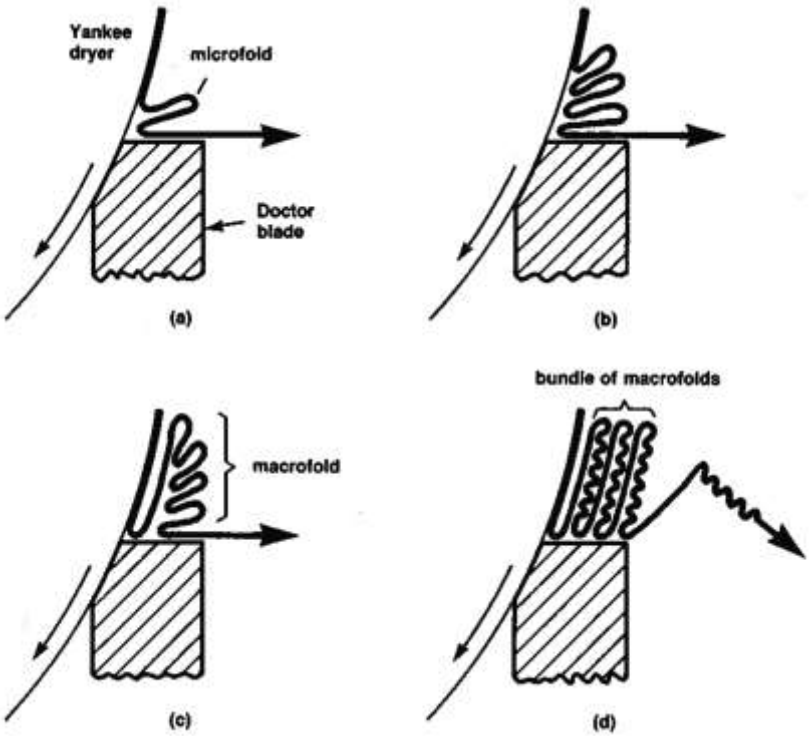
- Yankee surface speed $V_{in}(1000\sim2000m/min)$
- Creping angle δ $(80°\sim100°)$
- Crepe ratio $\frac{V_{in}-V_{out}}{V_{in}}$ $(10\%\sim30\%)$
- Adhesion G_c $(50\sim400\ N/m)$
- Blade Friction (0.25~0.35)

quality, runnability and productivity

Current situation: trial and error.

Fundamental study is necessary.
Guide the choice of adhesive chemicals,
process parameters, blade type and so forth.

Creping Mechanism

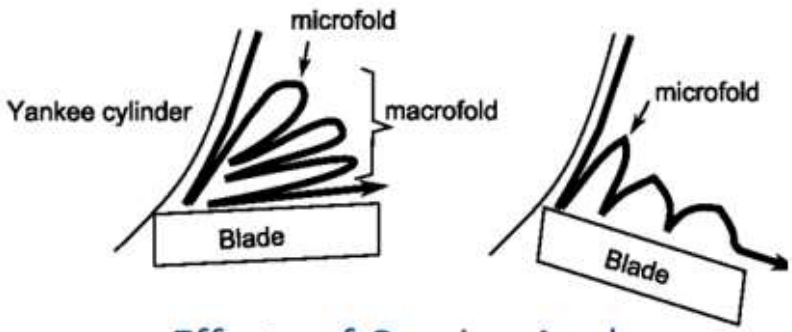


Micro-fold to Macro-fold Transition

High Speed Imaging Study

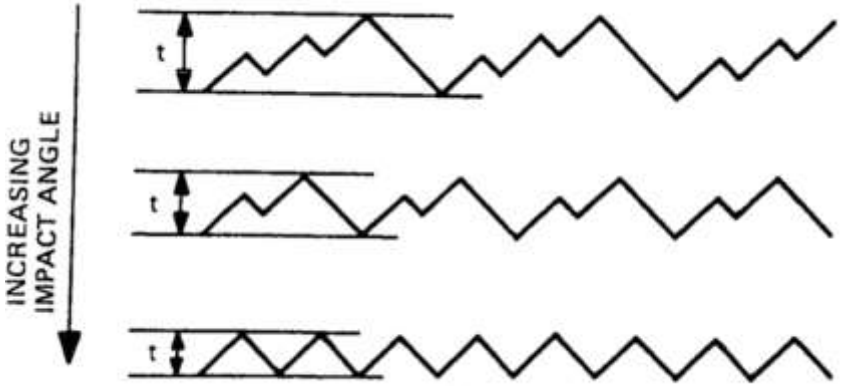
H. Hollmark, STFI 1972

Creping ratio: 32%



Effects of Creping Angle

J.P. Raunio and R. Ritala,
Nordic Pulp and Paper Research Journal , 2012



Limited surface speed: 140 m/min

No further validation about the mechanism.

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Research Objectives

Experiments:

- Observe the creping process under high speed to reveal relevant phenomenon and understand the mechanism.

Modeling:

- Develop mechanistic creping model to study the effects of process parameters (adhesion, creping angle…) and dynamic effects (creping ratio, surface velocity…) on tissue structure.

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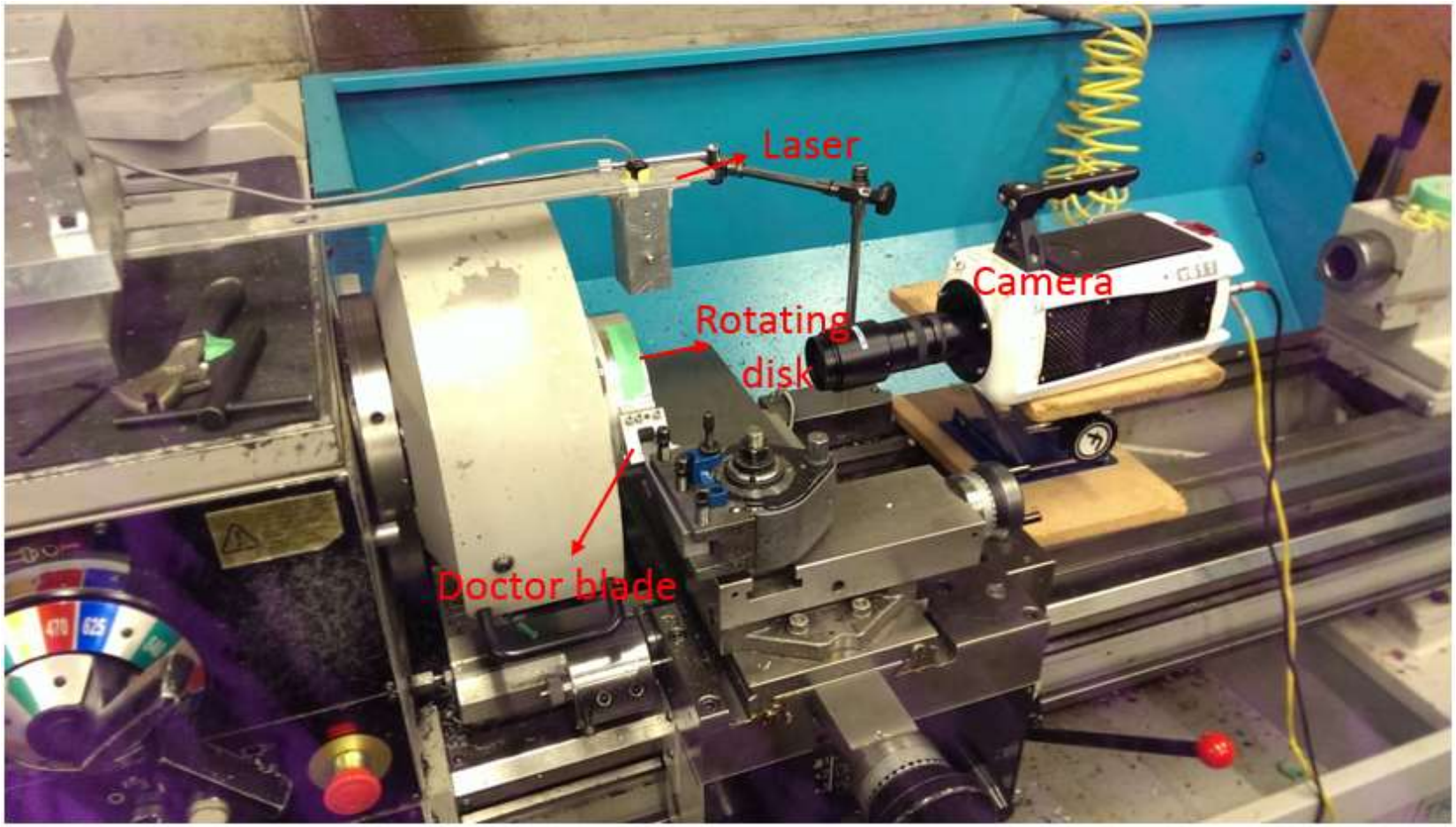
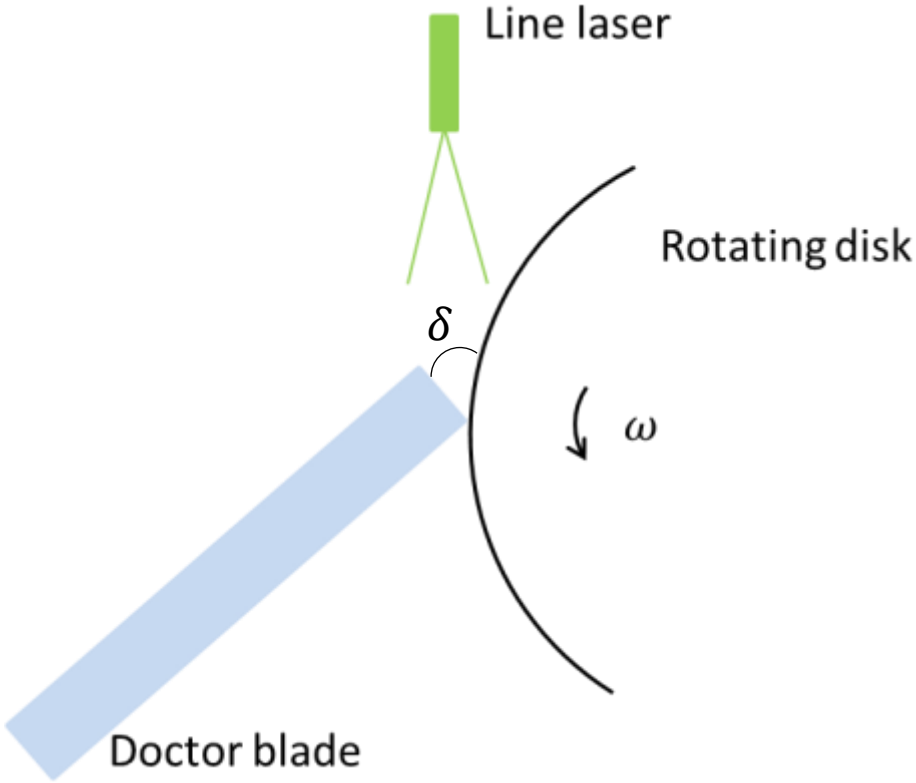
Methodology: High speed imaging



Creping testing rig based on Lathe

Goal: reveal creping mechanism at high speed

Edge-on view of set-up

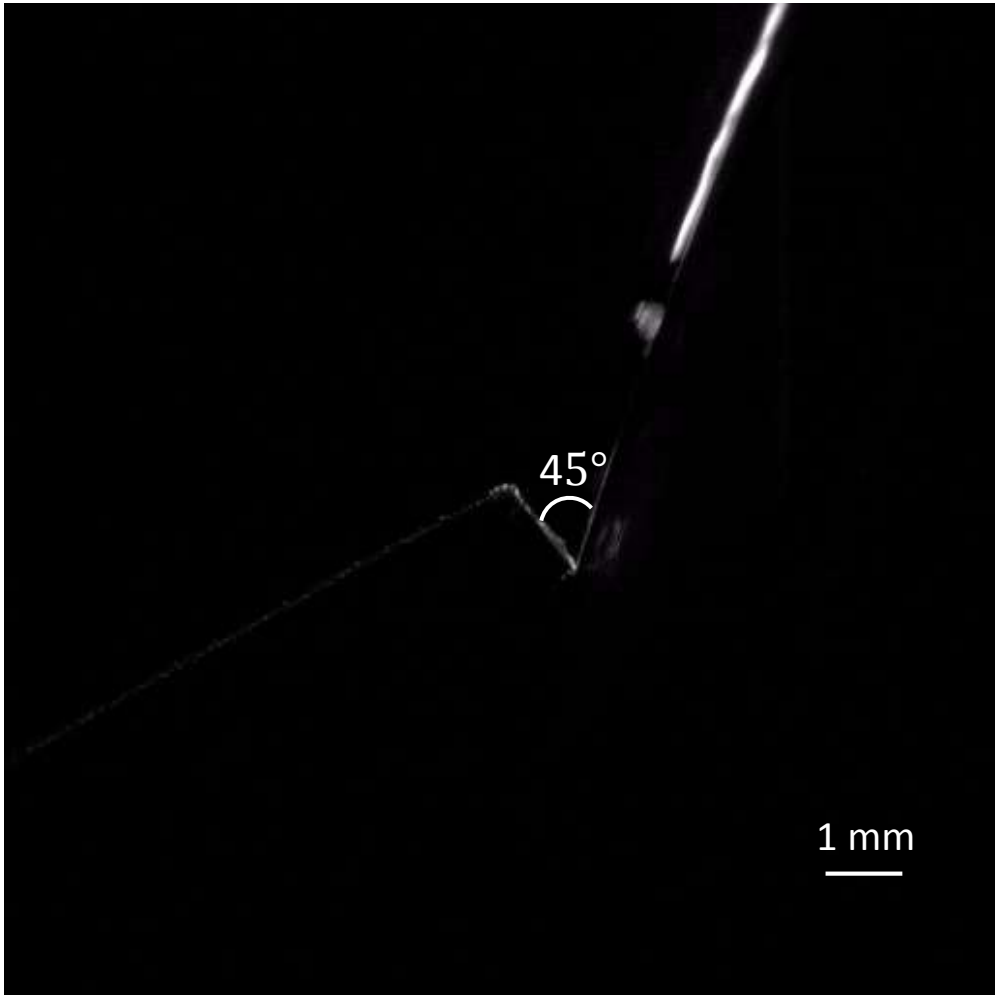


Laser information
Power: 500mW; Fan angle: 5°;
Length: 20mm; Thickness: 0.1mm.

Disk information
Radius: 89mm; ω_{max}: 1500 rpm;
Maximum surface speed: 838 m/min.

Doctor blade
Creping angle δ: adjustable;
Blade thickness: 1.2 mm.

Creping Video



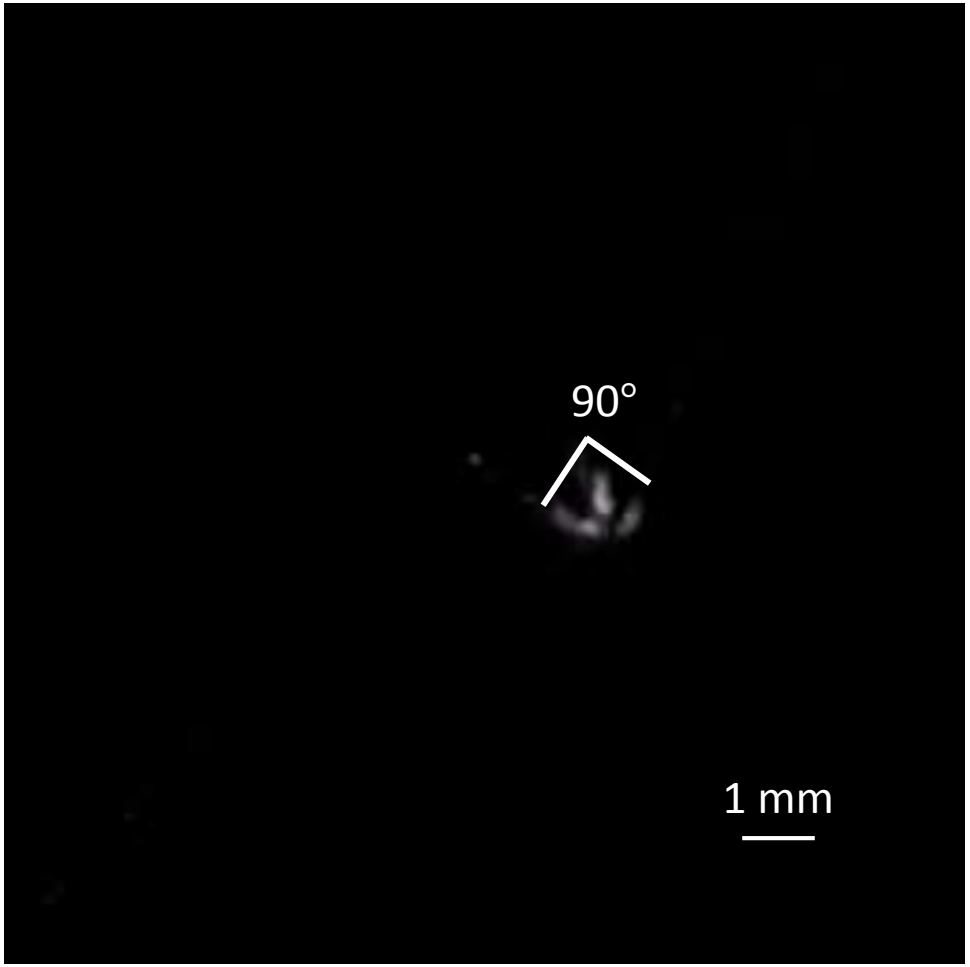
Surface speed: V_{in}=217 m/min

Creping angle δ =45°

No creping ratio: $V_{out} \approx 0$

Micro-fold to macro-fold transition is observed.

Increase Creping Angle



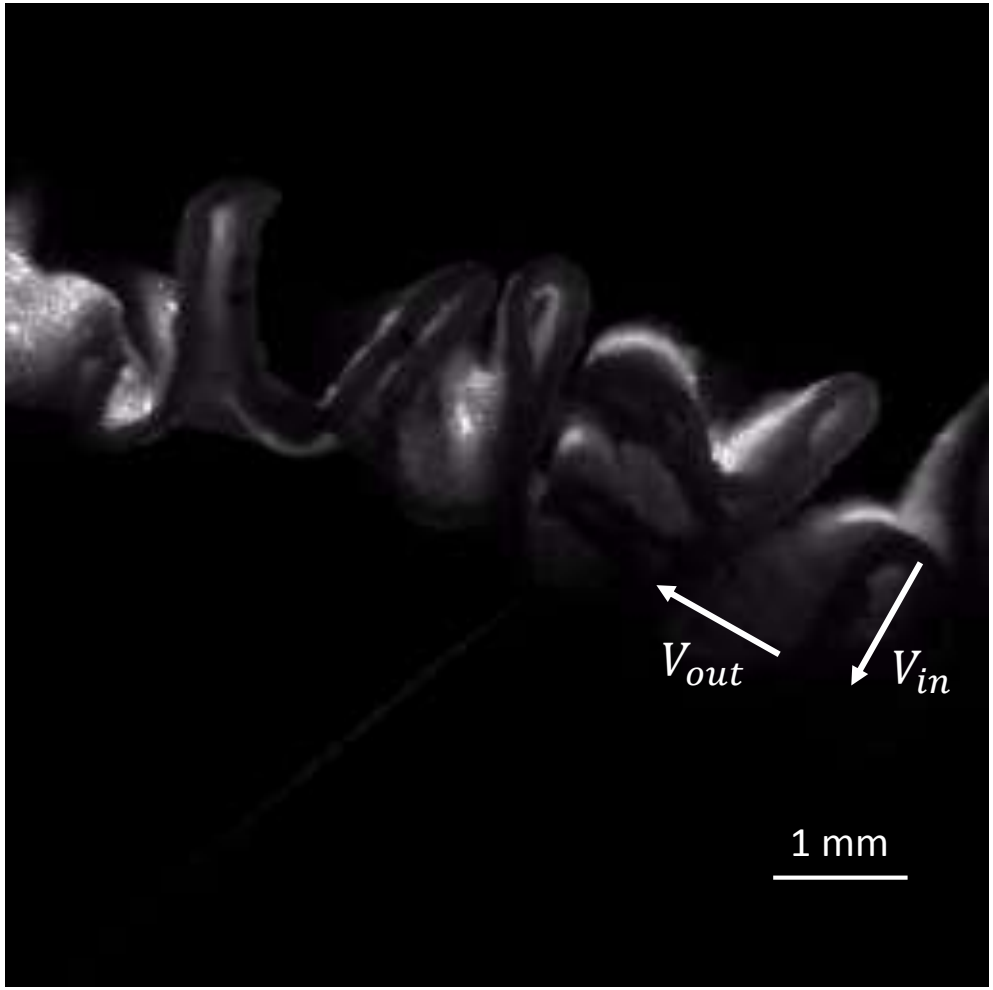
Surface speed: V_{in}=195 m/min

Creping angle $\delta = 90°$

No creping ratio: $V_{out} \approx 0$

Transition mechanism still exists, when we increase creping angle.

Creping Ratio by Hand Pulling



Surface speed: V_{in}=217 m/min

Creping angle $\delta = 90°$

Creping ratio: $\frac{V_{in}-V_{out}}{V_{in}} \approx 25\%$

Micro-fold to macro-fold transition disappeared
Indicating creping ratio is important.

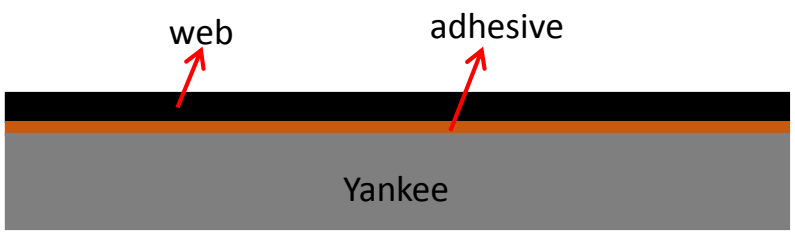
Summary of Current Experiment

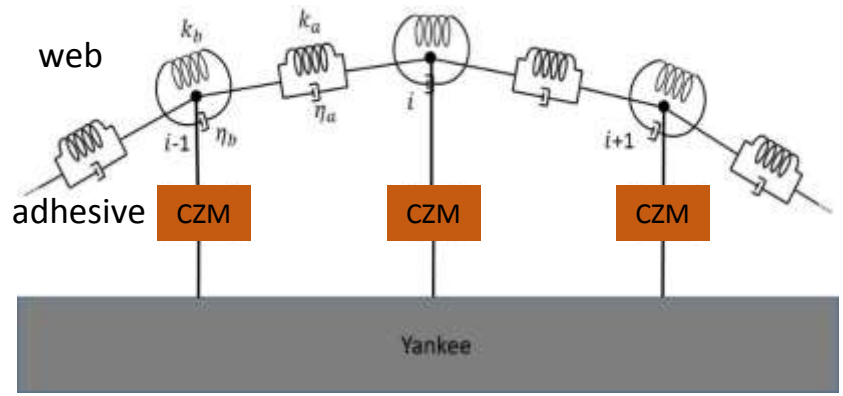
- Lathe creping experiment

Relative high speed 800 m/min; System is stable;
Creping process is clearly recorded;
Verified micro-fold to macro-fold transition mechanism.

Limitations: Creping ratio not well-controlled;
Non-uniform adhesion.

Methodology: Discrete Particle Model





Particle's mass: $M = \rho a_0 h w$.

axial elastic force : $\boldsymbol{f}_a = k_a(|\boldsymbol{r}_{i-1} - \boldsymbol{r}_i| - a_0)\boldsymbol{e}_{i,i-1} + k_a(|\boldsymbol{r}_{i+1} - \boldsymbol{r}_i| - a_0)\boldsymbol{e}_{i,i+1}$

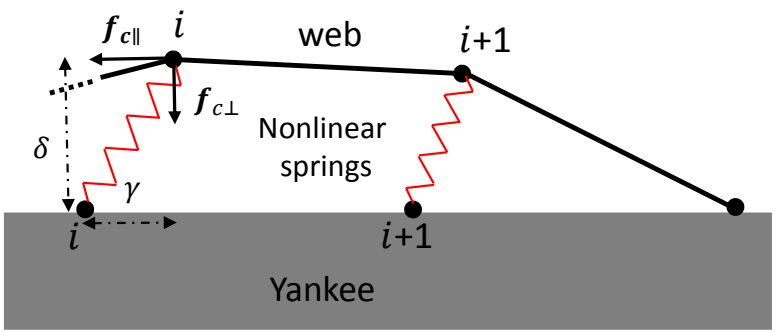
damping force: $\boldsymbol{f}_d = -\eta_a\left([\dot{\boldsymbol{r}}_i - \dot{\boldsymbol{r}}_{i-1}] \cdot \boldsymbol{e}_{i,i-1}\right)\boldsymbol{e}_{i,i-1} - \eta_a\left([\dot{\boldsymbol{r}}_i - \dot{\boldsymbol{r}}_{i+1}] \cdot \boldsymbol{e}_{i,i+1}\right)\boldsymbol{e}_{i,i+1}$

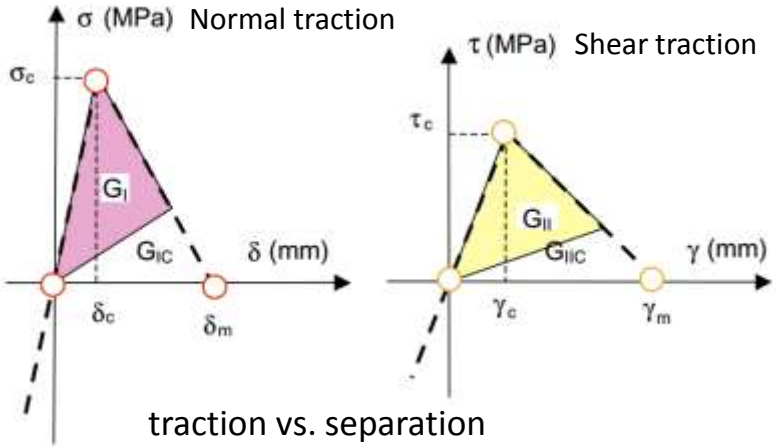
bending force and viscous bending force: $\boldsymbol{f}_b$, $\boldsymbol{f}_v$

h is thickness, w is width of paper, a_0 is initial spacing, η_a is damping coefficient, k_a is axial stiffness.

Spring damper coefficients are related to paper layer properties.

Cohesive Zone Model





traction vs. separation

D. Xie, A.M. Wass, Engng. Fract. Mech., 2006

Cohesive force applied on particle: $\boldsymbol{f}_c = -\sigma a_0 w \boldsymbol{e}_\perp - \tau a_0 w \boldsymbol{e}_\parallel$

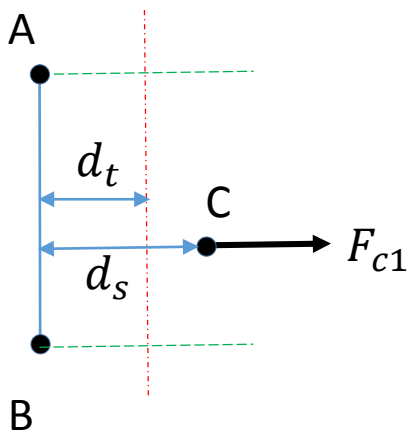
$\boldsymbol{e}_\perp$ and $\boldsymbol{e}_\parallel$: normal and tangential unit vectors

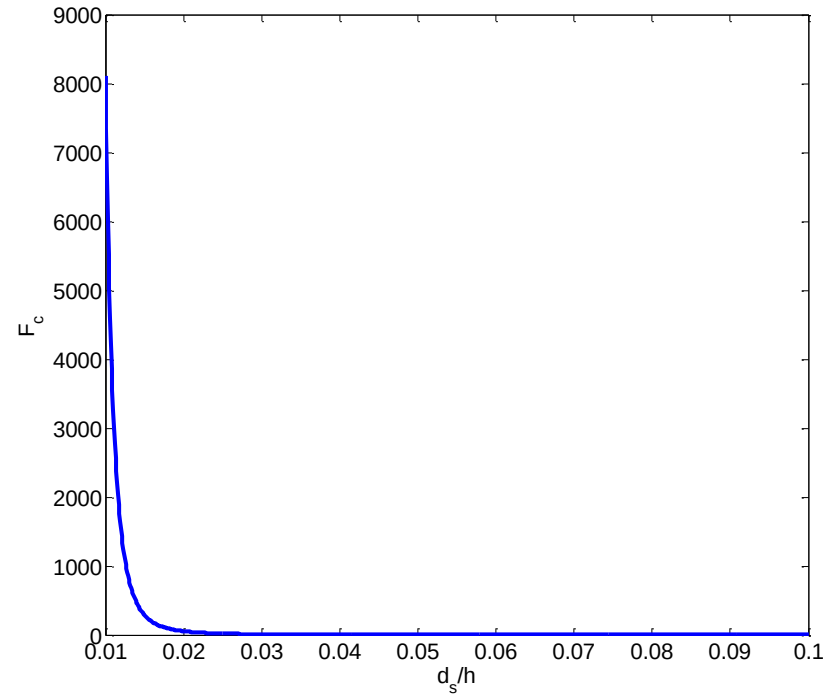
σ_c: normal strength; τ_c: shear strength;
G_{IC}: mode I fracture toughness; G_{IIC}: mode II fracture toughness. (adhesion)

CZM parameters are related to adhesive layer properties.

Newton's equations : $\boldsymbol{f}_{tot} = \boldsymbol{f}_a + \boldsymbol{f}_d + \boldsymbol{f}_b + \boldsymbol{f}_v + \boldsymbol{f}_c = M\boldsymbol{a}$

Self-Contact Model





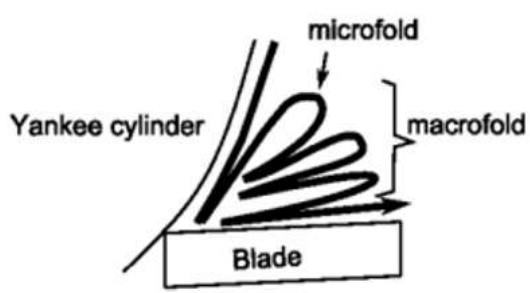
d_t: threshold distance. $d_t = h/100$.

When d_s>= d_t, no contact force $F_{c1} = 0$.

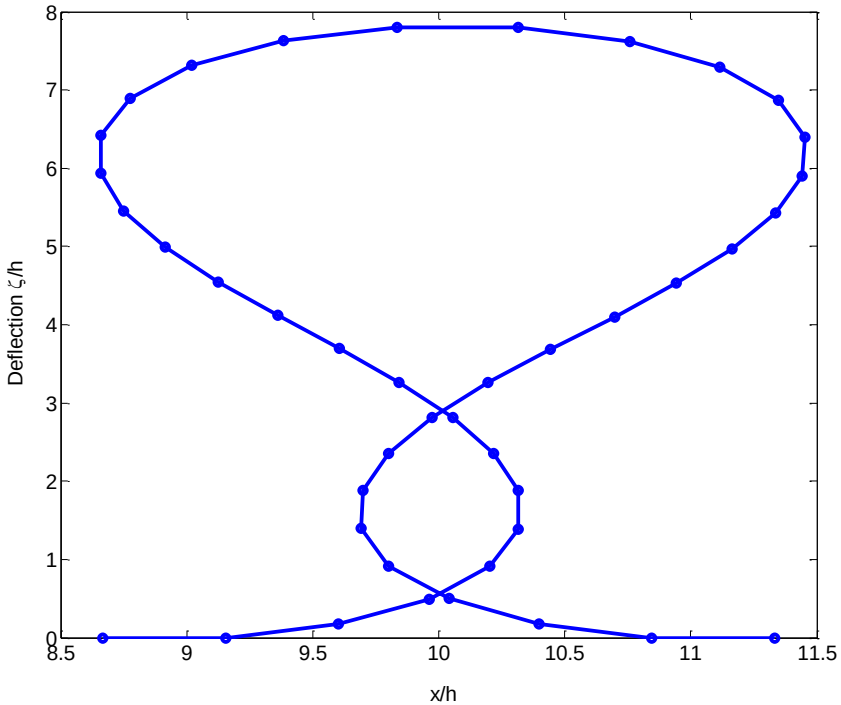
When $d_s < d_t$,

New function: $F_{c1} = \alpha[e^{\left(\frac{\beta}{d_s}\right)} - 1]$. α, β are constants

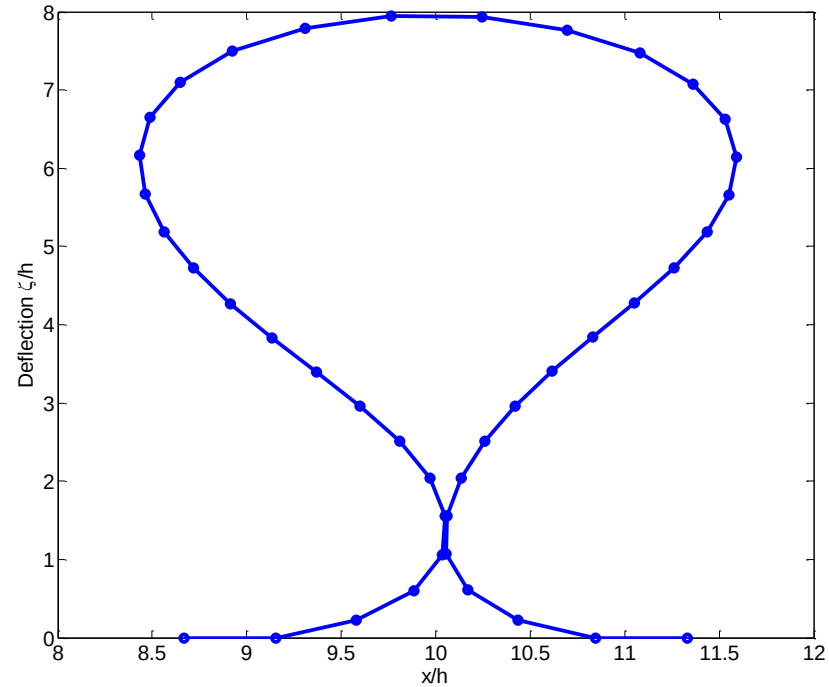
Motivation:



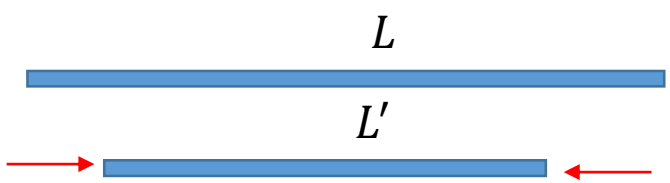
Self-Contact Model



No self-contact

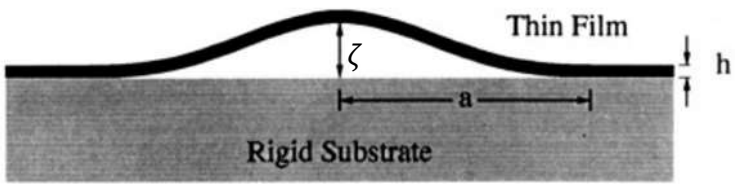


Include self-contact



$$\Delta L = L - L' = 0.87L$$

Validation of Model

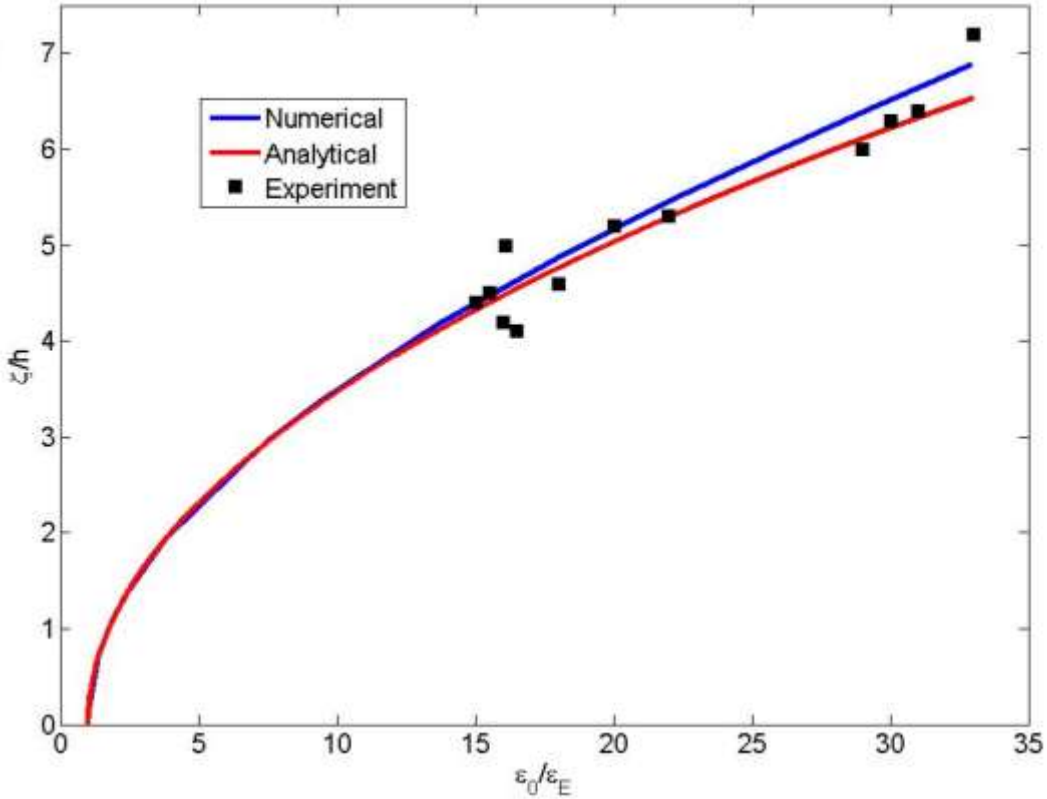


Buckle-delamination

maximum deflection:

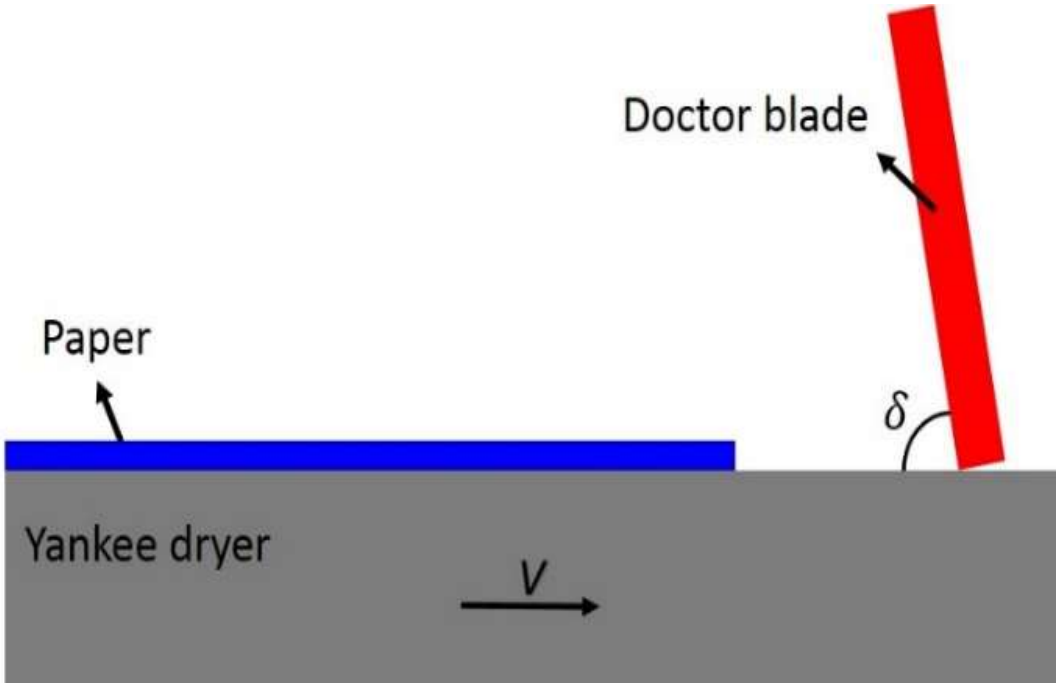
$$\zeta = h\sqrt{\frac{4}{3}\left(\frac{\varepsilon_0}{\varepsilon_*} - 1\right)}$$

$$\varepsilon_* = \pi^2 h^2 / 12a^2$$



The experimental data comes from: "Atomic force microscopy of in situ deformed nickel Thin films", C. Coupeau et. al., 1999, Thin Solid Films.

Creping Simulation

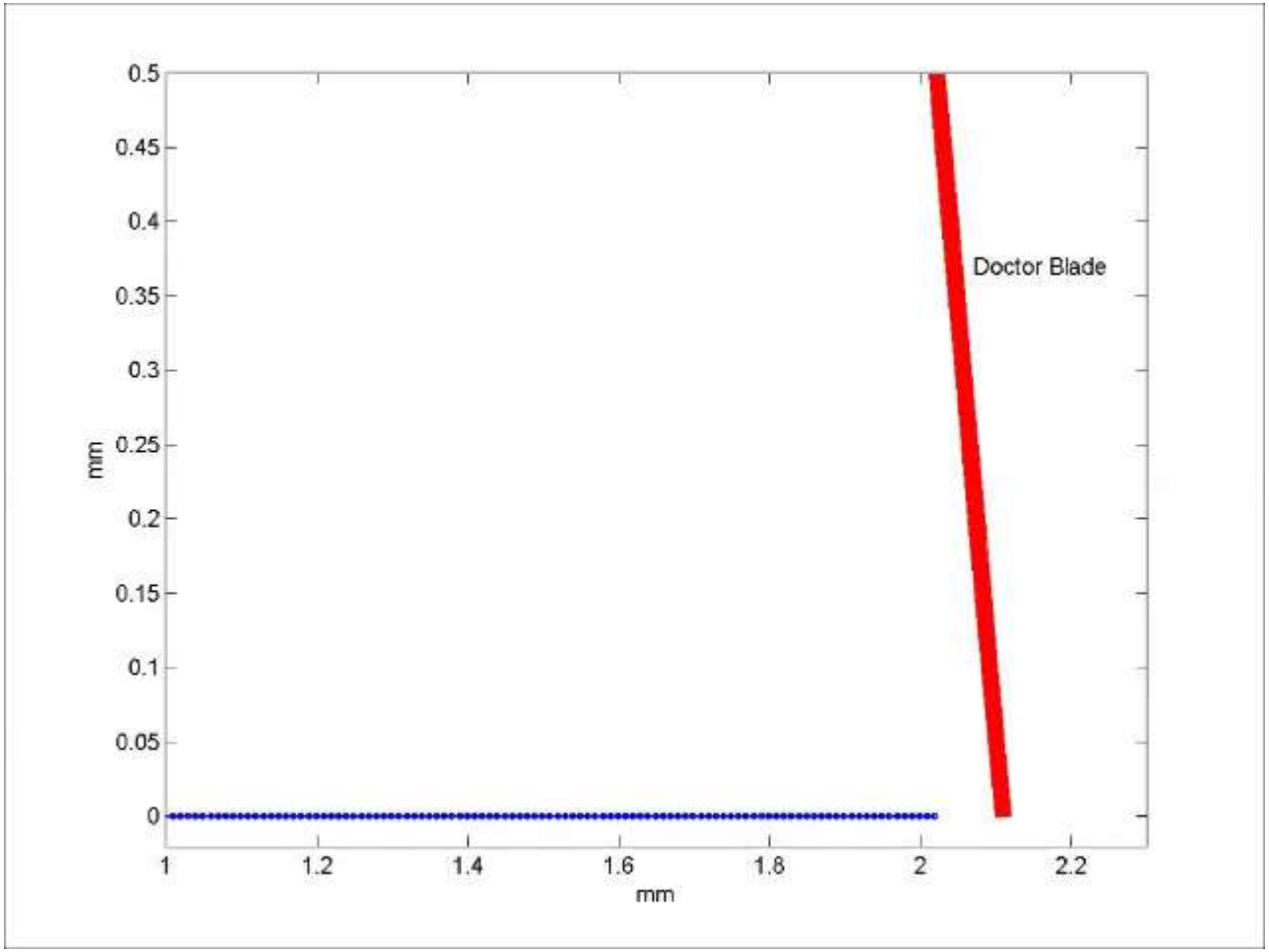


Schematic of creping model

V is Yankee surface speed, δ is creping angle.

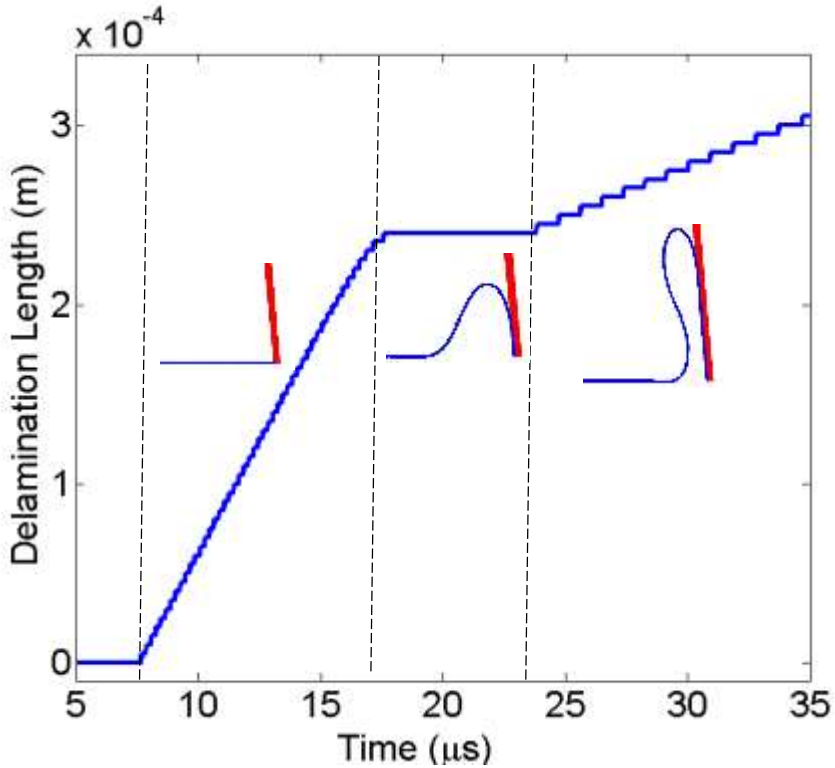
Radius of Yankee ($\sim 1.5m$) $\gg$ Paper thickness ($\sim 0.1mm$)
Surface can be considered as flat

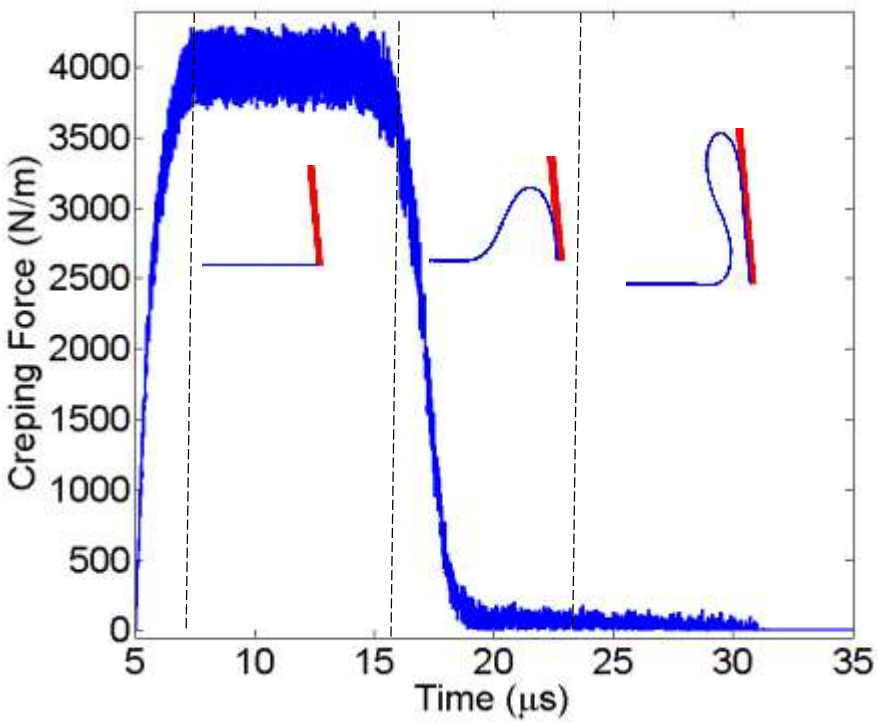
Single Fold Simulation



$V = 1200m/min, \delta = 80°.$

Single Fold Simulation

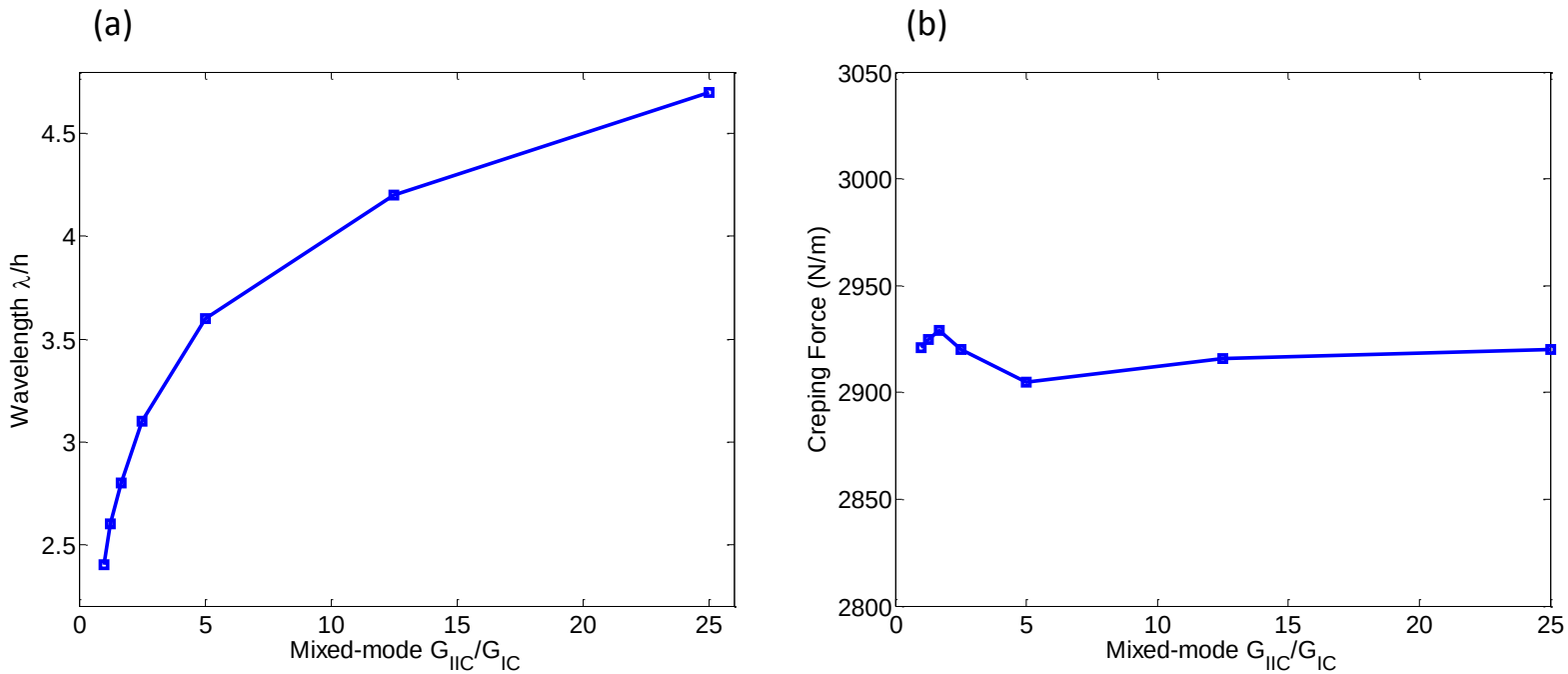




Three stages:

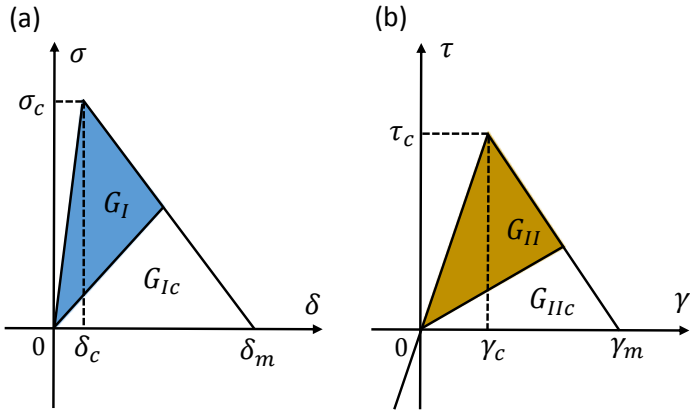
- ❑ delamination propagation (Mode I)
- ❑ buckle initiation;
- ❑ buckling-driven delamination. (Mixed-mode)

Mixed-mode fracture toughness

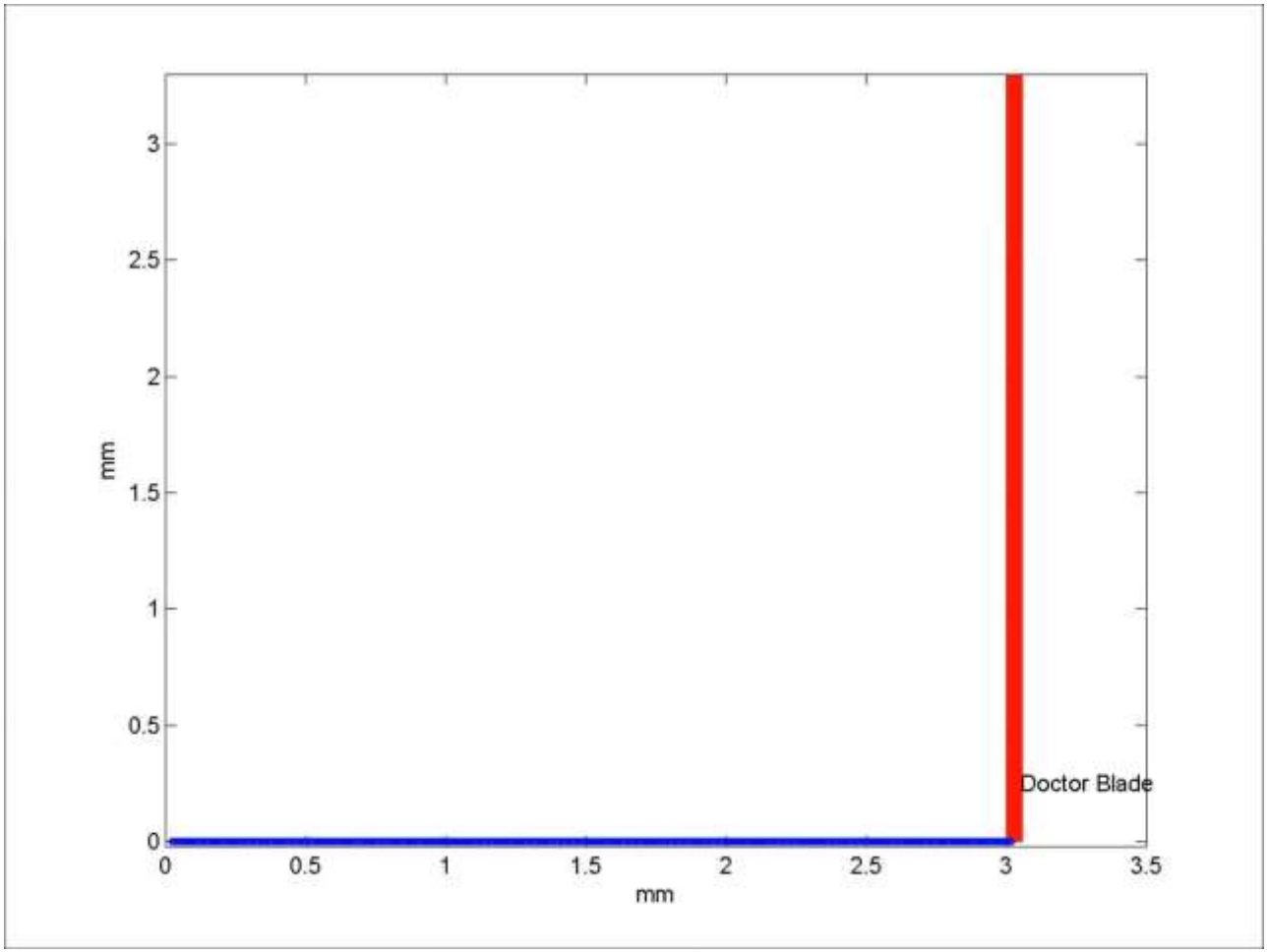


G_{IC} is varied to change the mixed-mode.

Creping wavelength is dependent on both G_{IC} and G_{IIC};
Creping force is determined by G_{IIC}.

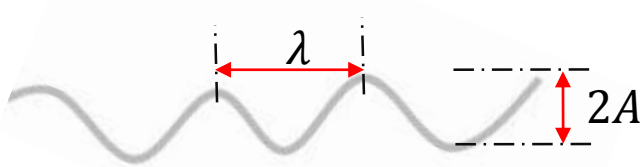


Periodic Folding Simulation



Creping angle: 85°;
V_in=20m/s;
V_out=0.7*V_in

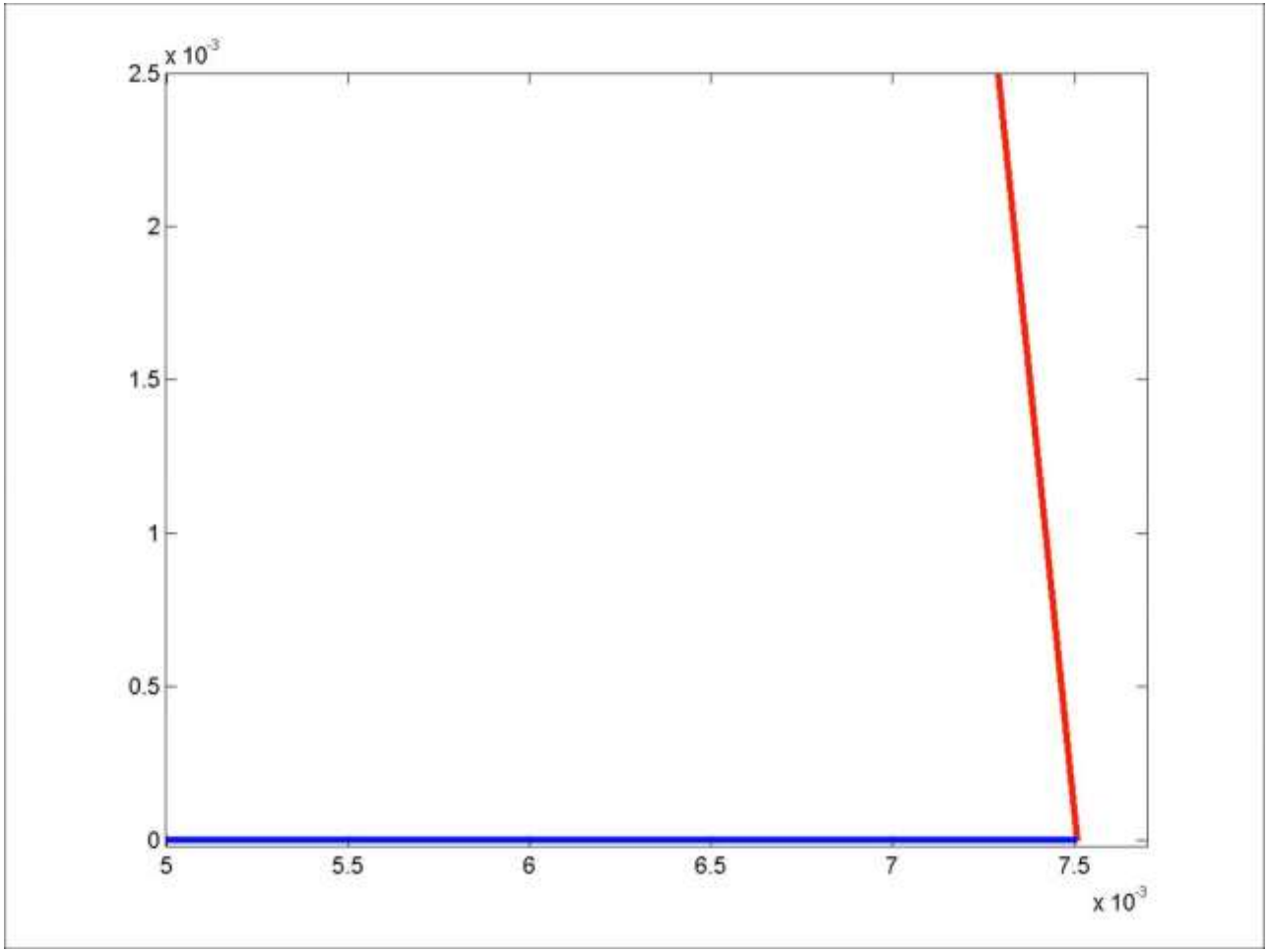
FFT analysis:
$\lambda = 0.35mm$
$A = 0.052mm$



Schematic of tissue structure

Wavelength: λ ~ 0.3mm
Amplitude: A ~ 0.1mm

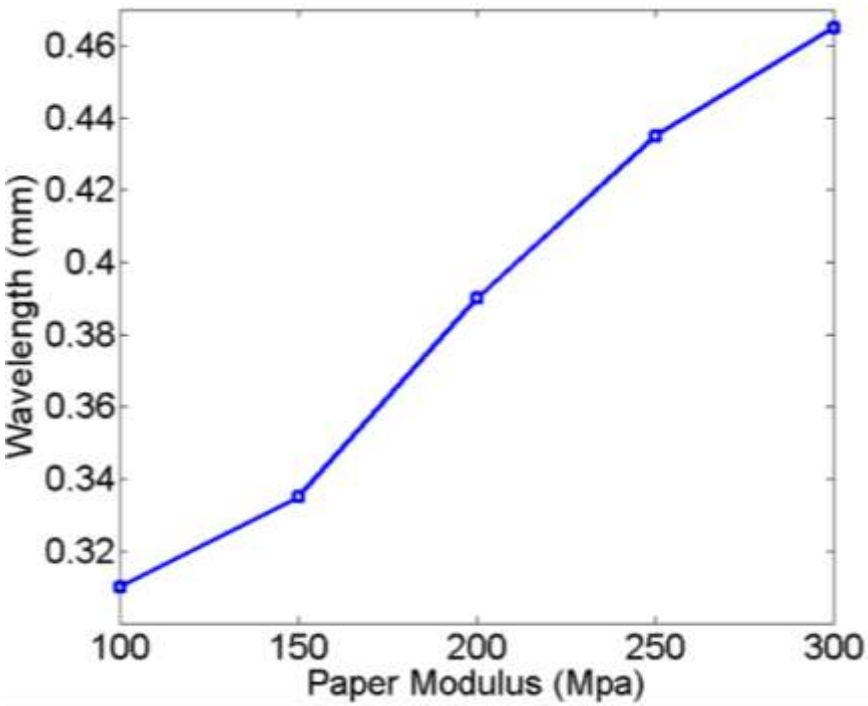
Self-Contact Simulation

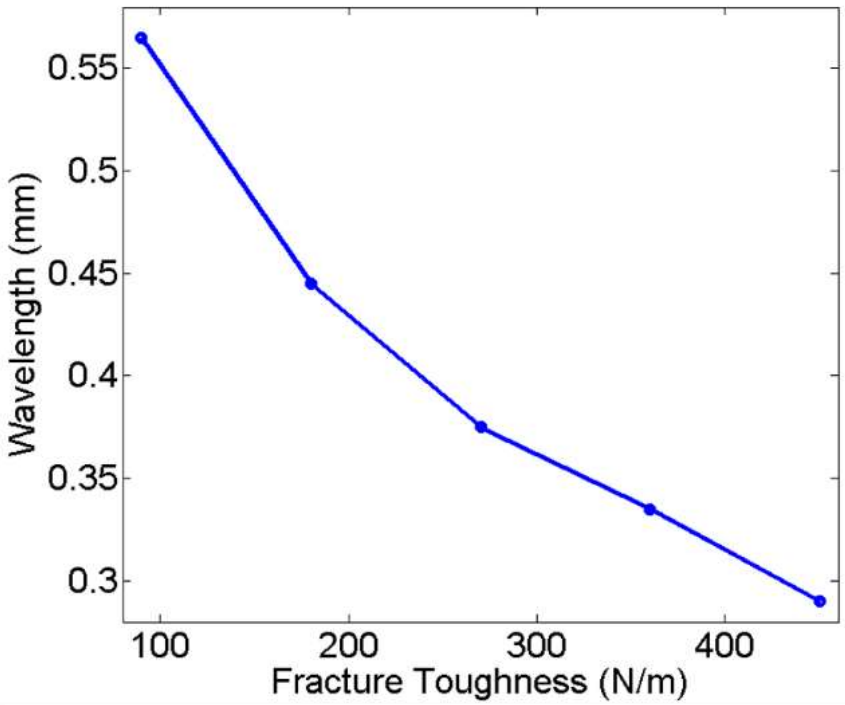


Creping angle: 85°; V_in=20m/s; V_out=0

A few micro-folds evolve into a macro-fold.

Parametric Study





Larger modulus results in larger creping wavelength;
Larger adhesion results in smaller creping wavelength.

Limitation of Current Model

- Currently one-dimensional model.
- Plastic deformation of fiber is not included.

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Conclusion

- Lathe creping experiment

  Relative high speed 800 m/min; System is stable;
  Clear view of creping process;
  Micro-fold to macro-fold transition mechanism is verified and it is found to be affected by creping ratio.

Conclusion

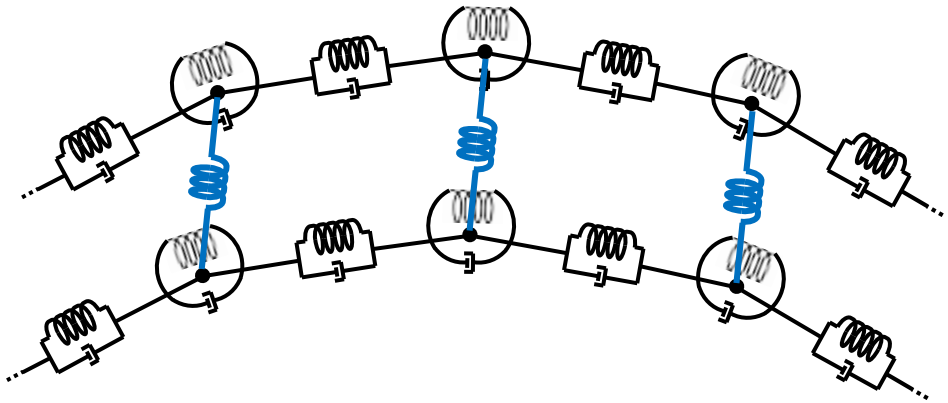
- Discrete particle model has been developed.
  One-dimensional dynamic, creping-ratio included.
  Process parameters included.

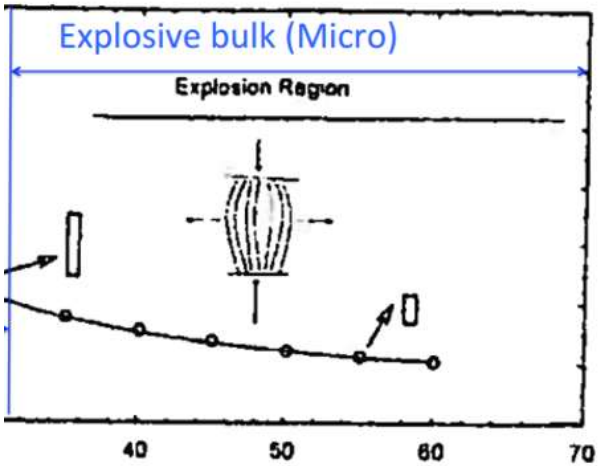
- Simulation of creping process.
  Single fold formation shows three typical stages.
  The periodic creping process is successfully simulated and simulation results are close to experimental values.

- Parametric studies.
  Effects of modulus, adhesion, and creping angle.
  Need to be compared with experimental data.

Future Work

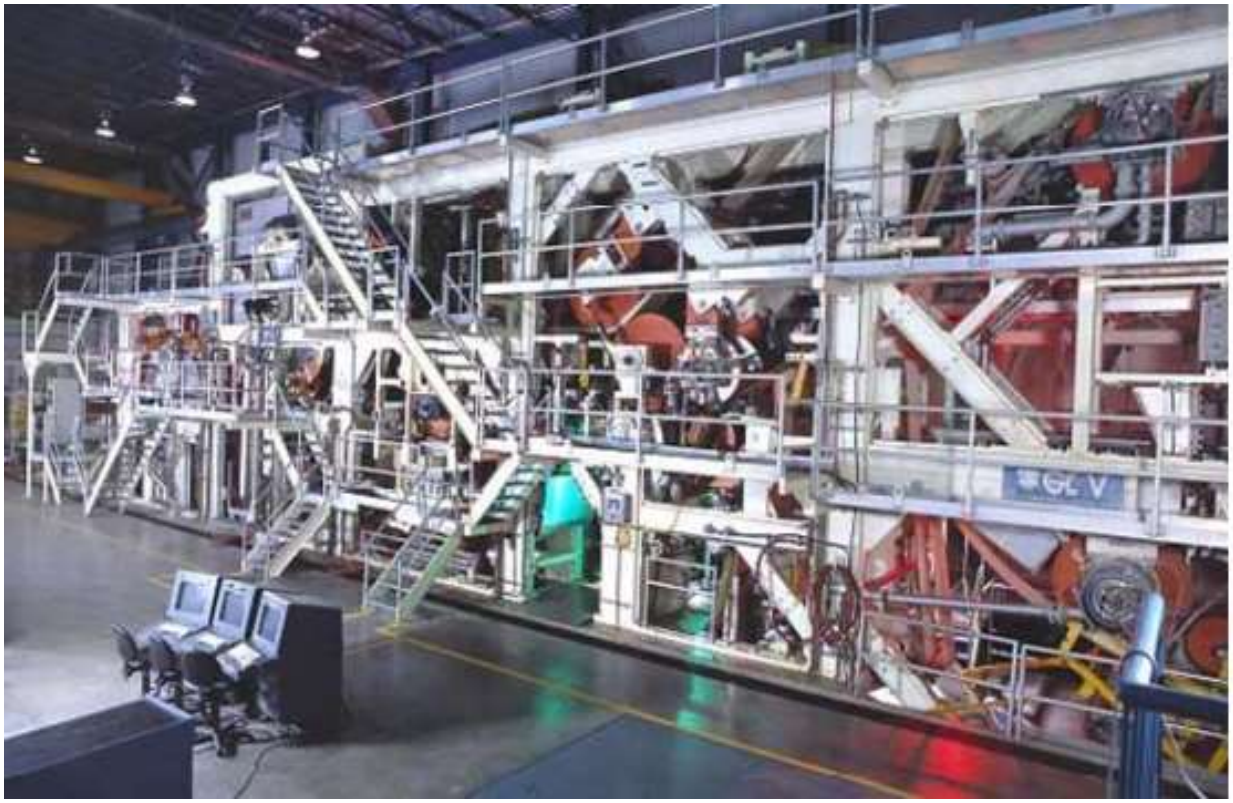
- Extend current model to microscopic level to account for fiber properties and explosive bulk.





Future Work

- Compare simulations with experimental data from commercial machine.



Pilot Tissue Machine, FPInnovations, Montreal.

Maximum Yankee surface speed: 1500 m/min;
Able to process parameters and furnish.

Thank you!