Determination of Paper Cross-Section Stress-Strain Properties with Zero/Short-Span Testing

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Introduction

- Stress-strain behaviour of fibres- large factor in sheet mechanical properties
- Measurement?
  - Single fibre tests?
    - Many tests
    - Representative of fibres in sheet?
  - Zero span test
    - Tensile test at zero span- no gap between jaws
    - Measure of mechanical properties of fibres in the sheet
    - Normally only measure breaking load

Our work

- Goal: measure stress-strain curve of fibres in sheet = the sheet cross-section stress-strain curve.
- Method: Pulmac zero/short span tester with additional instrumentation.
  - Kaman Corp. capacative transducer- measure jaw separation
  - Continuous measurement of load during test.
  - Thus can measure load-displacement during test
  - Need method to convert displacement to strain.

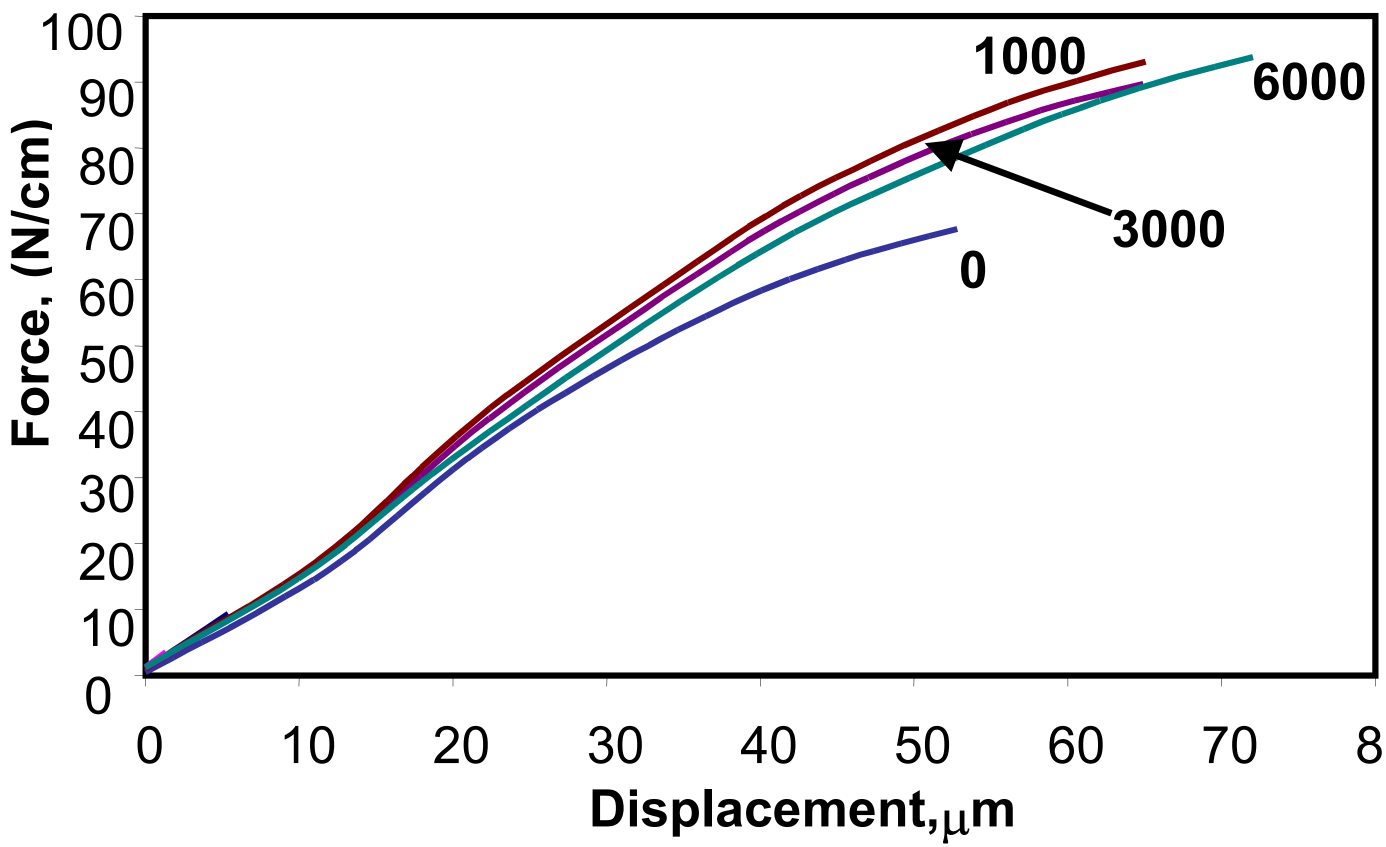
Experimental- pulps

- A: Never dried unbleached kraft (SCA's Östrand mill)
- B: Never dried bleached kraft (SCA's Östrand mill)
- C: Once dried bleached kraft
  - Free dried from pulp B:, reslushed and formed into handsheets
- ~~D: TMP, 120ml CSF, (SCA's Ortviken mill)~~
- ~~E: TMP, 54ml CSF, (SCA's Ortviken mill)~~

Measurements

- Sheets formed by teflon drying with heated drum
  - Low level of restraint
- PFI refining: 1000, 3000 and 6000 revs Zero/short span measurements
  - 0, 50, 101, 159 and 300 micron spans
  - Tests conducted dry
- Each curve shown here is average of 24 tests

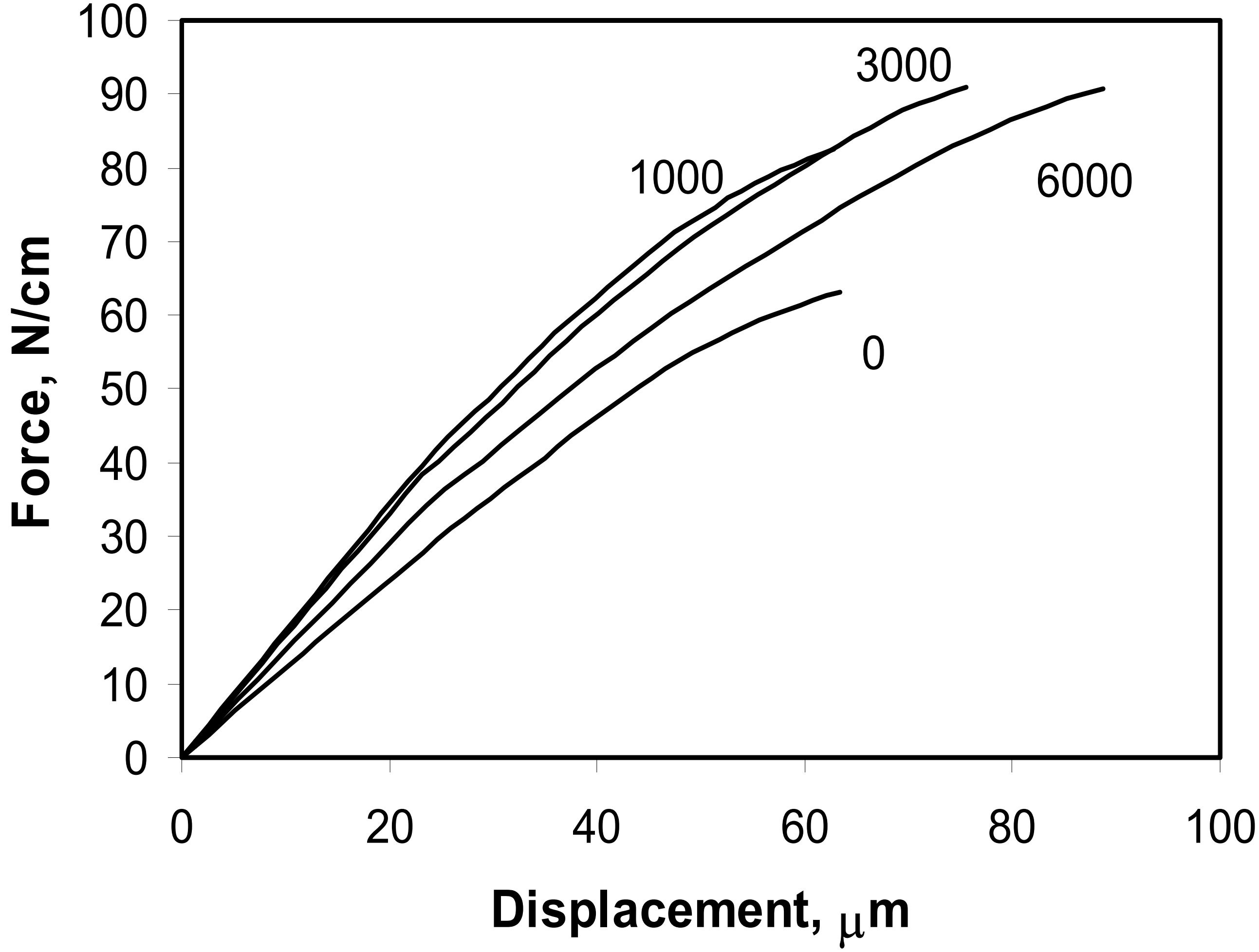
Zero Span 'Raw' Force-displacement curves for a bleached kraft pulp (B) for different refining levels (PFI revolutions)



Problem: Where is test start point?

- Load take up effects at start of test
  - Dependent on level of drying restraint
- Solution used:
  - Determine point of maximum slope of curve
  - Extrapolate gradient to determine displacement at 0 N force
  - Subtract extrapolated displacement from measured

Effect of PFI refining (revs) on bleached kraft pulp (B). Curves corrected to remove load take up effects

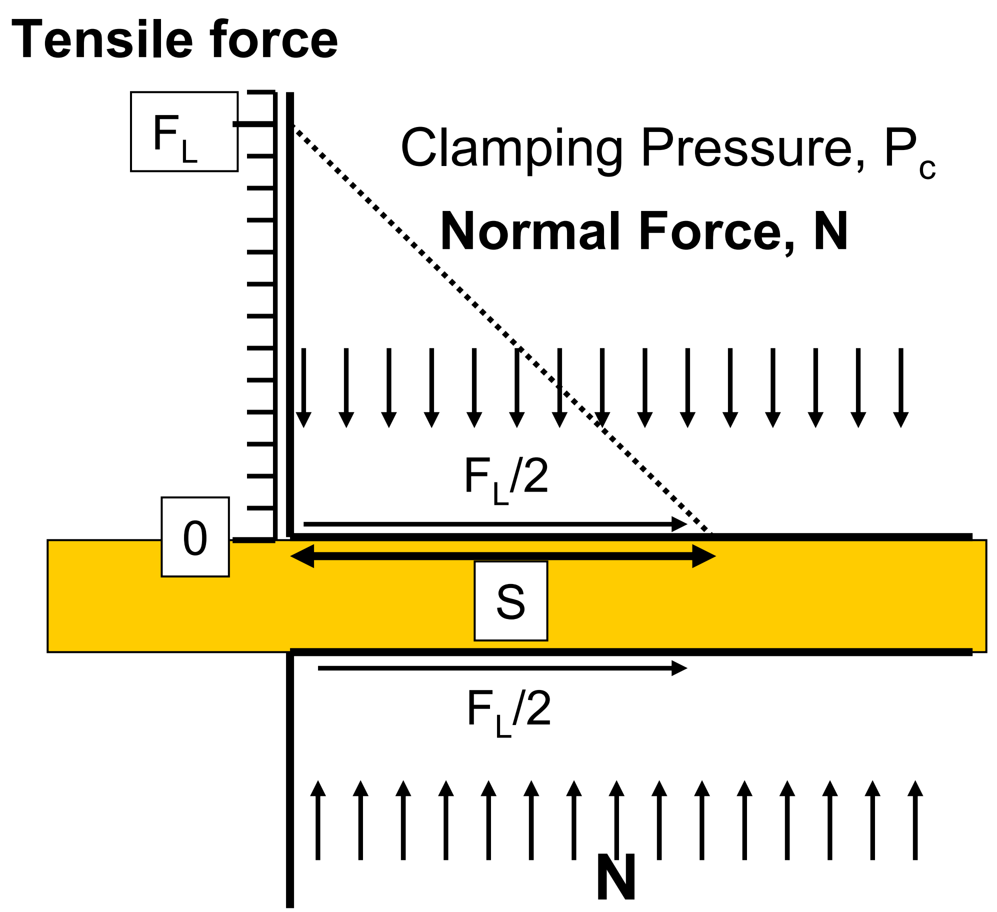


Residual span

- Fibres held in place by friction under the jaw clamping pressure.
- Requires a finite distance from jaw edge to work, and also depends on force at any point in the test.
- Residual span not known
- **Need method to convert measured displacement to strain.**

Zero span test- theory

- Load on sample, F_L
- Applied by friction, at two jaws over distance, S
- Displacement during test comes from slippage under both jaws
- Span is $$S = \frac{F_L}{2\mu P_c}$$
- μ: coefficient of friction



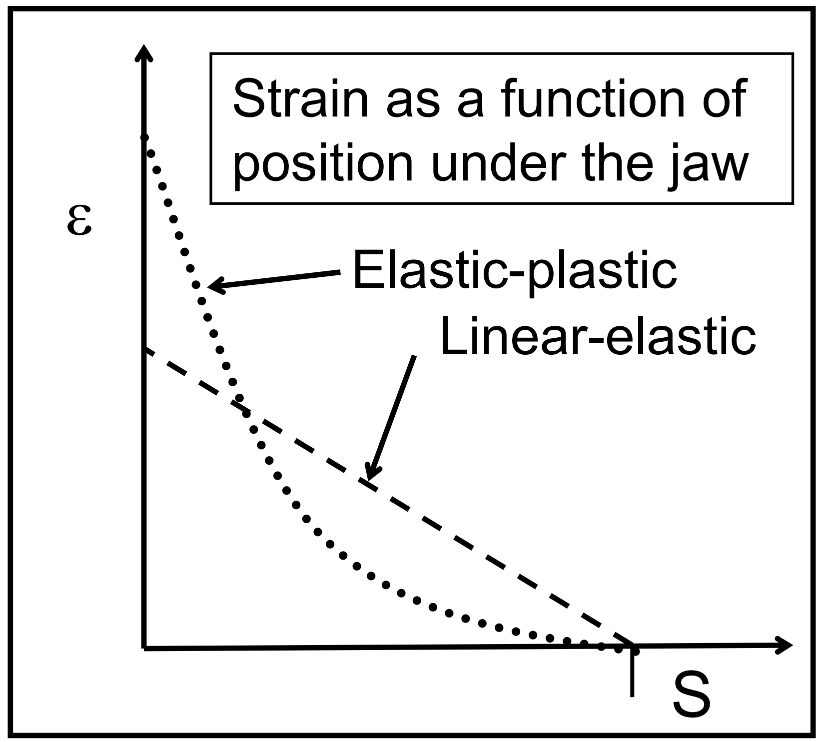
- **Linear-elastic behaviour**
  - Average strain is equivalent to load, F_L, applied over span, S
  - S is then the residual span

$$F_L = \left[\frac{\Delta G_j 2\mu P_c}{E_p}\right]^{1/2}$$

ΔG_j : Jaw displacement

E_p : Paper elastic modulus

- **Non-linear**
  - Average strain depends on stress-strain curve
  - Concept of a residual span is then meaningless



Non-linear behaviour

- Consider general case
  - Paper: stress-strain characterised by $\varepsilon = K(F)$
- Displacement is then given by (*x* is distance from jaw edge)

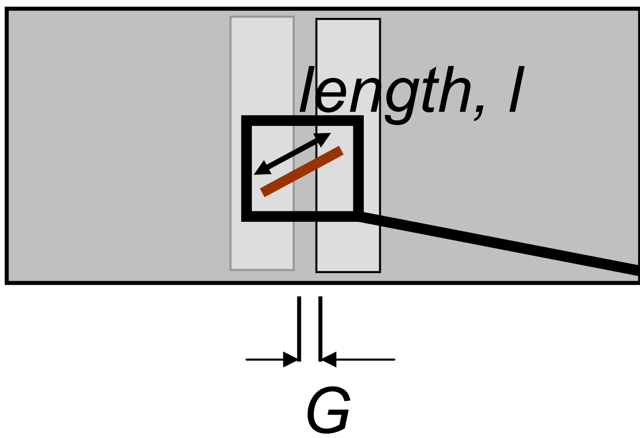
$$\Delta G_j = 2 \int_0^{F_L / 2uP_c} K(F(x))dx$$

- Problem: only determine stress-strain properties by knowing them in first place!

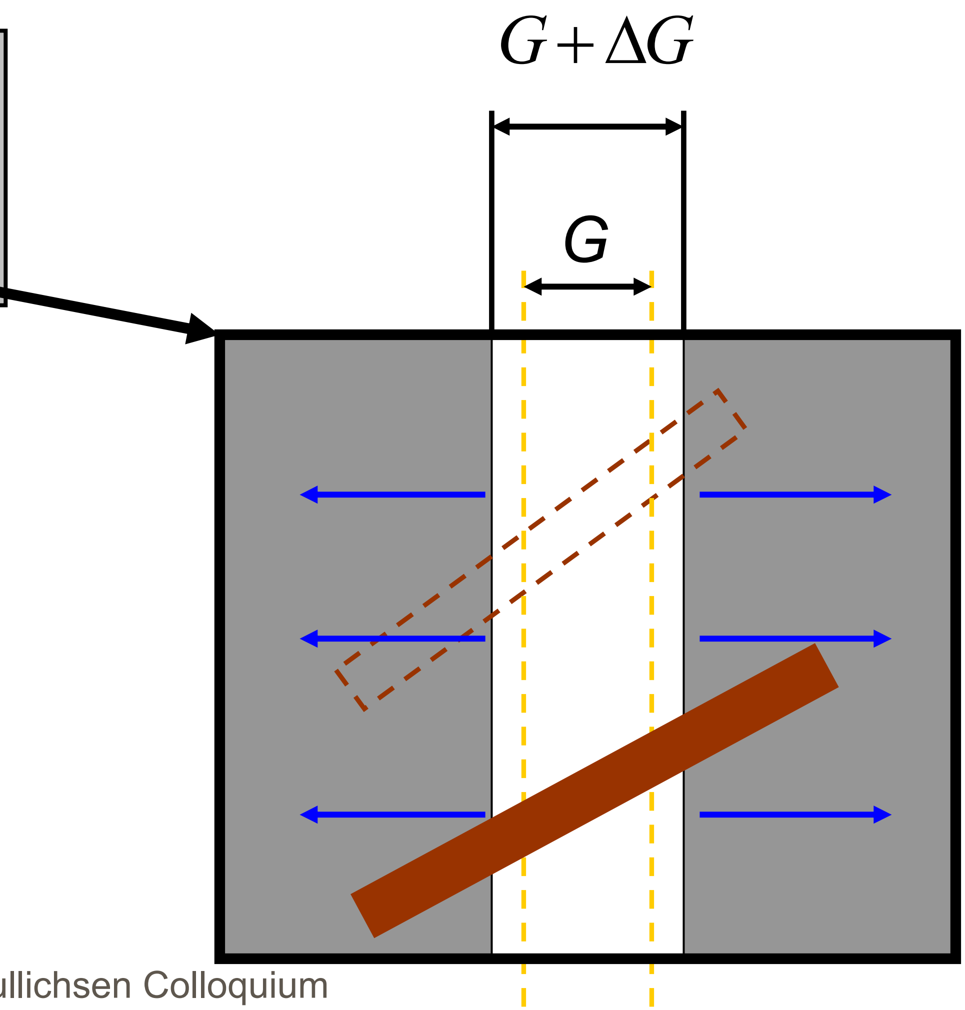
New method

- For same force, subtract zero-span displacement from short-span displacement to give displacement due to free span. Convert to strain.
- **How is this strain related to span at span of zero (cross-section strain)?**
  - Use short span theory

Short span test- theory



Overall strain: $\varepsilon = \dfrac{\Delta G}{G}$



Short span theory

$$F_L = E_p\left[1-(1-c)\frac{32}{9\pi}\frac{G}{\overline{\overline{l}}\big|_0}\right]\frac{\Delta G}{G}$$

F_L force (measured)

E_p paper cross - section elastic modulus

G test span

$\overline{l}\big|_0$ average load - bearing element length

ΔG displacement from straining span of G

c $= 1,$ long fibres, perfectly bonded

$= 0,$ unbonded

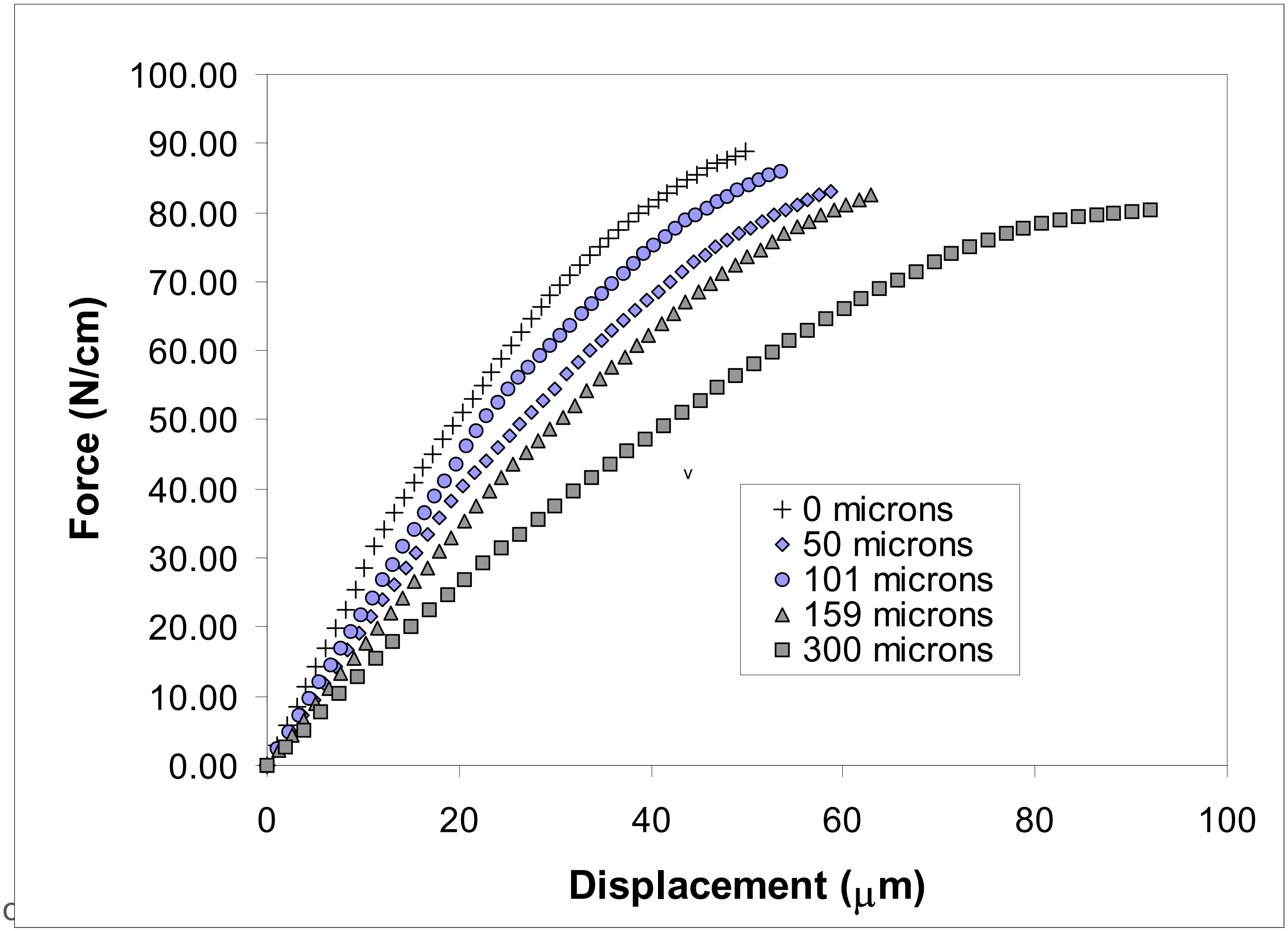
Assumptions

1) $G < 0.7\,\overline{l(0)}$

2) Random orientation

3) All fibres crossing both jawlines contribute

Load-displacement curves 0-300 micron spans, Bleached kraft (B), 1000 PFI revs refining



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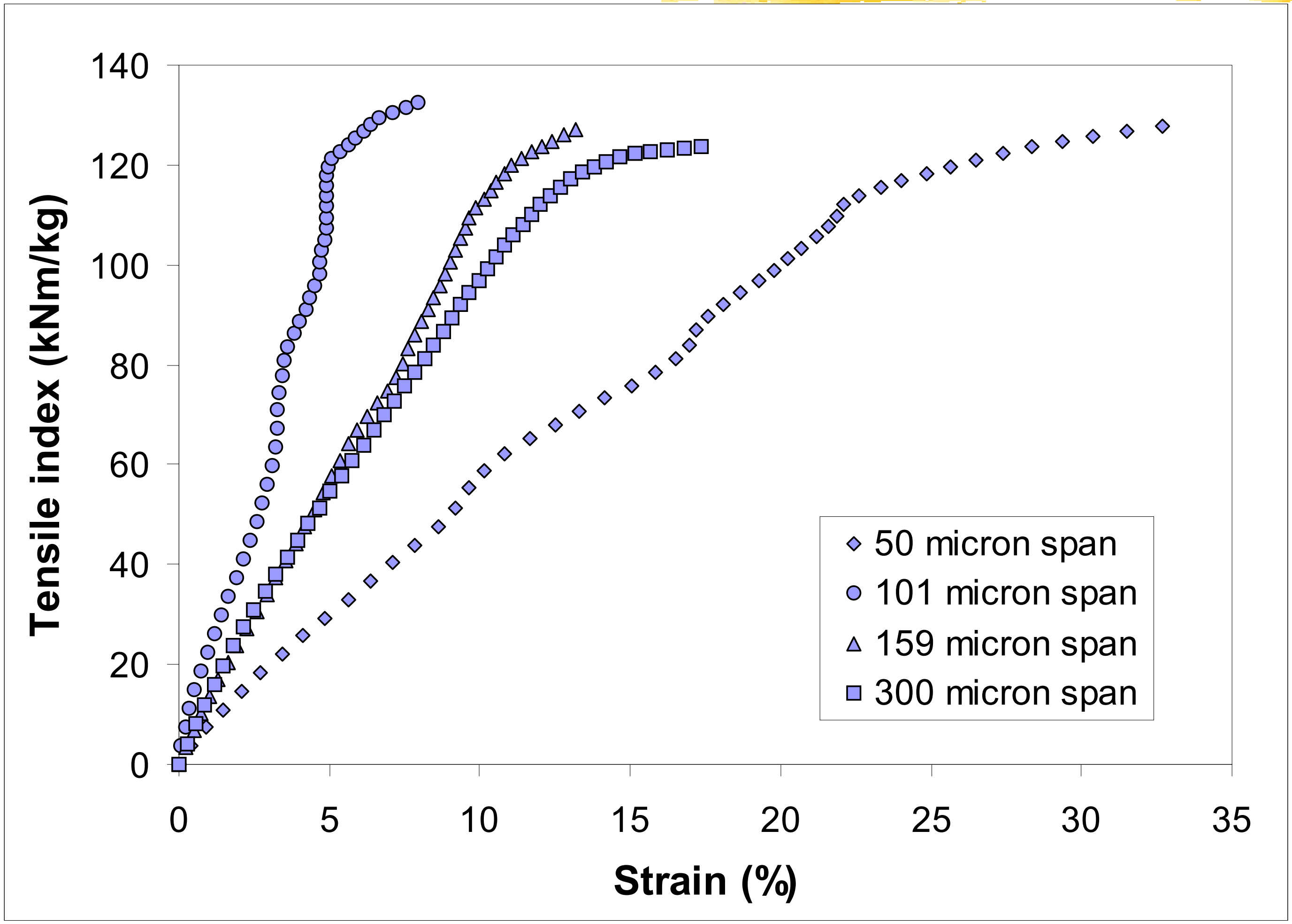
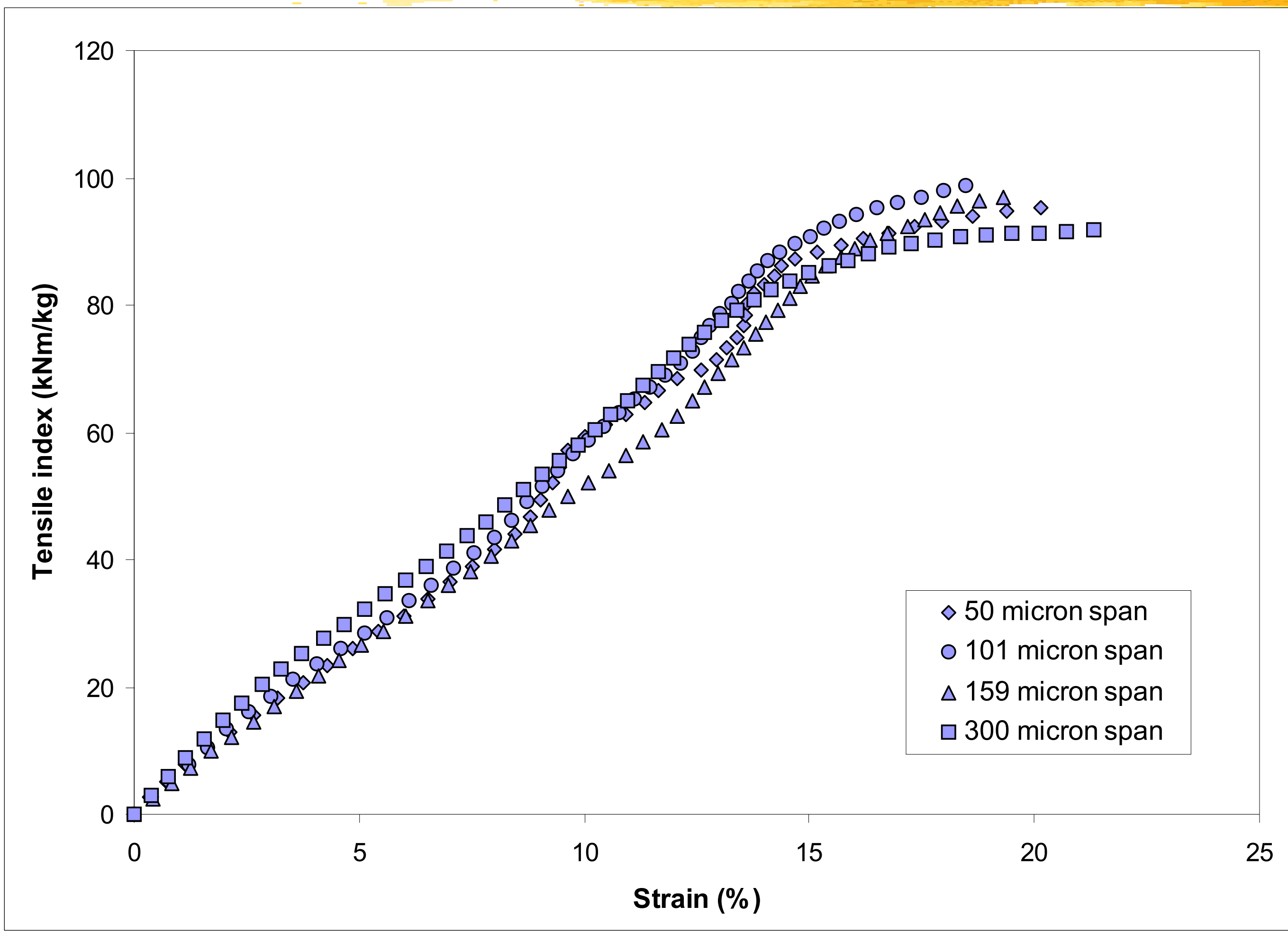
Stress-strain curves determined from subtraction, Bleached kraft (B), 1000 PFI revs beating



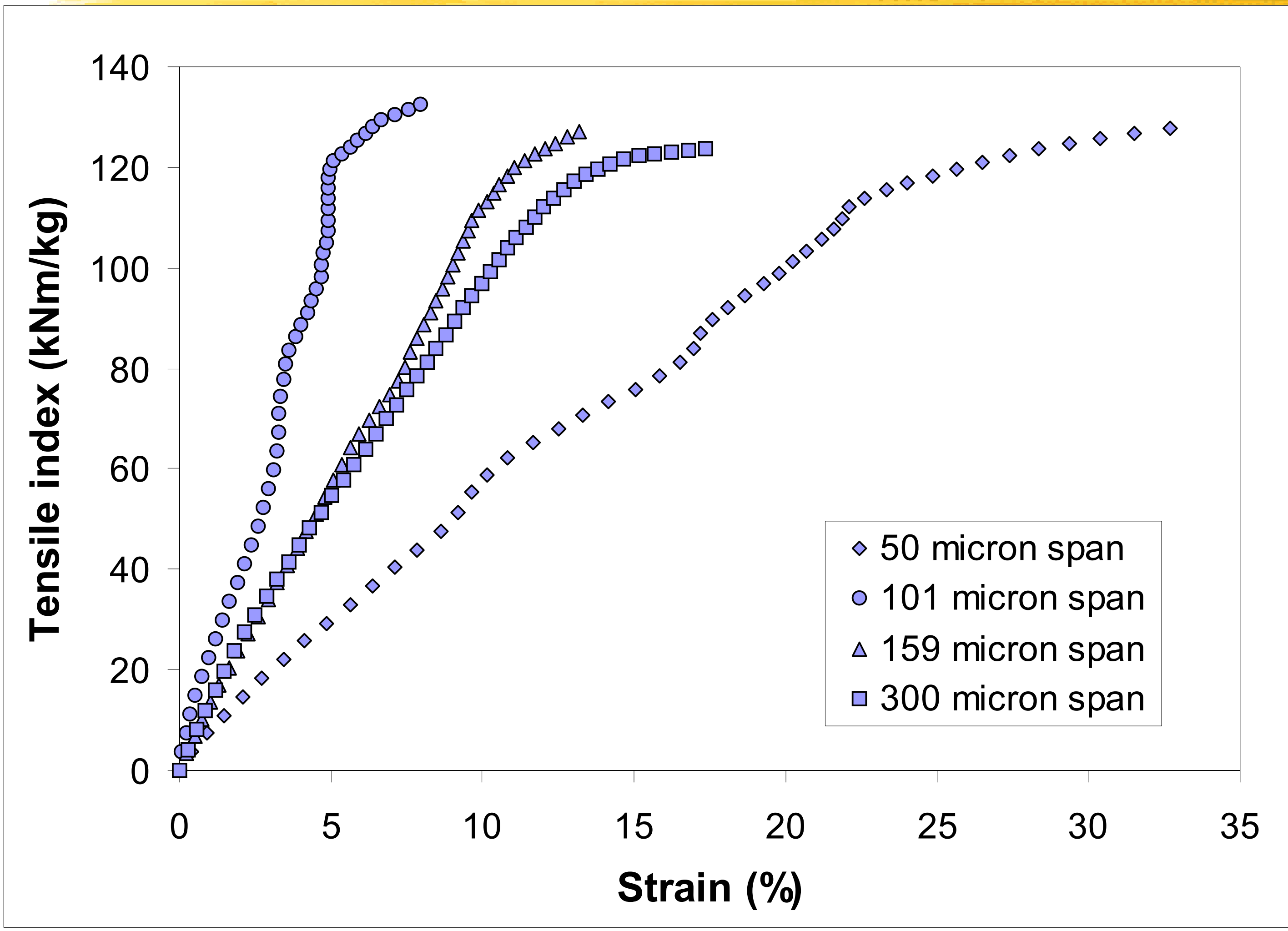
Method limitations

- Minimum span is 0.15 mm (150 microns)
  - Shorter spans- curves too close together, errors high
- Effect of span on stress-strain distribution in z-direction?
- Maximise accuracy of subtraction by
  - Long, straight fibres
  - Well beaten: high value of *c*- reduces effect of fibres not bridging between jaws

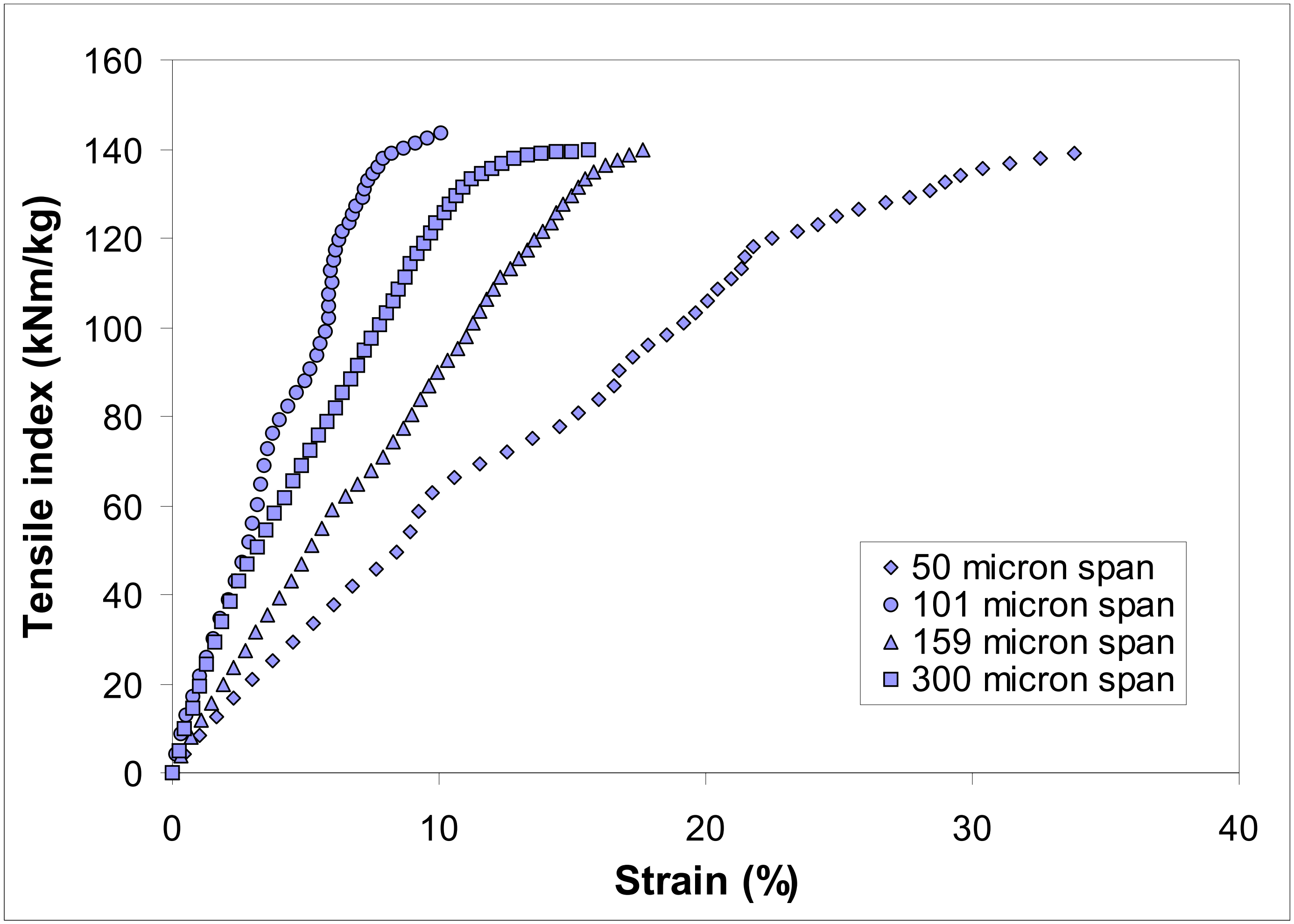
Stress-strain curves determined from subtraction, Bleached kraft (B), Unrefined



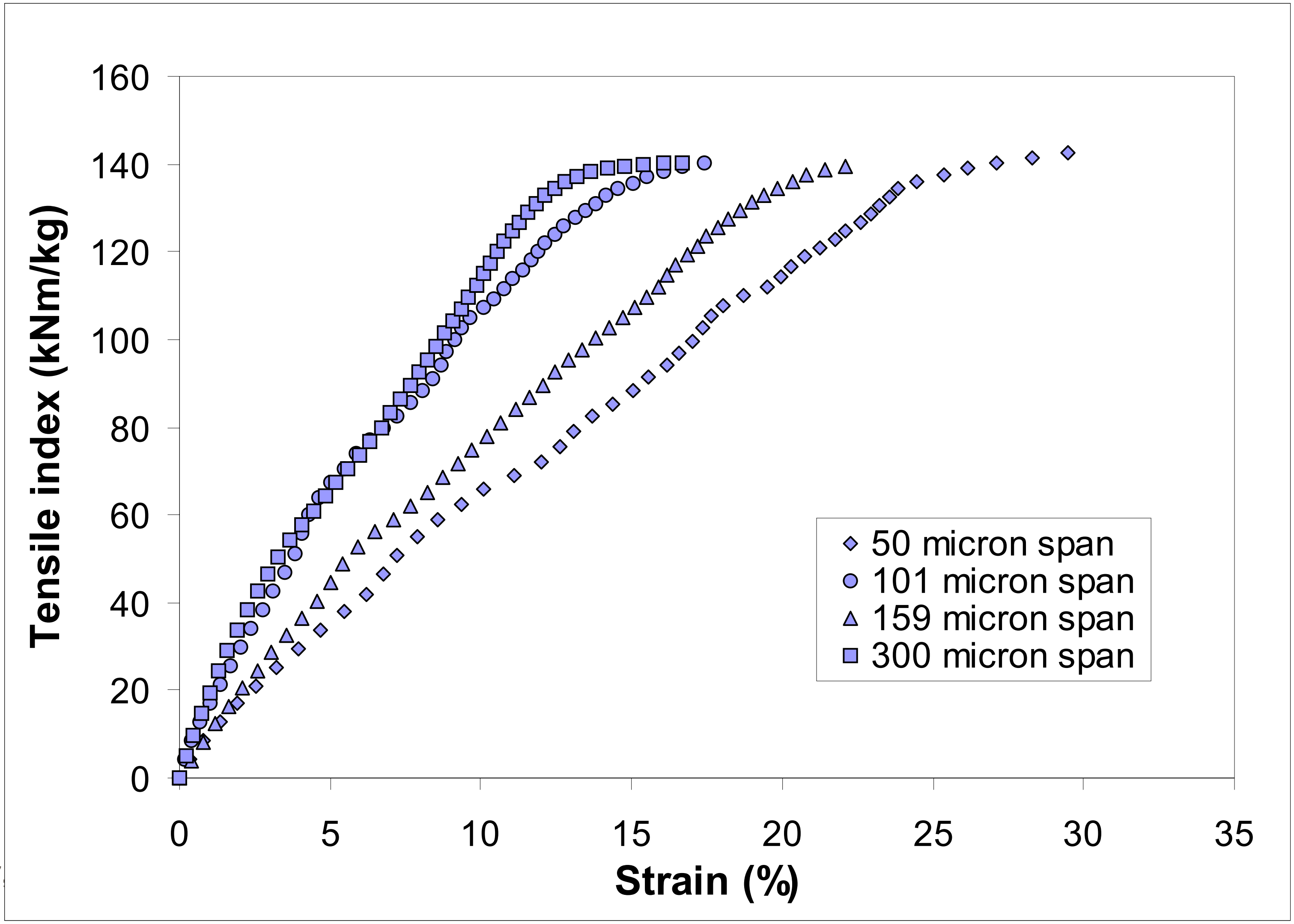
Stress-strain curves determined from subtraction, Bleached kraft (B), 1000 PFI revs beating



Stress-strain curves determined from subtraction, Bleached kraft (B), 3000 PFI revs beating

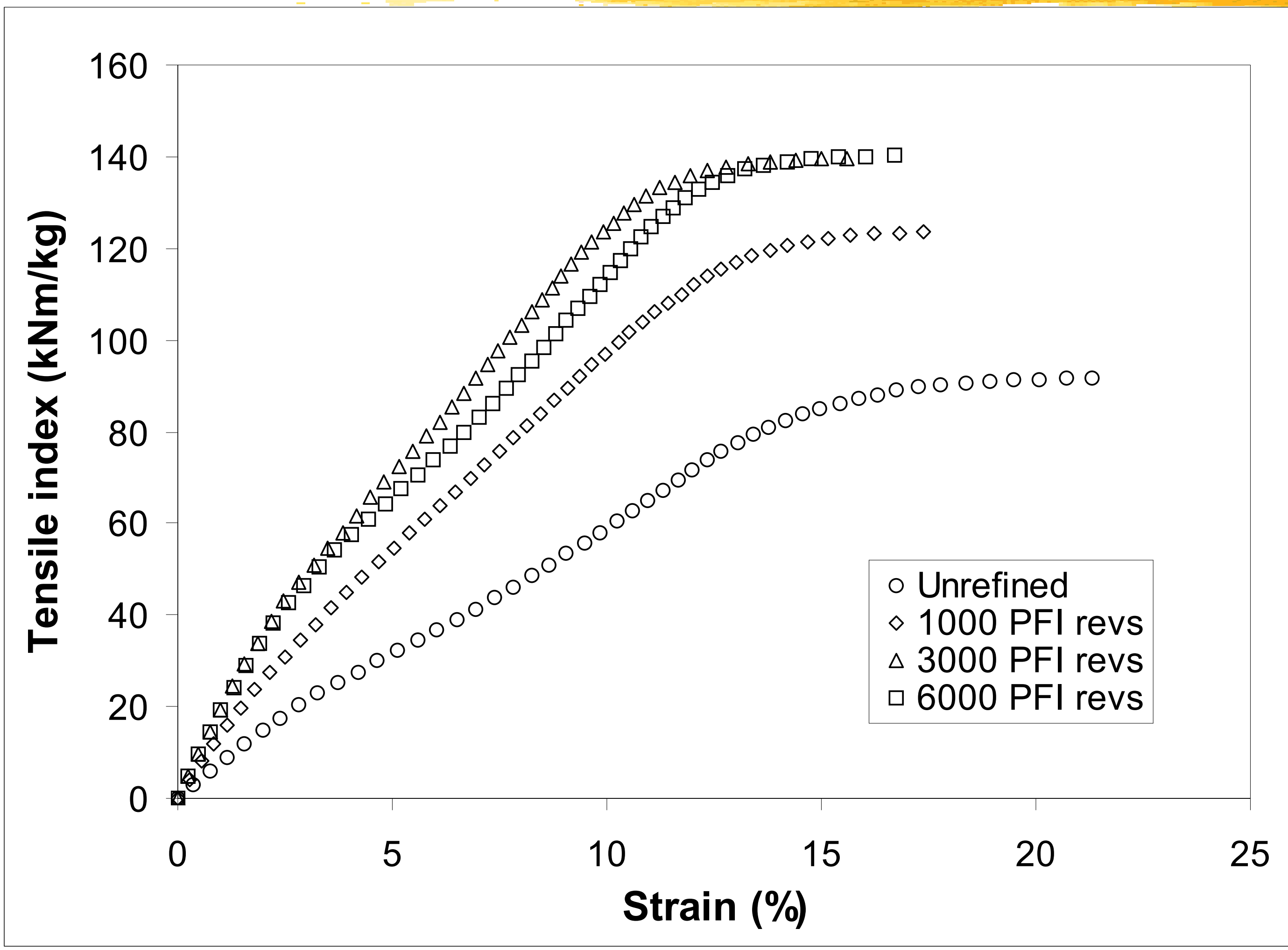


Stress-strain curves determined from subtraction, Bleached kraft (B), 6000 PFI revs beating

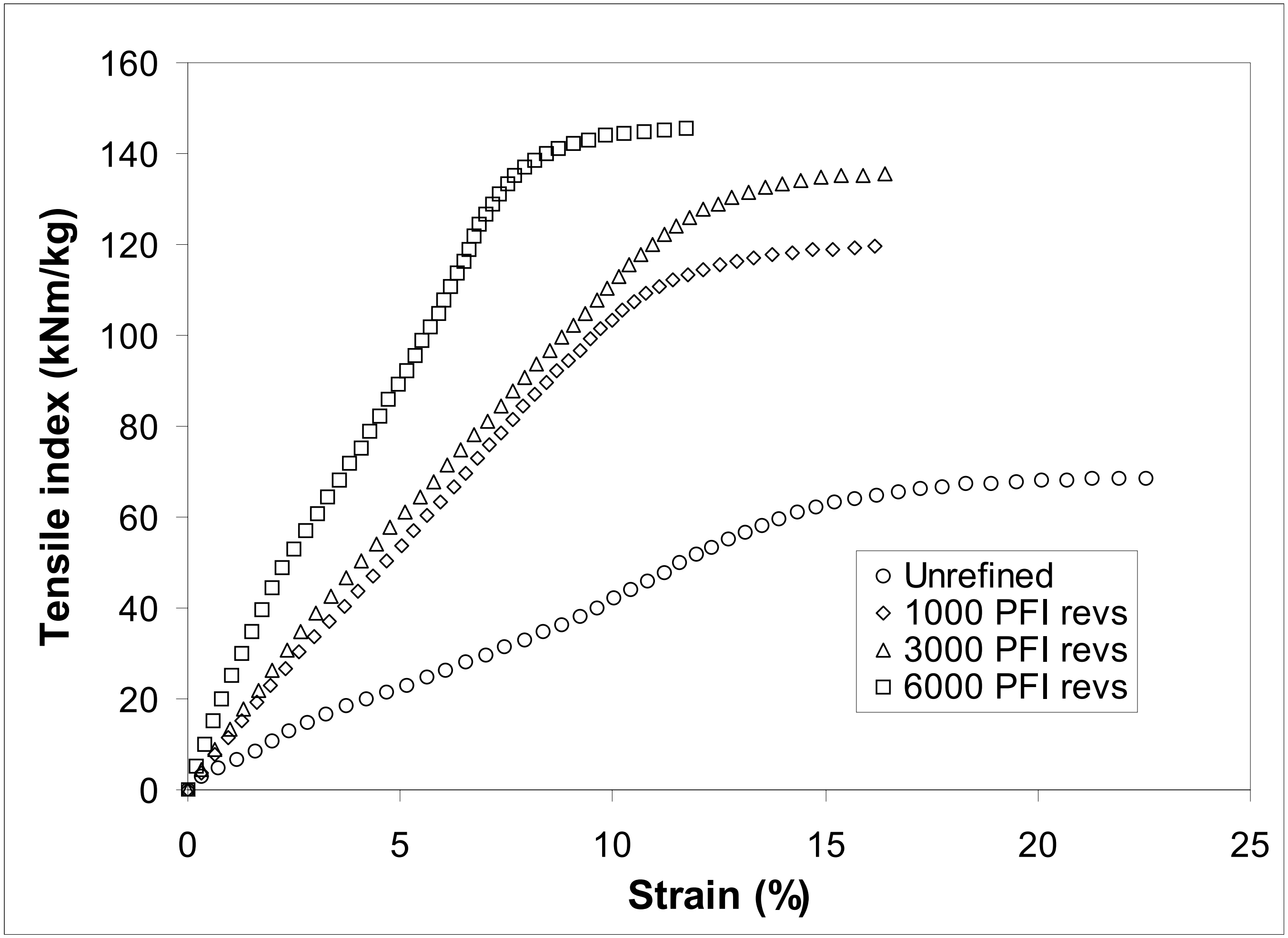


Batchelor

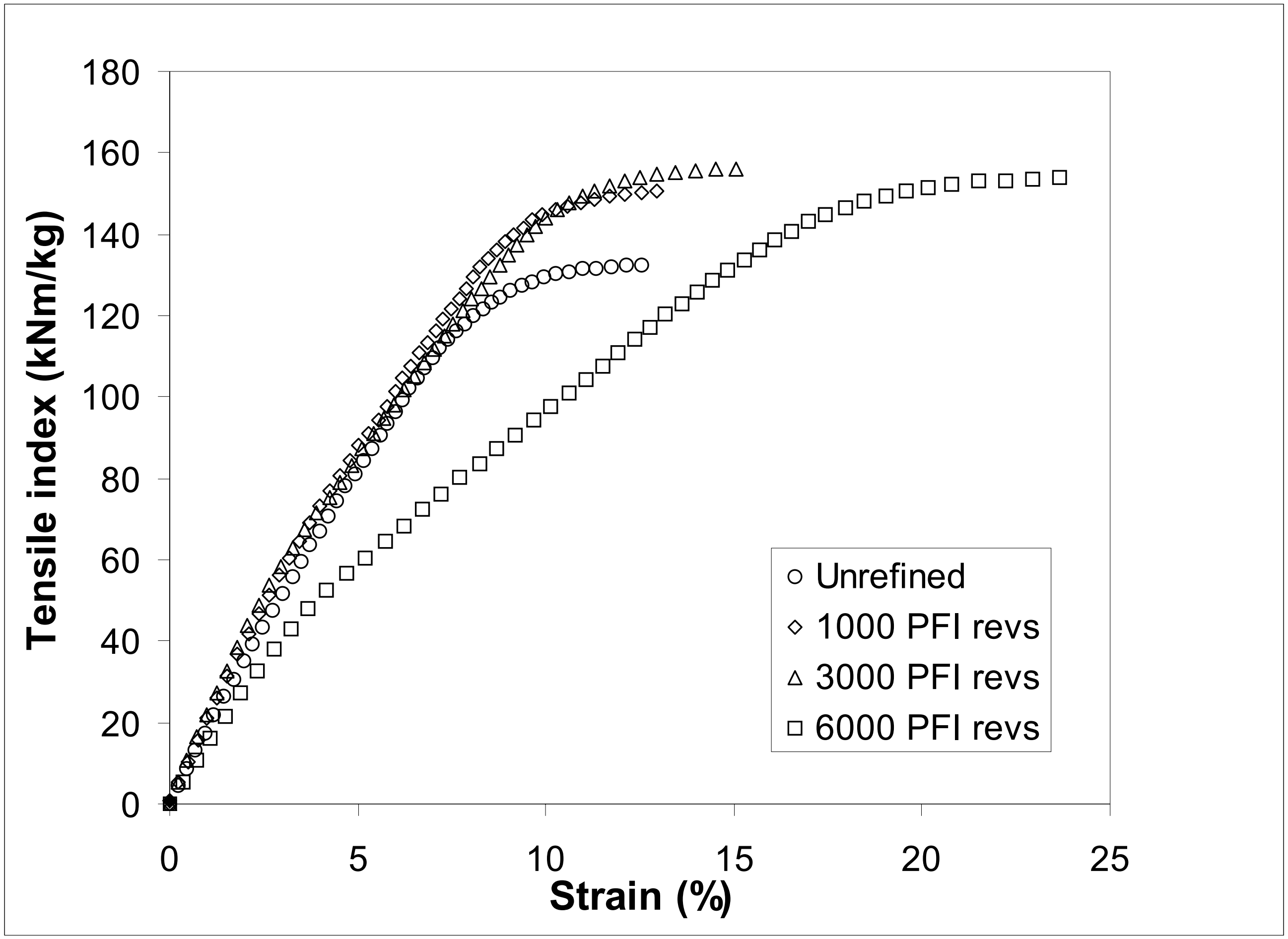
Effect of refining on Cross-section Stress-strain curves determined from subtraction, 300 μm span curves, bleached kraft (B)



Effect of refining on Cross-section Stress-strain curves determined from subtraction, 300 μm span curves, once dried, bleached kraft (C)



Effect of refining on Cross-section Stress-strain curves determined from subtraction, 300 μm span curves, unbleached kraft (A)



Conclusions

- New method developed to use short and zero-span measurements to obtain stress-strain curves
- An unbleached kraft sample: increasing cross-section strain at breaking and increasing breaking stress with refining
- An bleached never-dried sample and a bleached once-dried sample: decreasing strain at break, increasing breaking stress with refining

Acknowledgements

- SCA Research for funding this research
- Anneli Neumann and Ulrika Sedin
  - Sheet making and standard lab tests
- Sten Larsson
  - Data acquisition
- Rickard Boman, Tomas Unander
  - Matlab programming