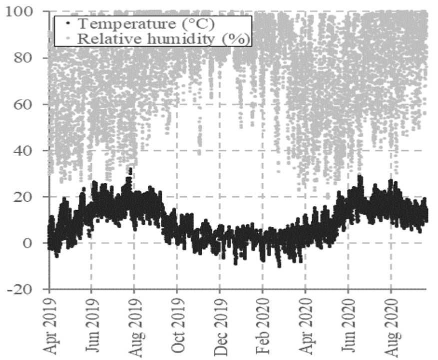

Hygro-thermal modeling of timber bridge decks considering the effect of solar radiation

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Petr Hradil, Timo Avikainen, Keijo Koski, Ludovic Fülöp

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Click Design (ForestValue)

Coordinator: BRE (UK), 28 partners; **Scientific partners**: Goettingen University (DE), Lund University (SE), VTT Ltd (FI), InnoRenew CoE (SI), FCBA (FR), NIBIO (NO) - Duration: March 2019-June 2022

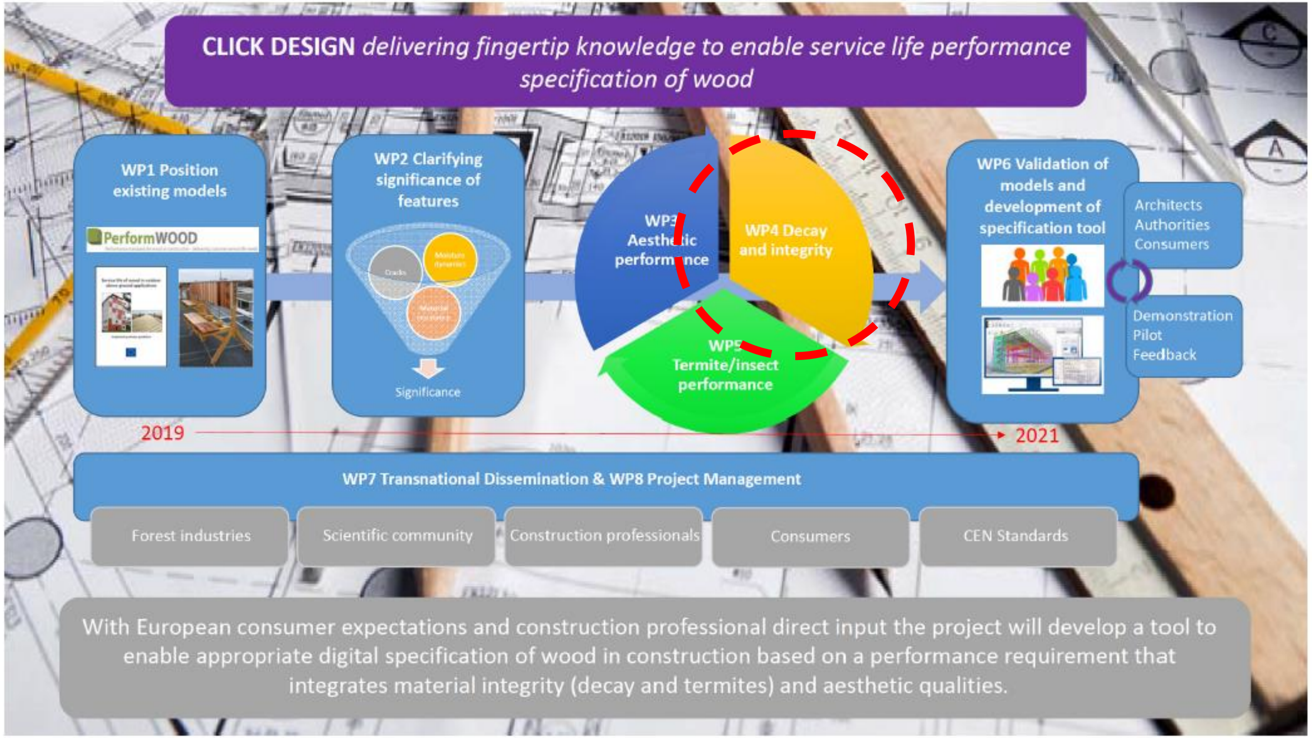
Finnish funder: Ympäristöministeriö

Finnish partners

- **VTT (WP4 leader)**
- Väylävirasto
- Puutuoteteollisuus
- Stora Enso

ForestValue

CLICK design

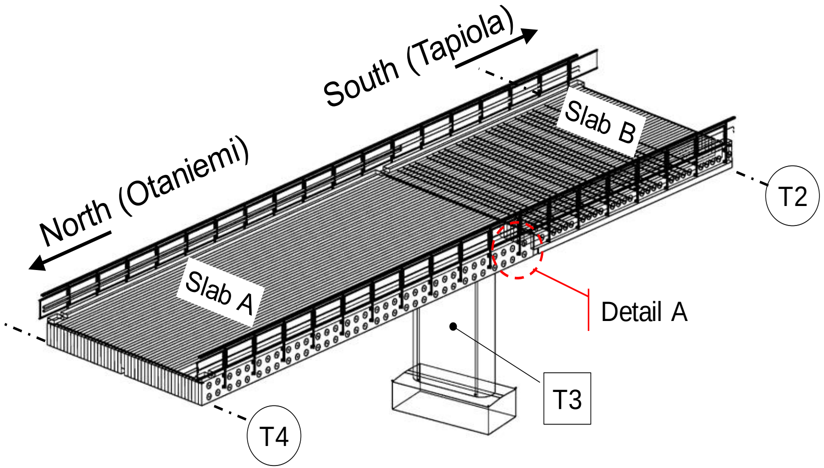


https://www.bregroup.com/services/research/clickdesign/

Monitoring of Tapiola Bridge in Espoo

Tapiola Bridge

Transverse prestressed glulam wooden slabs



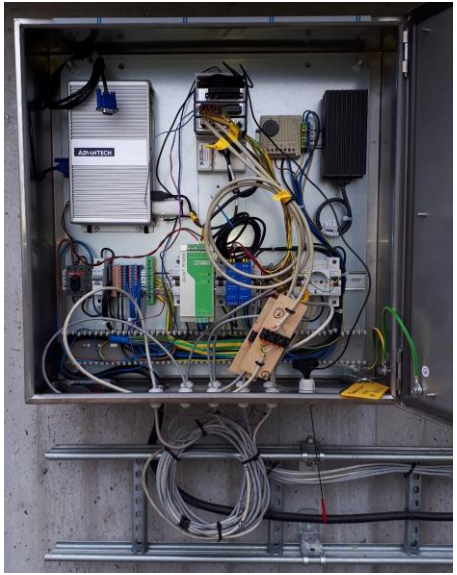
- 46 timber beams in the width direction
- beam widths = 0.215 m, heights = 0.765 m for the 13.45 m span and 1.035 m for the 22.13 m span
- deck width = 9.89 m, near to useful width 9.79 m
- weak paint

Fortino S, Hradil P, Koski K, Korkealaakso A, Fülöp L, Burkart H, Tirkkonen T. Health Monitoring of Stress-Laminated Timber Bridges Assisted by a Hygro-Thermal Model forWood Material. Applied Sciences 11(1):98 (2021)

Sensor-based monitoring

No.	ID	Sensor Type	Model
1	KC1	Humidity and temperature	HMP110
2	KC2	Humidity and temperature	HMP110
3	KC3	Humidity and temperature	HMP110
4	KC4	Humidity and temperature	HMP110
5	KC5	Humidity and temperature	HMP110
6	V1	Force	C6A
7	V2	Force	C6A
8	D1x	Slab longitudinal displacement	ELPC100 linear potentiometer of OPKON
9	D2y	Slab vertical displacement	ELPC 100 linear potentiometer of OPKON

Monitoring station with on-board computer

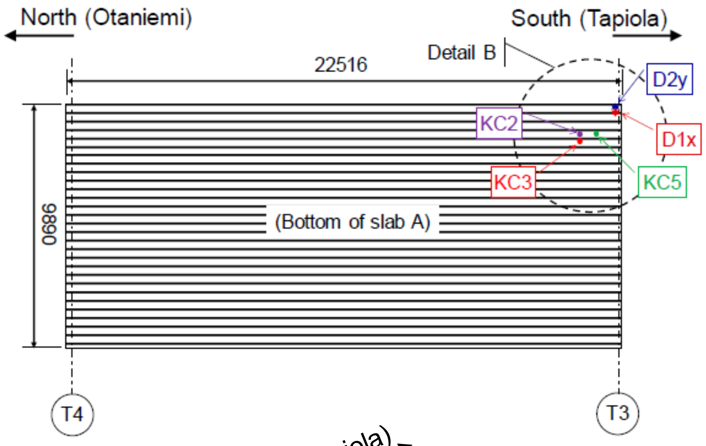


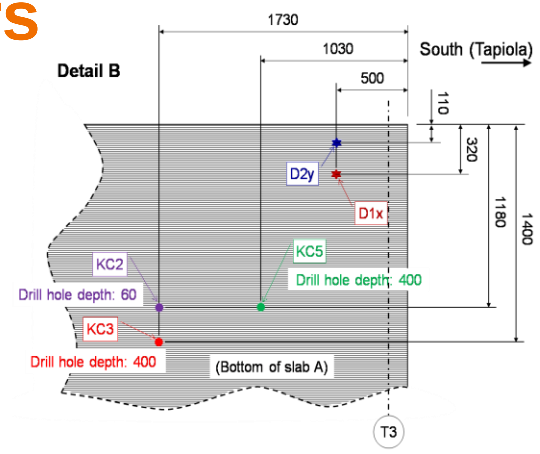
C6A, HBM

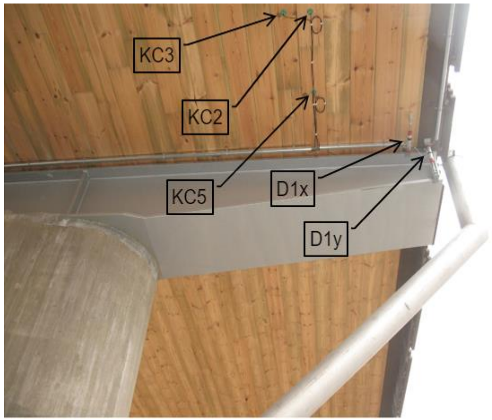
HMP110, Vaisala

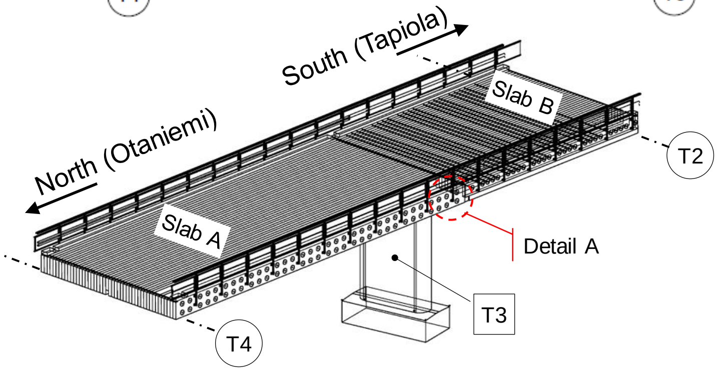
ELPC-100, OPKON

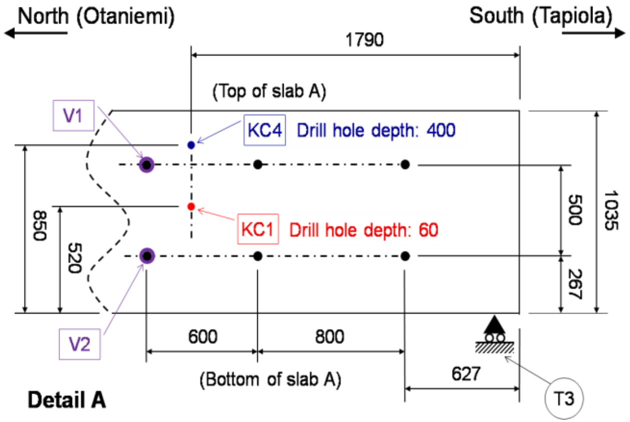
Locations of sensors

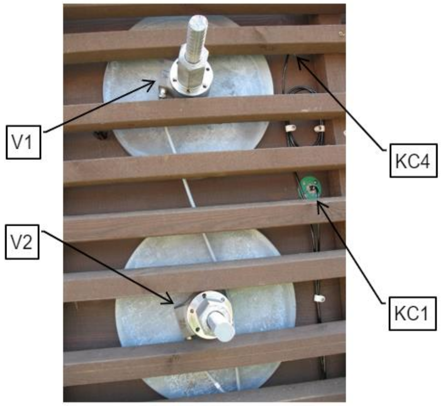












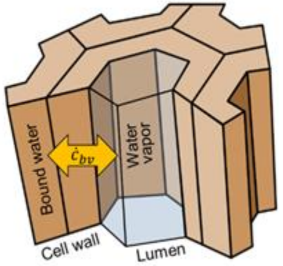
Multi-phase model for simulation of moisture transport in wood below the FSP

Multi-phase model – Gouverning equations

Phenomena below the fibre saturation point (FSP) of wood modeled through coupled differential equations and implemented in Uel subroutine of Abaqus FEM code

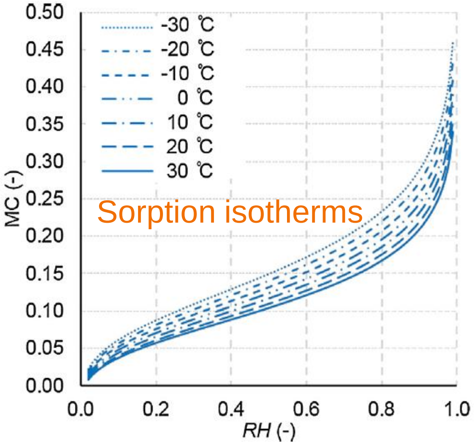
- Diffusion of bound water in wood cell walls $$\frac{\partial c_b}{\partial t} = -\nabla \cdot \mathbf{J}_b + \dot{c}_{bv}$$
- Diffusion of vapour water in lumens $$\frac{\partial c_v}{\partial t} = -\nabla \cdot \mathbf{J}_v - \dot{c}_{bv}$$
- Conservation energy (thermal equation) $$c_w \varrho \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{J}_H - \nabla \cdot \mathbf{J}_b h_b - \nabla \cdot \mathbf{J}_v h_v + \dot{c}_{bv} h_{bv}$$

with fluxes $\mathbf{J}_b = -\mathbf{D}_b \nabla c_b$ $\mathbf{J}_v = -\mathbf{D}_v \nabla c_v$, $\mathbf{J}_H = -\mathbf{K} \nabla T$



- Sorption between water phases

Results: moisture content (MC), temperature (T) and relative humidity (RH) in wood



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)

Boundary conditions

Boundary conditions for variables concentration of bound water and water vapour

$$\mathbf{n}\cdot\mathbf{J}_b = 0,\ \mathbf{n}\cdot\mathbf{J}_v = k_v^w\, c_v' - k_v^a c_v^a,$$

Boundary conditions for temperature including the net variance at the wood surface

$$\mathbf{n}\cdot\mathbf{J}_v = k_T(T - T^a) - q$$

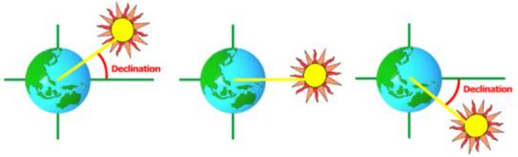
Net variance at the wood surface, function of Cos (I)

$$q = \alpha G + \varepsilon L - \varepsilon\sigma T_s^4$$

α: solar absorptivity
G: incident solar radiance
L: incident long-wave radiation
ε : long-wave emissivity
σ: Stefan-Boltzmann constant
T_s: surface temperature

Declination angle

$$\delta = -23.45^\circ \times \cos\left(\frac{360}{365} \times (d + 10)\right)$$



$$\mathrm{Cos(I)} = \cos(h)\cos(A_{ss})\sin(E) + \sin(h)\cos(E)$$

I: incident angle on a surface
h: solar altitude, function of declination angle
Ass: surface-solar azimuth
E: the angle of the surface from horizontal

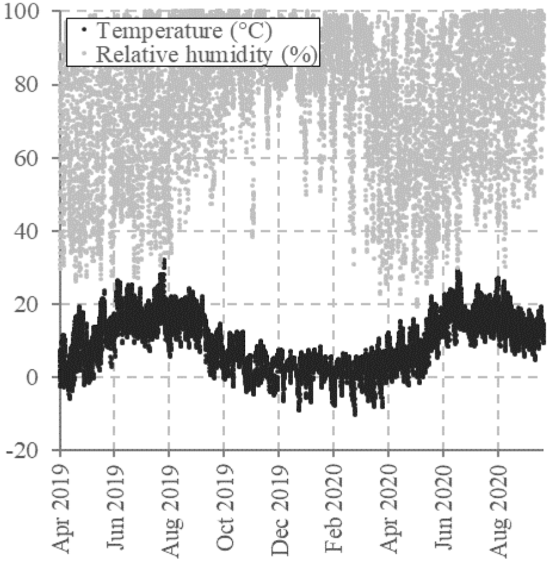
Kang W., Lee Y-H., Kang C-W., Chung W-Y., Xu H-L., Matsamura J. Using the Inverse Method to Estimate the Solar Absorptivity and Emissivity of Wood Exposed to the Outdoor Environment. J. Fac. Agr., Kyushu Univ., 56 (1), 139–148 (2011)

C.J.J. Castenmiller Surface temperature of wooden window frames under influence of solar radiation. TNO Building and Construction, Delft, The Netherlands. HERON, Vol. 49, No. 4 (2004)

Hygro-thermal analysis of Tapiola Bridge's deck

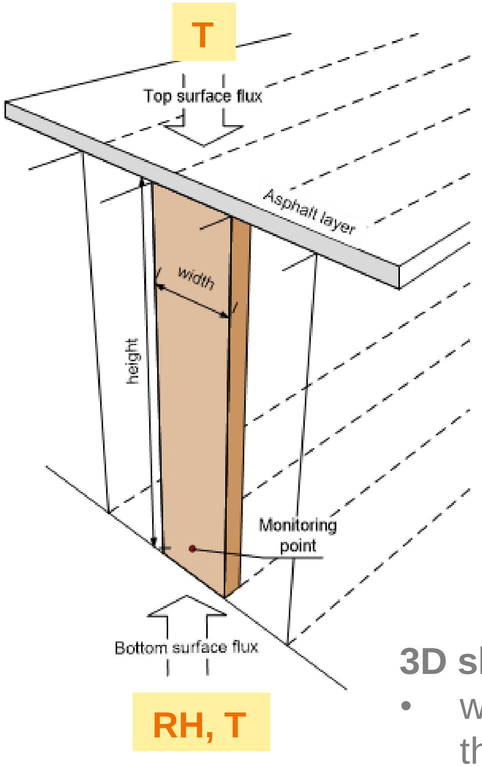
Model in Abaqus FEM code

weather



- Initial relative humidity RH_0 =65%
- Initial temperatures T_0 = 0.85 ºC
- initial moisture content in equilibrium with RH_0
  → MC_0 =15.3%

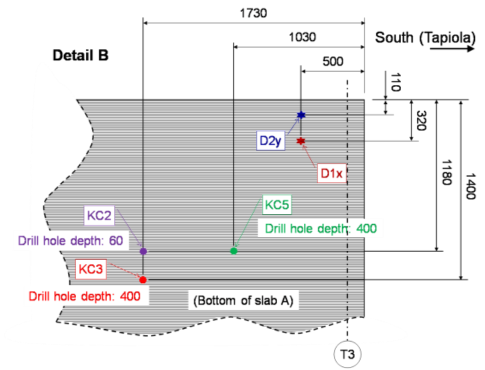
boundary conditions

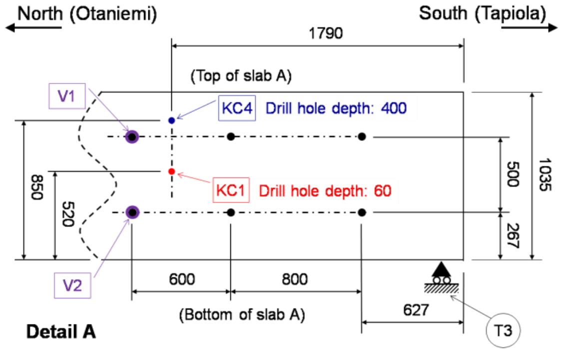


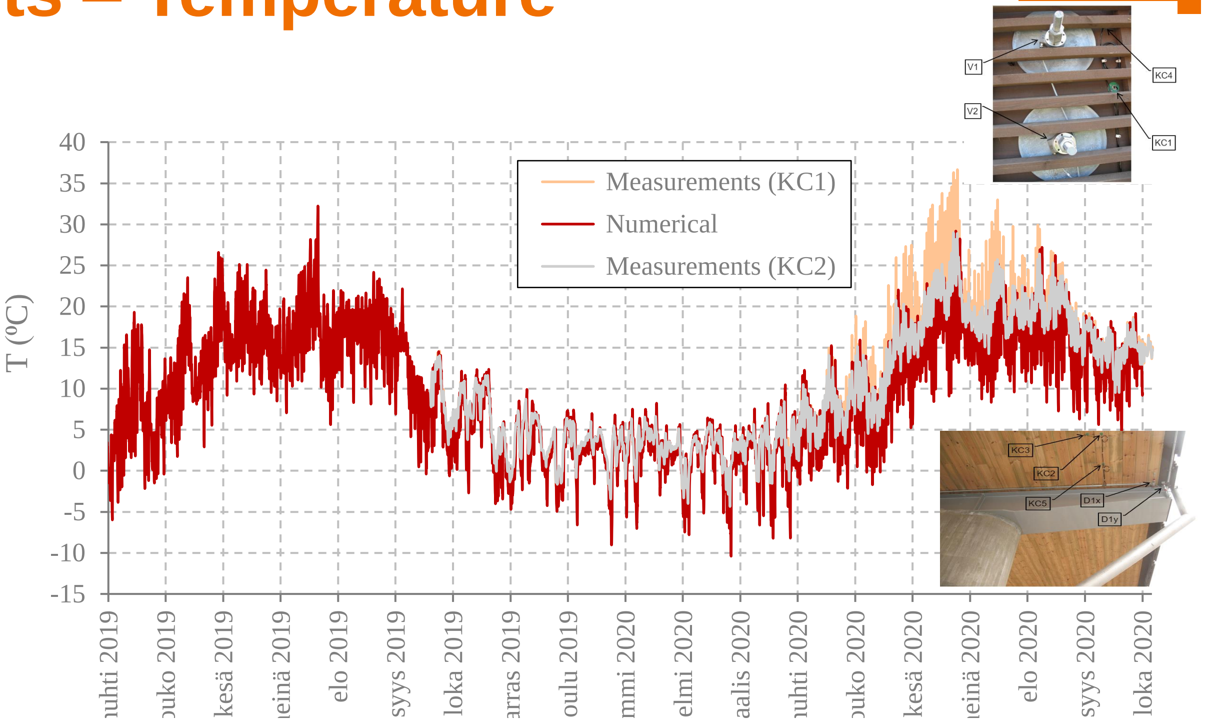
3D slice

- width = 107.5 mm (half of the lamination)
- height 1035 mm
- thickness 5 mm

Numerical results – Temperature



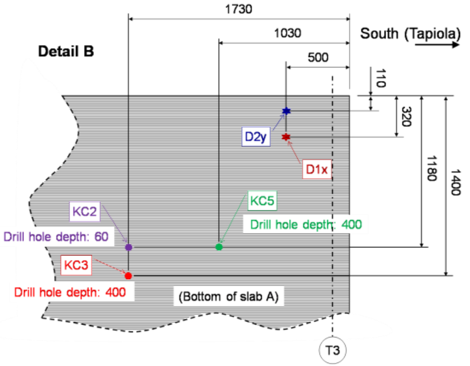


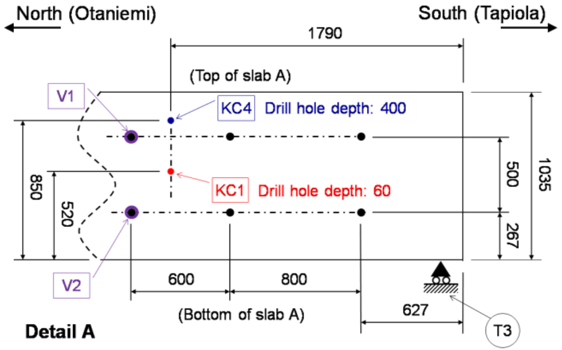


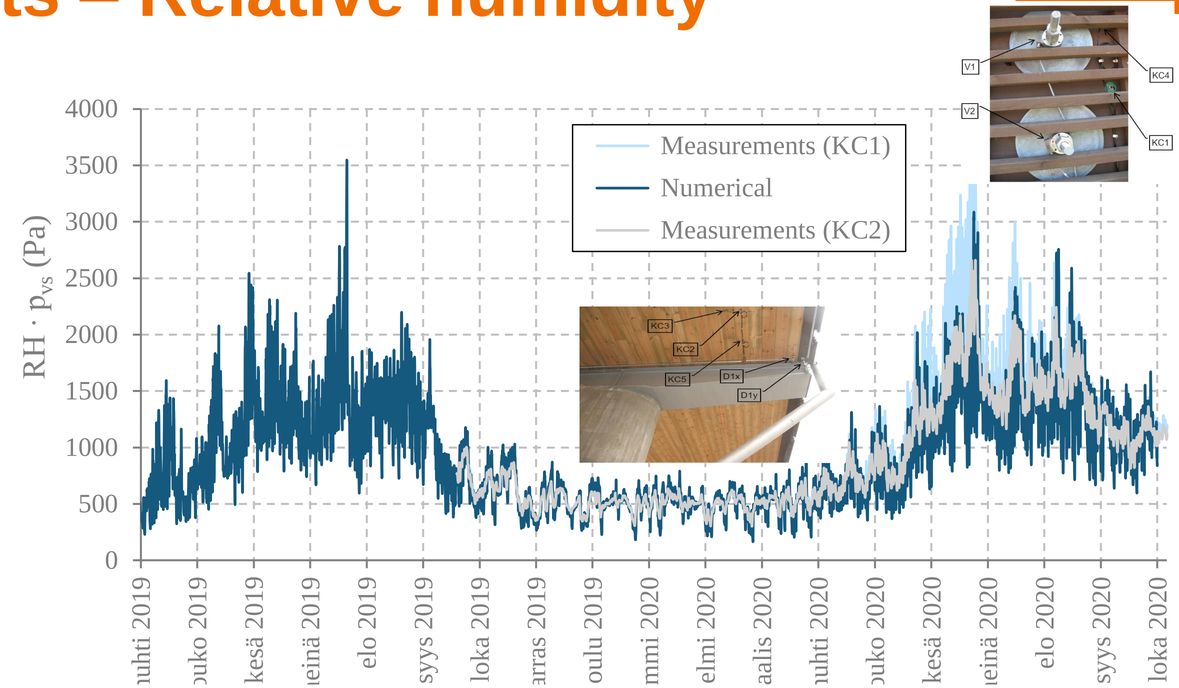
- **Measurements at 60 mm from surface**: slightly higher temperature peaks in KC1 in summer time from the lateral side exposed to the afternoon sun

- **Numerical model**: the current model shows an increase of temperature peaks below 5% compared to the model without the solar radiation effect

Numerical results – Relative humidity



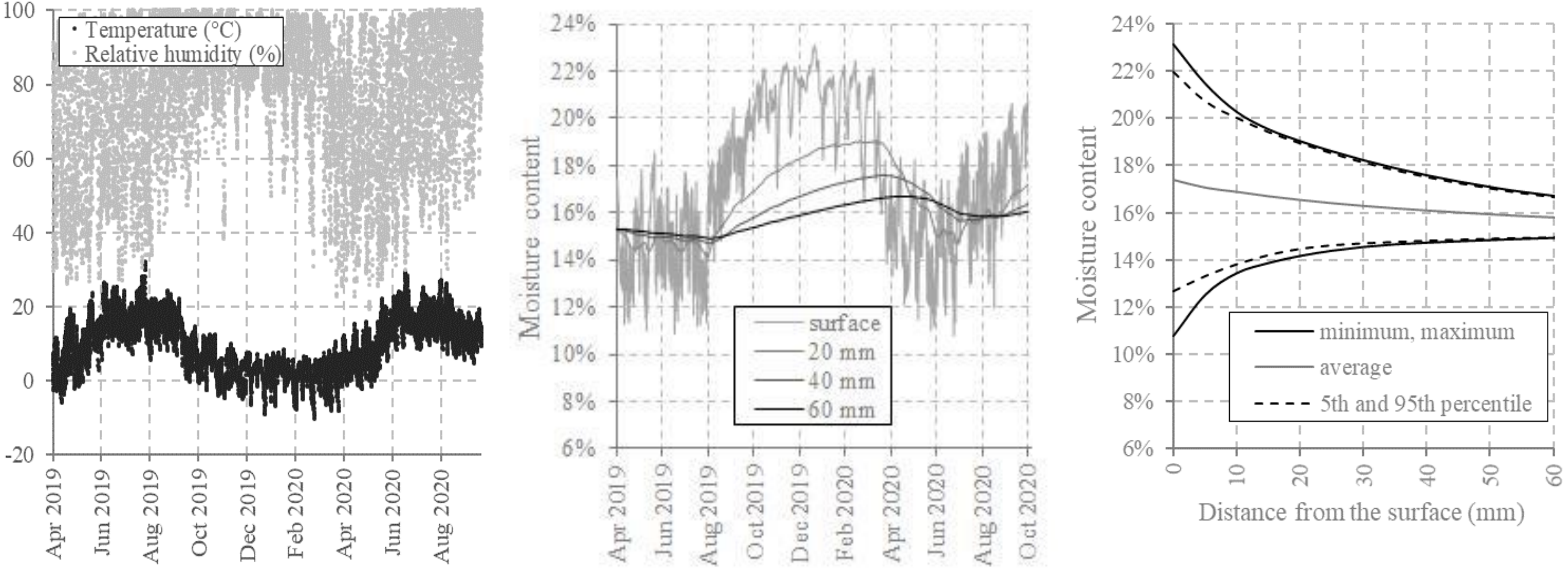




Saturated vapour pressure

$$p_{vs} = \begin{cases} exp\left(53.421 - \frac{6516.3}{T} - 4.125\ \ln(T)\right) & \text{for } T \geq 0°C \\ 100 \times 10^{\frac{9.5(T-273.15)}{T-7.65}+0.7858} & \text{for } T < 0°C \end{cases}$$

Numerical results – Moisture content



Discussion and future work

- Smart monitoring with implemented early warning systems can substantially decrease maintenance costs of timber bridges
- The current multi-phase model including solar radiation effects provides a small increase of temperature peaks in summer time (below 5%). The effect is negligible for the MC in wood
- Moisture peaks remain below 23% because Tapiola Bridge is protected, even if the used paint has low vapour resistance
- The average values of MC should not change significantly during the successive years
- The average MCs are around 16% up to 20 mm depth, and remain at an almost constant level up until 60 mm depth. However, 50% of the pre-loading force loss was measured before retightening in June 2022. Cupping phenomena should be investigated.
- The displacements and forces measured in the other sensors can be simulated in future work by integrating the hygro-thermal analysis with a mechanical model for wood
- The monitoring is currently on-going. The work will continue within the EU 5G-TIMBER project

VTT

European Commission

New projects

Twin Transition for The Timber Industry

Secure 5G-Enabled Twin Transition for Europe's TIMBER Industry Sector (5G-TIMBER)

- **HEU call**: CL4-2021-TWIN-TRANSITION-01-08: Data-driven Distributed Industrial Environments (IA)
- **Coordinator**: Tallinn University of Technology, 16 partners; **Duration**: 1.6.2022-31.5.2025
- **Main VTT's topics**: digital wood material models, IoT for predictive maintenance and structural health monitoring

ACADEMY OF FINLAND

Image-based Modelling of Water Transport In Wood including material biodegradation (WaterInWood)

- **Coordinator**: VTT Technical Research Centre of Finland
- **Partners**: University of Jyväskylä, LUKE - Natural Resources Institute Finland; **Duration:** 1.9.2021-31.08.2025
- **Main aim:** to fundamentally improve understanding on water transport in wood in hygroscopic and over-hygroscopic conditions and in the initial phases of fungal decay

WATER IN WOOD

WaterInWood project • 2022 - 2025 • Academy of Finland

ForestValue

VTT

CLICK design

Ympäristöministeriö
Miljöministeriet
Ministry of the Environment
ym.fi/puurakentaminen

European Commission

Thank you!

Questions?

5GT
Twin Transition for The Timber Industry

VÄYLÄ

Puutuoteteollisuus

JARTEK

storaenso