COST Action FP1004

Final Meeting

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Moisture-induced stresses in timber structures

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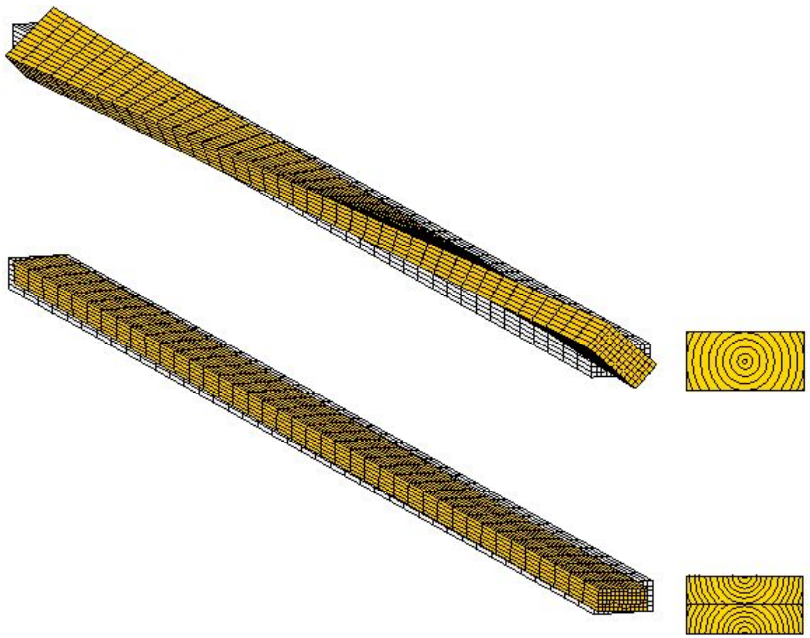
Presentation overview

- Introduction
- Material and methods
  - Material data
  - Modelling method for curved timber frames
- Moisture transport
  - Climate variation
  - Diffusion coefficients
  - Numerical example
- Moisture-induced stresses
  - FEM formulation
  - Numerical examples
- Conclusions

My previous modelling experience

3D distortion simulations



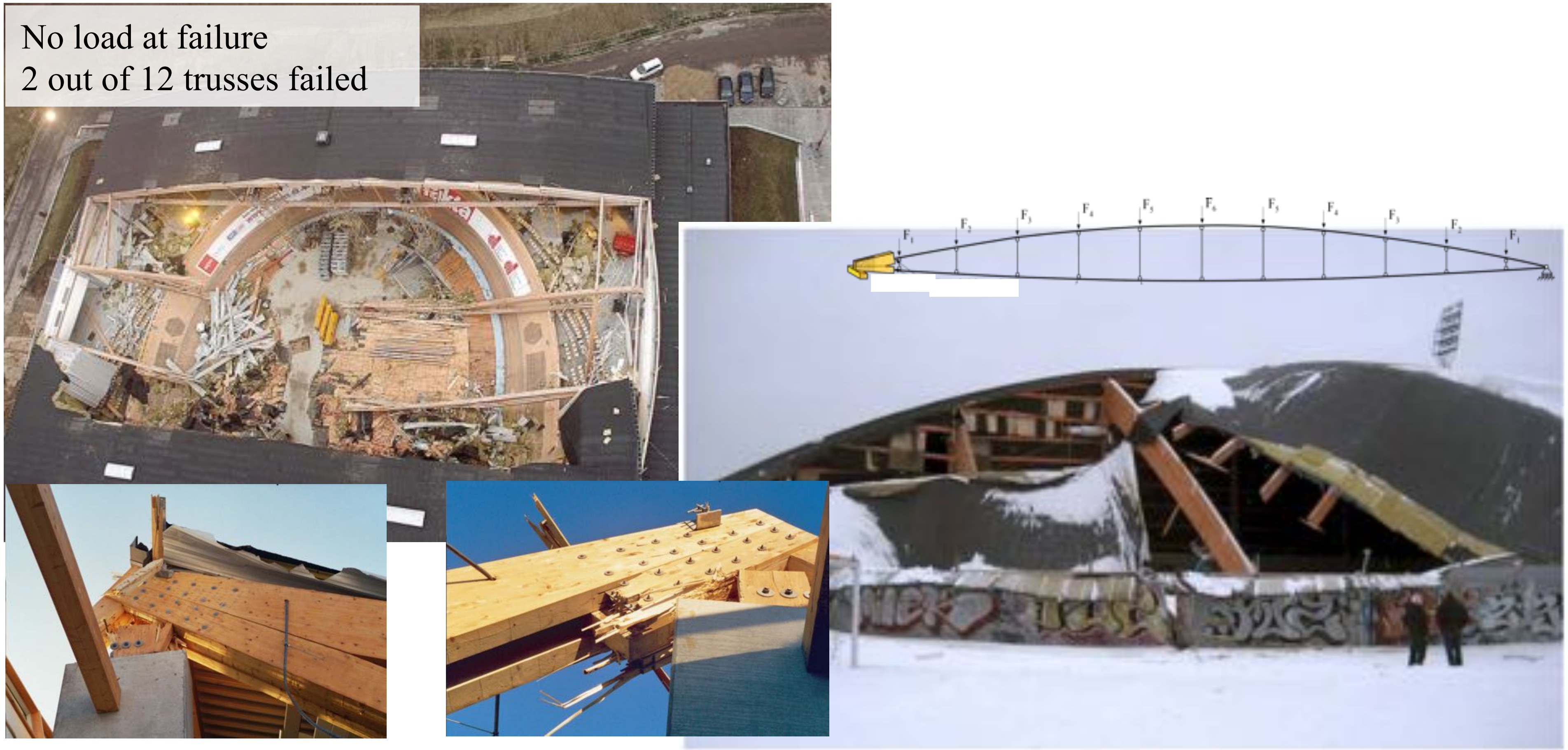
Introduction

Teacher in timber construction for eight years?

- Design based on EC5
- Design of structural elements
- Design of timber connections
- Exercises solved by hand, 1D or 2D
- Exercises that fits the expressions given in EC5
- Forced to do simplifications because of the design method.
- Difficult to use numerical stress simulations because the design criteria in EC5 are based on hand calculations
- Design of structural systems for advanced timber constructions was limited.

Introduction

Why is this happening? (low degree of robustness, wrong connection design)



Introduction

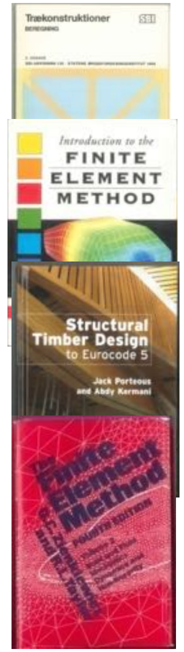
Timber structure exposed to outdoor climate variation

Introduction

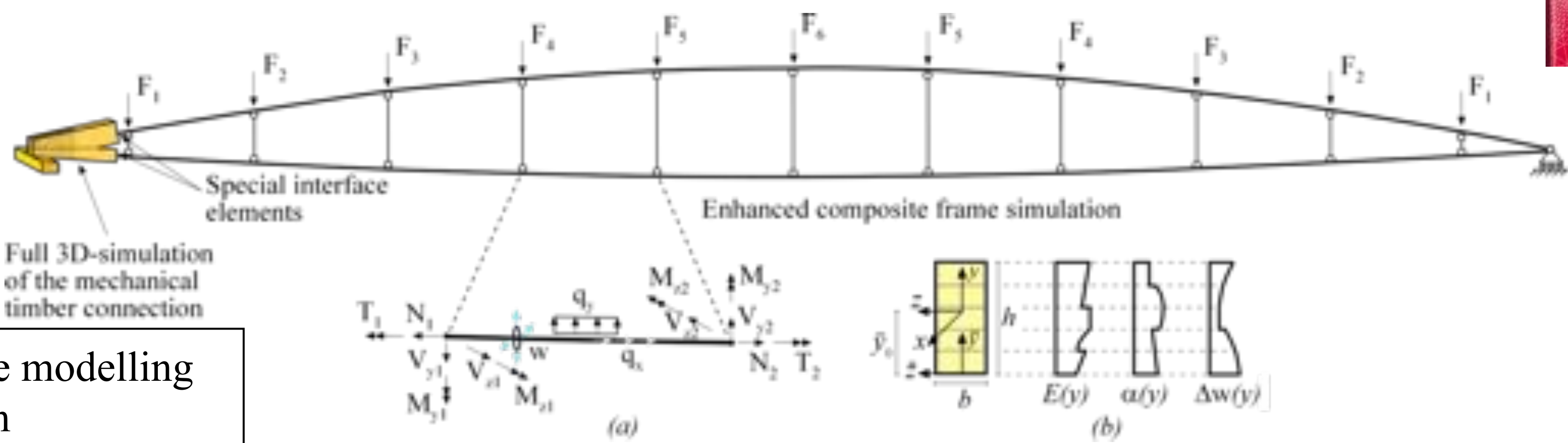
Old timber construction

Material and methods

How can we analyse advanced timber constructions?



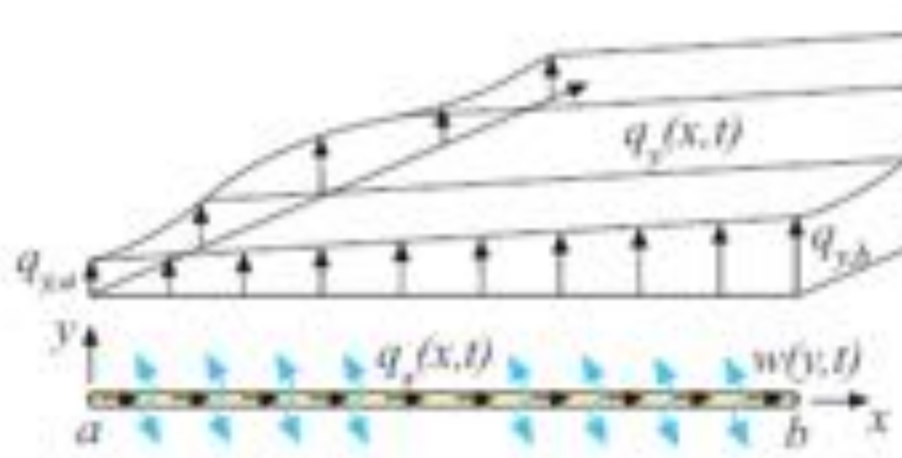
- There is a need of an **effective computer tool** to study how timber structures behave during both **mechanical and environmental loading**.
- In EC5 and in many textbooks on timber design it is stated that the **moisture sensitivity** of the wood material must be taken into account in the design process. **But the fact is that these matters are not dealt with properly.**

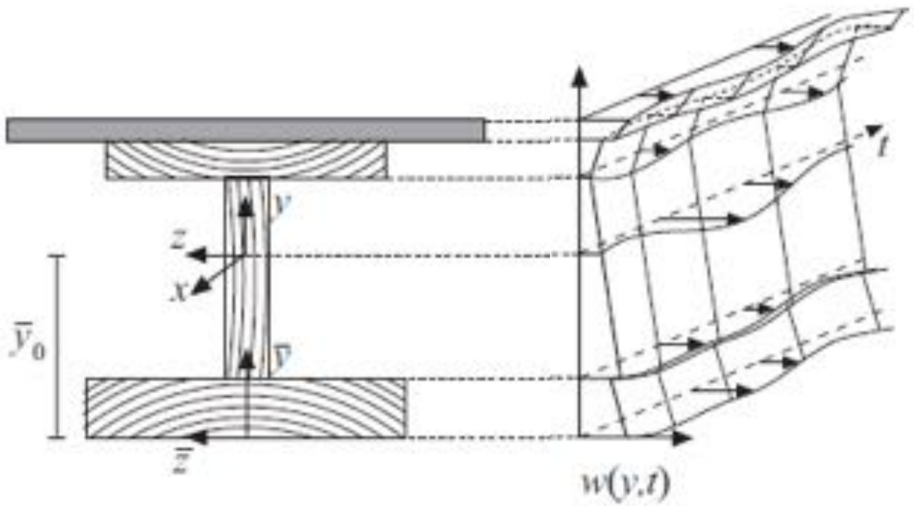


Adaptive modelling approach

Material and methods

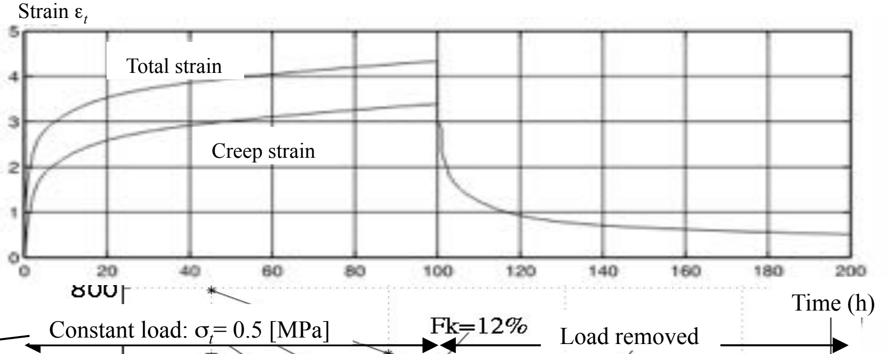
Extended beam model for simulation of hygro-mechanical and visco-elastic deformations and stresses in timber structures

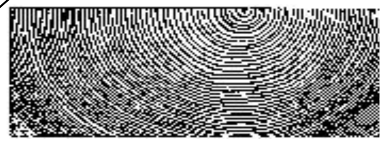


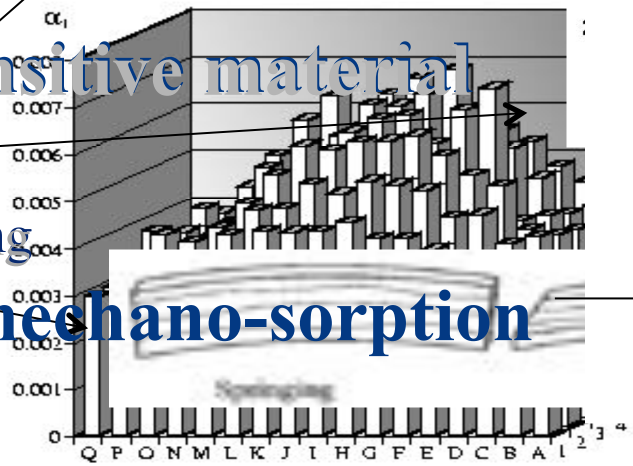


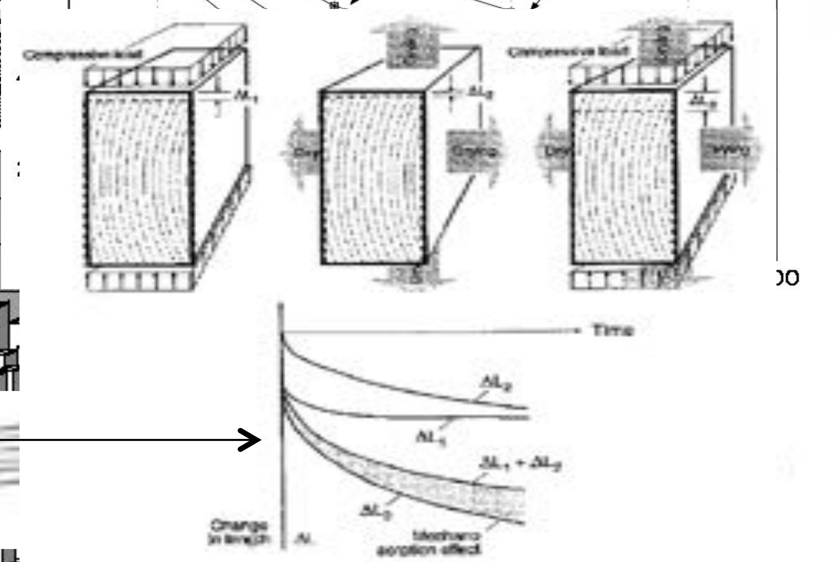
Material and methods

- Strongly orthotropic materia[l]
  - Stiffness: $E_l/E_t = 30$
  - Shrinkage/swelling: $\alpha_t/\alpha_l = 35$
- Inhomogeneous material
  - Stiffness
  - Shrinkage/swelling
- Moisture sensitive material
  - Stiffness
  - Shrinkage/swelling
- **Creep and mechano-sorption**





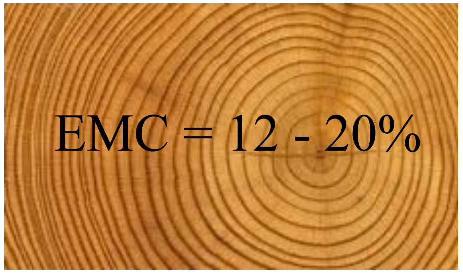


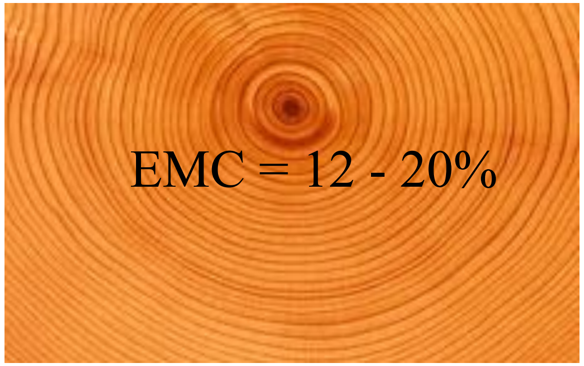


Hygroscopic material

- **Wood is a hygroscopic material** which means that it attempts to attain an equilibrium moisture content (EMC) with its surrounding environment, resulting in a variable moisture content during the year.

Variation in RH over a year, RH = 60 to 90%



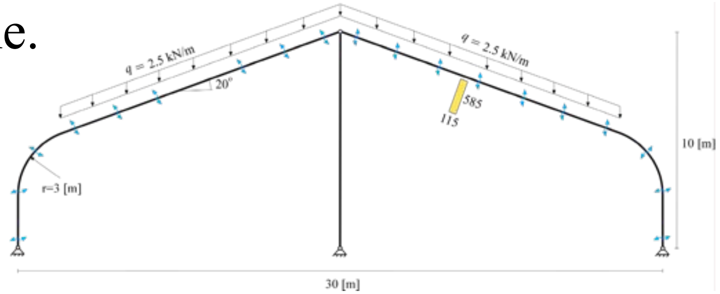


Variation in temperature over a year, T = -10 to 20^{o}C

Material and methods

Models needed for simulation of a curved frame structure

i) A two-dimensional transient non-linear moisture transport analysis of the cross-section of the frame.



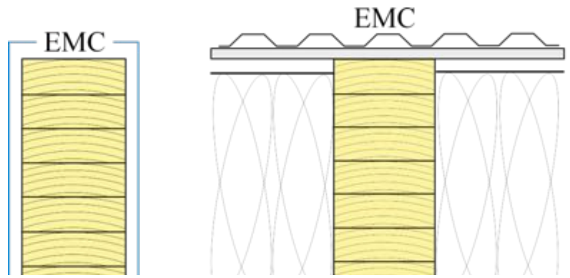
ii) A frame analysis used for simulation of the long-term visco-elastic and hygro-mechanical deformations of the timber frame structures.

iii) A two-dimensional distortion model of the cross-section to simulate the stresses found perpendicular to the direction of the grain.

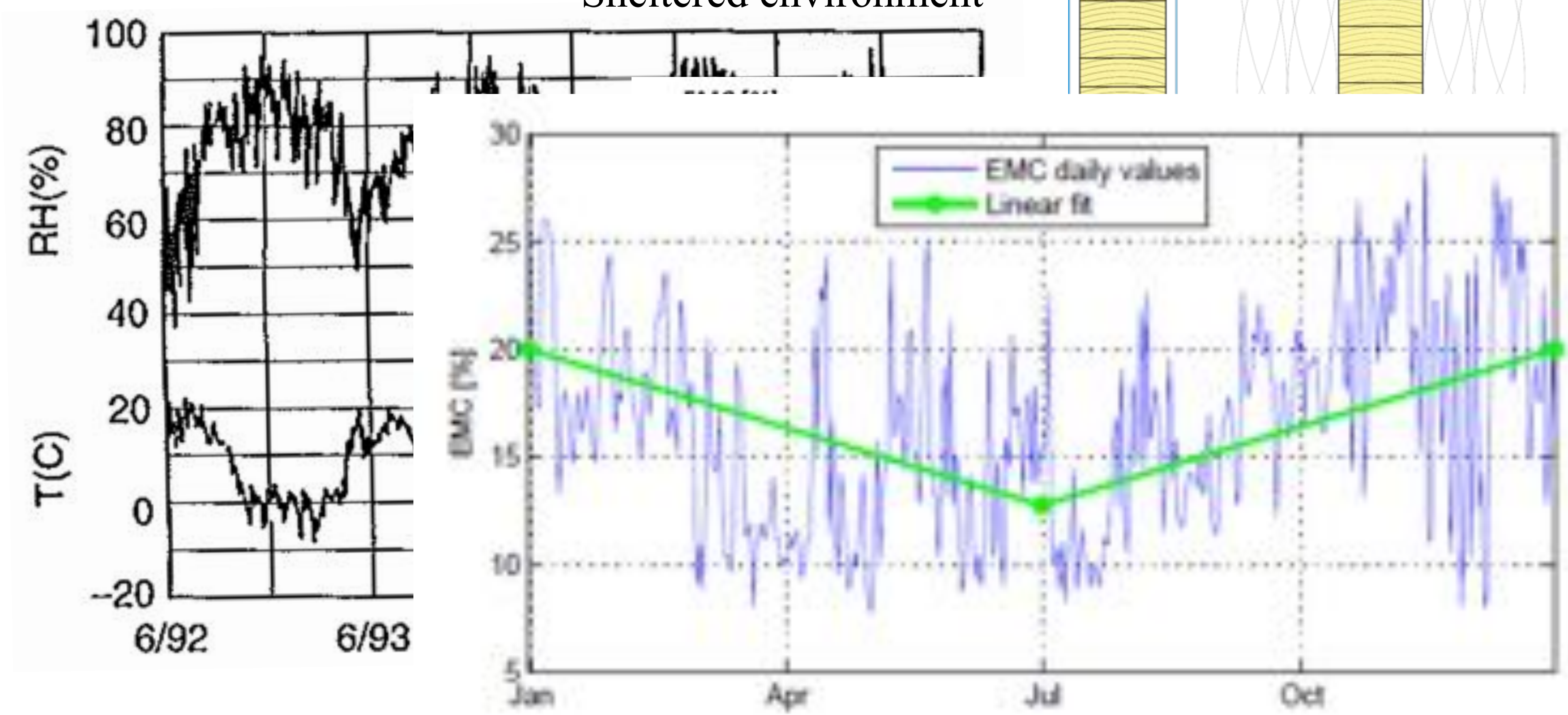
iv) A two-dimensional stress model of the frame structure to study stresses perpendicular to the grain direction in the curved part of the frame because of the structural constraints found concerning the free straightening or free bending of the curved part during moistening or drying of the frame.

Moisture transport

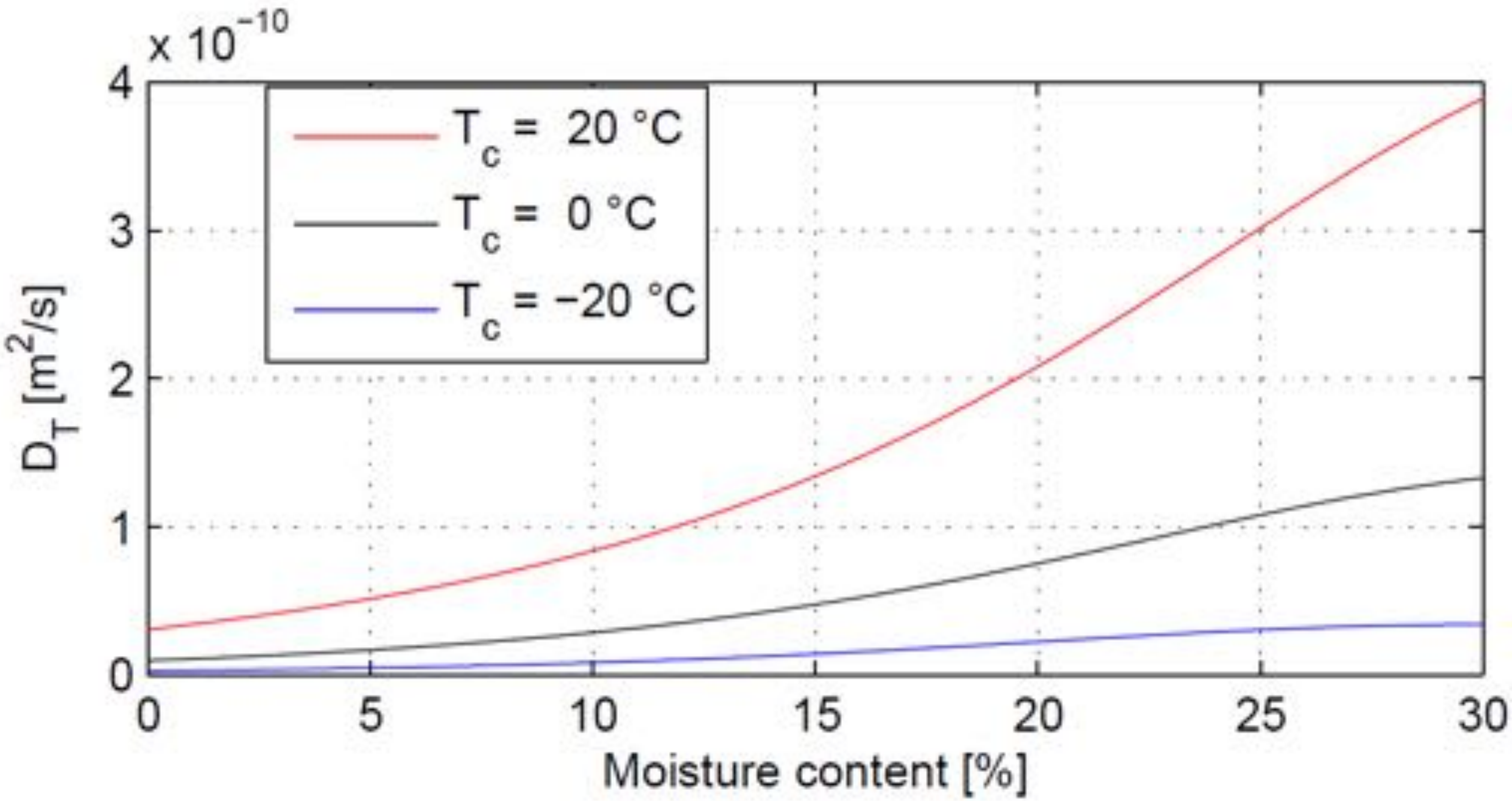
Typical climate variation in Scandinavia



Sheltered environment

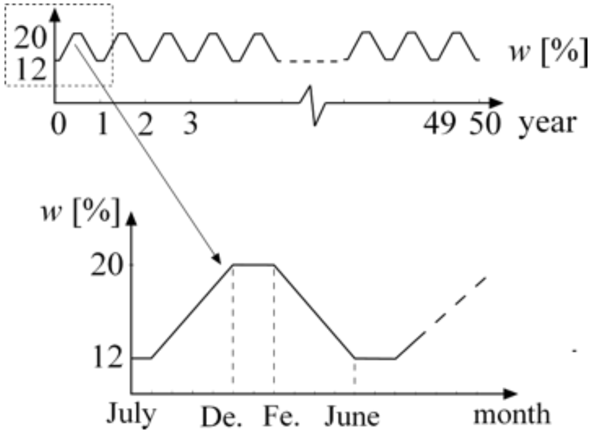


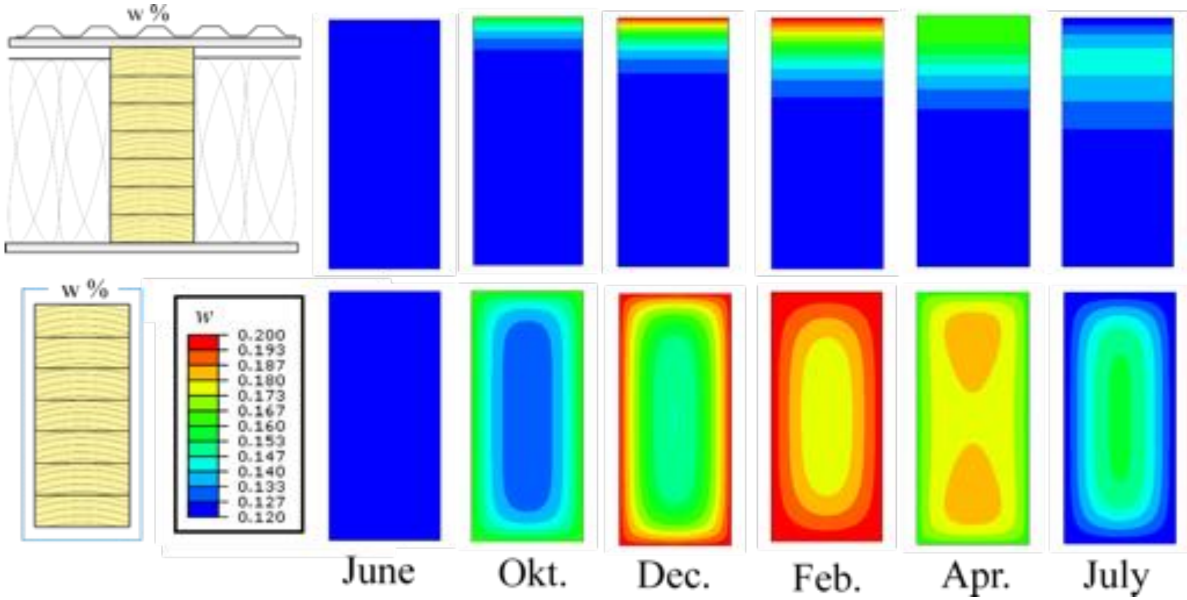
Variation in diffusion coefficients



Moisture transport

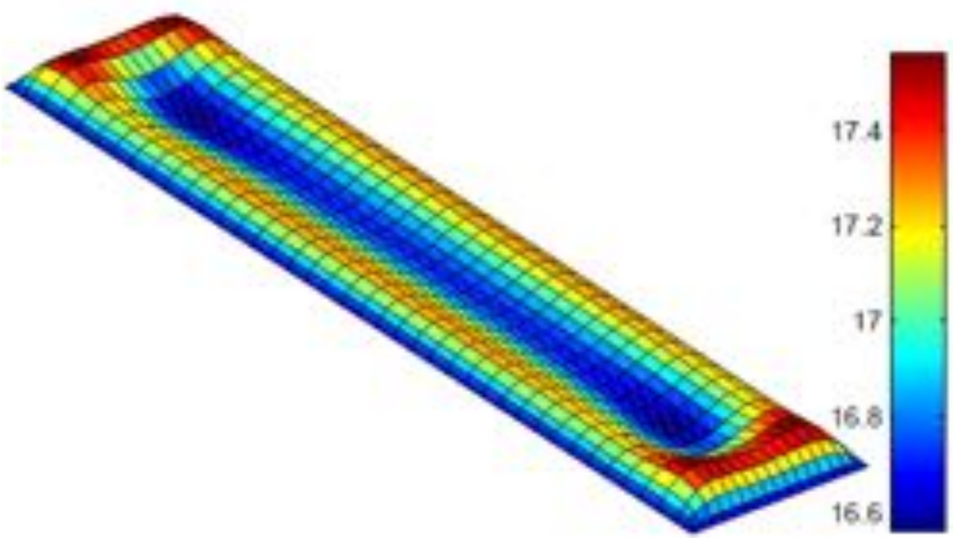
Moisture content gradients

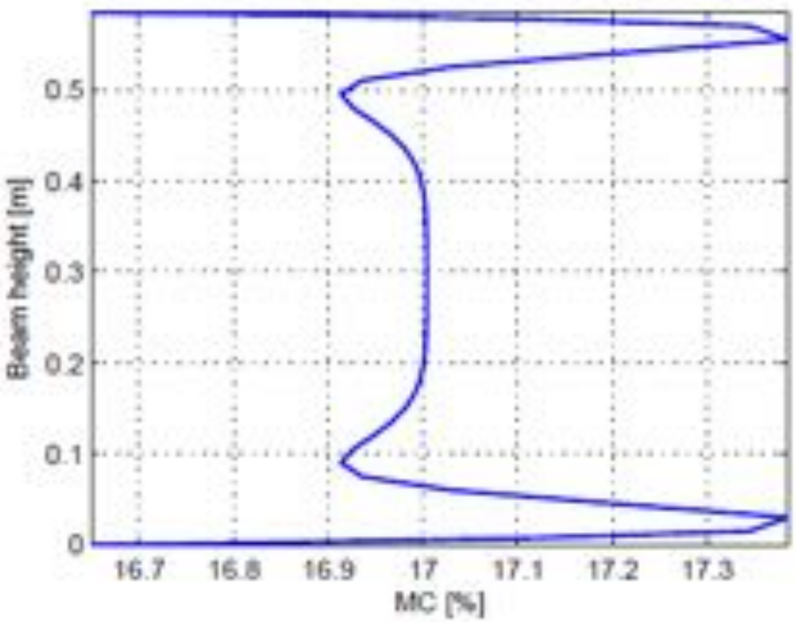




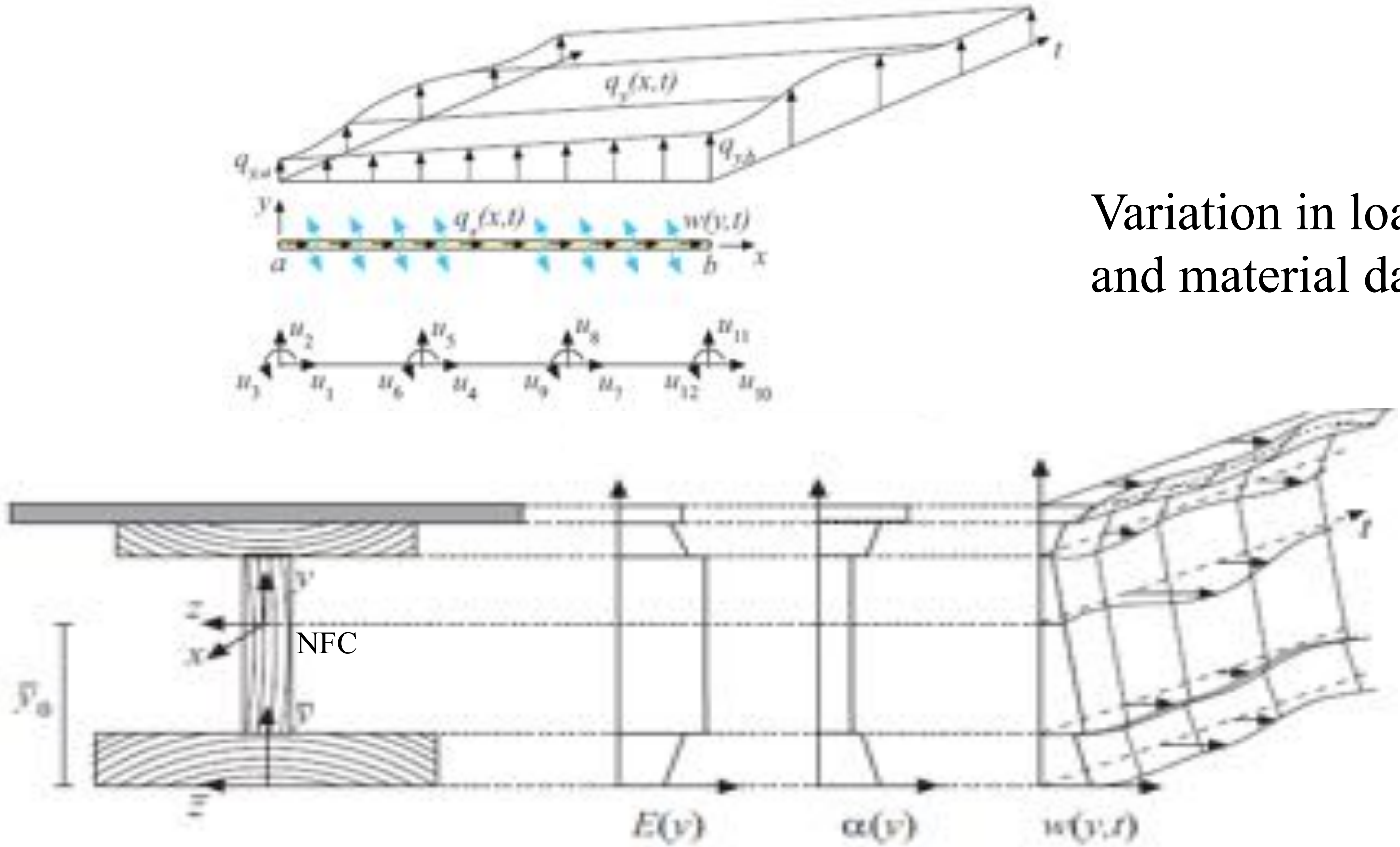
Moisture transport

1D MC-variation based on 2D analysis





A beam element with 4 nodal points



Variation in loads and material data

Moisture-induced stresses

Constitutive relations: (strains/stress)

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_w + \dot{\varepsilon}_m + \dot{\varepsilon}_c$$

Creep strain rate

$$\dot{\varepsilon}_c(x,y,t) = \hat{\boldsymbol{G}} \sum_{n=1}^{N} \frac{1}{\tau_n} e^{-\frac{t}{\tau_n}} \dot{\boldsymbol{\gamma}}_n(x,y,t)$$

Mechano-sorptive strain rate

$$\dot{\varepsilon}_m(x,y) = \hat{\boldsymbol{G}}\boldsymbol{m}\breve{\boldsymbol{G}}\sigma(x,y)\left|\dot{w}(x,y)\right|$$

Moisture induced strain rate

$$\dot{\varepsilon}_w(x,y) = \hat{\boldsymbol{G}}\boldsymbol{\alpha}(x,y)\dot{w}(x,y)$$

Elastic strain rate

$$\dot{\varepsilon}_e(x,y) = \frac{1}{E(x,y)}\dot{\sigma}(x,y) = C_{11}(x,y)\dot{\sigma}(x,y)$$

Total strain rate

$$\dot{\varepsilon}(x,y) = \dot{\varepsilon}_0(x) - \dot{\kappa}(x)y$$

$$\dot{\sigma} = E\dot{\varepsilon}_e = E(\dot{\varepsilon} - \dot{\varepsilon}_w - \dot{\varepsilon}_m - \dot{\varepsilon}_c)$$

The creep driver

$$\dot{\gamma}_n(x,y,t)=\int_0^t e^{\frac{t'}{\tau_n}}\overline{\boldsymbol{C}}_{c_n}\breve{\boldsymbol{G}}\dot{\sigma}(x,y,t')dt' =$$

$$\int_0^t e^{\frac{t'}{\tau_n}}\begin{bmatrix} \frac{1}{E_l(x,y)}\phi_n & -\frac{v_{rl}}{E_r}\phi_n & -\frac{v_{tl}}{E_t}\phi_n & 0 & 0 & 0 \\ -\frac{v_{lr}}{E_l}\phi_n & \frac{1}{E_r}\phi_n & -\frac{v_{tr}}{E_t}\phi_n & 0 & 0 & 0 \\ -\frac{v_{lt}}{E_l}\phi_n & -\frac{v_{rt}}{E_r}\phi_n & \frac{1}{E_t}\phi_n & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{lr}}\phi_n & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{lt}}\phi_n & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{rt}}\phi_n \end{bmatrix}\breve{\boldsymbol{G}}\dot{\sigma}(x,y,t')dt'$$

Moisture-induced stresses

Constitutive relations: (sec. forces/strains, curvature)

$$\dot{\boldsymbol{F}}(x) = \boldsymbol{D}(x)\dot{\boldsymbol{\zeta}}(x) - \dot{\boldsymbol{F}}_p(x)$$

$$\begin{bmatrix} \dot{N}(x) \\ \dot{M}_z(x) \end{bmatrix} = \begin{bmatrix} D_{EA}(x) & 0 \\ 0 & D_{EI_z}(x) \end{bmatrix} \begin{bmatrix} \dot{\varepsilon}_0(x) \\ \dot{\kappa}_z(x) \end{bmatrix} - \begin{bmatrix} \dot{N}_p(x) \\ \dot{M}_{p_z}(x) \end{bmatrix}$$

$$D_{EA}(x) = \int_A E(x,y)\,dA$$

$$D_{EI_z}(x) = \int_A E(x,y)\,y^2\,dA$$

$$\begin{bmatrix} \dot{N}_p(x) \\ \dot{M}_{p_z}(x) \end{bmatrix} = \int_A E(x,y)\left(\begin{bmatrix} \dot{\varepsilon}_w(x,y) \\ \dot{\varepsilon}_w(x,y)y \end{bmatrix} + \begin{bmatrix} \dot{\varepsilon}_m(x,y) \\ \dot{\varepsilon}_m(x,y)y \end{bmatrix} + \begin{bmatrix} \dot{\varepsilon}_c(x,y) \\ \dot{\varepsilon}_c(x,y)y \end{bmatrix} \right) dA$$

Moisture-induced stresses

Finite element formulation

$$\int_a^b \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B}dx\dot{\boldsymbol{a}} - \left[(\hat{\nabla}\boldsymbol{N})^T \dot{\boldsymbol{F}}\right]_a^b + \left[\boldsymbol{N}^T\dot{\boldsymbol{V}}\right]_a^b - \int_a^b \boldsymbol{N}^T\dot{\boldsymbol{q}}dx - \int_a^b \boldsymbol{B}^T\dot{\boldsymbol{F}}_p dx = 0$$

$$\boldsymbol{K} = \int_a^b \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B}dx$$ (Stiffness matrix)

$$\dot{\boldsymbol{f}}_b = \left[(\hat{\nabla}\boldsymbol{N})^T \dot{\boldsymbol{F}}\right]_a^b - \left[\boldsymbol{N}^T\dot{\boldsymbol{V}}\right]_a^b$$ (Boundary vector)

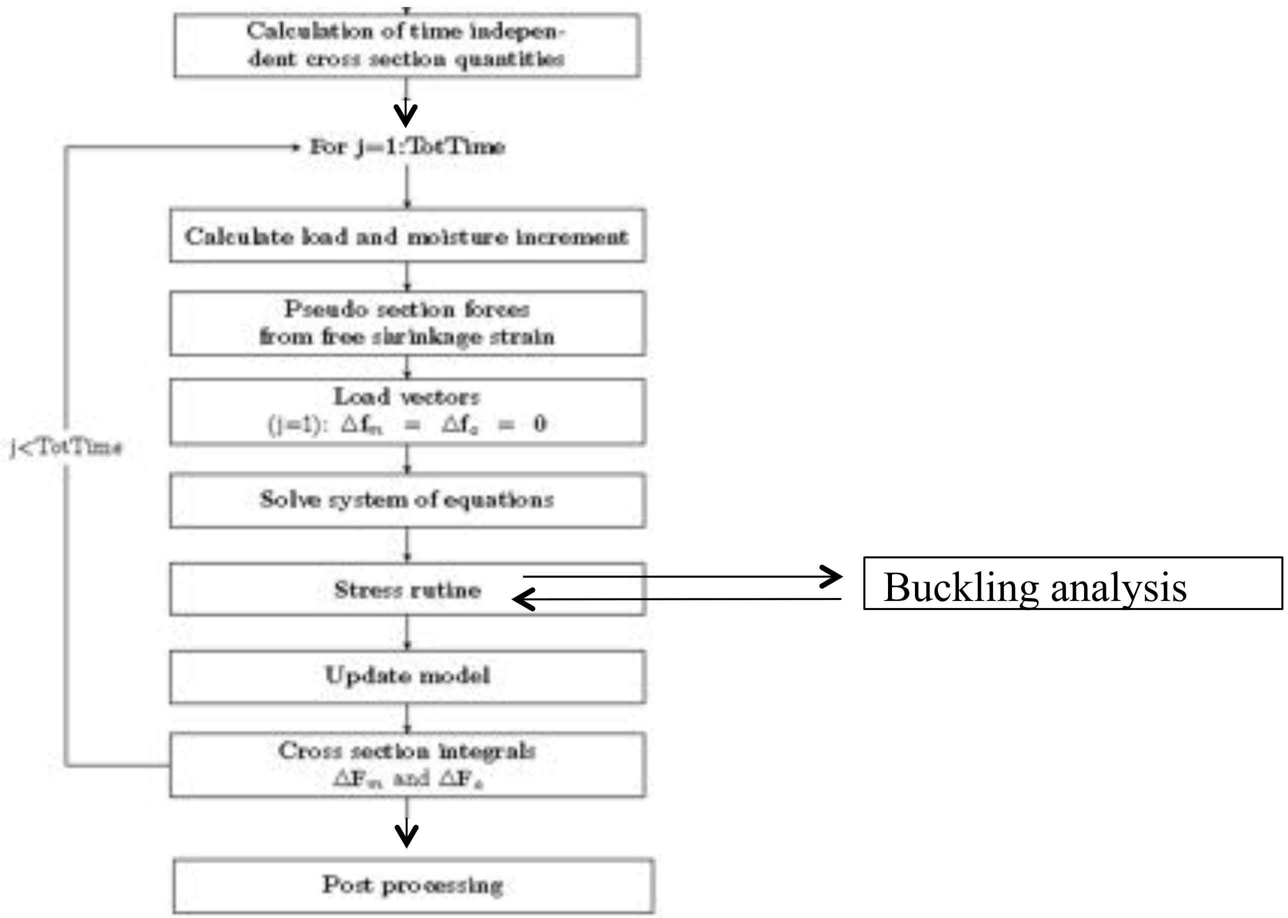
$$\dot{\boldsymbol{f}}_l = \int_a^b \boldsymbol{N}^T\dot{\boldsymbol{q}}dx$$ (Load vector)

$$\dot{\boldsymbol{f}}_p = \dot{\boldsymbol{f}}_w + \dot{\boldsymbol{f}}_m + \dot{\boldsymbol{f}}_c = \int_a^b \boldsymbol{B}^T\dot{\boldsymbol{F}}_p dx = \int_a^b \boldsymbol{B}^T(\dot{\boldsymbol{F}}_w + \dot{\boldsymbol{F}}_m + \dot{\boldsymbol{F}}_c)dx$$ (Pseudo-load vector)

$$\boldsymbol{K}\dot{\boldsymbol{a}} = \dot{\boldsymbol{f}}_b + \dot{\boldsymbol{f}}_l + \dot{\boldsymbol{f}}_p$$

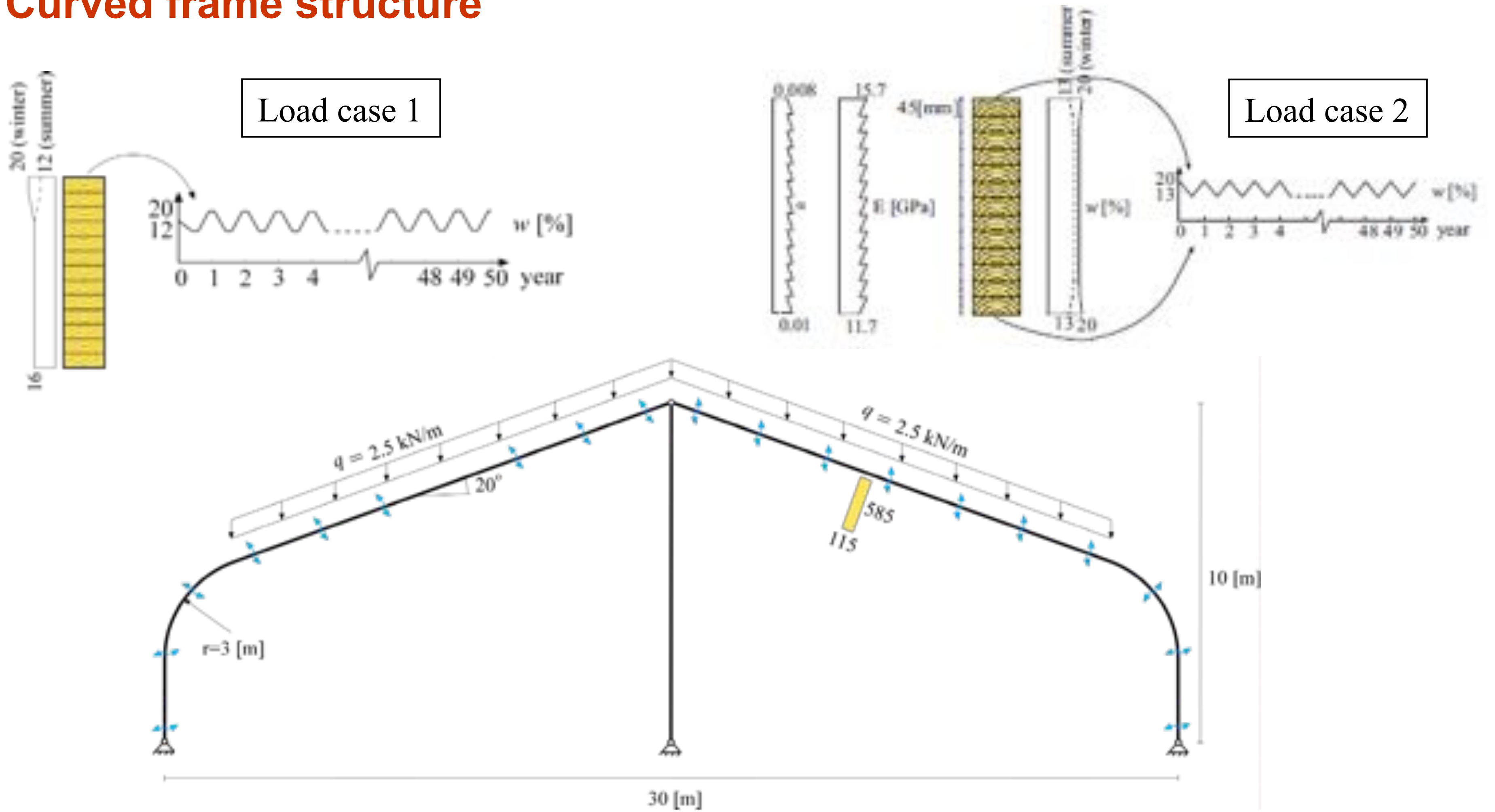
Moisture-induced stresses

Incremental formulation



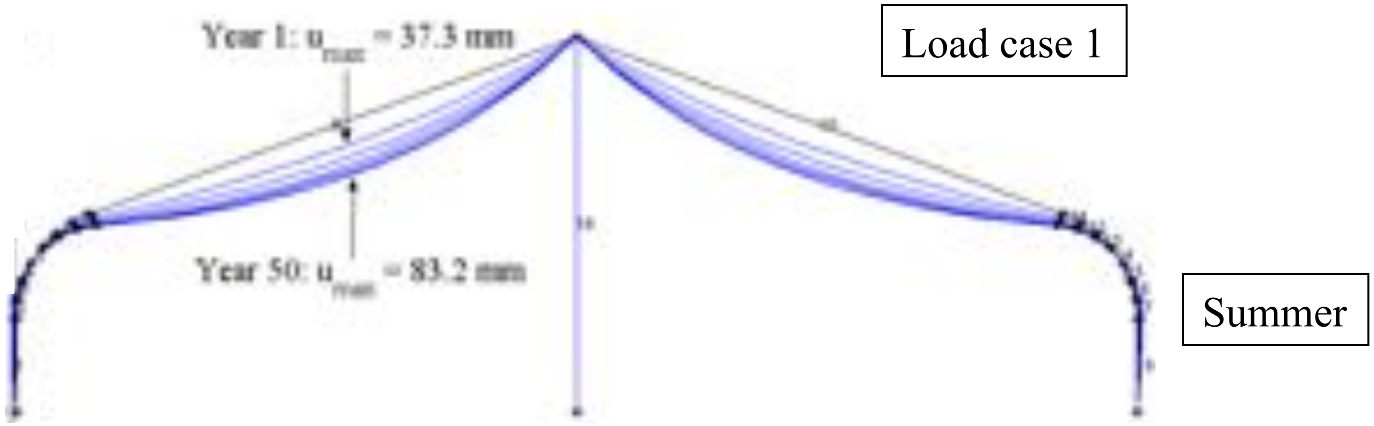
Moisture-induced stresses

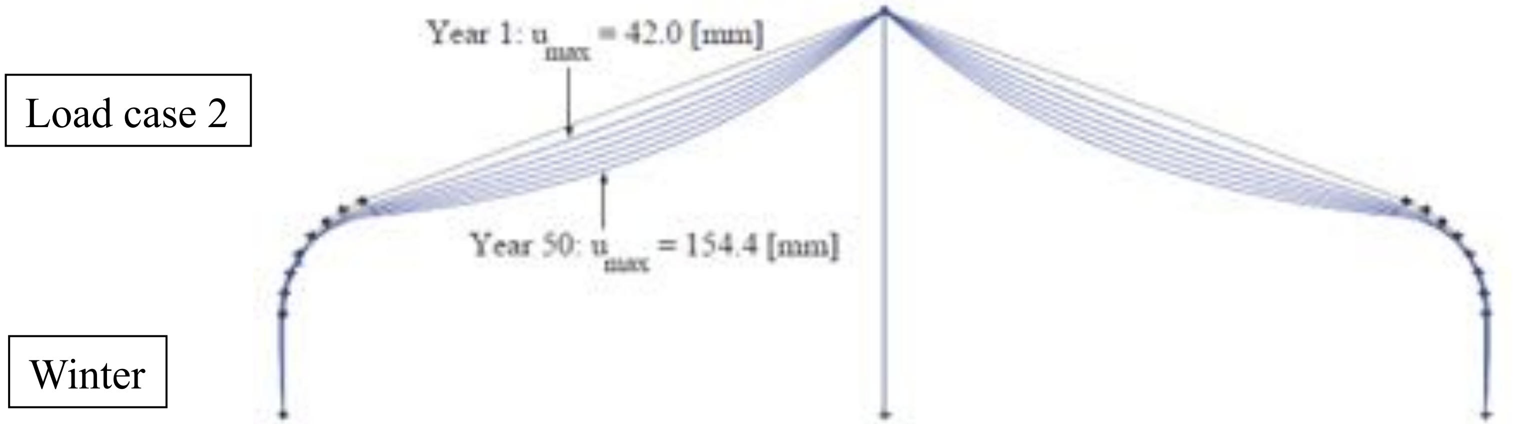
Curved frame structure



Moisture-induced stresses

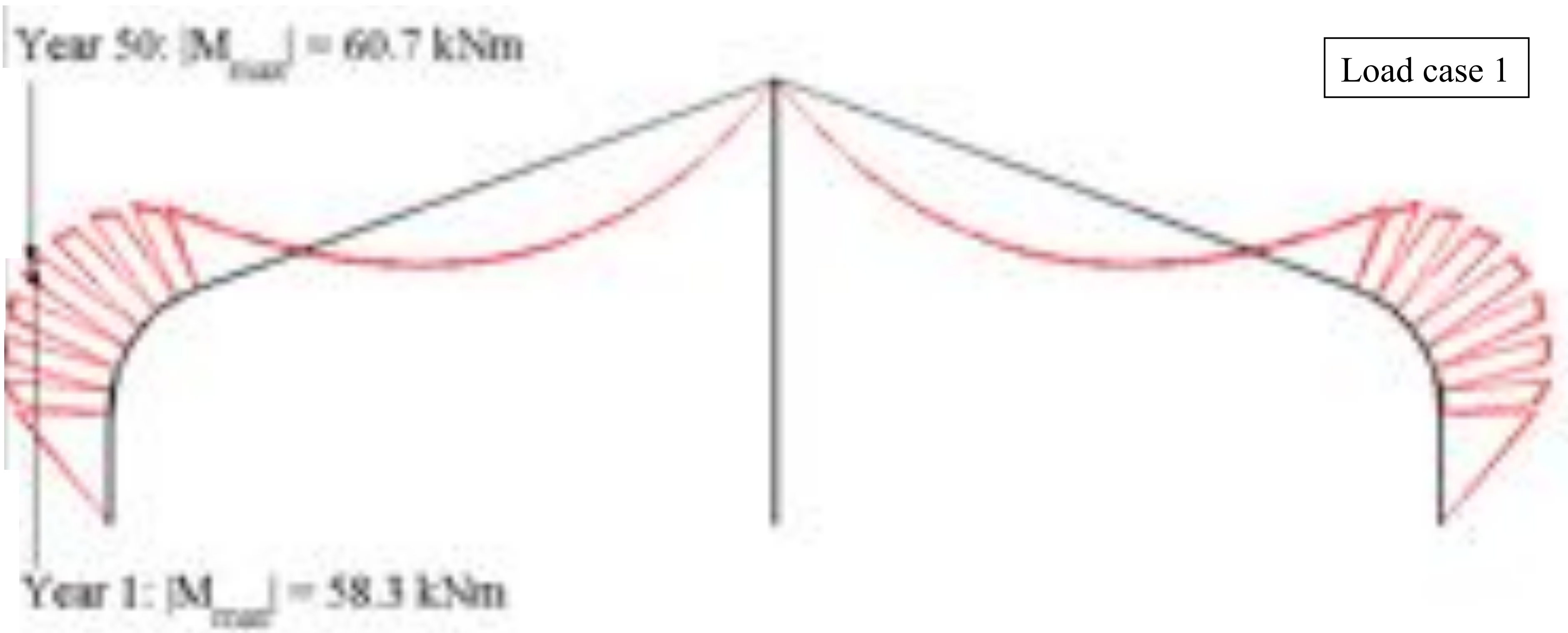
Displacements



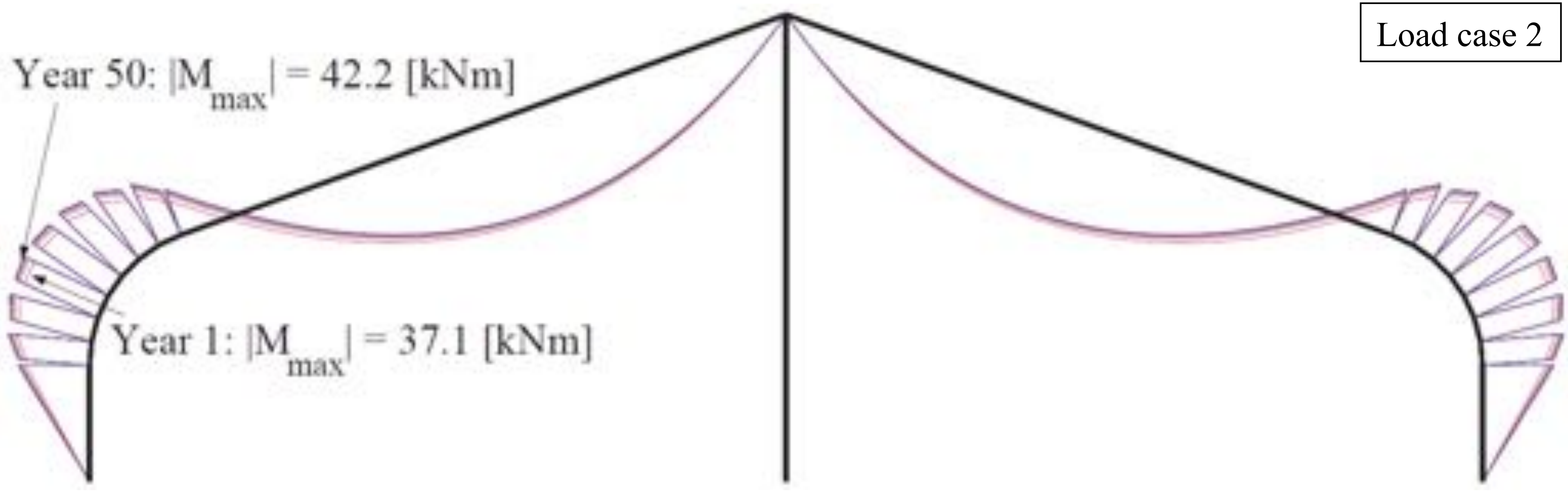


Moisture-induced stresses

Moment variation after 1, 10, 20, 30, 40 and 50 years in service

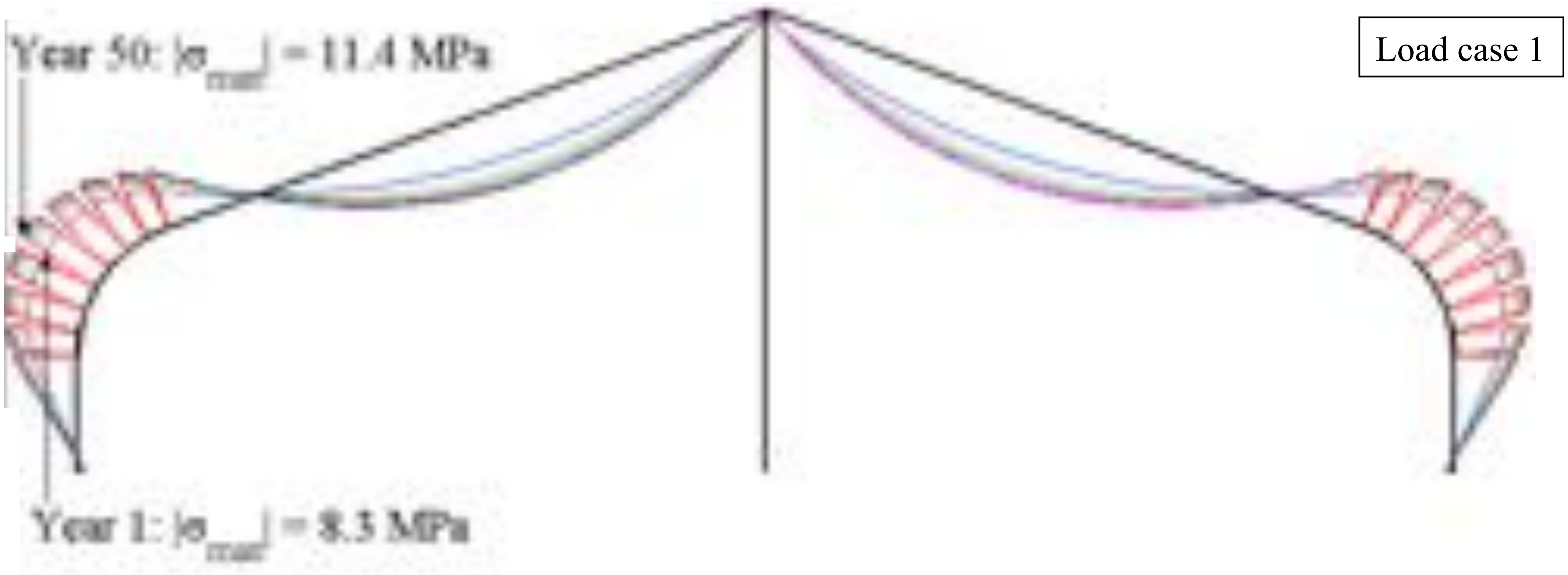


Moment variation after 1, 10, 20, 30, 40 and 50 years in service



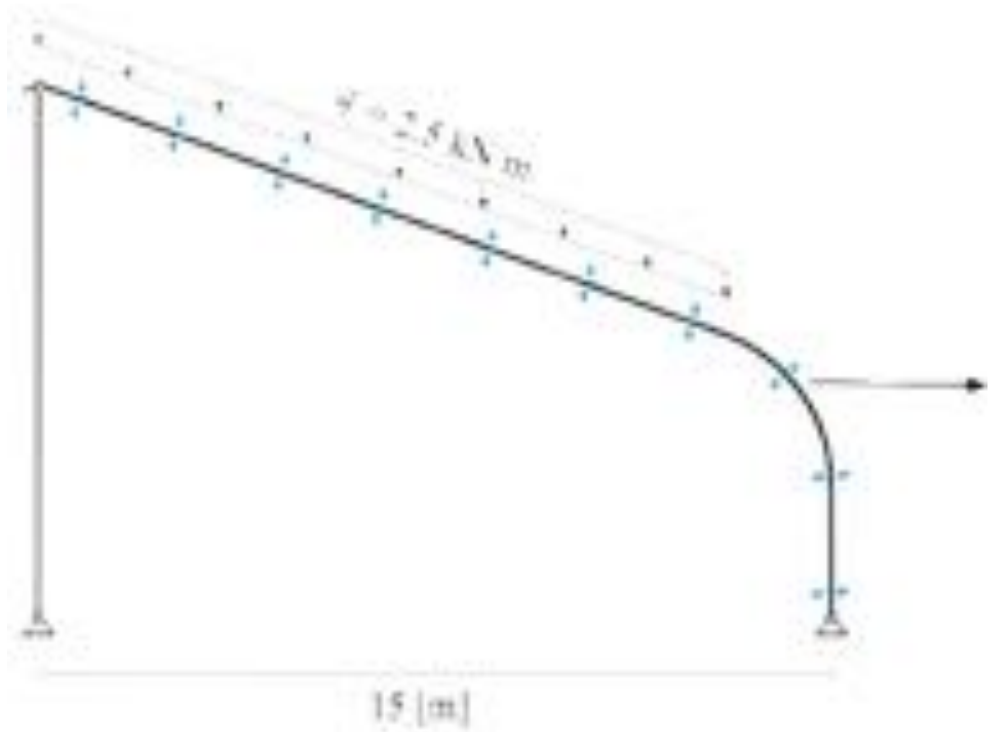
Moisture-induced stresses

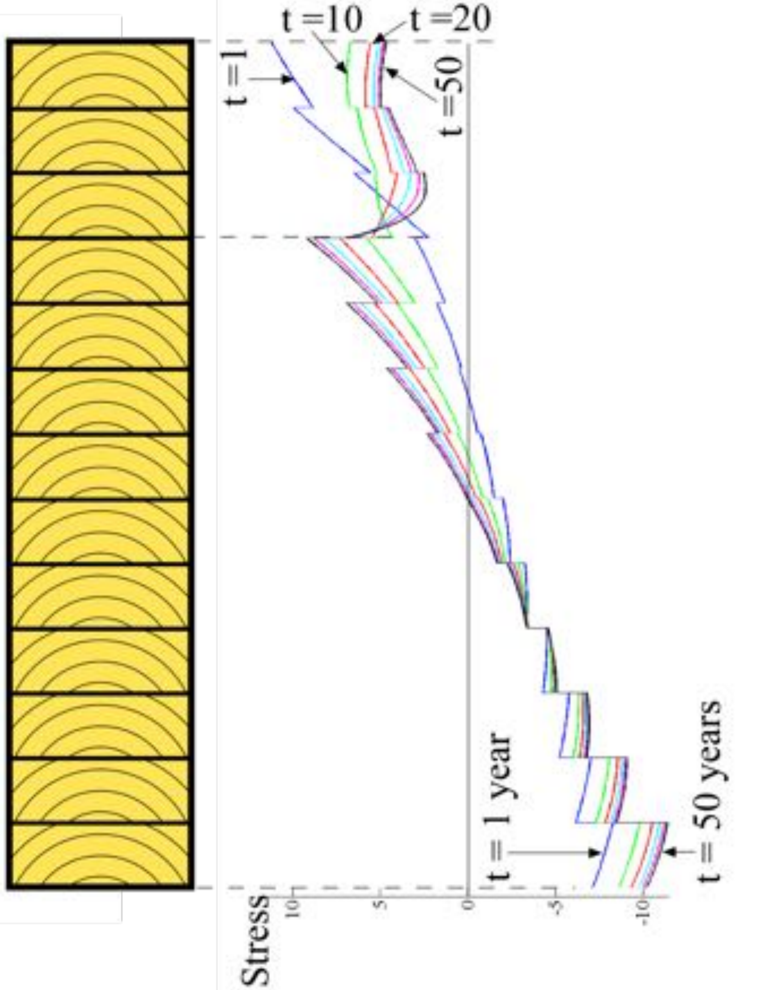
Stress variation along the first glueline counting from the bottom side



Moisture-induced stresses

Stress variation over the cross section

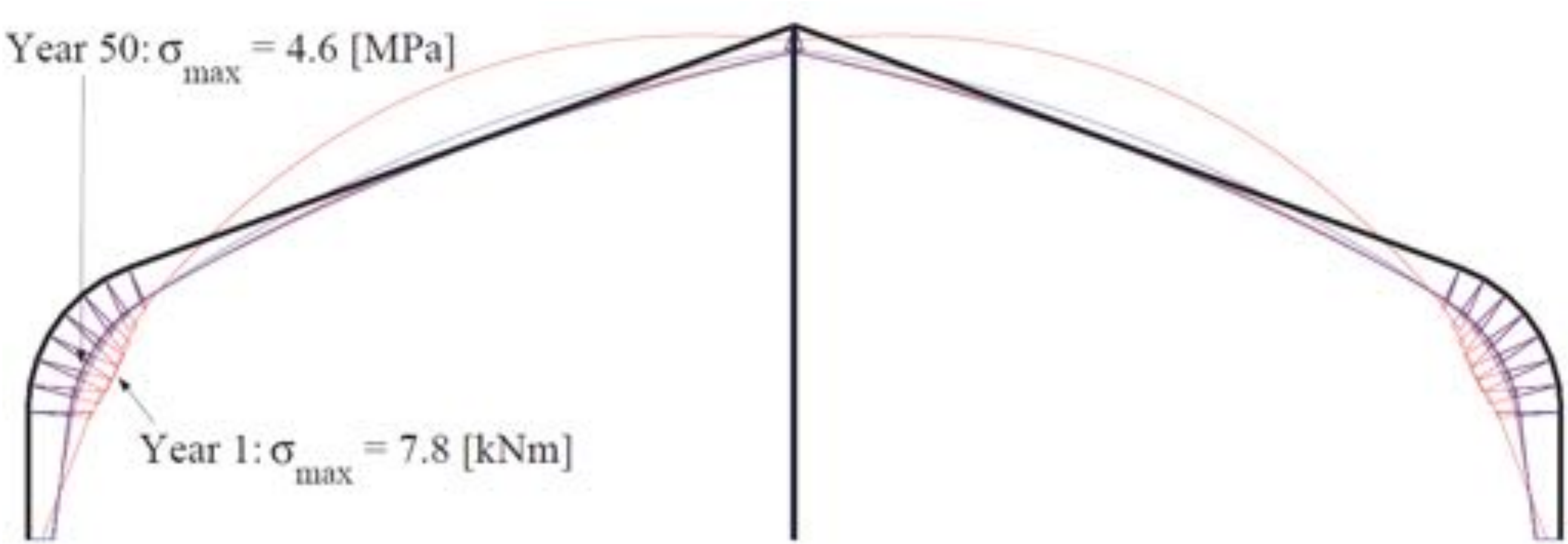




Moisture-induced stresses

Load case 2

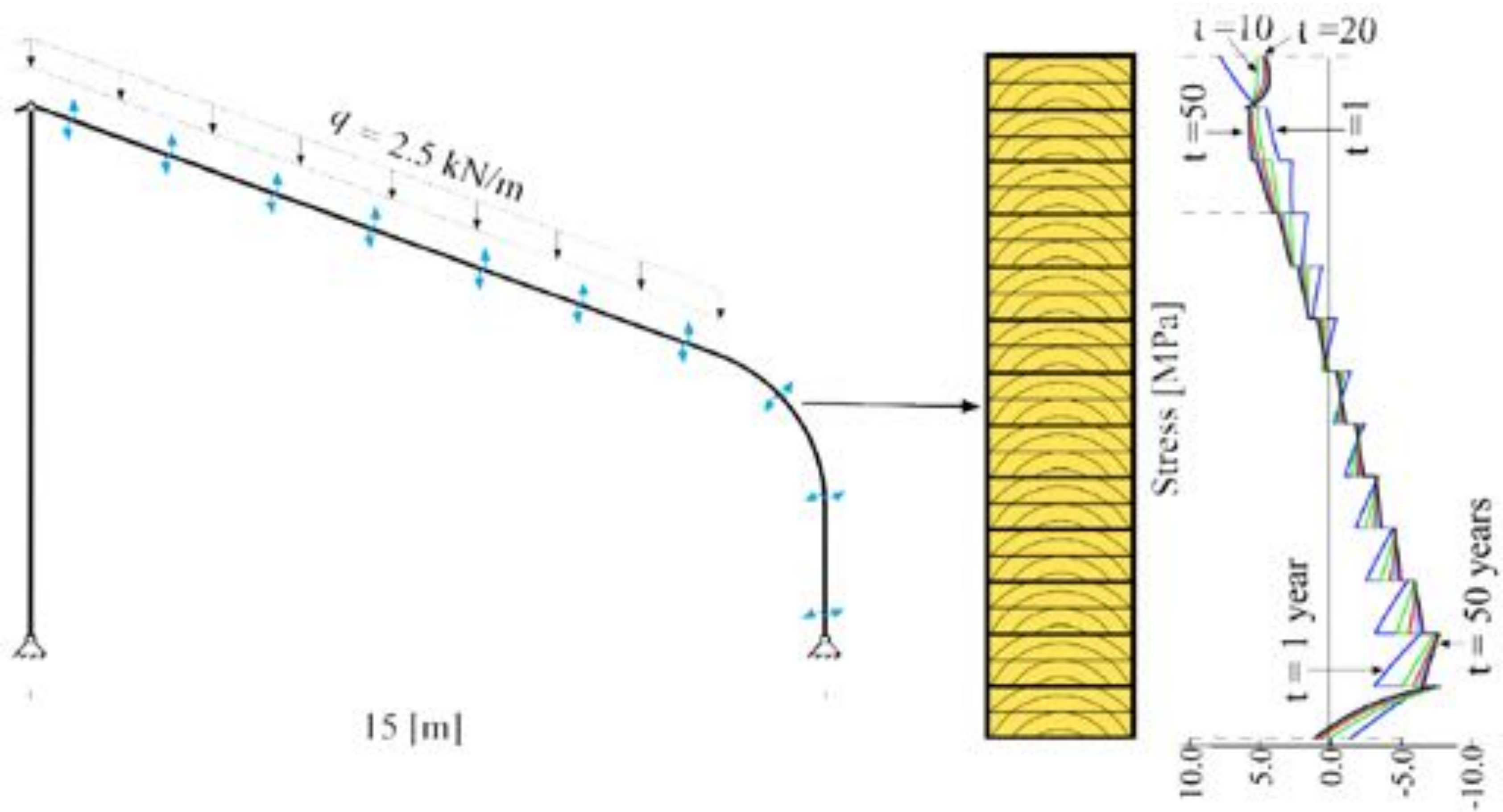
Stress variation along the outer surface



Moisture-induced stresses

Load case 2

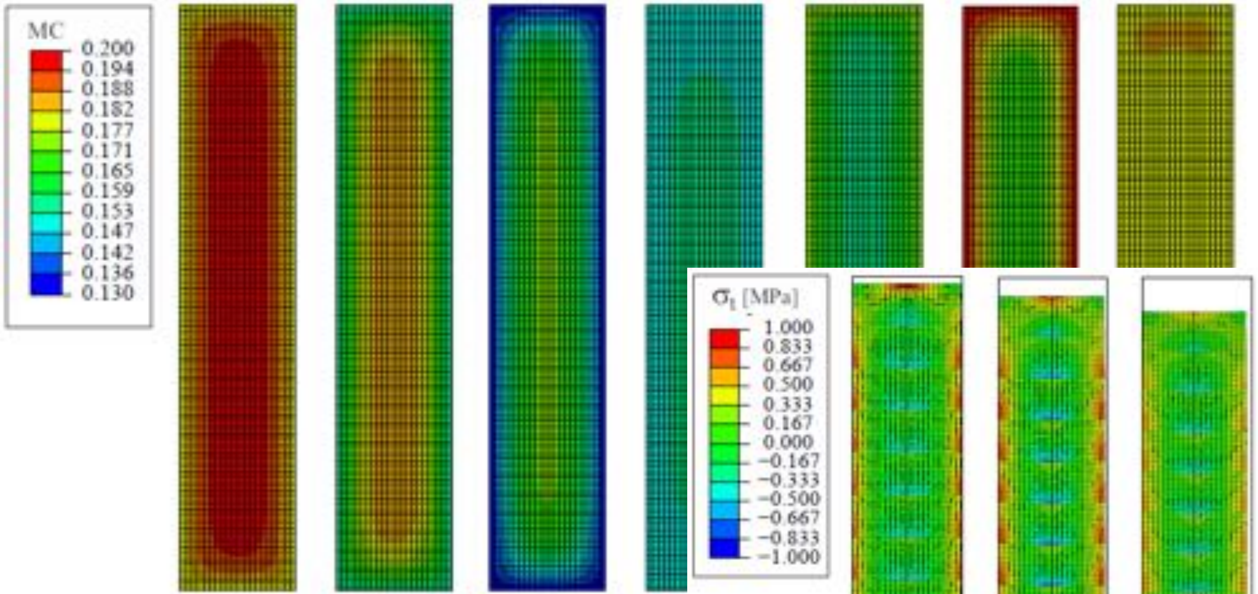
Variation in the longitudinal stress over the cross-section

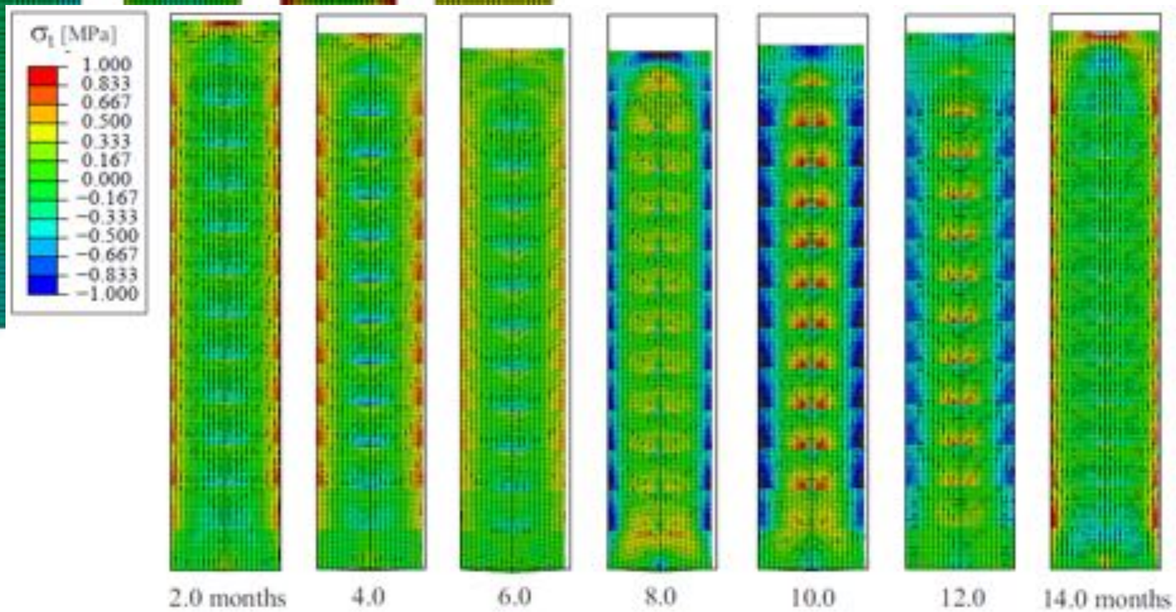


Moisture-induced stresses

Stresses perpendicular to the grain caused by MC-gradient

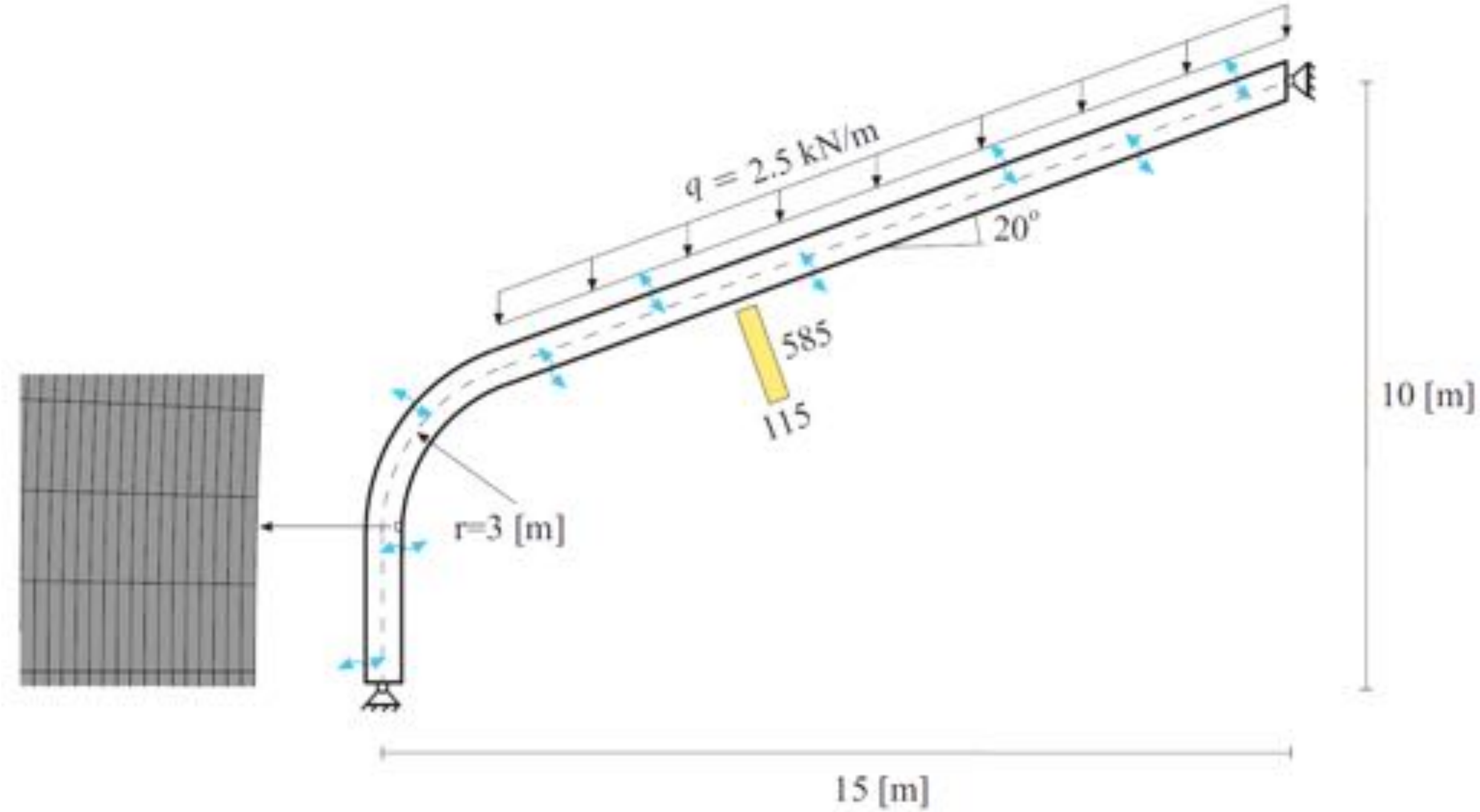
Load case 2





Moisture-induced stresses

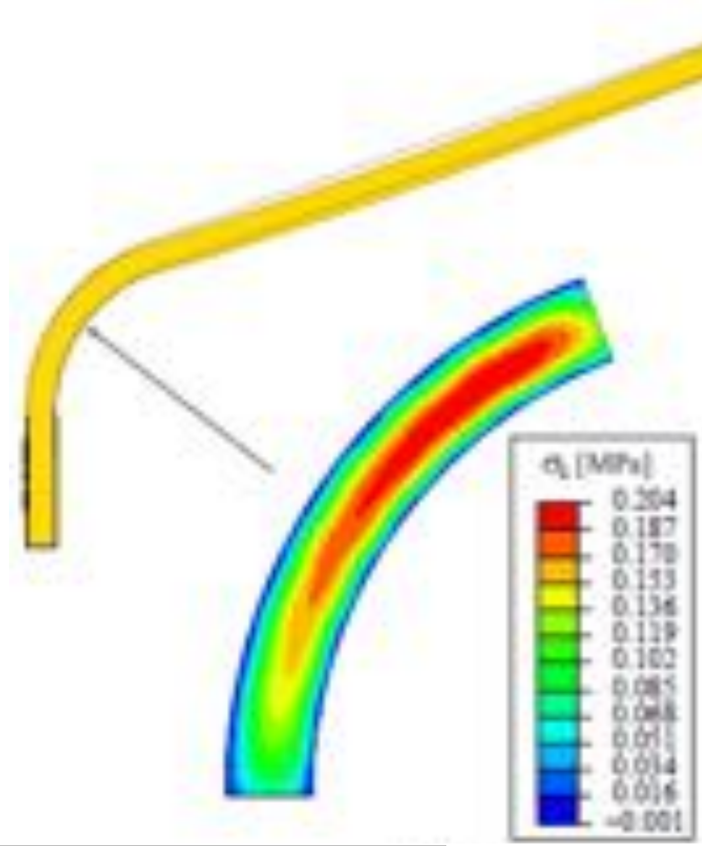
2D model to study stresses perpendicular to the grain direction



Moisture-induced stresses

Stresses perpendicular to the grain direction

Load case 2



Stresses caused by drying

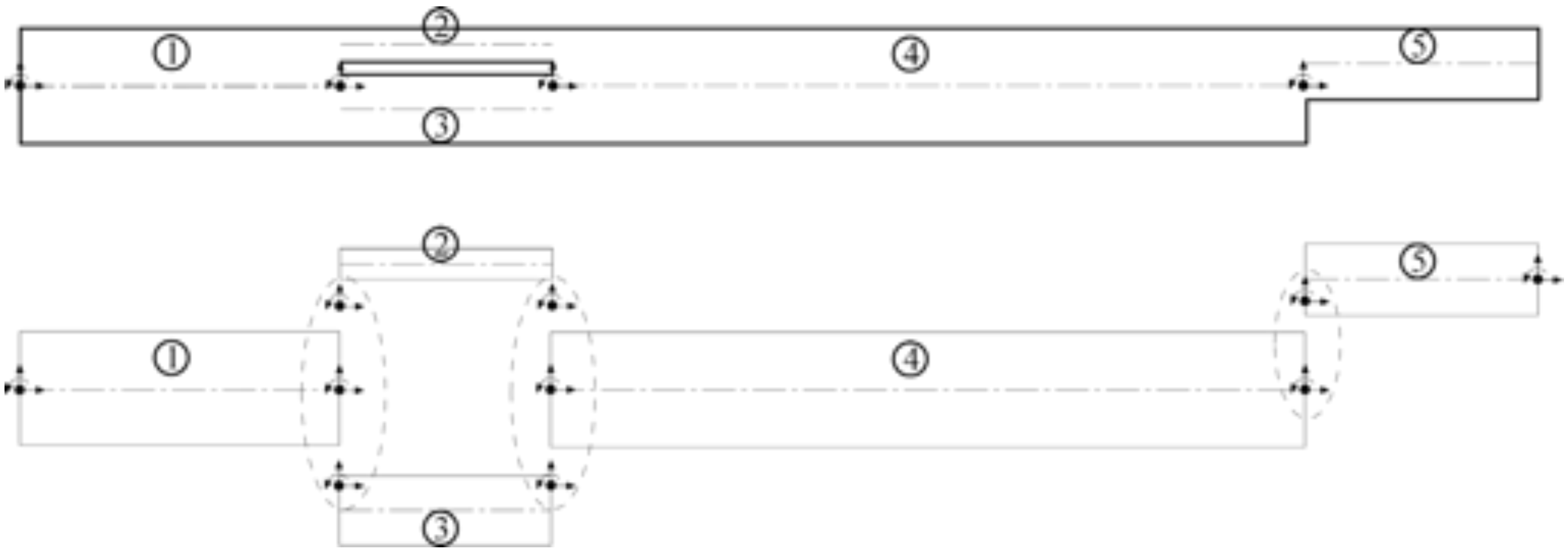
Stresses caused by mechanical loading

Conclusions

- Cyclic climate load action has a significant effect on both deformations and stress distribution in inhomogeneous timber structures.
- Climate loading should best be treated as a separate load case in connection with future design codes for timber structures that are exposed to natural variations in climate.
- There is a big need for better design tools?

Future work

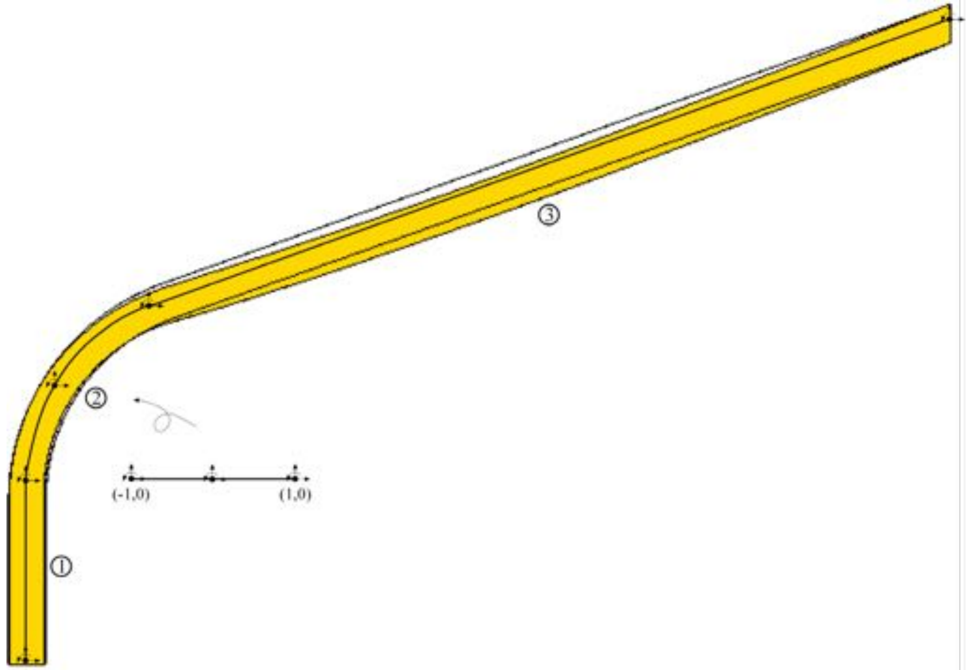
- A beam element able to simulate **beams with varying cross section dimensions** (single and double tapered beams)
- Beam element able to handle **eccentric normal force action**



- **3D beam element** able to simulate biaxial bending

Future work

- **Curved beam element** able to simulate perpendicular to the fibre direction



- **3D beam element** including moisture driven twist deformation and lateral torsional buckling
- **3D element** with round cross sections able to simulate progressive (lengthwise and radial) tree growth including both growth stresses and stresses from wind load.