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Can crawl space temperature and moisture conditions be calculated with a whole-building hygrothermal simulation tool?

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Abstract

The hygrothermal behaviour of an outdoor ventilated crawl space with two different designs of the floor structure was investigated. The first design had 250 mm insulation and visible wooden beams towards the crawl space. The second design had 300 mm insulation and no visible wooden beams. One year of measurements was compared with simulations of temperature and moisture condition in the floor structure and crawl space. The measurements showed that the extra 50 mm insulation placed below the beams reduced moisture content in the beams below 20 weight% all year. A reasonable agreement between the measurements and simulations was found; however, the evaporation from the soil was a dominant parameter affecting the hygrothermal response in the crawl space and floor structure.

Keywords: Outdoor ventilated crawl space; measurements; whole building simulation; large instulation thickness; temperature; moisture content

1. Introduction

Crawl spaces are understood as ventilated floor structures towards ground. In Denmark, traditional crawl spaces are constructed with foundations and an outdoor ventilated cavity between the floor structure and the soil. This type of crawl space is also widely used in other Nordic countries and was considered a good solution in old buildings with limited insulation thickness. However, compliance with stricter energy requirements resulting in increased insulation

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thicknesses in floor structures entails that the ventilated crawl space must be considered a high risk construction with respect to mould growth [1, 2]. It is well known that the moisture conditions (relative humidity) in outdoor ventilated crawl spaces can become problematic, especially in summer, because the crawl space remains cold due to the soil thermal inertia, while warm outdoor air with higher moisture content enters the crawl space – the larger insulation thicknesses only increase this problem as the heat loss from the house is reduced. Investigations showed that an increase in floor insulation from 100 mm to 200 mm might lead to an annual temperature drop of 2 °C in the crawl space [3]. Comparison of simulations on a crawl space with 100, 200, 300 and 500 mm insulation in the floor structure, and a plastic foil on the soil [4], has shown that an increase in insulation thickness increases the period (summer) where the relative humidity is higher than 80 %, which increases the risk for mould growth. In Denmark, it is now recommended only to use inorganic materials in outdoor ventilated (cold) crawl spaces, if the crawl space is ventilated with 1/500 of the ground floor area and a U-value that fulfils today's requirement [5]. If organic materials are used, they should be protected from moisture by placing at least 100 mm of non-moisture absorbing insulation below the organic material [6]. Furthermore, it is recommended to either increase the ventilation rate to 1/50 or even construct the crawl space as a warm crawl space.

A research project [7] on moisture problems in constructions with large insulation thicknesses was conducted by the Danish Building Research Institute on several typical constructions used in Denmark. In this paper, measurements of temperature and moisture content in the crawl space and in the floor structure from above-mentioned project are compared with simulations conducted in BSim [8], which is a whole-building simulation tool. Two different designs of the floor structure above the crawl space are investigated; a design with 50 mm insulation under the wooden support beams facing the crawl space, and a design without insulation under the beams.

2. Method

2.1. Crawl space design and temperature and relative humidity measurements

In part of a 110 m^2 outdoor ventilated crawl space, temperature and relative humidity was measured in the indoor air, crawl space air and different places in the floor structure, as shown in Fig 1. The crawl space had approx. 700 mm of free height and was placed above ground, i.e., the crawl space walls were not covered with soil on the outside. Ten ventilation openings were placed 300-500 mm above ground in the crawl space, each with a dimension of 50 x 300mm. The crawl space was un-insulated towards the soil and no moisture membrane was laid out on the soil; however, 100 mm of gravel was used as capillary material. As typical for outdoor ventilated crawl spaces, the outer walls of the crawl space facing the exterior climate are also un-insulated. Originally, the floor structure above the crawl space was insulated with 300 mm mineral wool, of which 50 mm was installed under the wooden support beams facing the crawl space, see Fig. 1b. In part of the floor structure, the insulation under the beams was removed; see Fig. 1a.

The measurement of temperature was made with a thermo-couple, whereas the moisture content was measured in a wood sample with two pins to measure electric resistance. The electric resistance was converted to wood moisture content in weight%. All sensors were calibrated against each other in an indoor environment. The sensors showed maximum deviations on the reference temperature of 20 ºC +/- 1 ºC and on the reference wood moisture content of 9 weight% +/- 0.1 weight%, corresponding to 40 % RH. The sensors were placed 1) in the house above the test area, 2) in the floor structure, where two sensors were placed at the upper edge of the wooden floor beams, and two sensors were placed under the wooden floor beams, but on top of the wind barrier (cf. Fig 1), and 3) in the crawl space on the gravel, but placed on a ceramic tile for protection from moisture evaporation from the soil. Data were collected every 30 minutes from 15 March 2015, and in this paper one year of data from 15 April 2015 to 15 April 2016 are reported.

2.2. Simulation model in BSim

BSim (Building Simulation) [9] was used to calculate the hygrothermal behaviour in the crawl space and the floor structure. BSim is a transient whole-building simulation tool to calculate; among others, thermal indoor climate, energy consumption and synchronous simulation of moisture and energy transport in constructions and spaces.

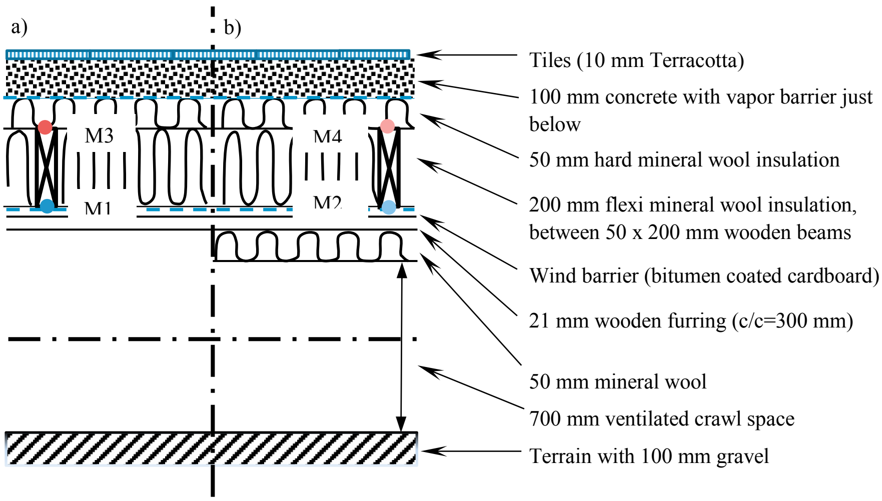

Fig. 1. The floor structure above the crawl space and indication of measurement points. (a) without 50 mm insulation installed under the wooden beams; (b) with 50 mm insulation installed under the wooden beams.

In BSim, the whole house was modelled, with the 110 m^2 crawl space as the thermal zone, and the room above as a zone with a well described temperature and relative humidity based on measurement data in the house. The crawl space walls were modelled as external walls exposed to outside climate. The floor structure above the crawl space is treated as a 1D model in the hygrothermal calculations in BSim. Therefore, the floor structure was modelled with insulation instead of wooden beams. With due respect for limitations, 1D simulation can in this case be used to give an indication of the differences in moisture content for both designs. However, to be able to evaluate the moisture content in the beams for comparison with measurements, a thin layer of wood was inserted at the surfaces representing the top and bottom of the wooden beams.

The outside climate was described by hourly values of temperature, relative humidity, wind speed, wind direction and atmospheric pressure. The weather data were collected at a nearby located private weather station.

Evaporation from the ground to the crawl space was included in the simulation by assuming 100 % relative humidity in the soil under the crawl space. The ventilation of the crawl space was modelled as infiltration where the amount of inlet air equalled the outlet air. The ventilation rate was set to 1.4 h^{-1} during summer and 0.35 h^{-1} during winter. The aforementioned description of the model produced the best convergence between the measured and calculated temperature and moisture content. The ventilation rate and evaporations from the soil are decisive factors in predicting the temperature and moisture behaviour in the floor structure and the crawl space.

3. Results

3.1. Measurement in crawl space and floor structure

Fig. 2 shows the measured temperature and Fig. 3 shows the moisture content in the crawl space, the floor structure (M1-M4), indoor climate and outdoor climate. In Fig. 2 the temperature in the different points behaves as expected, where the measuring points above the beams (M3, M4) are warmer than the measuring points below the beams (M1, M2). The measuring point (M1) without the extra 50 mm insulation is colder than the measuring point (M2) with insulation. Similar trends are seen for the moisture content in Fig. 3, where measuring point (M1) has a wood moisture content of 15-21 weight% compared to measuring point M2, where the wood moisture content never exceeds 15 weight%. Critical levels of moisture content in the case without extra 50 mm insulation are especially reached during summer and autumn.

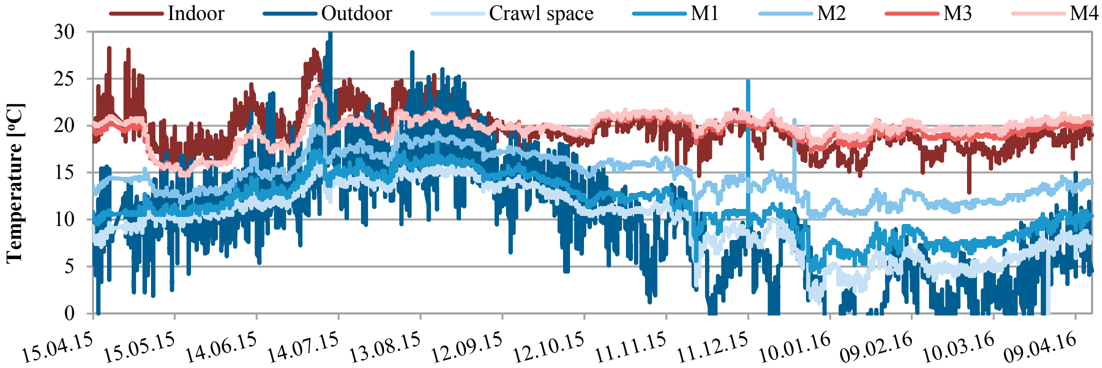

Fig. 2. Temperature in the crawl space, floor structure and indoor and outdoor climate in the period 15/4/2015-15/4/2016.

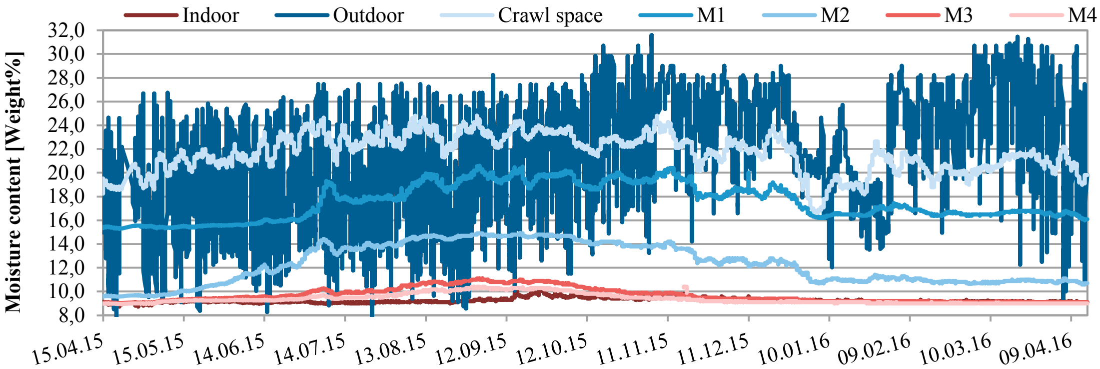

Fig. 3. Moisture content in the crawl space, floor structure and indoor and outdoor climate in the period 15/4/2015-15/4/2016.

3.2. Validation of model with measurements

Fig. 4 shows a comparison of the measured and simulated temperatures and relative humidity in the crawl space. The temperature in the crawl space shows good agreement, especially, from 12 September 2015 to 15 April 2016. The relative humidity has not similar good agreement between measurements and simulations. In the first six month the simulation results are approx. 20 % RH below the measured data. In the last six months a better convergence is achieved.

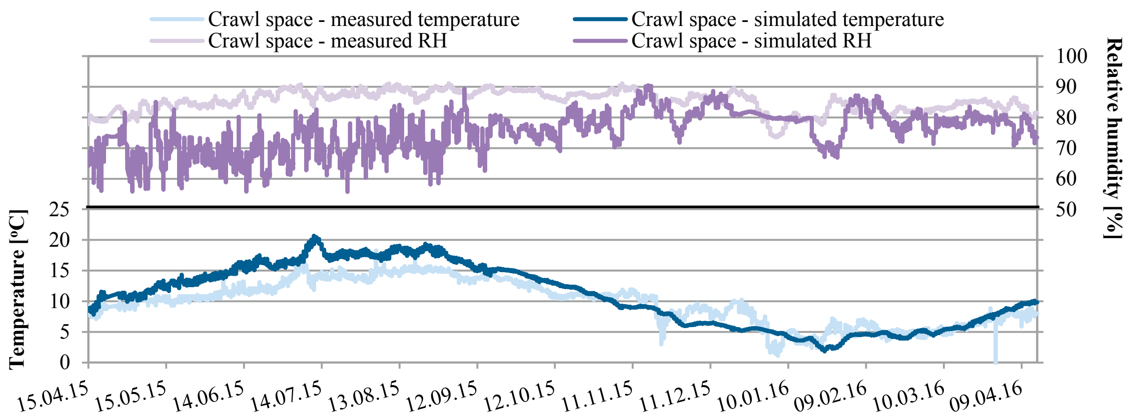

Fig. 4. Comparison of measured and simulated temperatures and relative humidity in the crawl space in the period 15/4/2015-15/4/2016.

In Fig 5, the temperature in the floor structure under the beams is given. Deviations up to 5 °C are seen, especially in the last six months for the design with insulation applied under the beams (M2-S2). Compared to measurements, simulated temperatures under the wooden beams follow the outdoor temperature more closely. Similar trends are found at the top of the wooden beams, however with higher temperature due to influence from the indoor climate.

The moisture content in the floor structure is shown in Fig 6, where results for both the top and bottom of the beam are shown. Generally, the convergence between measurements and simulations is not as good as for the temperature. The best representation is obtained at the top of the beams, where the graphs follow the same trend, but moisture content is overestimated by the simulations during summer. The moisture content at the bottom of the beams has no convergence, and similar trends for the measured and simulated data are difficult to find.

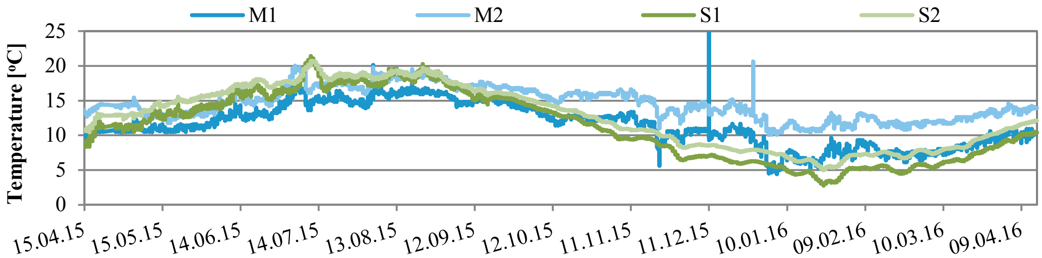

Fig. 5. Comparison of measured (M) and simulated (S) temperatures in the floor structure under the wooden beams (15/4/2015-15/4/2016).

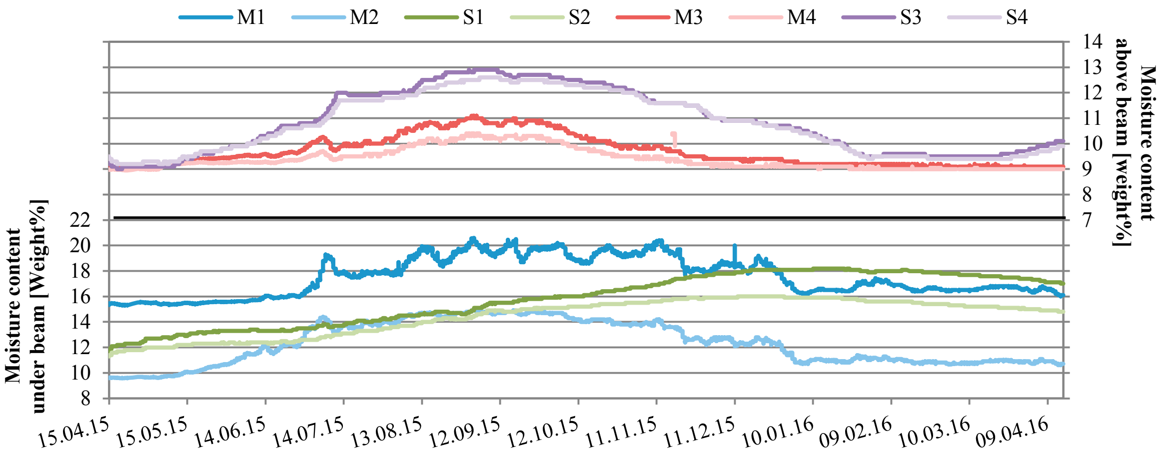

Fig. 6. Comparison of measured (M) and simulated (S) moisture content in the floor structure in the period 15/4/2015-15/4/2016.

4. Discussion

As the behaviour in a crawl space cannot simply be described based on boundary conditions from the outdoor climate, there exist specific calculations tools, e.g. CRAWL to determine the heat and moisture conditions in crawl spaces [9]. Instead of using a specific calculation tool developed for only crawl spaces, the whole building hygrothermal simulation tool BSim was used in this paper.

Comparison between measurements and simulations of temperature and moisture content/relative humidity in the floor structure and the crawl space has shown both good and poor convergences. Large deviations between measured and simulated results were found for relative humidity and moisture content in the crawl space and floor structure. Of note is that BSim is not originally developed to perform moisture simulations. BSim's moisture module includes calculation of the dynamic moisture balance in a zone (crawl space) and the moisture accumulation in the constructions (floor structure). The moisture accumulation in the constructions is based on vapour diffusion (including hysteresis) with the surrounding zones.

The relative humidity and moisture content in the crawl space and floor structure is strongly affected by the interaction between evaporation from the soil and ventilation rate in the crawl space. Exact figures for the evaporation from the soil to the crawl space depend on the climate, the construction etc. and are hard to obtain. In this preliminary study for using BSim, evaporation from the soil was included by assuming 100 % relative humidity in the soil under the crawl space. This is done in BSim by assigning a time-dependent (cosinus-profile) moisture load to the properties of the soil under the crawl space. Instead of this simplification, an advanced model for evaporation can be used in BSim. Preliminary simulations performed with both approaches showed better convergence with the measurements when assuming 100 % relative humidity in the soil instead of using the advanced model. However, it would definitely be worth to further investigate both approaches for further validation of BSim.

The amount of ventilation with outdoor air in the crawl space depends on wind conditions, location of the vents, location and surroundings of the building, obstructions in front of the vents, etc. Since no measurements on air change rates in the crawl space were available, a ventilation rate of $1.4h^{-1}/0.35h^{-1}$ was used in the modelling. The lower ventilation rate was chosen during the winter period, as the ventilation rate showed little influence on the relative humidity in the crawl space during winter and best agreement with temperature was found with a lower ventilation rate. The higher ventilation rate was chosen during the summer period, in order to increase the simulated relative humidity in the crawl space. Further investigations showed that increasing the ventilation rate even more did not help in increasing moisture content below the wooden beams and in the crawl space during summer. Instead, it was found that evaporation from the soil has larger influence.

5. Conclusion

Measurements and simulations showed that applying 50 mm insulation under the wooden beams in the floor structure above the investigated crawl space is a good option for raising the temperature and reducing the moisture content in the beams. The wood moisture content was for this design below 20 weight%. Comparison of the measured and calculated temperature and moisture content in the crawl space and floor structure showed that the temperature has a good convergence while the relative humidity in the crawl space has good convergence the last six months compared to the first six months. Simulations of the wood moisture content above the wooden beams followed the same trend as the measurements, but with an overestimation in summer. Similar trends for the measured and simulated wood moisture content at the bottom of the beams are, however, difficult to find.

All things considered, it is the authors understanding that BSim can be used to evaluate the temperature and moisture conditions in an outdoor ventilated crawl space, on the condition that further work is carried out to obtain a more validated BSim with regards to moisture simulation.

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