

# Moisture impact on dimensional changes and air leakage in wooden buildings

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## ABSTRACT

Wood is a hygroscopic material, it has the ability to adsorb or desorb water in response to the ambient relative humidity. Thus, the ambient air will affect the moisture content of the wood, and in turn, the dimension of the wood. If the wood itself is part of the air barrier in a construction, the shrinking and expansion can create gaps in the construction, for example in the window sill. In case of an air barrier consisting of a foil, the joints in the foil can be clamped by wooden joists, or the foil can be taped to wooden part. In both cases, the movement (shrinking, expanding) can cause air leakages, in particular since wood is an anisotropic material and will behave differently in different directions.

This project investigates the air leakages that occur in wooden buildings from seasonal variations in climate and from finished construction (first airtightness measurement) to equilibrium (when inbuilt moisture has dried out). Measurements are made in real buildings (full scale) and in laboratory (climate chamber). The full-scale measurements on buildings with wooden construction have shown magnitudes of up to 10% increase in air leakage (at 50 Pa) for the seasonal variations and the increase for reaching equilibrium in a newly built construction is 20%.

## KEYWORDS

Airtightness, wooden buildings, air leakage,

## 1 INTRODUCTION

The Swedish government has expressed an interest in increasing the use of wood in constructions. The described benefits are lower carbon footprint, decreased production cost, and an increased competitiveness of the Swedish wooden industry. Residential buildings are of particular interest since there is a housing shortage in many Swedish cities. Some challenges can however be found in wooden buildings, for example, fire resistance, sound propagation, moisture/durability and airtightness. The airtightness is of great importance to the performance of the building since it can greatly affect the energy use and the moisture safety.

Wood is a hygroscopic material which means that it can adsorb or desorb water in response to the ambient relative humidity. Thus, the ambient air will affect the moisture content of the wood, and in turn, the dimension of the wood. If the wood itself is part of the air barrier in a construction (for example cross-laminated timber, CLT), the shrinking and expansion can create gaps in the construction, for example in the window sill. In case of an air barrier consisting of a foil, the joints in the foil can be clamped by wooden joists, or the foil can be taped to wooden parts. In both cases, the movement (shrinking and expanding) can cause air

leakages, in particular since wood is an anisotropic material and will behave differently in different directions.

The current project aims to investigate the impact of moisture on the air leakage in light weight wooden houses (LW) and in cross laminated timber (CLT). Both seasonal moisture variations (summer/winter) and the initial drying of a building is studied.

Following investigations have been made:

- Field measurements of moisture conditions (LW)
- Moisture induced dimension changes (LW, CLT)
- Air leakage calculations (LW, CLT)
- Tape durability testing (CLT)
- Drying time calculations (LW)
- Full scale airtightness measurements (LW)
- Leakage consequences on heat exchange in a building

## 2 WOOD CONSTRUCTION AND AIRTIGHTNESS

Wood constructions are either lightweight constructions (load bearing wooden constructions, Figure 1) or massive constructions such as cross laminated timber, CLT (Figure 3).

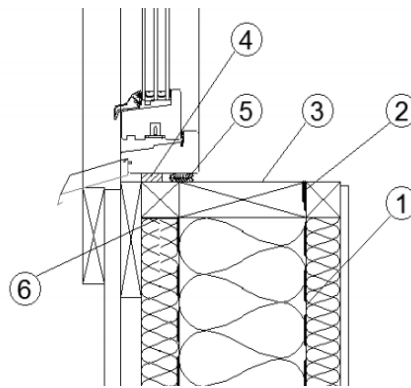


Figure 1: Light-weight wooden construction (Derome, 2019)

Commonly, light-weight wooden constructions depend on a polyethylene foil close to the inside for air tightness (the foil also serves as diffusion barrier). To have a completely airtight building, the air barrier must be continuous. For the window setting it is recommended that the foil is properly attached to the window. An example of a solution with good airtightness is shown in Figure 2 where one foil is stapled and taped to the window and one is extended from the wall. These separate foils will then be taped together.



Figure 2: Window setting with two separate foils that will be sealed together to an airtight joint (Wahlgren, 2010).

This type of work is quite time consuming to produce. However, with this solution the wooden members behind the foil are less affected by interior moisture. In Figure 1, the solution that is used for prefabricated walls is shown. Here, the polyethylene foil is cut around the perimeter of the window. It is taped, using double-adhesive butyl sealant (no. 2) and clamped with the inner joist of the wall. For this case, the shrinking of joist no. 3 in Figure 1 is essential. If this joist shrinks, it might create a vertical or horizontal gap under the diffusion tight sealing around the window (no. 5) or open up the gaps in the corners of the window created at the end of each window joist (no. 3).

The cross-laminated wooden elements, shown in Figure 3, are usually considered very airtight. However, Skogstad et al. (2011) measured two types of element; one type where the boards are glued on all four sides, and one type that are only glued on the two sides parallel to the largest element sides. They measured at two moisture content levels, 14% and 10%. The result was that the initial air leakage (at 14%) was almost the same for the two types, but when the elements were dried, the air leakage increased with a factor of ten for the type glued on four sides and doubled for the type glued on four sides.

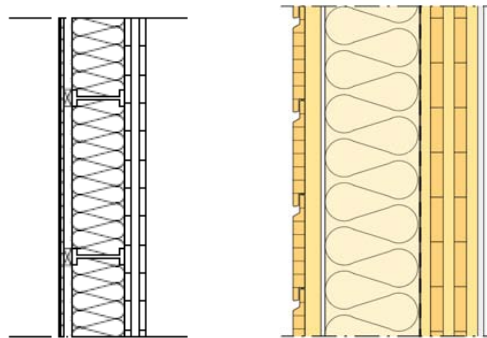


Figure 3: CLT wall (Stora Enso, 2019, left, Träguiden, 2019, right)

For both types of construction, it is essential that the connections between the elements are airtight. Swedish Wood (Svenskt trä, 2019, a department within The Swedish Forest Industries Federation) recommend a polyethylene foil to ensure airtightness. Stora Enso (CLT manufacturer) recommends no polyethylene foil in the construction and the connections can be sealed by flexible joint foams, self-adhesive tapes or tubular rubber seals (Stora Enso, 2019). There are different opinions on which strategy results in the best long-term airtightness and moisture safety. In this project, the durability of tape on wood is investigated.

### 3 MOISTURE LEVELS AND DIMENSIONAL CHANGES

Wood expand in moist environment (and shrink in dry environment), the dimensional change depends on the change in moisture content. How much the moisture content vary between different environments is described by the sorption isotherm, see Figure 4, where the condition of the environment is defined by the relative humidity, RH, in the air. The airtight layer is either the polyethylene foil or the CLT element. Both are placed on the inner side of the construction and, consequently, the inner relative humidity is more important to the airtightness. The relative humidity indoor ranges from 10-80% depending mainly on the activities in the building, the ventilation rate, the air leakage and the location of the building (10% RH indoor mainly occurs in northern Sweden during wintertime). However, the variation of indoor RH for a specific building is usually smaller.

In new buildings the wood is delivered with a certain moisture content (kg/kg, %), usually average 16% and allowed variation between 11,2 and 20,8% (as described in SS-EN 14289).

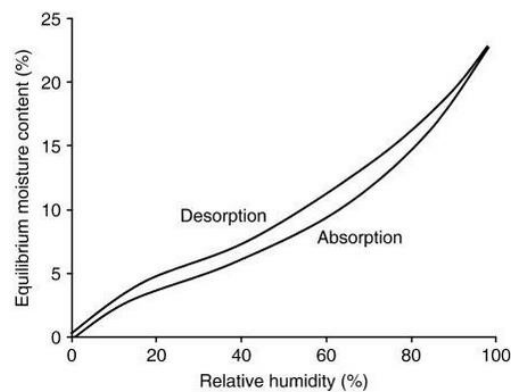


Figure 4: Sorption isotherm for timber (Building research establishment, xxxx)

To get an estimate of the moisture content that wood will have when it is built into a prefabricated light-weight construction, the moisture content (quotient) was measured at four different locations at the production site for prefabricated buildings during wintertime (Billemar, 2019). Each time 9 to 13 boards were measured at three different points on each board.

The first measurement is outdoor, after sawing. For this occasion, the average moisture content (quotient) is 10,2 %. When the prefabricated wall is being built, the average moisture content is 10,6% and when the wall is ready for application, the average moisture content is 10,5% and the maximum moisture content is 16,5% (at this production site, a moisture content of 18% is approved). After this, the wall might be stored in an environment with a higher relative humidity or rain exposed, without weather protection. This situation was studied by Olsson (2014). He followed 24 prefabricated detached houses from production of elements to finished house. Relative humidity, and moisture content was measured, and mold growth was evaluated. Elevated or high moisture content were found on one third of all the samples, 15% of the samples had a moisture content above 25% and microbial growth was found on almost one third of all the samples that were taken. There is not one single point of failure that causes the high moisture content, precaution is needed in all steps of the building process. However, protection of elements from rain is essential. In the following a moisture content of 25% is used as a worst case to estimate air leakage paths that are created when wood is drying after the building is finished.

## 4 DIMENSIONAL CHANGES

Wood is an anisotropic material, thus the shrinkage is different in different directions. According to Burström (2008), pinewood has a shrinkage of 7,7% tangentially, 4,0 % radially and 0,4% along fibres. The shrinkage,  $\alpha_f$  (%) from fibre saturation to dry wood is used to calculate the actual shrinkage from one moisture content,  $u_2$  (%) to another,  $u_1$  (%), where  $u_f$  is the moisture content at fibre saturation

$$\Delta\alpha = \frac{u_2 - u_1}{u_f} \cdot \alpha_f \text{ (%)}$$
 (1)

CLT elements consist of at least three single-layer panels (made of pinewood, fir or hardwood) that are bonded together crosswise to obtain good stability. Swedish Wood (2019) describes the dimensional changes along the plane of CLT elements as being between 0,016-0,023 % per percentage point of change in moisture content, which is slightly more than the change parallel to the fibres (stated average 0,01-0,02%). The dimensional change along the thickness of the element is not described but based on the construction of the component, it should be between the radial shrinkage, 0,19%, and the tangential shrinkage, 0,36%, per percent point change in moisture content. Using the values for shrinkage from Burström (2008) and a  $u_f$  of 30% to calculate the shrinkage per point change in moisture content results in values similar to those of Swedish wood.

To calculate the air gaps created by the shrinkage of a CLT wall, a wall to wall corner was studied where the walls are 15 m long and the CLT is 100 mm thick, insulated on the outside and thus exposed to the inner climate of the building, see Figure 5.

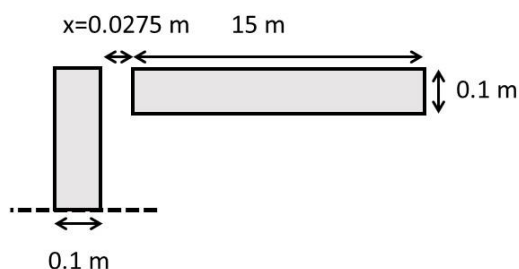


Figure 5: Resulting air gap,  $x$ , at the meeting of a 15 m long element and a 0.1 m thick element.

Using pinewood with an initial moisture content of 25% and drying to an indoor relative humidity of 20%, which corresponds to a moisture content of approximately 6% (worse case), results in a gap with a width of 0,0275 m. There will be additional insulation and wind protection outside this gap that substantially reduce the air leakage, but as a calculation example, a gap with the length of 100 mm and width of 0,0275 m will result in an airflow of 187 l/s per meter gap at a pressure difference of 50 Pa, which is the pressure difference used for the evaluation of a building's airtightness. A 100 m<sup>2</sup> quadratic building of height 3 m, with these gaps in each corner, would have an air permeability of 7 l/m<sup>2</sup>s. As a comparison, the Gothenburg municipality in Sweden require a maximum air permeability of 0,2 l/m<sup>2</sup>s for newly built schools. Consequently, it is essential to avoid gaps through the construction and joints must be additionally sealed. Another issue with CLT wood is that the elements are not always completely flat at edges, which also creates gaps.

For the window setting in Figure 1, the gap (at no. 5) caused by the shrinkage of the wood (from 25% to 6% as above) is calculated for a joist of 145 mm width. This results in a gap with the dimensions of 7 mm in case of the joist being attached to one side so that the whole

shrinkage occurs on the other side. Corresponding air flow around a window with dimensions 1,2·1,2 m and a pressure difference of 50 Pa is 226 l/s (without other materials). Thus 2 to 3 windows on each side of the building will result in the same air permeability as the previous case.

Another example of an important detail is the connection of an attic hatch in the attic floor. If this detail is not airtight, moist air will be transported to the cold attic above, in particular during wintertime, which can result in moisture damage. For low-energy houses with high demands on airtightness, the access to the attic is recommended from the outside instead. In Figure 6, an indoor attic hatch is illustrated including arrows that show the most likely leakage path. Calculations of the gap width and corresponding air leakage when the building is in use ( $\Delta P_{est}=4$  Pa) is made for different levels of indoor RH. It is assumed that the frame in which the attic hatch is fastened is swelling or shrinking which changes the gap width. Figure 7 shows simulations of the total airflow through the gap in the attic hatch at different RH at a pressure difference of 4 Pa. Maximum gap width is 0,0032 m (at RH 28%).

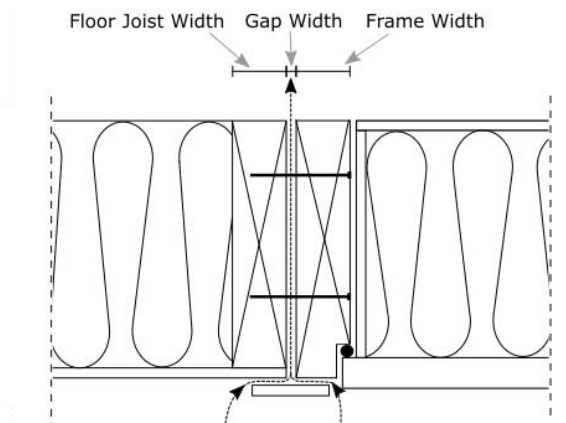


Figure 6: Connection of attic hatch to attic floor showing the most likely leakage path.

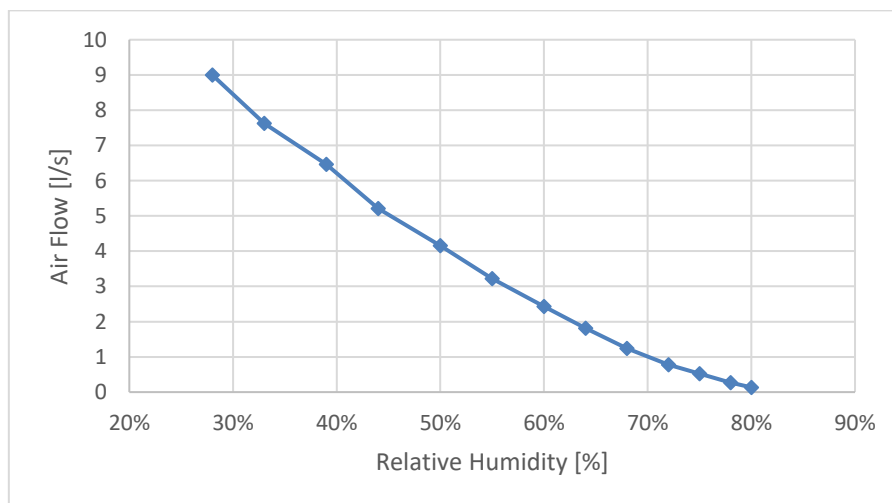


Figure 7: Total air flow through the gap around the attic hatch at a pressure difference of 4 Pa.

As a preparation for the field measurements described in section 6, an evaluation was made of the drying time (from construction) of a light-weight construction. The example consists of a construction with joists that clamp the joints of polyethylene foil behind a gypsum board/plaster board in a wall. The joists are exposed to the surrounding environment on three

sides and in connection with the polyethylene foil on one side (no moisture exchange). The simulation starts when the building is finished and has a moisture content of 16% (80% relative humidity), continues for two years, reaching equilibrium with the indoor environment. According to the simulation, the joists reach equilibrium after slightly more than two months. This is shown in Figure 8.

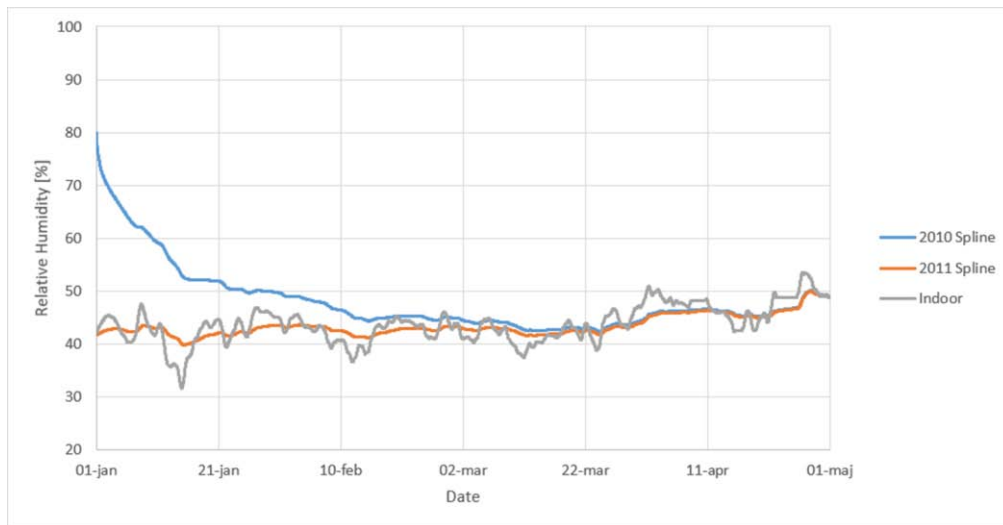


Figure 8: Drying of wooden parts behind the plaster board in an external wall.

In comparison, the drying out time of the external walls of CLT buildings with polyethylene foil has been numerically simulated by Shareef et al. (2019). The drying out time ranges from four to nine years. In addition, they conclude that the polyethylene foil increases the risk for mold growth, since the drying out time is increased, and that taping of joints should be enough to ensure airtightness.

## 5 TAPE DURABILITY

The joints in the CLT construction can be taped, as described above. There are some difficulties however, as described in Shareef et al. (2019) and Andersson et al. (2019), such as using the tape in moist, cold and dusty environments, getting a proper application in corners, avoiding stretching of the tape and creases.

The durability of two types of tapes on wood has been tested in a climate chamber (Andersson et al., 2019). The CLT wood pieces with tapes are cycled 50 times from 80% RH to 10%, with 4 hours at each level and 20 minutes for transition, checked and then run another 50 cycles. The tapes are applied to corners (a.), joints (b.) and with imperfect underlay. The underlay has dust from either concrete or wood, or is slightly moist, as can occur at a building site.

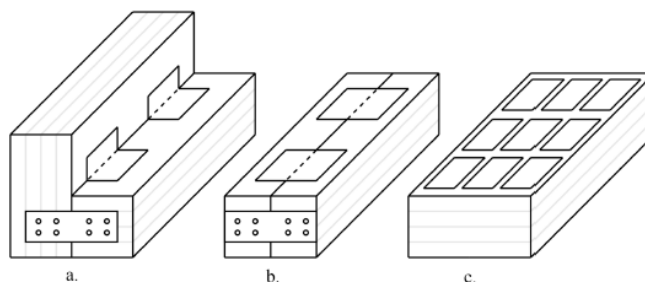


Figure 9: Configuration used for tape testing

After the tests, the tape has in some cases shrunk. This is probably caused by the tape being stretched too much when applied. The taping of corners resulted in some creases (Figure 10, left). These were worsened after cycling (Figure 10, right). As were the bubbles created by the dusty surfaces. Further evaluation of the long-time airtightness performance of tape on wood is recommended.



Figure 10: Change in adhesion (50 cycles apart).

## 6 AIRTIGHTNESS MEASUREMENTS AND SIMULATIONS

In order to evaluate the change in airtightness due to drying of the wooden construction, a newly constructed building (school, required  $q_{50} \leq 0.2 \text{ l/m}^2\text{s}$ ) with wooden frames was followed from completion and 1.5 years. The results are shown in Figure 11. The initial air permeability was  $0.21 \text{ l/m}^2\text{s}$  and the final air permeability  $0.25 \text{ l/m}^2\text{s}$ , an increase of almost 20%. The measurement performed on the 7<sup>th</sup> of August is performed at very high outdoor ( $27^\circ\text{C}$ ) and indoor temperatures ( $24^\circ\text{C}$ ) and in the middle of a heat wave in Sweden, this might have resulted in thermal expansion of parts of the thermal envelope. The relative humidity indoor is approximately the same as the measurement in June. Previous work (Wahlgren, 2014) has shown seasonal variations in wooden buildings of almost 10%.

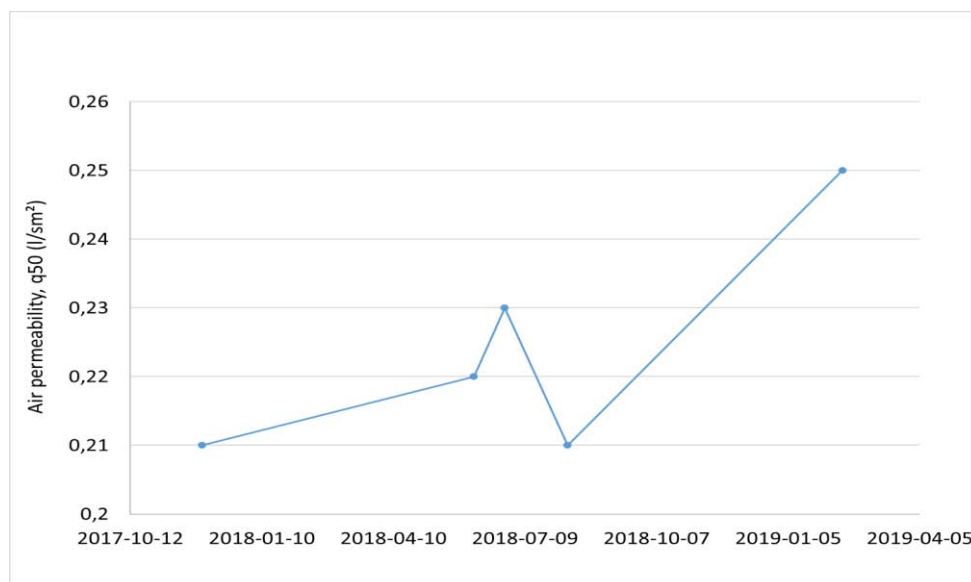


Figure 11: Measured air permeability from completion of building.



## 7 CONSEQUENCES

The impact of varying airtightness on energy use, moisture safety and transport of contaminants through the thermal envelope have previously been investigated and is discussed in for example Domhagen (2016), Domhagen et al. (2017 a) and Domhagen et al. (2017 b). There is also an impact on the heat exchange in the building, both on the heat exchanger efficiency, and because of air passing through the thermal envelope instead of through the heat exchanger.

The heat exchanger reduces the energy use in dwellings by using the exhaust ventilation air to preheat the supply air. In Sweden a common praxis is to adjust the supply ventilation flow to 90% of the exhaust ventilation flow. This causes a negative indoor pressure typically a few pascals. The purpose of the negative pressure is to reduce leakage of air from the interior to exterior and lower the risk of condensation inside the construction, such as the previous example with the attic hatch. The drawback however, is that the imbalance between supply and exhaust fans increases the air infiltration through the thermal envelope so that less air passes through the heat exchanger.

To investigate this phenomenon a dwelling with a heat exchanger is simulated. The building is a two storey building with a floor area of 180 m<sup>2</sup>. Simulation is carried out for a calm day (no wind) with an indoor air temperature of 20°C and outdoor air temperature of -4°C. Results show that if the air permeability increases from 0,2 to 0,6 l/s at 50 Pa, the efficiency of the heat exchanger increases with 1,2%. If the airtightness increased from 0,6 to 1,2 the efficiency of the heat exchanger increases with 0,08%. Thus, the effect on the efficiency of the heat exchanger is not very large. However, the airflow imbalance also affects the air infiltration. For the two cases the infiltration increased from 6,6 l/s to 14,7 l/s (122%) and from 14,7 l/s to 25,8 l/s (75%), this would require extra heating of 233 W and 320 W respectively.

## 8 CONCLUSIONS

Investigations have been made of the impact of moisture on the air leakage in light weight wooden houses and in cross laminated timber (CLT). Both seasonal moisture variations (summer/winter) and the initial drying of a building is studied. Field measurement at a production site of prefabricated light-weight wooden buildings resulted in a maximum moisture content in wood of 16.5%.

For estimation of dimensional changes in CLT buildings and in light-weight buildings a worse case of 25% moisture content was used. These calculations resulted in gaps due to shrinking of several centimeters. Resulting air flows were calculated both for fan pressurization tests ( $\Delta P=50$  Pa) and for normal usage ( $\Delta P_{est}=4$  Pa) showing the necessity to properly seal all leakages. In many cases, taping is used to seal such gaps, unfortunately, the durability of the tape is sometimes not enough to ensure good airtightness for a longer time. Also, the craftsmanship and surrounding circumstances such as dust and moisture may affect the performance of the tape.

Several full-scale measurements of the airtightness of a newly built light-weight building have been performed for 1.5 years. During this time, the airtightness increased from 0.21 to 0.25 l/m<sup>2</sup>s (almost 20% increase). The consequence of a decrease in air permeability is a slight increase in the efficiency of the heat exchanger and, at the same time, a much larger imbalance in the air flows through the thermal envelope, resulting in an increase in air infiltration to the building (more than 100% increase is shown).

## 9 ACKNOWLEDGEMENTS

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