Validation of finite element models by neutron imaging of moisture transport through wooden instrument materials

STSM – Scientific Report

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1 Introduction

Neutron imaging is a radiographic measuring method that uses neutrons and can be applied to many research fields.
One difference to x-rays is the way they are absorbed by different materials, so x-rays can be used to detect metals and other heavy elements, while neutron beams are strongly obstructed by different elements like hydrogen. This, and the fact that metals are nearly invisible for neutron imaging make the neutron imaging a useful and non-destructive method to measure the moisture and water content in wood or other materials.
In contrast to weight-based methods, it does not only give the average moisture content of a body but also the moisture profile, which makes the neutron imaging a suitable method to verify the transient moisture transport model by experiments.
This verification is very important to obtain the goal of a realistic presentation of the hygro-mechanical material behaviour, which is substantial for a reliable structural analysis.
With the results of this STSM, I do not only get a confirmation of the material models, but also a deeper insight into the experimental set-up and methods that are used to measure the data which form the basis of the numerical simulations. This inside view is necessary for an uncertain structural analysis, which has the aim to predict the possible structural responses like displacements and damages that are the basis for the examination of historic wood instruments.
The uncertain analysis of wooden structures is a special challenge due to the dispersion of the material parameters that can not be influenced.

2 Methodology

Ahead of the STSM, a series of diffusion experiments with and without coatings was carried out and the moisture distributions over the time were calculated as results.
This moisture profiles shall be compared with the profiles from the transient numerical simulation with appropriate geometrical and material parameters.

2.1 Diffusion tests

In this section, I would like to compare the experiment and the simulation, a short overview is given in Table 1

Characteristic	Experiment	Simulation
wood species	spruce	spruce
geometry	cuboid specimen $\{h \times l \times w\} = \{10\,\mathrm{mm} \times 50\,\mathrm{mm} \times 10\,\mathrm{mm}\}$	assumption of one-dimensional diffusion, so simplification of the body: $\{h \times l \times w\} = \{10\,\mathrm{mm} \times 1\,\mathrm{mm} \times 1\,\mathrm{mm}\}$
moisture entry	upper and lower surface, diffusion in tangential material direction	
humidity level of ambient air	$RH_{\mathrm{ref}} = 0.65$ $RH(0\,\mathrm{h} < t < 4\,\mathrm{h}) = 0.95$ $RH(4\,\mathrm{h} < t < 8\,\mathrm{h}) = 0.3$ $RH(8\,\mathrm{h} < t) = 0.95$	$RH_{\mathrm{ref}} = 0.65$ $RH(0\,\mathrm{h} < t < 4\,\mathrm{h}) = 0.95$ $RH(4\,\mathrm{h} < t < 8\,\mathrm{h}) = 0.3$ $RH(8\,\mathrm{h} < t < 14\,\mathrm{h}) = 0.95$
change of humidity	linear change over 5 min	
coating	still pending	
measuring method	neutron imaging	bound water (m_b) in the nodes of the model along one edge
optimisation	$\sum_{x,t}(\Delta m_{\mathrm{Exp}}(x,t) - \Delta m_{\mathrm{Sim}}(x,t))^2 \rightarrow \min$ • lin. interpolated $\Delta t = 5\,\mathrm{min}$ and $x = \{0.5, 1, \ldots 4.5\}\,\mathrm{mm}$ (exploitation of the symmetry in vertical direction) • evolutionary algorithm for optimisation	

Table 1: Comparison experiment to simulation

One can see that the set-ups of simulation and experiment are comparable, only for the geometry I chose a simplification with a one-dimensional set-up (one row of spacial elements in tangential direction). This leads to a reduction of the computation time and is justified, because the diffusion in

the other directions is stopped through tapes on the other surfaces and also evaluation of the moisture in the experiment was one-dimensional with averaged results in radial and longitudinal direction.
In Figure 1 and Figure 2 Δm means the difference between the initial moisture and the moisture for the time t. Table 2 gives a recap of the characteristics of the simulation and the used models. The bounds of the optimisation are useful assumptions without a physical derivation.

Characteristic	Value
Material models	
Sorption	Hailwood-Horrobin
	$m(RH) = RH(a + bRH + cRH^2)^{-1}$
Diffusion	Two-phase diffusion-model according to Frandsen
Surface emission	Boundary-Layer-Theory
Varied parameters and borders for the optimisation	
Air velocity	$v_{\text{Air}} \in \,]0.0001\,\mathrm{m\,s^{-1}}, 10\,\mathrm{m\,s^{-1}}[$
Diffusion	$D_v = (1 + x)\, D_{v,\text{char}} \mid x \in \,]-0.4, 1[$
Sorption rate	$\dot{c} = (1 + x)\, \dot{c}_{\text{char}} \mid x \in \,]-0.5, 10[$
Sorption	$a \in \,]1, 5[$
	$b \in \,]8, 16[$
	$c \in \,]-16, -8[$
Dry density, calculated from $\rho_{RH=0.35}$	$\rho_0 = 370\,\mathrm{kg\,m^{-3}}$
FE model	
Discretisation	$\{n_l \times n_b \times n_h\} = \{1 \times 1 \times 5\}$ elements
Element type	spacial 20-node-elements and 8-node-surface-elements

Table 2: Characterisation of the simulation

2.2 Parameter Identification

The aim of the Parameter identification was to reproduce the results of the experiment as exact as possible, which is an optimisation task. As a measurement of deviation between simulation and experiment the in Table 1 described difference $\sum_{x,t}(\Delta m_{\text{Exp}}(x, t) - \Delta m_{\text{Sim}}(x, t))^2$ was used.
This approach has the disadvantage that functions which have a similar profile as the target function, but maybe are displaced, possibly have a bigger distance in the optimisation than a function with a not so similar profile. This is for example the case comparing Figure 1a to Figure 2a, the nonlinear profile in Figure 1a resemble the experimental results closer than the nearly linear profile in Figure 2a. The reason for this is, that different physical effects like the sorption hysteresis could not be regarded in the simulation.
Also the noise of the experiment results complicated the optimisation, since even a perfectly fitted function that would reproduce the smoothed profile would still have a deviation in the optimisation.

A further factor that has to be considered is the weighting of the different functions depending on the place. A comparison of different weighting approaches showed that good results could be achieved through

$$\Delta m_{\text{weight}}(x) = \frac{1\,\text{mm}}{3.5\,\text{mm} + x}\Delta m, \tag{1}$$

with the distance from the surface x in mm.

2.3 Sorption hysteresis

A second part of the STSM contained sorption experiments. These were carried out on the same wood as the diffusion to get the upper and lower main hysteresis curves.
So far the sorption had been calculated with one averaged function of the main adsorption and desorption curve, which is a simplifcation that gives no correct results. To improve the simulation I began to implement a Preissach-Mayergoyz hysteresis model, fitted to the data of the sorption experiment. The model has already been fitted and the implementation should be finished in the next weeks as a part of my diploma thesis.

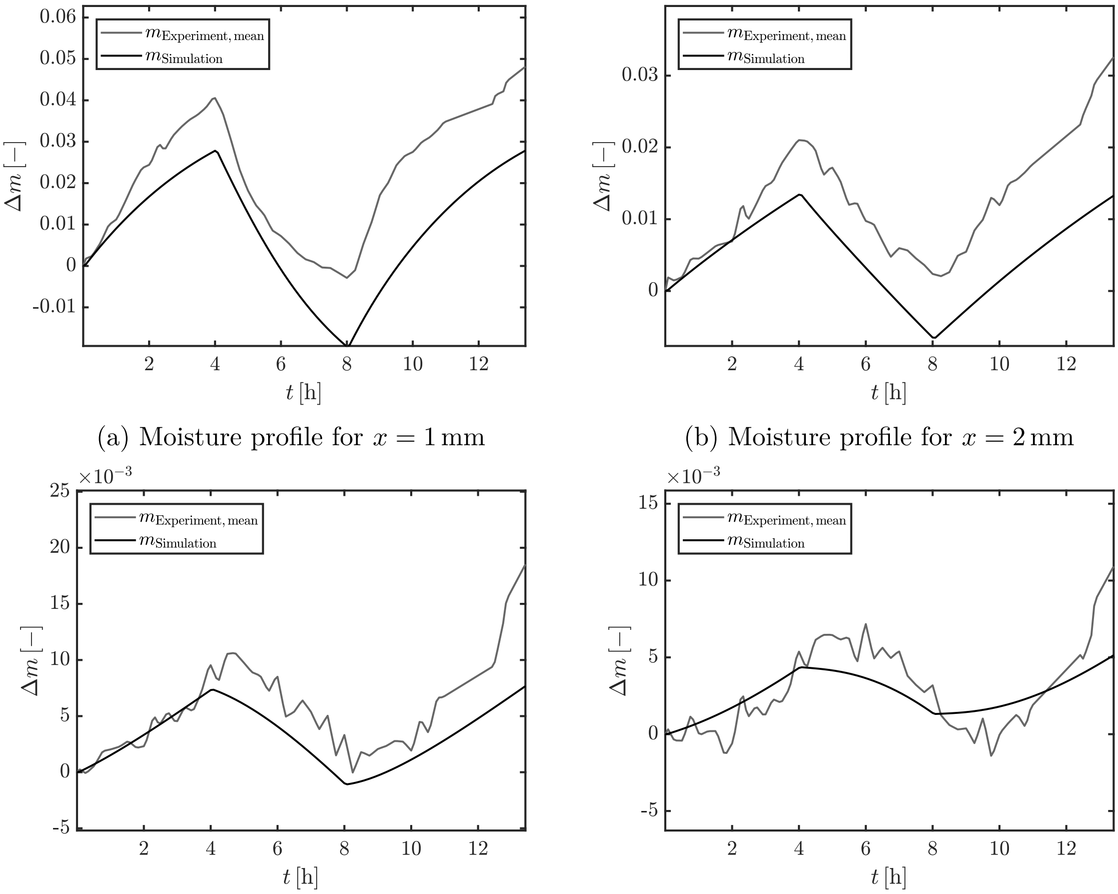
3 Findings

3.1 Results

In the diagrams in Figure 1, one can see that the simulation could not reproduce the results from the experiments with sufficient precision. This is why an optimisation of the material parameters becomes necessary. One aim of this optimisation is to identify the sensitive parameters that must be changed to obtain better results, which might show errors, necessary improvements in the material models or an improvement through the usage of alternative models.
In Figure 2 are the same diagrams shown, but for the optimised material parameters. These fit the experimental results much better. Comparing 2a to 2c and 2d, one can see that the results close to the surface are less appropriate than those deep inside.
A second observation is the missing delay of the reaction to the change of the humidity level in the simulation. This is caused by the missing hysteresis, that would bring a slower change of the moisture directly after load change, because the path is different for the adsorption and the desorption.

Parameter	Optimum
v_{Air}	$0.4028\,\text{m}\,\text{s}^{-1}$
D_v	$0.6944\,D_{v,\text{char}}$
$\dot{c}$	$3.0454\,\dot{c}_{\text{char}}$
a	1.6702
b	8.3889
c	-8.8

Table 3: Optimised parameters



(a) Moisture profile for $x = 1\,\text{mm}$

(b) Moisture profile for $x = 2\,\text{mm}$

(c) Moisture profile for $x = 3\,\text{mm}$

(d) Moisture profile for $x = 4\,\text{mm}$

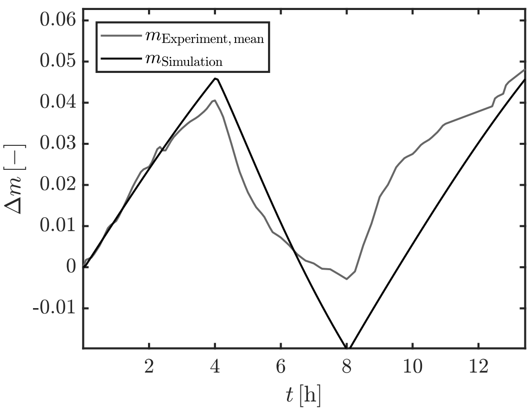
Figure 1: Moisture profile in comparison simulation to experiment for the characteristic material parameters (see Table 2)

3.2 Discussion

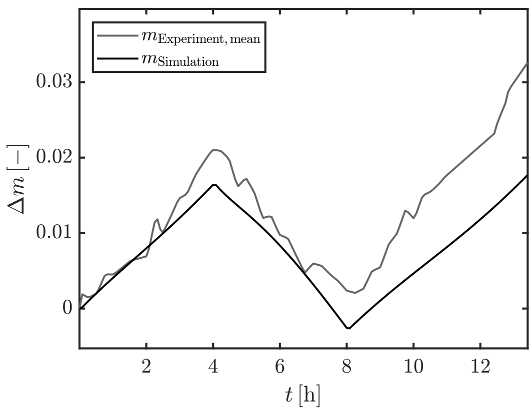
These results in general confirm the material models of the simulations and show that the simulation with fitted parameters is also suitable to give realistic predictions as an alternative to future experiments.
Nevertheless, there are still possible improvements that could be achieved in a future cooperation

- implementation of sorption hysteresis,
- adjusted experimental design to consider coatings,
- adaption of the model for better fitting of the results.

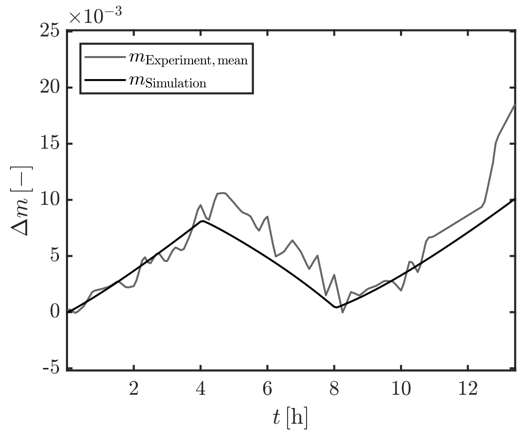
Unfortunately, there was no measurable surface emission through coatings so far, so no models could be developed for these. In future collaboration between Empa and TU Dresden, it is a main objective to rerun the adjusted experiments and to develop a moisture-dependent moisture transport model with respect to the coating layer thickness.



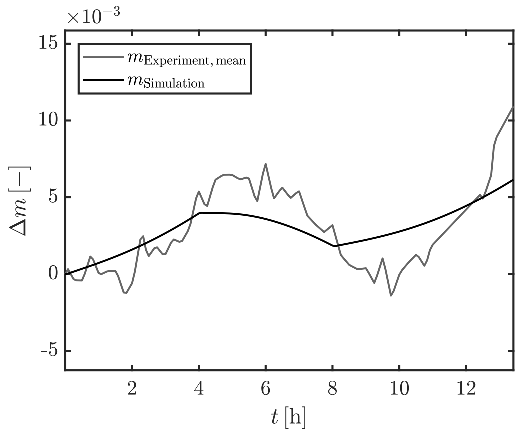
(a) Moisture profile for $x = 1\,\text{mm}$



(b) Moisture profile for $x = 2\,\text{mm}$



(c) Moisture profile for $x = 3\,\text{mm}$



(d) Moisture profile for $x = 4\,\text{mm}$

Figure 2: Moisture profile in Comparison Simulation – Experiment for optimised material parameters

4 Conclusions

Summarising, this STSM was successful and helpful for both sides. Even if not all subtasks could be processed, I think this mission is a great base for future researches.

I would like to thank all employees of Empa, mainly research partner Sarah Lämmlein, for the productive and pleasant cooperation, which is hopefully only the beginning of a long-range research partnership. Also I would like to thank the COST Action FP1302 that provided me the opportunity for this rewarding mission.

A Confirmation by host institution

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STSM (COST Action FP1302)

Dear Mr. Schmidt

With this letter I confirm your successful execution of the STSM at the Laboratory for Applied Wood Materials at Empa in Dübendorf in Switzerland. From the 27th March to the 7th April 2017 you have been able to compare, for the the first time, your hygro-mechanical simulation models to experimental data measured at a neutron beamline at the PSI in Villigen (Switzerland) and to evaluate, in collaboration with Sarah Lämmlein, potential improvements for the simulations and the experimental setup.

It would be nice to stay in touch with you and to continue the exchange and comparison of numerical and experimental data in future. Please do not hesitate to contact me, if you need any further support for your studies.

Sincerely yours,

Tanja Zimmermann

Tanja Zimmermann
Head Applied Wood Materials Laboratory