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Evaluation of 5 years' performance of VIPs in a retrofitted building façade

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ABSTRACT

The challenges to retrofit buildings urges for technologies and novel building materials to be developed. In many cases the space for additional insulation in the building envelope is limited. Vacuum insulation panels (VIPs) have a significantly lower thermal conductivity than conventional insulation materials which means less thickness is required to achieve the targeted thermal transmittance. VIPs have been used in buildings since the late 1990s and there exists experience from using them in numerous applications. Besides the higher initial cost for using VIPs in buildings there is still hesitation among architects and engineers whether this component will withstand long-term use in buildings. Therefore further investigations are needed to evaluate its long-term performance. This paper presents experiences from a case study of a previously non-insulated wall insulated with VIPs. Measurements of the temperature and relative humidity in the wall during 5 years show no sign of deterioration of the VIPs and there is a low risk for condensation in the construction. The measurements are continuous with the aim to determine the long-term performance of VIPs in building applications.

1. Introduction

During the 1930s and 1940s the modern Swedish housing policies were decided. Investigations of the general living conditions in Sweden were used to establish guiding principles for how a healthy and modern dwelling should be constructed. Old buildings in densely populated areas in the cities were demolished and replaced with modern buildings in new residential areas. These areas were constructed in the 1960s and 1970s, during the so-called million programme (1964–1975), when 1 million dwellings were built in Sweden. Today around 20% of the Swedish building stock was built during the million programme, see Fig. 1 (left). This is a substantial share of the building stock, but the percentage of buildings from before this time period is even greater with 47%. The buildings from this period are also the ones with the highest thermal transmittance (U-value, W/(m^2 K)) in the exterior walls of all the building stock, as shown in Fig. 1 (right). The average U-value is around 0.58 W/(m^2 K) while it is 0.42 W/(m^2 K) for buildings from the million programme [1] which should be compared to the current building regulations which recommend a U-value of 0.18 W/(m^2 K) [2]. The old buildings are now in need of retrofitting measures. In fact all buildings from the time before 1975 have to be retrofitted before 2050. This is close to two million apartments which is three times more than what will be built until 2050. To reach the energy reduction targets by 2050 in Sweden, the retrofitting measures should include measures for improved energy performance [3].

There are many aspects, besides energy performance, that have to be considered in every building project. For renovation and retrofitting projects it is even more complex since there are several stakeholders who all have their views on how the project should be implemented. From a societal aspect legislation on e.g. accessibility, architecture, thermal comfort, ventilation and historic context makes the number of solutions that is possible for each project limited. The property owners want to maximize the profit while the tenants want to minimize the rental cost. These questions have been discussed ever since the first buildings were constructed. Today many buildings that have been retrofitted stand for their second or even third retrofitting. Following the retrofitting measures used in the 1970s and 1980s the appearances of many buildings were changed. With new technologies and improved measures some of these changes could be reversed to bring back lost building qualities while the energy performance is maintained. These solutions need to be evaluated and studied during a longer time perspective since buildings typically are designed for a service life of 80–100 years.

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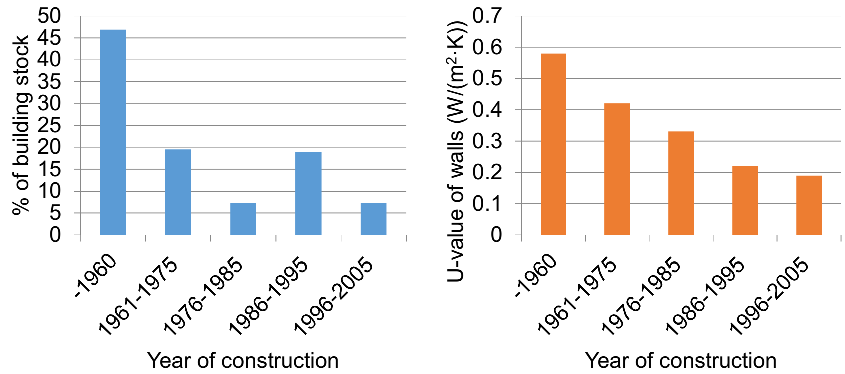

Fig. 1. Left: Percentage of the multi-family building stock from different time periods. Right: Average U-value of the exterior wall in buildings from different time periods [1].

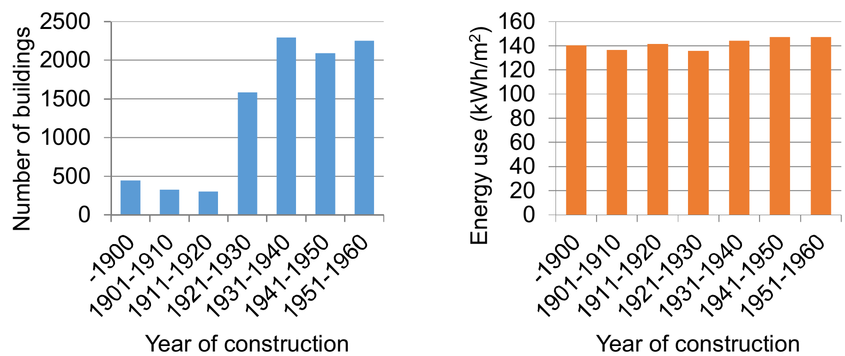

Fig. 2. Left: Number of multi-family buildings in Gothenburg from different time periods. Right: Average energy use for space heating, cooling, domestic hot water and facility electricity in builidings from different time period.

The technical documentations and drawings of old buildings are often of bad correspondence with the present conditions or completely lacking. The Swedish National Board of Housing, Building and Planning (Boverket) concluded that out of 1 800 investigated buildings, 40% had technical documentations and drawings that could not be used or were completely lacking [4]. This makes the knowledge of the energy performance of large parts of the building stock hard to evaluate. However, since 2006 the Energy Performance of Buildings Directive (EPBD) [5] requires Energy Performance Certificates to be issued for all buildings. In Sweden, these are based on the measured energy use for space heating, cooling, domestic hot water and facility electricity during 12 consecutive months for normal use during a reference year (30 year average). As an example the energy use in 9 291 buildings from before 1961 in Gothenburg in the south of Sweden is presented in Fig. 2. The buildings are divided on the number of buildings from different decades (Fig. 2 left) and their average energy use (Fig. 2 right).

The measured energy use in these old multi-family buildings is on average between 136 and 147 kWh/m^2 for the different time periods. However, to reach the goals of less greenhouse gas emissions in society, the energy use has to be further decreased to an average energy use of 92–102 kWh/m^2 by 2050 [4]. As discussed above, one way to reduce the energy use is to insulate the building envelope. However, in many cases the space for fitting additional thermal insulation in existing buildings and systems is limited. Therefore, super insulation materials with lower thermal conductivity than seen before are being developed. One of these components is the vacuum insulation panels (VIPs) which have been used in buildings since the early 1990s. A VIP is composed of mainly two parts; the core material and the surrounding envelope. The core material (often fumed or precipitated silica) is evacuated and wrapped in a metalized multi-layered polymer laminate. The resulting center-of-panel thermal conductivity is less than 4 mW/(m K). The thermal conductivity increases by time due to air and moisture diffusion through the laminate. Also, the laminate itself creates a thermal bridges around the panel. Therefore, the declared thermal conductivity of a VIP is 7–8 mW/(m K). A fully air filled VIP with fumed silica core has a thermal conductivity of 19–20 mW/(m K).

The first applications of VIPs in buildings were realized in the late 1990′s why the long-term performance of VIPs in real conditions is not yet known. A study by Simmler and Brunner [6] showed that VIPs available a decade ago typically have a service life of around 25–40 years, which is much shorter than for a building but similar to most other building materials. The service life was confirmed by Wegger et al. [7] who re-evaluated the performance of VIPs with various barrier laminate solutions over time. They found that accelerated ageing in the laboratory had little effect on the thermal performance of the VIPs but also that some of the tested conditions were too severe to evaluate the performance properly. Therefore, in 2013, the IEA EBC Annex 65 'Long-Term Performance of Super-Insulation in Building Components & Systems' was initiated which will study the long-term performance of several super insulation materials. The long-term performance of the VIPs is one of the focus areas which will generate new knowledge and better predictions of the long-term durability of the VIPs. This paper is a continuation and follow-up on the study presented in [8] and introduces a broader discussion on the long-term hygrothermal performance started in [9] and [10]. The aim of this paper is firstly to present an analysis of the long-term performance of VIPs in a retrofitted exterior wall. Secondly, the aim is to explore and evaluate the use conditions in the building and show that potential built-in moisture in the wall still has the possibility to dry out, and thirdly to investigate the influence by thermal bridges around the

VIPs on the hygrothermal performance of the wall. The basis for the evaluations are measurements of the temperature and relative humidity (RH) performed in a multi-family building in Gothenburg retrofitted in 2010. The hygrothermal performance is monitored by sensors integrated in the construction. The temperature and RH in the wall have been recorded during 5 years, from January 2011, to December 2015.

2. Durability of VIPs

It is not only the long-term performance of the insulation material itself that has to be considered for service life prediction of a construction. It is also the temperature and moisture conditions in the construction that are crucial to consider. For instance condensation inside a construction and large temperature variations over the day and night create stress and strain on the material structure which could cause premature failures. An issue when using VIPs is the risk of puncturing of the laminate, leading to loss of vacuum and an increased thermal conductivity. One methodology which has been used to evaluate the performance of VIPs in buildings is the infrared thermography. This methodology shows temperature differences over a surface which makes it possible to identify air filled VIPs. Heinemann and Kastner [11] used infrared thermography to investigate 19 buildings insulated with in total 3 224 m^2 VIPs, a few years after the construction finished. Of these buildings 7 were new buildings and 12 were retrofitting projects. Three buildings stood out in the investigation with more than 15% of the VIPs damaged. In one of these buildings it was assumed that errors were made in the design by installing unprotected panels close to an uneven plaster surface. In another building the researchers found that the VIPs had been stored and handled improperly by the construction workers. In the remaining 16 buildings with 1 999 m^2 VIPs, the total percentage of damaged VIPs was 4.9%. The conclusion of the study was that the percentage of damaged panels installed in a construction is low, as long as the recommendations by the producers are followed [11]. It should be noted that the study was based on infrared thermography which is a technique only possible to use when the VIPs are not covered by a highly conductive material or a ventilated air space. This is an important limitation when using infrared thermography to evaluate the thermal performance and durability of the VIPs in a finished wall.

Follow-up on other building constructions with VIPs are ongoing by several research groups. One example is the Canadian experiences documented by Mukhopadhyaya et al. [12]. An exterior wall was retrofitted externally by adding a 12 mm thick VIP, covered by 6 mm flexible polyurethane foam and 25 mm polystyrene foam board on each side of the VIPs. The polyurethane and polystyrene were added to prevent mechanical rubbing of the outside surface of the VIPs. The wall was monitored with temperature sensors during 4 years (3 winters). The measurements showed that the temperature difference across the VIP layer was 70% of the total temperature difference over the wall construction during all 3 winters. There was no significant ageing of the VIPs observed during the 3 winters presented in the study [12].

In Europe, the declared thermal conductivity of insulation materials is given as the average performance over 25 years, e.g. SS-EN 13162 [13]. Since all materials are influenced by the surrounding conditions, such as temperature shifts, exposure to moisture and by ultraviolet radiation, the material has to be exposed to these conditions to give predictions of the service life. Garnier et al. [14] identified a number of factors that influence the durability of the aluminum layers in the VIP laminate. Fluoride ions, which are present in drinking water, were identified as one of the chemical compounds that could cause early degradation of the laminate. The influence of moisture and elevated temperatures on the durability of VIPs was further investigated by Brunner et al. [15]. They studied a number of VIPs in different conditions in the laboratory and found that the laminate failed within a year in the most severe conditions. In a case study by Brunner and Ghazi Wakili [16], a number of VIPs were installed in a flat roof where the internal pressure and thermal conductivity were monitored. In 2013, after 8–9 years of operation, the thermal conductivity in two VIPs had increased from around 4 mW/(m K) to 6.6 mW/(m K) and 7 mW/(m K) which was higher than anticipated. Structural changes of the silica molecules due to migration of water molecules inside the core material was proposed as a third ageing mechanism, besides air and moisture diffusion. The larger contact surface between the molecules is supposed to increase the thermal conductivity. Morel et al. [17] studied this effect and concluded that fumed silica reacts with the water molecules leading to a decreased surface area and increased rigidity of the molecules. Therefore, more knowledge on how VIPs withstand long-term use in buildings with a service life of 80–100 years is crucial to foster wider acceptance among architects and engineers for the use of VIPs.

3. Case study building in Gothenburg

The building chosen for the study was built in 1930 in Gothenburg, Sweden. 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 were many complaints on draught and insufficient thermal comfort from the occupants. 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 and 80 mm wooden planks in three layers in the two upper floors. Therefore the building was in great need of retrofitting measures. Due to the protected exterior aesthetics, the space for additional insulation in the wall was limited. Therefore, the retrofitting was done with 20 mm thick VIPs placed on the exterior side of the wall, see Fig. 3. Between the old wall and the VIPs, a polyethylene foil was applied as an air barrier to prevent indoor air entering the wall. To protect the VIPs from damages, they were covered by 30 mm of glass wool on the outside. An air space, 28 mm thick, was added to the façade which makes the total additional thickness of the wall to be 80 mm [8]. To maintain the exterior aesthetics, the existing windows were moved 80 mm to stay in line with the façade.

The energy use for space 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. Calculations of the energy use show that the additional insulation of the wall will reduce the energy use by 20% (including influence of all thermal bridges). As a comparison, changing the old windows to new windows with a U-value of 1 W/(m^2 K) give an energy use reduction of 15%. The combination of changing windows and installing VIPs give an energy use reduction of 34% [8].

To evaluate the hygrothermal performance of the wall after the retrofitting, four temperature and RH sensors were installed in the brick and wood walls, respectively. The accuracy of the sensors is ±2.5% for RH between 10% to 90% and ±0.5 °C for temperatures between −40 °C–85 °C. The sensors were located in the exterior part of the existing wall, before the new polyethylene foil. The influence of the indoor climate was studied by installing sensors in the rooms closest to the monitored part of the wall. 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.

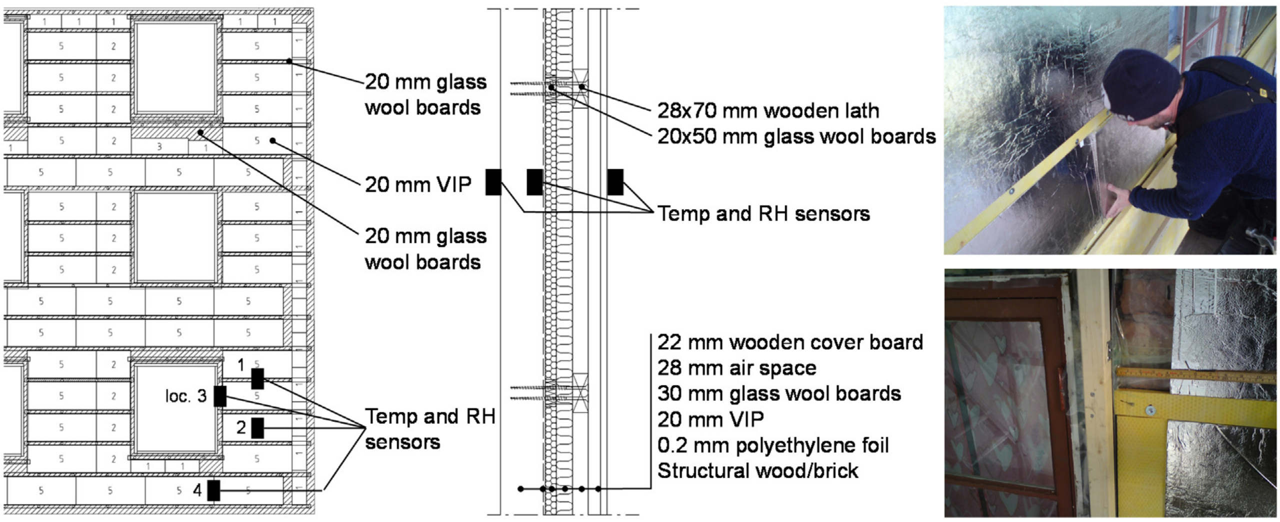

Fig. 3. Left: wall layout after retrofitting with 20 mm VIPs and 30 mm glass wool boards. The location of the temperature and RH sensors in the wall are marked by the black boxes (not in scale); 1) behind the strips of mineral wool, 2) behind the center-of-panel, 3) at the window frame, 4) behind the VIP–VIP joint. Right: installation of the VIP layer with the glass wool boards creating a thermal bridge between the VIPs themselves and between the VIPs and windows.

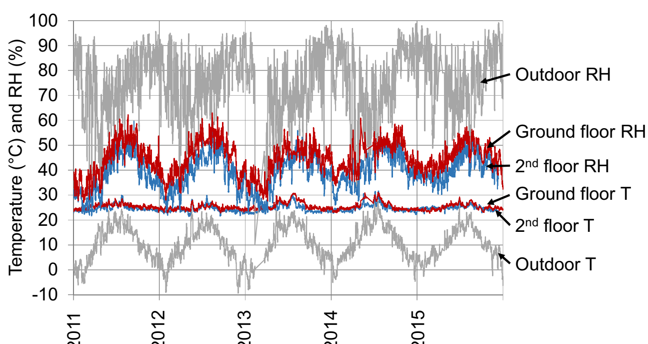

Fig. 4. Temperature and RH presented as the 24-h moving average in the apartments on the ground floor and 2nd floor, respectively, compared to the outdoor temperature and RH, for the period from January 2011, to December 2015.

4. Measurement of the indoor temperature and relative humidity

The long-term performance of a construction is dependent on the hygrothermal conditions it is exposed to. In this section, the intention is to present the variations of the indoor and outdoor climate in the case study building to illustrate how the use conditions vary with the occupants' behavior. The temperature and RH in the apartments on the ground floor and 2nd floor, respectively, are presented in Fig. 4. For easier readability, the 24-h moving average indoor and outdoor temperature and RH were calculated for the presented results.

It is clear that the temperature and RH in the two apartments is different throughout the 5 years. Both the temperature and RH is higher in the apartment on the ground floor than on the 2nd floor. Since the ground floor wall is made of brick and the 2nd floor wall is made of wood, the hygrothermal inertia is higher in the ground floor wall. This makes the daily variations lower in the apartment on the ground floor than on the 2nd floor. However, this does not explain the difference between the average temperature and RH. These are due to differences in the occupants' behavior which are virtually impossible to foresee. Therefore parametric studies of the design is needed before the construction is realized. In Table 1, the 5-year average temperature in the two apartments in the case study building is compared to two apartments in a neighboring reference building and the outdoor climate. The 5-year average RH in the apartments and outdoor is presented in Table 2.

The maximum temperature differed with 4.1 °C during the 5 years between the warmest (1st floor case study) and least warm apartment (2nd floor reference) while the minimum temperature was 4.8 °C lower in the coolest apartment (2nd floor reference) than in the least cool (2nd floor case study). The apartment with the highest average temperature was on the 1st floor case study building, followed by the 2nd floor case study building, the 1st floor reference building and finally the 2nd floor reference building. Since there is no information available on the temperatures before the retrofitting it is not possible to conclude if the retrofitting has influenced the temperature in the apartments. However, it is indicative for an increased thermal performance that the indoor temperature is higher (about 2 °C) in the case study building than in the reference building.

The differences of the 5-year average RH in the apartments also appear to be more affected by the occupants' behavior than on the location of the apartments. The highest average RH is found in the 2nd floor reference building, followed by the 1st floor case study building, the 1st floor reference building and finally the 2nd floor case study building. When studying the absolute vapor content (g/m^3) instead of the RH, the situation changes. It is the 1st floor case study building which has the highest absolute vapor content ($10.6\,g/m^3$) while the apartment on the 1st floor reference building has the lowest ($8.9\,g/m^3$). The difference between the average vapor content indoor and outdoor is called the indoor moisture supply. This is on average $1.2\,g/m^3$ in Swedish multi-family buildings [4]. In this study the moisture supply is on average $3.1\,g/m^3$ for the apartment on the 1st floor case study building, $2.7\,g/m^3$ on the 2nd floor reference building, $1.4\,g/m^3$ on the 1st floor reference building and finally $1.3\,g/m^3$ on the 2nd floor case study building. The indoor moisture supply is therefore slightly higher to 2.6 times higher than the average moisture supply for Swedish multi-family buildings. However, these values are all below or in the range of the recommended design value of $3–4\,g/m^3$.

5. Measurement of the relative humidity in the wall

The temperature and RH is measured in 4 different locations in each of the two case study walls see Fig. 3 (left). In the ground floor wall, two sensors monitors the thermal bridge behind the strips of

Table 1
Temperature (°C) shown as the 5-year average in the two apartments in the case study building, two apartments in the neighboring reference building and the outdoor climate.

	1st floor case study	1st floor reference	2nd floor case study	2nd floor reference	Outdoor
Maximum	32.6	28.6	32.3	28.5	35.5
Average	25.4	23.6	24.7	22.9	10.7
Minimum	19.7	18.9	20.5	15.7	−12.7

Table 2
RH (%) shown as the 5-year average in the two apartments in the case study building, two apartments in the neighboring reference building and the outdoor climate.

	1st floor case study	1st floor reference	2nd floor case study	2nd floor reference	Outdoor
Maximum	78.8	71.8	62.4	70.8	100
Average	44.7	41.4	39.4	49.9	74.5
Minimum	23.4	17.6	18.3	29.0	10.2

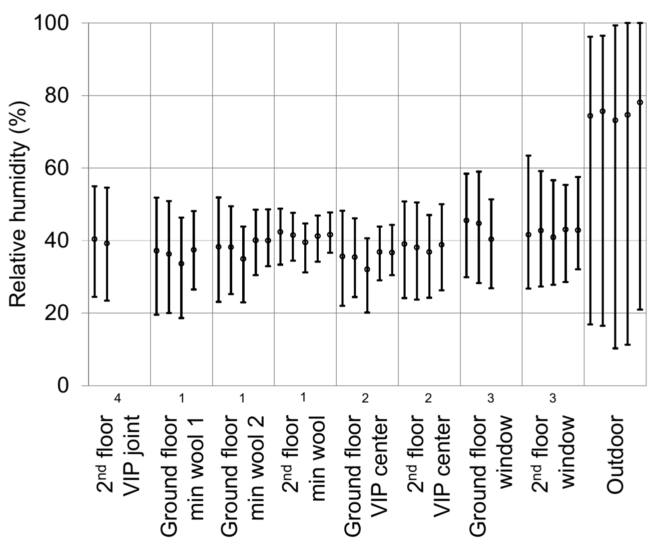

Fig. 5. The minimum, average and maximum RH at the 8 measurement locations in the walls and outdoors for 2011, 2012, 2013, 2014 and 2015. The numbers show the same locations in the ground floor wall and 2nd floor wall as defined in Fig. 3 (left). From left: 2nd floor VIP–VIP joint, ground floor mineral wool 1, ground floor mineral wool 2, 2nd floor mineral wool, ground floor center-of-panel, 2nd floor center-of-panel, ground floor window, 2nd floor window and outdoors.

mineral wool (Fig. 3 left, loc. 1), one sensor is located behind the center-of-panel (Fig. 3, left loc. 2) and one at the window frame (Fig. 3 left, loc. 3). Approximately the same locations were chosen for the wall on the 2nd floor but one of the sensors at the strips of mineral wool were here instead installed behind the VIP–VIP joint (Fig. 3 left, loc. 4). The minimum, average and maximum RH for the 8 different locations in the walls and outdoors during 2011, 2012, 2013, 2014 and 2015 are presented in Fig. 5. Unfortunately, a number of the built-in sensors have stopped sending data. The sensor at the VIP–VIP joint on the 2nd floor stopped sending data already in September 2013, which means only 2 years of data are available for this location. The reason for this is unknown. The battery should last for 15 years with hourly data sampling [18]. However, there could be other reasons for the malfunction like sensors working at their maximum range leading to excessive energy use, that an old battery was installed or sensor production error. The sensor behind the center-of-panel in the 2nd floor wall stopped sending data in March 2015. This is unfortunate since the measurements behind the center-of-panel was used for the previous evaluation [9]. Furthermore, the sensor located at the window frame in the ground floor wall stopped sending data in November 2014, one of the sensors behind the strips of mineral wool in the ground floor wall stopped sending data in July 2015, and, finally, the sensor in the 2nd floor reference wall stopped sending data in December 2015.

The highest RH is found at the window locations both on the ground floor and 2nd floor. This is because of a lower temperature at these locations. The maximum yearly RH at the window on the 2nd floor was 63.4% in 2011 but has after that reduced and was 57.5% in 2015. The same result was found at the window locations on the ground floor. This could be due to built-in moisture due to exposure during the retrofitting which is drying out with time. For the other locations the maximum RH was between 48.2% and 55.0% while the minimum RH was between 18.6% and 31.2%. The difference between yearly minimum and maximum RH in the walls has decreased in the years following 2011. However, this is not the case for the indoor and outdoor air, which, as shown in Figs. 4 and 5, varies with the same amplitude. This means that for all the monitored locations, built-in moisture is drying out with time. For instance for the location behind the center-of-panel on the ground floor, the difference was 26.3 percentage points in 2011 and only 13.9 percentage points in 2015. When studying the absolute vapor content, the difference between maximum and minimum have not changed significantly between 2011 (6.9 g/m^3) and 2015 (5.4 g/m^3) but remains on the same level. For the moisture content of the materials in the wall it is the RH which is decisive which means the moisture content in the materials varies less in 2015 than in 2011 even though the variation in absolute vapor content is the same. The smaller RH variations are beneficial for preventing moisture induced movements and cracks in the materials of the wall.

6. Measurement of the temperature in the wall

The temperature at the sensor position in the walls can be expressed in a dimensionless form. In the standard SS-EN ISO 10211 [19] this is denoted the temperature factor, f (−), which here is defined as

$$f = \frac{T_{indoor} - T_{sensor}}{T_{indoor} - T_{outdoor}} (-) \quad (1)$$

where T_{indoor} (°C) is the indoor temperature, T_{sensor} (°C) is the temperature at the sensor position and $T_{outdoor}$ (°C) is the outdoor temperature. The temperature factor is 0 on the interior side and 1 on the exterior side of the wall. The lower the temperature factor is, the higher the thermal insulation performance on the exterior of the sensor is. In Fig. 6 the temperature factor for the 4 measurement locations in the ground floor wall and 2nd floor wall in the case study building, respectively, are presented based on the annual average temperature indoor, at the sensor location and out-

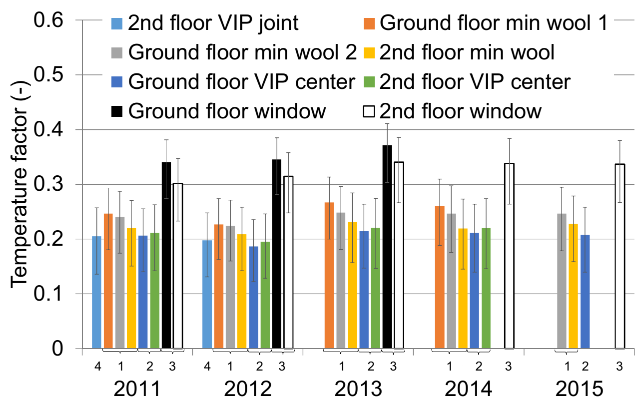

Fig. 6. The temperature factor calculated using Eq. (1) for the annual average temperatures for 2011, 2012, 2013, 2014 (and January till September 2015). The error bars show how the temperature factor could vary in the worst case with a sensor accuracy of ±0.5 °C. The braces show the same locations in the ground floor wall and 2nd floor wall as defined in Fig. 3 (left). From left: 2nd floor VIP–VIP joint, ground floor mineral wool 1, ground floor mineral wool 2, 2nd floor mineral wool, ground floor center-of-panel, 2nd floor center-of-panel, ground floor window and 2nd floor window.

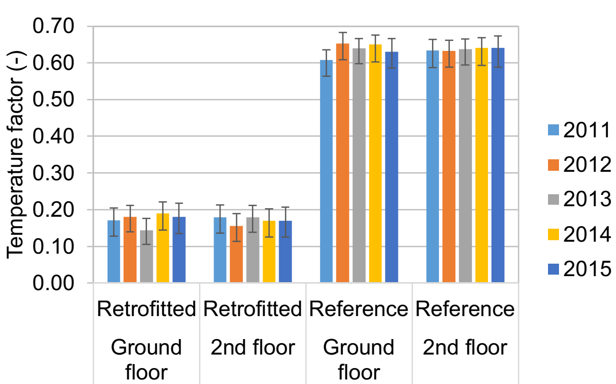

Fig. 7. The temperature factor calculated using Eq. (1) for January, 2011–2015 for the retrofitted walls (behind the center-of-panel, Fig. 3 left, loc. 2) and reference walls. The error bars show how the temperature factor could vary in the worst case with an accuracy of the sensor of ±0.5 °C.

door together with the maximum deviation which could be caused by the sensor accuracy of ±0.5 °C.

The temperature factor is expected to be lowest at the center-of-panel. However, in 2011, the temperature factor is lowest at the VIP–VIP joint but in the following year it is lowest at the location at the center-of-panel in the 2nd floor wall. Unfortunately, these measurement locations are only possible to compare during 2011 and 2012. Based on these two years, the thermal bridge between the VIPs seems not to influence the thermal resistance of the wall as much as the thermal bridge at the mineral wool strips between the VIPs. The difference is not as large between this location and the center-of-panel for the 2nd floor wall as in the ground floor wall. The reason for this is not known. It could be that the overall thermal resistance of the 2nd floor wall is lower than for the ground floor wall which makes the differences between the temperature factors smaller.

Comparing the reference wall with the retrofitted wall gives an approximation of how much the thermal resistance of the wall has been improved. For this analysis the average temperature for January each year 2011–2015 was used to calculate the temperature factor. The temperature factor in the retrofitted walls (behind the center-of-panel, Fig. 3 left, loc. 2) and reference walls during January are presented in Fig. 7 together with the maximum deviation which could be caused by the sensor accuracy of ±0.5 °C.

Table 3
Standard values for the thermal conductivity, λ (mW/(m K)), of the materials in the wall and corresponding thermal resistances, R (m^2 K/W), for the layers of thickness d (mm) and the heat transfer coefficient between the surface and air.

Material	*d* (mm)	λ (mW/(m K))	*R* (m^2 K/W)
Wood	80	140	0.57
Cover board	22	140	0.16
Brick	340	700	0.49
VIP	20	4	5.0
Glass wool	30	40	0.75
R_{si}	–	–	0.13
R_{se}	–	–	0.04
$R_{ventedfaÇade}$	–	–	0.20

It is clear that the thermal resistance of the wall has been substantially improved after the retrofitting. In the reference wall about 64% of the temperature drop was over the uninsulated brick and wooden parts. After the retrofitting only about 17% of the temperature drop was over that part of the wall. The tendency is most clear during winter time since the solar radiation during summer sometimes increased the temperature in the wall above the outdoor temperature, giving a negative value for the temperature factor. The same situation was reached when the outdoor temperature exceeded the indoor temperature. The stable temperature factors during the five years for both the reference and retrofitted walls showed that the thermal performance of the walls were roughly the same during this periods.

7. Calculations of the thermal performance of the wall compared to measurements

The expected temperature factors were calculated based on the standard thermal conductivity for the materials in the wall by using the resistance on the interior and exterior side of the measurement location:

$$\varepsilon = \frac{R_{\text{interior}}}{R_{\text{interior}} + R_{exterior}}(-) \tag{2}$$

where $R_{interior}$ (m^2·K/W) is the thermal resistance of the structural wall and $R_{exterior}$ (m^2 K/W) is the thermal resistance of the materials on the exterior side of the sensor. The standard values for the thermal conductivities, λ (mW/(m K)), the thickness of each material layer, *d* (mm), and the resulting thermal resistance, $R = d/\lambda$ (m^2 K/W), are presented in Table 3.

Using the standard values for the thermal conductivity, the temperature factor at the sensor location was 0.77 in the reference wall and 0.12 in the retrofitted wall. The measurements gave an average temperature factor of 0.64 in the reference wall and 0.17 in the retrofitted wall. The lower measured temperature factor in the reference wall could be explained by different surface heat transfer resistances on the interior or exterior side of the wall. The sensor was located in a perforated plastic box placed underneath the roof eave, mostly protected from wind, which leads to a higher surface heat transfer resistance than what was used in the first calculation. With an exterior surface heat transfer resistance of 0.22 m^2 K/W instead of 0.04 m^2 K/W, the calculated temperature factor matched the measured temperature factor of 0.64. The thermal bridges created by the VIP laminate and glass wool strips were not included in the calculation. These could explain the higher measured temperature factor in the retrofitted wall compared to the calculation. In reality these thermal bridges increase the heat flow through the VIP layer. To reach the measured temperature factor of 0.17, the effective thermal conductivity of the layer with VIP and glass wool strips needed to be 9 mW/(m K). Using the exterior surface heat transfer resistance of 0.22 m^2 K/W, the effective thermal conductivity increased to 10 mW/(m K). However, other factors could contribute to increasing the heat flow through the wall. One of these factors is airflow through the wall which was not considered in these calculations.

8. Conclusions

It is difficult to evaluate the performance of the VIPs when installed in the wall. In the retrofitting solution presented here, the external air space makes it impossible to identify the different panels by thermography. Only indirect methods, like evaluation of the measured temperatures in the wall, can be used to follow the long-term performance of the panels. This paper shows that there is no sign of degradation of VIPs installed in a retrofitted wall during the period 2010–2015. There was also no measured or reported condensation in the wall. The risk for moisture induced movements in the wall has decreased with time since the annual variations in RH decreased. The thermal bridges between the VIPs had minor influence on the temperature factor in the 2nd floor wall while the temperature factor was slightly higher in the ground floor wall. This could be caused by a lower thermal resistance of the 2nd floor wall which increases the percentage of temperature drop over the VIP layer in this wall. To be certain that the VIPs are not degraded, the VIPs should be transported to the laboratory where the internal pressure and thermal conductivity should be measured.

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