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AIR LEAKAGES IN A RETROFITTED BUILDING FROM 1930: MEASUREMENTS AND NUMERICAL SIMULATIONS

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ABSTRACT

Many buildings in Sweden are in need of renovation in order to meet the current standards of energy use in buildings. Particularly challenging are old listed buildings, the majority built before 1950, because the renovation is restricted to the parts that do not change the appearance of the building. This paper presents experiences gained during the renovation of a listed building where aging of materials, movements and settlements during the building operation have left trails in form of air leakage paths that are difficult to cover by renovation. The aim of the work is to bring up certain issues related to air movements in old houses that are not necessarily present in new ones. In the renovation project in question, efforts were made to seal the exterior walls with polyethylene foil before additional insulation in form of vacuum insulating panels was installed. The blower door tests taken in the apartments showed that the air permeability of the building remained basically unchanged after the retrofit. Complementary diagnostics with thermal imaging camera revealed that air leakage paths in intermediate floors and interior walls substantially contributed to the overall air leakage of the building. It was then concluded that the blower door tests alone were not sufficient for the estimation of the air permeability of the building. In addition, hygrothermal measurements in exterior walls showed that new air leakage paths were created between the old wall and the additional insulation. By using numerical simulations, it has been proven that it is the outdoor air that flows through these new air paths, which is advantageous from the moisture safety point of view. However, the flow of outdoor air through the exterior wall increases the overall thermal transmittance of the wall and thus decreases the effects of additional insulation.

KEYWORDS

Retrofit, listed buildings, hidden air leakage paths, increased thermal transmittance, moisture safety

1 INTRODUCTION

There are approximately 2.1 million buildings in Sweden distributed on 1.9 million single family houses, 165 000 multi-family buildings and 46 000 commercial buildings (Boverket, 2009). These buildings are from different time periods which mean they were built with different building techniques and technical solutions. A majority (47%) of the buildings were built before 1960, while 32% were built during 1961-1975. Buildings from the following 10 years comprise 12% of the building stock and thereafter 31% from 1986-1995 and 12% from 1995-2005 (Boverket, 2010).

Building codes were first implemented in 1946 in Sweden (IEA, 2013) and the first energy use requirements were introduced in 1975 after the oil crisis in 1973-1974. The requirements were specified with maximum U-values and demands on the airtightness for different building parts. The codes have been developed during the following years, tightening the demands on the energy use. The latest performance based energy codes are aiming at reducing the energy use further by introducing the same demands on retrofitted buildings as for new developments (Boverket, 2011). The requirements on airtightness have also varied over the years. Currently there are no requirements on maximum air permeability of the buildings in Sweden, except for specifications of passive houses (less than 0.3 l/(m^2s)). Figure 1 shows the air permeability in a selection of newly constructed buildings in Sweden. As can be seen, the majority of the buildings have an air permeability of around 0.8 l/(m^2s), which was the air permeability requirement in the Swedish building code until 2008. However, there are buildings with much larger air leakages (air permeability above 1.5 l/(m^2s)).

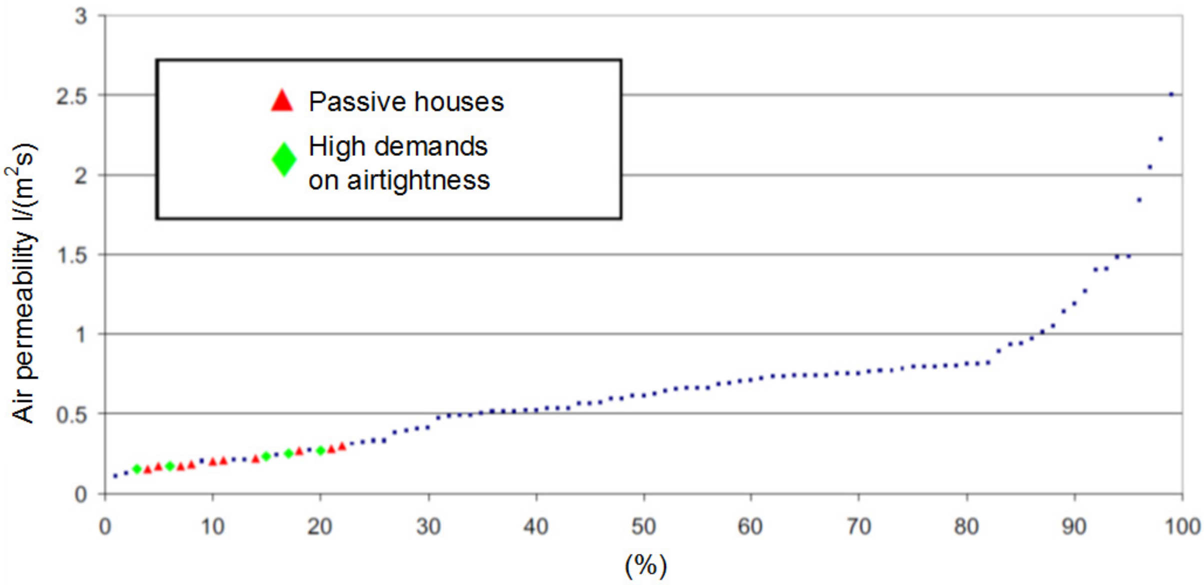

Figure 1: Airtighness in 100 newly constructed Swedish buildings. The sample includes single and multi-family buildings, (individual apartments are measured) and schools; both wooden and concrete structures (Wahlgren, 2010).

Low air permeability of a building envelope is essential to avoid unwanted consequences such as high energy use and insufficient thermal comfort, caused by draft and cold surface temperatures. Other consequences by a leaky building is that spreading of odour, particles and radioactive gases, such as radon from the ground, can take place between apartments. Also the acoustic insulation between apartments is affected by air leakages. Sandberg et al. (2007) discussed the economic consequences by insufficient air tightness. They concluded that a building with a good air tightness is, with a large probability, profitable for the builder and leads to increased well-being, less spreading of odours and better acoustic insulation.

There is much knowledge and techniques on how to achieve good airtightness in buildings, but one gets the impression that the focus is mainly on new buildings. As presented above, a majority of the building stock in Sweden is older buildings. This is also the case for the rest of Europe. One of the keys to successful retrofit is to achieve control over the air movements in these buildings. Natural or climate induced aging of materials and movements and settlements during the building operation have left trails on these buildings. These are typically visible as angle and surface distortions, cracks, and displacements. A large number of air flow paths through the building can be created by these geometrical changes. Since many of them are hidden inside the building envelope, they need to be treated in renovation projects to prevent undesired heat losses, comfort disturbances, or moisture damages.

The aim of this paper is to bring up certain issues related to air movements in old houses that are not necessarily present in new ones. Therefore, we present here the findings from a field study on airtightness and air movements in an old house, before and after the retrofitting. Unexpected air paths in the building envelope are revealed by hygrothermal measurements. These are further analysed and explained by numerical simulations.

2 CASE STUDY BUILDING

The building chosen for the study is a landshövdingehus "County governor's house" built in 1930 in Gothenburg, Sweden, see Figure 2. Most of these buildings were constructed during 1876-1936 when fire regulations limited the height of wood buildings to two floors. Today there are over 1 400 similar buildings in the Gothenburg region. The exterior aesthetics of the building are protected by Swedish legislation as a cultural environment of national interest. The building contain rented apartments and there are many complaints on draught and insufficient thermal comfort from the occupants. Therefore the building is in great need of retrofitting measures (Johansson et al., 2014).

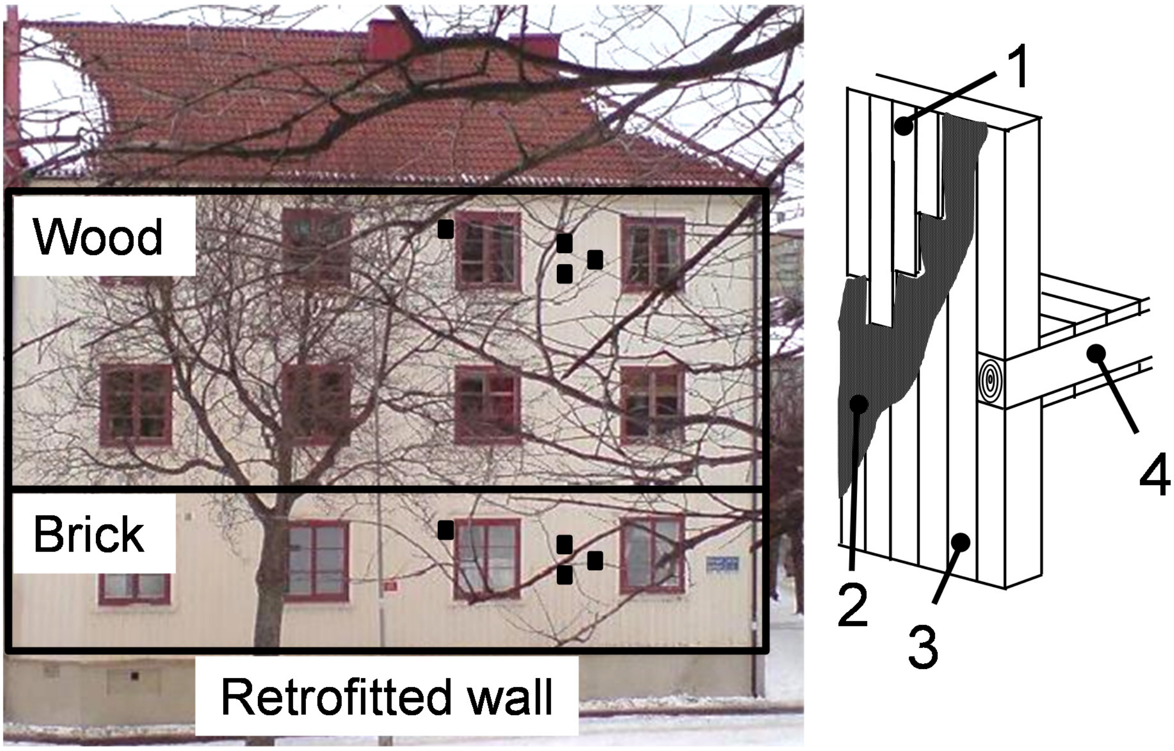

Figure 2: Left: The studied Landshövdingehus "County governor's house" with approximate location of the hygrothermal sensors in the walls. Right: construction of the original wood wall. 1) Wooden cover boarding, 2) Tar paper, 3) Structural wood or brick, 4) Intermediate wooden floor

In the time when the building was constructed, thermal insulation was normally not used in the walls. This building was no exception with brick walls of 1.5 stone thickness, approximately 340 mm, in the ground floor. In the two upper floors, the walls were made of 80 mm wooden planks in three layers. Flax fibres were used between the boards to decrease the air permeability of the wall. On the exterior, a 22 mm thick vertical wooden cover board with rib flanges was installed on top of a wind and waterproof tar paper as shown in Figure 2. The interior side of the walls was originally covered with a thin finish of plaster on reed (Larsson & Lönnroth, 1972), which was later replaced by modern plaster boards.

Due to the very limited space for additional insulation in the wall, the retrofitting, presented in Figure 3, was done with 20 mm thick vacuum insulation panels (VIPs) placed on the exterior side of the wall and protected by 30 mm of glass wool. Between the old wall and the VIPs, a polyethylene foil was applied as an air barrier to prevent indoor air entering the wall. An air space, 28 mm thick, was added to the façade which makes the total additional thickness of the wall to be 80 mm (Johansson, 2014).

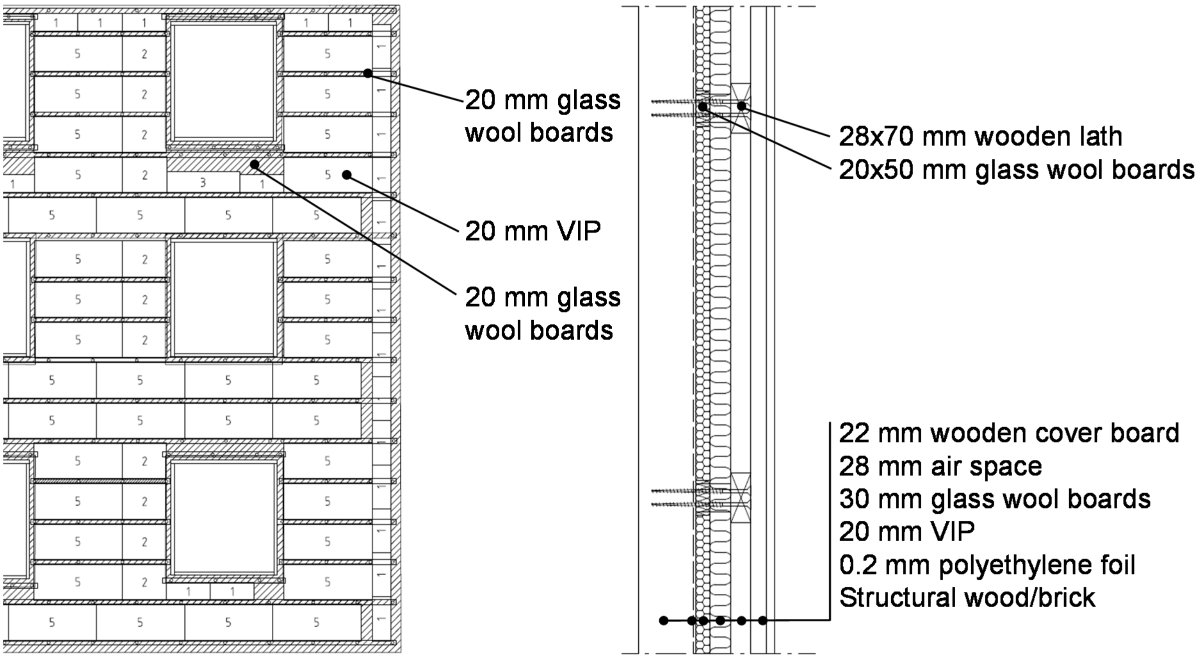

Figure 3: Wall layout after retrofitting with 20 mm VIPs and 30 mm glass wool boards.

The energy use for heating and domestic hot water before retrofitting was estimated to 160 kWh/m^2 (exact figures are not possible to obtain because the energy use in this building is measured together with many other buildings in the area). It is estimated that the additional insulation of the wall has reduced the energy use by 20% (with all VIPs functioning and all thermal bridges included). As a comparison, changing the windows to windows with a U-value of 1 W/m^{2}K gave an energy use reduction of 15%. The combination of changing windows and installing VIPs gave an energy use reduction of 34% (Johansson, 2014).

To evaluate the hygrothermal performance of the wall after the retrofitting, four temperature and relative humidity (RH) sensors were installed in the brick and wood wall, respectively. The sensors were located on the exterior of the existing wall, before the polyethylene foil. To study the influence of the indoor climate in the building, one sensor was located in one of the kitchens closest to the monitored part of the wall in the brick and wood wall, respectively. The outdoor temperature and RH at the building site was monitored by a sensor located in a perforated plastic box placed underneath the roof eave facing southwest (Johansson, et al., 2014).

3 RESULTS FROM AIR PERMEABILITY MEASUREMENTS

There were complaints from the occupants on an insufficient thermal comfort in the building due to draft and low surface temperatures. Thus, the building was investigated before and after the retrofitting using blower door and infrared thermography (Svensson, 2010, 2011). It was found that the interior wall surface temperature was around 1.5-2.4°C lower than the indoor air temperature before the retrofitting. After the retrofitting the surface temperature was only 0.3-0.8°C lower than the indoor air.

The blower door measurements were performed in single rooms since only one of the façades was equipped with VIPs. The results before and after the retrofitting are presented in Table 1. The air leakage paths were dominated by leakages around the windows, at the connections between the interior and exterior wall and along the floor (see Figure 4). These air leakage paths remained after the retrofitting but from the air temperature we can conclude that it is the indoor air that infiltrates through these leakages. Any further general conclusions of changed air tightness after the retrofitting could not be made based on the blower door measurements performed in single rooms. A better picture would be obtained if the blower door measurements were supplemented with, for example, tracer gas measurements that could separate infiltration of outdoor air from the air leakage paths through interior walls and floors.

Table 1: Results from blower door measurements at ±50 Pa (Svensson, 2010, 2011). According to Swedish regulations, the leakage area is the area that separates the indoor from the outdoor environment. The ground floor apartment is above the unheated basement, therefore, the leakage area includes both the wall and floor.

Floor	Size (length x width x height)	Leakage area (m^2)	Room volume (m^3)	Before retrofitting ($l/(s \cdot m^2)$)	Before retrofitting (1/h)	After retrofitting ($l/(s \cdot m^2)$)	After retrofitting (1/h)
Ground floor	3.9 x 4.4 x 2.7	27.7	46.3	2.6	5.6	2.7	5.8
1st floor	3.8 x 4.8 x 2.7	10.3	49.2	4.3	3.2	3.8	2.9

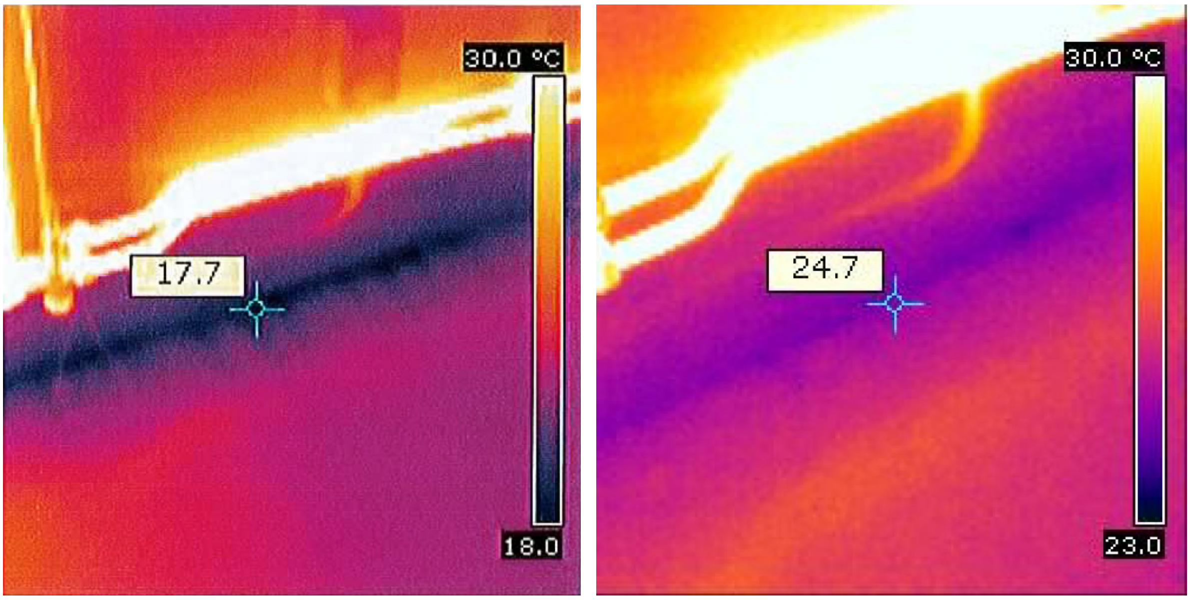

Figure 4: Thermograms showing air leakages in an apartment on the 2nd floor along the floor to wall connection before (left) and after (right) the retrofitting. The air leakage is less after the retrofitting (Svensson, 2010, 2011). At the site visits before and after the retrofitting, the indoor temperature was 21°C and 23°C and the outdoor temperature was 4°C and 6°C, respectively. The temperature of the air passing through the air leakage is around 24°C, which indicates that it is indoor air, possibly from the apartment below.

4 COMPARISON BETWEEN MEASUREMENTS AND HYGROTHERMAL SIMULATIONS

The temperature and RH was measured in the wall by the sensors described in Section 2. The measurements were compared to numerical simulations in the hygrothermal calculation tool WUFI 2D (Fraunhofer IBP, 2010). This software solves coupled heat and moisture transport equations by finite volumes where the temperature and RH are the driving potential for the heat and moisture transport through the construction. The numerical simulations were performed using the measured indoor and outdoor climate together with material data for the materials in the construction, see Table 2. Air flow in the wall is simulated by adding a coupling for the heat and moisture transfer between the wall and the indoor or outdoor air, respectively. The resulting temperature and RH in the wall without air leakages is presented in Figure 5.

Table 2: Material data used in the numerical simulations based on data from WUFI 2D material database (Fraunhofer IBP, 2010).

Material	*d (mm)*	λ (mW/(m·K))	ρ (kg/m^3)	c_p (J/(kg·K))	μ (-)
Gypsum board	20	200	625	850	8.33
Spruce, tangential	80	200	430	1600	83.3
Spruce, radial	80	200	455	1500	130
PE membrane	0.2	1 650	130	2200	$8.7 \cdot 10^4$
Glass wool	-	33	60	850	1.3
Glass wool board	20/30	33	115	850	3.4
Air layer	30	25	1.3	1000	0.46
Evacuated VIP core	18	5	200	850	1.3
Air filled VIP core	18	20	200	850	1.3
VIP laminate, tangential	1	540	189	134	Inf.
VIP laminate, radial	1	200 000	189	134	Inf.

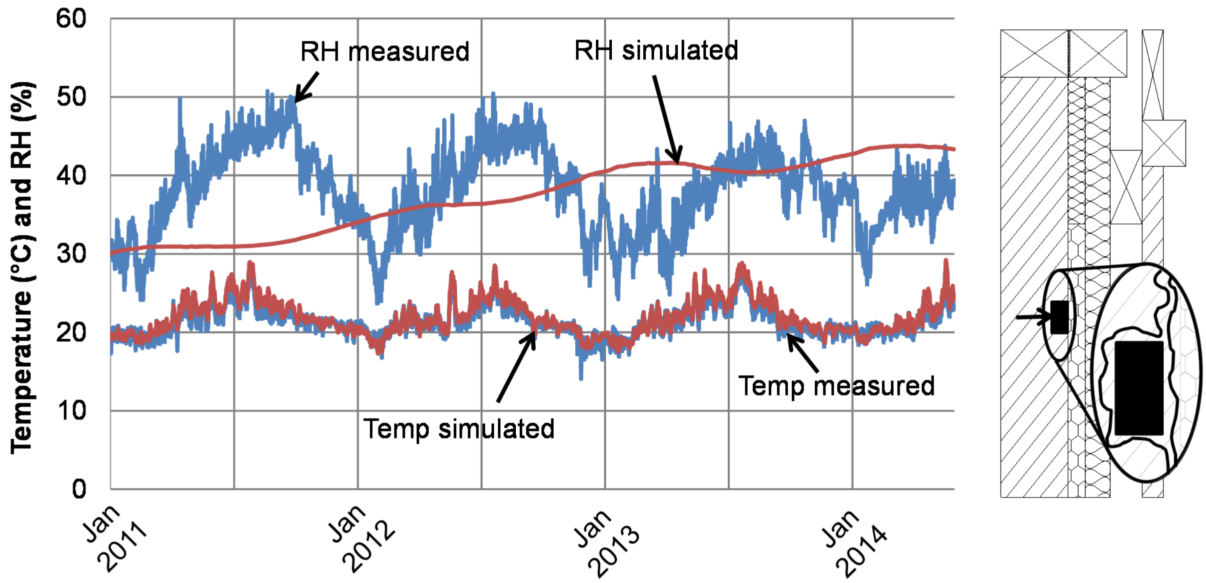

Figure 5: Comparison of the hygrothermal simulations with the measurements of the temperature and relative humidity behind the VIP in the wood wall. The simulation was based on the measured indoor and outdoor climate from January, 2011, to June, 2014. The location of the sensor is marked by the black box with a black arrow pointing from the left.

The average simulated temperature and RH at the sensor position in the wall was 21.9°C and 37.4% while the measurements gave 21.5°C and 37.8% on average during January, 2011, to June, 2014. It was noted that the vapor content was on average 1.3 g/m^3 higher in the numerical simulations than in the measurements. This suggested that there was an additional drying process in the wall. The sensor is located in an air filled void in the wall, measuring the temperature and RH of the air closest to the sensor. The high fluctuation in the measured RH indicated a leaky construction with air leakage from the interior or exterior side of the vapor barrier into the construction. It is anticipated that the air could enter e.g. through details around windows and flow along the interior of the vapor barrier to the sensor position. Although measures were taken to make the exterior wall air tight with the polyethylene foil, due to uneven surfaces certain connections have remained loose. Therefore, an air exchange with the outdoor air was added to the model between the vapor barrier and wood. The resulting temperature and RH is presented in Figure 6.

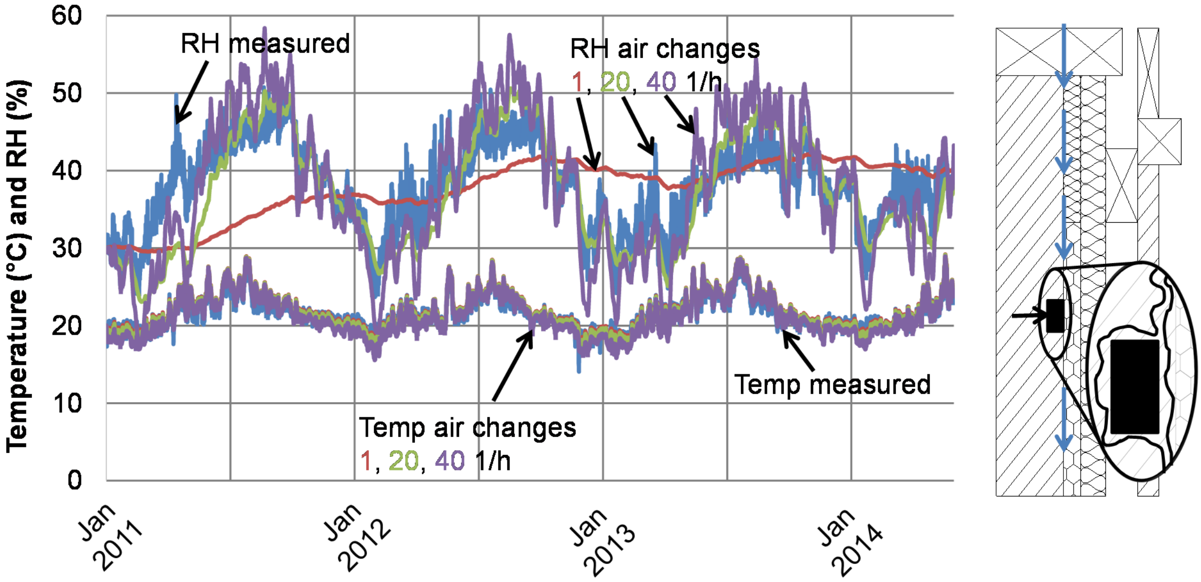

Figure 6: Comparison of the hygrothermal simulations with the measurements of the temperature and relative humidity behind the VIP in the wood wall. The air changes per hour with the outdoor air were varied from 1 1/h to 40 1/h. The location of the sensor is marked by the black box with a black arrow pointing from the left. The material surfaces in the wall are rather uneven which makes air flow through the small voids between them possible.

When an outdoor air exchange rate of 40 1/h was used, the simulated average temperature was 21.2°C. This is close to the measured average temperature 21.5°C. The simulated average RH was 37.6% which is also close to the measured average RH 37.8%. In addition, the simulated variations during the year corresponded well with the measurements. However, one cannot be entirely sure that the air is really coming from the exterior without testing this. Figure 7 presents the temperature and RH in the wall given that the air is coming from the interior.

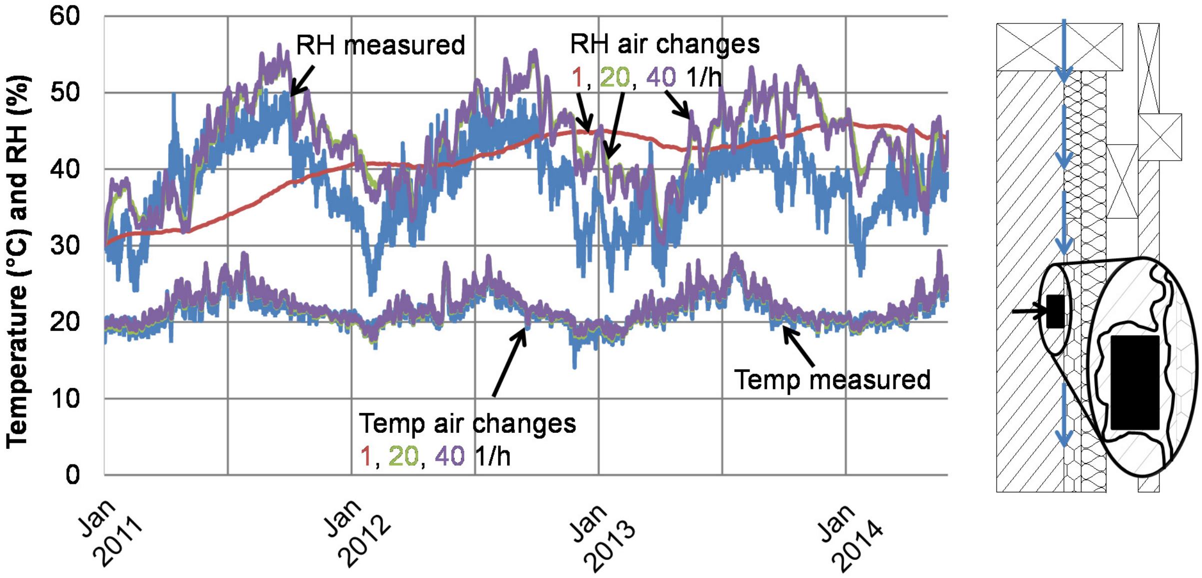

Figure 7: Comparison of the hygrothermal simulations with the measurements of the temperature and relative humidity behind the VIP in the wood wall. The air changes per hour with the indoor air were varied from 1 1/h to 40 1/h. The location of the sensor is marked by the black box with a black arrow pointing from the left. The material surfaces in the wall are rather uneven which makes air flow through the small voids between them possible.

The simulated temperature and RH deviated more when the air was coming from the interior than in the previous case. The simulation gave an average temperature 22.1°C and 43.4% RH for the case with 40 l/h, compared to the measurements that were 21.5°C and 37.8% on average. This shows that the air leaking into the wall is most certainly coming from the exterior.

5 CONCLUSIONS

This work presents the findings from a field study on airtightness and air movements in an old listed building. The building was retrofitted on the exterior with vacuum insulating panels. Although efforts were made to seal the wall with polyethylene foil on the interior of the additional insulation, blower door tests showed that the air permeability of the building remained basically the same before and after the retrofitting. Complementary diagnostics with thermal imaging camera revealed that air leakage paths at the intermediate floors and interior walls substantially contributed to the overall air leakage of the building. This implies that the blower door tests alone is not sufficient for estimation of the air permeability of buildings with large internal air leakage paths, and when the blower test cannot cover the whole building at once.

The hygrothermal measurements in the exterior wall revealed that new air leakage paths were created between the existing wall and the additional insulation. By using numerical simulations, it has been proven that it is the outdoor air that flows through these new air paths. This is advantageous from the moisture safety point of view. However, the flow of outdoor air through the exterior wall increases the overall thermal transmittance of the wall and thus decreases the effects of the additional insulation.

Based on these findings, we conclude that one of the keys to successful retrofit of old buildings is to achieve control over the air movements in these buildings. Knowledge of how potential air flow paths could affect the wall is crucial for making predictions of the long-term performance of a construction based on hygrothermal simulations.

6 ACKNOWLEDGEMENTS

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