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Multi-scale modeling of the irreversible behavior of paper fibres subjected to moisture cycles

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materials innovation institute

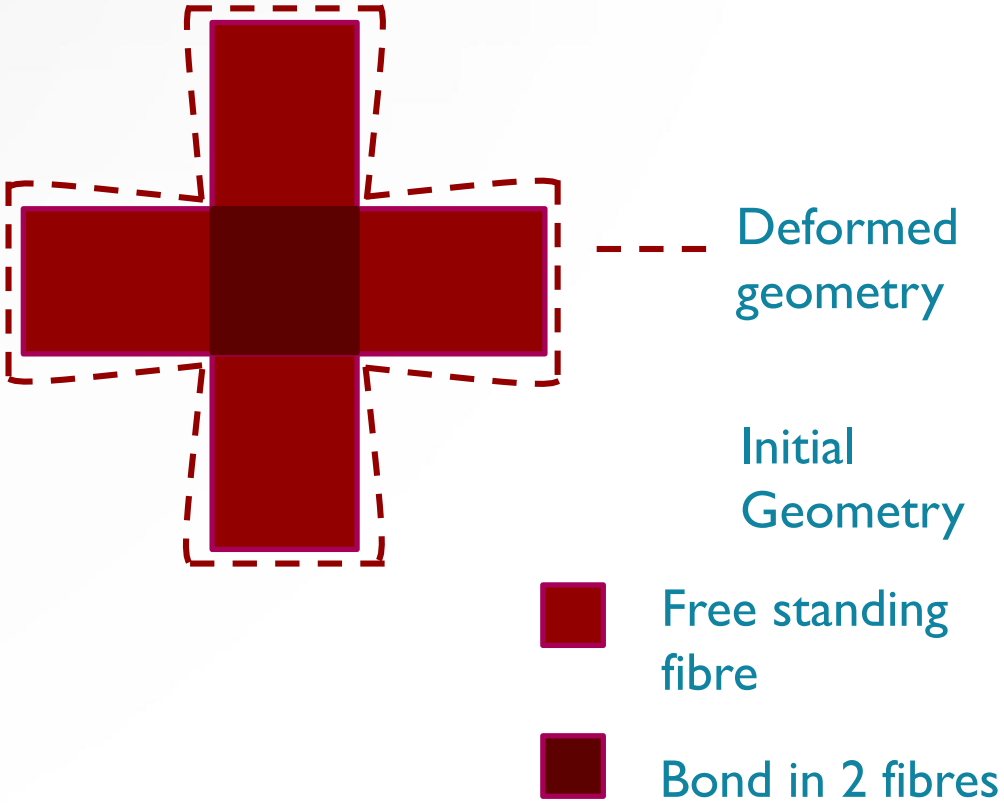
Introduction & industrial relevance

- During productive inkjet printing, there is deposition & drying of ink
- Hygro-expansive behavior
- Macrosocopic response e.g. curl
- Dimensional stability
- Depends on the ink, conditions of printing and media transport

Retrieved from:
http://media.bestofmicro.com/

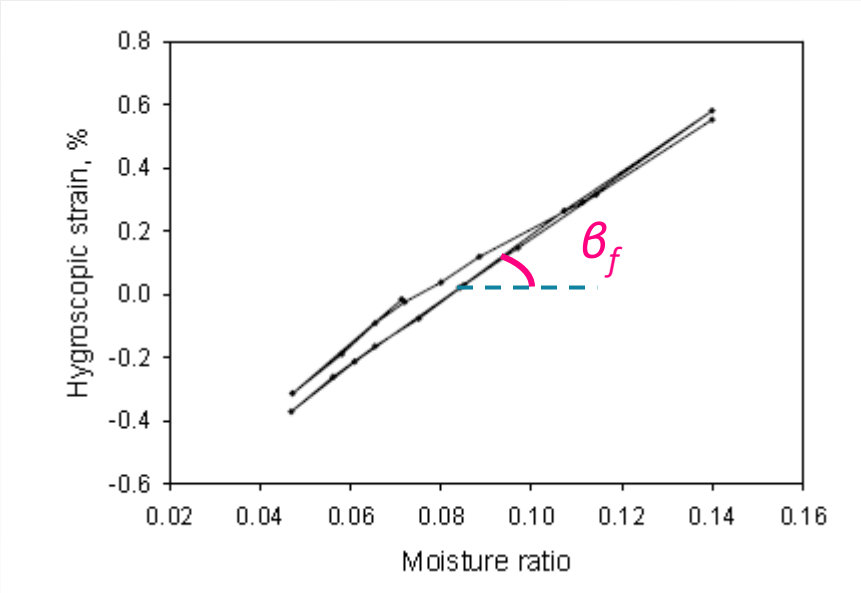
Hygro-mechanical behavior of fibres in paper

- $\beta_t = 20\ \beta_l$ (Niskanen, 1998)
  β = coefficient of hygroscopic expansion
- Highly anisotropic
- Hygro-expansive response originates at fiber level and gets transferred to network through bonds.
- Occurence of micro-stresses.

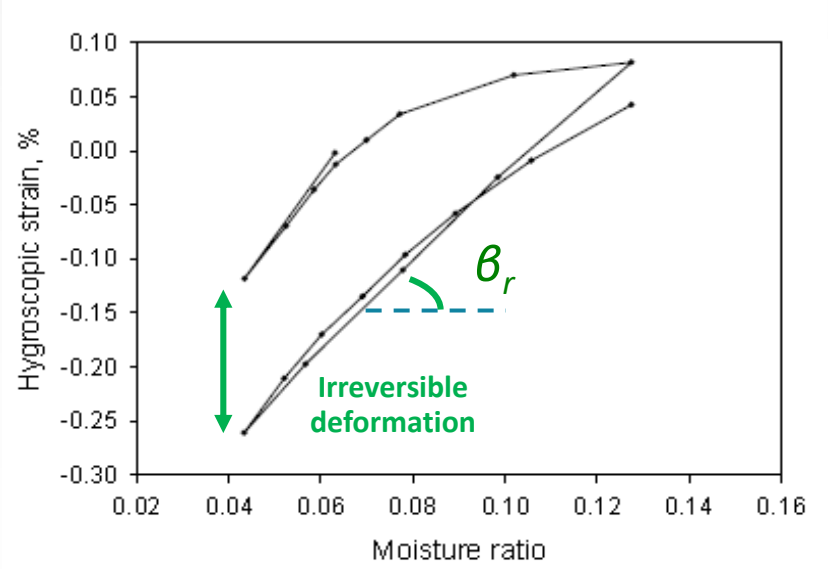


Addressing irreversible paper response

Freely dried paper



Restrained dried paper



Acknowledgment experimental data: Petri Makela

- In manufacturing process, dried in strains are developed due to restraint/web tension. (Restraint for handsheets and web tension in real, machine-produced paper)
- Applying a new moisture cycle without any restraint e.g. printing, the dried in strains are released.

Objectives

Earlier Work

Modelled the hygro-elastic (reversible hygroscopic) response of fibrous network using Level set-XFEM formalism

Goal

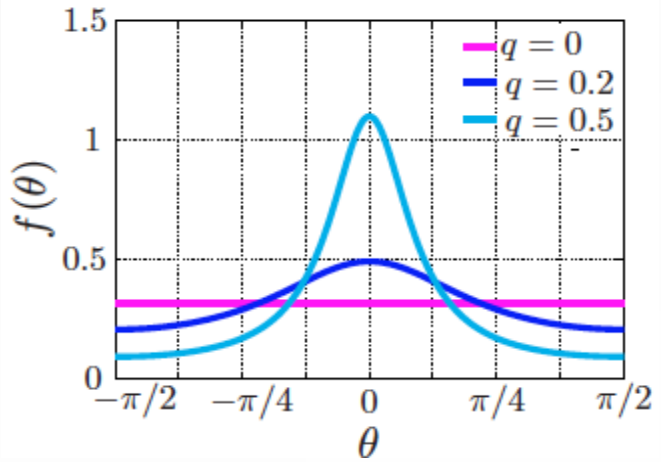
Study the effect of the network properties on the predicted sheet scale irreversible hygroscopic strain

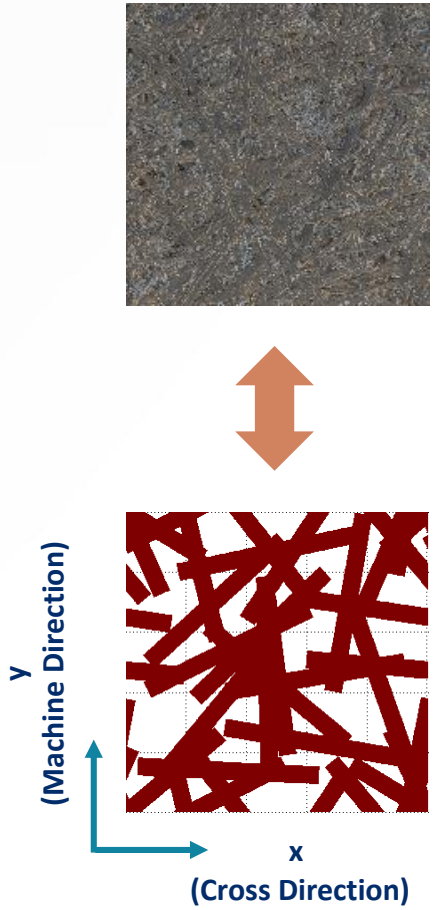
Approach

Using FEM (numerical modelling) and a suitable yield function (material modelling) to model irreversibility phenomena in the network.

Random fiber network generation in current model (2D idealization)

- Periodic unit cell (homogenization)
- The centers of rectangular fibers are randomly generated
- The orientations of fibers are generated using a probability distribution function
- Overlap regions perfectly bonded





Bosco, Peerlings, Geers, 'Predicting hygro-elastic properties of paper sheets based on an idealised model of the underlying fibrous network', IJSS, 2015.

Modeling the reversible hygroscopic response

Assumptions: a) Hygroelastic model
b) Small strains
c) Thermal effects neglected
d) No moisture transport

Micrograph of paper

- The hygroscopic strains for each fibre are represented by,
  $\varepsilon^h = \{\beta_l \, \Delta\chi, \beta_t \, \Delta\chi, 0\}^T$,
  where β is coefficient of hygroscopic expansion for a fibre, $\Delta\chi$ is the change in the moisture content

- The total strains in each fibre are represented by

$$\varepsilon = \varepsilon^e + \varepsilon^h$$

Addressing irreversible paper response

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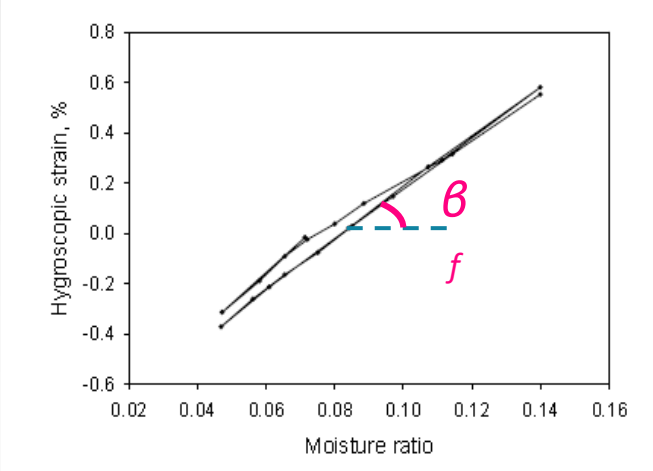
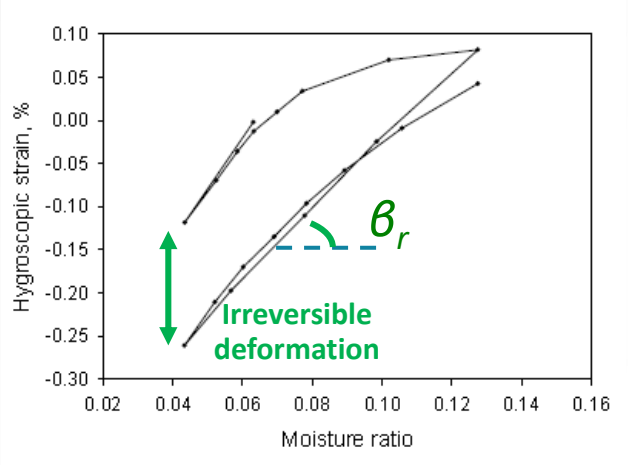
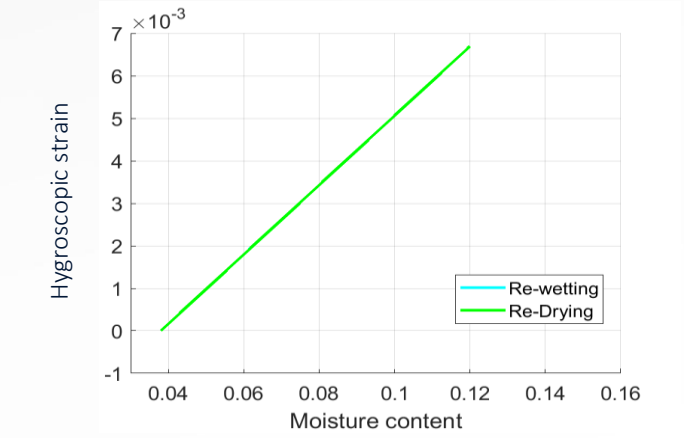


Restrained dried paper





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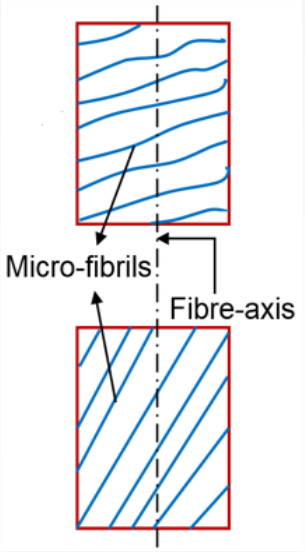
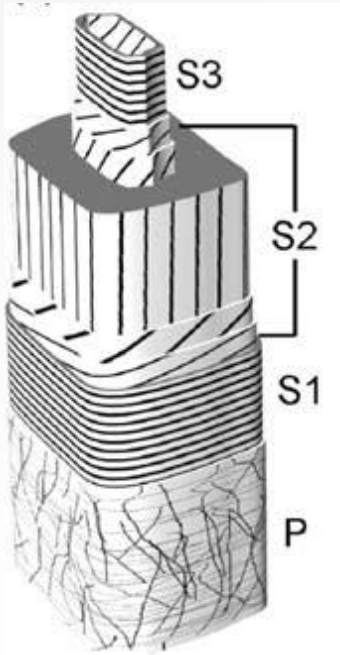
Irreversibility mechanism





[Neagu, Gamstedt, 2007]

Schematic design of cell wall of softwood fibre

✓Fibre segment activation mechanism

A) Constrained drying B) Elastic modulus↑ C) Micro-fibril angle↓

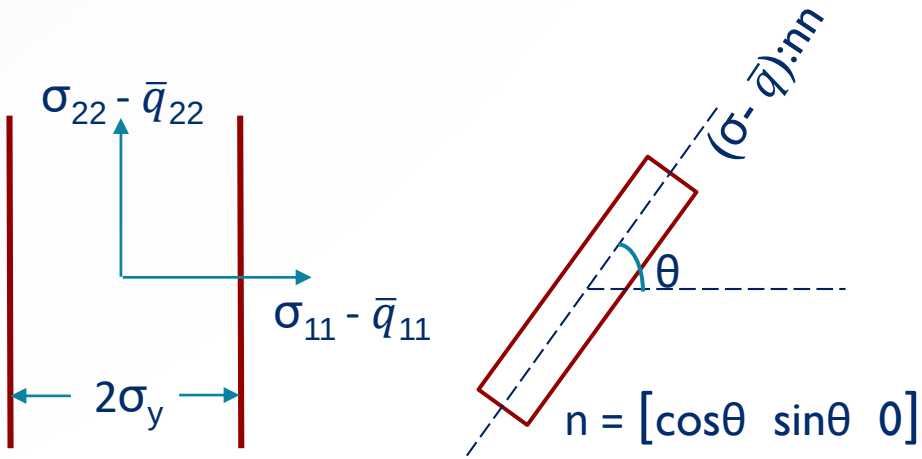
The Kinematic hardening Model

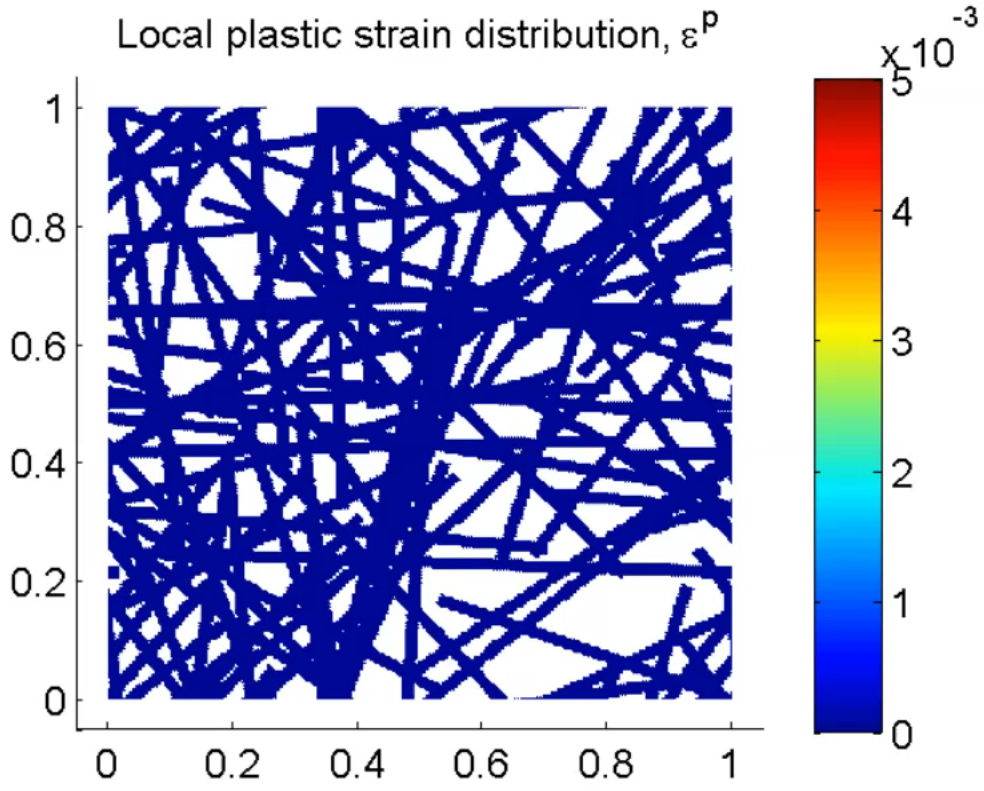
The total strains are now represented, $\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^h$

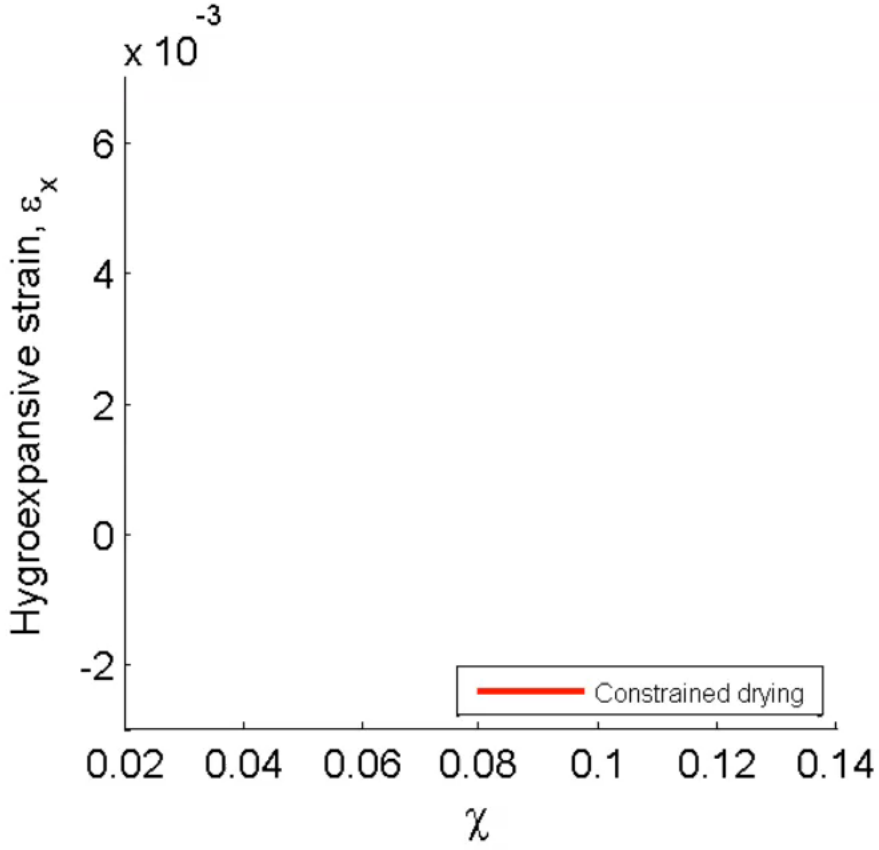
Yield Function, $f = |(\sigma - \bar{q}):nn| - \sigma_y$, $\sigma_y = \sigma_{y0}\left(1 - \frac{\chi}{\chi_w}\right)$

σ_{y0} = yield stress when fully dried, χ_w = moisture content at which yield stress vanishes
n = vector for longitudinal projection

- Stress free expansion
- Driving force is the backstress
- No external stress in the problem
- Models plasticity in tension in longitudinal direction





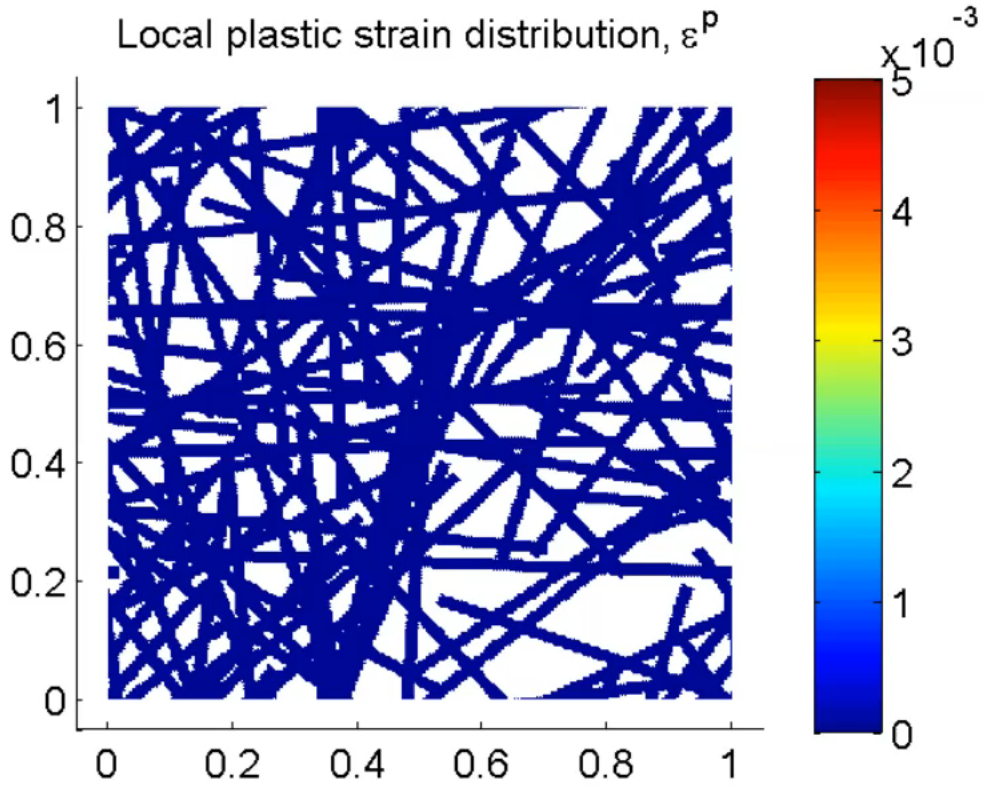


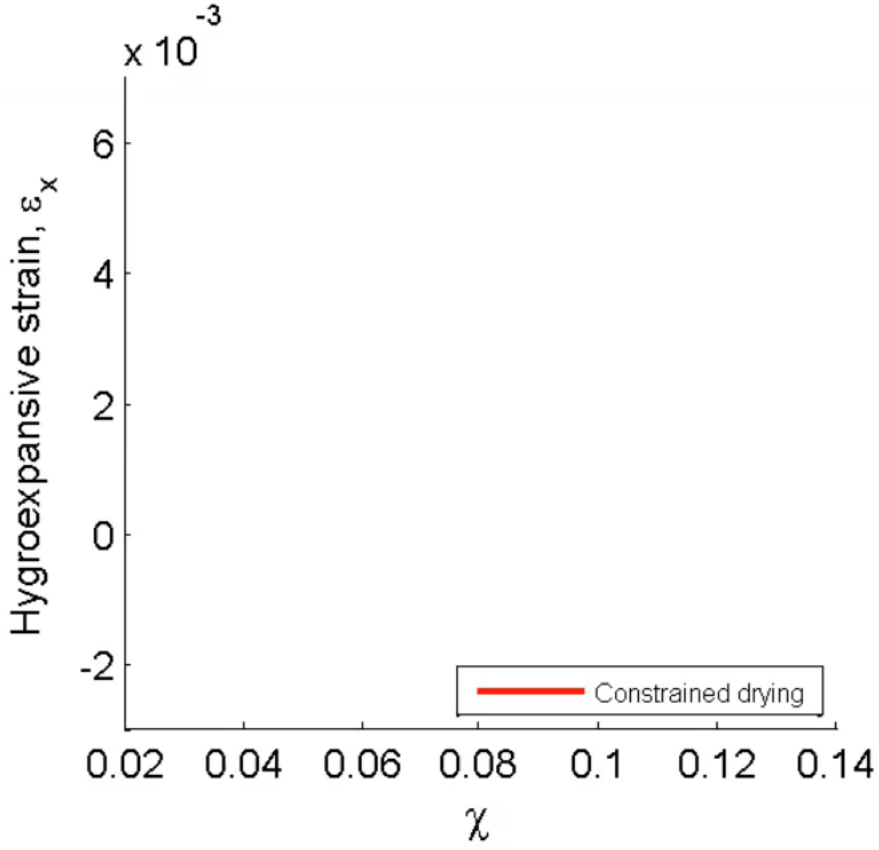
Constrained Drying
Stress release
free drying

Manufacturing process

Rewetting
Drying

Printing Operation





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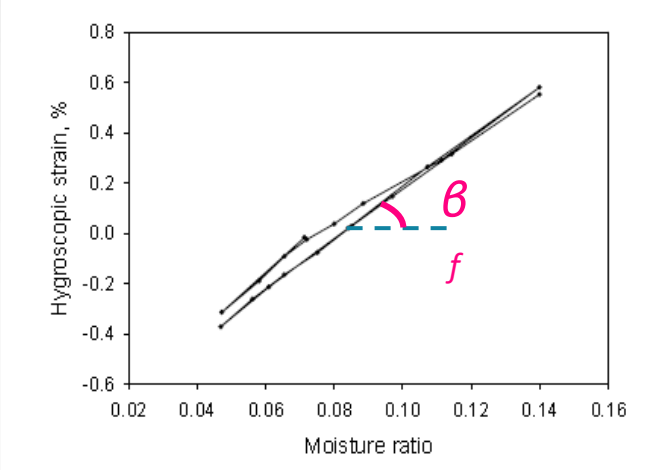
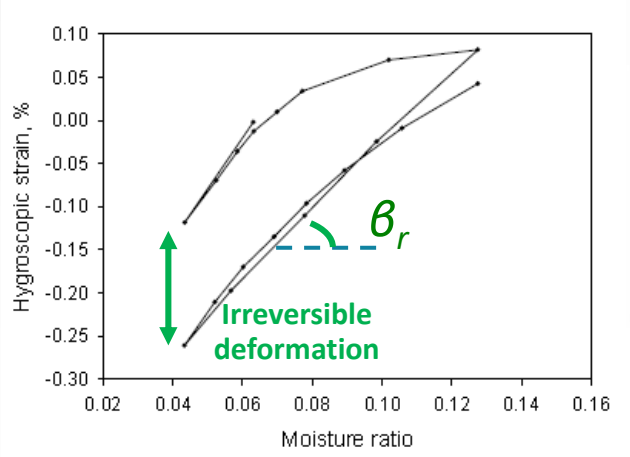
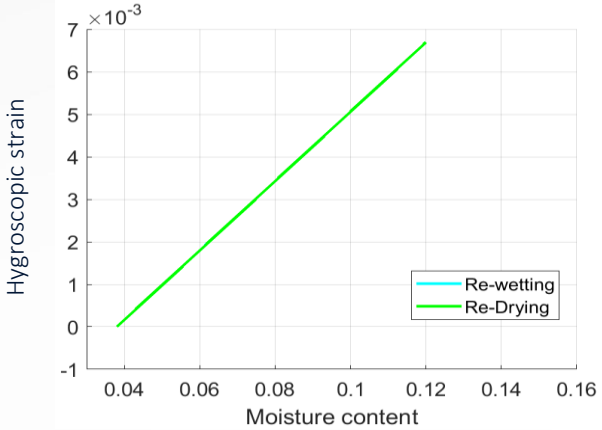
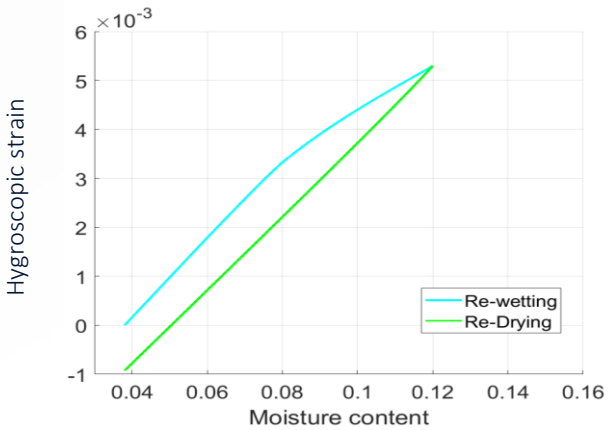


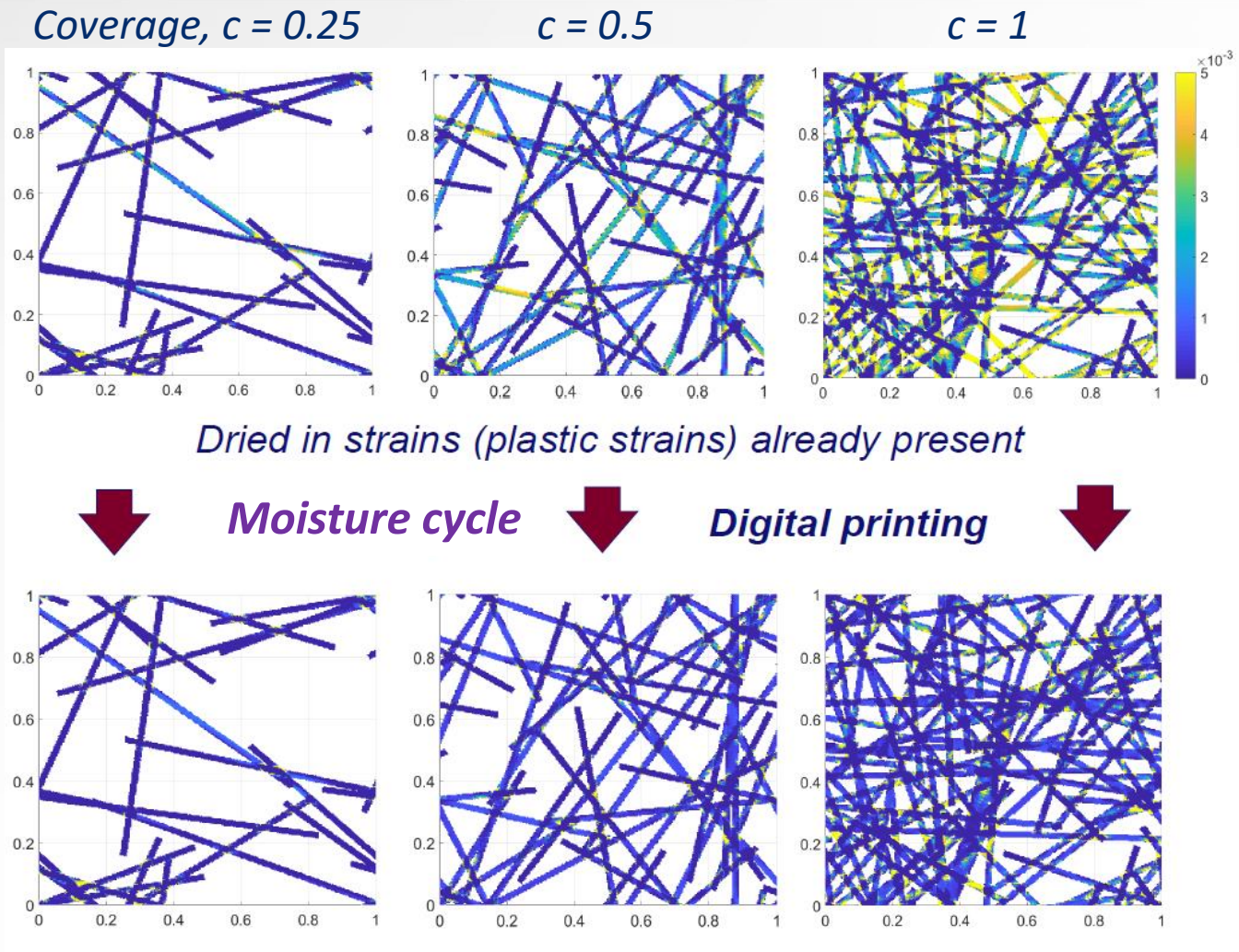
Restrained dried paper





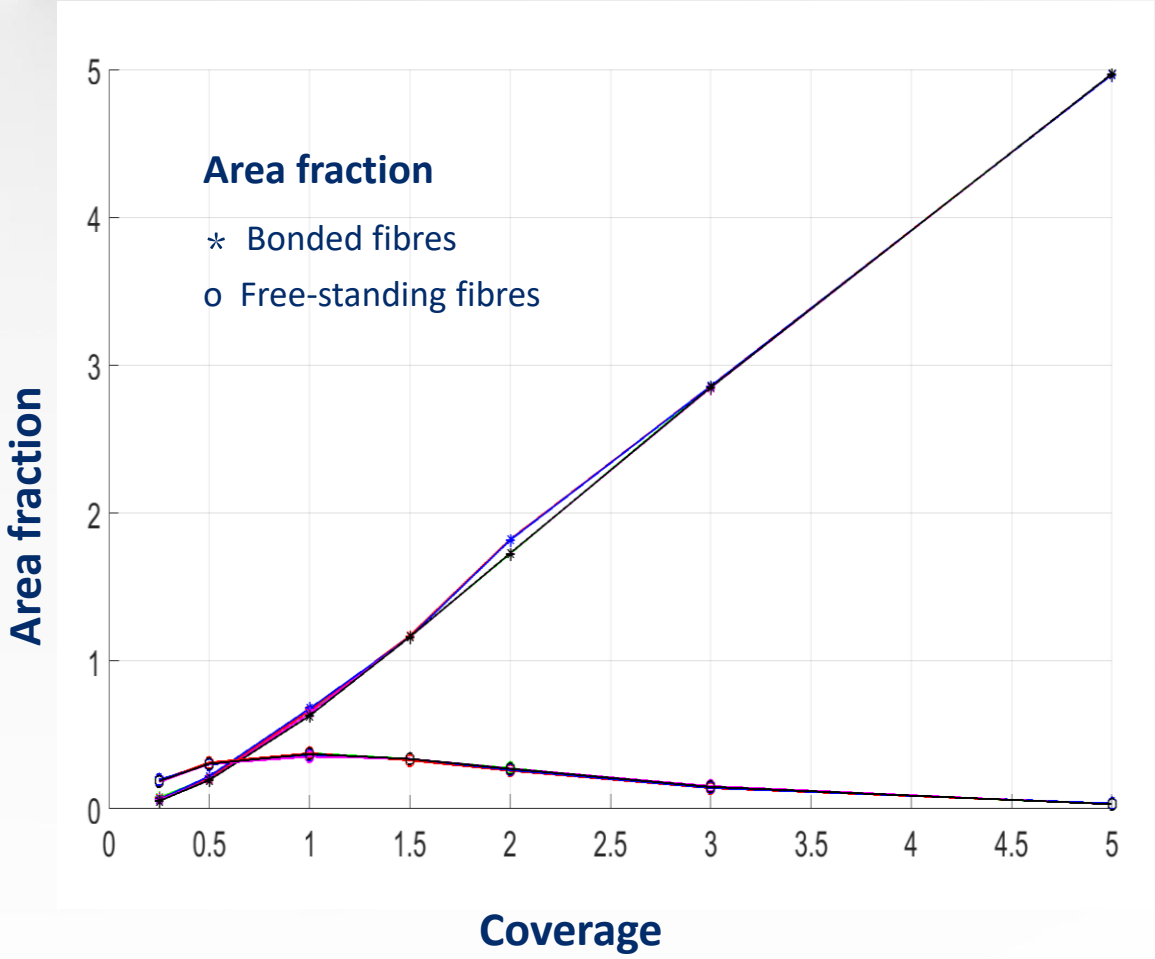


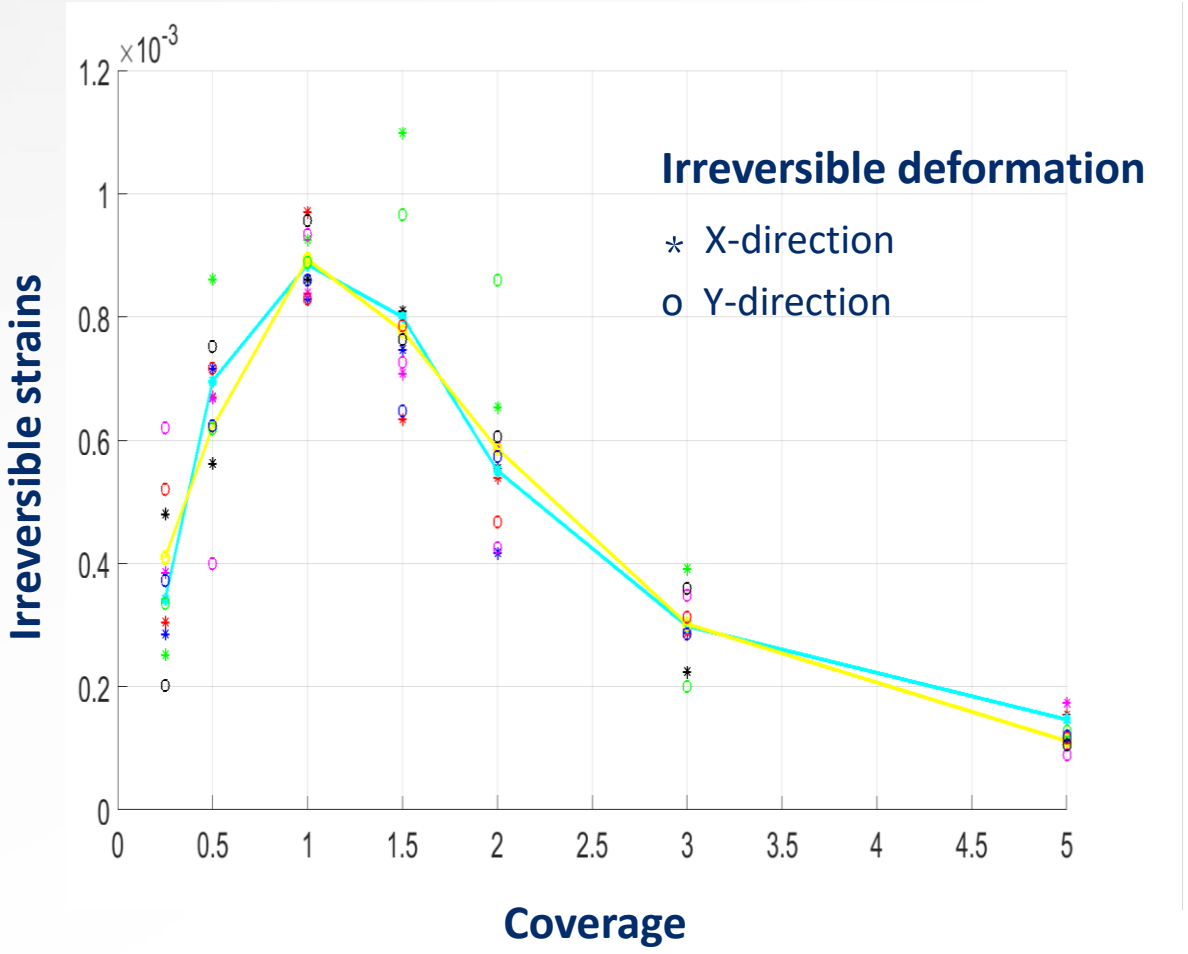
Local plastic strain distribution in manufactured paper fibres (Restrained-dried random isotropic networks)



(The plastic strains are partially released)

Irreversible strains & area fraction





(*5 realizations for each of the coverages. They are denoted by colors*)

Conclusions

- Sheet scale irreversibility is predicted as a function of microstructural properties of the network
- At the macroscopic scale, the effect of coverage on the irreversible deformation increases initially but decreases after a coverage =1.

Outlook:

- Rate dependency effects of moisture on paper networks
- Relaxation of kinematic constraints in the bonded regions

THANK YOU