On moisture induced stresses in timber structural elements

Picture: Courtesy of Johan Jönsson, Lund University, 2005

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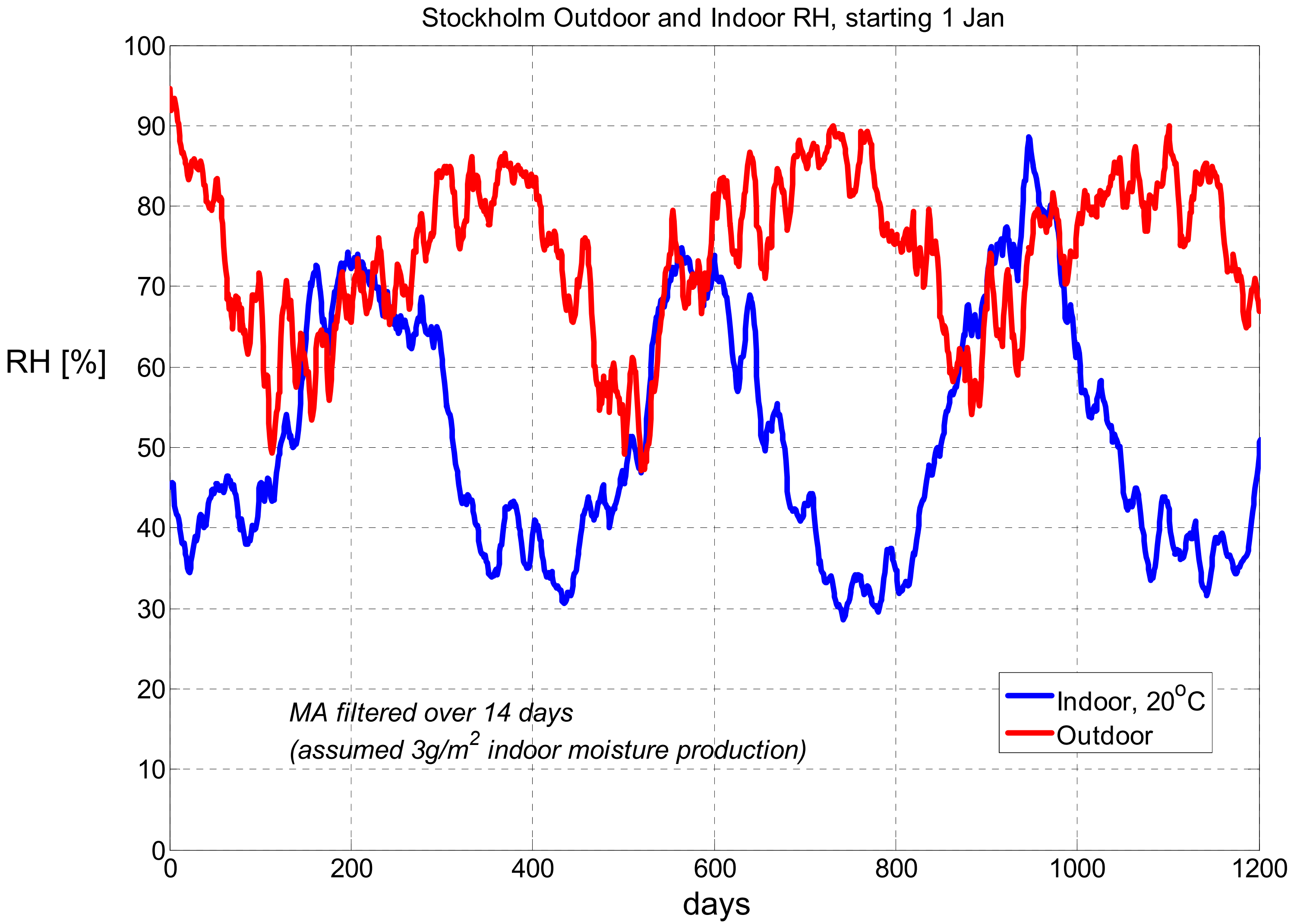
COST E55 Meeting in Helsinki 13-14 March 2007

Outline

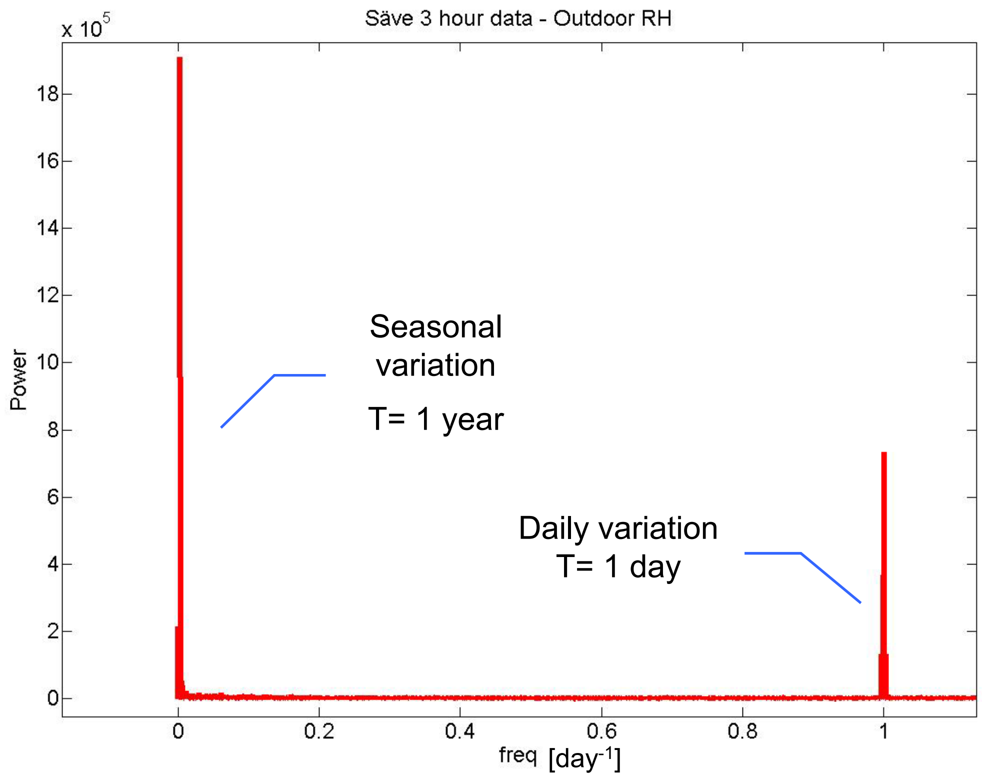
- Varying Climate
- Properties of wood
- Moisture in wood
- Moisture induced stress (MiS)
- Consideration of moisture as an action
  - an external “load” to be combined with other loads
- Discussion

Varying Climate



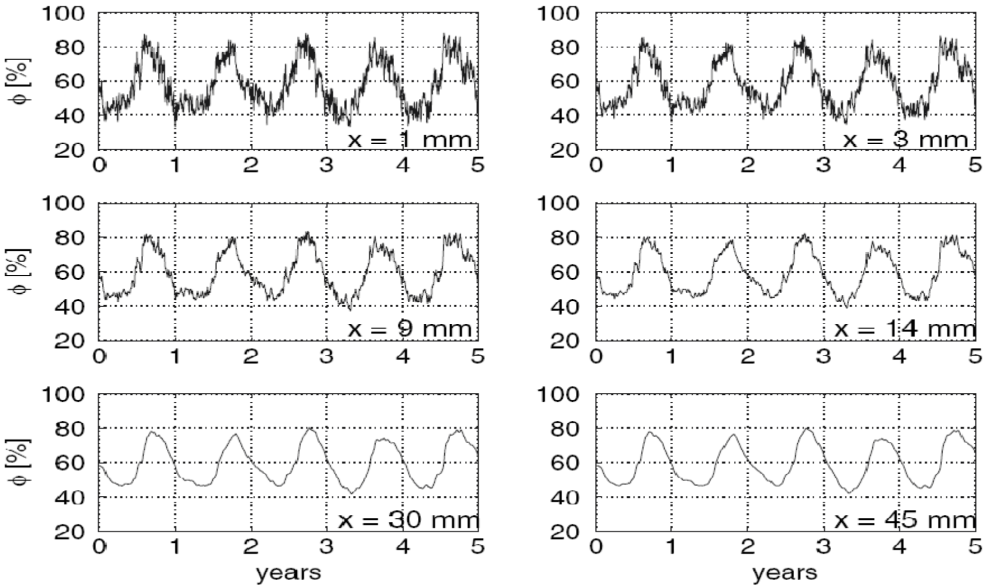
Varying Climate

- Climate variation
  - ”Noisy” behavior
  - “Regular” oscillations are on a daily and annual basis

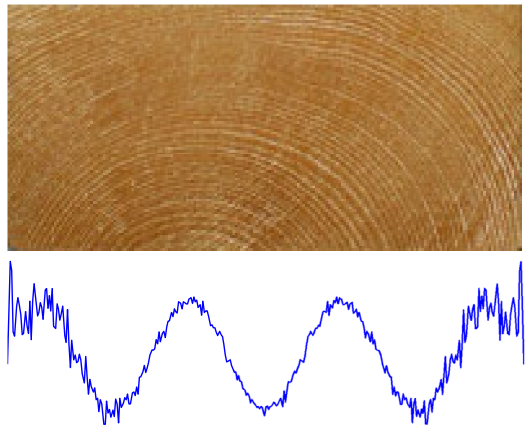


Varying Climate

- Moisture penetration in timber
  - Wood is basically a low-pass filter
    - Swift variations are damped
    - Seasonal variations penetrate, although somewhat phase-shifted (cf. surface and middle)



"illustrative cross-section"



(note: not from calculation, solely a visual interpretation)

Properties of wood

- Principal properties
  - Hygroscopic
  - Anisotropic
    - Material parameters functions of direction, moisture content, temperature…
  - Natural
  - High Variability
    - Environment (growth conditions)
    - Heredity (species)
  - Adaptable – complex detailing on factory floor or on site
  - High strength to weight ratio *(not perpendicular however)*

Properties of wood

- 3 orthotropic directions
  - Radial
  - Tangential
  - Longitudinal

  Radial, Tangential: **Transversal directions / Perpendicular to grain**
- Typical strength ⊥ to grain f_k = 0.5 MPa (5%-fractile)
- However highly size dependant (e.g. weakest link, varying stiffness)

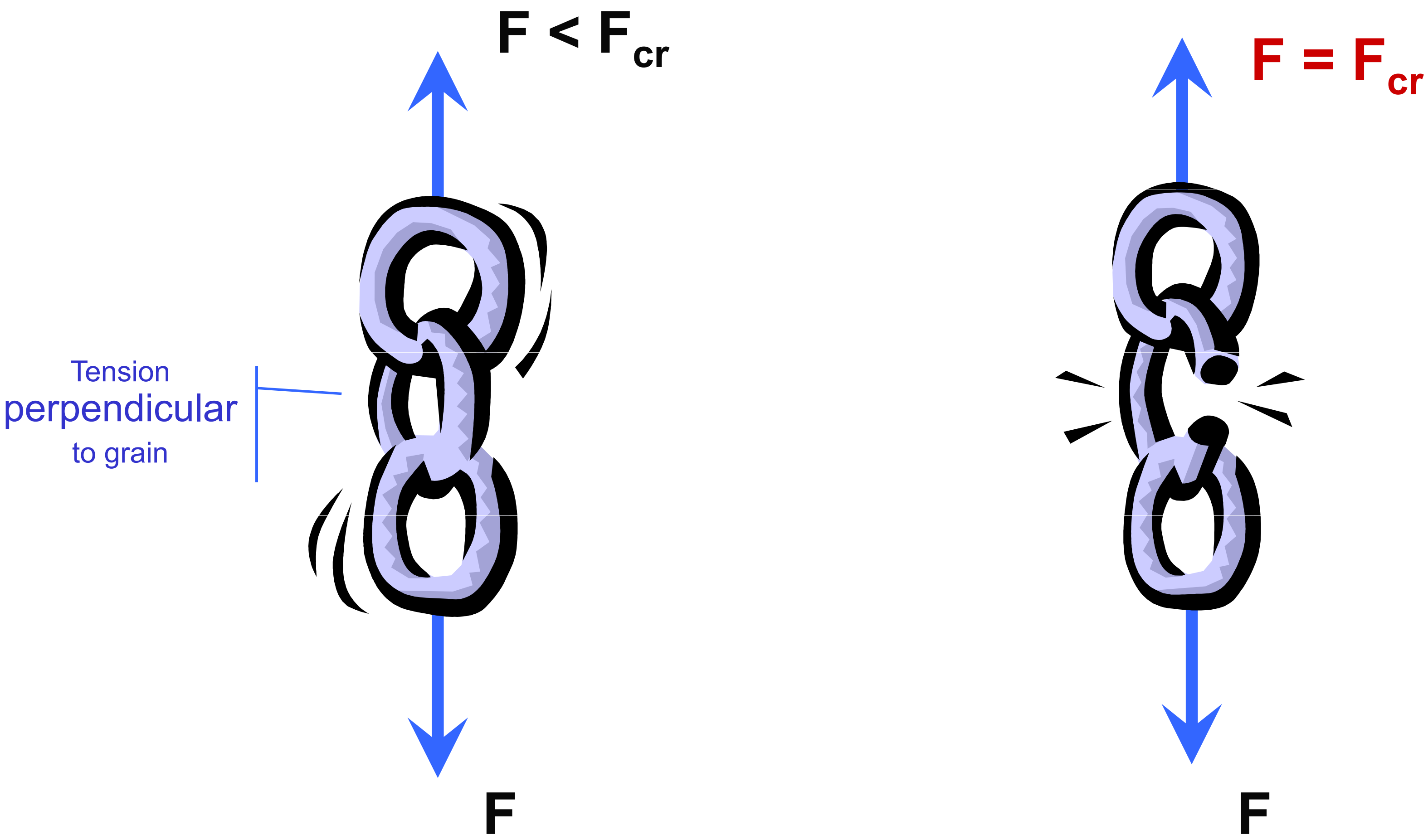
Table 7.3 Perpendicular to grain tensile strength of spruce for specimens of various volume

Specimen: geom., mat., dens.	Specimen: b*h*l, mm^3	Volume, dm^3	Strength, MPa Mean (5%-fract.)	Reference
Prismatic, solid, 467	15*16*20	0.005	4.0 (2.7)	G-88
Prismatic, glulam, –	–	0.027	2.4	LR-83
Prismatic, glulam, –	–	0.28	1.8	LR-83
Prismatic, glulam, –	–	2.5	1.0	LR-83
Prismatic, glulam, –	–	26	0.63	LR-83
Prismatic, glulam, 530	90*275*400	10	0.89 (0.74)	ADR-98
Prismatic, glulam, 493	140*405*528	30	0.67 (0.55)	ADR-98
Curv. beam, glul., 470	90*400*1000	36	1.21 (0.95)	ADR-98
Curv. beam, glul., 496	90*600*2000	108	0.85 (0.72)	ADR-98
Curv. beam, glul., 503	90*600*4000	216	0.71 (0.59)	ADR-98
Curv. beam, glul., 493	140*600*4000	336	0.61 (0.46)	ADR-98

(from PJ Gustafsson, Timber Engineering, Wiley, 2003)

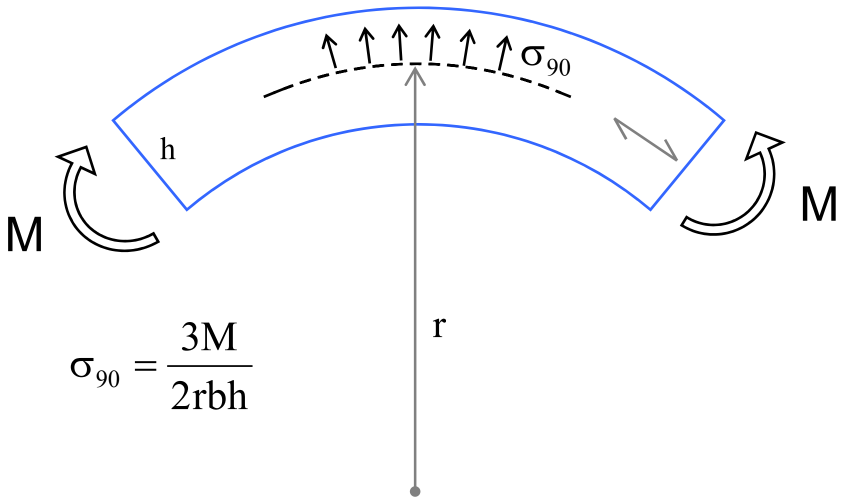
Properties of wood

- "Weakest link"

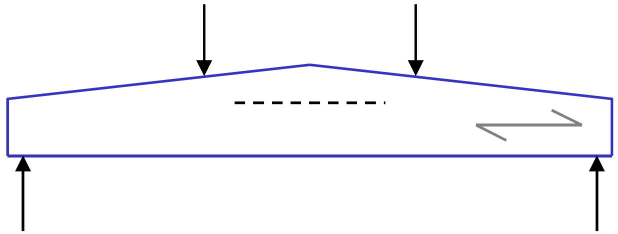


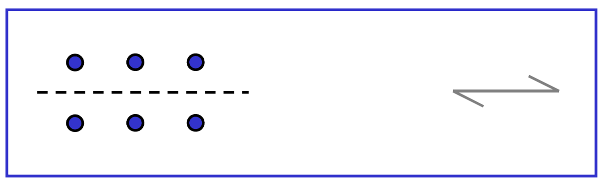
Properties of wood

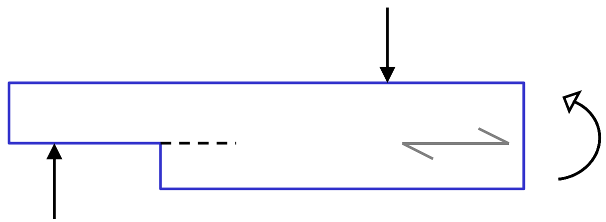
- Combination of moisture induced stress and mechanical loading
  - Detailing (fasteners), curved beams, tapered beams, notched beams …



$$\sigma_{90} = \frac{3M}{2rbh}$$







Moisture in wood

- Transient transport of moisture
  - Drying / wetting - until equilibrium is reached
- Resistance to transport
  - Surface (boundary) / Body (the domain)
- Continuity equation
  - Fickian law

$$\mathbf{q} = -D_\theta \operatorname{grad} \theta$$

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x} \right)$$

Moisture in wood

- Outdoor
  - Sheltered / unsheltered
  - Temperature, relative humidity, sun exposure
- Indoor
  - Relative humidity (mainly)
    - Location – ”normal” or humid/dry conditions (e.g. public baths)
- Moisture gradients and changes important
  - Restraint of hygroexpansion
  - Absolute values not as important (beside the risk for rot and decay)

Moisture in wood

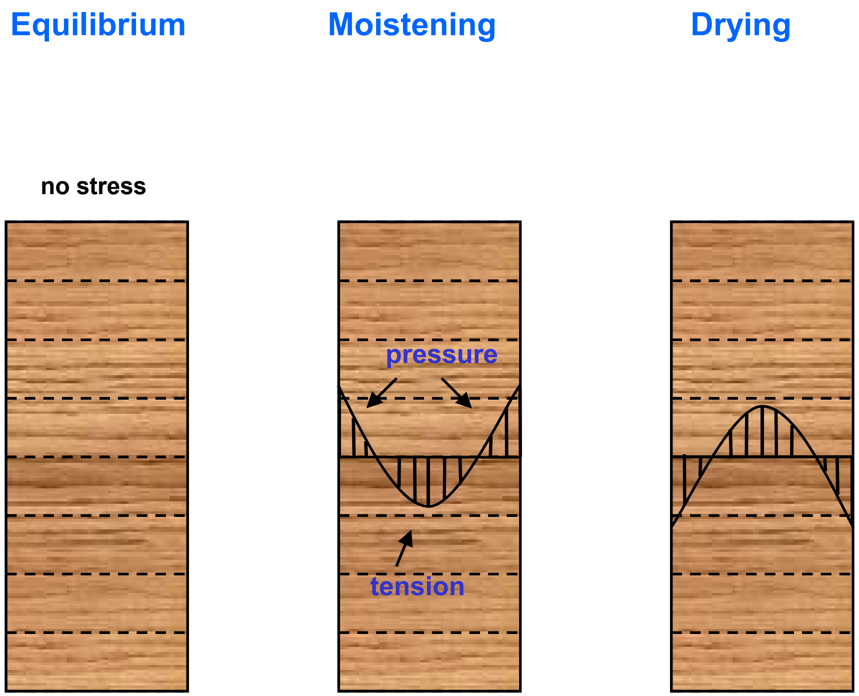
- Hygroexpansion
  - Swelling/shrinking wood (cell wall expansion due to hydrogen bonding)

+

=

Moisture in wood

- Uneven moisture distribution



(rough schematic distribution of stress)

Moisture induced stress

Moisture induced stress

- Stress models
  - Assumption that different types of stress are additive

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{e} + \dot{\varepsilon}_{c} + \dot{\varepsilon}_{ms} + \dot{\varepsilon}_{u}$$

elastic

Viscoelastic creep

Mechano-sorptive

Hygro-expansive

Viscoelastic creep known to be negligible to MS creep:

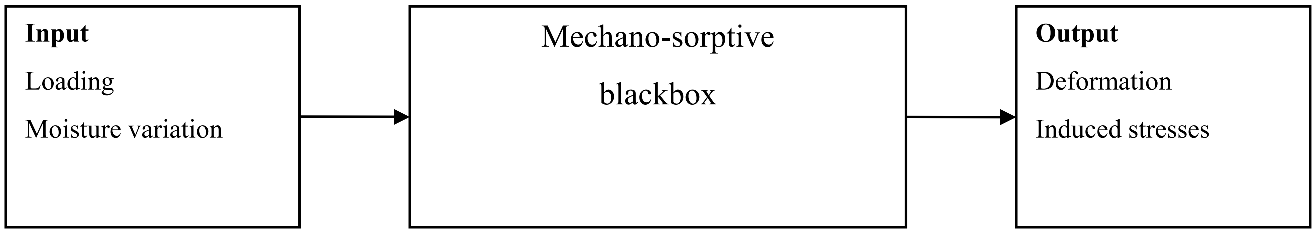
$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \sigma(m|\dot{u}| + \beta\dot{u}) + \alpha\dot{u}$$

Moisture induced stress

- Mechano-sorption
  - 1960s – new phenomenon
  - Effects due to interaction of mechanical loading and sorption
  - Some example of observed effects:
    - (i) moisture variation accelerates creep, pure DOL creep contribution to the total deformation is generally much less,
    - (ii) mechano-sorption exists in all three dimensions,
    - (iii) creep increases during drying and decreases during wetting,
    - (iv) deformation is to a large degree reversible under moisture change,
    - (v) the size (range) of moisture variation is more important that the duration regarding deflection

Moisture induced stress

- Mechano-sorptive modeling
  - Input/output observation
  - “curve fitting”
  - explanatory models (e.g. hydrogen bonds - breaking and rebonding; slip-planes)

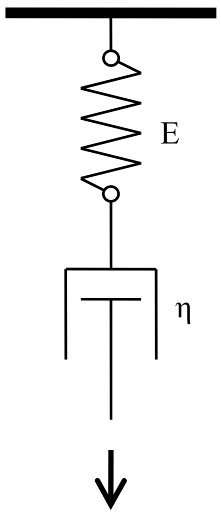


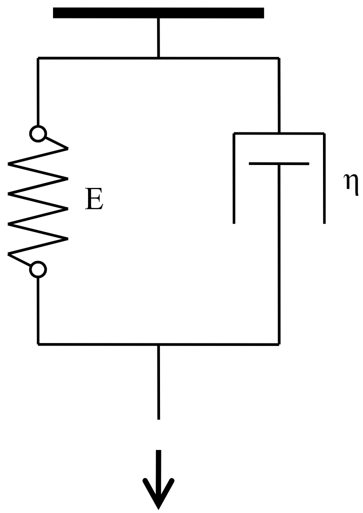
Moisture induced stress

- Mechano-sorption modeling elements
  - Maxwell –> Series (additive strains)
  - Kelvin-Voigt –> Parallel (additive stresses)
  - Combinations of these two (e.g. Burgers model)
  - Maxwell-type / Kelvin-type
    - Dependant on moisture change

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

$$\frac{d\varepsilon_{ms}}{|du|} = \sigma m$$



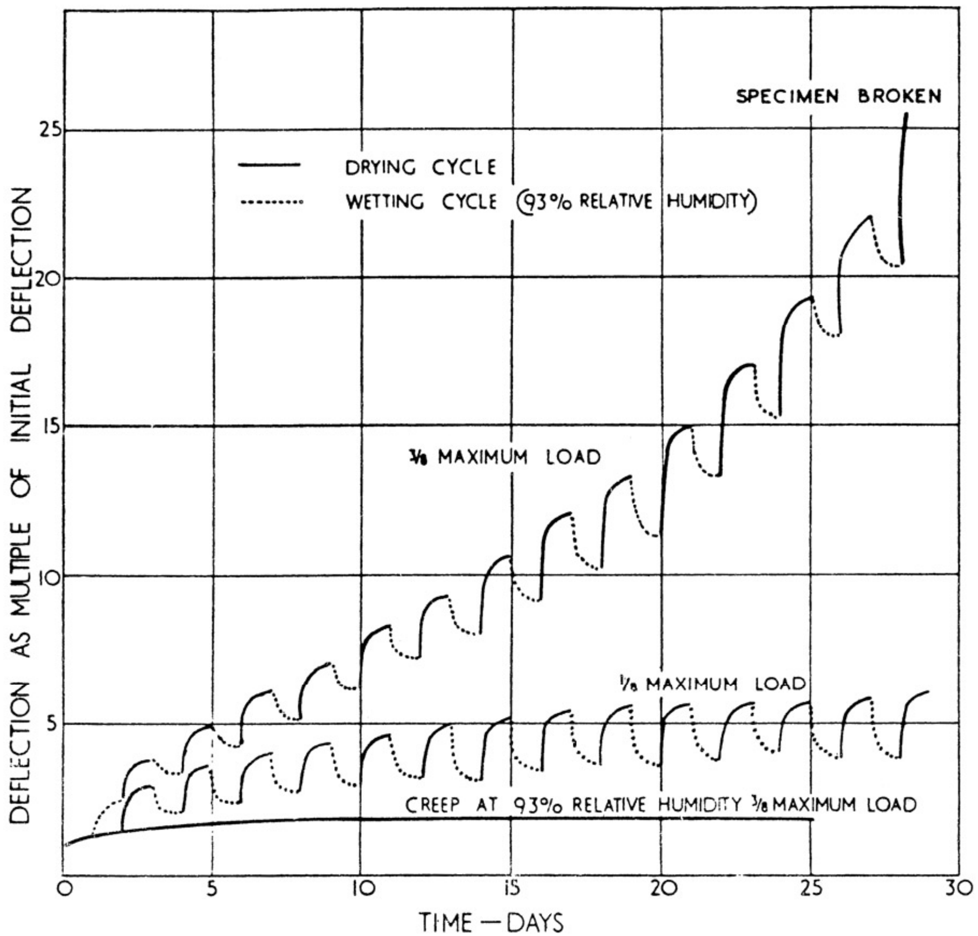


$$\frac{d\varepsilon}{dt} = \frac{\sigma - E\varepsilon}{\eta}$$

$$\frac{d\varepsilon_{ms}}{dt} = \frac{\sigma - E_{ms}\varepsilon_{ms}}{\eta_1}\left|\frac{du}{dt}\right|$$

Moisture induced stress

- Classic illustrative figure (note: small clear wood specimens)



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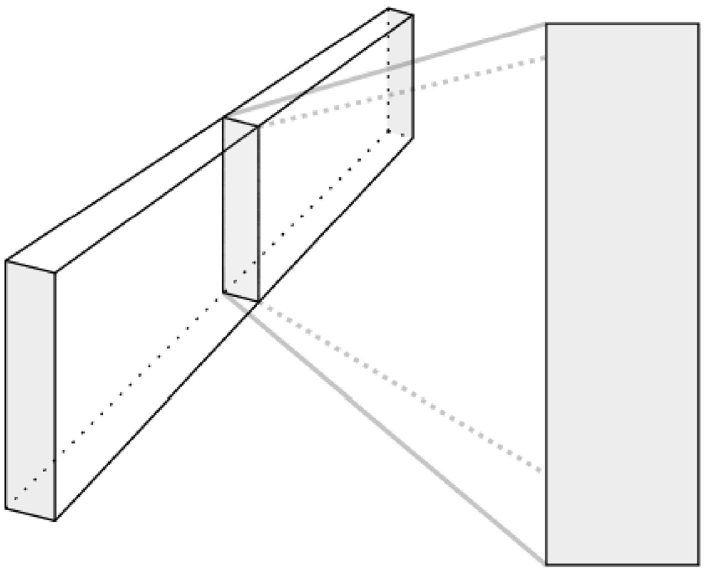
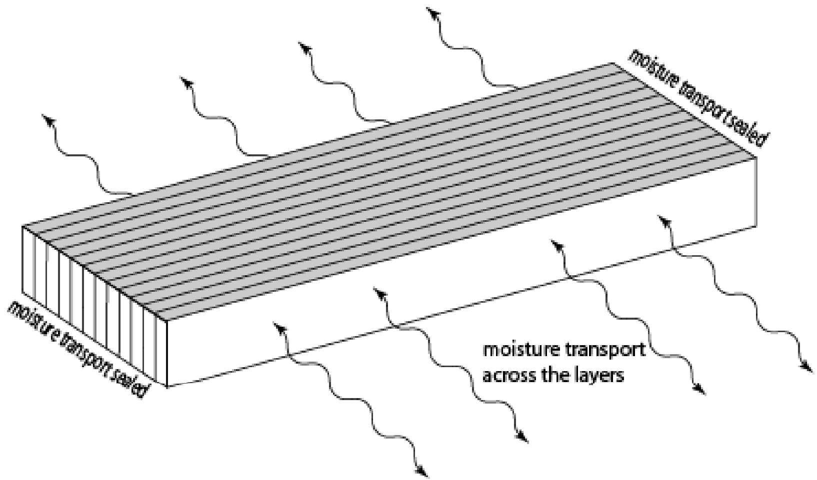
Moisture induced stress

- Stress calculation in one dimension – Some results
  - perpendicular to grain





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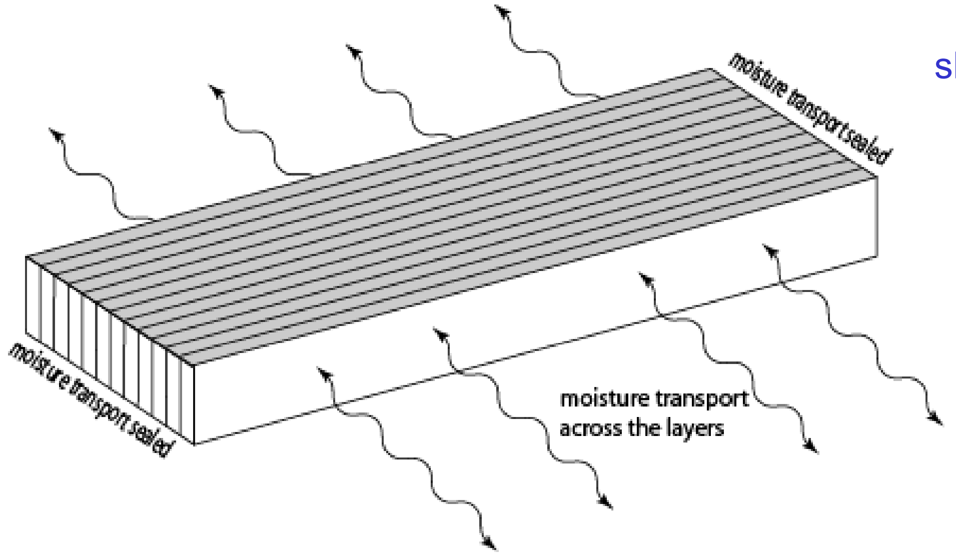
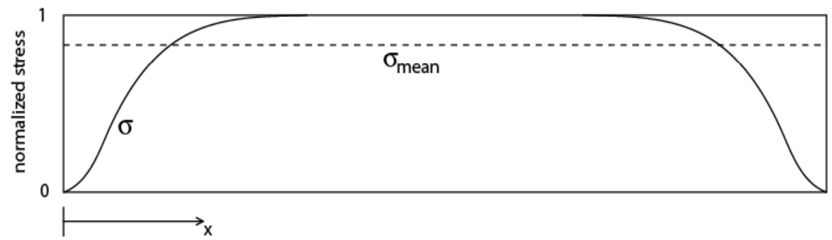
Moisture induced stress

- Moisture induced stress due to self balancing cross-sectional forces

Redistribution between shear and normal forces at the ends





Schematic stress distribution (1D)

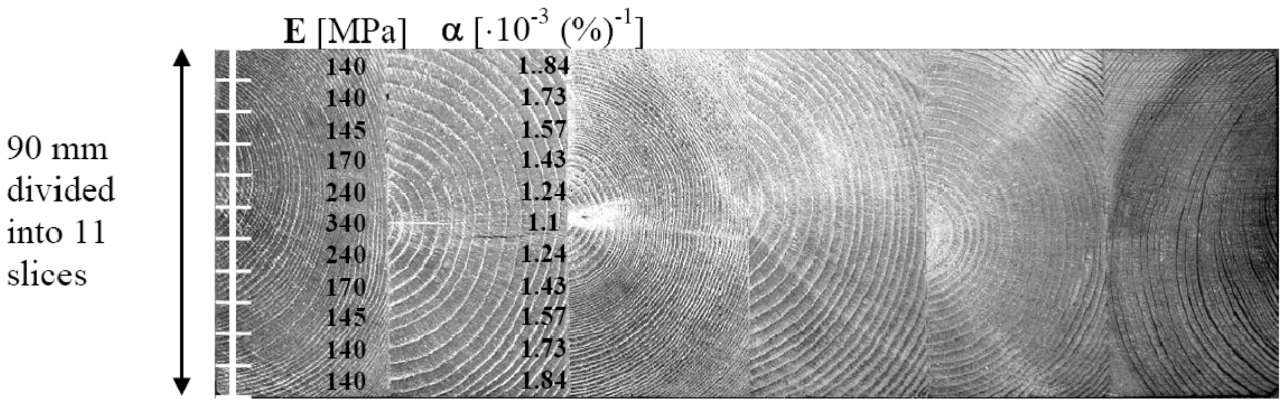
Moisture induced stress

- Force and moment equilibrium

$$\int_0^L \Delta\sigma(x)dx = \int_0^L \Delta\sigma_{ext}(x)dx \qquad \int_0^L \Delta\sigma(x)xdx = \int_0^L \Delta\sigma_{ext}(x)xdx \qquad \Delta\sigma_{ext}(x) = \Delta\overline{\sigma}_{ext}\frac{E(x)}{\overline{E}}$$

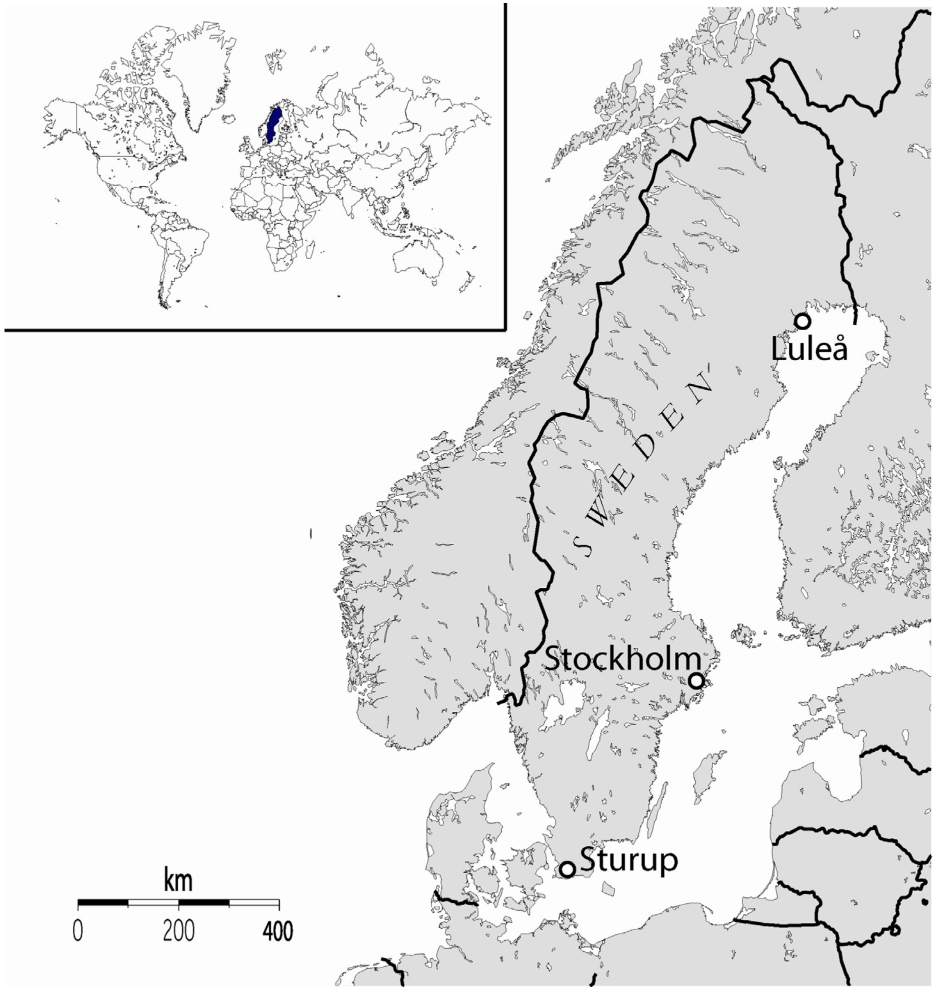
Stress distribution proportional to E(x)

- E-modulus and hygro-expansion



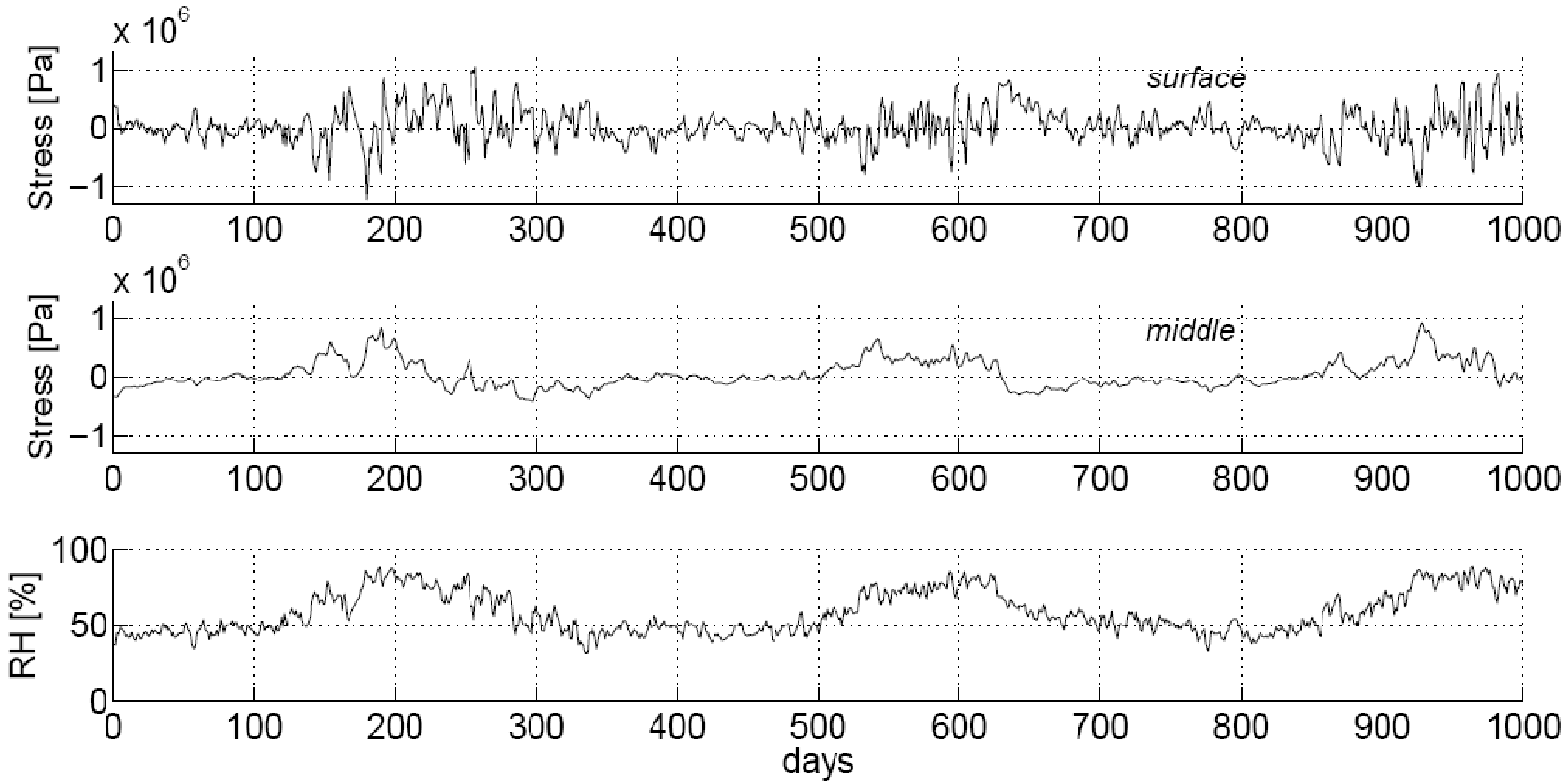
Moisture induced stress

- Stress calculation for three different locations in Sweden



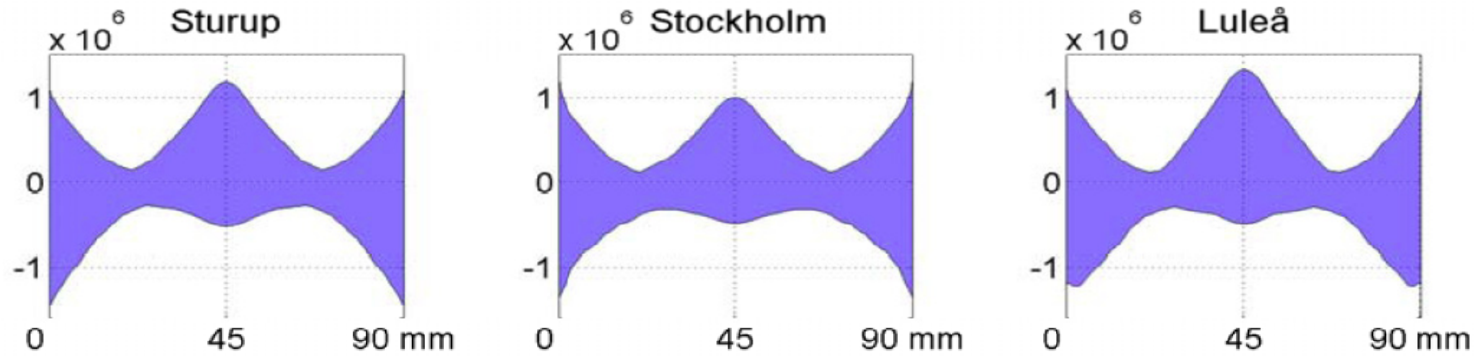
Moisture induced stress

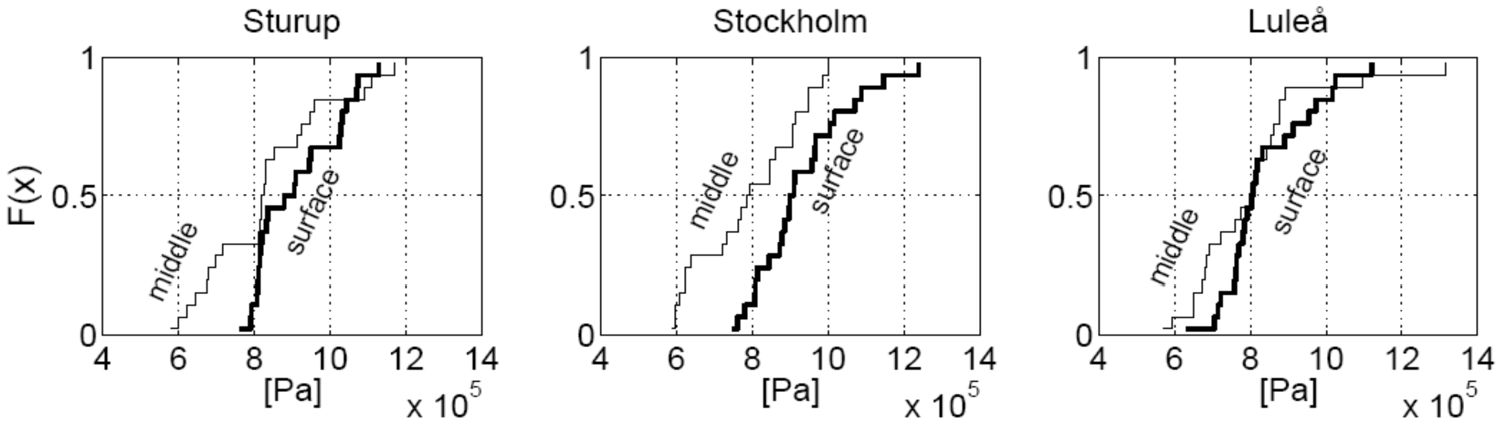
- Induced stresses at the surface and in the middle during 1000 days for Sturup together with indoor variation in relative humidity (starting January 1st).



Moisture induced stress

- 23 years calculation: Stress range and CDFs (max tension)





Moisture induced stress

- Parametric study
  - Influence of different parameters on moisture induced stress

Table 1 Parameter variation for the stress calculations

Parameter	Variations
Cross-section (CS)	42, 90, 215 mm
Moisture capacity (MCap)	factors 0.5, 1.0 and 1.5 times $C_{w, calculation}$
Mass transfer coefficient (MTC)	factors 1.0, 1/5, 1/50 times β_v ($0.156 \cdot 10^{-3}$ m/s)
Indoor moisture production (IMP)	0, 3, 6 g/m^3
Restraint (R)	No and complete restraint
External force (stress) (EF)	0, 0.5, 1.0 MPa (tension)
Hygroexpansion (α)	factors 0.5, 1.0 and 1.5 times values in Figure 2
Mechano-sorption (m)	factors 0.5, 1.0 and 1.5 times 0.085 MPa^{-1}
Mechano-sorption (β)	factors 0.5, 1.0 and 1.5 times -0.045 MPa^{-1}
MOE	factors 0.5, 1.0 and 1.5 times values in Figure 2

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Moisture induced stress

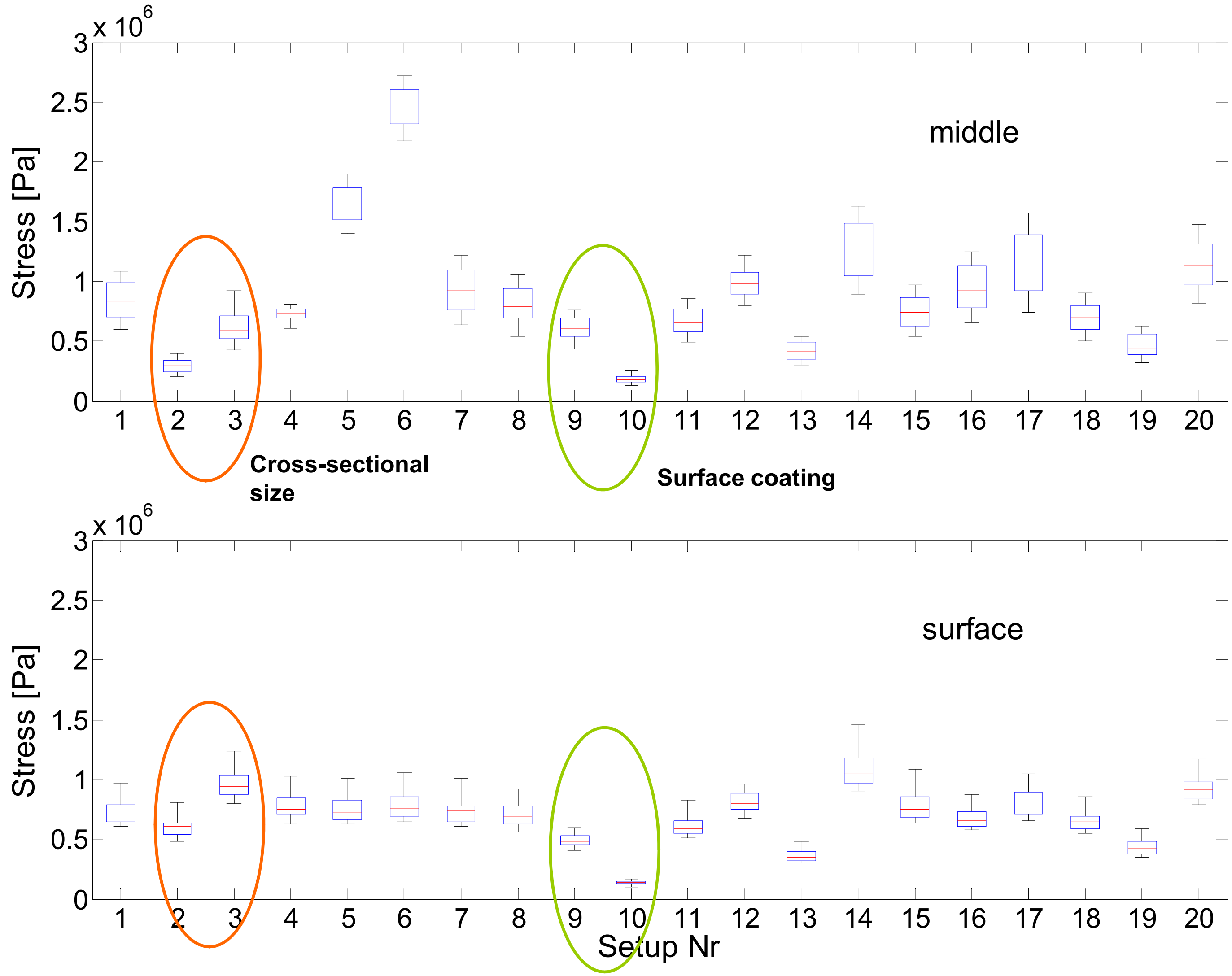
- Different setups

Table 2 Calculation setups. Based on outdoor climate data in Stockholm for the full years of 1961 to 2002, i.e. 42 years. (factor 1.0 in the reference row is for relative comparison only).

Setup No.	CS	MCap	MTC	IMP	R	EF	α	β	m	MOE
1 (reference)	90	1.0	1.0	3	No	No	1.0	1.0	1.0	1.0
2	**42**	-	-	-	-	-	*adjusted**	-	-	*adjusted**
3	**215**	-	-	-	-	-	*adjusted**	-	-	*adjusted**
4	-	-	-	-	**complete**	-	-	-	-	-
5	-	-	-	-	-	**0.5**	-	-	-	-
6	-	-	-	-	-	**1.0**	-	-	-	-
7	-	**0.5**	-	-	-	-	-	-	-	-
8	-	**1.5**	-	-	-	-	-	-	-	-
9	-	-	**1/5**	-	-	-	-	-	-	-
10	-	-	**1/50**	-	-	-	-	-	-	-
11	-	-	-	**0**	-	-	-	-	-	-
12	-	-	-	**6**	-	-	-	-	-	-
13	-	-	-	-	-	-	**0.5**	-	-	-
14	-	-	-	-	-	-	**1.5**	-	-	-
15	-	-	-	-	-	-	-	**0.5**	-	-
16	-	-	-	-	-	-	-	**1.5**	-	-
17	-	-	-	-	-	-	-	-	**0.5**	-
18	-	-	-	-	-	-	-	-	**1.5**	-
19	-	-	-	-	-	-	-	-	-	**0.5**
20	-	-	-	-	-	-	-	-	-	**1.5**

Moisture induced stress

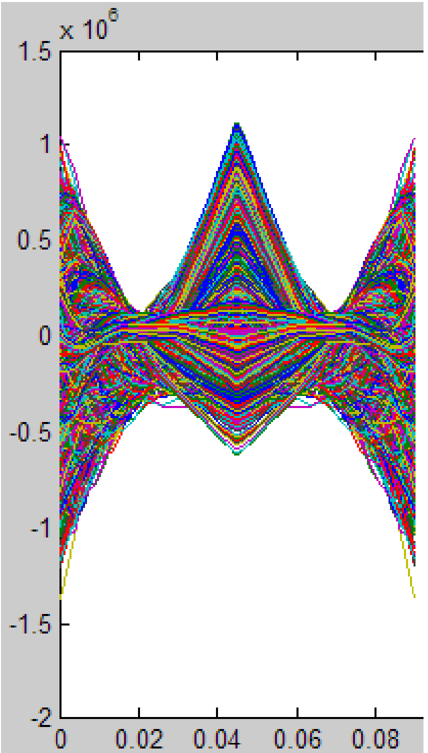
Boxplot showing the 5th, 25th, 50th, 75th and 95th percentiles of annual maximum tensile stress at the surface and in the middle.



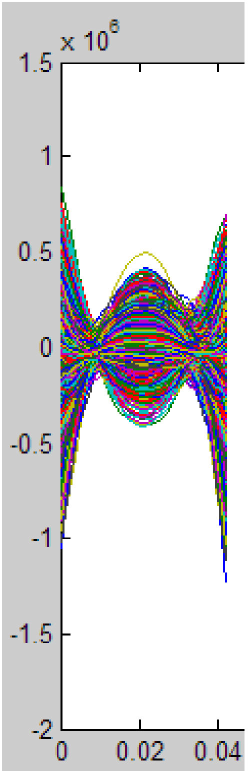
Moisture induced stress

Influence of cross-section on stress distribution

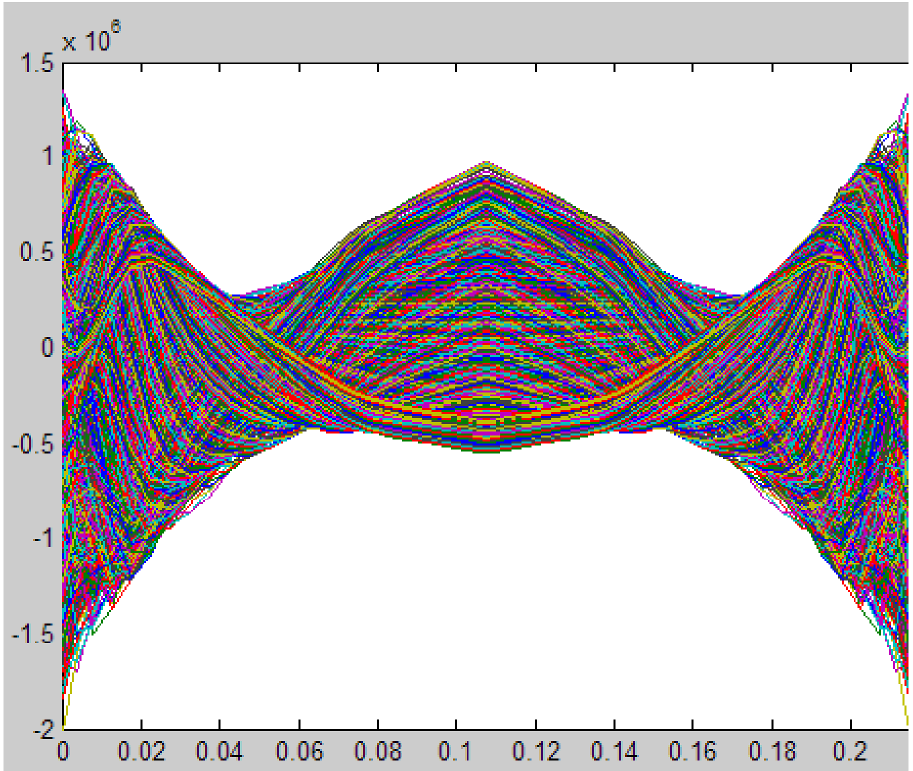
90 mm



42 mm



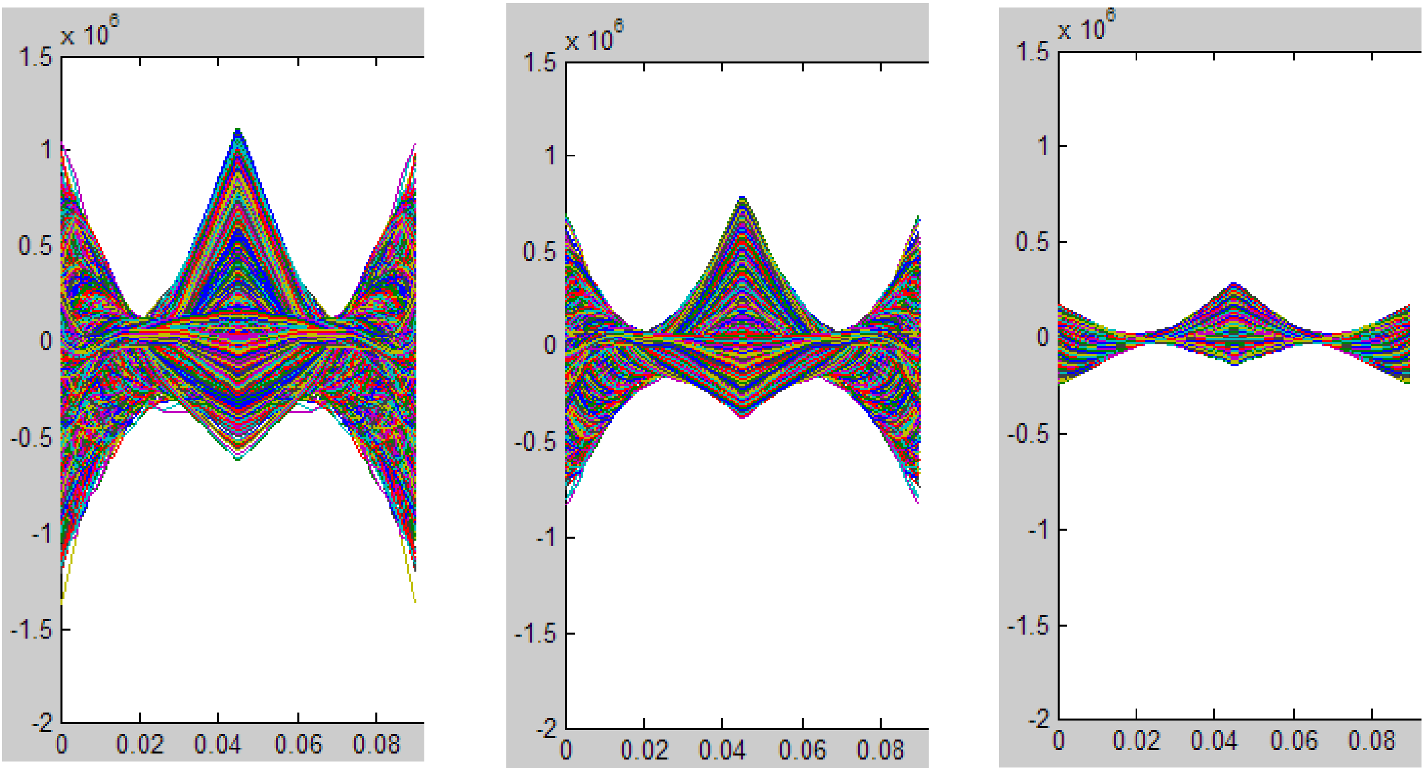
215 mm



Moisture induced stress

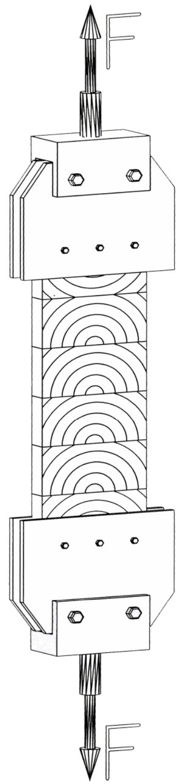
Influence of MTC on stress distribution

“1.0” “1/5” “1/50”



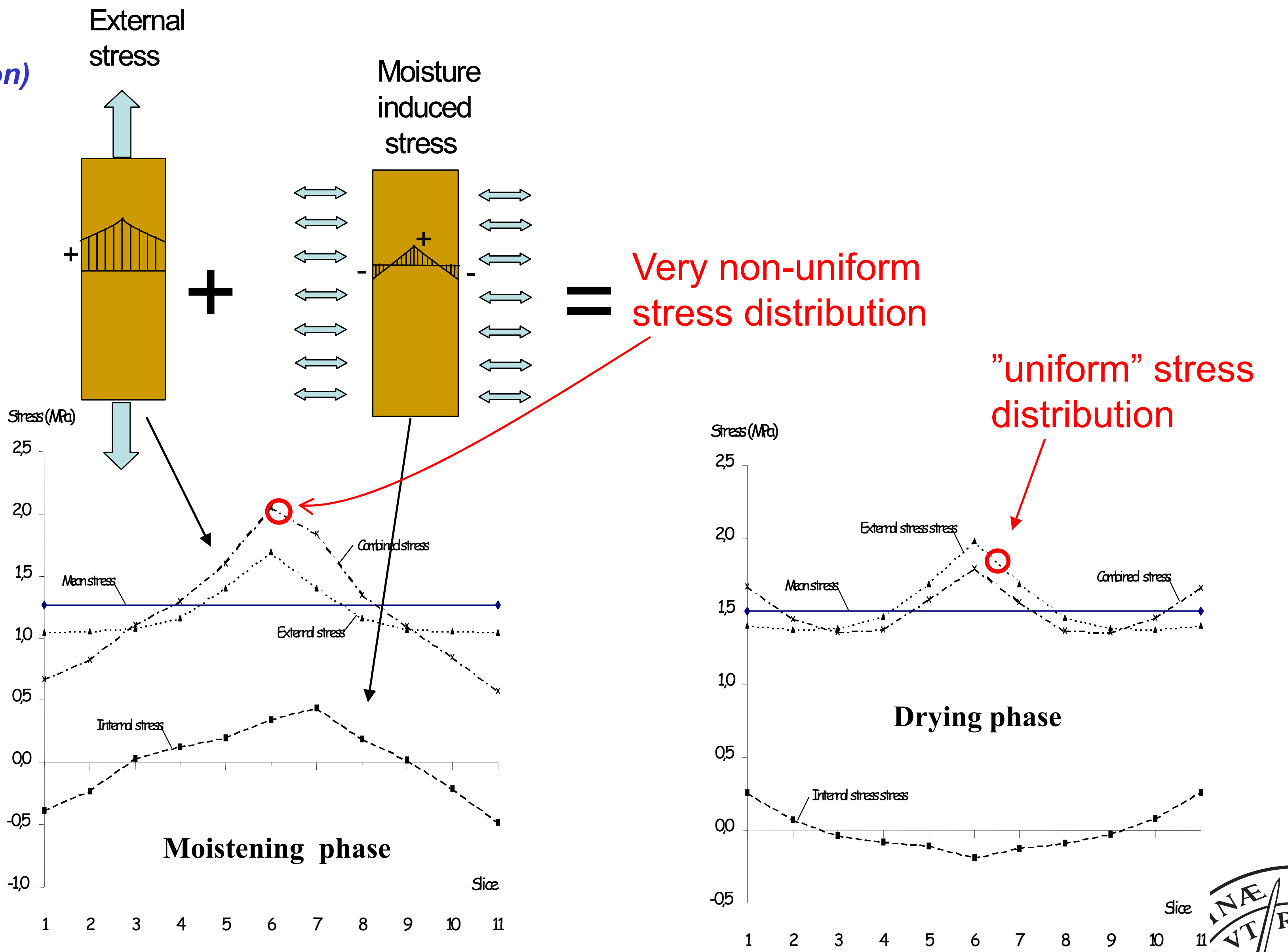
Moisture induced stress

- Experiments show effect of moisture on tensile capacity
  (Jönsson J. 2005)



Moisture induced stress

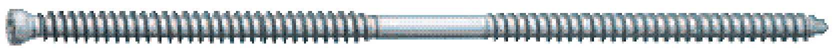
(From Jönsson)



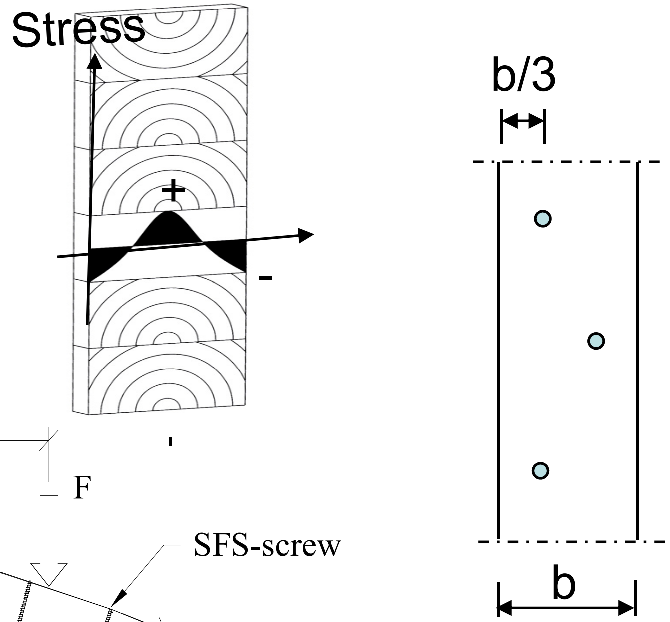
Moisture induced stress

(From Jönsson)

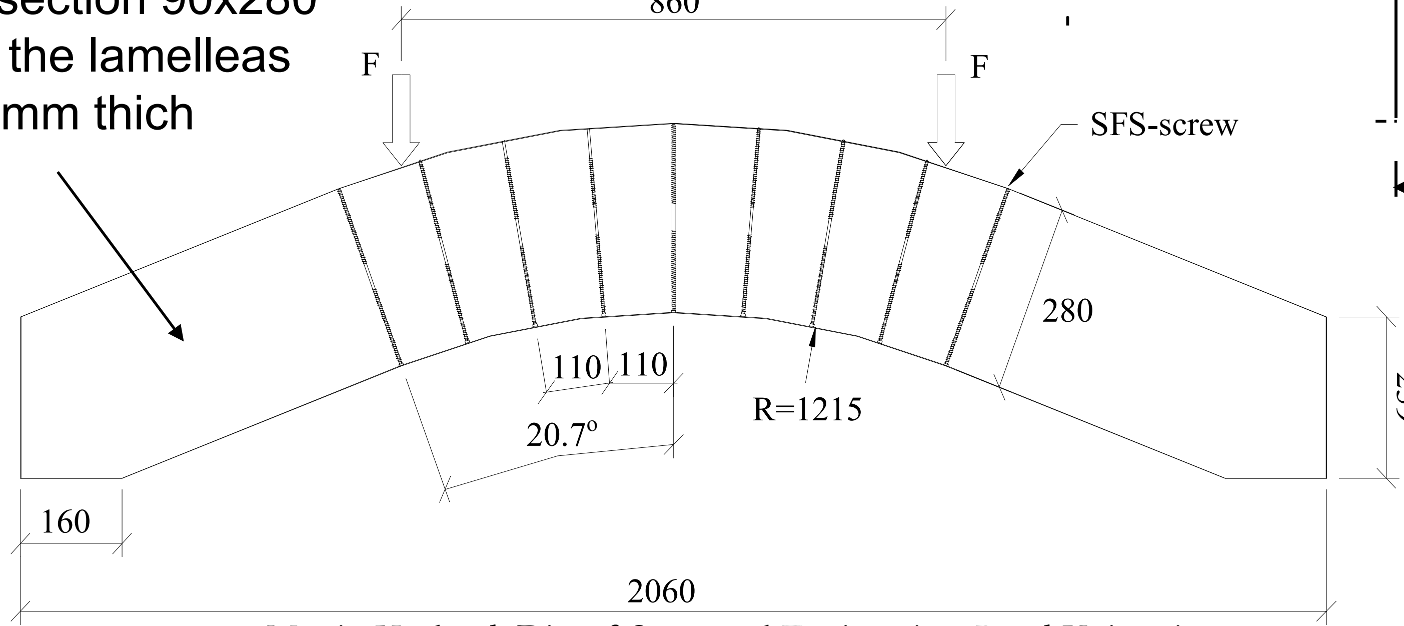
✓when using reinforcement



✓when exposing the beam to moisture induced stresses



The beam used in the test, cross-section 90x280 where the lamelleas are 20mm thich

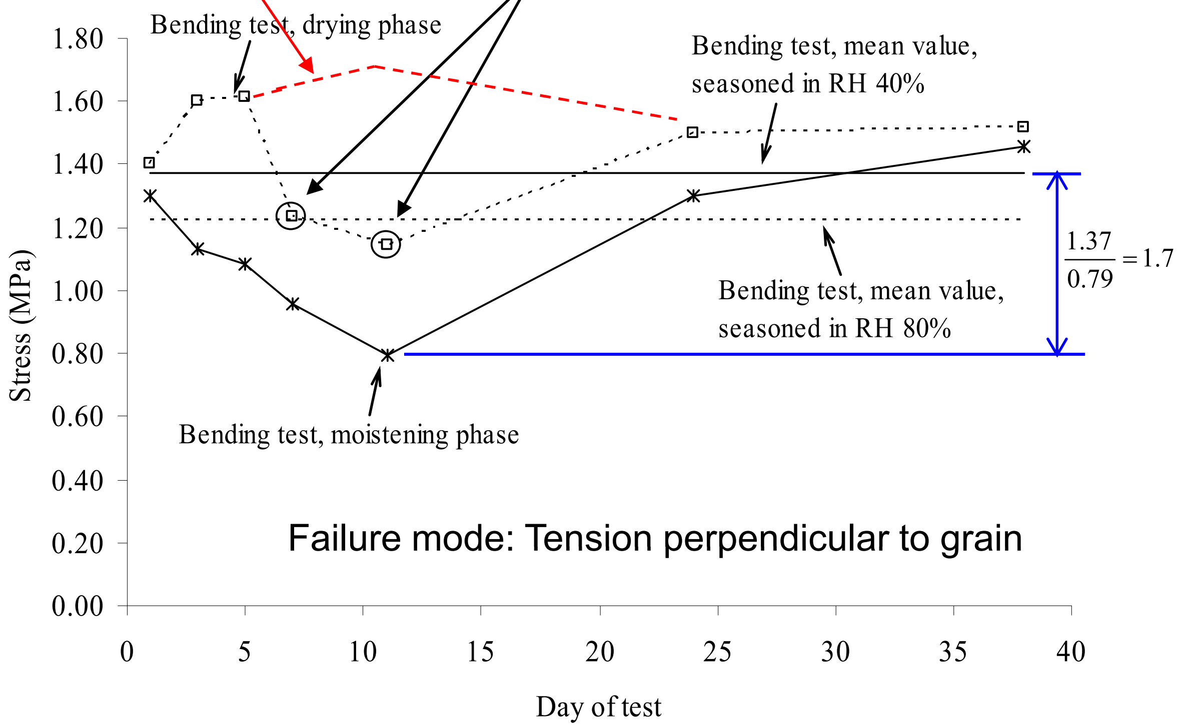


Moisture induced stress

(From Jönsson)

More reasonable shape of the curve, if the shear failure was prevented

Failed in shear, meaning that the tensile strength perpendicular to grain is not the limiting factor



Can clearly see an effect on the strength when moistening and drying the beam.

In the moistening phase the tensile stresses are added in the inner part, leading to a very uniform stress distribution.

Leading to lower strength

✓Rh 40-80% and 80-40%

Moisture induced stress

- Superposition of stress distribution
- Wetting and drying effect differs
  - Drying leads to more uniform combination of stresses – BETTER!
  - Wetting leads to the opposite

Consideration of moisture as an action

Consideration of moisture as an action

- Moisture induce stress in timber structures
  - Results in non-uniform stress field
  - Strength perpendicular to grain is “weak”

- General design criteria $$\sum_{i=1}^{k}\left(\gamma_{Gi}\sigma_{Gi}\right)+\sum_{i=1}^{k}\left(\gamma_{Qi}\psi_{i}\sigma_{Qi}\right)\leq k_{mod}\frac{f}{\gamma_{M}}$$

- Two general design options
  - Should the action be considered on the resistance side, or on the action side ?
    - Today it is on the resistance side in form of strength reduction factor

Consideration of moisture as an action

Moisture effects in current codes

- Considered by service classes based on expected **equilibrium moisture levels**
- Time dependent **variation** of moisture exposure is not considered

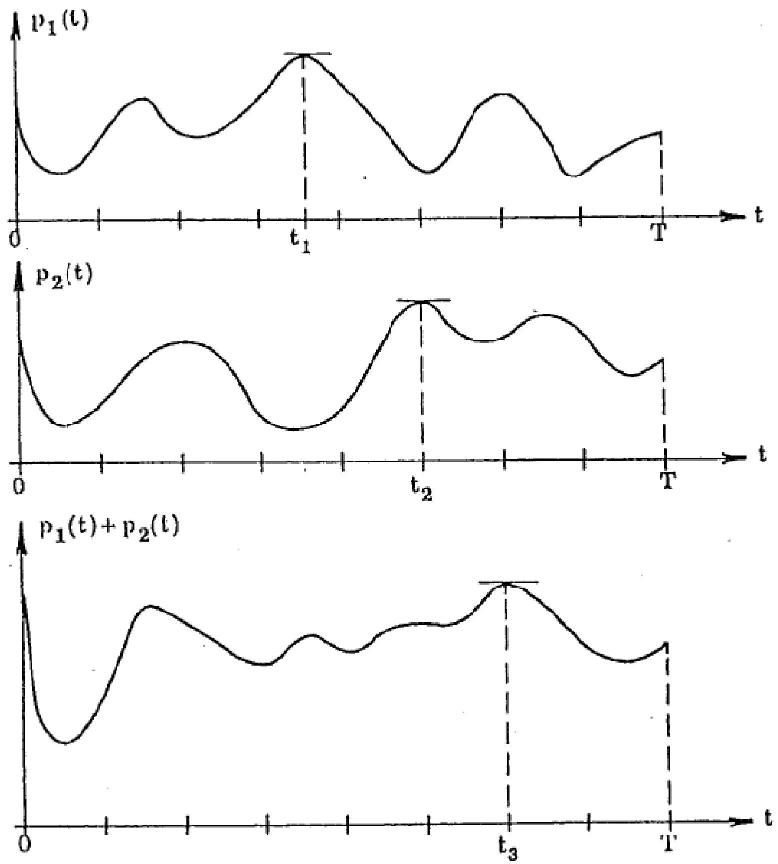
A more precise characterisation is desired to improve the way moisture is considered

Consideration of moisture as an action

- How should effects of actions be combined?
  - Factors ψ_i to consider effect of concurrent actions and their combined effect
  - Summation of individual annual design values not correct
    - Variation in time different for t ex snow, wind and MiS.
  - Two (or more) loading process(es) are not prone to reach their maximum load within a given reference period (e.g. 1 year suitable in order to have (“fairly”) stationary processes at the same instance of time.

Consideration of moisture as an action

"Barrier crossing problem": What is the probability (risk!) that the combined effects will cross a predetermined level during a specific time period?



From Thoft-Christensen & Baker, 1982

$$F_{X1}(x) = \max_T \{X_1 + X_2 + ... + X_n\}$$

"correct"

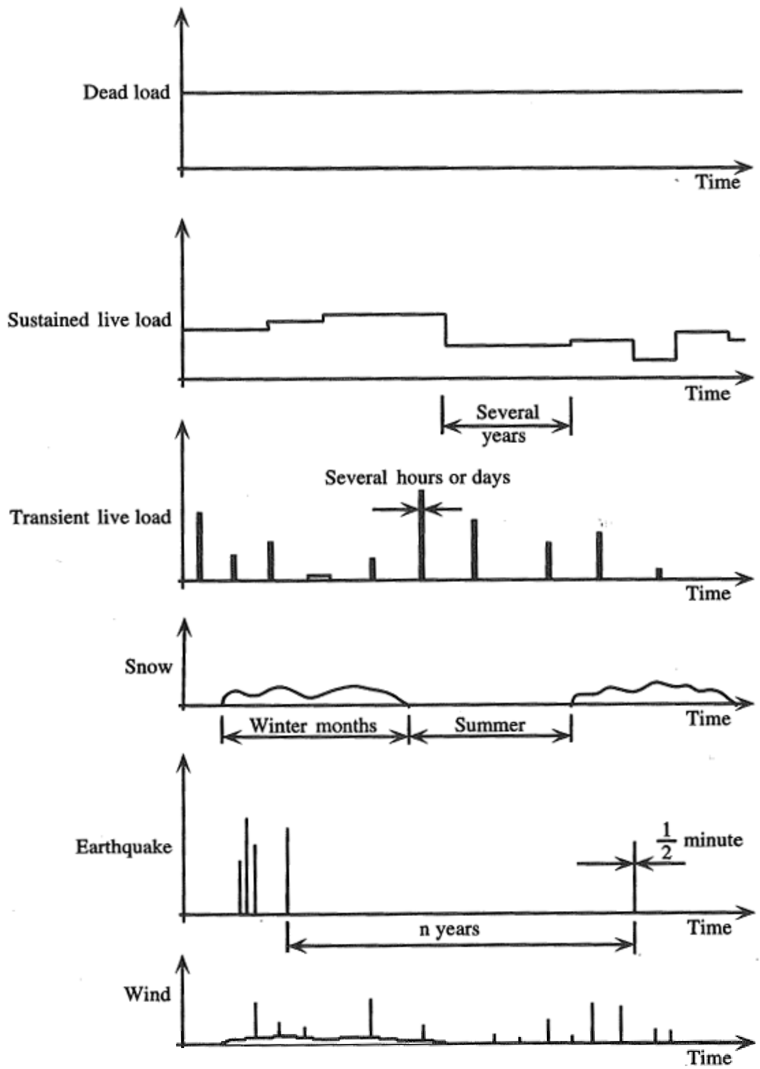
Practical problems

- Processes not known well enough?, sampling of realizations limited in time (e.g. snow load)
- "Impossible" to implement in codes in its original theoretical form

$$F_{X2}(x) = \max_T (X_1) + \max_T (X_2) + ... + \max_T (X_n)$$

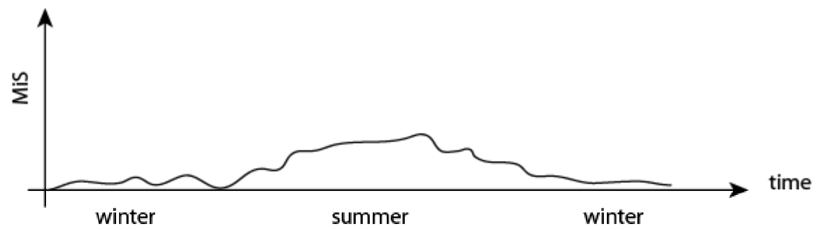
"to conservative"

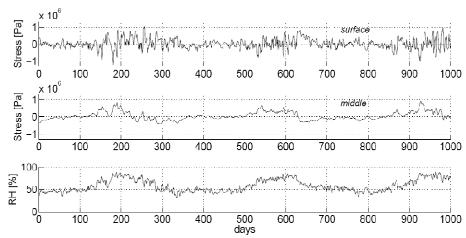
Consideration of moisture as an action



(From Nowak & Collins, 2000)

- Different typs of loads have their typical variation in time
- Coinciding loads or time separated loads
- Moisture induced stress predominant during summer season





Consideration of moisture as an action

- In summary…
  - Moisture variation can induce high tensile stress
    - Different theories on modeling of stress (mechano-sorption)
    - High variability between timber elements (stress distribution)
    - How should this be accounted for?
  - Moisture as an action
    - How to describe moisture as an action (load effect)
    - Lack of data / experiments ?
    - Implementation in engineering design - usability
  - Protective measures
    - Reinforcement
    - Painting / water vapour resistance
      - Durability (e.g. cracking)

Thank you for your attention

Acknowledgement
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