# Performance of a Retrofitted 1950s Multi-Unit Residential Building—Measurements and Calculated Transient Hygrothermal Behaviour

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## ABSTRACT

*In this study, a Swedish multi-unit residential building built in the 1950s is investigated. The house, situated in the Gothenburg metropolitan area, with a lightweight concrete structure and brick cladding, was severely affected by weathering and had accumulated moisture in its structure, leading to high moisture content throughout the walls. In addition, the energy performance of the building was poor. To improve its hygrothermal performance, an exterior insulation and finishing (EIF) system with mineral wool and a thick layer of mineral scratch rendering (stucco) was chosen to not alter the time typical aesthetics of the 1950s house and cultural historic neighbourhood.*

*The walls most affected by moisture were instrumented with wireless hygrothermal gauges and monitored before, during, and for more than one year after the retrofitting. This paper presents the final results from the in-situ measurements and compares the findings to calculated transient hygrothermal simulations of the façade as well as the whole building. The thermal properties of the building components and their impact on heat losses are evaluated as well as the energy performance for the whole building by the energetic building simulation.*

*The results show that the chosen EIF system facilitated a quick drying of the accumulated moisture in the autoclaved aerated concrete (AAC) and that simulations are in accordance with monitored hygrothermal behaviour, both for the façade and the whole building simulations. It is also shown that the effect of the moisture taken up by the façades on energy performance can be estimated using a holistic whole building simulation model.*


## INTRODUCTION

This paper deals with the refurbishment of a 1950s multi-dwelling residential building situated in the Gothenburg metropolitan area. The energy performance of multi-dwelling blocks from the 1950s in Sweden is quite poor and external thermal insulation composite systems are often proposed to improve the thermal performance of the walls of these buildings, but the hygrothermal effects caused by the retrofitting have not been fully investigated. The studied building, see Figure 1, has a brick cladding façade with an autoclaved aerated concrete (AAC) structure behind. The façade was in a poor state and severely affected by weathering with deteriorated mortar joints and moisture accumulating in its structure. The building supervisor reported high moisture content throughout the walls in some apartments with possible hygienic problems and health risks for the tenants due to mould growth at the interior.

Apart from moisture related damages, high moisture content in the walls also negatively affect the thermal properties of the AAC, as thermal and hygric behavior of porous building materials are closely interconnected (Sandin 1984). In particular, the south facing walls suffered from moisture damages and several of the buildings apartments had been affected. The property owners had over the previous years unsuccessfully attempted to treat the exterior surface with different hydrophobing agents to reduce the water uptake and also tried to raise the indoor temperature of the apartments to

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***Figure 1*** *The investigated building before retrofitting (photos taken early March 2010): (a) west façade with gable and (b) details of the south façade's bay windows.*

drive out the moisture. This resulted in a high energy demand and proved not to be a sustainable solution.

With the aim of stopping the water uptake by the AAC, rapidly improving the façades hygrothermal performance, and facilitating drying of the lightweight concrete, an exterior insulation and finishing (EIF) system (EIFS; in Europe referred to as ETICS, or external thermal insulation composite system) with 50 mm mineral wool and a thick layer of mineral scratch rendering was chosen after a first hygrothermal investigation. This investigation revealed a much faster drying process of the selected EIFS compared to traditional EIFS using expanded polystyrene (EPS) insulation. Another reason for the choice of cladding with the mineral scratch rendering was not to alter the time-typical aesthetics of the 1950s house and its place in the cultural historic neighborhood. The original windows were also replaced during the renovation as they were in a poor state and had low thermal performance. The building after the completed retrofit is shown in Figure 2.

This study presents the final results of a three-year study where the hygrothermal properties of the retrofitted walls depending on choice of EIF system have been investigated. The final results from the field measurements in the monitored building are shown and compared with modeled hygrothermal simulations. The effects of moisture on the transient thermal transmission through the walls are also presented, elaborating on the difference found between different EIF systems and choice of materials. The building's energy demand for space heating supplied by district heating, pre- and post-retrofit, is presented along with the results of the whole building simulation.

## FIELD MEASUREMENTS

The original building's walls consisted of 20 cm of AAC and had a half stone (65 mm) brick cladding façade more or less directly adjacent without any proper air gap in between. With deteriorating bricks and brick mortar, this contributed to the strong water uptake by the lightweight concrete and subsequent indoor problems.

The renovation started August 2010 when the building was weather protected, see Figure 3, and the refurbishment of the walls began. Using hydrophobic and vapor permeable insulation materials for exterior insulation and in EIFS is a very effective way of preventing further rainwater from reaching the inner walls and will enable the walls to dry out. The installed EIF system consisted of a 50 mm dense mineral wool board (85 kg/m$^3$), and two layers of render (total 20 mm) on top, a base coat with a stainless steel mesh embedded, and a scratch coat.

The original dual glazed windows with an approximate U-factor of $U = 3$ W/(m$^2$·K) were replaced by more energy efficient triple glazed windows, $U = 1.0$ W/(m$^2$·K).

The field measurements included an inventory performed end of March 2010 with reference core samples taken from the inside of the building through the aerated concrete of the south and west facing walls at the second and third floor. The moisture content was then established for different depths of the walls by the laboratory at the Department of Building Mate-

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***Figure 2*** *The investigated building after completion of the retrofitting (photos taken September 2011): (a) complete with new windows and EIF system and (b) details of the south facades bay windows.*

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***Figure 3*** *(a) Weather protection during renovations and (b) selected EIF system used for the retrofit of the building. Two layers of stucco on a mineral wool board attached by mechanical fasteners and metal mesh.*

rials at Lund Technical University. To minimize the disturbance of the tenants, a wireless system for continuous monitoring was installed at the same time allowing instant access to sensor readings.

Field measurements and hygrothermal monitoring of autoclaved aerated concrete have in the past been carefully investigated (Sandin 1987) and the experience from these results guided the placement of the monitoring equipment. The south and west facing walls most affected by weathering were instrumented in two apartments: a south facing wall in the first apartment on the third floor and two walls in the second apartment on the second floor, facing south and west respectively, see Figure 4. Temperature and relative humidity at different depths of the lightweight concrete was measured by wireless hygrothermal gauges as well as moisture content (wood moisture equivalent, WME) at 5 cm depth in the AAC.

The equipment used for the wireless monitoring was the GE HygroTrac v2 sensors. They allow for three gauges at

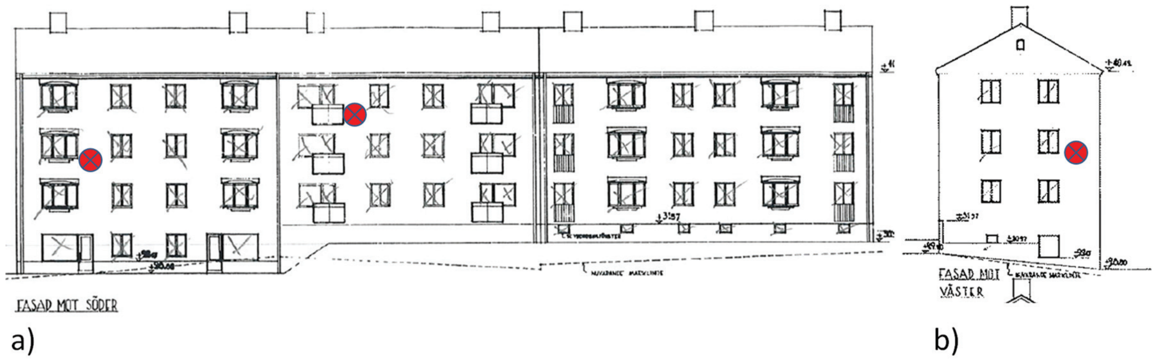


***Figure 4*** *Original drawings of the building's (a) south and (b) west facing facades. The apartments' locations and approximate monitoring points are marked with red.*

each transmitter: two RH/temperature sensors and a moisture (WME) 2-pin probe. The sensors were calibrated by laboratory staff at Lund University. For very high relative humidities in the AAC, >95%, the sensors are not very precise, as is shown later in the results. The data from the wireless sensors were received by a gateway placed in the basement of the studied building and forwarded by a 3G router to a server for storage.

In order to monitor the conditions pre- as well as post-retrofit, the in-situ measurements started in March 2010 and were finalized early 2013. Energy for space heating and domestic hot water by district heating was also monitored and data was delivered by the property owner.

## HYGROTHERMAL SIMULATIONS

The demonstration building has also been modeled by the hygrothermal software WUFI Pro and WUFI Plus. This software has been experimentally verified for many types of building component assemblies (Künzel 1995; Karagiozis 2001) and similar setups (Tariku 2006) as the studied building and is well established. Before the renovations began and in order to select a suitable EIF system, the existing building façade walls and two possible EIF system solutions were analyzed, including the installed one. The alternative EIF system (ETICS) is a more common EPS insulation and acrylic render system. Material data and initial moisture conditions were supplied by material producers as well as from material databases such as MASEA Datenbank and the IBP Fraunhofer Material Database and from measurements.

Precise historic material data is always lacking and, as the studied building originates from the early 1950s, appropriate assumptions had to be made. As many materials age, their properties will change with time. For instance, there occur microstructure changes in AAC during carbonation as reported by Matsushita et al. (2004) and these will most likely affect hygrothermal properties such as sorption isotherms and thermal conductivity.

For the comparative hygrothermal analysis of the walls and subsequent retrofitting, normalized climatic data supplied by Lund University was used for the Gothenburg outdoor climate. For initial moisture conditions of the AAC, the results from the core sample measurements were used as shown in Table 1. To simulate the leaky mortar joints of the brick façade, a moisture source of 2% of the driving rain was added to the outer layer of the AAC to redistribute to the wall and raise the moisture levels to values presented in Table 1, at least once a year. For the interior, a vapor resistance was added to simulate a few layers of paint or vapor-tight wallpaper, as was found in the actual apartments.

Energy calculations were also performed with WUFI Plus. This software can simulate whole buildings and introduce the effect of built-in moisture on heat flows and heating demand. The studied building in Gothenburg was modeled from its original state (Figure 5), and with different renovation measures: window change, additional insulation, and combined window change with EIFS. The different measures were analyzed and the results studied along with the effect of moisture in the walls. Again, the measured moisture contents were used for the calculations.

## RESULTS AND DISCUSSION

From the field monitoring, core sample analysis, and the simulations, interesting results were revealed. First, the autoclaved aerated concrete core sample from the south wall that had been segmented, sealed in glass containers, and brought to laboratory for testing showed elevated moisture contents throughout the wall, see Table 1. Moisture contents reaching almost 30% by weight was found in the outer parts of the wall, indicating leakage and water uptake by the AAC. This was well anticipated as some apartments with south facing walls had reported much more severe moisture problems earlier with damp surfaces on the inside of the apartments' walls. This was not seen during the inventory which took place in early spring, and some drying had probably occurred during the winter and heating season.

**Table 1. Results from AAC Core Sample—Moisture Content by Weight of the AAC Measured at Different Depths from the Interior of the South Facing Wall**

| Depth from Interior, cm | Average Moisture Content, M-% |
|---|---|
| 0–3 | 19,1 |
| 4–8 | 24,1 |
| 8–12 | 25,0 |
| 13–16 | 26,7 |
| 17–19 | 29,0 |

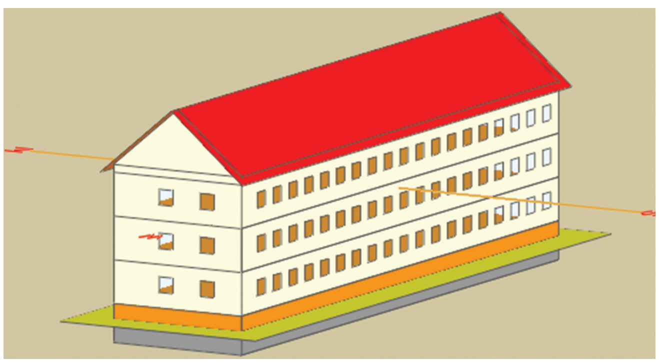

*Figure 5* *Model in WUFI Plus of the studied building pre-retrofit, seen from southwest.*

From the hygrothermal simulations study, it is clear that the choice of EIFS assembly has a great effect on the drying of moisture from the AAC, see Figure 6, but also on the transient U-factors. The drying rate was much slower and moisture content higher for the EPS and acrylic stucco because both materials are less permeable.

The field monitoring revealed varying moisture conditions in the walls with height of building and direction of exposed outer surface. Figure 7 shows the measured relative humidity and temperature as well as the simulated relative humidity of the south facing façade at the outer most part of the AAC, which was also the most humid point of all the measurement points. It is clear that the EIF system installed allows for a rapid drying of the AAC. The rate of drying is visibly affected by seasonal changes with different outdoor moisture content in the air. A high rate of drying was seen in the first winter period and this was repeated the next year. As the relative humidity in the AAC decreases, the corresponding moisture content goes down as well. The reason for the apparently slower drying rate in the first winter is partly due to the limitations of the RH sensors for very high relative humidities, but also due to the high specific moisture capacity of AAC at high relative humidities compared to a much lower at relative humidities below ~90%.

To illustrate the amounts of moisture this correlates to, Figure 8 display a desorption isotherm for a typical AAC based on data from Kumaran et al. (2002). The corresponding moisture contents (M-%) of the AAC from the RH measurements in Figure 7 are highlighted from the beginning of the first drying to the end of the measurements (i.e., from approximately 30% to less than 5%).

Heating of domestic hot water (DHW) is seldom measured separately in older buildings. Based on previous research on tenants' energy behaviour it is possible to estimate approximately the use of DHW of the tenants as suggested by Warfvinge (2008) who studied Swedish residents' use of DHW and give approximate values on the energy for producing DHW. In Figure 9 the

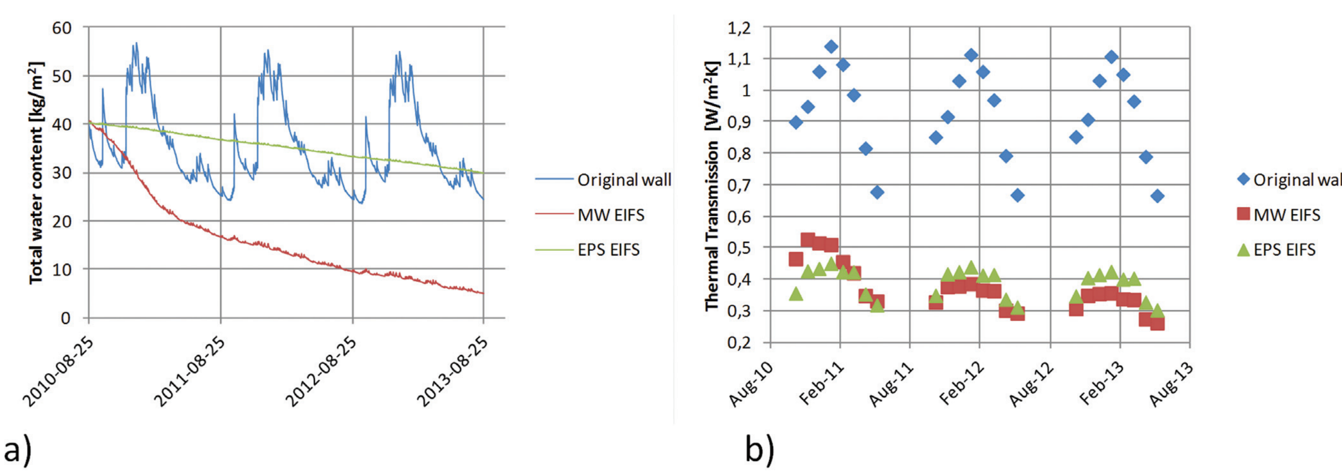


*Figure 6* *(a) Total water content of the walls as a function of time for all three cases simulated and (b) corresponding monthly transient U-factors.*

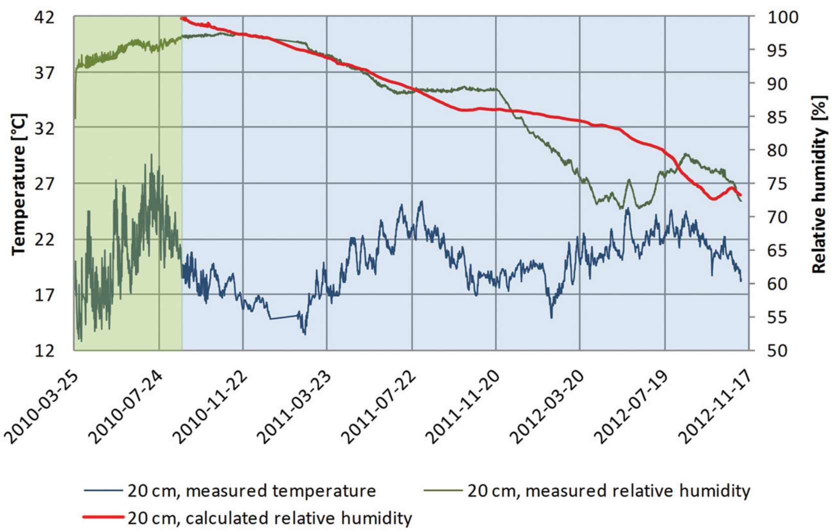


***Figure 7*** *Measured relative humidity and temperature as well as calculated relative humidity for the outermost point (20 cm) in the AAC of the south wall, third floor.*

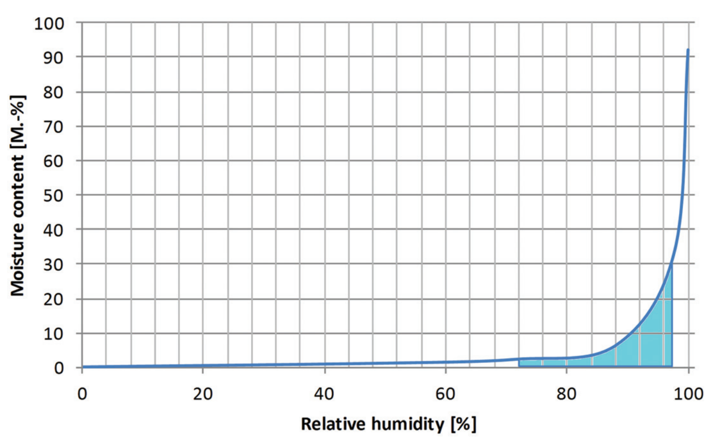


***Figure 8*** *Example of an AAC desorption isotherm. The corresponding moisture content of the AAC from the RH measurements in Figure 7 is highlighted from the beginning of the first drying to the end of the measurement.*

degree day corrected heating demand (without DHW) is presented for a five year period, including both pre- and post-retrofit. It is clear that approximations of DHW are not precise and vary over the building stock and individual houses depending on the demographics of tenants. With the above approximation even the summer month of July shows a need for space heating which is, of course, not so. The July value is most likely a part of the DHW and should be added to this and deducted from the heating demand.

The degree day corrected values indicate a reduction in supplied energy by 25% from 2010 to 2011. The measured average 2009/2010 to 2011/2012 shows a reduction by 22%. The cold month of January 2011 (post-retrofit) compared to the same month 2010 (pre-retrofit) showed a drop in energy by 41%, showing a significant reduction in peak power.

In Table 2 the heating demand (without DHW) for the whole building is shown; the measured demand supplied by the energy company (in red), pre- and post-retrofit, but also the calculated, with and without the effect of moisture on the heat flows, as simulated by WUFI Plus. Individual measures are also shown. To study the effect of the high moisture contents of the south facing wall, an average moisture content equivalent measured in the AAC was applied for some cases.

## CONCLUSION

AAC can hold large amounts of water and it is crucial that excess moisture is allowed to dry out. The material's thermal conductivity will be much higher as long as the material contains excess water and proper drying must be facilitated. The chosen EIF-system facilitated a quick drying of the accu-

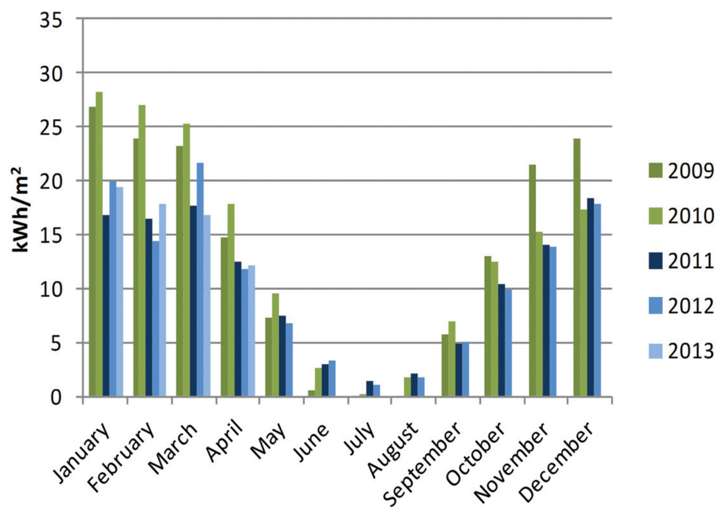


***Figure 9*** *Measured values of supplied energy by district heating for space heating (district heating net of DHW). Values 2009–2010 are mainly pre-retrofit and are marked in green. However, for the months of November and December 2010 the walls were already insulated and can be considered as post-retrofit. Values 2011–2013 are post-retrofit and marked in blue.*

**Table 2. Measured and Calculated Heating Demand with Different Renovation Measures and Considering the Effect of Moisture on Heat Flows**

| Case | $kWh/m^2 \cdot year$ |
|---|---|
| Pre-retrofit, measured average 2009/2010 | 161,5 |
| Pre-retrofit, calculated, with moisture | 162,3 |
| Pre-retrofit, calculated, without moisture | 157,1 |
| Window change, calculated, with moisture | 147,9 |
| Window change, calculated, without moisture | 142,7 |
| With 50 mm EIFS, calculated, without moisture | 137,7 |
| Window change and 50 mm EIFS, calculated, without moisture | 123,3 |
| Post-retrofit, with window change and 50 mm EIFS, measured average 2011/2012 | 126,0 |

mulated moisture in the AAC and simulations are well in accordance with monitored hygrothermal behaviour with some seasonal differences. For very high relative humidities, >95%, the RH sensors only give an indication of the moisture content and the actual amount can be much higher. Core samples can supplement this data for reference and initial values.

There was a clear reduction in heating demand after the retrofit and a significant reduction in peak power. Calculated and measured energy figures are well in accordance, but the effect of moisture on energy demand is more difficult to estimate precisely for older buildings as a more comprehensive picture of the walls moisture content needs to be established. The results do give a good indication of the effect of elevated moisture contents in the walls and it is clear that excess moisture in AAC significantly increases the energy demand.

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