

Air leakage paths in buildings: Typical locations and implications for the air change rate

Lars Gullbrekken^{1*}, Nora Schjøth Bunkholt¹, Stig Geving² and Petra Rütter¹

¹SINTEF Community, 7046 Trondheim, Norway

²Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, 7491 Trondheim, Norway

Abstract. The harsh Norwegian climate requires buildings designed to high standards. An airtight building envelope is crucial to achieve an energy efficient building and to avoid moisture problems. Results from the SINTEF Building defects archive show that a considerable part of the building defects is related to air leakages. In addition, air leakages increase the energy demand of buildings. A literature study has been conducted in order to map typical air leakage paths of Norwegian wooden houses. In order to increase the performance, different sealing methods including the use of tape has been reviewed. The results show that the most common air leakages reported from field measurements in the literature are in the connections between external wall and ceiling or floor, external wall and window or door, and external wall and penetrations in the barrier layers. Results from laboratory investigations showed that the traditional solutions can be further improved by introduction of modern foil materials in combination with sealing tapes. However, questions can be raised regarding the necessity of tape sealing all available joints.

1 Introduction

In light weight building structures in Europe the vapour barrier is commonly used to ensure an airtight building envelope [1]. However, it is labour intensive to assure the airtightness because of the joints, intersections and penetrations for electrical and plumbing services [2, 3].

In order to avoid extra heat loss through the insulation layer due to both natural and forced convection, an airtight wind barrier should cover the cold face of the insulation. In addition, the function of the wind barrier includes avoiding water intrusion into the structure [4]. The harsh Norwegian climate requires buildings designed according to high standards. An airtight building envelope is crucial to achieve an energy efficient building and to avoid moisture problems. Hence, Norway has a long tradition of obtaining the airtightness of the building envelope by using both an airtight wind barrier and an airtight vapour barrier [5, 6].

The requirements for airtightness in the Norwegian building regulations were strengthened in 2017, from 2.5 air changes per hour (n_{50}), measured at 50 Pa pressure difference, for residential buildings and 1.5 for other buildings, to 0.6 for all buildings [7]. Relander et al. [8] have shown that improving the airtightness of a residential building from the previous requirement to the present one can result in an energy saving of approximately 20 kWh/m² per year. Considering that the average total energy consumption of a Norwegian household is 185 kWh/m² per year this adds up to a substantial potential for energy savings.

During many years of laboratory testing, SINTEF has experienced that the air permeability of the wind and vapour barrier materials is very low. Air leakages through building envelopes is associated to joints in the materials, intersections between building components and penetrations through the wind and vapour barrier. Carrié et al. [9] have performed a comprehensive investigation of typical air leakage paths in both lightweight timber constructions and more heavy brick constructions. Hence, the locations of air leakages are well known in the literature. Furthermore, Prignon et al. [10] developed a method to understand air displacements at weak spots using PIG-charts which is a graph presenting the airflow against an important parameter. However, the contribution of different air leakages on the air change rate of a building is not studied in detail. Traditionally, the overlaps and connections of the air-tightening system to other building components like windows, foundations, roof constructions, and air and electric ducts, were performed by clamping a wooden batten or board material to the wind- or vapour barrier layer. However, given the stricter requirements regarding airtightness of buildings, recent field and laboratory measurements are questioning if these solutions can guarantee the airtightness of a building. A promising solution seems to be the application of self-adhesive tapes [11-13].

As the use of adhesive products for securing satisfactory airtightness of the building envelope is a relatively new application, there is a substantial lack of knowledge regarding prediction of both initial and long-term performance, especially for exterior applications [14, 15]. Guidelines regarding which joints are necessary to

* Corresponding author: lars.gullbrekken@sintef.no

further improve by tape and which solutions can have sufficient performance by use of clamped joints only are required. Furthermore, the discrepancy between air leakage rates measured in field conditions and in laboratory measurements is considerable [12], which further emphasizes the need for more accurate evaluation methods.

The aim of this study, carried out as a scoping literature review, is to gain information on typical air leakage paths in small and large building structures. Important objectives are:

- identify critical building component connections.
- identify if tape is a possible sealing method and evaluate the airtightness-performance of taped joints.
- provide recommendations regarding sealing methods and possible future laboratory measurements.

2 Method

The literature review conducted in the present study is based on a research methodology [16] that aims to ensure transparency and reproducibility of the research process. The methodology was originally developed in the field of social sciences, but its principles are applicable to other research fields. The literature review was carried out as a scoping study, as defined by [17].

The first step of the review process involved outlining the scope of the research in order to focus the research question of the study [16]. This helped defining key concepts of the research process and facilitated the definition of search terms. In addition, the scope provided the inclusion criteria of the research.

The PICOC framework [18] was used to define the key concepts of the research process, as given in Table 1. The resulting research question is: "What are typical air leakages affecting the airtightness of buildings, and in what ways can they be improved?".

Table 1. The PICOC framework.

Population	Buildings
Intervention	Typical air leakage places, critical connections
Comparison	Comparison of different ways to improve critical connections
Outcomes	Measurement of air leakage/impact of air leakage on airtightness/improvement of air leakage
Context	Unintended air leakages through specific connections in building envelopes. Primary focus on buildings in Nordic climate and Nordic building traditions, but other studies may be considered if the results are relevant to the setting. Both large and small structures as well as all construction methods are included.

The keywords applied in searches were defined based on titles and keywords found in the literature [2, 3, 8, 19-25] resulting from a preliminary screening using the databases Scopus and Oria. The keywords, Boolean operators and nesting combinations that were used are

presented in Table 2. The keywords were applied at title – keywords – abstract level in the searches.

The exclusion criteria used in evaluation of the literature is shown in Table 3. The search scheme and number of publications identified in each step of the review process is presented in Table 4. In the final screening (database search), the databases Scopus, Engineering Village and Web of Science were used. The last search was performed 25.11.2019.

In order to look for additional sources, literature screening based on citation searching (snowballing) [16] and author searching was performed. The final number of publications included in the study was 12 (Table 4).

Table 2. Keywords, Boolean operators and nesting combinations used in the database search.

Population	Intervention (AND)	Outcome (AND)
building OR house	joint* OR junction OR connection OR intersection OR air leakage path OR air leakage place	airtightness OR air leakage OR air change OR air infiltration OR air permeability OR

Table 3. Exclusion criteria used in evaluation of the literature.

Exclusion	Method	What is excluded
1 st	Qualitative based on type of literature	Literature other than English articles, reviews, proceeding papers, books (chapters), reports, theses
2 nd	Qualitative based on title and keywords	Literature not discussing unintended air leakages at specific leakage places in the building envelope, e.g. articles treating airtightness of a building in general
3 rd	Qualitative based on abstract	
4 th	Qualitative based on full article	

Table 4. Search scheme. Number of publications identified in each step is presented.

	Scopus	Web of Science	Engineering Village
First search	161	76	238
After 1 st exclusion	141	72	214
All results	427		
Duplicates removed	248		
After 2 nd exclusion	65		
After 3 rd exclusion	31		
Full text availability	16		
After 4 th exclusion	7		
After citation and author searching	12		

3 Results and discussion

3.1 Typical air leakages

Table 5 summarises studies that have investigated the localizations of air leakages in buildings through field measurements of building air change rate. The studies included in the table are carried out in buildings and climates that are equal or similar to that in Norway. Table 6 presents laboratory measurements of air leakage rates of

specific joints in the building envelope. The results are given in $Cn50$ (h^{-1}) which is the contribution from unitary joint leakage to n_{50} . Some of the studies [8, 12, 22, 23] have also aimed at investigating the effect of different sealing methods. The results show that the most common air leakage location is in the connection between external walls and floors/ceilings. In addition, the joint between windows and external walls and penetrations in the barrier layers (e.g. due to electrical installations, chimneys etc.) are mentioned as the most typical leakage locations.

Table 5. Field measurements of building airtightness and location of air leakages. Numbers in parentheses indicates number of buildings. The typical air leakages listed are the most frequent leakages reported in the literature. Other leakage locations may have been mentioned in the studies. DSF = detached single-family house, SD = semi-detached house, A = apartment.

Reference	[26]	[27]	[2]	[28], [29]	[3]
Country	Norway	Norway	Estonia	Denmark	Finland
Year	1980	2009	2007	2016–2017	2008
Number of buildings	14 + 6	19	32	16	21 + 16
Age of buildings	1-5 years	Year of construction: 1986-2000	2-3 years	Year of construction: 1880-2007	1-13 years
Type of building	DSF (14) and AB (6)	DSF (10) and SD (9)	DSF	DSF	DSF (21) and A (16)
Construction	DSF: wood-frame A: wood/steel-frame + concrete intermediate constructions	Wood-frame	Lightweight wood-frame (29) or steel-frame (3)	Mainly brick	DSF: wood-frame, brick or concrete (various, e.g. blocks or LECA blocks) A: timber-frame or concrete block
Method	Thermography at $\Delta P = -50$ Pa	Review of existing thermograms	Thermography at $\Delta P = 0$ and $\Delta P = -50$ Pa	Thermography at $\Delta P = -25$ – 80 Pa	Thermography at $\Delta P = 0$ and $\Delta P = -50$ Pa
Airtightness	DSF: $n_{50m} = 3.2$ – 7.7 h^{-1} (avg. 5.6 h^{-1}) A: $n_{50m} = 1.3$ – 1.5 h^{-1} (avg. 1.4 h^{-1})	DSF: $n_{50m} = 2.5$ – 10.7 h^{-1} (avg 6 h^{-1}) SD: $n_{50m} = 3.1$ – 7.4 h^{-1} (avg 4.82 h^{-1})	$n_{50} = 0.7$ – 13.6 h^{-1} (avg. 4.9 h^{-1})	$q_{F50} = 1.1$ – 5.8 $l/(s \cdot m^2)$	$n_{50} = 0.7$ – 8.1 h^{-1} (avg. 3.2 h^{-1})
Typical air leakages	DSF: Ext. wall – ceiling Int. wall – ceiling Ext. wall – floor Ext. wall – window/door A: Ext. wall – ceiling Ext. wall – floor Ext. wall – window/door	* Ext. wall – ceiling Through ceiling Ext. wall – floor Penetrations Int. wall – ceiling Ext. wall – window/door	Ext. wall – ceiling/floor Ext. wall – int. wall Int. wall – roof Penetrations Ext. wall – window/door	Penetrations Ext. wall – window/door Ext. wall – ceiling/floor	DSF: Ext. wall – roof Ext. wall – window/door Ext. wall – ceiling/floor Penetrations Ext. wall – base floor A: Ext. wall – window/door Ext. wall – ceiling/floor Ext. wall – roof Penetrations

*Critical connections. Based on complaint cases, i.e. not representative for the Norwegian building stock

Table 6. Laboratory measurements on air leakage of specific joints in the building envelope and calculated C_{n50} (h^{-1}) (the contribution from unitary joint leakage to n_{50}) depending on sealing method.

	Air change rate C_{n50} (h^{-1})			
Reference	[12]	[22]	[23]	[8]
Ext. wall – floor base -without sealing between sill and concrete -with sill membrane sealing between sill and concrete -continuous wind and vapour barrier- taped joints	0.00002		0.13-1.35 0.01-0.18	
Ext. wall – structural floor (floor/ceiling) -without wind barrier -with rolled wind barrier and clamped joints - continuous wind and vapour barrier- taped joints	0.00012	2-3.5 0.03-0.05		
Ext. wall – window PU-foam/Mastiff Sealed with taped joints	0.00001			0.014

3.2 Influence of air leakages on the airtightness of reference buildings

The contribution made to C_{n50} is estimated when the length of the air leakage paths e.g. perimeter of basement wall, and the volume V (m^3) of the different reference buildings are known, see Table 6. In this case it is useful to compare the influence on the n_{50} of the different specific joints. There are different reference houses in the different studies. Mutual among the houses are that they are single family houses with wood frame constructions and concrete floors with two or three floors and a heated floor area from 150-230 m^2 . The results are evaluated in relation to the current demands in the Norwegian building requirements (TEK17) [7]: $n_{50}=0.6 h^{-1}$.

3.3 Critical building component connections

Table 5 shows results from field measurements of building airtightness performed in Norway, Estonia, Finland and Denmark. Typical air leakage paths reported in these studies included the joints external wall-ceiling and external wall-window [2, 3, 26-29]. In addition, external wall-floor was reported by [2, 26-29]. Air leakages through penetrations is also a typical air leakage path and was reported by [2, 3, 27-29].

3.3.1 Ext. wall – intermediate floor

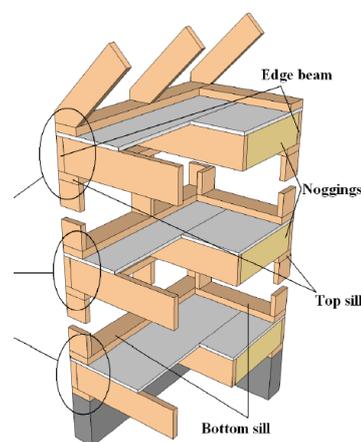


Fig 1. Visualisation of the ext. wall – intermediate floor construction [8] Circles indicate location of air leakages.

The laboratory measurements performed by Relander et al. [22] showed that it was difficult to achieve a low air leakage by use of the vapour barrier alone. This is due to practical challenges related to beams and sheeting materials penetrating the vapour barrier, see Figure 1. The airtightness of the joint was remarkably improved by use of a gypsum board as wind barrier. The results were further improved by adding a rolled wind barrier with joints clamped by wood battens. Vertically and horizontally rolled wind barriers without gypsum boards were found to be just as good. The laboratory measurements performed by Relander et al. [22] showed that it is possible to construct very airtight intermediate floors with negligible contribution to the total air leakages of a wood-frame house. Further, a more recent laboratory study performed by Kalamees et al. [12], showed that by using continuous wind barrier on the wall and taped joints in the vapour barrier the measured airtightness was in the magnitude of 1000 times smaller compared to the measurements by Relander et al. [22]. This is an indication that by use of modern building materials including sealing tapes and thorough workmanship, it is

possible to construct structural floors which are close to completely airtight.

3.3.2 Ext. wall – base floor

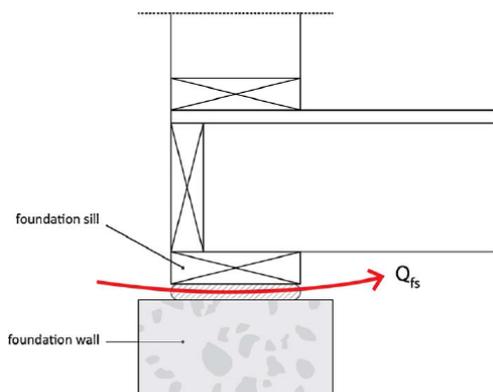


Fig. 2. The structure of the joint between the basement wall and the wood-frame wall [23].

The structure of the joint between the basement wall and the wood-frame wall is shown in Figure 2. Laboratory measurements performed by Relander et al. [23] shows that the airtightness of this joint was dependent on the sealing method in the joint between the bottom sill and the tolerances of flatness of the concrete foundation. The laboratory measurements showed lower air leakages when using sealing materials which were able to seal varying air gaps between the bottom sill and the concrete foundation. In addition, a smooth concrete foundation was positive regarding reducing the air leakage. By using a sill membrane in combination with a level foundation, the influence by this joint on the air change rate of the reference house was very small. The measurements performed by Kalamees et al. [12], was in the magnitude of 1000 times lower compared to the measurements by Relander et al. [22]. Hence, close to completely airtight joints between the wall and concrete foundation seems to be possible by use of modern building materials including sealing tapes.

3.3.3 Ext. wall – window

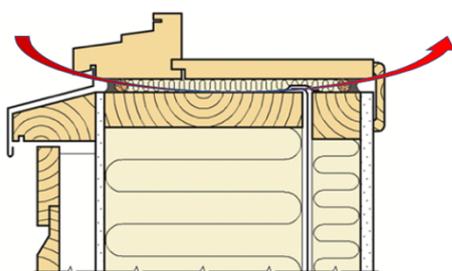


Fig. 3. Visualisation of air leakage path in the joint ext. Wall – window.

A visualisation of a possible air leakage path in the joint between window and wall is shown in Figure 3. According to Relander [8] the airtightness of the window joint is dependent on the sealing method. Thorough

workmanship and use of PU-foam or mastiff can give sufficient results as shown in Table 6. Measurements performed by Kalamees et al. [12] indicated that by using roll materials both for wind and vapor barrier in combination with sealing tapes it is possible to construct nearly completely airtight joints.

3.4 Sealing methods

The laboratory investigations performed by Relander et al. [22, 23] includes use of traditional solutions for sealing joints including clamped joints by battens and use of PU-foam/Mastiff. Results from these studies indicates that in relation to the demands in the building regulation it may not be necessary to further improve the joints by use of sealing tape. A laboratory study performed by Norvik [30] indicated that the air permeability of clamped joints increased by shrinking and swelling of the battens caused by seasonal variation of the indoor air. However, calculations showed that use of ideal dimensions of batten and nails resulted in a small increase in air permeability and hence a small impact on the air change rate of two case buildings. Hence, the question of what joints need to be sealed by tape in order to secure low air permeability is relevant and needs further investigation.

SINTEF's experience from previous laboratory studies indicates that an airtight solution also often has a high rain tightness performance [31]. Given the harsh climate of Norway, it may be reasonable to put extra effort on challenging details such as window joints in order to avoid rain leakages. The airtightness measurements performed on finished buildings reported by Kalamees et al. [12], also indicates that it is difficult in practise to obtain a high-performance result. Regardless of sealing method the results are very much depending on the workmanship performed by the carpenter.

3.5 Recommendations regarding future research

The future research need is related to three main challenges:

- 1) Missing laboratory measurements. We have not been able to find documentation for penetrations such as electrical cables and ventilation ducts.
- 2) The durability of the air leakage performance both for the traditional clamped batten solutions, but also for the newer sealing tape solutions.
- 3) Recommendations regarding the sealing method of different joint types in order to answer the question whether taped joints are necessary to secure low air permeability with high durability.

4 Conclusion

The most common air leakages reported from field measurements in the literature are located in the connections between external wall and ceiling or floor, external wall and window or door, and external wall and penetrations in the barrier layers. Results from laboratory investigations indicate that solutions with wind barrier

foil in combination with clamped joints have a sufficient airtightness performance. However, the results also indicate that the air permeability can be further improved by introduction of sealing tapes. Still, questions can be raised regarding the necessity of tape sealing of all available joints. In order to achieve a high rain tightness performance, taping may be a preferential solution. Further studies are necessary in order to compare and state the durability of the air leakage performance both for the traditional solutions, but also for the newer sealing tape solutions.

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