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Long term measurements and HAM modelling of an interior insulation solution for an office building in cold climate

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ABSTRACT

Excessive mould damage was detected in an office building in Northern Europe and thus a renovation need was established. This paper studies a renovation solution using measurements and heat, air & moisture (HAM) modelling. Polyurethane (PUR) foam was used to fill the air gap in masonry while capillary active calcium silicate (CaSi) insulation was used on the interior surface at thermal bridges. During renovation works temperature and relative humidity (*t*&*RH*) and heat flux sensors were installed throughout the wall.

Nearly 3 years of measurements are presented. Average thermal transmittance (*U*) of the wall was reduced around 3 times. While the climate was probably not critical during the monitoring, the measured values stayed within hygrothermally safe limits.

The paper also compares the measurement data to 2D HAM modelling and discusses the discrepancies. Calibrated models were used to model the wall using real 42-year weather data and give a more thorough assessment of the hygrothermal performance. Although the original wall stayed fairly moist, no performance limits were exceeded and the interior surface became safer in terms of mould risk.

KEYWORDS
interior insulation, HAM modelling, capillary active, cold climate, case study

INTRODUCTION

Interior insulation has usually been disapproved in Northern Europe as a hygrothermally risky solution. However, "capillary active" insulation has gained ground in Central Europe and become a compelling choice by taking a different approach to mitigating the risks caused by insulation on the interior side (compared to traditional mineral wool + vapour barrier solution). This study took place on the last floor of an 8-storey office building (built in 1936; cultural heritage). Existing interior insulation (gypsum board, PE foil, min. wool) exhibited excessive mould damage and a renovation solution had to be found. Main challenges were: low surface temperatures, high thermal transmittance and avoidance of future biological decay. Preliminary HAM modelling showed that "closed cell" PUR foam injected into air cavities of the masonry and "capillary active" CaSi on the surface of the wall could perform well. This paper discusses the monitoring and modelling of the chosen solution.

METHODS

Measurement setup

Vertical and horizontal sections of the studied wall are given in Figure 1. The wall structure, renovation solution and sensor placement are also shown. Sensors and their positions were selected both to assess the hygrothermal situation after the insulation and to have enough reference points to calibrate the HAM models.

The following measurement devices were used: T&RH probes: Rotronic HygroClip HC2-C05 (accuracy ±0.3°C, ±1%RH); heat flux plates: Hukseflux HFP01 (accuracy ±5%); data logger Grant Squirrel SQ2020 1F8 (accuracy ±0.05% of readings ± 0.025% of range); temp. probes & logger: Onset Hobo UX120-006M & TMC6-HD (accuracy ±0.15°C); T&RH data loggers: Onset Hobo U12 and UX100 (accuracy ±0.21°C, ±2.5-3.5%RH). Measurement interval: 1h.

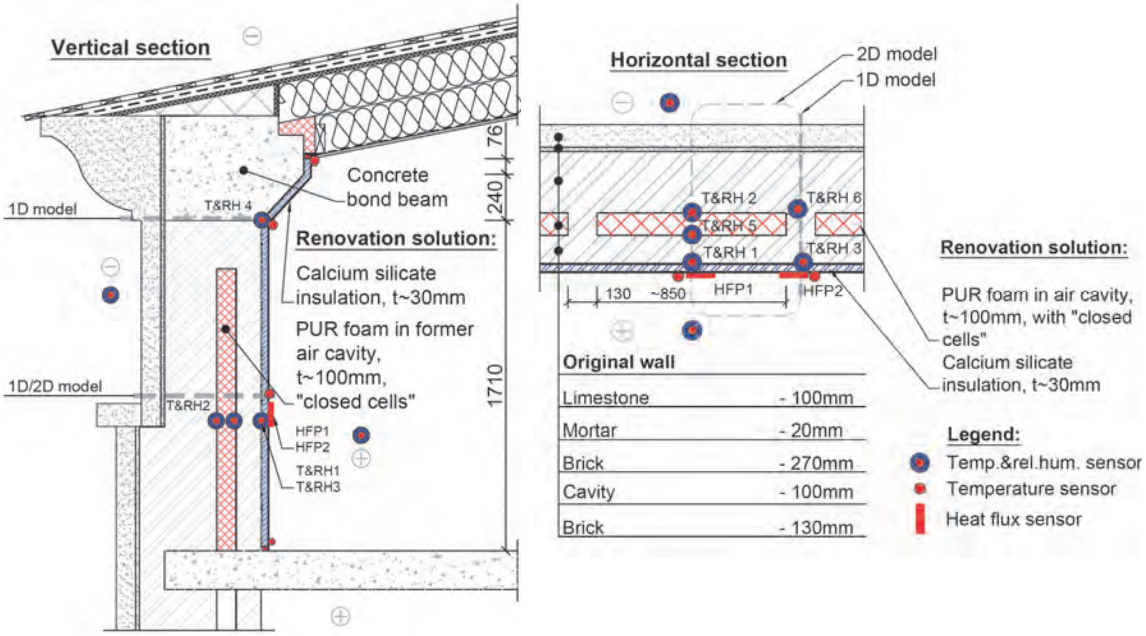

Figure 1. Vertical and horizontal sections of the wall showing sensor placement and wall layers.

Performance criteria

WTA Merkblatt 6-5 (Künzel et al. 2012) proposes to avoid frost and condensation in insulation and glue. Assessment according to saturation degree should be carried out – maximum of $30\%_{sat}$ is allowed to avoid frost damage. However, our previous research (Klõšeiko et al. 2017) showed that freeze-thaw cycling affected tensile strength of capillary active insulation material even though saturation degree stayed below the $30\%_{sat}$ limit. Therefore, slightly stricter limits of $RH_{crit.} = 95\ \%_{RH}$ and $t_{crit} = -5$ °C (Künzel 2011) are used in this study. Minimizing freeze-thaw cycles of the limestone cladding was not a criterion as conversion to ventilated façade is planned for the building.

Hygrothermal modelling

IBK Delphin 5.9.0 (Grunewald 1997; Nicolai et al. 2009) was used to model the hygrothermal performance of the exterior wall. Modelling consisted of 2 steps: 1) model calibration and 2) modelling with 42-year weather data. 1D and 2D models of the masonry section were created (while brickwork was treated as a homogenous material for both). Concrete bond beam was modelled as a 1D case. Model geometry is given in Figure 1.

During calibration, measured (t, RH (+ calculated vapour pressure), heat flux) and modelled data were compared. Then the HAM models were iteratively changed within plausible extents to achieve a better match between the two. Different bricks and concrete types from Delphin material database were tested (finally settling with ID 543 and 569 for brick and concrete respectively), PUR foam properties were fine-tuned according to limits given in its datasheet (based on ID 195; following changes were made: $\rho = 39$ kg/m^3, $\mu = 39$, $\lambda = 0.022$ W/(m·K)). Rest of the material IDs from Delphin database used in models were 464, 143, 424, 21, 230.

Boundary conditions for model calibration were: *t*&*RH* (measured on site); wind, rain (measured 10km away) and solar radiation (measured 165km away). 42-year weather data (*t*, *RH*, wind, rain, solar radiation; all measured 165km away) was used to assess the performance in more critical conditions. As the indoor humidity load in the test room was very low, more critical indoor *t* & moisture excess profiles were used for 42-year modelling (roughly moisture class 2 given in EN ISO 13788 Table/Figure A.2). They were based on an earlier study in a similar building (Klõšeiko & Kalamees 2016).

RESULTS & DISCUSSION

Measurement results

Temperatures behind CaSi (Figure 2 top, sensors TRH1, 3, 4) were closest to limits during the winter of the first year. At sensor TRH4 (concrete section) they fell to as low as -2.5°C, but not reaching the critical -5°C. In masonry section the temperatures were higher due to PUR insulation adding further thermal resistance. Consequently, sensors on the exterior side of PUR (TRH2 shown here) measured far lower temperatures than between CaSi and concrete bond beam. Figure 2 (bottom) gives the measured relative humidities. Dryout of the built-in moisture to stable levels took about 2.5…3 months. *RH* values between exterior brick leaf and PUR (sensor TRH2) were quite stable (fluctuating about $5\%_{RH}$ throughout the year) after the dryout of CaSi built-in moisture.

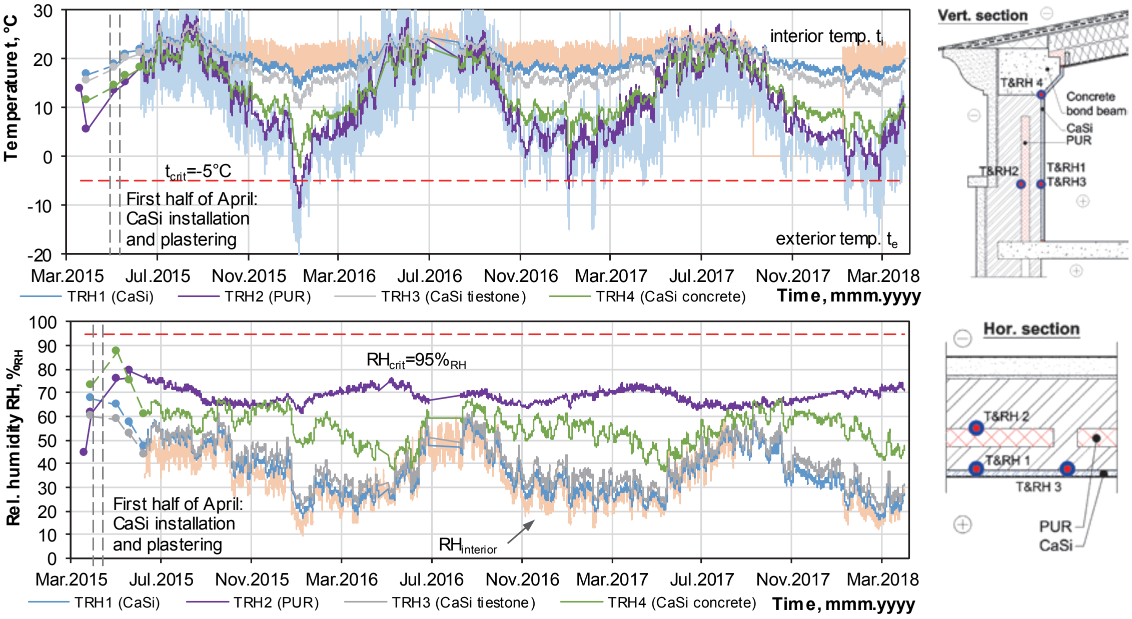

Figure 2. Measured temperatures (top) and relative humidities (bottom) throughout the monitoring period.

Moisture excess during the measurement period in the test room was very low (close to moisture class 1 according to EN-ISO 13788 A.2), as a well-functioning HVAC system was installed. Analysis of measured data hints that moisture contents of air in the pores of exterior masonry leaf are governed by outdoor climate while lagging about half a week. A ~ 4 g/m³ rise in moisture contents compared to indoor and outdoor air in autumn (mid-Aug...Oct.) is pronounced, possibly due to rain. However, moisture does not seem to be accumulating in the wall over time, which could be the case with vapour tight interior insulation and heavy wind driven rain loads. Sensors behind CaSi insulation measured moisture contents quite close to that of the indoor air throughout the year. A lag of a couple of days was detected.

Temperature indexes (f_{Rsi}) were calculated from surface temperatures to assess mould and condensate risk on the wall surface. The worst situation was detected at wall-floor intersection ($f_{Rsi} = 0.79$) and at concrete bond beam ($f_{Rsi} = 0.83$). None of those results should indicate a risk, however, as indoor moisture load was low. f_{Rsi} values at the rest of the intersections were also considerably higher (i.e. safer).

Average heat flux and temperature data from 1. Nov. 2015… 29. Feb. 2016 was used to calculate the thermal transmittances (*U*) of the insulated wall (see Figure 1 for placement of the sensors). At tie bricks (HFP2) $U = 0.52$ W/(m²·K) was measured and between tie bricks (HFP1) the value was $U = 0.31$ W/(m²·K). 2D thermal transfer modelling of the insulated structure results in average thermal transmittance of $U = 0.39$ W/(m²·K), which is ~ 3-fold reduction compared to the uninsulated case ($U = 1.14$ W/(m²·K)).

Calibration of HAM models

Results from the models which achieved the best fit and positions that are most relevant to the assessment criteria are presented here. Figure 3 shows data from TRH2 (between CaSi and tie brick) and TRH4 (between CaSi concrete bond beam). Relative humidity is given as it integrates the errors in thermal and moisture calculations.

Agreement of calculated and measured temperatures (TRH3 2D model; TRH4 1D model) was within ±1°C for most of the year with overestimation of temperatures by 2…3°C taking place in summer (possibly due to deficiencies in solar modelling of the south facing wall). TRH3 1D model exhibits too low temperatures which results in higher than measured *RH*. Modelled *RH* values exhibit less fluctuation in all cases, however, that seems to be the characteristic of the Delphin program (Klõšeiko et al. 2015; Klõšeiko & Kalamees 2016; Klõšeiko et al. 2017). 24h avg. heat fluxes in masonry section achieved less than ±1 W/m² (~5…10%) difference for most of the heating period using 2D model; in case of 1D models, the errors were 4…8 times higher. Possible sources of errors could be: material data (limestone as location specific and inhomogeneous material; only basic parameters were measured for brick), unknows concerning the actual wall structure, wind driven rain modelling, solar radiation modelling.

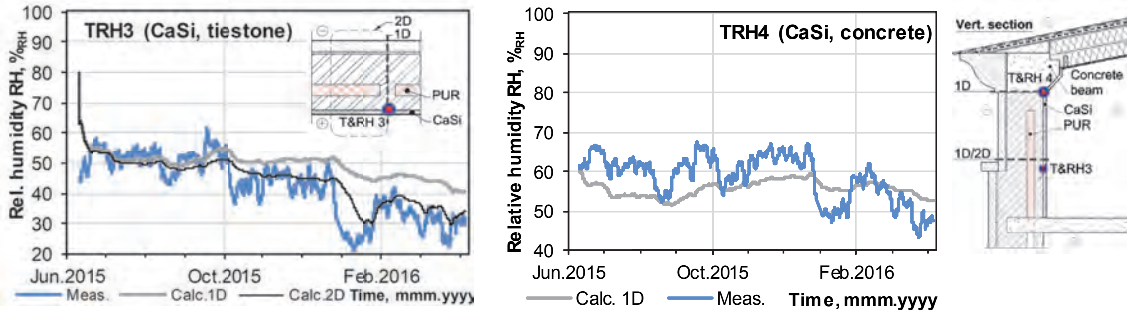

Figure 3. Comparison of measured and modelled relative humidities at TRH3 (between CaSi and tie brick; left) and TRH4 (CaSi insulation on top of concrete; right).

The correlation between measurements and modelling was deemed satisfactory. For performance assessment of CaSi insulation the 1D model of the masonry section might be good enough as the errors on that part were conservative. However, as wind driven rain could cause accumulation of moisture in the exterior masonry leaf, 2D model is also necessary.

Modelling with 42-year weather data

Due to limited space only the most critical point in the wall (TRH4 behind CaSi on concrete bond beam) is discussed here. Modelled *t&RH* values are given in Figure 4. Yearly minimum temperatures and maximum relative humidities are shown so the most critical year can be highlighted. In the case of TRH4, the 1986/1987 season was the harshest and is shown in Figure 4 (right). Yearly maximum relative humidities are much more stable than temperatures. “Flattening” the peaks of the RH graphs is possibly due to relatively high moisture capacity and redistribution of moisture in both concrete and CaSi.

Figure 4 also illustrates that 42-year modelled *t&RH* are far more critical than measured values. While lower *t* is largely the result of colder outdoor climate, the significantly higher modelled *RH* are caused by using higher indoor moisture load.

During 10 out of 42 years (~24%) *t* behind the insulation fell below critical -5°C. Still, *RH* was far below the 95%$_{RH}$ limit. Thus, according to the modelling data, frost damage in insulation system will not be a problem and the solution could be approved for use in the rest of the building. However, as previous research (Binder et al. 2013; Klõšeiko et al. 2017) has shown, the modelling results of “capillary active” materials can also be non-conservatively skewed, especially when higher moisture contents are concerned and values are closer to the performance limits. To overcome that, development of improved liquid and vapour conductivity curves for CaSi as well measurements of limestone and brick properties are in progress.

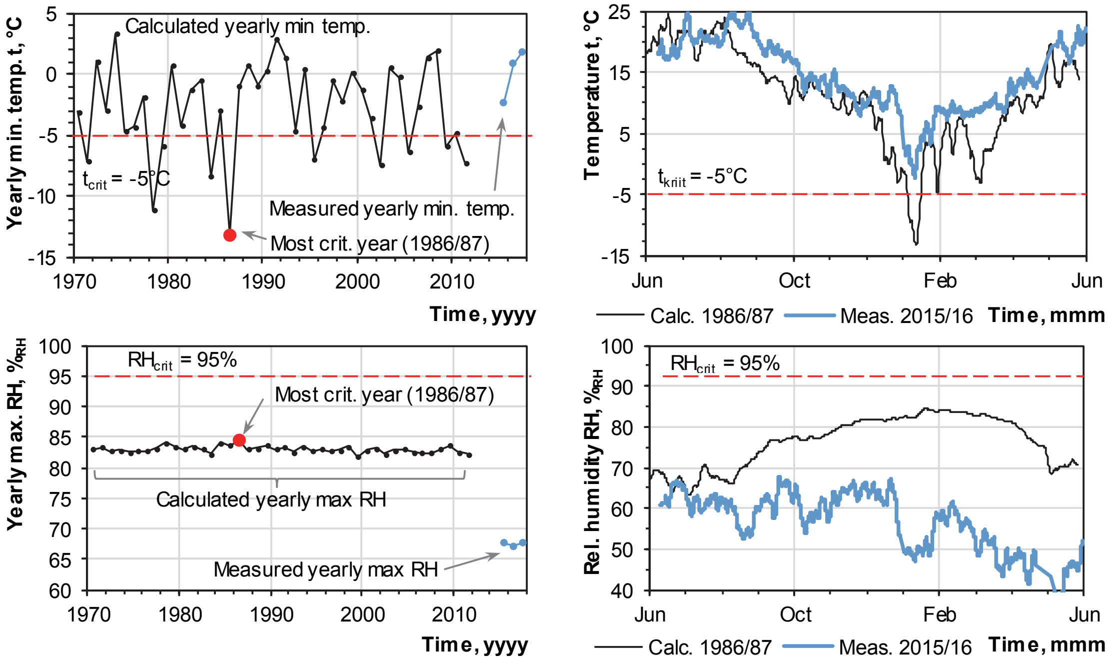

Figure 4. Most critical point in the wall (TRH4 – betw. CaSi insulation and concrete beam): yearly min. temperatures (top left) and max. rel. humidities (bottom left) of the 42-year HAM modelling and hourly values for the most critical year (right) compared to the measured values.

CONCLUSIONS

Measurements show that interior insulation can perform well at least if HVAC systems function nominally. Wind driven rain did not cause a notable accumulation of moisture on the exterior side of "vapour tight" PUR foam. Comparison of modelled and measured data shows that 2D modelling should be used for this type of structure. If interior insulation layers are thin, the HAM models can still fairly adequately portray the processes behind the insulation even if detailed material data for existing wall is unavailable.

Modelling results suggest that even in the case of increased moisture load, the CaSi boards are quite a robust solution and provide an extra layer of safety thanks to quite high moisture capacity and lack of biological decay. Modelling with long-term weather data gives an increased confidence in the results. For example, if test reference years are used, the principle of their selection might not always match that of the current modelling aim. Also, the measured data was far on non-conservative side compared to 42-year modelling results, partly due to current winters being quite mild. To test an experimental structure in more critical boundary conditions, modelling with historic data and calibrated model can be a viable option.

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