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Numerical Modelling of the Damage Potential of Indoor Climate Variations to a Historic Wooden Cabinet

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Abstract:
The two wooden cabinets of Jan van Mekeren that are located in Amerongen Castle show comparable wood damage; in particular large cracks in the cabinet doors are clearly noticeable. It is assumed that these cracks were caused by bad indoor climate conditions in the castle. Combined computational modelling of the indoor climate conditions in the castle and the hygroscopic and mechanical behaviour of the wood in the cabinet doors has been carried out in COMSOL to predict the damage potential of indoor climate variations to the doors. The preliminary results show that with COMSOL, the climate variations in the cabinet as a result of the indoor climate conditions in a room can be calculated. In addition, a prediction of deformation due to climate variations can be generated that complies with the visible damage. However, further investigation to the correct mechanical and hygroscopic properties of the materials in the cabinet is needed to acquire more accurate results.

Keywords: Climate change, cultural heritage, wood damage, damage risk assessment

1. Introduction

Seven similar examples of the wooden cabinets that are attributed to the Dutch cabinetmaker Jan van Mekeren and were created around 1690-1710 are currently known. The cabinets are considered as masterpieces of Dutch seventeenth-century furniture, due to the high quality of the marquetry decoration and the fine details in the wood. Two of these highly valuable cabinets are located in the Grand Salon in Amerongen Castle in The Netherlands. Based on historical records, it is assumed that the two cabinets were brought in the castle around 1748 [1].

The Van Mekeren cabinets completely consist of an oak construction with a veneer layer of different types of wood, such as kingwood, tulipwood, rosewood, ebony, olive wood and holly. Flower patterns have been created in the veneer layer using the technique of marquetry. An exploded view of the construction of a cabinet door is shown in Fig. 1. Nowadays, both cabinets in the castle show comparable wood damage: in particular, large cracks in the cabinet doors are clearly noticeable (Fig. 2). Besides that, craquelure with a penetration depth of approximately 1 to 2 mm has occurred on the veneer layer. Based on historical data, it is assumed that the mechanical degradation was caused by bad indoor climate conditions in the castle.

Amerongen Castle was built in the 17th century. The five-storey building has brick walls with a thickness varying between 0.7 and 1.5m. Until recently, the castle has remained mainly unheated. Therefore, indoor climate conditions have primarily been determined by the outdoor climate. Besides that, the indoor climate conditions have regularly been affected by flooding events in the basements, which occurred several times in the past due to high water levels in the adjacent river. The castle is currently open as a museum.

The occurrence of the deterioration for historic wooden objects is commonly attributed to uncontrolled variations of ambient temperature and relative humidity (RH). These variations induce physical damage to the wood due to its hygroscopic nature and dimensional response to the moisture sorption or desorption [2]. Moisture changes generally have the greatest structural effect at extreme low and high relative humidity levels and the least effect in the central RH regions [3]. For a variety of wood types and wooden objects, the moisture sorption and desorption and corresponding dimensional change in tangential and radial direction have been investigated. For instance, Bratasz et al. [4] conducted measurements to study the moisture induced dimensional changes of a lacquer box and defined domains of the tolerable variations that produces safe, reversible response of the wood and lacquer. It was shown that for this case, the domain of tolerable RH fluctuations is considerable in the mid-RH region and becomes narrower only at high RH levels (Fig. 3).

Figure 1. Exploded view of the construction of one cabinet door (Source: Rijksmuseum, Amsterdam)

Figure 2. Cracks in a door of one of the cabinets

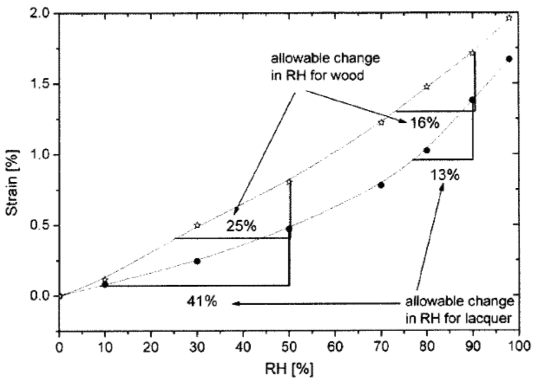

Figure 3. Allowable changes in relative humidity for wood and lacquer (Bratasz et al., 2008b)

Collections that have been housed in monumental buildings for many decennia/centuries may have responded to large RH fluctuations in the past. The largest RH fluctuation to which an object has responded in the past is given by the proofed RH [5]. Objects that have been exposed to fluctuations of +/- 20% to +/- 40% and that have not weakened much earlier by material strength changes are expected to experience little or no damage at one half of these fluctuations. In case of a large proofed RH, maintaining a strict guideline for the range of RH values is of no avail.

The objective of this study is to analyse the climate variations in the cabinet as a result of the indoor climate conditions in the Grand Salon. Climate chamber experiments were carried out to investigate the response of a wooden panel to a sudden RH increase. In addition, combined on-site measurements of the indoor climate conditions inside the Grand Salon and inside one of the Van Mekeren cabinets were taken to evaluate the RH variations in the cabinet doors. Both experiments have been modelled in COMSOL based on the transfer equations for heat and moisture and the thermal and hygroscopic properties of the wood. The COMSOL models have been validated with the on-site measurements and the predicted climate variations have been compared with the tolerable variations that were derived from literature. Finally, deformation of a door panel due to climate variations is predicted.

2. Modelling in COMSOL

COMSOL Multiphysics has been applied for three purposes:

1. Calculation of the response in the core of a wooden panel to a sudden RH increase
2. Calculation of the indoor climate conditions inside the cabinet based on the climate conditions in the room
3. Prediction of the deformation of a wooden door panel due to climate variations

For the first two purposes, a simplified 3D model of the wooden cabinet has been created. Heat and moisture transport by diffusion through the cabinet has been calculated with a non-isothermal heat flow model.

Heat transport is calculated by:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k \nabla T) \qquad [1]$$

where:
ρ = density [kg/m³]
c_p = specific heat capacity [J/kgK]
T = temperature [°C]
k = thermal conductivity [W/mK]

Moisture transport by diffusion is calculated by:

$$\frac{\partial Pv}{\partial t} = \nabla(D(Pv)\nabla Pv) \qquad [2]$$

where:
Pv = vapour pressure [Pa]
D(P) = moisture diffusion coefficient [m²/s]

The boundary conditions have been defined as following:

Heat flow:

$$q = h(T_0 - T_s) \qquad [3]$$

where:
q = heat flux at surface [W/m²]
h = heat transfer coefficient [W/m²K] (= 7.7)

Moisture flow:

$$g = \beta(P_0 - P_s) \qquad [4]$$

where:
g = vapour flux at surface [kg/m²s]
β = vapour transfer coefficient [s/m] (= 3e-8)

Second, deformation of the cabinet door due to swelling and shrinking of wood has been predicted with the COMSOL structural mechanics module. A linear elastic model has been created and hygroscopic behaviour is taken into account by a thermal expansion model. In contrast with the dimensional change in the radial and tangential direction, the dimensional change is the longitudinal direction is relatively small. Therefore, strain is considered only the radial and tangential direction.

For an anisotropic material, the relation between stress and strain is calculated by:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \boldsymbol{\gamma_{xy}} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_Y} & 0 \\ -\frac{\nu_{yx}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} + \begin{pmatrix} \alpha_x \\ \alpha_y \\ 0 \end{pmatrix} \Delta\theta + \begin{pmatrix} \kappa_x \\ \kappa_y \\ 0 \end{pmatrix} \Delta w \qquad [5]$$

where:
$\varepsilon_x \varepsilon_y$ = normal strain components [-]
γ_{xy} = shear strain component associated with two axis [-]
ν_{xy}, ν_{yx} = Poisson's ratio [-]
E_x, E_y = Young's moduli [N/m²]
G_{xy} = shear modulus [N/m²]
α_x, α_y = linear thermal expansivity [m/mK]
θ = temperature [°C]
κ_x, κ_y = linear deformation due to changes in moisture content [m/m(kg/m³)]
w = moisture content [kg/m³]

In this study, linear thermal expansivity due to temperature changes is not taken into account. The Poisson's ratio has been taken as a constant (= 0.3) and the shear modulus has been taken equal to $1e^9$. Because limited data on the hygroscopic properties of the different wood types in the cabinet is currently available, material properties for lime wood derived from Jakiela et al. have been applied [6]. The hygroscopic properties of lime wood can be found in the appendix.

3. Results

3.1. Climate chamber experiments

To investigate the response of one cabinet door to an increasing RH, an oak panel has been placed in a temperature and humidity test chamber. The construction of this panel corresponds with the oak construction in the doors of the Van Mekeren cabinet. At the start of the measurements, the temperature in the climate chamber was 21°C and the RH was 48.4%. Hereafter, the RH in the climate chamber was increased to 70%. The measured temperature in the room during the experiments was 20±1°C, the measured RH in the room was 70±2%. The RH in the core of the panel was measured every five minutes during 34 days.

The climate chamber experiment has been modelled in COMSOL to calibrate the material properties of the wooden panel. An isothermal moisture flow (T = 20°C) has been assumed in the COMSOL model. Fig. 4. shows a comparison between the measured RH inside the climate chamber, the measured RH in the core of the panel and the RH in the core of the panel that has been calculated with COMSOL. At the start of the measurement, a deviation is found between the measured core RH and the simulated core RH. This could be caused by a temperature effect in the climate chamber that has not been included in the simulation model. After a few days, the COMSOL model adequately complies with the measurements.

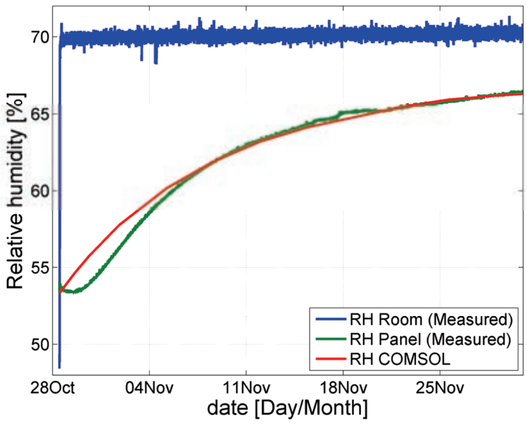

Figure 4. Comparison between measured relative humidity in climate chamber and simulated relative humidity in COMSOL

3.2. On-site measurements

Recently, combined on-site measurements of the indoor temperature and RH inside the Grand Salon and inside one of the Van Mekeren cabinet were started. The climate conditions have been measured with a ten-minute interval. A simplified model of the cabinet has been created in COMSOL. The cabinet has an estimated volume of 1.5m³ (length x width x height = 1.8 x 0.6 x 1.4m³). The climate conditions around the cabinet have been taken equal to the measured room conditions. The air flow through the cracks in the doors has been modelled by an air inlet and outlet at each side of the cabinet. The estimated inflow velocity of the air is 0.01 m/s. A comparison between the measured temperature and RH in the Grand Salon and inside the cabinet with the simulated temperature and RH in COMSOL is shown in fig. 6 and 7. The simulated temperature complies well with the measurements, but the predicted RH deviates from the measured RH. The response time of the wood to moisture variations is overestimated in COMSOL. This can probably be improved by the use of a turbulence model in order to more accurately simulate the air flow inside the cabinet.

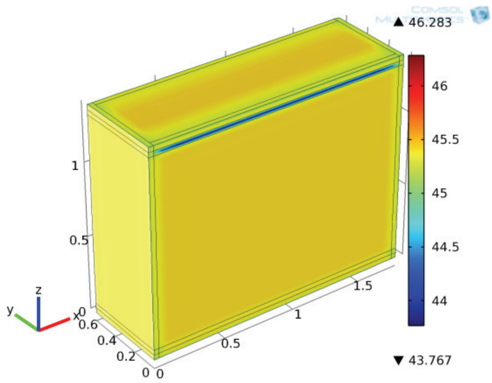

Figure 5. RH distribution over cabinet at t = 1000

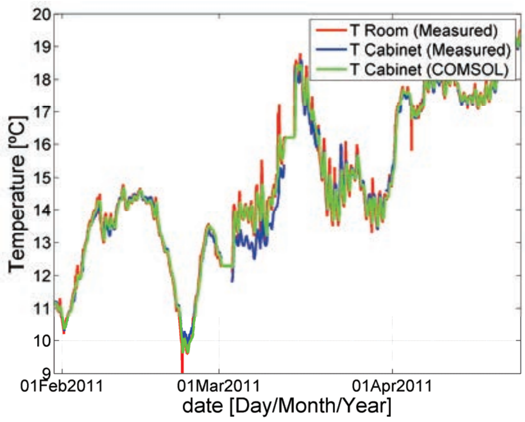

Figure 6. Comparison between measured temperature in castle and cabinet and simulated temperature in COMSOL

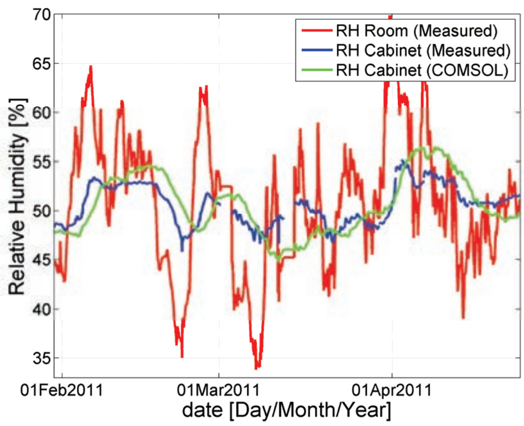

Figure 7. Comparison between measured relative humidity in castle and cabinet and simulated relative humidity in COMSOL

3.3. Deformation of cabinet door

Deformation of the cabinet doors due to swelling and shrinking of the wood has been predicted by combining the heat and moisture transfer model with the solid mechanics model in COMSOL. A 3 dimensional model of one cabinet door has been created based on Fig. 1. The modelled door panel consists four cross beams (length x width x height: 800 x 40 x 18mm) that are at both sides fixed to three 7mm thick wooden panels. The three wooden panels, which each have a width of 200mm, are covered with a 600mm width veneer layer of 1mm thickness. The sides of the cabinet door are restricted from deforming by joints; therefore these boundaries have been modelled as fixed constraints.

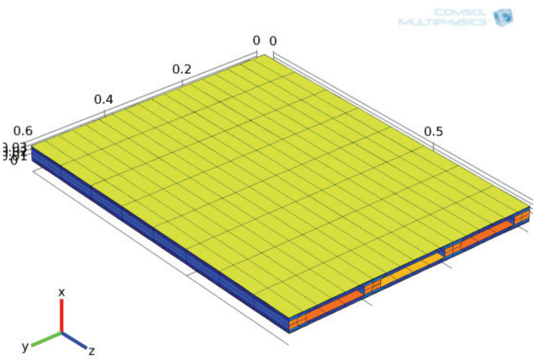

Figure 8. COMSOL model of cabinet door

The climate conditions around and inside the cabinet have been taken equal modelled conditions of Section 3.2. As was mentioned in Section 2, the hygroscopic and mechanical properties that have been assumed do not comply with the exact properties of the materials in the cabinet, so this model only generates a prediction of possible deformation due to climate variations. The largest deformation that has been predicted is found in the centre of the cabinet and in the panels of the oak construction behind the veneer layer (Fig. 8). An agreement is found between the predicted deformation and the visible damage at the front side of the cabinet doors (Fig. 2). At the internal side of the door, the RH fluctuations are considerably smaller. As a consequence, less deformation is predicted at this side (Fig. 9).

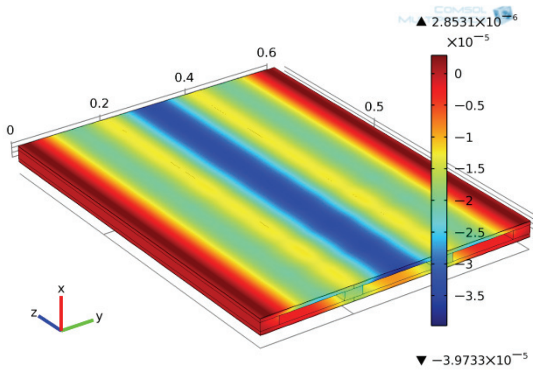

Figure 8. Predicted deformation at the external side of the cabinet door at t = 1000

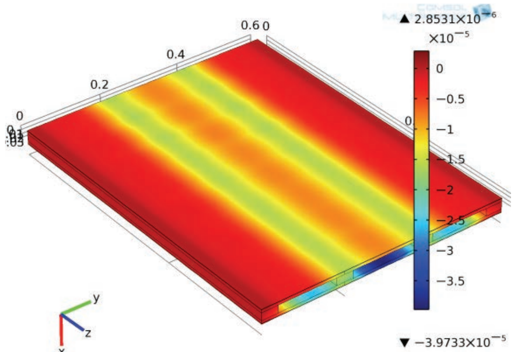

Figure 9. Predicted deformation at the internal side of the cabinet door at t = 1000

4. Conclusions

The objective of this study was to analyse mechanical damage to a wooden cabinet door as a result of climate variations. The preliminary results show that with COMSOL and assumed thermal and hygric material properties, the heat and moisture transfer through the cabinet can be modelled. With this model, the microclimate conditions inside the cabinet can be calculated based on the measured room indoor climate conditions. In addition, the response of the wooden door panels to climate variations can be analysed and deformation of the wooden door panels can be predicted.

In the near future, more detailed measurements will be carried out to determine the correct hygroscopic and mechanical properties of the various wood types in the cabinet. This information will be used to more accurately calculate stress and strain in the cabinet as a result of climate variations. In combination with scenarios of the historic indoor climate conditions in the Grand Salon, a possible scenario of the historic indoor environment that could have caused mechanical degradation of the cabinets can be generated.

5. References

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6. Acknowledgements

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7. Appendix

Table 1. Thermal properties of wood and air

Oak	d [m]	0.034
	k [w/mK]	0.17
	ρ [kg/m³]	800
	C [J/kgK]	1880
Air	d [m]	0.53
	k [w/mK]	0.023
	ρ [kg/m³]	1.2
	C [J/kgK]	1000

Table 2. Dimensional change in tangential and radial direction and diffusion coefficient of lime wood as a function of RH, derived from [6]

RH [-]	Dimensional change in tangential direction [%]	Dimensional change in radial direction [%]	Diffusion coefficient [m²/s]
0	0	0	1e-13
0.1	0.70	0.33	1e-13
0.2	1.1	0.52	5e-12
0.4	1.9	0.87	3.5e-12
0.6	2.9	1.4	5e-12
0.8	4.1	1.9	4e-12
0.9	5.3	2.5	3.7e-12
1	6.7	3.1	3.5e-12

Table 3. Young's moduli of lime wood in tangential and radial direction as a function of RH, derived from [6]

RH [-]	Young's modulus in tangential direction [MPa]	Young's modulus in radial direction [MPa]
0.2	600	1120
0.35	490	900
0.5	450	820
0.65	420	770
0.8	400	760