The distribution of the air leakage places and thermal bridges in Finnish detached houses and apartment buildings

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SUMMARY:
Air leakage path affect infiltration and air pressure conditions in building. The main objectives of this study were to analyse the distribution of the air leakage places and thermal bridges in detached houses and apartment buildings. Field measurements have been carried out in 21 detached houses and 16 apartments during the years 2005-2007. To determine typical air leakages and thermal bridges and their distribution, an infrared image camera and a smoke detector were used during winter period. Temperature factor was used to determine and to classify thermal bridges. Relative decrease of the surface temperature was used to determine and to classify air leakage places. Typical thermal bridges in the studied detached houses were around the doors and windows. Low temperatures were determined also in the junction of the base floor with the external wall. Typical air leakages were in the junction of roof and external wall, penetrations through the air barrier systems, and around and through windows and doors. Typical thermal bridges in the studied apartments were around the doors and windows. Typical air leakages were around and through windows and doors, in the junction of ceiling/floor and external wall, penetrations through the air barrier systems, and walls and floors between apartments.

1. Introduction

The uncontrolled air infiltration is an important factor in a building's energy consumption (Jokisalo et al. 2007) and energy efficiency of a ventilation system (Binamu and Lindberg 2000), especially in cold climate. In well insulated buildings, the infiltration energy loss is a relatively more important factor than in a poorly insulated building. Local moisture convection through the building envelope may cause severe moisture loads imposed on the structure (Ojanen and Kumaran 1992, Hagentoft and Harderup 1996, Kilpelainen et al. 2000, Karagiozis 2002, Janssens and Hens 2003, Derome 2005). Indoor air exfiltration in cold climates may cause moisture accumulation or condensation, leading to the microbial growth on materials, change of the properties of the material or even to structural deterioration. This moisture load due to air leakage may cause moisture accumulation that can be many times more important than the moisture accumulation due to diffusion transport. Air leakage through a building envelope could introduce outdoor or crawl space airborne pollutants (Mattson et al. 2002, Airaksinen et al. 2004) as well radon gas into the indoor air (Nazaroff and Doyle 1985, Kokotti et al. 1994, Ljungquist and Lagerqvist 2005).

Almost all building envelopes have thermal bridges - locations where the thermal resistance of the assembly is locally lower. Thermal bridges are caused mainly by geometrical or structural reasons. In cold climates, the assessment of thermal bridges is important for many reasons. Thermal bridges may lead to surface condensation, mould growth, and staining of surfaces. Due to lower temperatures on the thermal bridge, higher RH occurs. While surface condensation starts at the RH 100%, the limit value for RH in respect of mould growth is above RH 75% to 90% depending on the material (Johansson 2005). Thermal bridges lead to an increase of heat losses. An increase in the thermal insulation level will increase the relative significance of the thermal bridges in the energy consumption of buildings. If large poorly insulated or uninsulated envelope areas exist, the surfaces will be cold in the winter and may cause thermal comfort problems due to cold draughts or radiation (in particular, asymmetric radiation).

The distribution of the air leakage places affects infiltration and air pressure conditions in building. The main objectives of this study were to analyse the distribution of the air leakage places and thermal bridges in detached houses and apartment buildings. Field measurements of the air tightness and thermography measurements have been carried out in 21 detached houses and 16 apartments in Finland.

2. Methods

2.1 Studied dwellings

Analysis of the distribution of the air leakage places and thermal bridges were carried out in 21 detached houses and in 16 apartments in different buildings. Studied dwellings were selected from the databases of national research projects: “Air tightness, indoor climate and energy efficiency of residential buildings” (2005-2008) and “Moisture-proof healthy detached house” (2002-2005). Dwellings in research projects had different structures: 170 detached houses with timber-frame (TF), log (L), light expanded clay aggregate concrete (LECA), autoclaved aerated concrete (AAC), brick, concrete sandwich element (CSE), and concrete block (CB) external walls structures and 56 apartments in buildings with concrete and timber-frame wall structures. Typical base floor was slab on ground (SG) or floor with crawl space (CS). Roof, attic floor or intermediate floors were made with concrete slab (CS) or with timber-frame structure. Dwellings were randomly selected from the databases of the companies manufacturing and building houses. Air leakage and thermal bridge distribution investigations were carried out during winters 2005-2007, allowing the analysis in all representative types of houses in Finland.

Main data of the studied dwellings are shown in tables 1 and 2. In the case of timber-frame envelope, the vapour barrier that controlled water vapour diffusion through the envelope was designed to function also as an air barrier. Brick and block walls were plastered from inside or from both sides.

TABLE 1 The main characteristics of the studied apartments

Code	Constr. year	No. of floors	n_{50}, ach	Vent. air change rate	External wall		Base floor		Roof/ceiling	
					TF	CB	SG	CS	CS	TF
5201	2000	5/7	1.9	0.6		X	X		X	
5202	2000	4/7	4.5	0.61		X	X		X	
5203	2000	1/7	1	0.68		X	X		X	
6601	2006	4/4	0.8	0.5		X	X		X	
6602	2006	2/4	0.4	0.5		X	X		X	
6603	2006	1/4	1.1	0.49		X	X		X	
7101	2006	4/4	3.2	0.45	X					X
7102	2006	4/4	2.9	0.63	X					X
7103	2006	3/4	2.9	0.48	X					X
7104	2006	3/4	3.2	0.28	X					X
7105	2006	2/4	2.2	0.45	X					X
7301	1996	5/5	4.8		X					X
7302	1996	4/5	3.3		X					X
7303	1996	3/5	3.8		X					X
7304	1996	2/5	2.9		X					X
7305	1996	1/5	5.5			X			X	

TABLE 2 The main characteristics of the studied detached houses

Code	Constr. year	No. of floors	n_{50}, ach	Vent. air change rate	External wall							Base floor		Roof/ceiling		
					TF	L	AAC	LECA	B	CB	CSE	SG	CS	CS	AAC	TF
1042	1994	2	3.4	0.32	X								X			X
1047	2002	2	3.5	0.37	X							X				X
2014	2000	2	3.9	0.31	X							X				X
3106	1997	1	8.1			X						X				X
3110	2006	2	3.7	0.19		X						X				X
3114	2005	2	6.9	0.31		X						X				X
3202	2001	2	2.1	0.38			X						X		X	
3204	2000	1	1.5	0.47			X						X		X	
3205	1999	2	1.2	0.29			X					X			X	
3302	2004	4	3	0.35				X				X				X
3303	2005	1	3.5	0.29				X				X				X
3305	2004	2	4.2	0.46				X					X			X
3402	1997	2	2.3	0.3					X			X				X
3405	1997	1	2.4	0.19					X			X				X
3406	2005	2	3.5	0.45					X			X				X
3503	2003	2	1.9	0.5						X		X				X
3505	2004	1	1.6	0.46						X		X				X
3508	2003	1	0.7	0.47						X		X		X		
3602	2004	1	4.1	0.24							X	X				X
3603	2003	1	2.5	0.73							X		X			X
3609	1999	2	2.7	0.48							X	X				X

2.2 Measurement methods

The air tightness of each house and apartment was measured with the standardized fan pressurization method, using ‘‘Minneapolis Blower Door Model 4’’ equipment with an automated performance testing system (flow range at 50 Pa 25–7.800m^3/h). All the exterior openings: windows and doors were closed; ventilation ducts and chimneys were sealed. To determine typical thermal bridge and air leakage places and their distribution, an infrared image camera FLIR ThermaCam P65 (thermal sensitivity of 0.08 °C, measurement range -40 °C to +500 °C) and a smoke detector were used. The difference between the indoor and the outdoor air temperature was at least 20 °C. Thermography investigations were done twice. First, to determine the thermal bridges, the surface temperature measurements were performed without any additional pressure difference. Next, to determine the air leakage places, the 50 Pa negative pressure under the envelope was set with fan pressurization equipment. After (~30…45 min) the infiltration airflow had cooled the inner surface of the envelope, the surface temperatures were measured with the infrared image camera from the inside of the building.

2.3 Assessment of thermal bridges and air leakages

Temperature factor was used to assess and to classify thermal bridges. The temperature factor at the internal surface ($f_{R.si}$, -) shows the relation of the total thermal resistance of the building envelope (R_T, (m^2·K)/W) to the thermal resistance of the building envelope without the internal surface resistance (R_{si}, (m^2·K)/W) and it depends on the indoor (T_i, °C) and the outdoor (T_e, °C) air temperature and on the temperature on the internal surface of the building envelope (T_{si}, °C), see Eq. 1.

$$\frac{R_T - R_{si}}{R_T} = f_{Rsi} = \frac{T_{si} - T_e}{T_i - T_e} \qquad (1)$$

Many countries have set limit values or guidelines for the temperature factor. According to Finnish instructions regarding housing health (Asumisterveysohje 2003) temperature factor for floors $f_{Rsi} \geq 0.97$ and for walls $f_{Rsi} \geq 0.87$ reflect good level and temperature factor for floors $f_{Rsi} \geq 0.87$ and for walls $f_{Rsi} \geq 0.81$ reflect tolerable level. Temperature factor values for the thermal bridge are $f_{Rsi} \geq 0.65$ on good level and $f_{Rsi} \geq 0.61$ on tolerable level (on the basis of an indoor temperature T_{in} +21 °C and relative humidity RH_{in} 45 %, an outdoor temperature T_{out} −10 °C, and the highest relative humidity at the surface of the building envelope RH_{si} 100 %). According to mould growth criterion in cold climate the temperature factor on the thermal bridge should be $f_{Rsi} \geq 0.80$ in dwellings with high occupancy and/or low ventilation (moisture excess Δv=6g/m^3 during cold period T_{out}<5°C) and $f_{Rsi} \geq 0.65$ in dwellings with low occupancy and normal ventilation (moisture excess Δv=4g/m^3 during cold period) (Kalamees 2006). In this study, temperature factor values were classified into five groups (characterisation of these groups is received also from the Finnish guide of thermography investigations of building, RT 14-10850 2005):

- f_{Rsi} <0.61 (includes healthy risks or hazards and should be repaired);
- f_{Rsi} 0.61…0.65 (possibility for healthy hazards or structure risks, the details/structure must be checked and repairing necessity should be clarified);
- f_{Rsi} 0.65…0.69 (includes obvious hygrothermal defects or faults but fulfils the requirements of the housing health)
- f_{Rsi} 0.70…0.74 (fulfils of the requirements of the good level, no risks in dwellings with low occupancy)
- f_{Rsi} 0.75…0.80 (includes some risk in dwellings with high occupancy and low occupancy)

Relative decrease of the surface temperature was used to determine and to classify air leakage places. Relative decrease of the surface temperature shows the relation of the difference between indoor (T_{in}, °C) and the outdoor (T_e, °C) air temperature to the temperature difference between internal surface of the building envelope measured before ($T_{s.i1}$, °C) and after ($T_{s.i2}$, °C) the depressurization, see Eq. 2.

$$\Delta T_s = \frac{T_{si1} - T_{si2}}{T_{in} - T_{out}} \times 100\% \qquad (2)$$

The values of the relative decrease of the surface temperature were classified into five groups: 5-9%, 10-14%, 20-24% 25-30%, and >30%.

Air leakage and thermal bridge places were classified according to location:

- penetrations through the air barrier system;
- junction of external wall with the base floor;
- junction of external wall with the intermediate floor;
- junction of external wall with the attic floor of roof;
- junction of external wall with the external or separating wall;
- doors and windows;

and according to the shape:

- linear;
- spot.

3. Results

In statistical analysis, measurement data from 21 detach house and 13 apartment building was used. Figure 1 shows the example of measurement procedure of a junction of external wall and attic floor.

3.1 Thermal bridges

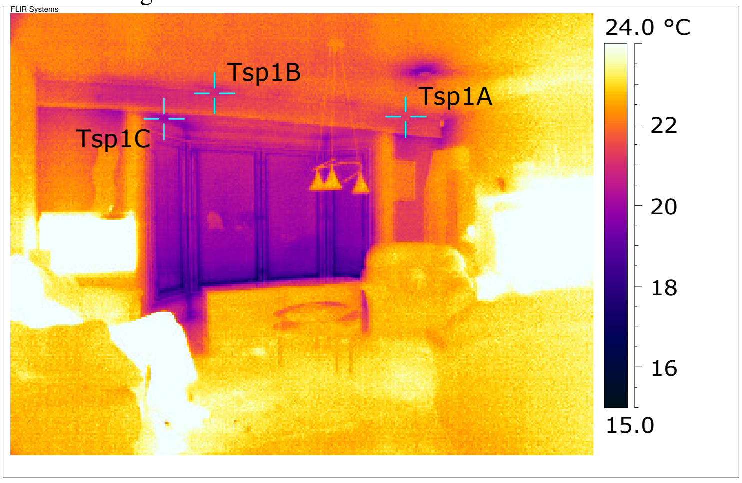
Typical thermal bridges in the studied dwellings were around the doors and windows, Figure 2 left. These thermal bridges include both thermal bridges of windows and doors in themselves and in connections of windows and doors with building envelope. In addition, at normal conditions, low surface temperatures were determined also in the junction of external wall with base floor, intermediate floor, attic floor or roof and with external or separating walls. One fourth of the determined thermal bridges were severe (f_{Rs}<0.65). Figure 2 right shows the distribution of severe thermal bridges in detached houses. In apartments, all the severe thermal bridges were around the doors and windows.

Picture

Detached house:

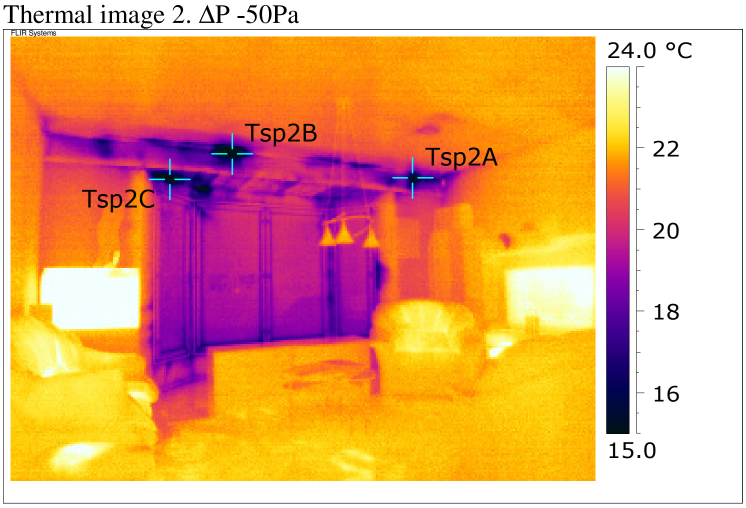
Attic floor: timber frame structure, plastic air/vapour barrier (joints taped);
External wall: concrete sandwich element;
Base floor: insulated concrete panel with crawl space;
Air leakage rate of the building envelope: n_{50}: 2.5 1/h
Ventilation system: mechanical supply and exhaust with heat recovery (CO_2 controlled)
Air change rate on using level: 0.73 1/h
Heating system: floor heating with water
Year of construction: 2003

Thermal image 1. ΔP -4Pa



Environmental conditions	
Outdoor temperature	-1.7 °C
Indoor temperature	+21.5 °C
Measurement results	
T_{sp1A}	+21.2 °C
T_{sp1B}	+20.8 °C
T_{sp1C}	+19.9 °C
Temperature factor	
$f_{Rsi\ sp2A}$	0.99
$f_{Rsi\ sp2B}$	0.97
$f_{Rsi\ sp2C}$	0.93

Thermal image 2. ΔP -50Pa



Environmental conditions	
Outdoor temperature	-1.7 °C
Indoor temperature	+21.5 °C
Measurement results	
T_{sp2A}	+14.3 °C
T_{sp2B}	+12.8 °C
T_{sp2C}	+13.5 °C
Temperature factor	
$f_{Rsi\ sp2A}$	0.69
$f_{Rsi\ sp2B}$	0.62
$f_{Rsi\ sp2C}$	0.65
Relative decrease of surface temperature	
ΔT_{SA}	30%
ΔT_{SB}	34%
ΔT_{SC}	28%

FIG 1. Air leakage on the junction of the wall and attic floor

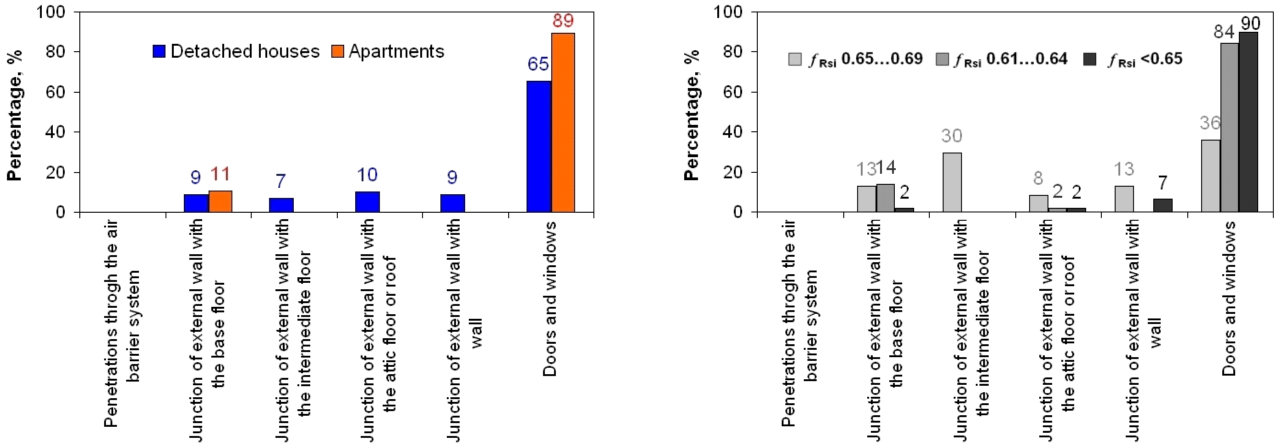


FIG 2. Location (left) of the thermal bridges f_{Rsi}<0.8 and severity of the thermal bridges in detached houses (right)

76% on houses had no thermal bridges in junction of overall building envelope and 48% on houses had no thermal bridges around the doors and windows, Figure 3 left. 77% on apartments had no thermal bridges around the doors and windows, Figure 3 right.

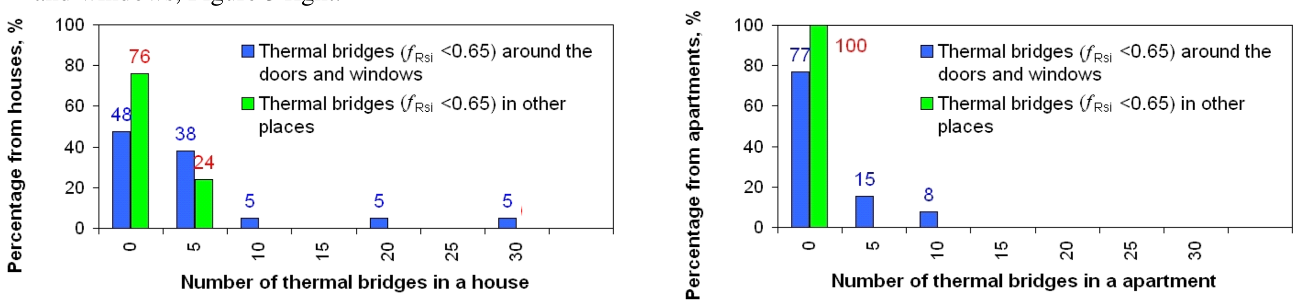


FIG 3. Number of severe thermal bridges f_{Rsi}<0.65 in detached houses (left) and in apartments (right)

3.2 Air leakages

Typical air leakage places were around and through windows and doors, in the junction of ceiling/floor with the external wall, penetrations through the air barrier systems, and walls and floors between apartments, Figure 4 left. The main typical air leakage place was in detached houses in the junction of the roof and the external wall (Figure 4 right). In apartments most typical air leakage was around the doors and windows.

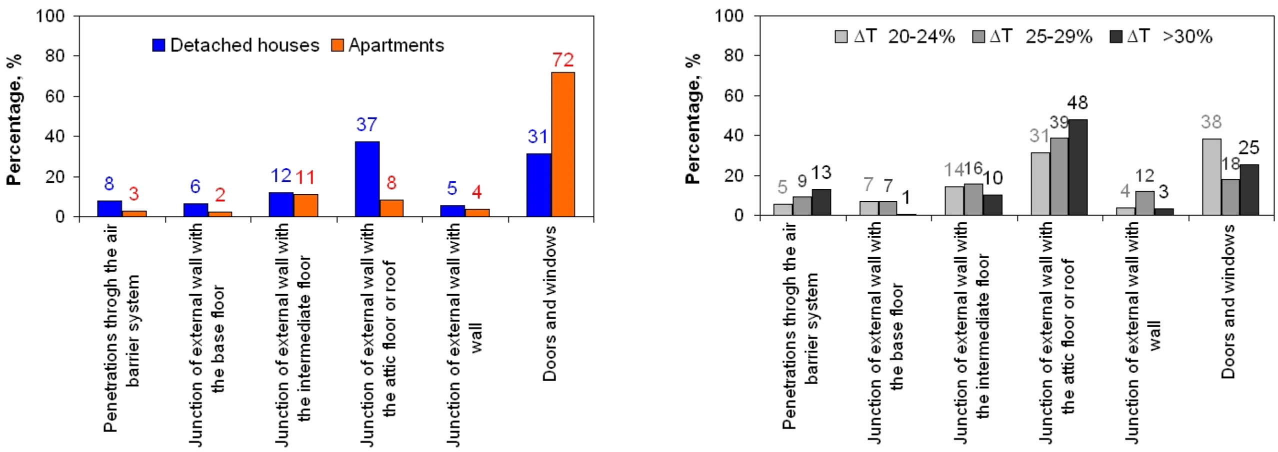
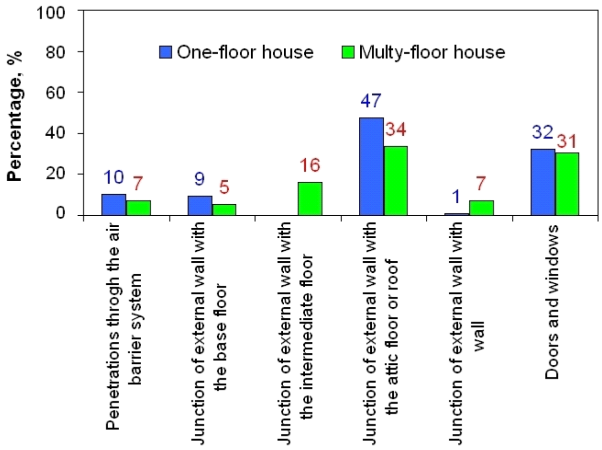


FIG 4. Location of the air leakage places (left) and severity of the air leakage places in detached houses (right)

4. Discussion

In this study, the distributions of the air leakage places and thermal bridges were analysed in detached houses and apartment buildings. Field measurements of the airtightness and thermography measurements have been carried out in 21 detached houses with different structures and in 16 apartments during the years 2005-2007 in Finland.

In the current study, one of the main typical air leakage places in detached houses was in the junction of roof with external wall. Another study (Kalamees 2007) has shown that one of the main critical junctions is also the junction between intermediate floor and external wall. The distributions of thermal bridges and air leakage places are influenced by their representation. For example, there is no junction of intermediate floor and external wall in one-storey detached house and not all apartments have a junction of roof and external wall. Therefore, measured data from one-storey houses and multi-storey houses, as well as data from apartments in the first, last and intermediate floor were analysed separately. Figure 5 shows the influence of the number of floors to the distribution of air leakage places. Especially the junction of external wall and intermediate floor, attic floor or roof are compared.



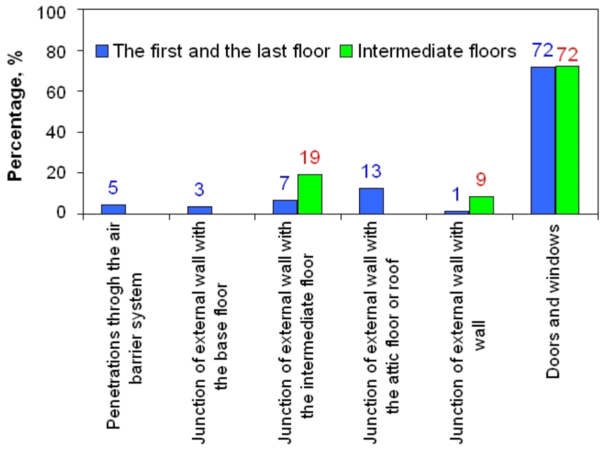


FIG 5. The distribution of air leakage places in detached houses with different number of floors (left) and in apartments on different floors (right)

Relative decrease of the surface temperature was used to determine and to classify air leakage places. If the junction has also a thermal bridge, this factor shows lower criticality than a junction without thermal bridge does. Different air leakage paths affect the temperature profile and two air leakages with the same airflow may show different surface temperature. Therefore, the relative decrease of the surface temperature is not direct and absolute characteristic of air leakage.

5. Conclusions

In this study, typical air leakages and thermal bridges and their distribution were statistically analysed based on field measurements in 21 detached houses and 16 apartments. Temperature factor was used to determine and to classify thermal bridges. Relative decrease of the surface temperature was used to determine and to classify air leakage places.

Severe thermal bridges are not typical failure in new Finnish dwellings. Typical thermal bridges in the studied detached houses were around the doors and windows. Low temperatures were determined also in the junction of the base floor with the external wall. Typical air leakages in detached houses were in the junction of roof with the external wall, penetrations through the air barrier systems, and around and through windows and doors.

Typical thermal bridges in the studied apartments were around the doors and windows. Typical air leakages in apartments were around and through windows and doors, in the junction of ceiling/floor with the external wall, penetrations through the air barrier systems, and walls and floors between apartments.

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