

FORUM  
WOOD  
BUILDING  
NORDIC

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Aalto University, Finland



VTT

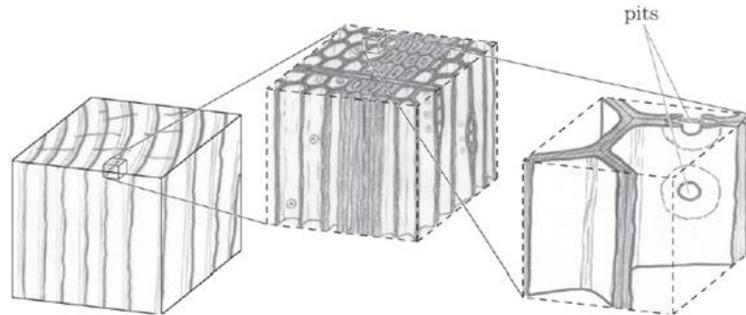
**Moisture-induced stresses in glulam beams  
of timber bridges. Case-study: Vihantasalmi Bridge**

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*VTT Technical Research Centre of Finland Ltd*

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# Study of hygro-thermal effects in wood from science..... to technology



# Multi-Fickian model for moisture transport for wooden members below FSP (sheltered from rain and sun)

## TRANSPORT EQUATIONS

*bound water concentration*  
(dry wood volume as reference)

$$\frac{\partial c_b}{\partial t} = \nabla \cdot (\mathbf{D}_b \nabla c_b) + \dot{c}$$

*diffusion tensors*
*sorption rate*

*water vapor concentration*  
(dry wood volume as reference)

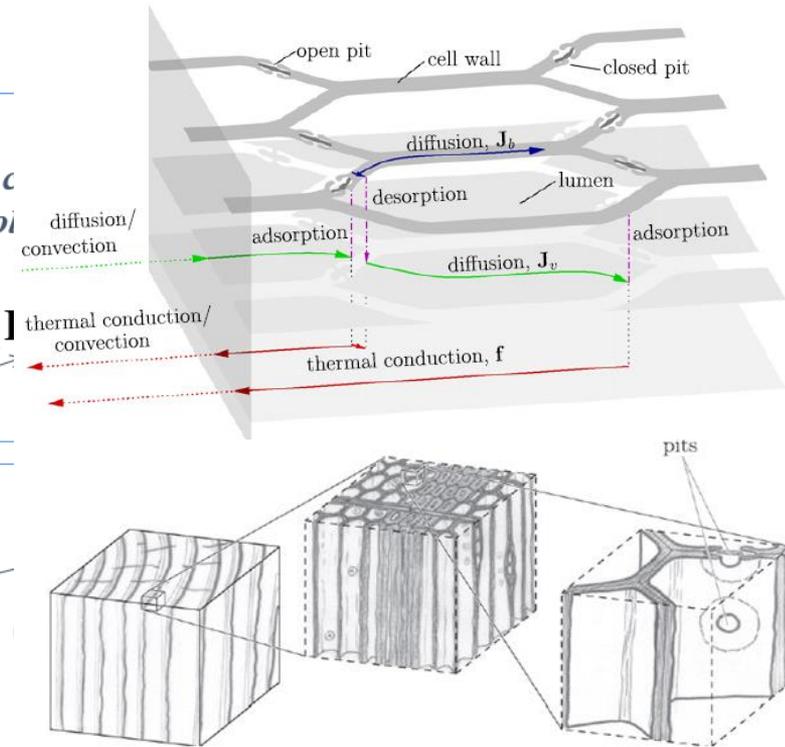
$$\frac{\partial c_v}{\partial t} = \nabla \cdot (\mathbf{J}_v)$$

*diffusion tensors*
*diffusion/convection*

## ENERGY CONSERVATION

$$c_w \rho \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{K} \nabla T) + \nabla \cdot (\mathbf{D}_b \nabla c_b) h_b + \nabla \cdot (\mathbf{J}_v) h_v$$

*specific heat*
*temperature*
*density*
*thermal conductivity tensor*



Fortino S., Genoese A., Genoese A., Nunes L., Palma P. Numerical modelling of the hygro-thermal response of timber bridges during their service life: A monitoring case-study. Construction and Building Materials 47, 1225-1234 (2013).

# Material properties

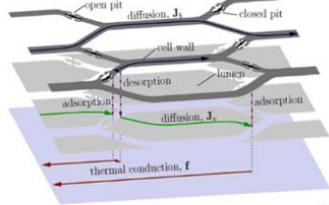
## Diffusion tensors

$$\mathbf{D}_v = \xi \left( 2.31 \times 10^{-5} \left( \frac{P_{atm}}{P_{atm} + P_v} \right) \left( \frac{T}{273} \right)^{1.81} \right) \left( \frac{m^2}{s} \right)$$

(Schirmer, 1938)

$$\mathbf{D}_b = \mathbf{D}_o \exp \left( -\frac{E_b}{RT} \right) \left( m^2 s^{-1} \right)$$

(Siau, 1995)



## Boundary conditions

$$\mathbf{n} \cdot \mathbf{J}_b = 0$$

$$-\mathbf{n} \cdot \mathbf{D}_v \nabla c_v = k_v (c_{1v} - c_v^a)$$

$$-\mathbf{n} \cdot \mathbf{K} \nabla T = k_T (T - T^a)$$

$c_v/\varphi$

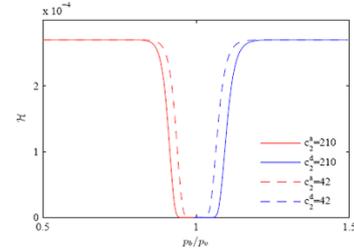
surface emission coefficient for water vapour (m/s):

$$k_v = \frac{1}{\frac{1}{k_{vs}} + \frac{1}{k_p}} \quad \text{uncoated wood} \rightarrow \text{paint}$$

## Sorption rate

$$\dot{c} = H_c (c_{bl} - c_b)$$

$$H_c = \begin{cases} C_1 \exp \left( -C_2 \left( \frac{c_b}{c_{bl}} \right)^{C_3} \right) + C_4 & c_b < c_{bl} \\ C_1 \exp \left( -C_2 \left( 2 - \frac{c_b}{c_{bl}} \right)^{C_3} \right) + C_4 & c_b > c_{bl} \end{cases}$$



Variation of the  $h$  function with the relation between the equilibrium vapor pressure  $p_b$  and the actual vapor pressure  $p_a$ .

- $c_{bl} = r_o m_{bl}$ : bound water concentration in equilibrium with a given relative humidity (hysteresis model).
- Adsorption (a) and desorption (d) isotherms:

**Hailwood-Harrobin equation**

$$m_\alpha = \frac{h}{f_{1\alpha} + f_{2\alpha} h + f_{3\alpha} h^2}$$

**Anderson-McCarthy model**

$$m_\alpha = \frac{\ln(\ln(1/h)/f_1^\alpha)}{f_2^\alpha}, \quad \alpha \in \{a, d\}$$

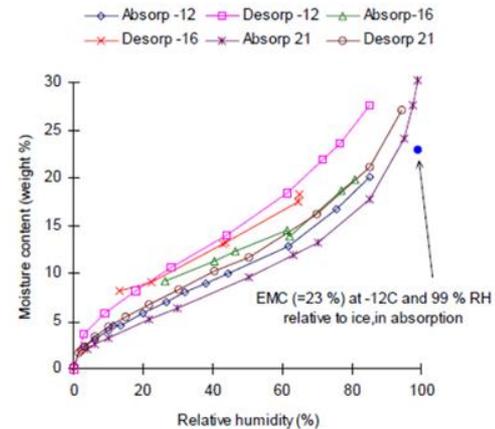
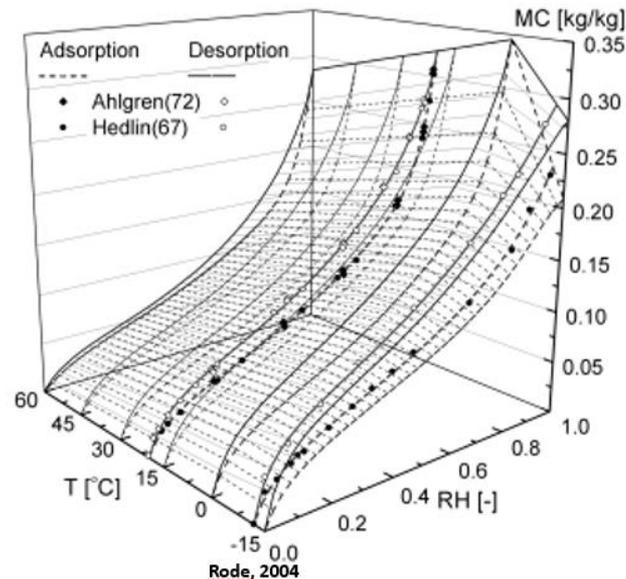
$$f_i^\alpha = \sum_{j=0}^n b_{ij}^\alpha T^j, \quad i \in \{1, 2\}$$



Frandsen HL (2007). Selected Constitutive models for simulating the hygromechanical response of wood. Dissertation 10. Dep. of Civil Engineering, Aalborg University.

# Material properties

## Temperature-dependent sorption isotherms

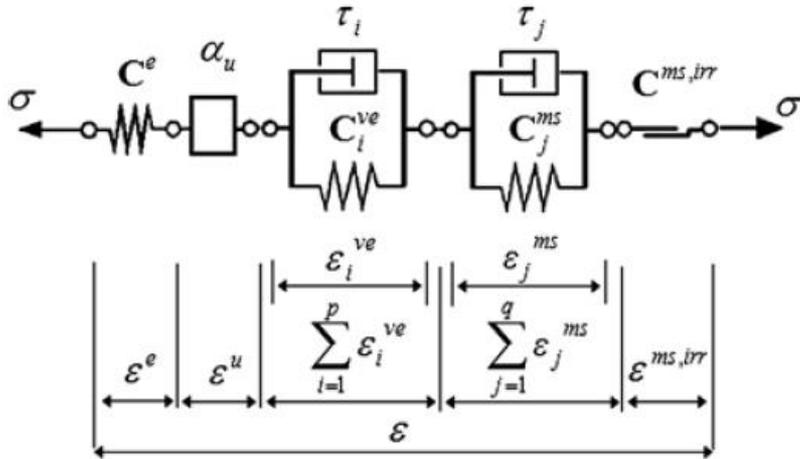


Sorption isotherm data for spruce at  $-12^{\circ}\text{C}$ ,  $-16^{\circ}\text{C}$  and  $21^{\circ}\text{C}$  reported by Hedlin (1967).



Fortino S., Hradil P., Genoese A., Genoese A., Pousette, A. Numerical hygro-thermal analysis of coated wooden bridge members exposed to Northern European climates. *Construction and Building Materials*, 208, 492--505 (2019).

## Rheological model



## Total strain

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^u + \sum_{i=1}^p \boldsymbol{\varepsilon}_i^{ve} + \sum_{j=1}^q \boldsymbol{\varepsilon}_j^{ms} + \boldsymbol{\varepsilon}^{ms,irr}$$

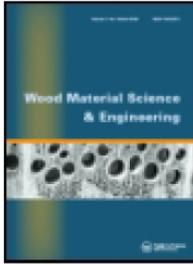
## Algorithmic operator of stress-update algorithm in Abaqus code

$$\mathbf{C}_T = \left( \mathbf{C}^{e-1} + \sum_{i=1}^p \mathbf{C}_{i,n+1}^{ve-1} + \sum_{j=1}^q \mathbf{C}_{j,n+1}^{ms-1} \right)^{-1}$$



Fortino S., Mirianon F., Toratti T. A 3D moisture-stress FEM analysis for time dependent problems in timber structures. *Mechanics of Time Dependent Materials* 13 (4), 333--356 (2009).

# Study of hygro-thermal effects in wood from science... to technology



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## Moisture-induced stresses in large glulam beams. Case study: Vihantasalmi Bridge

Stefania Fortino, Petr Hradil & Giovanni Metelli

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To link to this article: <https://doi.org/10.1080/17480272.2019.1638828>

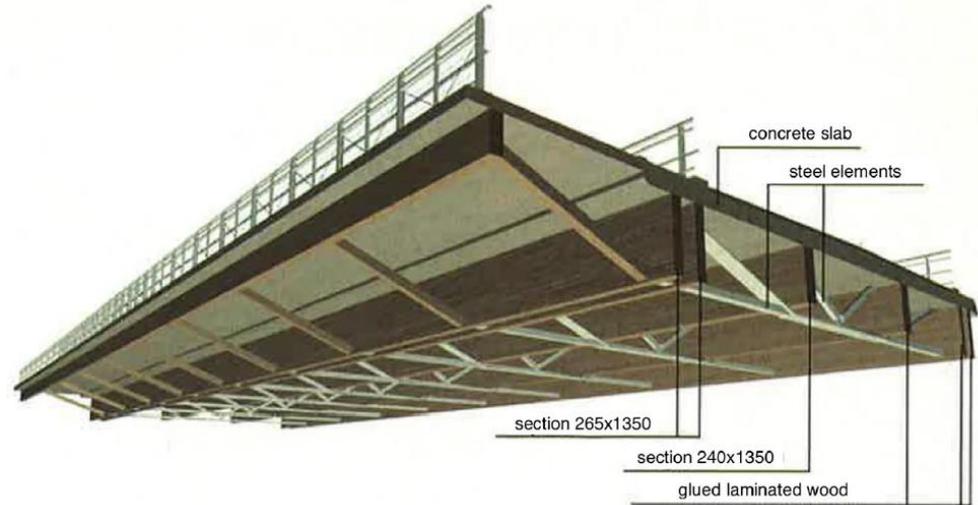
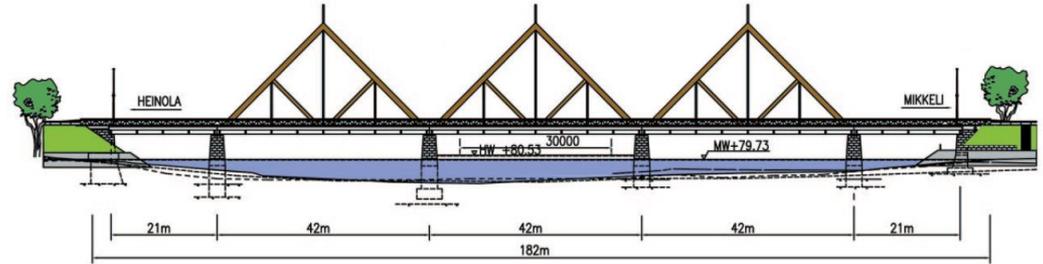
# Vihantasalmi Bridge (Built September 1999)

**Location** : road no. 5 in Mäntyharju about 180 km North of Helsinki

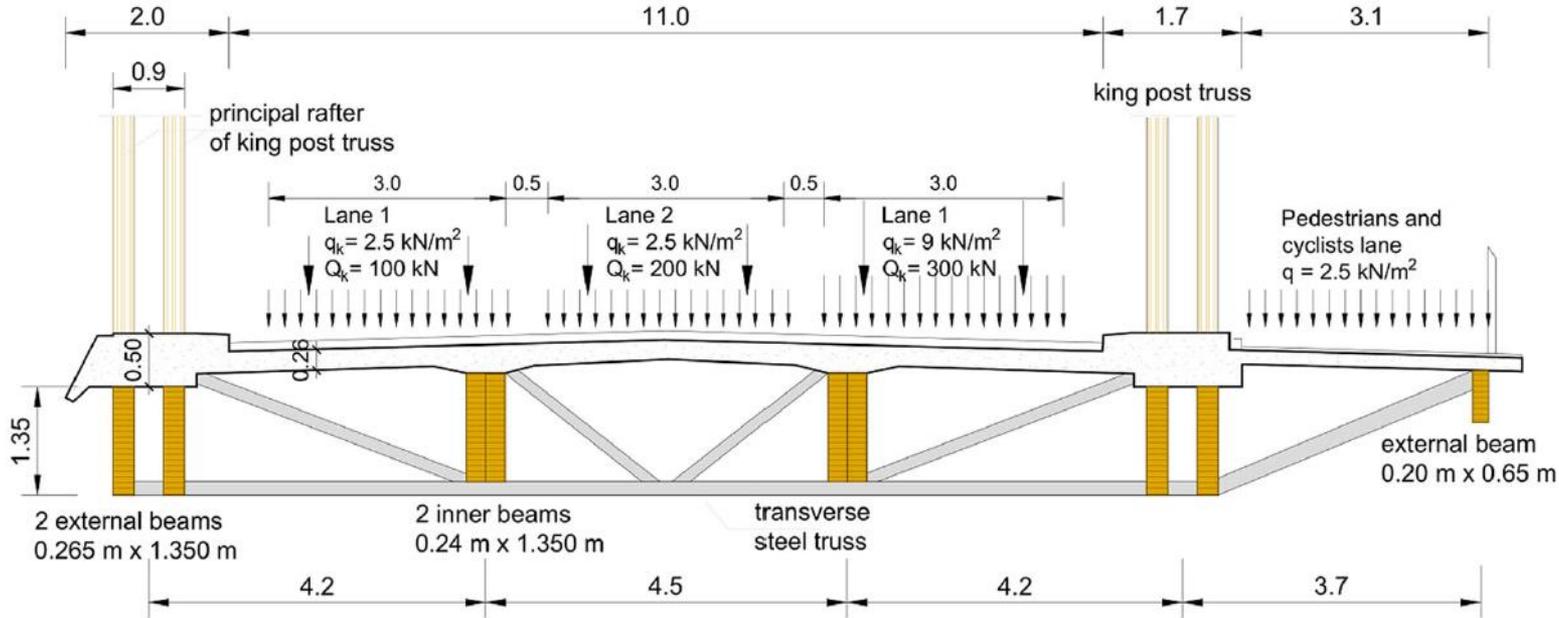
**Structure** : Five spans (21 + 42 + 42 + 42 + 21 = 168 m) king-post truss bridge.

**Material** : glulam, steel and reinforced concrete.

**Designer** : Consulting Engineers Rantakokko & Co.



# Mechanical analysis according to Eurocodes



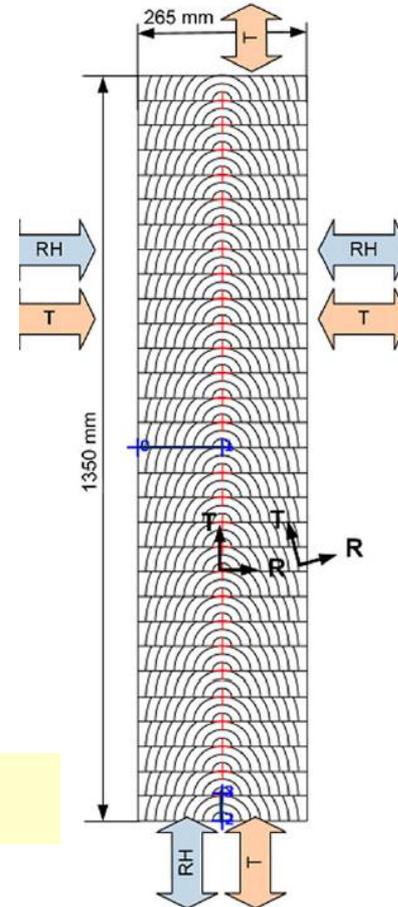
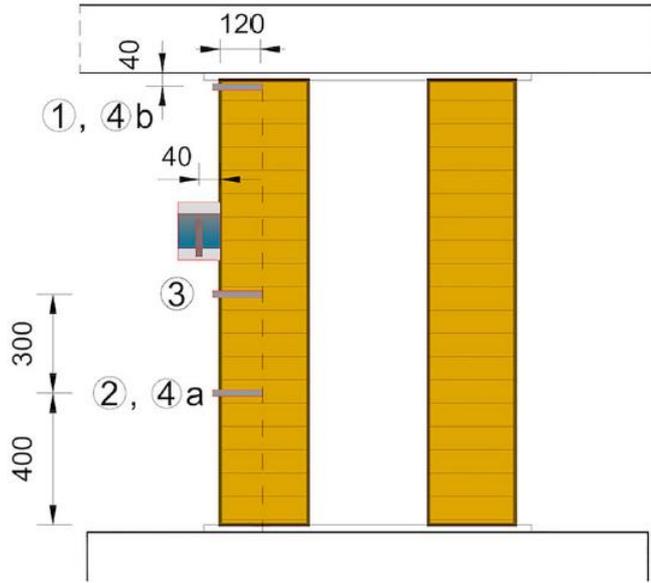
Transverse section



Musci, A. (2016) Effects of moisture content on timber structural elements. Case-study: Vihantasalmi Bridge. MSc Thesis, University of Brescia.

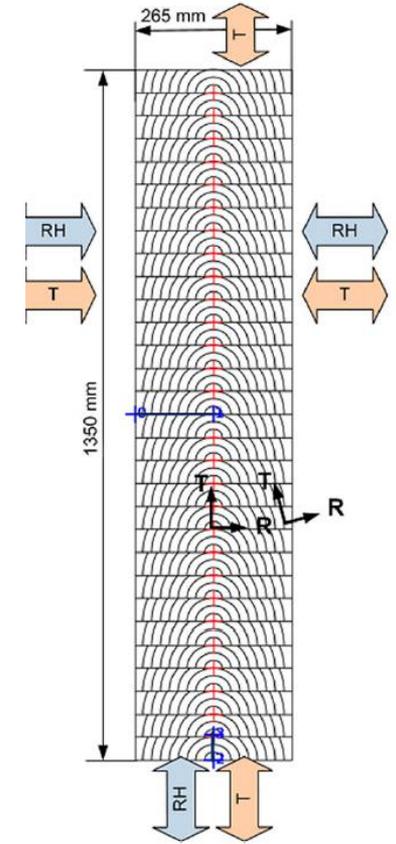
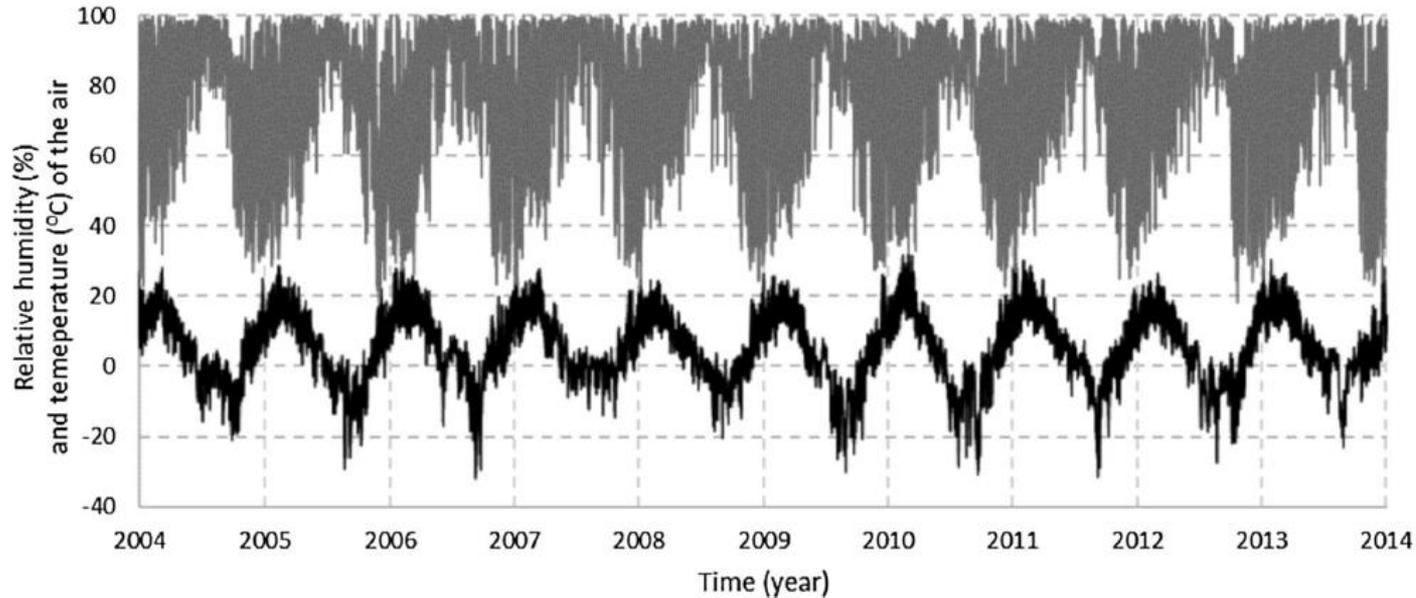
# RH and temperature monitoring in beam cross section

# Cross section (3Dslice) Modelled in Abaqus

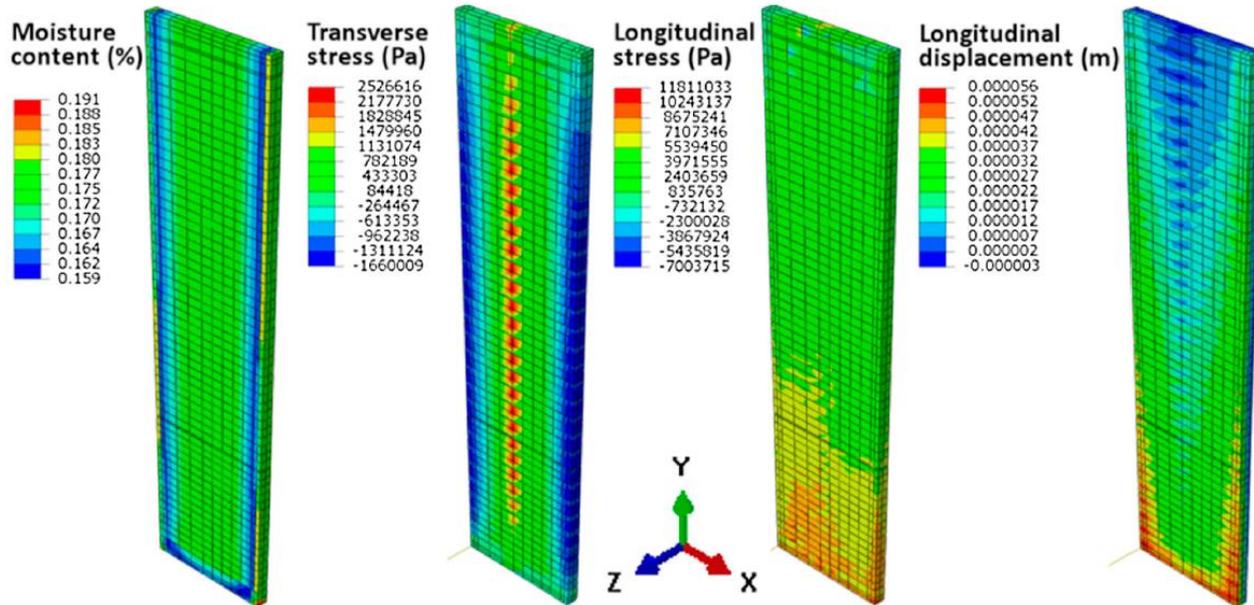


Salokangas, L. and Jutila, A. (2003) Vihantasalmen sillan seurantatutkimus [Follow-up report of the Vihantasalmi Bridge]. Technical report TKKSRT-32, Tampere, Finland, 40 pp. (in Finnish).

# 10 years of sequential hygro-thermo-mechanical analysis (case-study of untreated wood)



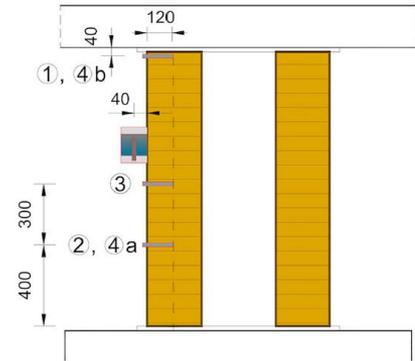
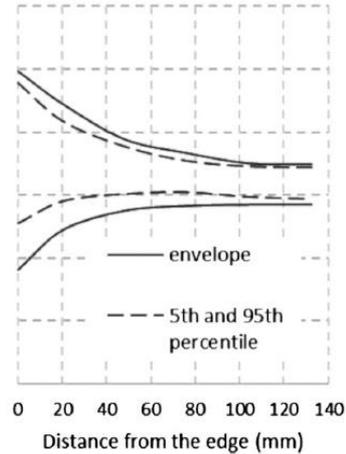
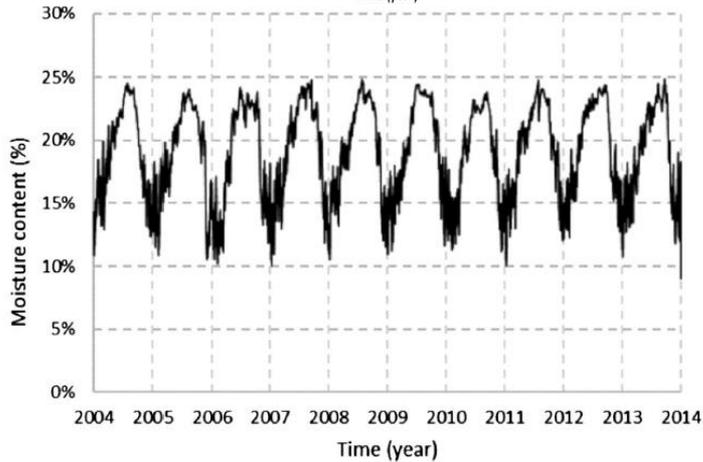
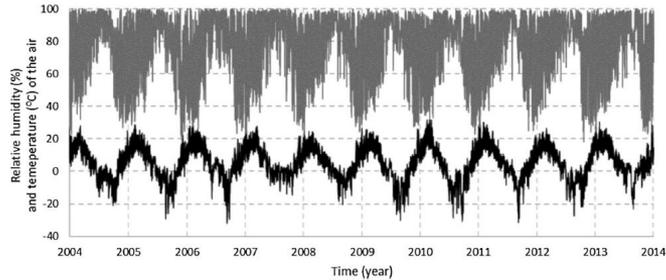
# Example of distribution of MC and Moisture-induced-stresses (MIS)



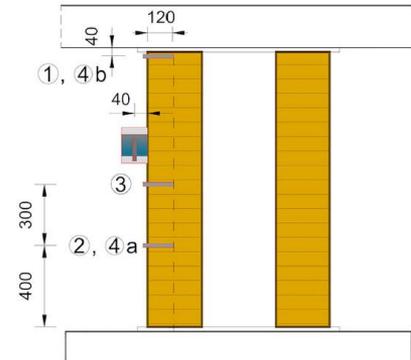
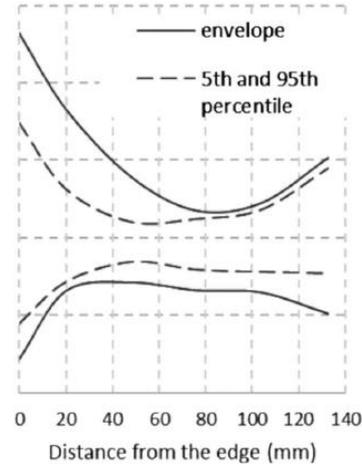
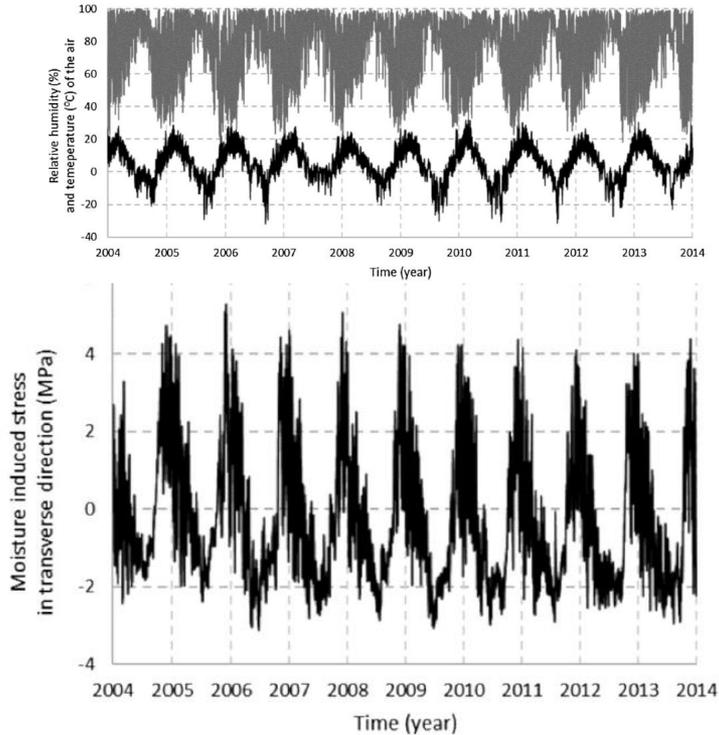
**Table 1.** Elastic properties used for the *MIS* analysis.

$E_R$ (MPa)	$E_T$ (MPa)	$E_L$ (MPa)	$G_{RT}$ (MPa)	$G_{RL}$ (MPa)	$G_{TL}$ (MPa)	$\nu_{RT}$	$\nu_{RL}$	$\nu_{TL}$
900	600	13,500	40	700	700	0.558	0.038	0.015

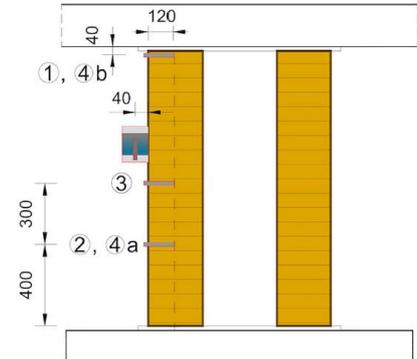
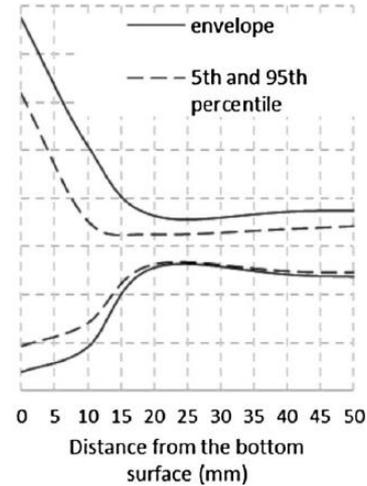
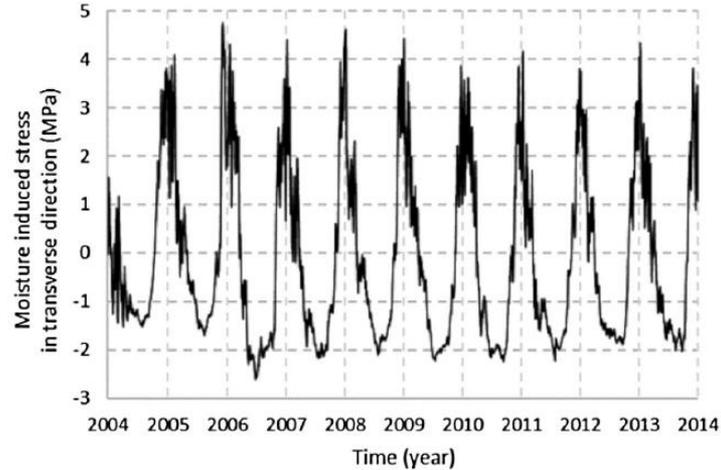
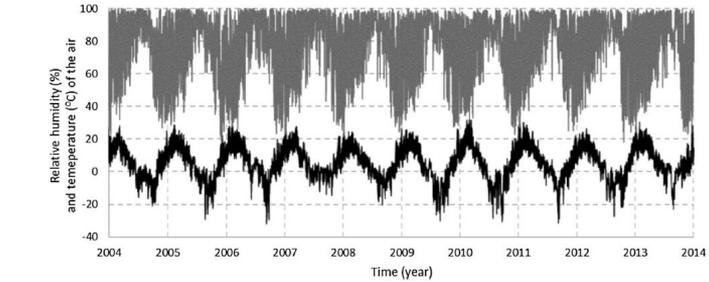
# Moisture content



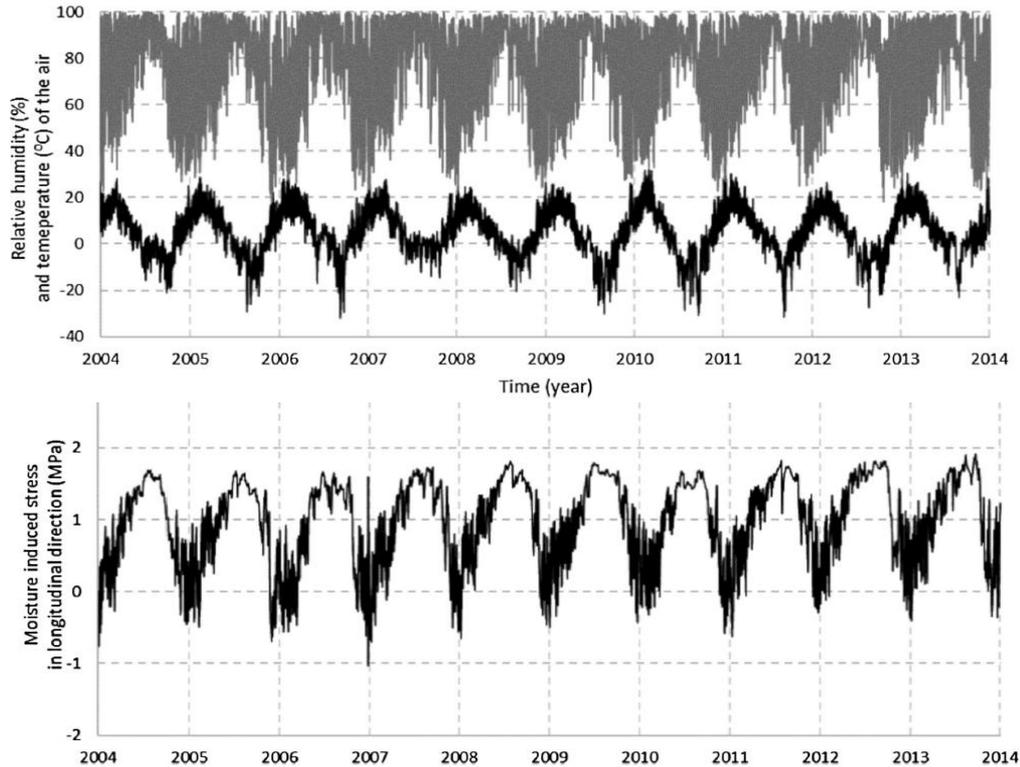
# MIS perpendicular to grain (horizontal path)



# MIS perpendicular to grain (vertical path)



# MIS in grain direction



**Table 2.** Numerical results: moisture content.

Moisture content (%)	Max	95th perc.	Mean	5th perc.	Min
Bottom surface	21.6%	21.2%	18.7%	14.2%	12.5%
Lateral edge	24.9%	24.0%	19.7%	12.8%	9.0%
Middle cross-section	17.4%	17.2%	16.1%	14.7%	14.3%

**Table 3.** Numerical results: moisture-induced stresses.

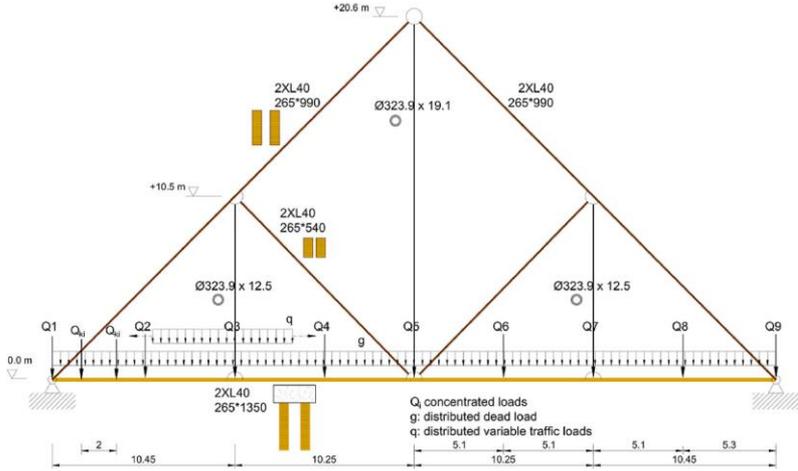
Moisture-induced stress (MPa)	Max	95th perc.	Mean	5th perc.	Min
Longitudinal, bottom surface	1.91	1.71	1.11	-0.10	-1.03
Longitudinal, middle cross-section	1.17	1.07	0.18	-0.81	-1.31
Transverse, bottom surface	4.75	3.19	-0.73	-2.07	-2.61
Transverse, lateral edge, half height	5.28	2.95	-0.56	-2.22	-3.13
Transverse, middle cross-section	2.05	1.79	0.56	-0.92	-1.95

Maximum MC reached peak is 24.9% (almost critical for durability) and the minimum 9% in the outer fibres

Maximum MIS values in tension (5.28 MPa, reached on 3 May 2006) and compression (3.13 MPa, reached on 25 November 2006) exceed the characteristic strength values perpendicular to grain of glulam defined by EN14080 (0.5 and 2.5 MPa).

# Use of results of the mechanical analysis according to Eurocodes in the FEM model

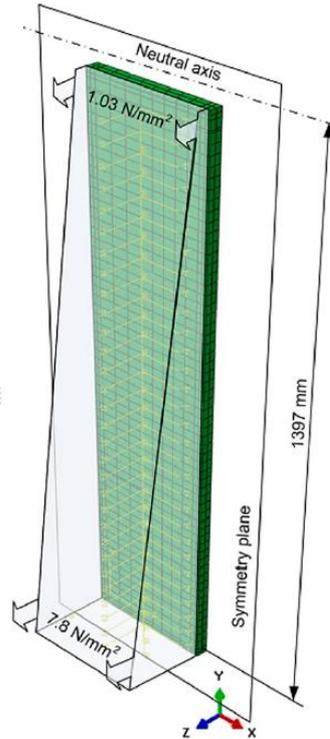
## Symmetric half of king post truss (2D model)



Characteristic bending moment of the main girder due to permanent and variable actions

$$M_k = M_{G,k} + \psi_2 M_{Q,k}$$

combination factor  $\psi_2 = 0.3$  according to Jaaranen (2016)

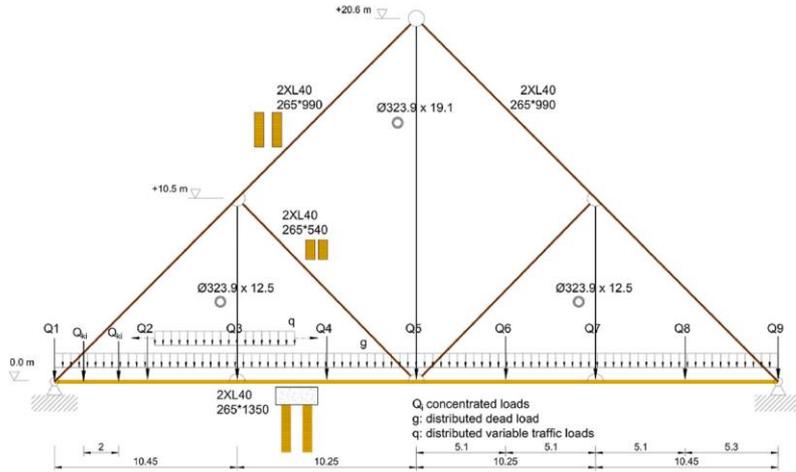


3D FEM model

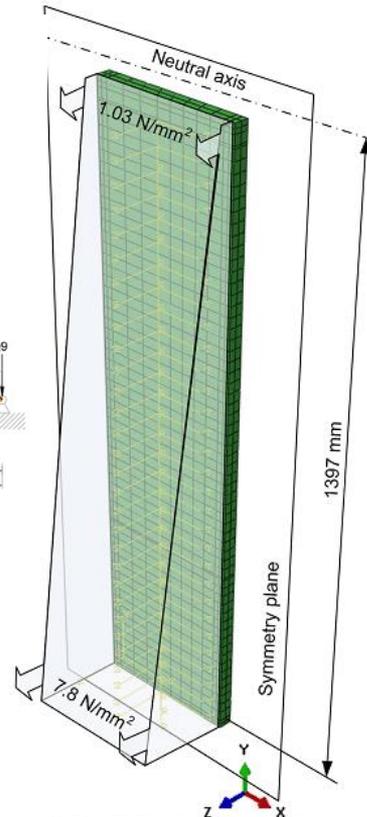
- Axial stress due to the resulting bending moment considered as the representative internal action for long-term loads on the bridge beam.
- Axial stress implemented as the initial surface pressure on the modelled cross-section with gradually decreasing intensity from bottom fibres to top fibres.
- Whole timber cross-section initially in tension because of the composite action of the bridge concrete deck that carries the compressive part of bending action

# Moisture-induced deformation

## Symmetric half of king post truss (2D model)



Moisture-induced deflection restrained by the vertical hanger



3D FEM model

$$\Delta \varepsilon = \frac{\Delta \delta_{MI}}{t}$$

Axial strain from the horizontal deformation of FEM model



$$\Delta y'' = \frac{\Delta \varepsilon}{h}$$

Beam curvature from the axial strain



$$\Delta u_{MI} = \Delta y'' \frac{L^2}{8}$$

Moisture-induced deflection from the beam curvature

# Moisture-induced deformation

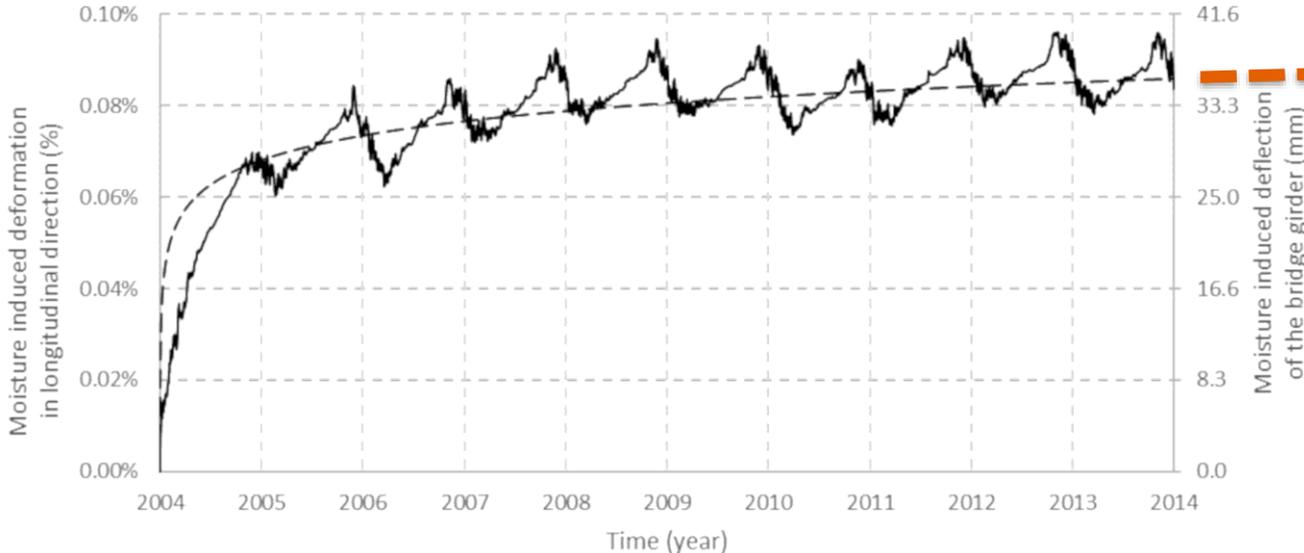
$$u_{fin} = u_{inst,G}(1 + k_{def}) + u_{inst,Q}(1 + \psi_2 k_{def}) \leq \frac{L}{500} = 82.8 \text{ mm}$$

**Eurocode  
serviceability  
deflection limit**



$$u_{creep} = u_{inst,G}k_{def} + u_{inst,Q}\psi_2 k_{def} \leq 45.7 \text{ mm}$$

**Deflection attributed to quasi-permanent creep deformation**



**Extrapolated to 100  
years design life  
 $u_{creep} = 43.2 \text{ mm}$**

Moisture-induced longitudinal deformation on the bottom edge of the cross-section, corresponding calculated vertical deflection of the bridge girder (solid line) and its logarithmic approximation (dashed line).

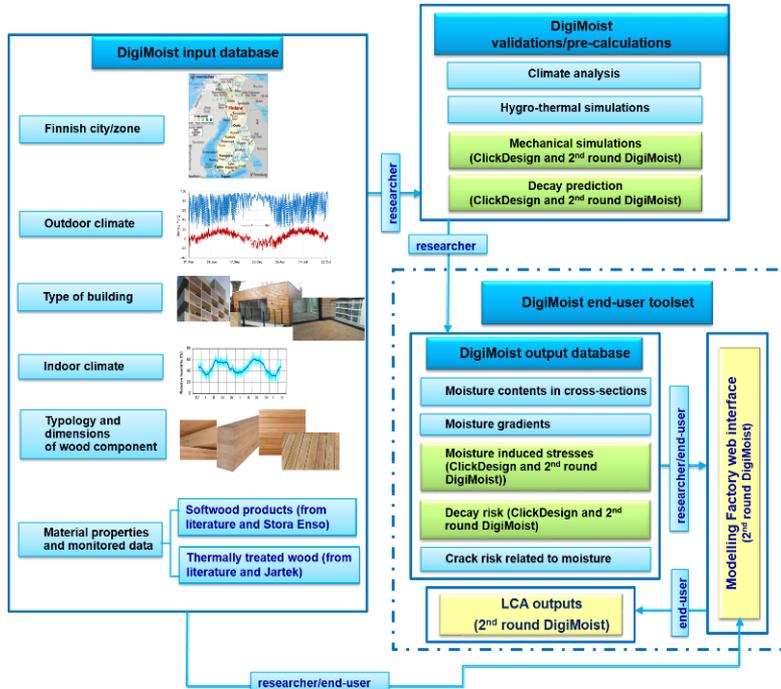
# Conclusions and future work

- FEM prediction of moisture content during time can support/complement the long-term monitoring of wooden structures based on traditional sensor-techniques as well as advanced NMR and CT technologies.
- FEM prediction on moisture-induced stresses perpendicular to grain provide suggestions in relation to protection by coatings and maintenance controls
- FEM prediction of moisture-induced deformation confirmed that serviceability during 100 years design life would be achievable even without surface treatment
- The model needs to be further developed to include effect of free water
- The hygro-thermo-mechanical model can be easily coupled with a decay model **(ForestValue Click Design project)**



## A Digital end-user toolset for Moisture assessment in Wooden buildings.

### 1<sup>st</sup> part: Hygro-thermal database (DigiMoist1)

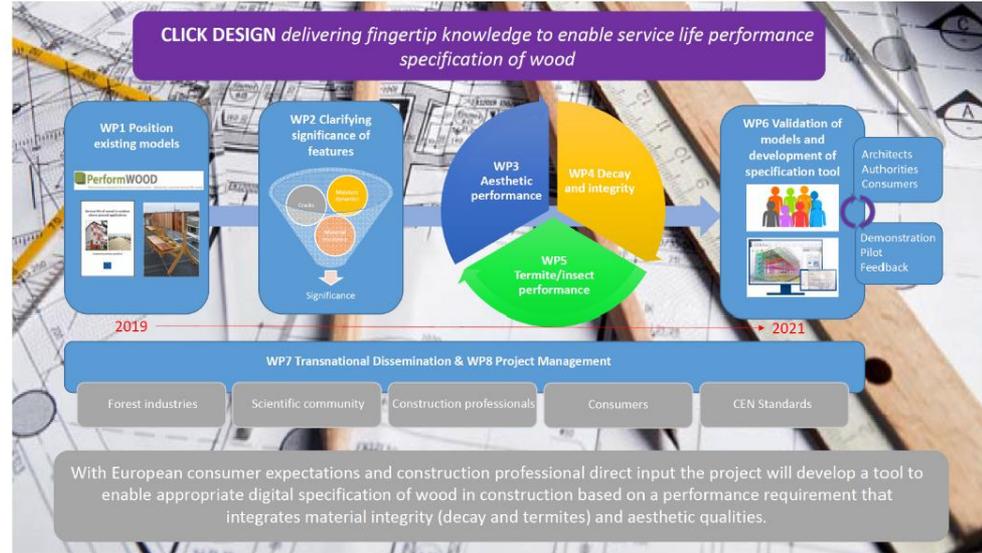


30/10/2019

## ForestValue



Coordination: BRE (UK) (2019-2022)



# Thank you!

## ...Questions?