Air leakage levels in timber frame building envelope joints

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ABSTRACT

Air leakage levels from eight joints that use different tightening solutions for a prefabricated timber frame building envelope were measured under laboratory conditions. Air tightness levels in field conditions were also studied by using houses that have already been built.

Joints in the external wall with an inserted floor and separating walls, as well as in the external corner of walls, all showed the largest levels of air leakage. The lowest air leakage levels were recorded in the joint between the external wall and the window.

Tightening up the external weather barrier significantly improved the air tightness levels of the joints. Using self-adhesive tape in tightening up the air-vapour barrier and the weathering barrier seems to be the most promising solution when it comes to guaranteeing the air tightness of wooden-framed structures.

The difference between air leakage levels as measured in field conditions and those which were calculated based on laboratory measurements was noticeably large. This was caused mainly by workmanship quality levels on the construction site sealing the building envelope’s joints and the fact that there were other leakage places in addition to the typical joints that were studied. Improved research, development, design, construction, and supervision are needed to fulfil airtightness requirements in future construction when it comes to producing nearly Zero Energy Buildings (nZEB).

In order to be able to estimate the airtightness levels of a building in the design phase a larger database is needed, with different combinations made available in terms of joints, materials, and workmanship.

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1. Introduction

Air leakage is an important aspect of a building, which influence energy use [1–4], the hygrothermal performance of the building envelope [5–7], indoor air quality [8–10], air pressure conditions over the building envelope [11,12], the performance of natural ventilation [13], and fire safety [14]. The critical influencing factors of air leakage of the building envelope are building management and the methods used in that management process, dwelling type [15,16], the age of the building [17], and the number of stories within the building [17,18]. Two main parameters are required in order to guarantee the air tightness of the whole building: a durable air barrier and its connectivity to other building components.

The location of the air barrier could vary depending on the design solution being used. It can be located either in the interior or exterior surface of the building envelope. The air barrier could be the insulation or the load bearing structures themselves. In cold climates the traditional solution has been to use vapour barrier as an air barrier in a timber-framed building envelope [18–20].

Tightening up and sealing air barrier joints is as important in guaranteeing the airtightness levels of the whole building as the material used in the air barrier itself, because air leakage usually occurs in the building envelope’s connections. Relander et al. [21] concluded in their review about airtightness estimations that component leakage methods could be a possible estimation method, but the AIVC [22] and other [23] component leakage databases are rather old and the results are very sensitive to workmanship quality. This could be the reason why this methodology is questionable for Mediterranean countries [24]. The influence of the sealing and tightening method on air leakage has later been studied for its connection to structural floors [25], basement walls [26,27], chimneys [28], and windows [29,30]. Measuring the air leakage rate before signing off a new building for use has become more and more part of common practice. If the air leakage test at the final stage of construction shows too large an air leakage, then repairing the leakage is very expensive and it can be very difficult to reach the

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required target. Therefore, information about air leakage from
different building envelope joints is very important when it comes
to understanding and proofing performance, as well as guaran-
teeing the realisation of future nearly Zero Energy Buildings (nZEB).

In this study, typical timber-frame external wall connections to
other building envelope parts were studied under laboratory con-
ditions in order to understand tightness performance levels, and
also to be able to get information about air leakage values in joints
that utilise different tightening and sealing solutions. In order to be
able to see the influence of workmanship and the performance of
studied joints in reality, the full air leakage rates of houses which
used the same jointing methods were measured on site.

2. Methods

2.1. Laboratory measurements

Measurements of the air leakage from building envelope joints
were conducted under laboratory conditions, based on the EN
12114 standard [31]. Air leakage test equipment (Fig. 1) consists of
the following:

- Hermetic chamber (plywood with 0.5 mm steel plate) with the
test area at a width of 1360 mm, a height of 2260 mm, and a
depth of 900 mm.
- Fan (Elmo Rietschle G-BH1, positive pressure difference
≤100 kPa, negative pressure difference ≤90 kPa, air flow
50–2450 m³/h) for creating air flow; frequency converter
(EATON DC1-S24DNN-A20N) to regulate air flow.
- Air flow calibrator (Dwyer: GFC 1109 for 0–5 l/min, GFC 1131 for
0–30 l/min, GFC 1144 for 0–500 l/min, with an accuracy of
±1.5%).
- Differential manometer (Produal PEL-DK for 0–1000Pa and
Dwyer Magnesense MS for 0–100 Pa, with an accuracy of ±1%)
for pressure difference measurements.
- Temperature and relative humidity sensor (Rotronic HygroClip
SC05).
- Data-logger (Grant Squirrel SQ2010, 8 channels) for automatic
and simultaneous data reading and saving.

Air leakage measurements were conducted at different air
pressure differences, depending on the individual test, of up to
±600 Pa together with three pressure pulses (Fig. 2, left) according
to EN 12114 standard. The air flow rate and static air pressure
differences were measured and recorded at each step automatic-
ally. The relation between the pressure difference and the airflow
through the building envelope (Fig. 2, right) allowed the results to
be presented using the power law (Eq (1)):

\[
\dot{V} = C \cdot \Delta P^{n}, \text{ m}^3/\text{h}
\]  

(1)

Where \(\dot{V} [\text{ m}^3/\text{h}]\) is the airflow, \(\Delta P\) is the air pressure difference [Pa], and \(C [\text{ m}^3/(\text{h Pa}^n)]\) and \(n [-]\) are constants obtained from curve
fitting, with \(n\) ranging from 0.5 to 1.

By knowing the characteristics of all air leakages (joints from i to
x and building envelope parts from j to y), it is possible to estimate
future air leakage across the whole building (Eq (2)):

\[
\sum \dot{V} = \sum_{\text{joint } i} C_i \cdot \Delta P_{i}^{n_i} + \sum_{\text{joint } x} C_x \cdot \Delta P_{x}^{n_x} + \sum_{\text{building envelope } j} C_j \cdot \Delta P_{j}^{n_j} + \sum_{\text{building envelope } y} C_y \cdot \Delta P_{y}^{n_y}
\]

(2)

2.2. Structures studied

Timber-framed external wall connections with other building
envelope parts were subject to current measurements. The external
wall (\(U = 0.17 \text{ W/(m}^2\text{K)}\) was fully insulated with 240 mm
(195 mm + 45 mm) mineral wool. In order to regulate the moisture
diffusion a vapour barrier (plastic sheet) was installed on the inner
part of the insulation (45 mm from the internal side of the insu-
lation), for the external walls that were studied. The vapour barrier
also functioned as an air barrier. The external side of the insulation
was covered with a wind barrier (9 mm gypsum board) and a
weathering membrane. As both of them have some level of air
resistance, they also provide the sole means of ensuring airtight-
ness in the joint. The building envelope joints that were studied
(Fig. 4, Fig. 3) were selected based on the field study [18] as the
most typical examples:

- The external wall joint with the external wall (EW/EW): 1 -
  without a taped weathering membrane; 2 - with a taped
  weathering membrane; the air-vapour barrier was installed
  with an overlap in both cases;
2.3. Field measurements

In addition to laboratory measurements, a study was conducted about how airtight houses will be when they use tested joints in the building envelope. The air tightness of five buildings was measured with the standardised fan pressurisation method, using the ‘Minneapolis Blower Door Model 4’ equipment with an automated performance testing system (a flow range at 50 Pa 25 m³/h - 7.800 m³/h, with an accuracy of ±3%). Pressurising and depressurising tests were conducted with closed windows and doors and sealed ventilation ducts and chimneys.

In order to determine typical air leakage locations and their distribution, an infrared image camera FLIR Systems E320 (sensitivity 0.1 °C, accuracy 2% or 2 °C, measurement range: ~20 °C–500 °C) following EN 13187 standard [33] and a smoke detector were used. These methods were also used in previous studies [18,34–37]. All of the thermography tests were carried out later in the year, during the winter period, with an air temperature difference between indoors and outdoors of at least 20 K. Thermography investigations were carried out twice. The first time was to determine the normal situation, with surface temperature measurements being carried out without any additional pressure difference. Next, in order to determine the main air leakage locations, a pressure of 50 Pa negative under the envelope was set using fan pressurisation equipment. After the infiltration airflow had cooled the inner surface of the envelope (which took about 30 min), the surface temperatures were measured using the infrared image camera from the inside of the building.

The temperature factor was used to assess and classify air leakages under normal building conditions. The temperature factor for the internal surface (t\text{int} °C) depends on the air temperature indoors (t\text{in} °C) and outdoors (t\text{out} °C) and on the temperature on the internal surface of the building envelope (t\text{int} °C), see Eq. (3).
Fig. 4. Building envelope joints being studied (joints in the upper two rows present vertical sections, other horizontal sections), dimensions in mm.
The relative decrease in the internal surface temperature $\Delta t_{si}$, % was used to determine and classify air leakage locations. The relative decrease in the surface temperature shows the relation in the difference between the air temperature indoors ($t_i, ^\circ C$) and outdoors ($t_e, ^\circ C$) and the temperature difference between the internal surface of the building envelope, which was measured prior to ($t_{s.i1}, ^\circ C$) and following ($t_{s.i2}, ^\circ C$) depressurisation (see Eq. (4)).

$$\Delta t_{si} = \frac{t_{s.i1} - t_{s.i2}}{t_i - t_e} \times 100\%$$

### 3. Results

#### 3.1. Laboratory measurements

Air leakage levels for a total of eight joints in the timber-framed building envelope were measured in the laboratory. Of the total measured air leakage, the minor air leakage between the measuring chamber (measured separately at the beginning of the study) and the joint being studied was subtracted from the results and the remaining air leakage level was divided by the length of the joint being studied. The air leakage results are presented in Table 1 at an air pressure difference ±4 Pa and ±50 Pa. Fig. 6 presents variations in the maximum and minimum readings (negative and positive pressure), and the average air leakage in the joints studied at an air pressure difference of 50 Pa.

The smallest air leakage reading was at the joint between the external wall and the window. If the wooden window with its aluminium external frame is tightened with tape from aluminium frame (EW/W-2), leakages will remain between the frames and the joint will be ‘leakier’ when compared to tightening with tape from wooden frame (EW/W-1).

The largest air leakage reading came from the corners of the external walls. In this joint, taping up the internal air and vapour barrier is difficult to do if prefabricated wall panels are used with interior finishing. In this case, taping the external weather barrier (EW/EW-2) significantly improves the joint’s air tightness levels.

The external wall joint with the inserted floor and the separating wall showed one of the largest air leakage readings under laboratory conditions. This showed that an airtight weather membrane is needed - (EW/IF-1&2; EW/SWA-1&4) as without this (EW/IF-3&4; EW/SWA-2&3) air leakage readings are much higher. Taping up the internal air and vapour barrier (EW/IF-2&3; EW/SWA-3&4) only had a smaller influence on air tightness levels because two beams at the end of inserted wall (EW/IF-1&4; EW/SWA-1&2) already exhibited sufficient air tightness readings.

Using taping (EW/BF-2) or fastening with slats (EW/BF-3) for the external weathering barrier and the internal air and vapour barrier

<table>
<thead>
<tr>
<th>Building envelope joint</th>
<th>Air leakage rate, l/(min m)</th>
<th>Positive pressure indoors</th>
<th>Negative pressure indoors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4Pa</td>
<td>-4Pa</td>
<td>10Pa</td>
</tr>
<tr>
<td>EW/EW-1</td>
<td>2.6</td>
<td>3.2</td>
<td>5.8</td>
</tr>
<tr>
<td>EW/EW-2</td>
<td>2.3</td>
<td>1.9</td>
<td>4.6</td>
</tr>
<tr>
<td>EW/BF-1</td>
<td>0.6</td>
<td>0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>EW/BF-2</td>
<td>0.4</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>EW/IF-1</td>
<td>0.9</td>
<td>1.1</td>
<td>2.0</td>
</tr>
<tr>
<td>EW/IF-2</td>
<td>1.1</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>EW/IF-3</td>
<td>3.2</td>
<td>4.5</td>
<td>7.2</td>
</tr>
<tr>
<td>EW/IF-4</td>
<td>4.0</td>
<td>4.5</td>
<td>10.2</td>
</tr>
<tr>
<td>EW/SWA-1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>EW/SWA-2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>EW/SWA-3</td>
<td>1.5</td>
<td>1.8</td>
<td>2.7</td>
</tr>
<tr>
<td>EW/SWA-4</td>
<td>1.3</td>
<td>1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>EW/SWB</td>
<td>1.4</td>
<td>1.2</td>
<td>3.1</td>
</tr>
<tr>
<td>EW/R</td>
<td>1.5</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>R/R</td>
<td>0.8</td>
<td>0.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Fig. 5. Examples of different tightening methods in connection with the external wall and inserted floor, EW/IF, dimensions in mm.
when sealing them against the foundations is important for the joint at the external wall and the floor base. If this was not carried out (EW/BF-1) then the air leakage reading was much higher. Testing this joint with a smoke test showed a leakage between the concrete foundation and the wall’s lower beam that could be the result of roughness or the curvature of the lower beam. Guaranteeing a building’s airtightness may also serve to set out a much higher quality level for the building’s basic construction work and materials.

3.2. Field measurements

3.2.1. Air leakage rate

In order to see the difference between air leakage in field conditions (involving tightening in field conditions) and in the laboratory (using the best possible tightening), the air leakage rate of four timber-framed houses (which were constructed by the same company), with similar building envelope solutions which were studied in laboratory conditions, was measured under field conditions.

The average airtightness levels of four houses that were measured (\( q_{50} = 3.1 \text{ m}^3/(\text{h} \cdot \text{m}^2) \), Table 2, left-hand columns with data) were far from suitable for a nZEB or for Passive House requirements. Nevertheless, they do represent rather well the current average condition [18,20]. Small variations in airtightness levels across multiple houses show the current levels of building technology.

Using the area, length, and air leakage rate of the building envelope’s parts and joints, the best possible air leakage reading was calculated based on laboratory measurements using Eq. (2) (Table 2, right-hand columns with data).

3.2.2. Air leakage locations

The difference between air leakage which was measured under field conditions and one which was calculated based on laboratory measurements was large. One reason for this was that, in addition to typical joints in a building envelope (studied in the laboratory), additional air leakage points also existed in other two-dimensional (2D, linear) and three-dimensional (leakage locations (3D, point) locations. Figs. 7–9 presents an array of 2D and 3D air leakages in which the air leakage was larger than those for joints which were studied in the laboratory.

4. Discussion

The use of air tight adhesive tape seems to be one of the most reliable and robust tightening solutions available for windows, as air leakage readings where taping was used were much lower than Van Den Bossche et al. [29] found with other tightening solutions. Field measurements have shown that air leakage levels through the joint between the window and the external wall is one of the most typical leakage points [37]. Therefore long-term airtightness must also be guaranteed. A common standard at the European or international level is needed so that all of the requirements can be set

<table>
<thead>
<tr>
<th>House</th>
<th>Air leakage rate at 50 Pa ( q_{50} \text{ m}^3/(\text{h} \cdot \text{m}^2) )</th>
<th>Air change rate at 50 Pa ( n_{50} \text{ m}^3/(\text{h} \cdot \text{m}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field measurement</td>
<td>Calculated based on lab.</td>
</tr>
<tr>
<td>House K (two-storey, net area 204 m², internal volume: 601 m³, envelopes area 560 m²)</td>
<td>3.2 0.33</td>
<td>3.0 0.30</td>
</tr>
<tr>
<td>House L (two-storey, net area 190 m², internal volume: 539 m³, envelopes area 457 m²)</td>
<td>3.8 0.39</td>
<td>3.2 0.32</td>
</tr>
<tr>
<td>House P (two-storey, net area 190 m², internal volume: 418 m³, envelopes area 391 m²)</td>
<td>2.2 0.34</td>
<td>2.0 0.29</td>
</tr>
<tr>
<td>House V (two-storey, net area 115 m², internal volume: 291 m³, envelopes area 285 m²)</td>
<td>3.3 0.37</td>
<td>3.2 0.37</td>
</tr>
</tbody>
</table>
out officially (adhesion properties, long-term durability, tear resistance, elongation, etc.) where airtight adhesive tapes are used for a building’s airtightness levels.

The airtightness problem for the joints of the external wall and the inserted floor has also shown up in field measurements [18,37]. Tightening up that joint is difficult because the inserted floor or separating walls cause a break in the internal air and vapour barrier. Therefore an airtight weather membrane helps significantly when it comes to decreasing air leakage levels. The same result was found by Relander et al. [25]. On the other hand, Langmans et al. [38] have shown that when the air barrier is located on the exterior of a building instead of on the interior as is traditional, the moisture load may increase as a result of buoyancy-driven convection, leading to an increased risk of mould growth and interstitial condensation against the upper position of the exterior sheathing in winter conditions.

The airtightness levels of those walls that have been studied was guaranteed with airtight foil materials: an air-vapour barrier and a weathering barrier based on current construction practice. In addition, an airtight board (which is orientated strand board or cross-laminated timber) could be the solution for guaranteeing airtightness levels. Strong airtight boards are much better when it comes to making a joint airtight when self-adhesive tape is used in addition. Eykens et al. [39] showed a large variation in air permeability levels for the different OSB brands and questioned the application of OSB as an air barrier system. Further studies are required in order to provide airtight boards with a guaranteed level of airtightness.

Specific heat loss in the building envelope \( (H, W/K) \) depends on the thermal transmittance of the plane building envelope parts \( (U, W/(m^2 \cdot K)) \), the linear thermal transmittance of joints \( (\Psi, W/(m \cdot K)) \), the point thermal transmittance in local discontinuance of insulation \( (\chi, W/K) \), and air infiltration. First of all, the parameters are calculable during the design phase. One of the purposes of the current study was to test how accurately air leakage levels can be calculated when different leakage characteristics are known. The
current study showed that in the case of air leakage in real houses as measured in field conditions, the readings could be six to ten times higher than those estimated based on laboratory tests (which used joints that were tightened to an optimum level). Also, Pereira et al. [24] showed that it is difficult to achieve the same air leakage levels for in situ tests when compared to those which have been achieved in the laboratory - more set-ups should be created. Nevertheless, in our study the difference was smaller than that shown by Pereira et al. [24] (35 times larger in field conditions). Field measurements showed that in addition to typical joints in the building envelope (which were studied in the laboratory) other two-dimensional and three-dimensional air leakage locations also existed where the air leakage readings were larger than through those joints that had been studied in the laboratory. Field measurements showed different air leakage in the same joint of the building envelope. Therefore a larger database is required, one that contains different joint options and different material and workmanship combinations.

A comparison of air leakage readings as measured in field conditions and those calculated based on laboratory measurements showed significant differences. This underlines the importance of working quality in field conditions. The better training of workers and better supervision is required in order to be able to gain improved airtightness levels in the building envelope. Josephson and Hammarlund [40] showed that approximately 45% of defects in construction originated from site works (in relation to site management, the workers, and also the sub-contractors). As 32% of defect costs originated in the early phases (in relation to the client and the design), a better design is needed, especially in the early stages of design (regarding the selection of materials for the airtight layer). Current design, construction, and supervision methods may not be appropriate for future nZEB.

Field measurements showed that air leakage rates ($q_{50} = 3.1 \text{m}^3/(\text{h} \cdot \text{m}^2)$) were lower than the airtightness base value in energy calculation methods in Estonia ($q_{50} = 6 \text{m}^3/(\text{h} \cdot \text{m}^2)$). Also, the variation in different measurements was small. This shows that if the building company follows its internal quality procedure, the results will be similar and repeatable.

5. Conclusions

The air leakage levels for eight joints which used different tightening solutions in the prefabricated timber-framed building envelope were measured under laboratory conditions. The air tightness levels of four real, fully-constructed houses were measured under field conditions.

The joints between the external wall and the inserted floor and separating walls, as well as in the external corner of the walls, where the internal air and vapour barrier is discontinued, showed the largest air leakage readings. The smallest air leakage reading was at the joint between the external wall and the window.

Using self-adhesive tape in tightening the air-vapour barrier and the weathering barrier seems to be the most promising solution when it comes to guaranteeing the airtightness levels of wooden-framed structures. A common standard is required to set out the requirements for airtight adhesive tapes used in building airtightness.

The difference between air leakage levels as measured under field conditions and those calculated based on laboratory measurements was large. The two main reasons for that difference are workmanship quality and the fact that in addition to those typical joints, measured in laboratory, other two-dimensional and three-dimensional leakage places (for example plumbing penetrations, electrical service penetrations, connections between spaces outside etc.) also existed in which the air leakage readings were higher than those taken through the joints that were studied in the laboratory. Therefore a larger database is required with different joints and different material and workmanship combinations included.

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