The quantification of the moisture distribution in renovated historical wall structures and exposed monuments

P. Häupl, H. Fechner, J. Grunewald & H. Petzold

Dresden University of Technology, Germany

Abstract

The renovation of buildings in middle and northern Europe should be coupled with an energetic improvement of the envelope parts. Often the preservation of the typical facades does not allow the use of an outside insulation. The application of an interior insulation, however, increases the risk of interstitial condensation. In a 200-year-old framework house in East Saxony, Germany (fig.1) eight different inside insulations were tested. The ground floor of the building consists of a wooden beam wall, the first floor and the gable are a classical framework structure with a straw loam filling. The heat-transmissivity coefficient of the old frame work wall is $U = 1.8 \text{W/m}^2\text{K}$.

In the ground floor eight and in the first floor three different indoor insulation structures had been installed and investigated over a period of 4 years from October 1995 to October 1999. The surrounding climate components and the hygrothermal values within the wall were continuously measured (Häupl et al. [1], Fechner et al. [2]).

All measured results were compared to the results of numerical simulations with the computer code DIM 3.1. The software is based on the physical model of the coupled heat-, air-, moisture and salt transfer in porous building materials and building structures (Grunewald et al. [3], Plagge et al. [4], Häupl et al. [5]).

In section 3 the numerical simulation of the hygrothermal behaviour of a silt wall belonging to a historical monument in Japan is presented. The wall is freely exposed to the natural climate. The simulations were performed with measured Japanese climate values. The results will be used to decide on preservation and renovation measures.
1 Insulation measures and measurement equipment

The test house in Ebersbach/East Saxony provided the possibility to test several interior insulations at two fundamentally different outside wall constructions, a massive wooden wall in the ground floor and a framework wall in the first floor (fig. 1). Measurements at the wooden wall began in 1995. The wall was separated into 8 fields by wooden laths. The following insulation materials were used:

- mineral wool
- Perlite
- calcium silicate
- Cellco (cork-loam mixture)
- calcium silicate with a coupling layer of Cellco
- air space
- Isofloc (paper scraps)
- and soft wood fibre board.

The design of inside insulations without vapour retarder can be a critical issue depending on insulation thickness and vapour diffusivity of the used materials. Occurring condensate at the cold side of the insulation could mean a potential damage risk for the old building parts. Calciumsilicate with its high capillary suction ability is able to distribute possible condensate water and transport it back to the warm side of the construction.

In September 1996 the measurements were extended to the framework wall in the first floor. An interior insulation of mineral wool and calcium silicate, resp., was used. In three fields of the framework the old straw loam filling was removed. The old wooden beams were equipped with moisture content sensors from the room side and at the sides to the filling. Then a new filling of light clay mortar was built in (fig. 1).

In order to test the old straw loam filling in connection with an interior insulation another framework field was prepared with calciumsilicate insulation boards and measured from July 1998 to September 1999. The ability of the calciumsilicate insulation to transport liquid water from the potential condensation location to the roomside depends strongly on a good contact to the outside wall surface. In the framework fields where the new filling was built in the contact was provided by splashing the fresh filling mortar from the outside against the insulation. In the field with the old straw loam a layer of fresh loam mortar was used for the coupling of the calcium silicate boards to the wall.

First the old inside plaster was replaced by a new loam plaster to give a smooth surface. Later 50mm calciumsilicate boards were applied using a thin coupling layer of loam (fig. 2) and fixed to the wall.

The location of the sensors (surface and interstitial temperatures, interstitial relative humidities, moisture content in the wooden frame work, heat flow densities, indoor and outdoor climatic components) was chosen according to fig. 3. The outdoor climate measurements included solar radiation, wind speed and direction, rain on a horizontal area and driving rain on the test wall. Altogether 152 sensors were used with a measurement time step of 10 minutes (Fechner et al. [6]).
2 Measurement results and comparison with the numerical simulation

All measurements were evaluated and compared to numerical simulations with the software DIM 3.1. From the numerous results only the framework with straw loam filling and calciumsilicate insulation shall be presented here.

Besides its low heat conductivity, calciumsilicate possesses a high capillary conductivity for liquid water. This combination of material properties enables the use of calciumsilicate as internal insulation without vapour retarder.

If condensate occurs on the cold side of the insulation it is transported away from the condensation plane which keeps the amount of liquid water low. Additionally, eventually penetrating water from outside (through cracks between framework and filling) can also be distributed and will not damage the wooden parts of the construction.

Fig.4 and 5 show the temperature and relative humidity behind the insulation with a good correspondence between measured and calculated values. During the cold season the temperature drops only shortly below 0°C. The condensation period, indicated by 100% relative humidity, lasts until April 1999, afterwards the construction dries rapidly. The measured and calculated heat flux density through the wall is presented in fig.6. From the measurements the effective thermal conductivities of the materials and the resulting U-Value can be retrieved (straw loam: \( \lambda = 0.40 \text{W/mK} \), calciumsilicate \( \lambda = 0.066 \text{W/mK} \), \( U = 0.75 \text{W/m}^2\text{K} \)).

Fig.7 and 8 show simulations of the water content profile in the middle of the straw loam for a time period of 2 years. To demonstrate the effect of the high capillary forces no capillary suction ability was assumed for all materials in fig.7. In this case the built-in moisture and the occurring condensate water can only be distributed into the loam plaster and a thin layer of the insulation, resulting in a maximum water content of 50Vol% and a water mass of 2.6kg/m² in the second year which would not be acceptable for the construction.

The simulation with real capillary conductivities (fig.8) shows that the calciumsilicate can accelerate the drying of the built-in moisture and distribute the condensate and thus limit the moisture content to uncritical values below 10Vol%.

Fig.9 compares the total overhygroscopic water content for the two cases. With the capillary active insulation the water content stays below 1kg/m² even in the first year with built-in moisture. In the second year approx. 0.6kg/m² occur.

For the hygrothermal situation around the wooden framework beam a two-dimensional simulation was performed. Fig.10 shows the water content at Feb 18th, 1999 when the water content in the calciumsilicate reaches its maximum. The moisture profile in the calciumsilicate shows the distribution of the condensate to the roomside. The maximum moisture content at the inside of the beam stays below the critical value of 10Vol%.

The water profile at the front right side of fig. 10 corresponds to the one-dimensional simulation shown in fig. 8 at the same time (5.13 years on the time axis). Until May 1999 all materials have dried out.
Figure 1: Insertion of the new filling material (light clay mortar) into the framework fields of the first floor.

Figure 2: Calcium silicate board with a thin layer of coupling loam mortar before fixing it to the wall.

Figure 3: Cross-section of the wall and location of the measurement sensors

- $\theta_e, \theta_c$: external and internal air temperature
- $\theta_1, \theta_i$: temperature and relative humidity
- $\theta_{seB}$, $\theta_{seF}$: external surface temperature at the beam and at the filling
- $\theta_{siB}$, $\theta_{siF}$: internal surface temperature at the beam and at the filling
- $\phi_{1B}$: temperature and relative humidity in air space between insulation and plaster at the beam (combined sensor)
- $\phi_{1F}$: temperature and relative humidity in air space between insulation and plaster at the filling
- $q_B, q_F$: heat flux density at beam and filling
- $w_1, w_2, w_3$: wood moisture content at 3, 13, and 38mm depth
Figure 4: Temperature at the boundary insulation and coupling mortar, comparison of calculated and measured values

Figure 5: Relative humidity at the boundary insulation and coupling mortar, comparison of calculated and measured values

Figure 6: Heat flow density through the wall, comparison of calculated and measured values
Figure 7: Water content profile in the center of the straw loam in time (one-dimensional simulation) without consideration of capillary forces for all materials

Figure 8: Water content profile in the center of the straw loam field (one-dimensional simulation) with measured capillary conductivity for all materials
Figure 9: Total overhygroscopic moisture content of the construction, calculated with and without capillary activity of the materials.

Figure 10: Moisture content in the construction according to the two-dimensional calculation at 18 February 1999.
Structural Studies, Repairs and Maintenance of Historical Buildings

3 Numerical simulation of a historical weather-exposed silt wall in Japan

In Japan a number of detached silt walls belonging to historical buildings are exposed to the natural climate conditions. In some cases frost and moisture damages were observed. In a research project sponsored by the Japanese government the hygrothermal situation in these walls (fig. 11) was simulated in two-dimensional calculations to show the damage reasons and to support decisions about preservation or reconstruction measures.

Fig.12 and 13 show the calculated water content in cross-sections through a wall and the supporting ground. The moisture content is shown on the x-Axis.

The calculation was performed with natural Japanese climate (hourly values) including rain and solar radiation. The top of the wall is covered with a roof which results in a smaller rain load for the upper part of the wall. The material data for ground and wall materials were taken from soil physical measurements. The influence of gravity on the moisture transport is also included.

Figure 12 shows the situation at the end of the cold and wet season. The ground has a moisture content of approx. 30 Vol% due to rain events. In the wall a significant difference between north and south is visible with the higher moisture content of approx. 10 Vol% in the north. At the end of the dry period during the summer (Fig.13) the moisture content at the north side has decreased but the material is not completely dry. The moisture integral shows an accumulation of moisture to the next year.

The simulations show the effect of the high rain load combined with the low radiation of the north side of the wall, especially in the north of Japan with low outside temperatures. Protection measures should therefore focus on the reduction of the rain load for the wall.

Figure 11: Schematic drawing of the silt wall
1: very heavy clayey silt (PV=47%)
2: very heavy clayey silt (PV=38%)
3: weakly clayey silt (PV=45%)
4: medium silty clay
5: roof
Figure 12: Moisture field in the silt wall at the location Shiwa on March, 17th - 1st year (begin was October 1st), Climate of Morioka (Japan)

Figure 13: Moisture field in the silt wall at the location Shiwa on August, 14th - 1st year (begin was October 1st), Climate of Morioka (Japan)
4 Conclusions

Fibre dotted calciumsilicate has been shown as a suitable material for the interior insulation of buildings with worth preserving facade. With a thermal conductivity of \( \lambda = 0.055 \text{W/mK} \) and a thickness of 40mm the U-value in old buildings can be halved. The low vapour resistance leaves the construction open for diffusion. Possibly occurring condensate water behind the insulation layer is distributed, therefore no vapour retarder is necessary. The inner wall surface is free of condensate. The material is mould resistant due to its pH-value. With its average hygroscopic properties it works additionally as a buffer against moisture peaks in the room climate. Calciumsilicate is free of harmful substances, possesses excellent fire protection and a recycling is possible (Häupl et al. [7], [8]).

The reasons for moisture and frost damages in historical silt walls in Japan could be verified by a numerical simulation. The selection of effective measures for the preservation is supported by the results.

The correspondence of the presented testhouse measurement results and the numerical simulations of the hygrothermal behaviour with the developed software DIM 3.1 is satisfactory. The computer code DIM can be used in general and complex cases for the hygrothermal evaluation of structures.

References