The use of COMSOL to explore flooding and rising water problems related to heritage
Case study St. Catherine's Chapel, Lemiers, The Netherlands

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Abstract: In St. Catharine's chapel in Lemiers, The Netherlands, wall paintings are deteriorating for years. During the past years the condition of the wall paintings has worsened even more. The paintings have started to crack and peel off more and more from their background. There were some indications that lead to expected high groundwater levels due to a nearby lying Selzer creek and its flooding. A result was a flooded crypt underneath the chapel.
In the past two years several climate conditions in and around the chapel have been measured. The performed measurements had various objectives: one is to get insight in the current indoor and outdoor climate conditions in relation to the deterioration of the wall paintings; second objective is to provide data for validation of a simulation model. The chapel had been modelled with a multi-zone model, which is a simulation model for heat and vapour flows in a building. Based on this first model no direct indication was found what might have caused the damaged wall paintings. Therefore a second model was constructed with COMSOL. Based on the earlier taken measurements in groundwater levels it is assumed that the foundation is nearly always in contact with water, because the groundwater levels averagely vary around 75 centimetres below field. From there on, the further course of rising moisture was investigated. The results show that rising moisture nearly always takes place and is also depending on the amount of evaporation at the inner and outer surface. Solutions to prevent rising moisture are costly and mostly rigorous. Impregnation of the foundation is a possibility. The capillaries of the marlstone wall are then injected with a chemical fluid to prevent moisture to rise up in the wall.

Keywords: rising water, flooding, inverse modeling

1. Introduction

The interior of Saint Catherine's Chapel in Lemiers was painted by the artist Hans Truijen in 1977-1978. The paintings show Truijen's interpretation of the Christian story of creation and the life of Christ. Part of the wall paintings has been significantly deteriorated because of moisture problems in the church. The aim of this study is to provide environmental data that would help explain the deterioration of the wall paintings and to give recommendations on how the indoor climate in the church can be improved. For a period of two years continuous measurements have been performed of the outdoor and indoor climate conditions as well as the microclimate conditions close to the walls. In addition, instantaneous measurements of the moisture content of the walls have been carried out. Furthermore, hygrothermal building simulation models of the church have been created to derive heat and moisture sources in the building. With help of these models, sustainable strategies have been investigated to diminish the moisture problems in the church.

2. The building

2.1 History

Saint Catherine's chapel is a hall church in Romanesque style. It dates either from the second half of the 11th century or from the 12th century. Among the foundations are remains of an older building, probably from the 8th century, the time of Charlemagne. The choir was added in either the 13th or 14th century, possibly in 1350 when the building was consecrated to St. Catharine. Until then the chapel has belonged to the nearby castle.
As a whole, the building is the only complete surviving example of the earliest type of stone churches known in the Netherlands, a one-aisled building without a tower (Figure 1). Despite its later addition, the rectangular closed choir is typical for these earliest churches as well.

Figure 1. The exterior of the church of Lemiers (Source: nl.wikipedia.org 2012).

The building has undergone several changes: in 1648, the choir was heightened and vaulted and the small turret was added to the roof. In 1683, the small windows were enlarged. In 1893-1897, after a new church was built in the village, the chapel was closed and restored by P.J.H Cuypers, who reconstructed the small windows and closed the large ones. In addition, the entrance in the south wall, which had been closed with brick, was reopened while the entrance at the north side, which dated from the 17th century, was closed. The building was registered as a Dutch state monument in 1967. The chapel can be visited by a guided tour on request and is occasionally used for events.

2.2 Building Environment

The church is located in Lemiers, in the municipality of Vaals (Limburg), at coordinates 50.47° latitude and 5.59° longitude (Figure 2). The church was probably built on the site of a former religious building. The surrounding buildings in the street are low-rise buildings, so these building do not form obstacles for the entering of daylight. However, trees at the north side of the church and the nearby building at the west side block the entering of sunlight during a few hours in the afternoon.

2.3 Constructional analysis

The typical ground plan of a church in Romanesque style is a basilica plan with three naves and a transept. Small rural churches usually consist of a longitudinal plan oriented from east to west with a simple central nave and an altar at the east side.

Figure 2. Map of Lemiers, the location of the church is indicated by a red dot [Source: Google maps].

The nave has a rectangular shape and has no side aisles (Figure 3). The ground floor in the nave consists of approximately 300mm sand, 10mm concrete and 27mm natural stone marble floor tiles. The floor of the altar has a surface uplift of 150mm with respect to the central nave floor. The floor is not thermally insulated.

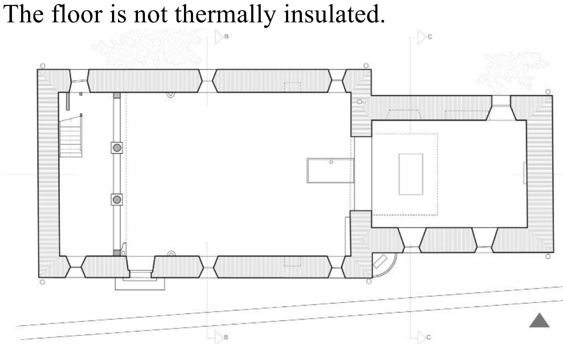


Figure 3. Ground plan of the church

From the outside, the church is accessed through a door located on the south wall of the central nave. The door is made of timber and has a thickness of 70mm.

Inside the nave, a stairs brings one to the choir. The floor of the choir consists of a timber construction with a total thickness of 185mm. The central nave is wider and higher than the altar. The crypt, a domed space of rectangular-shaped where the relics of the saints were kept, is located below the altar. It has a depth of 3.10 meters and a length of 2.80 meters. The estimated floor construction of the crypt consists of 300mm sand, 150 gravel concrete and 15 mm concrete.

The central nave has a width of approximately 5.60 meters and a depth of approximately 10 meters. The altar has a width of approximately 3.70 meters and a depth of approximately 5.40 meters. The internal wall between the central nave and the altar is made of masonry, is on both sides covered with plasterwork and has a thickness of 750 mm.
The central nave has a barrel-vaulted roof construction, which replaced the original wooden roof for security purposes. The roof is composed of a series of semi-circular arches, which are reinforced by three transverse arches that divide the barrel-vaulted in four equal sections. The external walls support the roof construction. The vault of the central nave is made of wooden beams that are fixed to a wooden construction. Two fan vaults that are completely constructed out of stone cover the altar.
The vault of the central nave starts at approximately 4.1 meters above the ground floor and its highest point is located at approximately 6.2 meters above the ground floor.

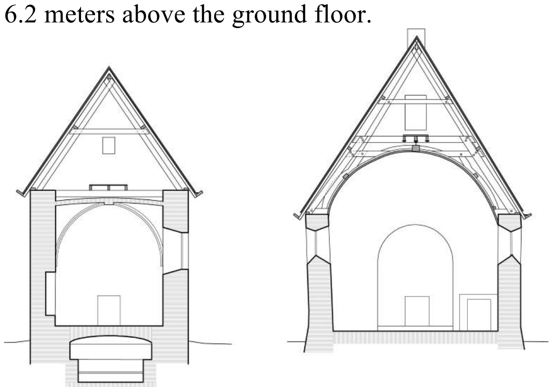


Figure 4. Cross sections of the chapel

The attic floor above the altar is made of plasterwork and natural stone and concrete. The vault of the altar starts at approximately 2.20 meters above the ground floor. The highest point of the vault is located at approximately 4.30 meters above the ground floor. The attic above the nave can be reached via the attic above the central nave.
The main supporting elements of the church are the stone walls. The thick masonry walls provide a high thermal mass. The outdoor walls are free of adornments, the facade is very uniform, linear and crude and the stones are unpolished; these are all characteristic elements of the simple Romanesque style.

The external walls of the nave are made of masonry with lime mortar; their thickness varies between 750 and 900mm.

For structural reasons, the windows had to be rather small. Moreover, the church served as a place of shelter, so there was also a need for the door and windows to be small. For this reason, the amount of daylight entering the church is very small. The external walls of the nave contain 10 windows. All the windows are made of leaded glass and divided in parts with frames made of steel. The windows have blank single glazing. Only two windows can be opened for ventilation of the church: W2 at the south wall and W7 at the north wall. The windows of the central nave have a textile protection inside, probably to protect the painting from direct solar radiation.

The furniture in the church is sober: some wooden benches and chairs are placed around the perimeter of central nave. There are several cracks present in these benches, which could be caused by unfavorable climatic circumstances at the time the church had warm air heating. A stone pulpit is located on the altar. The internal walls are covered with plasterwork, on which the famous frescoes of Hans Truijen were painted.

3. Measurements

The measurements performed in this study have various objectives: one is to get a complete image of the current indoor and outdoor climate of the church and to relate these conditions to the deterioration of the wall paintings; the other objective is to provide data for the simulation model and to validate the outcome of the model. When the outcome of the model is in agreement with the measurements, the model will be used to answer several research questions.
The measured parameters of this report can be divided into instantaneous and continuous measurements. Instantaneous measurements have been carried out for the moisture content of the walls and the groundwater level.
Continuous measurements were taken of the following parameters:

- Outdoor and indoor air temperature
- Outdoor and indoor air relative humidity
- Indoor surface temperature
- Indoor surface relative humidity
- Heat Flux of external walls
- CO_2 concentration
- Global solar radiation

3.1 Moisture content of the walls

The subsurface moisture content of the walls was measured by a digital microwave measuring tool. For measuring the moisture content the measuring tool takes the relative high dielectric constant of water in comparison to the dielectric properties of other materials. For example common sand has a dielectric constant of about 4 compared to the dielectric constant of water, which is about 80. So when a value of 80 is measured one can say that the material is fully saturated with moisture. However, this measuring tool is limited in its accuracy, since it can only measure up to a depth of 300mm. The penetration depth is reduced further when the region near the surface of the wall is fully saturated with moisture or when water is dripping from the wall. On the other hand, the measuring device gives a clear indication of dry or wet materials at the surface.

Measurements of the moisture content of the walls were performed twice: on October 26th 2012 and on the 4th of March 2013. These measurements were performed close to the floor, so at a height of approximately 0 meters, further on at a height of 0,5 m from the floor and at 1 meter. The distance between the measuring points was approximately 1 meter. At the very first visit to the chapel, before the start of the research, the crypt was completely flooded up to the entrance hatch. During the first measurements, the water level in the crypt was a few centimetres measured from the hatch of the crypt as can be seen in figure 5. During the second measurement the crypt was dry. Figures 6 and 7 give an indication of the average measured results

It can be noticed that the highest dielectric values were measured closely to the floor and in the wall above the crypt between nave and altar. In these areas the loss of wall paintings has also been severe. Furthermore the measurements indicated rising moisture caused by high ground water levels.

Figure 5. Entrance of the wet crypt (up) with a few centimetres of standing water (down)

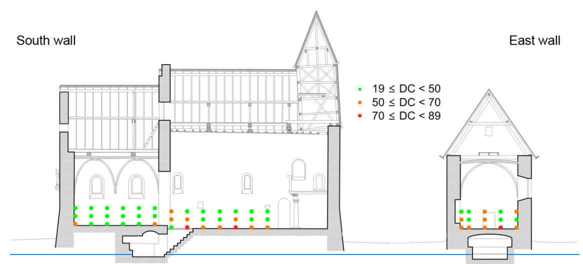


Figure 6. Indication of the averaged measured dielectric moisture content in the chapel's walls, blue line is the groundwater level

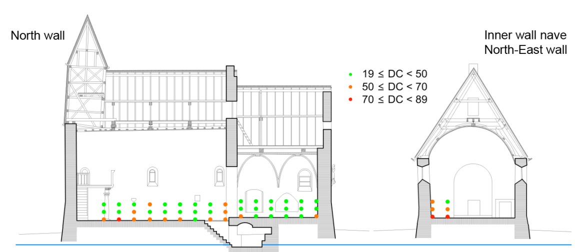


Figure 7. Indication of the averaged measured dielectric moisture content in the chapel's walls, blue line is the groundwater level

3.2 Groundwater level

Besides measuring the moisture content in the walls, the ground water level is measured. At the north side of the chapel, closely to the corner of the nave and choir, a monitoring well is placed. Weekly measurements indicate high ground water levels. There is small variation in the groundwater level up to 10 centimetres. Yearly it is quite steady-state around 75 centimetres below field.

4. Simulation

4.1 HAMBase

The multi-zone hygrothermal building simulation model HAMBase [10] was used to calculate the indoor temperature and relative humidity (RH) inside the chapel as a result of the outdoor climate conditions, the building properties, the climate control system and the building use. HAMBase characterizes the indoor climate by uniform values for radiant temperature, air temperature and RH per zone. The HAMBase model of the church consists of three zones: the chapel, the attic and the crypt. The indoor climate conditions were first simulated for a constant ventilation rate per zone and without internal heat loads, additional vapour sources and heating plants. Secondly, the additional demands for heating, cooling, humidification and dehumidification were calculated in HAMBase by setting the measured temperature and RH as set points for the minimum and maximum temperature and RH in the HAMBase model.
A comparison between the measured and simulated indoor temperature, RH and humidity ratio in the chapel showed that the simulated temperature was slightly lower than the measured temperature.

4.2 Inverse modelling

Besides the use of HAMBASE, which is a forward modelling approach, a multi-zone model was developed using Inverse Modelling. Inverse Modelling is also called System Identification. Inverse Modeling is the inverse of traditional modeling. In traditional modeling, the system is known and the output is unknown. By modeling the system, the output can be simulated.
In Inverse Modeling, the output is known, e.g. measured, but little is known about the system's parameters. The objective is to identify the parameter values of the model by repeatedly trying different parameter values and comparing the simulated output with the measured output. The goal is to minimize the simulation error, formulated as an objective function e.g. mean squared error. The process of finding the parameter set, which minimizes the objective function, is called optimization.
The church of Lemiers has also been modeled using Inverse Modeling. Six models were identified: a thermal and a hygric model for the three zones: attic, chapel, crypt. Because the models are represented in State Space form, the simulations are very fast: 1 year with hourly time steps is simulated in 0.016 seconds on an ordinary computer (i5-processor). After validation of the identified models, the three thermal models were coupled resulting in one multi-zone thermal model and the three hygric models were coupled resulting in a multi-zone hygric model.

5. Results

As mentioned before, the chapel was divided into three zones: chapel (nave + choir), attic and crypt. In the following sections a validation is made between the measured data and the simulated data.

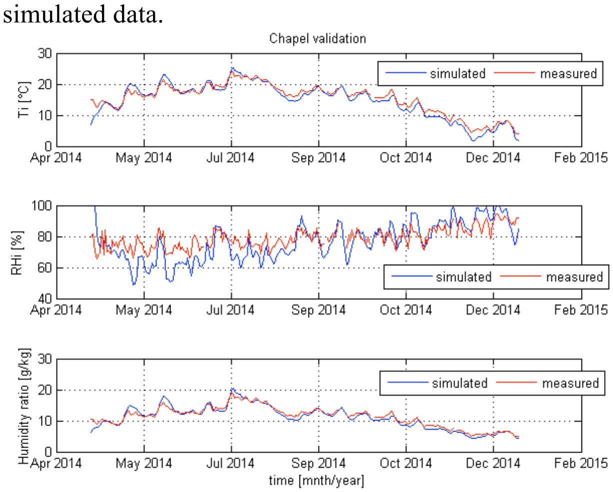


Figure 8. Chapel: validation between the simulated and measured data

5.1 Chapel

A first comparison in the output was made for the nave and choir, defined as the zone called chapel. The differences between the original model and the optimized model are small, but noticeable as can be seen in figure 8.

5.2 Attic

The simulation results were validated with the measurements and show comparison with each other as can be seen in figure 9. During summer the temperature in the attic is slightly higher compared to the measurements.

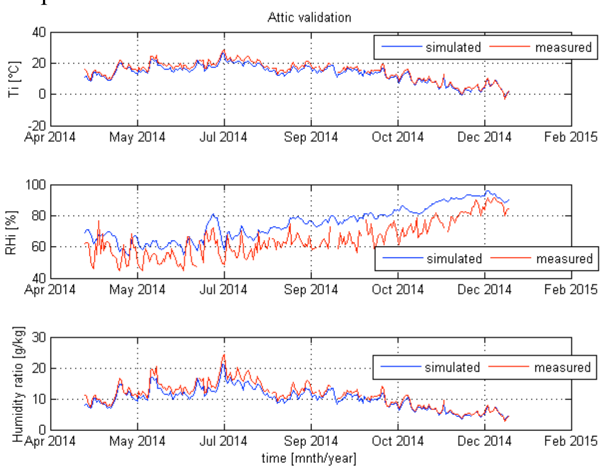


Figure 9. Attic: validation between the simulated and measured data

5.3 Crypt

For the validation with the measurements the absolute humidity in the crypt compares well.

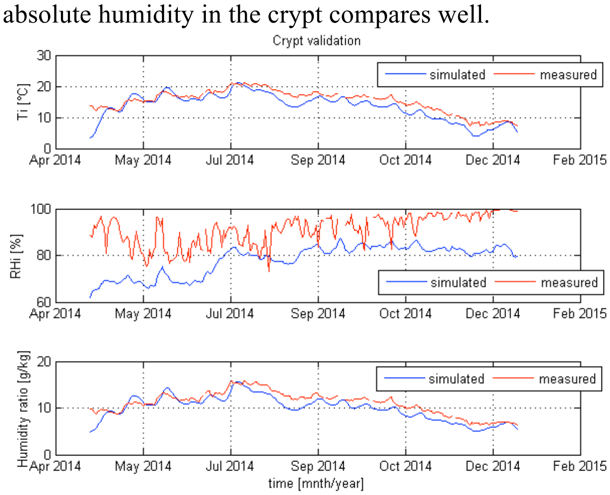


Figure 101. Crypt: validation between the simulated and measured data

Although the relative humidity is still much higher compared to the simulation for which most deviation occurs during winter. No additional moisture source was modelled in the crypt, while during certain periods a layer of standing water occurs in the crypt and evaporates. To model the quantity of moisture inversely the profile for the crypt was set different. The relative humidity was set equal to the measured relative humidity of the crypt. So evaporation and condensation lead to humidification and dehumidification. Both humidification and dehumidification were activated in the model in order to match the relative humidity curve with the measured data.

As can be seen in figure 9 the relative humidity of the measured data is a highly fluctuating curve. This led to a demand in humidification and dehumidification in order to match this highly fluctuating curve. If an average is taken between humidification and dehumidification the quantity of moisture is more or less in balance and smaller than it appeared at first sight. Most measured data of the relative humidity was above 80% as can be seen in figure 9 and 10. The range for which the measuring equipment showed large deviation within the calibration.

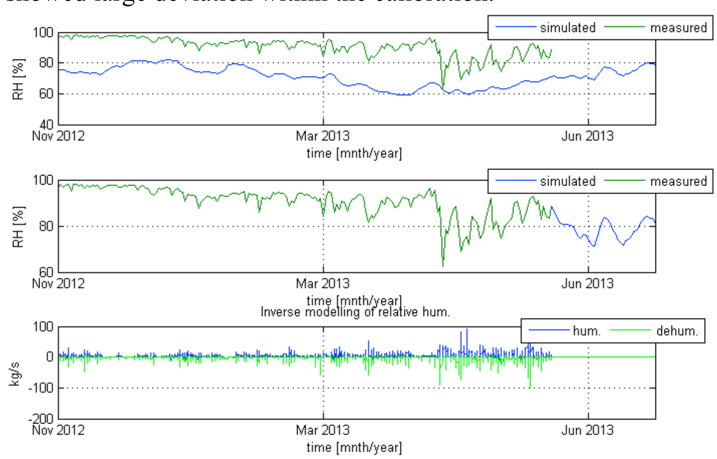
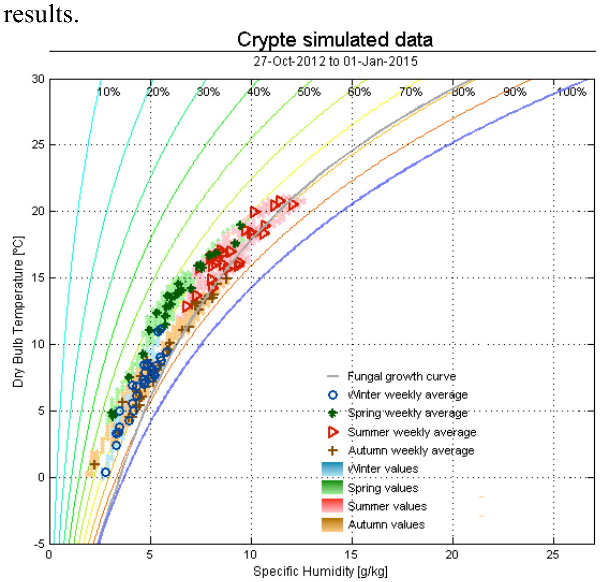


Figure 11. Inverse modeling of the relative humidity, with the activation of hum/dehumidification in order to match the measured data

Another cause that could have led to the large deviation in relative humidity is related to the lower air temperatures in winter for which deviation is large. Closer looking into the background of the relative humidity a plot was made of the Mollier diagram. Figure 11 shows that for lower air temperatures the (curved) lines of the relative humidity are closer to each other. This means that for a slight deviation (of less than one degree Celsius) in air temperature this could mean a large deviation in relative humidity (up to 10%). Together with the higher inaccuracy of the measuring equipment and not modelling an additional moisture source this can be seen as the main cause for the (at first sight) large deviation between simulated and measured results.



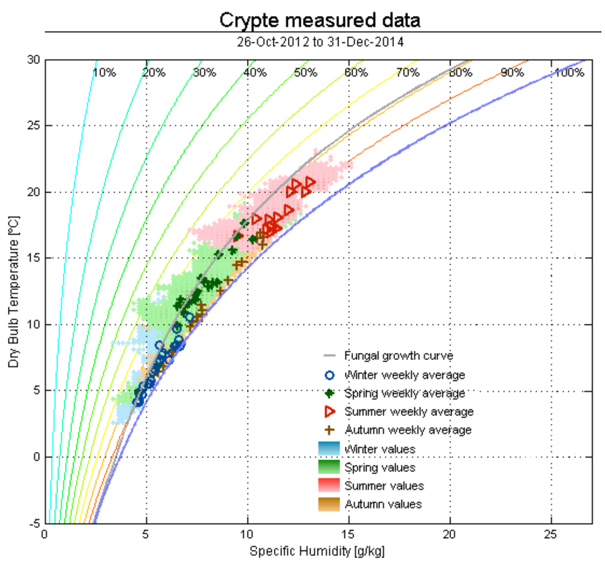


Figure 12. Mollier diagram of the simulated (left) and measured data (right) show that for lower temperatures the (curved) RH lines are closer to each other, which means that for a slight deviation (< 1 °C) in air temperature this could mean a large deviation in

Figure 13. Crypt entrance: measurement equipment is placed on the screen of the hatch between chapel (nave) and crypt

Besides, the measuring equipment in the crypt is placed on the screen of the crypts access hatch (figure 12). This means that the crypt is in open connection with the chapel. Therefore the measured data of the crypt can be influenced by the chapel, but to what extend is not further considered.

Summarized, the indoor climate conditions do not immediately indicate a relation with the damages that occur in the chapel. Surface condensation did occur as the measurements in section 3 indicated, but not as frequently as the damage analysis shows (section 2). Validation between the simulated indoor climate and measured climate conditions correspond quite well. The difference in the results is due to the difficulty of setting user profiles that correspond exactly with the logbook, which is too time consuming to model. Also the inaccuracy of the measuring equipment decreases for higher relative humidities. Finally, as just had been pointed out the zone that had shown most deviation is the crypt. Here the measuring equipment is placed on the screen between crypt and chapel (nave), and an additional moisture source had not been modelled, which could had influenced the measured data.

8. Comsol

This chapter focuses specifically on the moisture problems (2D) in the walls using COMSOL Multiphysics).

8.1 Moisture Transfer

When a wall is in contact with water, moisture will rise by capillary suction. This depends on the capillary properties of the wall (e.g. the water sorption coefficient, radius of the capillary pores), but also on the evaporation at the surface. In narrow capillaries the water rises higher than in wide ones. Although, in a vertical capillary the flow will stop eventually by gravity. Since the capillary properties of the construction are unknown, focus lays on other aspects of moisture transfer.

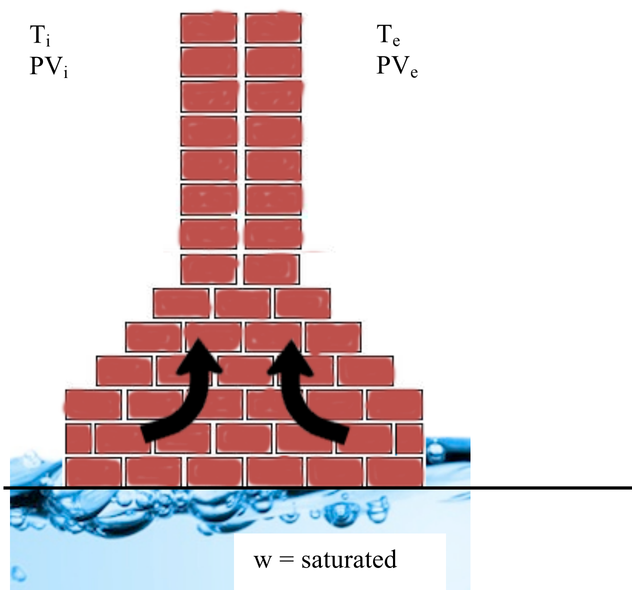


Figure 14. Visualization of the 2D moisture transfer in the chapel's wall with a saturated foundation

The moisture transfer equation used combines two extremes: the vapour transfer equation and the liquid water transfer equation. There are three possible moisture potentials in the moisture transfer equation that can be measured/solved, namely: relative humidity, capillary pressure and the moisture content. The moisture content is preferable above the other two, because it is the only one that can be measured in a construction.

Figure 14 visualizes the construction and its basic behaviour: wetting and drying of the walls in both directions and a constant upward force of water on the foundation. Parameters mentioned in the figure can all be implemented from the HAMBASE model. So for this specific case the moisture transfer equation for the moisture content becomes:

$$\frac{\partial w}{\partial t} = div\, D_w\, grad\, w$$

For which the diffusion coefficient D_w varies with the moisture content:

$$D_w = \frac{\delta_a}{\mu}\, p_{sat} \frac{1}{\xi} \qquad \text{for vapour transfer}$$

$$D_w = \frac{k_m}{\Xi} \qquad \text{for liquid water transfer}$$

The moisture content is not continuous at an interface between two different materials. In this case there is only one material, that is why the moisture content is chosen as potential. Figure 15 shows an example [10] of the diffusion coefficient for vapour and liquid moisture transport.

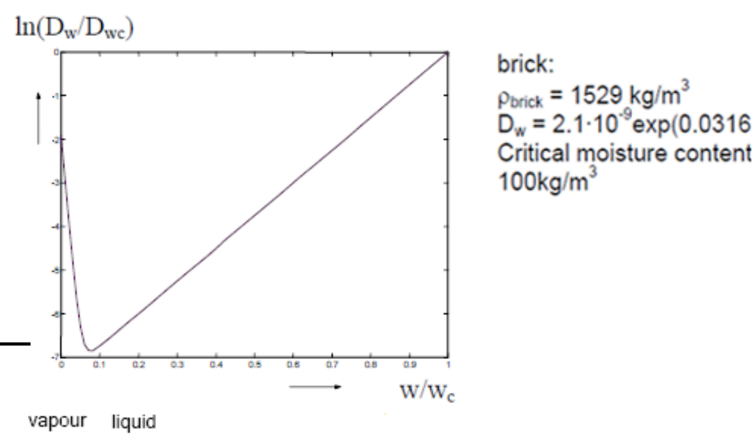


Figure 15. Function of the diffusion coefficient varying with the moisture content. Left part vapor transfer, right part liquid transfer

The moisture diffusivity in the liquid part (so the right part of the figure) is represented by an exponential function. In the vapour part (so the left part) the diffusion coefficient is a decreasing function of the moisture content, while for liquid the opposite occurs as it is increasing. The diffusion coefficient has a minimum near the critical moisture content.

8.2 PDE Comsol

The COMSOL module called 'Coefficient Form PDE Interface (c)' was used for this study in version 5.0. This tool contains the feature of a scalar coefficient form equation that is described by a balance equation [12]. The balance equation contains a single dependent variable *u* that is an unknown function on the computational domain Ω. For this study the single depend variable *u* is the moisture content *w*.
The partial differential equation (PDE) in COMSOL is described by the following:

$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla(-c\nabla u - \alpha u + \gamma) + \beta \nabla u + au = f$$

$$-n * (-c\nabla u + \alpha u - \gamma) = g - qu$$

The upper equation is the PDE that must be satisfied within the computational domain Ω. Whereas the lower equation is the Neumann boundary condition that must hold on the domain boundary Ω. Since the convective heat transfer within the material is neglected in this study, the coefficients e_a, *α, β, γ* and *a* are equal to zero. Therefore the equation can be simplified to:

$$d_a \frac{\partial u}{\partial t} + \nabla(-c\nabla u) = f$$

$$-n * (-c\nabla u) = g - qu$$

In the equation above *n* is the outward unit normal vector on ∂Ω (-). From the material properties *c* is the diffusion coefficient D_w that can be determined. As mentioned before *u* is the dependent variable that is unknown, in this case the moisture content *w*. Adding a damping or mass coefficient d_a of 1 to the upper equation makes the problem transient. The lower equation defines the boundary conditions whereas *g* is defined as the flux/source. If no boundary absorption is assumed, than *q* is equal to zero. At the top boundary of the model a so-called zero flux condition is assumed. At the bottom boundary according to figure 14 the foundation is saturated, so that the moisture content is at its critical value. Therefore a Dirichlet boundary condition was applied here in the model, so a boundary within the model with a fixed value.

8.3 Model setup

The entered parameters for the constructed model are described in table 1. Properties for the diffusion coefficient and critical moisture content are assumed to be the same as for brick.
Table 1. Entered model parameters diffusion

Para-meter	Value	Unit	Definition
D_w	$2.1e^{w/w_c}$	m^2/s	Diffusion coefficient
w_c	100	kg/m^3	Critical moisture content
w_i	15	kg/m^3	Initial moisture content
T_e	$T_e(t)$	°C	External temperature
T_i	$T_i(t)$	°C	Indoor temperature
$\phi_e(t)$	$RH_e(t)/100$	-	External relative humidity
$\phi_i(t)$	$RH_i(t)/100$	-	Indoor relative humidity
β	$3*10^{-6}$	s/m	Surface coefficient of vapour transfer
$g_e(t)$	$\beta*(psat(T_{si})*w(p_c)$	kg/m^2s	External moisture flux
$g_i(t)$	$\beta*(psat(T_{se})*w(p_c)$	kg/m^2s	Indoor moisture flux
D	0.8	m	Thickness of the wall

The flux on the outer and inner surface of the walls is also depending on the moisture content. This is based on the moisture retention curve. The graph of the moisture content w (kg moisture/m^3) as a function of relative humidity is called the sorption curve. Instead of a plot of moisture content versus relative humidity a plot of the moisture content versus the suction is more convenient and is therefore called the moisture retention curve. Figure 16 is a moisture retention curve for brick.

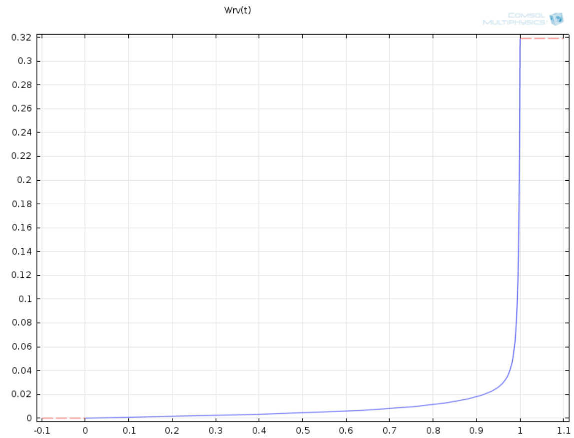


Figure 2. A plot of the moisture retention curve for brick plotted from COMSOL

9. Results and conclusions

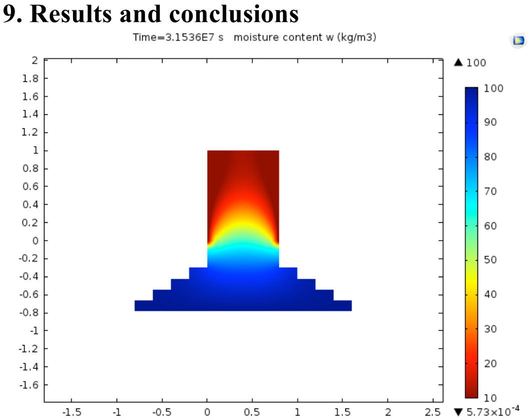


Figure 17: Moisture content in the construction after one year

Figure 17 shows the uptake of water of the wall construction of the chapel due to the continuous contact of water with the foundation. Apart from the unknown exact material properties of wall and foundation, the results clearly indicate the effect of water uptake on the surface moisture content near the floor. The evaporation of water at the bottom of the paintings, together with the transportation of salts, makes clear that the uptake of water is the main origin of the deterioration of the wall paintings in the chapel.

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